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Groundwater Models for Watersheds

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by

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Certificate

This is to certify that the M.tech stage II report titled **"GROUNDWATER MODELS FOR WATERSHEDS"** prepared by Parth Gupta is approved for submission at Centre for Technology Alternatives for Rural Areas (CTARA), IIT Bombay, Powai.

Signature of Guide

Prof. Milind Sohoni

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<u>Declaration</u>

I hereby declare that the report entitled "**GROUNDWATER MODELS FOR WATERSHEDS**" submitted by me, for the partial fulfilment of the degree of Master of Technology to CTARA, IIT Bombay is a record of the work carried out by me under the supervision of Prof. Milind Sohoni.

I further declare that this written submission represents my ideas in my own words and where other's ideas or words have been included, I have adequately cited and referenced the original sources. I affirm that I have adhered to all principles of academic honesty and integrity and have not misrepresented or falsified any idea/data/fact/source to the best of my knowledge. I understand that any violation of the above will cause for disciplinary action by the Institute and can also evoke penal action from the sources which have not been cited properly.

Place: Mumbai

Date: 22.06.2016 Signature of the candidate

<u>Acknowledgement</u>

It is matter of great pleasure for me to submit this report on "**Groundwater Model For Watersheds**" as a part curriculum of **TD-696** of Centre for Technology Alternatives for Rural Areas (CTARA) with specialization in Technology & Development from IIT Bombay.

I express my sincere gratitude to my guide **Prof. Milind Sohoni** for encouraging me to take up this topic and extending his constant support and guidance. I specially thanks Hemant Belsare for his guidance and encouragement. I also thank all my friends for their constant help.

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List of Abbreviations

BPCL	Bharat Petroleum Corporation Ltd.
CNBs	Cement Nala Bunds
CSR	Corporate Social Responsibility
GIS	Geographical Information System
GoM	Government of Maharashtra
GMS	Groundwater modelling software
GRASS	Geographic Resources Analysis Support System
GR	Government Resolution
GSDA	Groundwater Survey and Development Agency
IWMP	Integrated Watershed Management Programme
JYS	Jal Yukta Shivar Abhiyan
MGNREGS	Mahatma Gandhi National Rural Employment Guarantee Scheme
QGIS	Quantum Geographic Information System
NGOs	Non-Governmental Organizations
NRDWP	National Rural Drinking Water Programme
ZP	Zilla Parishad

Abstract

When the well is dry, we learn the worth of water. Drought is a complex phenomenon and its prediction is not easy. Development of ground water becomes even more important when drinking water is supplied mainly by shallow dug wells. But the ground water estimation methodology used by GSDA do not predict the stage of ground water development in hilly areas accurately. Impacts of drought in these areas are largely determined by the amount of water available in a shallow aquifer. In this project, an innovative model has been developed especially for predicting water scarcity, amount of base flows present in the region and water available in the aquifer for further development. This project is carried out in a tribal dominated watershed of Mokhada taluka. This model is based on the fluctuation of water level and flows observed in the area. The model is prepared on the basis of geological and hydrogeological features of the watershed. The model can predict the scenarios of groundwater scarcity based upon the duration of monsoons in the region. Further, it can predict the amount of water available for protective irrigation and where it can be done. The impact of various interventions like afforestation on the amount and duration of base flows can also be analysed using this model.

Chapter 1 Introduction

1.1 Background

In Maharashtra, people of rural and to some extent urban population are dependent upon groundwater. Since water is spatial and timely uneven in the region it's computation and management is a cumbersome task. With the increase in the number of wells and water extraction technology water is becoming scarce in this region. As the difference between demand and supply increases, there is need to estimate groundwater resources accurately. The exercise of groundwater budgeting is carried out by central groundwater board (CGWB), ministry of water resources with the help of respective state departments. The central government from time to time has appointed various committees to give guidelines for groundwater water estimation. First such attempt was made in 1973. Latest guidelines proposed by the groundwater estimation committee known as GEC 97[1][2]. With little modification suggested by the R&D committee of GOI, GSDA has carried out the latest budgeting exercise in 2011-12. Since groundwater extraction varies every year and amount of rainfall also varies every year, this exercise of groundwater budgeting needs to be carried out every year. This exercise requires huge amount of data sets such as well census data, rainfall data, and data from agriculture department. Doing this exercise every year is not possible. GSDA carries out this exercise every two years. There are some problems with groundwater estimation methodology. The same methodology cannot be applied in every region of Maharashtra. To make the exercise less time consuming and more accurate a present study has been proposed.

1.2 Ground Water Resource Estimation Methodology

Here we summarize the report on groundwater resource estimation policy in DYNAMIC GROUNDWATER RESOURCES OF MAHARASHTRA prepared by GSDA [1]. GSDA uses the Ground Water Resources Methodology - 1997 (GEC'97) in estimating the ground-water resources. They mainly uses two methods, one is Water Level Fluctuation (WLF) method and the other is Rainfall infiltration (RIF) Method in groundwater recharge assessment. They use watershed as the groundwater assessment unit. They remove the areas of hilly regions which have slope greater than 20% and other bad quality groundwater area from total assessment unit area and use the remaining area for estimation. Next they do the assessment in the monsoon period with the WLF method. The monsoon recharge is expressed as

$$R = h * S_y * A + D_G$$

Where h is the rise in water table in monsoon period, S_y is the specific yield, A is the area for computation of recharge and D_G is gross groundwater draft during monsoons. Rainfall is not the only source to groundwater recharge in monsoon period, there is recharge from canals, ponds, and irrigation etc. This correction improves the equation.

After assessing the recharge with WLF, GSDA compares the values of recharge with RIF values. If the difference is more than 20% then RIF values for the monsoon period recharge is used. GSDA uses RIF method to assess the recharge in non-monsoon period. Total annual groundwater recharge is sum of monsoon and non-monsoon recharge. Then they compute the total annual groundwater availability using following expression.

Net Groundwater Availability=Annual Groundwater Recharge - Natural Discharge in Non-monsoon

Table 1 Categorizing criteria for Assessment units

Stage Of GW Development	Significant Long Term Decline		Category
	Pre-Monsoon	Post- Monsoon	
70 %	No	No	SAFE
> 70 to 90 %	No	No	SAFE
> 70 to 90 %	Yes/No	No/Yes	SEMI CRITICAL
> 90 to 100 %	Yes/No	No/Yes	SEMI CRITICAL
> 90 to 100 %	Yes	Yes	CRITICAL
> 100 %	Yes/No	No/Yes	OVER EXPLOITED
> 100 %	Yes	Yes	OVER EXPLOITED

Ground Water Draft is total groundwater extraction from existing groundwater structures in monsoon and non-monsoon periods. Using Net Groundwater Availability, Ground Water Draft they compute stage of ground water development percentage. They use Stage Of Groundwater Development % value and Significant Long Term Decline factor to classify the assessment area (watershed) in to 4 categories, i) Safe areas which have groundwater potential for development, ii) Semi-Critical areas where cautious groundwater development is recommended, iii) Critical areas, and iv) Over-exploited areas where there should be intensive monitoring and evaluation and future groundwater development be linked with water conservation measures. To determine Significant Long Term Decline factor value they use past 10 years data (pre-monsoon levels and post-monsoon levels as different time series) and they consider the long term decline or rise if water level change is greater than +5 or less than -5 cm per year.

Stage of Groundwater Development% =Ground water Draft/Net groundwater availability*100

Finally, the net annual available groundwater is distributed between domestic, industrial and irrigation usages in that priority order[3][4][5][6].

1.3 Water balance in WF 15 watershed using GSDA methodology

Using GSDA methodology water balance in the WF-15 watershed was calculated. This watershed contains 4 mini watershed and 83 micro watersheds. Total area of this watershed is 38889 ha. It has 12observation wells in the whole area. The major type of formation in the region is basalt. The region is hilly and totally rain fed. The specific yield in the region is 0.015[1]. This means that out of 1m thick layer 15 mm of water can be stored, which is very low. Infiltration factor in the region has been estimated to be only 3.5 %[1]. This means there is not much recharge happening in the region. Most of the rainfall which happens in the region is concentrated in small part of the year with high intensity. This gives very less time for recharge and most of water goes as surface runoff.

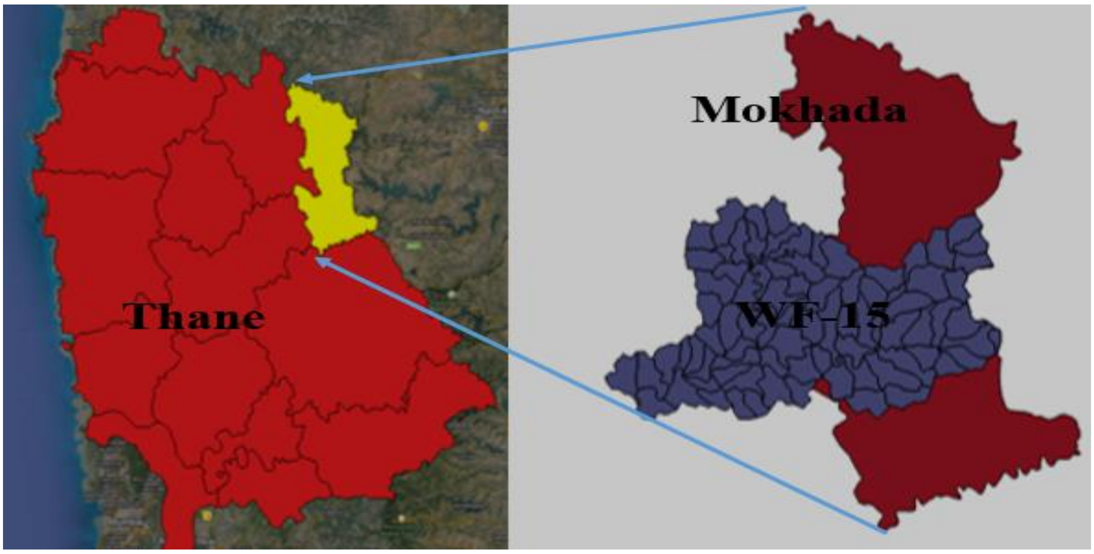


Figure 1 WF-15 watershed

There is usualy not much of water left for taking a second crop. There are few wells which are used for irrigation. The experience is that after taking first crop there is not much of water left in the region for a second crop which is reason for the less number of wells for irrigation. Due to this draft from these wells is not very significant. Moreover,beyond march there is frequently not much water left for meeting the drinking water and other domestic needs. An important reason that the administration has not been able to give much attention to this is because this scarcity never appears in the GSDA numbers.

Table 2 Characteristics of WF-15 Watershed

Rock	Area	Hilly	Command	Non-Command	Specific yield		Rainfall Infiltration
	Area in **ha**				Formation	Value	
Hard	38889	21497	183	17209	Weathered basalt	0.015	0.035

Assessment sub unit	Type	Irrigation	Domestic	Draft (ham)	
				Monsoon	Non
Command	Bore well with hand pump		14	0.03	0.07
Command	Bore well with power pump		1	0.06	0.12
Command	Drinking water manual		6	0.03	0.07
Non-command	Bore well with hand pump		118	0.03	0.07
Non-command	Bore well with power pump		1	0.06	0.12
Non-command	Dug well manual		150	0.03	0.07
Non-command	Dug well elect/diesel	34			0.44

To analyze the GSDA methdology, WF-15 watershed was slected. The area is underlain by basaltic terrain having very low specific yield. Rainfall in the region is typically high with annual ground water fluctuation of 5-6m. Infilteration rate observed by the GSDA is low.Using the GSDA data and methdology water balance of WF-15 watershed was calculated. Out of 38889ha total area 21497ha is hilly and only 17392ha is fit for groundwater recharge. Out of this 17392ha 17209 is non-command area while 183ha is command area. Water level for both the area is measured separately. Recharge in the area is calculated with both methods. After comparing WLF and RIF values, the difference comes out to be less than 20%. So, watertable fluctation method was used for calculating the recharge over the command and non command area. Recharge from other sources during monsoon and non-monsoon have been added to calculate the total groundwater recharge. Then 5 % of total annual ground water recharge has been used as natural discharge or baseflow going out of the system. Subtacting this value from the groundwater recharge gives net availability of groundwater. In net groundwater avaialbility domestic and industrial draft was accounted while calculating the recharge rate. So after subtracting irrigation draft and provision for future domestic and industrial requirement we get net groundwater availability which can be used for future irrigation development. Total present draft both domestic and irrigation divided by net ground water availability gives us stage of development. This in WF-15 watershed is under 4 %. But area faces accute water shortage. This is mainly due to the higher basflows and second case may be recharge is even less then what GSDA has been accounting. This is where calculation of surface runoff and baseflow for the region becomes important. Since recharge rate calculation is already very less possiblilty of higher baseflows is more.

Table 3 Water budget of WF-15 Using GEC Methodology (ham)

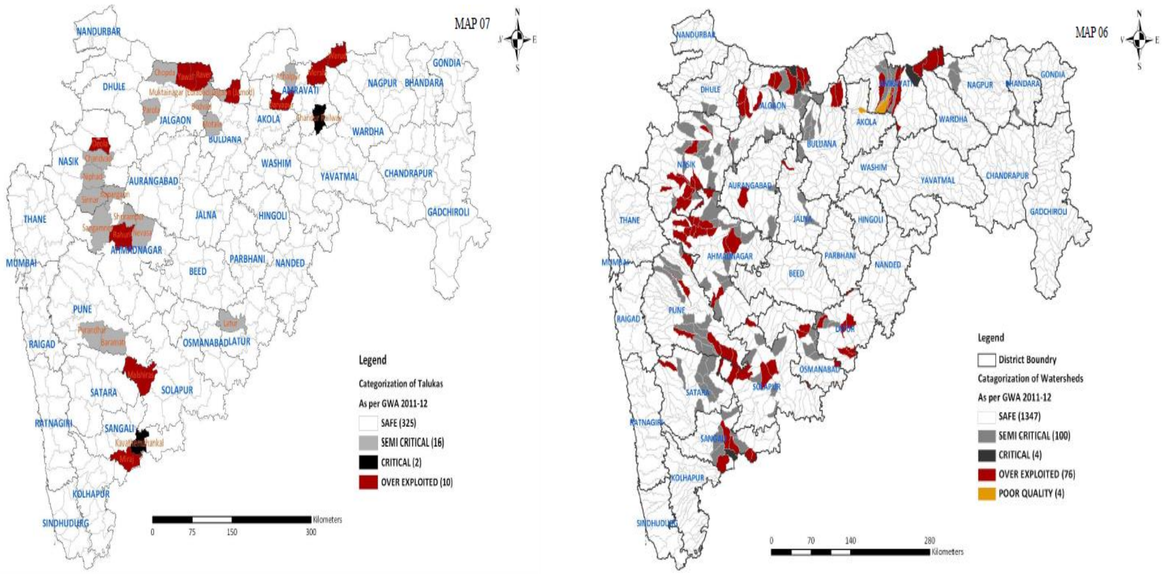
CMD / NCMD / Total	Recharge Monsoon		Recharge Non-Monsoon		Total available Groundwater Recharge (2+3+4+5)	Natural Discharge	Net Annual GWA (6-7)
	Rainfall	Other	Rainfall	Other			
2008-09							
CMD	13.51	5.98	0	8.46	27.95	1.40 (5%)	26.50
NCMD	1270.64	0.00	0	3.77	1274.42	63.72 (5%)	1210.70
Total	1284.16	5.98	0	12.24	1302.37	65.12	1237.25

Existing groundwater draft for			Provision for domestic & industrial Requirement Supply	Net Groundwater Availability For Irrigation Development (8-9-12)	SGWD {11/8 * 100}%
Irrigation	Domestic/Industrial	Total			
2008-09					
15.10	26.99	42.08			
15.10	29.17	44.26	58.24	1163.82	3.58

Assessment unit	Rainfall	Monsoon Table		Area
	mm	Pre m	Post m	ha
Command	2574.72	5.69	0.91	183
Non-Command	2477.00	5.04	0.54	17209
hilly				21497

1.3 Current stage of groundwater development in Maharashtra

GSDA carries out the groundwater estimation for 33 districts except Mumbai and Mumbai Suburb districts. Total 1531 watershed units have been delineated based on newly formed districts. On the basis of the current groundwater resource estimation, out of the total 1531 watersheds, 76 watersheds are categorized as Overexploited i.e. the groundwater development is more than 100% of the recharge and the water table during either Post or Pre monsoon interval or both shows declining trend. Four watersheds are categorized as Critical where groundwater development is between 90 to 100% of the recharge and where water table, either Post or Pre monsoon interval or both, shows significant declining trend and 100 watersheds are categorised as Semi-Critical where groundwater development is between 70 and 90% of the recharge and where water table, either Pre or Post monsoon interval, shows declining trend. Out of the total 353 talukas, 10 talukas are categorized as Overexploited, 2 talukas are categorized as Critical and 16 talukas are categorized as Semi-Critical. Out of 16 semi-critical taluka, in 7 taluka the exploitation is more than 95% i.e. they are on the verge of transformation into the Over-exploited category. It is revealed from the data that the areas which have emerged as overexploited, critical or semi-critical are predominantly from the DPAP areas, where there is highest percentage of water intensive commercial crops as well as low rainfall[1].



Source [1]

Figure 2 Overexploited zones of Maharashtra based on taluka and watershed

1.4 Problem Statement for WF-15

For the whole of Maharashtra GSDA follows the same methodology for groundwater estimation. Maharashtra has different rainfall regions, climate, and hydrologic parameters due to which same methodology cannot be applied everywhere. Places like Mokhada which have high annual rainfall in small period of time, falls in safe category according to GSDA norms. But during the months of April-June water in most of the wells dry up. According to GSDA stage of water development in Mokhada is 6-7%. The extraction of water for industrial and agriculture purpose is very less because there is hardly any water available for drinking purpose during the month of April-June. There can be two possible reasons for such a low stage of development**.** Either GSDA is overestimating the infiltration or groundwater recharge or it is underestimating the base flow or evapotranspiration. But GSDA is using very low factor of infiltration for the water budget calculation in Mokhada region which is 4-7%. It is important to look into both the components surface runoff and base flow to get the more accurate assessment.

Thus, to make the estimation process match ground realities is an important objective of this research. This will aid in the design of interventions which will address the three core problems of the region: (i) absence of protective irrigation in kharif, (ii) drinking water unavailability from March, and (iii) very low rabbi crop area

1.4 Need for assessment

Government of Maharashtra has launched its flagship program named Jal Yukta Shivar Abiyan whose purpose is to make Maharashtra water scarcity free by 2019. The JYS programme was notified by GoM through a Government Resolution (GR) dated 5th Dec 2014. The solution according to this GR is make all the villages self-sufficient in terms of water availability. This will be done through water conservation works which would aim to harvest maximum water within the village boundary. The works include several watershed interventions like building bunds, deepening and desilting existing bunds, ridge area treatment, farm ponds, farm bunds, funding micro-irrigation on farms, recharging drinking water wells and so on. The most important planning step is the estimation of village level water budget. The aim is to estimate the drinking water and agriculture water demand in the village and match it with the supply-side. Supply-side consists of rainfall and water availability created by existing or proposed water conservation structures [7]. There are number of watershed programs which are implemented in the Maharashtra. The Integrated Watershed Management Programme was developed to have better utilization of water and land resources. The programme mainly focuses on enhancing the land productivity and hence was very useful for India. From 2009, Integrated Watershed Development Programme (WF15-IWMP2) was introduced in Mokhada tehsil. The second IWMP (WF15-IWMP7) was started the following year, 2010. While IWMP2 was designed to cover 20 villages of Mokhada tehsil, IWMP7 covered 15 villages of the same tehsil. Calculation of water balance is important part of this programme [8].

Thus, constant need for village level assessments is yet another motivation for this work.

1.5 Maharashtra Ground Water Act

The Maharashtra ground water act, 2009 has made significant improvement over the previous act of 1993. Both are made to regulate the exploitation of groundwater in order to protect the public drinking water sources. In this act the Government of Maharashtra has defined some terms like public drinking water source, public water supply system, wells, watersheds and etc. According to this act a watershed is said to be over exploited if its annual groundwater extraction is more than 85% of estimated average annual recharge. In 1993 act, the major responsibility was given to district collector and technical officer (assistant geologist) for implementing this act. In the latest acts various bodies and committees have been created and powers have been given to them to implement this act. The following are the main points in this act

- The Watershed Water Resources Committee shall specify the cropping pattern for the area based on the water budget and a plan for the required withdrawal of groundwater, from the existing wells, for different usages like domestic, agriculture, industry or any other use, based on the Groundwater Use Plan.

- No one should sink any well within 500 m distance from the public drinking water source except the state government and concerned authorities. If anyone wants to sink a well he should get a prior permission from concerned authorities.

- The District Authority, Panchayat or Panchayat Samiti based on the advice of the GSDA or on the request of the Watershed Water Resources Committee or Panchayat by order, can declare an area to be a water scarcity area for particular period.

- After declaring an area as water scarcity area, district authorities can regulate the water extraction in wells that are within 1 km distance from a public drinking water source.

- On the advice of technical or concerned authority can declare an area as over exploited.

- These authorities can prohibit the sinking new wells or close down an existing well in or restrict the extraction of water from wells in over exploited areas.

- The authorities can also make orders to pay the compensation to owners of wells which are closed to protect the public water sources in case of causing any loss to owners.

- The District Authority shall enforce the decisions of the Watershed Water Resources Committee. Whenever it is necessary it should make an inquiry, undertake surveys or take levels thereon; conduct pumping tests and geophysical surveys, install and maintain water level recorder and water gauges on the well, inspect the well, seize any equipment or device utilised for illegal sinking to implement or enforce any decisions under this Act.

District watershed management committee shall prepare the integrated watershed development and management plan for the artificial recharge of groundwater on priority for notified areas and then for non-notified areas for the whole district with the help of the GSDA, watershed water resource committee and panchayat. This plan should be part of basin or sub basin wise plan for entire state. The decision of the committee shall be implemented by district authority. State water board shall integrate the integrated watershed development and management plan for whole state and should submit to the state watershed management council which will approve the entire plan.

District watershed management committee shall consist of the Guardian Minister of the District as Chairperson and one member of the State Legislature from the concerned area including such other members as may be prescribed to be nominated by the State Government. The Collector shall be the Member-Secretary of the District Watershed Management Committee**.**

District authority The State Government shall, by notification in the Official Gazette, designate any officer not below the rank of Tahsildar, to be the District Authority. It has power to notify Public Drinking Water Source, notification of area of influence and prohibition of construction of Wells within certain limits, Prohibition of extraction of water from existing well for a certain period, Protection of drinking water sources against contamination. The District Authority shall be assisted by Panchayat in sustainable management of drinking water sources and protection of drinking water sources during water scarcity, under this Act.

State Groundwater Authority the Maharashtra Water Resources Regulatory Authority established under section 3 of the Water Resources Act, shall be the State Groundwater Authority for the purposes of this Act. It has Powers to notify areas to regulate development and management of groundwater, Powers to de-notify areas, Protection of water quality, Registration of well owners in State, Prohibition of drilling of deep-wells, withdrawal of groundwater from existing deep-well and provision for levy of cess, Rain water harvesting for artificial recharge of groundwater, Groundwater Use Plan and Crop Plan, Guidelines for preventive measures, Registration of drilling agencies, Safety measures for well, Delegation of powers and duties of State Authority.

Watershed water resource committee The State Authority shall constitute a Watershed Water Resources Committee for the notified area comprising of area of more than eleven villages. The Watershed Water Resources Committee, with the technical support of the GSDA shall update the watershed or aquifer based groundwater use plan every year, monitor the withdrawal of the groundwater, ascertain the existing users of groundwater and owners of wells, the implementation of individual measures for artificial recharge of groundwater, specify the cropping pattern for the area based on the water budget. The Watershed Water Resources Committee shall recommend to the District Authority, the steps to be taken for regulation of groundwater. It shall recommend measures to the State Government, Panchayat, Panchayat Samiti, or urban local body to augment the groundwater resources in the area. No person shall sink a well in the notified area without the prior permission of the Watershed Water Resources Committee. Watershed Water Resources Committee shall be responsible for the concept of community ownership of the groundwater, the concept of protection of the rights of the small and marginal farmers. The decisions of the Watershed Water Resources Committee which are regulatory in nature shall be executed by the District Authority.

In most of the government schemes either its drinking water, rural water or bulk water schemes estimation of groundwater budget is an important activity. Even for district collector knowing the water budget for approving the various schemes is very important. Knowing the ground water balance is important need but with current GSDA methodology water balance calculations are not accurate. Hence there is need to improve the current GEC 97 methodology. There is need to build the predictive models which can predict the future ground water level based upon the groundwater use and changing rainfall pattern. There has been some work done to improve the estimation using the same data as used by GSDA. [9]. Some work has been done to build a decision support tool based upon mathematical models to predict the water scarcity based upon the real time data.("Institute for Resource Analysis and Policy , Hyderabad report,"2015).

This act also talks about preparation of water budget before deciding cropping pattern. This is another motivation for exploring new techniques for calculating water budget.

1.6 Soil Water Assessment Tool

Soil water assessment tool (SWAT) is a basin or watershed level model which can be used to predict the impact of change in land use, weather, variation of soils on the water, sediment, agricultural yield, chemicals over long period of time [10][11]. SWAT uses a Hydrologic Response Unit (HRU) concept to subdivide the watershed into smaller units, with the assumption that within these individual units the watershed responds uniformly to hydrologic processes. This software takes into account the change in land use, soils and external parameters, this was the prime reason for its use. As it does not take into the interactions among the various HRU's, this becomes its major shortcoming in modelling the ground water parameters. But we can still use some output components from this software, which can be combined with other software's like modflow which are dedicated for groundwater modelling. These output can also be used to manually build local model.

Significant model improvements are needed before SWAT can be used for applications in groundwater budgeting. Furthermore, SWAT has been criticized for its use of the SCS Curve Number, its large of number of empirical parameters, and its inability to distinguish between streamflow-generating processes, (specifically infiltration excess runoff and saturation excess runoff).

1.7 Objective

From the above analysis of GSDA methodology we can conclude that it fails to predict the ground water scarcity in many areas. There is significant amount of base flows are present in the region. Improving this number in calculation can improve the estimation methdodology. There is very less work done in the field of modelling hard rock aquifers. Finding a way to model hard rock aquifers is very challenging task. Since water is very scarce in the region it is very difficult to tell whether there is water left for the protective irrigation. How much area can be brought under Rabi crop? There are many villages in the region which face drinking water problem. These villages are tanker fed in the month of April and May. What kind of interventions can help in improving the current situation?

Main objective of study is

- To develop a conceptual model for groundwater budgeting using GIS, MODFLOW and other possible techniques, which can strengthen the current GSDA methodology.
- To model the hard rock terrain.
- To see the availability of groundwater in the region.
- To see what kind of interventions can improve the current scenario.

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Chapter 2 Literature review

The groundwater models can be used as predictive tools with the objective of determination of future conditions or the impact of a proposed action on existing conditions of the subsurface groundwater regime. There are a number of integrated models which have been developed in the past 10 to 20 years including, MIKE SHE, HMS, SWATMOD, MODBRANCH, and FHM. Many of these software's try to link the surface and groundwater interactions. MIKE SHE can predict the transportation of solutes and sediments in the ground and surface water. HMS is a basin level model. SWAT does not simulate water in the unsaturated zone. Percolation is directly applied to the water table. MODBRANCH can simulate the interactions between the streams and subsurface flow. FHM is an integrated hydrologic surface water and ground water model. It is made of two public domain components: HSPF and MODFLOW models. All these software's use modflow to simulate the confined and unconfined aquifer flow[12]. MIKE SHE can simulate both the surface and groundwater flow. If we need to simulate all the hydrologic conditions like runoff, infiltration, evapotranspiration and unsaturated flow then MIKE SHE is good option. On the other hand our work is limited to Groundwater only then MODFLOW is better option [13]. Since we are manually calculating the recharge rate we will be using MODFLOW in the current studies. There are few stream flow observations and we model them through the drain module of MODFLOW.

MODFLOW, supported by the USGS, computes aquifer flows and storages [14]. MODFLOW was developed to simulate ground water flow in three dimensions using a block-centered, finite-difference approach. It provides for simulation of unconfined and confined ground water flow conditions.

In hard rocks, thickness of unconfined shallow aquifer is few meters. Groundwater occurs in the weathered and fractured layers under unconfined to semiconfined conditions, which have specific hydrodynamic properties from the top to the bottom. In such cases quantification of groundwater is important as well as difficult. In Indian peninsular 80% of the region is overlain by hard rock aquifers. Although it's difficult to model the ground water through such areas due to heterogeneity present in such areas, it gives valuable insights in the area by building models which uses bore logs. Many researchers have successfully modelled the inflows and outflows including base flows and lateral flows through such aquifers[15], [16]. A three-dimensional groundwater flow model for the Osmansagar and Himayathsagar catchments—a semiarid hard rock area in India with two conceptual layers—is developed under transient conditions using visual MODFLOW [17]. In Musi sub Basin of Krishna River, MODFLOW has been successfully used to predict the different components of base flow. The results were consistent and give better results than WTF method [18]. Studies have been done to estimate the amount of water to be pumped out of mines and appropriate pumping locations of pumping. In Andhra Pradesh, India, six workable coal seams have been identified in Barakar formation by the analysis of the geologic logs of 183borewells. A groundwater flow model is developed with twenty conceptual layers and with a total thickness of 320m.The flow model was calibrated under steady state conditions and predicted ground water inflows into the nine pits at different mine development stages[19]. The groundwater flow and particle tracking modelling was carried out to determine in detail the groundwater flow and particle migration in the shallow unconfined aquifer of the Upper Anga'a river watershed. Flow model results indicated that the topography controls groundwater flow in the watershed and that base flow to river is an important factor moderating groundwater movement in the Anga'a river watershed [20]. The groundwater flow model for a tannery belt using Visual MODFLOW has been developed for analysing groundwater velocity and its response to various pumping strategies in two stages, viz., steady and transient conditions [21][22]. Sometimes in data scarce region a single approach for finding the possible reasons for water scarcity may not be useful. The multiple-hypothesis approach presents a systematic way to quantify the relative contribution of proximate anthropogenic and climate drivers to hydrological change [23]. Modflow has been successfully used to manage the artificial recharge and impact of interventions in areas[24][25].

One of the purpose of modelling is to simulate the situation or scenarios closest to the ground reality. Our model will give better results if it is simulated closer to actual ground reality. Care should be taken while building these models as small error in model can give adverse results[26]. Hence building of Conceptual model should be carefully done which is the first part for any watershed and aquifer level simulation. Conceptual model help us to design the number of layers type of rock, soil depth, boundary conditions and grid size [27] [28]. When modelling the aquifer, the size of the grid is important. Geostatistical approach based on the variogram concept is used for decisions about the size of a grid network applicable to a groundwater model. One of the important properties of the variogram function is the range of influence, which is interpreted as a measure of similarity and correlation distance between spatial phenomena [29]. GIS is an important tool in development of conceptual model for any groundwater flow and contaminate transport problem. GIS offers data management and spatial analysis capabilities that can be useful in groundwater modelling [28]. Remote sensing is another useful tool in the acquisition of spatially distributed data for groundwater modelling. Airborne geophysical surveys allow for the identification of faults and dikes, changes in lithology.

Since we are using modflow we need to give it recharge rate as input. For this knowing of rainfall runoff in the watershed is important. One of the popular methods for computing the depth of surface runoff for a given rainfall event is the Soil Conservation Service Curve Number (SCS-CN) method. Many software's use this method to compute the runoff from the rainfall data. But over the period of time many changes have suggested in this method. The important modified versions of the method include Mishra and Singh (MS) model[30], [31], [15], [32]Sahu model and SME model. The results indicated that the SME and the Sahu et al. model perform equally well compared to each other, and the duo perform consistently better than the original SCS-type method. The performance of the MS model is found to be better than the Michel et al. model[33].

Hemant Belsare in his report has tried to build the groundwater model for the Mograj area and Ikrichpada in Raigad and Palghar districts respectively. He proposed the use of GMS to see the effects of Contour trenches in the area. This tool which lies over modflow can be used to see the effect of CNB's structures on streams and its impact on nearby wells. This can be done by building stream level model (Belsare, 2012)(Belsare, 2013).

In our report we are focussing on building watershed model which can be used for calculating the ground water balance at village level. Once the model is ready we can calculate the water balance based upon the administrative boundaries. We are using drains to model the streams in hard rocks. This helped us is predicting the base flows in the region.

Chapter 3 Description and analysis of Study area

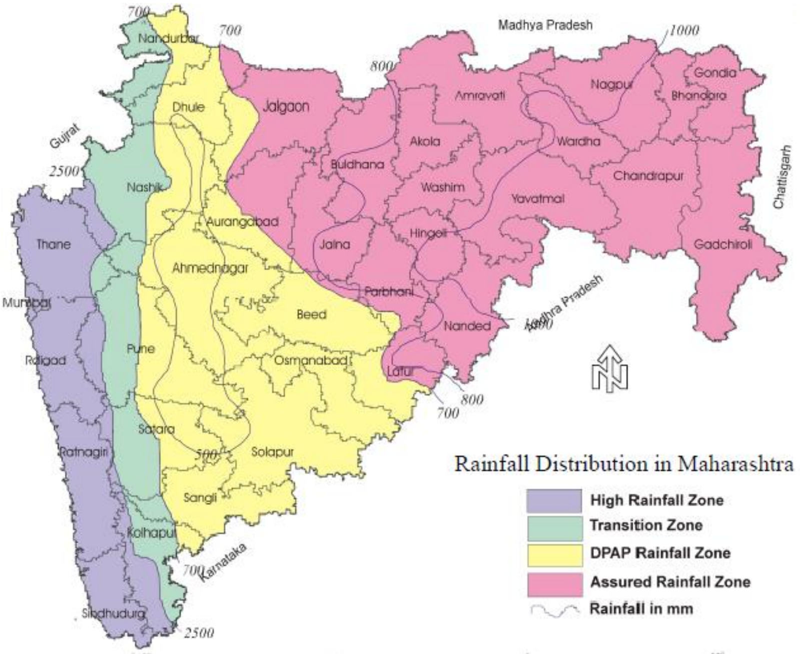
3.1 Geography and region

As Mokhada taluka is situated in the northern part of Western Ghats, the region is hilly and mountainous with varying slopes. The elevation in Mokhada varies from 175-650m. The area is covered with forests. Two major rivers Waal and Wagh flow through the region. The rivers are flooded during monsoon season, but significantly dry up during dry months. It consists of 28 gram panchayats, 59 villages and 236 habitations. The area of Mokhada taluka is 494.8 km^2 and its perimeter is 169.3 km. Total number of household in Mokhada is 17789. Total population of taluka is 83453. Male's population is 41691and female population is 41762. ST population of taluka is 76,842. All the population falls in rural category. This tells us that most of the taluka is tribal dominated[36].

3.2 Climate

It falls in the high rainfall zone of the north Konkan agro-climatic zone. The region receives very high rainfall (between 2000 mm and 3000 mm per annum) from south-west monsoon winds in the months of July to September. In spite of such heavy rainfall, the region faces acute water scarcity in the dry season. This is due to hilly terrain because of which most of the rainwater runs off quickly.

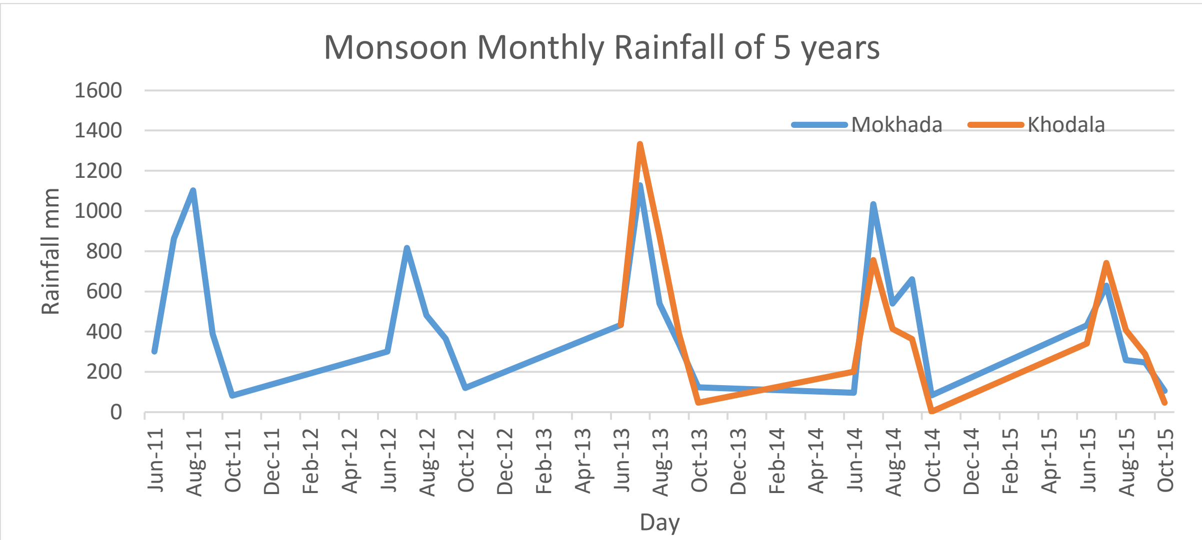
Thus, much of the rainwater is lost as surface runoff due to hill slopes and very shallow hard rock, resulting in very low infiltration. This leads to very low yields of the wells in the region, on which the people depend for their drinking water. The wells go dry in few months of post-monsoon. This compels the people to depend largely on irregular and insufficient tanker-supply for their drinking water and domestic needs in the dry months from March to May. The temperature in the region ranges from 10°C and 38°C but daily variation of temperature ranges from 10°C to 15°C.



Source [1]

Figure 3 Agro climatic zones of Maharashtra

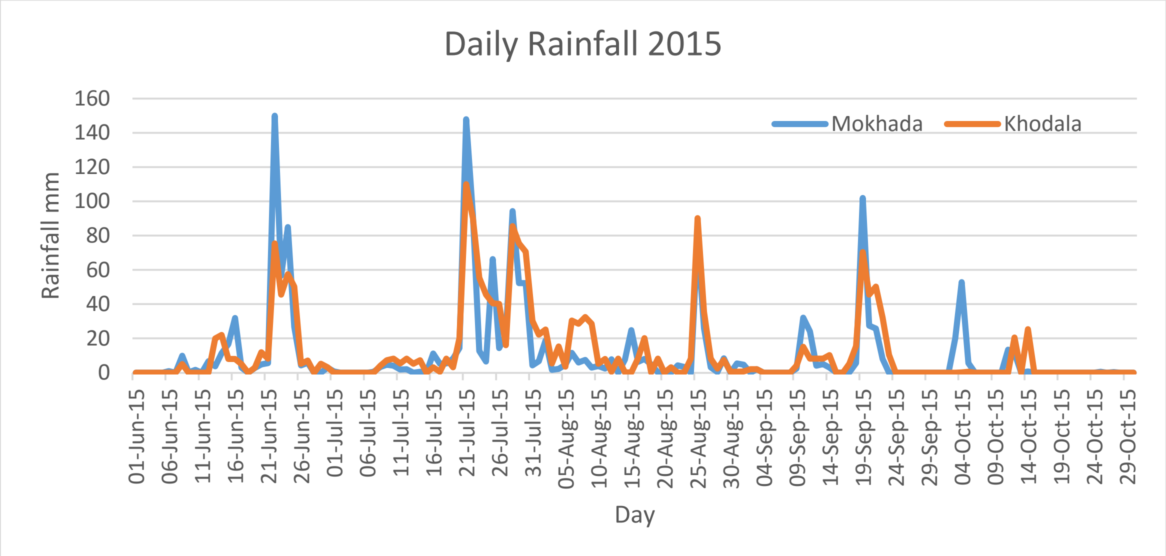
The region does not receive much rainfall throughout the year except for the months of monsoons. Due to this rainfall data of June, July, August, September and October is plotted. The following figure shows the monthly rainfall of 5 years for the Mokhada taluka in two circles Mokhada and khodala. Even though both the circles are close to each other still they show different amount of rainfall received. Khodala circle started working only three years back. The date of onset of monsoon is very important in predicting the different scenarios in region. It becomes very important to measure the rainfall within the region as close to each other receives different amount of rainfall.



Source http://maharain.gov.in/

Figure 4 Monsoon Monthly Rainfall of 5 years

Both the region shows different amount of rainfall received with Mokhada circle showing more rainfall. This analysis become important when we want to see the duration of dry spells with in region. As we can clearly see the region has a dry spell of 15 days in between the monsoons. This helps up to predict the drought behaviour of the region. The region has received last rainfall around 15 October. Without this 2-3 days rainfall around 15 October which helped the aquifer to recharge itself again, the region would have faced water crisis 20-30 days earlier than the current scenario. This makes the monitoring of rainfall even more important as ultimate goal of the government is to increase the availability of water in these regions for longer period of time.



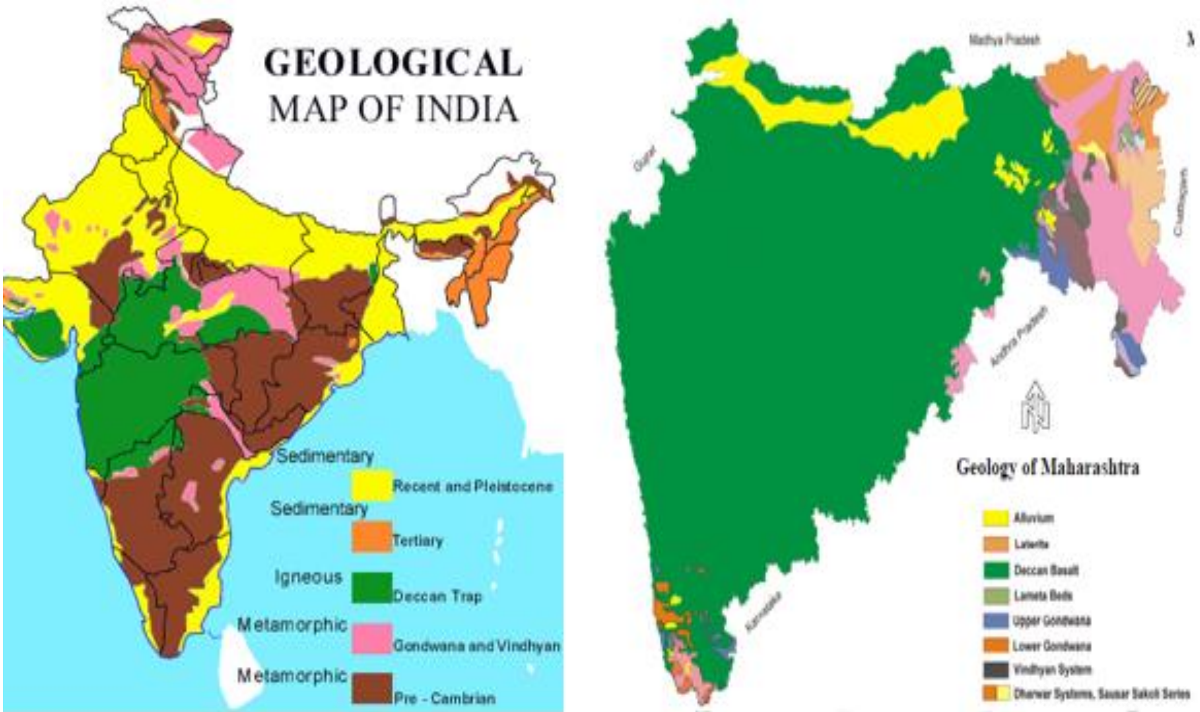
Source http://maharain.gov.in/

Figure 5 Daily Rainfall 2015

In this chapter an attempt is made to describe the physical framework of the watershed and to understand the groundwater system. Base-level hydrogeological investigation was made to describe the makeup of watershed, to map the various aspects like land use and land cover using remote sensing and GIS platform.

3.3 Regional Geology

The geology and geohydrology plays an important role in studying the groundwater availability in the region. The region is a part of Deccan Basalt which is formed from solidification of molten lava. It is made of several successive flows of basalt (igneous rock) of variable thickness and lateral extent, commonly known as Deccan Traps. The Deccan volcanic province of the western central India marks an important geological feature. It covers an area of 500000km2. The Deccan basalt trap covers more than 80% of the Maharashtra[37]. It also extends into the adjoining states of Gujarat, Madhya Pradesh, Karnataka and Andhra Pradesh. The type of basalts, amount of weathering and intensity of fracturing controls the occurrence, movement and storage of groundwater. These basalts are disposed in the form of tabular sheets of lava stacked one over the other. All over the world basaltic flows are classified into two major morphological types Pahoehoe and AA. The surface texture produced during the placement of these lava decide the nature of flow. If lava cools slowly and does not move too fast it forms smooth ropy lava called pahoehoe. However, if it cools quickly and moves fast it can tear into clinkery pieces called AA[38]. If lava slows, cools, and stops in direct response to the corresponding increase in viscosity only, it retains its pahoehoe form. If lava is forced to continue flowing after a certain critical relationship between viscosity and rate of shear strain is achieved, the lava changes to AA[39].



Source [1], http://www.mapsofindia.com/maps/india/geological.htm

Figure 6 Geology of Region

The term simple and compound flow is completely different from Pahoehoe and AA. The simple flows are generally formed by effusive eruption of large quantity of low viscosity lava. The compound flow is formed due to the explosive activity or high viscous lava. Viscosity can be increased due to Colling and degassing. Compound flow is related to presence of number of units. The characterization does not depend upon the physical character of the lava. Simple flows are devoid of basalt flow units whereas compound flows consist of number of overlapping units**.** Pahoehoe are mostly compound where as AA rarely shows this character.

The area around Jawhar and Mokhada exposes the two oldest formation in the chemo stratigraphy of the Deccan traps. This Jawhar and Mokhada formation is made up of the simple compact flows. Above this formation is Igatpuri formation consisting of compound pahoehoe flows. There is Giant phenocryst basalt (GPB) which helps in dividing both the plates. One can initially identify this feature while travelling from Jawhar to Mokhada.

3.4 Watershed Area

Our study area is located in the central part of Mokhada taluka. The area is located in the SW quadrant of the Survey of India Toposheet 47 E/5. The area is bounded by latitudes 19°51'5.48''E and 19°46'53.61''E and by longitudes 73°21'51''N and 73°27'34.88''N. The watershed covers an Area of 4273.52 ha can be approached from the Jawhar or from Mokhada, coming from Mumbai or Nashik respectively. For the convenience purpose the watershed in the current report will be referred as Adoshi watershed. This region is typically in the undulating topography of region and valleys. This region lies on the divide which separate the Deccan upland plateau and Konkan coastal belt.

3.4.1 Watershed Description delineation

GSDA does the water budgeting of a region based on small number of observation wells. Due to this it can over and underestimate the groundwater budget. Keeping this thing in mind duration of project and the resources available, we have selected a smaller watershed with more number of wells which can be covered in the given time period. The NGO Aroehan who is actively working in the area and has done large number of interventions to improve the groundwater recharge. They have built a subsurface bund in the Adoshi village. Taking this as outlet point we have delineated a watershed. Creation of subsurface bunds or cement bunds have played an important role in improving the water scarcity of the area. Due to construction of bund, not only has the water situation improved but area under Rabi crop has increased. For our study, this structure and its watershed has been selected.

The area of its watershed has been delineated using the Qgis and Grass. GRASS GIS, commonly referred to as GRASS (Geographic Resources Analysis Support System), is a free and open source Geographic Information System (GIS) software suite used for geospatial data management and analysis, image processing, graphics and maps production, spatial modelling, and visualization. SRTM (http://earthexplorer.usgs.gov/) DEM (digital elevation model) has been used for the purpose of watershed delineation. All the cells in the DEM which are being drained by the 100 cells are delineated as streams in the area. Giving this subsurface bund as outlet in QGIS Grass module we have obtained the given watershed for this structure. This helps us in monitoring the discharge through the area and also gives an area on which certain boundary conditions can be assumed.

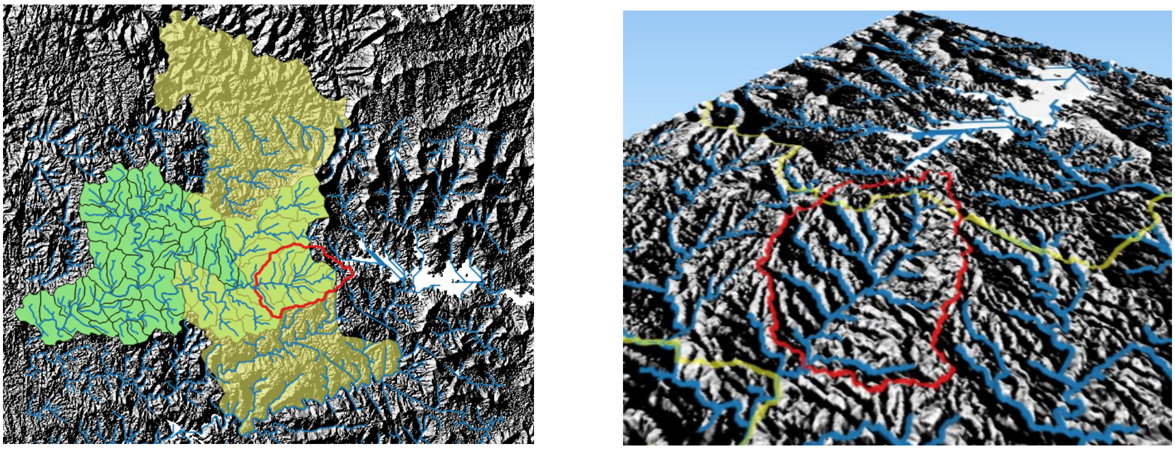


Figure 7 Delineation of Watershed

The watershed which has been selected includes villages like Shirasgaon, Adoshi, Dholara, Nasehra, khodala and Deogaon and Met Humbhachi. This watershed falls in the sub watershed (named WF-15) of vaitarna basin, whose budget has been given in report prepared by GSDA. This budget can be compared with calculated budget in the Research model. Watershed Project carried out in area IWMP 2009-10. Area of watershed is 4273.52 ha. It is part of Mini watershed number 02 of micro-watershed (WF-15). Many Micro watersheds like 22, 23, 3, 8, 11, 19, 17, 15, 11, 6, and 3 are overlapping with selected watershed. In this watershed number of number of wells have been selected such that they can adequately represent and predict the watershed behaviour. Map of the watershed has been represented in the figure below.

Figure 8 Villages in selected watershed

3.5 Geology of Adoshi watershed

Simple compact basalt flows and Giant phenocryst basalt is the dominant lithology exposed in the Adoshi watershed. Total 8 flows have been identified along the road cross-section and river cross sections. Thickness of these flows varies from 30-50 metres along the altitude of 180-650 meters. First flow identified was amygdaloidal basalt which was around the top elevation of the watershed it can be seen above elevation of 600m. Since it forms the top part of the watershed it is highly weathered.

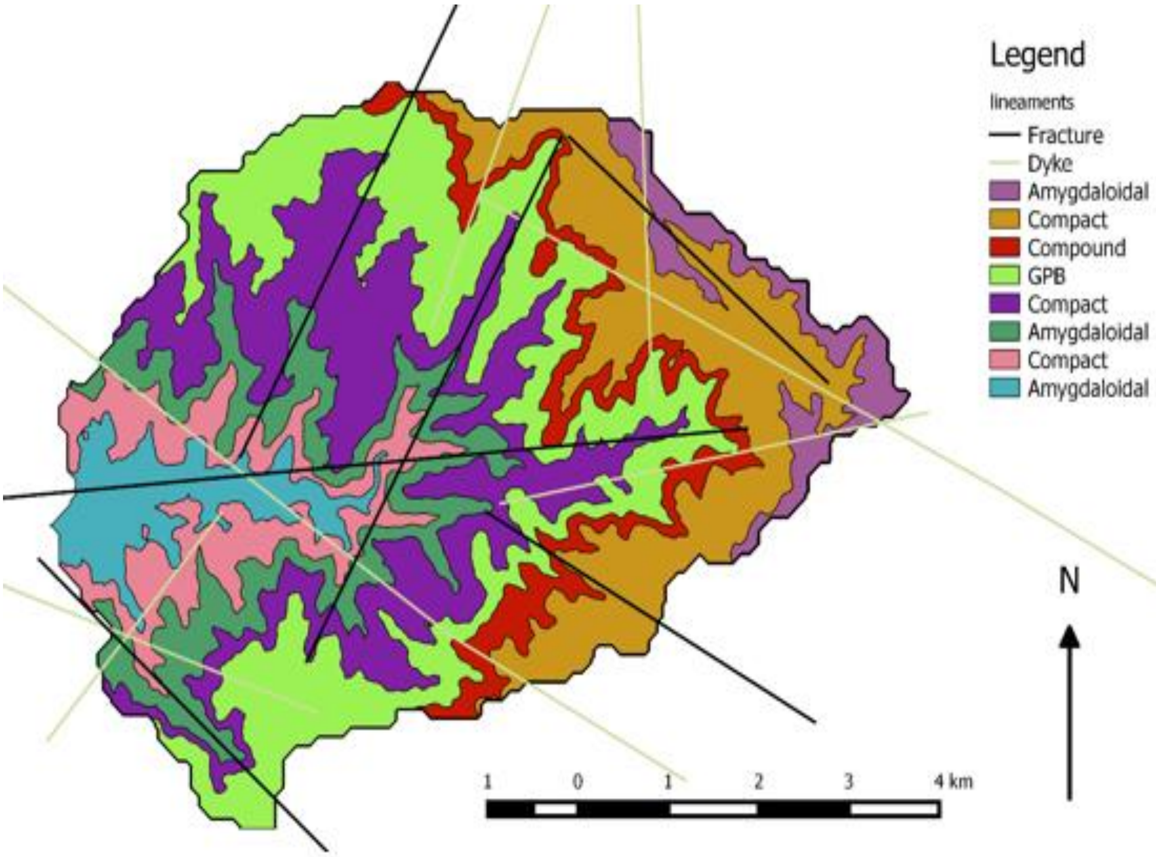


Figure 9 Geological map of Adoshi watershed

Below this comes the compact basalt. This can be observed till the elevation of 480meters. This is broadly jointed and highly compact at some places. Vertical and sub vertical joints can be observed in this part.

Figure 10 Broadly Jointed Compact Basalt

From 480-430 comes the compound flow. Two three units can be easily observed in this flow. It does not show any jointing and weathering pattern. At some places vertical joints can be observed. Then comes the GPB whose thickness varies from 430 to 380. From 430-410 GPB1 can be observed which has less amygdales as compared to GPB2. The GPB is characterised by the abundant phenocrysts of size up to 5cm. It sometimes occurs as bands in the compact basalt. GPB in the watershed is divided into two units. GPB1 and GPB 2[40]. This GPB is underlain by simple Compact basalt. During journey from khodala to Mokhada one can easily observe that flows are considerably lateritized. Even on lateritization large white plagioclase are observed embedded in the reddish brown more easily weathered ground mass. The lower portion of GPB1 is highly sheet jointed. Big sheet joints can be observed along the roadside in GPB2 also.

Figure 11 Giant Phenocryst Basalt

From 380 to 340 comes the layer of compact basalt. This is sheet jointed. Big joints can be observed in this portion most of them are horizontal in nature. These joints provide high transmissivity and hydraulic conductivity to this zone. At some places joints are narrow and closely spaced.

Figure 12 Sheet Jointed Compact Basalt

From 340 to 280 again comes the massive basalt black in color. Highly compact in nature and very few joints can be observed in this region. This zone has very low conductivity and specific yield.

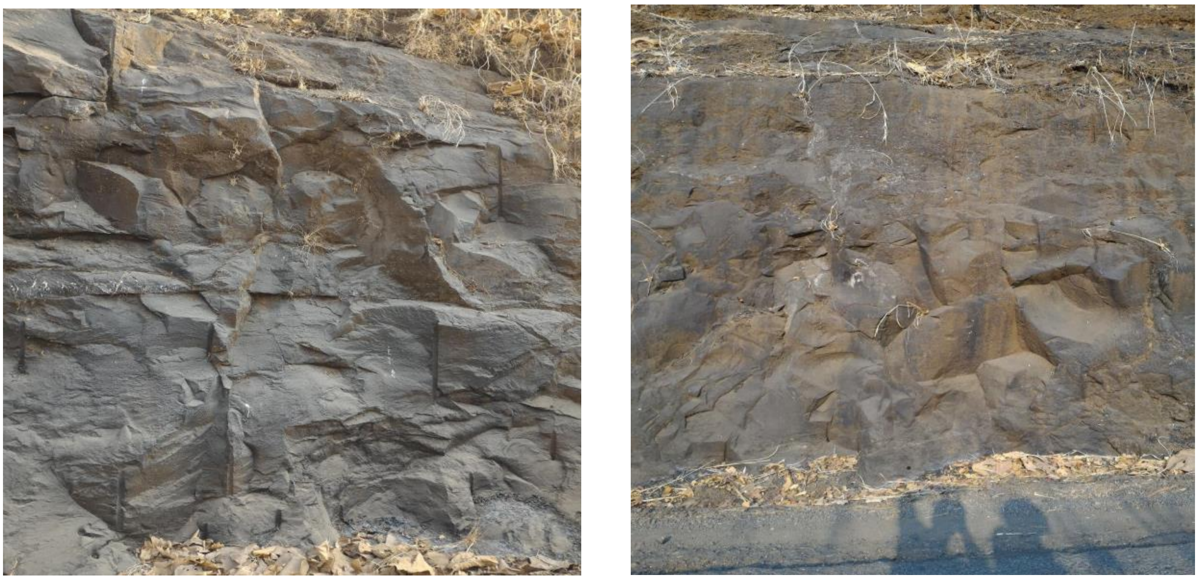


Figure 13 Massive Compact Basalt

From 280-240 is again a layer of amygdaloidal basalt which is highly compact without any vesicles completely filled with amygdals. Since it is completely filled with amygdales and highly compacted in nature it does not have tendency to transmit and store water. From 240-200 a layer of compact basalt can be observed. This layer again has sheet joints as well as narrowly spaced rectangular joints. Along the well cross section it can be easily seen that water is oozing out of these spaces which can also be regarded as small springs. Due to such pattern some wells in the region shows high yield and provide water throughout the season.

Figure 14 Narrowly Jointed Compact Basalt

From 200- 160 again comes the layer of amygdaloidal basalt. These layer does not have any jointing and are highly compact in nature. At some places where it is exposed to the atmosphere it shows different color and seems that it has undergone some change but not much weathering has happened. The drilling has been carried out in the stream bed and it shows the compactness of basalt. In the other image sheet joining can be observed in this basalt. Amygdales can be observed in both the images.

Figure 15 Amygdaloidal Basalt

Joints and fractures are the two most important features in the hard rock region. They represent the occurrence and movement of water both at surface and ground. The GPBS in watershed shows the sub horizontal sheet joints which must have developed during the weathering process. Sheet joints are generally develop during the release of burden during the process of weathering and erosion. Some of these sheet joints in streams, well cross section are open. The compact basalt in the watershed shows sub vertical jointing which joints are not as open as sheet joints in GPB.

Numerous linear features can be observed in the satellite image or google earth which traverse the region surrounding Adoshi watershed. These lineaments on the image represent the fractures zones and vertical or sub vertical types which cut through the lava flows. At number of places fractures have been observed to control the drainage. These are often manifested in field as narrow valleys. The interconnectivity between units and the fracture openings within each unit control the storage and transmission of groundwater in these basalts. Compact basalts have very little storage and transmission capability, except when jointed or fractured[41]. Even then, the permeability of the fractured portion of compact basalts is quite limited as compared to that of weathered vesicular-amygdaloidal basalts / compound basalts.[42][38]

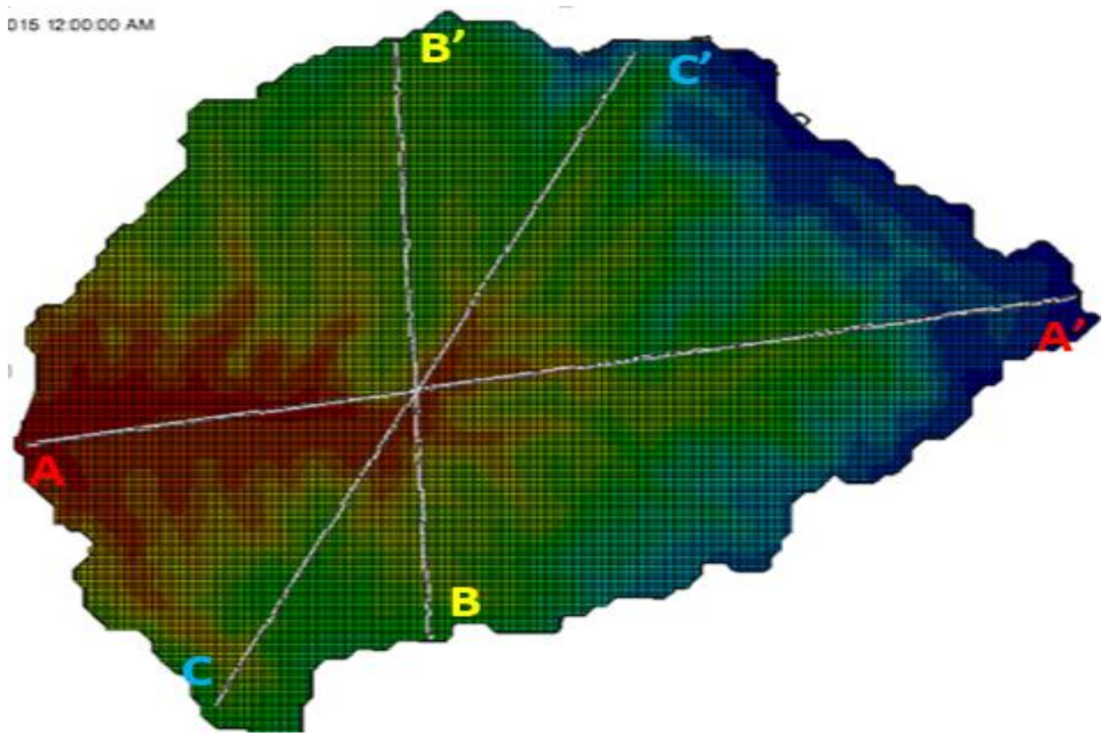
3.6 Hydrogeology

The region is underlain by basaltic rocks of Deccan volcanic province. These Deccan traps basalt rocks form the region which have low porosity, hydraulic conductivity or permeability. The hydrogeological properties like hydraulic conductivity and specific yield are very low for basalt rock, which makes it a poor groundwater store. Thus, due to the basalt formations and the hilly terrain, the rain water runs off quickly and very less amount of the rainfall is infiltrated to recharge the groundwater storage. Hence, the yields of the wells in the region are low and the wells generally start drying up from February. Most of the rainfall in the region is concentrated in the months of June, July, August and September. Rainfall is very intense and large surface runoff can be observed in the region. Base flow contribution to streams is large during the non-monsoon period. Paddy is the main crop of the region which is rain fed. There is very less Rabi crop in the region as water system in the region during non-monsoon period is sustained by springs. April and May are the driest months when people have to travel long distances to fetch water. There is no certainty of water during non-monsoon period. This makes it further difficult for the development of groundwater system. However, it is important to understand the factors which control the storage and accumulation of groundwater system. It is also important to understand how physical framework of watershed controls the recharge and discharge properties of watershed.

Hydrogeological mapping of the Adoshi watershed was primarily a field exercise. Both the toposheet and DEM was used to mark the drainage network in the region. Slope map, elevation map, contour map, groundwater table map were prepared to analyse the data. Location of wells, streams were identified from the Google earth and were marked. One similar study has previously been conducted in the region Kelghar-Ranjanpada watershed in Jawahar taluka by ACWADAM Pune in 2000. Vertical electrical sounding of the region has been conducted by Acwadam to understand the lithology of the area. An attempt has been made to describe the physical setup of the watershed using land use land cover map, geomorphology, soils and drainage.

3.7 Geomorphology and soils

The topography of the area is rugged. The north, south and western boundary of watershed is formed by flat topped interlocked spurs through which many first order streams start in the watershed. These ridge tops marks the small plateau which forms the boundary of watershed. Eastern boundary of the watershed is formed by the big flat plateau at a greater elevation then the entire watershed. Khodala-take harsha road runs along the plateau from southern part of the watershed boundary to the eastern boundary of the watershed. Three different cross section of the topography were made to understand the topography better. Steep slopes were observed in the different part of the watershed. Cross section AA' reveals the high slops in the region with lesser slopes at places like Adoshi, shirasgaon and Nashera village. In the northern part of watershed area, in Dholara village flat land or plateau can be easily observed (Cross section BB'). Then there is sudden steep fall or high slope can be observed. High slope can be observed while viewing from the point B of watershed, with few interruptions. Third cross section (CC') also shows the plateau near the Dholara village and steep slopes with few interruptions throughout the cross section. From the slope map we can easily see the places where there is sudden rise in the steepness and drop of slopes all these places can be marked as separate zones in the watershed. (Fig 17).



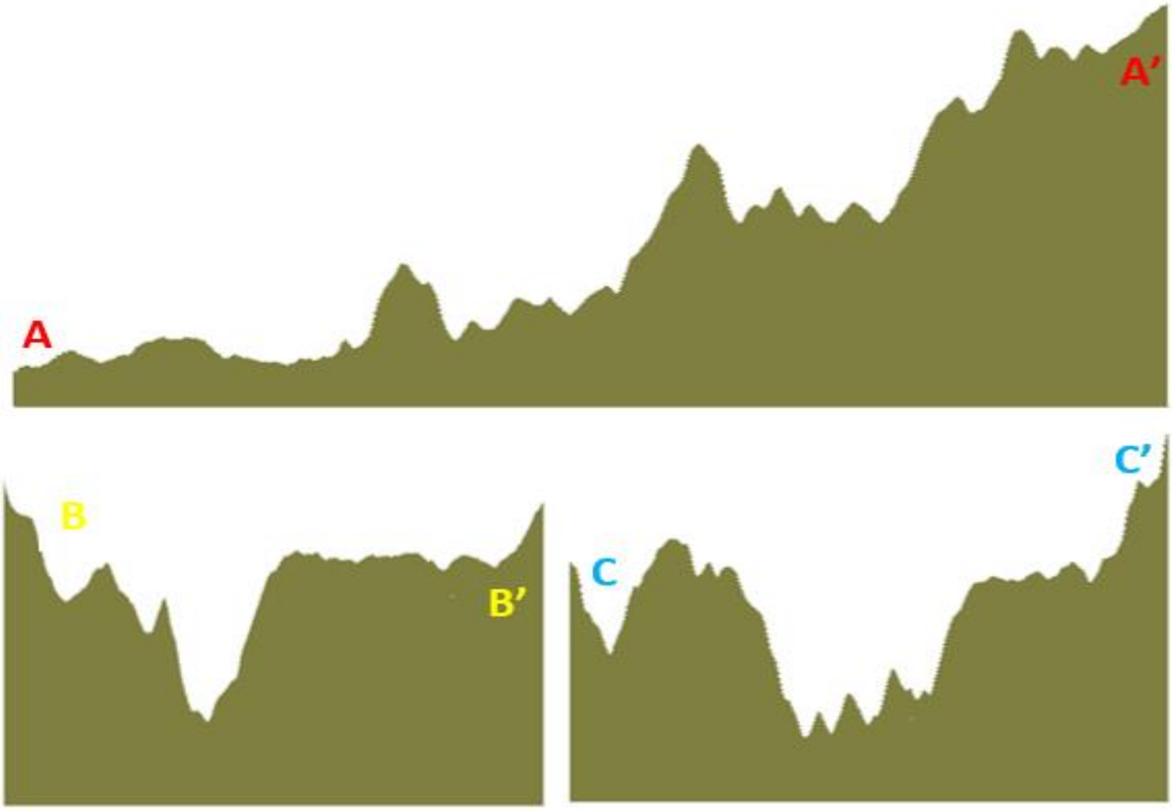


Figure 16 Cross Sections of watershed

Based on the slope map the region can be divided into four zones the flat hillocks, steeper slopes, plateaus and low lying areas and transition zone. The red region represents the area with slope less than 5%, yellow colour represents the area with slope between 5-12%. Blue colour represents the slope between 12-20% and green colour represents the slope between 20-28.67%. Area with high slopes can be observed throughout the watershed. These ridges gives rise to numerous first and second order streams in the watershed.

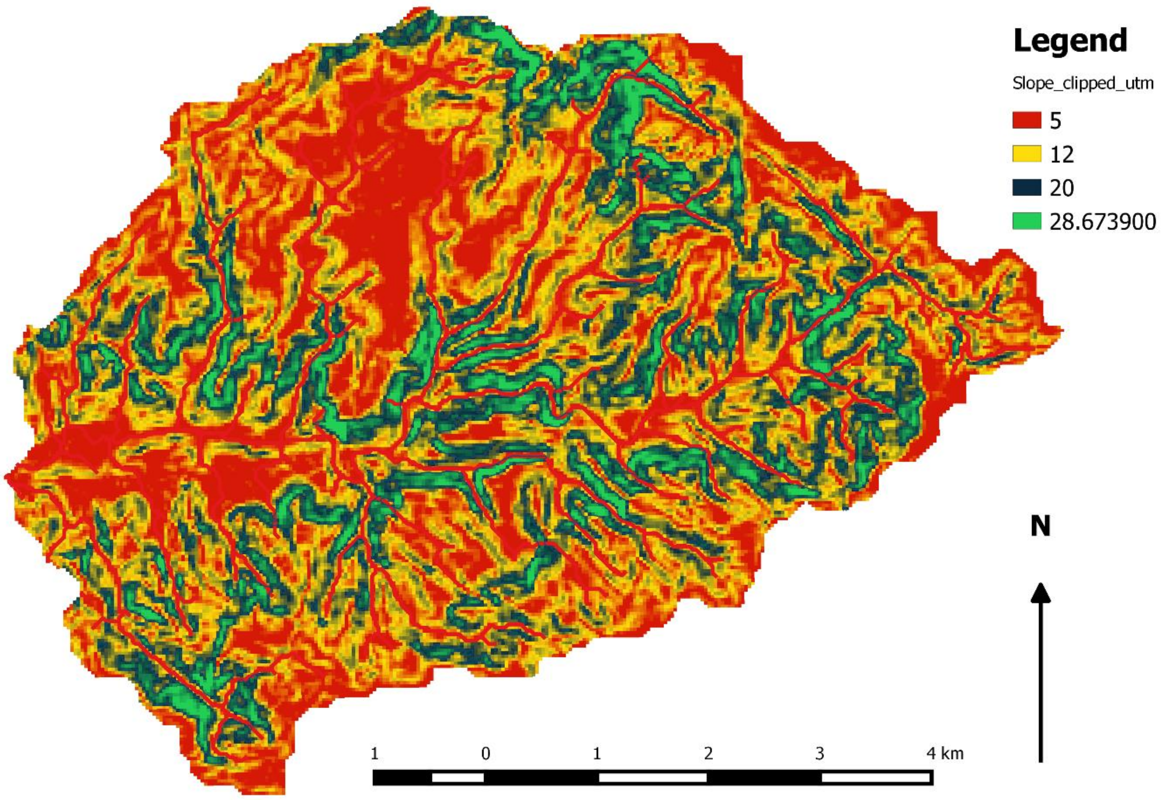


Figure 17 Slope Map

The soils in the region also follow the certain pattern which is in agreement the physiographic unit. It is difficult to find the in-situ soils in the region as most of the soils have undergone some weathering process and due to high rainfall and surface runoff they have been transported. But on flat hillocks we can observed some in-situ soils. Most of the soil in the watershed is lateritic in nature. We can find different type of texture along the drainage lines of the soil. This soil contains transported as well as residual material. Because of puddling soil structure has gone under some change.

Soil map has been prepared through various observations in field, through satellite data, google earth. Four categories of soil can be easily mapped. The coarsest soil can be found on the top of the hillocks and along the steep slope. Actual portion of soil along these steep slope is small as compared to weathered material. With decrease in the slope the soil content increase as compared to weathered portion. Coarse to medium grained soils can be found along the slope. With the slope deposits in the low lying region soil becomes less coarse and sandy. Most of the soils in the region have been formed mostly due to human factor. This is either mainly because of contour trenching, terracing deforestation and farming practice. Thickness of soil varies from .2cm to few meters in the watershed.

Figure 18 Variation in Soil Thickness

Most of the farmers in the region grows paddy (crop sataistics, 2014-15). The land has been manipulated to suit this practice. Many step fields can be observed along the drainage lines that are bunded and puddled. At many places soils have been terraced along the slopes although it is not fit for the paddy cultivation. This leads to drop in the productivity of soil. On the slopes where soil thickness is less it is used to grow crops like Nagli,warai (hill millets) as additional crop in the kharif season. The ridge tops are mostly barren which supports periodic grasses. There are many trees have been planted under the initiative of department of agriculture and through Local NGOs. These trees are mainly cashew and mango. In some part of the watershed constant green cover can be easily observed throughout the season. A long ridge which is topped by flat plateau separates this watershed from the other watershed. Drainage is dendritic to sub dendritic in nature.

3.8 Drainage

The Adoshi watershed can be subdivided into mainly two parts namely Nashera and Dholara. The drainage of Nashera originates from eastern and south eastern part of the watershed. Dholara drainage originates in the north and north eastern part of the watershed. Drainage analysis was done to obtain the drainage parameters and correlate these to geological and hydrogeological observations made during mapping. Drainage analysis reveals the nature of contributing surfaces, both to surface drainage as wells as to the infiltration component. Moreover, it was thought that drainage analysis would help reveal the nature of water flow in a regime, where there are permeable soils above relatively impermeable rocks.

The watershed is a fifth order basin. In order to do the drainage analysis watershed delineation was done and streams were generated using DEM in QGIS. Streams were also digitized from the Toposheet so that all the drainage pattern can be included in the map. The drainage analysis include the method given by Strahler 1952 of stream ordering where first order drainage represents the streams originating in the head region, two first order streams form the second order stream , two three order streams for the third order streams and so on[43][41].

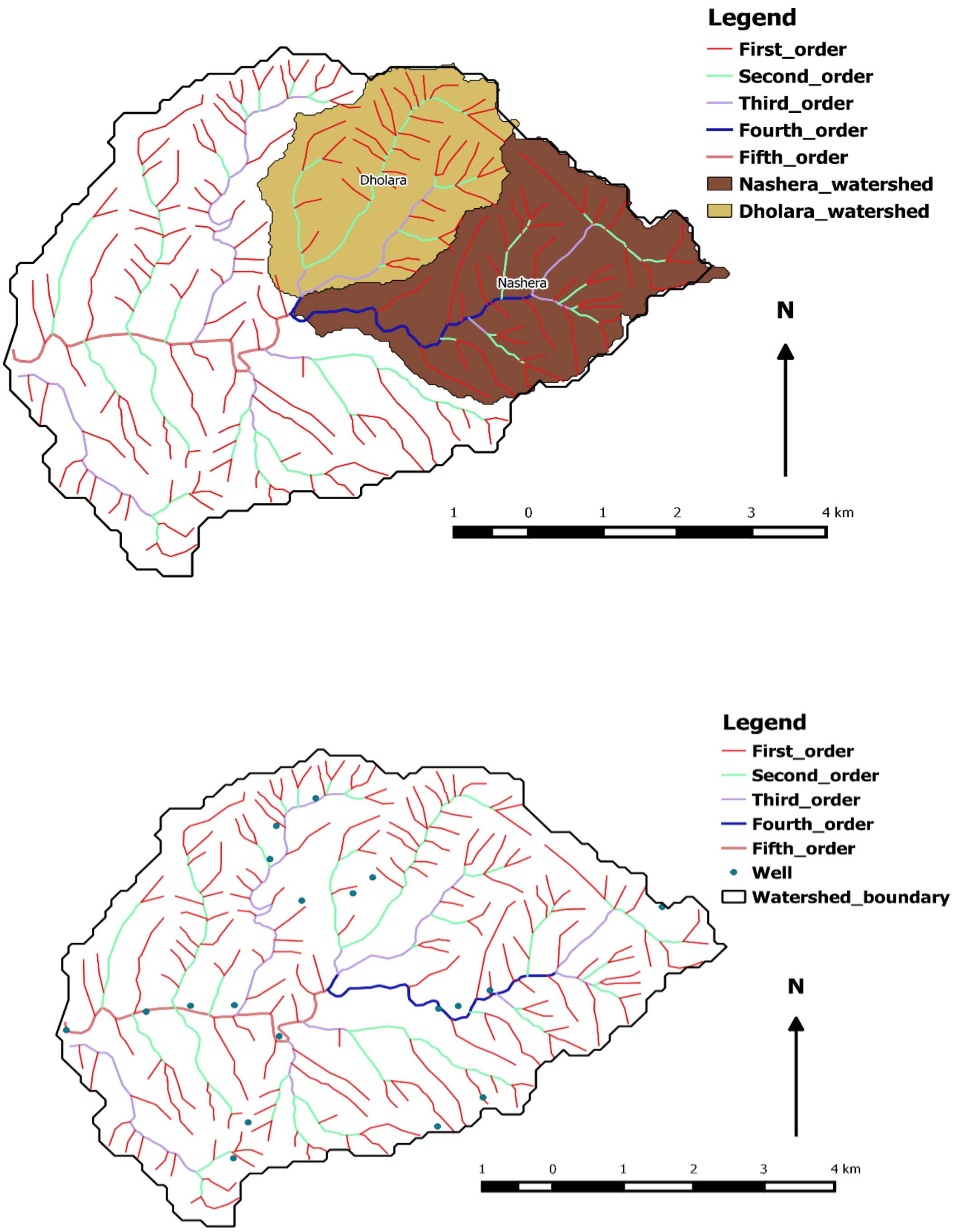


Figure 19 Drainage of Watershed

Bifurcation ratios exceeding five indicate structurally controlled drainage (Strahler, 1952). The average bifurcation ratio for the watershed is 3.82 and hence does not indicate a structural control. Structural control is local and along fractured zones. In Adoshi watershed the first order streams does have a bifurcation ratio more than 5 which does indicates some control. In Dholara watershed this bifurcation ratio is more than 6 which again tells us about the nature of control. In Nashera it is least hence indicates the difference which exists across the watershed.

The length of a stream, which is a dimensional property, indicates the hydrological nature of the contributing surfaces of the drainage network. Permeable media support fewer streams that are longer. Smallest length ratio, indicating that they flow through areas where surface permeability is likely to be least. Fourth order streams in Adoshi and Dholara watershed shows least length ratio which means surface permeability is least in these places. In Nashera watershed second order streams display least length ratio which means area is less permeable. Fifth order stream shows the highest length in the Adoshi watershed which means slopes are flat in the region and adjoining area are contributing lot of water. Lot of second order streams meet directly to the 5th order stream in Adoshi watershed which explains the adjoining region permeability and availability of water in this stretch for longer period of time.

Table 4 Drainage characteristics of Adoshi, Dholara and Nashera watershed

Basin Name	Stream Order	Number of streams	Bifurcation Ratio	Total stream length Km	Average Stream length Km	Length ratio
Adoshi	1	169	5.12	87.681	0.518	-
	2	33	3.66	28.817	0.873	1.68
	3	9	4.5	15.111	1.679	1.92
	4	2	2	4.391	2.195	1.30
	5	1	-	5.347	5.347	2.43
Dholara	1	37	6.16	16.437	0.444	-
	2	6	3	6.903	1.150	2.58
	3	2	2	3.054	1.527	1.32
	4	1	-	0.027	0.027	0.01
Nashera	1	43	4.77	22.312	0.518	-
	2	9	3	4.631	0.514	0.99
	3	3	1.5	2.249	0.749	1.45
	4	2	-	3.962	1.981	2.64

Drainage density represents the texture of a drainage basin or watershed. It is basically a ratio of stream length to the basin area, indicating the basins carrying larger volumes of surface runoff. Higher drainage density means higher runoff expected. Since Nashera watershed has high drainage density higher surface runoff is expected in this region as compared to the other regions. Stream frequency indicates that around 5 streams are required in Adoshi watershed to drain 100 ha of area. A higher stream frequency indicates that watershed has combination of both higher relief and low hydraulic conductivity. The Nashera watershed has highest stream frequency which means more streams are required to handle high runoff. The constant of channel maintenance suggests that about 30 hectares of catchment area is required to support a 1 km long stream for Adoshi watershed. Nashera has lowest constant of channel which again suggests that lesser area will produce more runoff for one km stretch of stream. This suggests that this region has less permeability as compared to the other region in watershed.

Table 5 Area and ratio analysis

Basin Name	Basin Order	Number of streams N	Basin Area A Km2	Total length of streams Km	Drainage density L/A	Stream frequency N/A	Constant of channel maintenance 1/Dd
Adoshi	5	214	42.73	141.37	3.30	5.00	0.30
Dholara	4	46	7.73	26.421	3.41	5.95	0.29
Nashera	4	57	8.96	33.154	3.70	6.36	0.27

3.9 Groundwater systems in the project area

Groundwater systems are often a combination of different lithologies (rock types) within an area. In other words, combination of lithologies (rather than individual lithology) constitute the geological domain within which groundwater accumulates and moves. It is useful to describe the groundwater system which may include one or two lithologies rather than describing the capacity of individual layers to hold water. [44]

Wherever the flows are exposed irrespective of their nature they are highly weathered. Thickness of soil in this portion can vary from 2cm to 2-3m. Below the soil highly weathered basalt up to 15 meter thickness can be observed in the different region of watershed. In the well cross sections it can be observed that the basalt is sheet jointed and closely spaced joints can be observed. In lower region of watershed till month of May water can be observed coming out of these joints. This top highly weathered layer of thickness 15 meters constitute the unconfined aquifer of the watershed. This is major portion for the groundwater movement storage and accumulation. Most of the joints in compact basalt are in upper portion of the flow so it act as a region which can easily transmit water to the top layer. Since it is highly compact in nature it has low porosity and hence cannot store much water. Below compact basalt there is layer of compound flow. This does not contain any vertical or horizontal joints and hence does not store much water.

Figure 20 Weathering in Unconfined Aquifer

GPB layers are sheet jointed so they can help in transmitting water. Especially GPB 2 is highly sheet jointed and weathered and is likely to have more specific yield, hydraulic conductivity and permeability as compared to other layers. At places they are highly weathered in nature and can store some amount of water. Below that there is layer of compact basalt which is highly sheet jointed. Vertical joint can also be observed in this portion. This also been explained in the geology section. This region generally lies between the elevations of 350-400m. This provides this layer of compact basalt high transmissivity and high specific yield. Below this layer there are layers of highly compact basalt which do not show any joints and hence are not capable of forming an aquifer. Amygdaloidal basalt layer is filled with vesicles and highly compact in nature and this also fails to form the separate aquifer. From the elevation 200-250 there lies highly weathered zone consisting of sheet jointed compact and amygdaloidal basalt. This forms a confined aquifer which continuously provides water to village of Adoshi and shirasgaon. In the following graph elevation of various wells have been plotted with their water level. This graph clearly shows the location of two confined aquifer in the region. This shows that most of the wells are located in the two zones only varying from 400-350m and other varying from 200-250m.

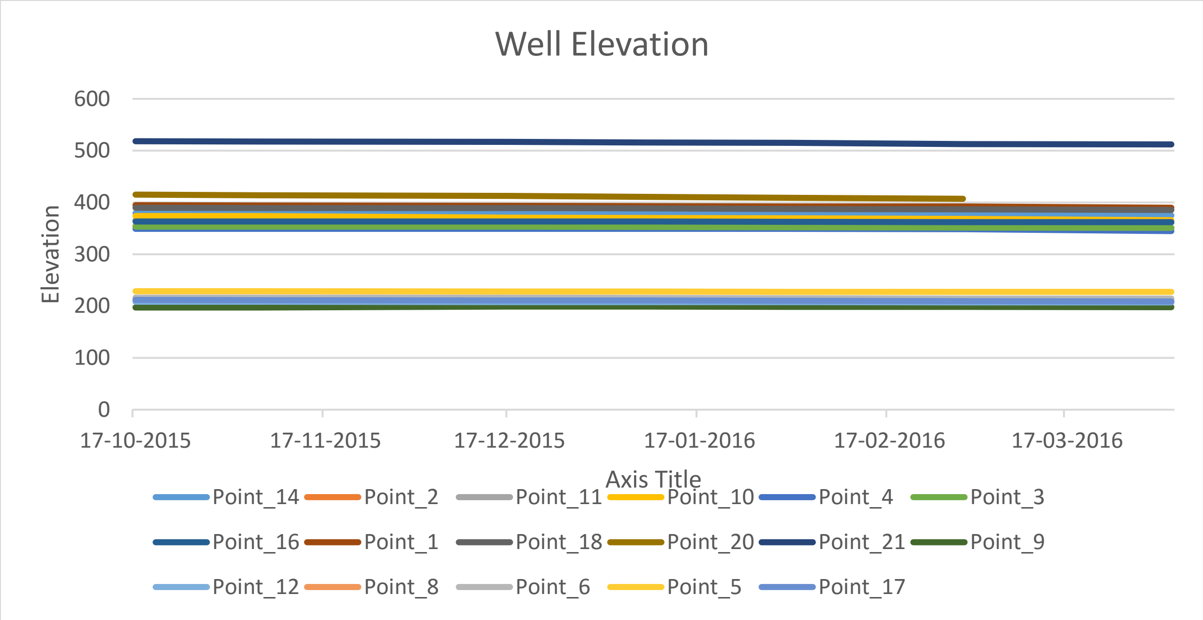


Figure 21 Elevation Of Wells

3.10 Aquifer properties

The shallow groundwater system has a good network of horizontal openings that are favourable for groundwater movement and accumulation. The transmissivity and storage potential of the shallow aquifer depends upon the thickness of the weathered layer that forms the principal component of this groundwater system. The magnitude of storage in the aquifer is perhaps limited to a couple of years of annual recharge and estimates indicate that if the aquifer completely desaturates to its base, about 150 mm is necessary to fill it up again. Transmissivities in the range of 10 to 1000 are not uncommon, although there is a considerable variability spatially. Generally transmissivity is of the magnitude of 10 -100 m2/day[45]. In practice though, a well that can sustain a daily pumping of 50 m3/day can be said to have a moderate but sustainable yield[46].

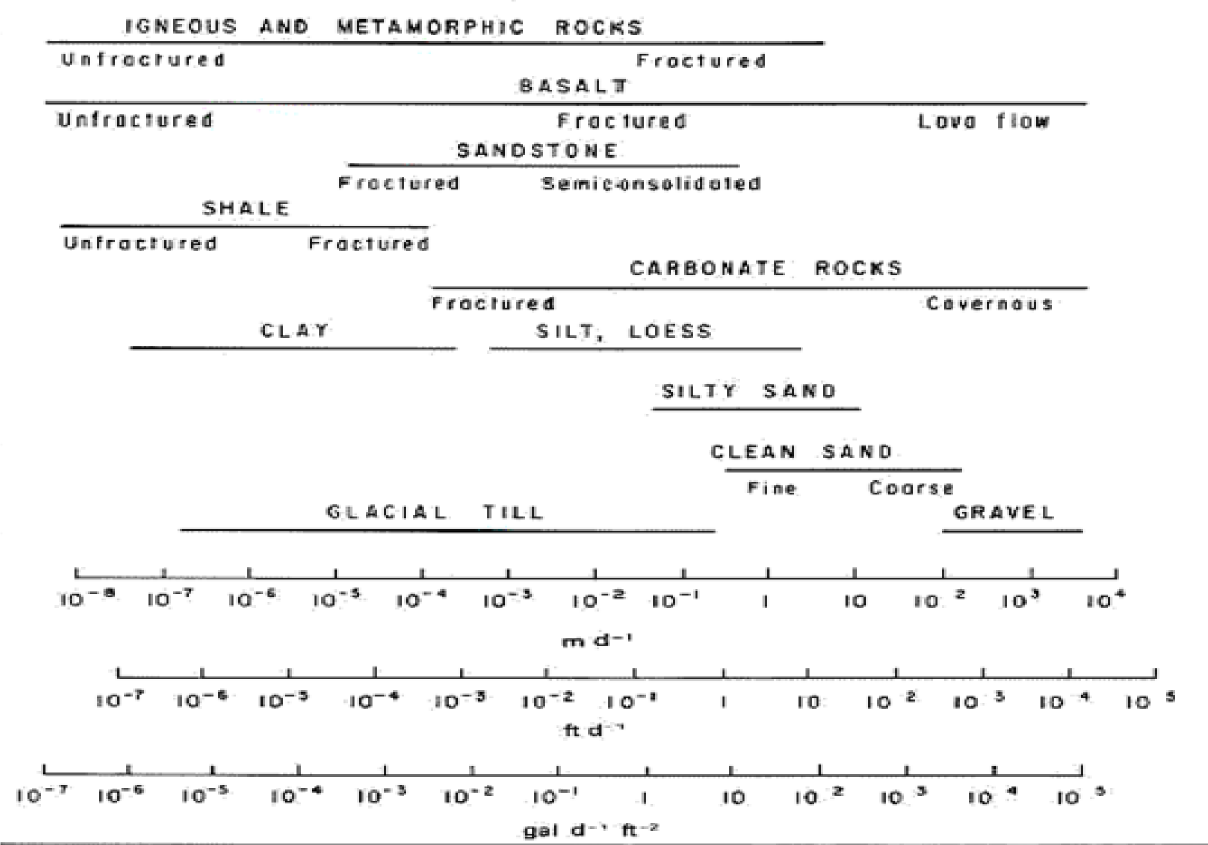
If transmissivity of weathered vesicular, amygdaloidal and compact is compared vesicular shows higher transmissivities. When transmissivity of weathered basalt is compared with the fractured or jointed compact or amygdaloidal basalt the number is significantly higher[47][48][43]. This also shows that joints and fractures impart greater amount of transmissivity to the basalt. Both the vesicular and amygdaloidal basalt have higher specific yield as compared to fractured amygdaloidal and compact basalt. This means jointing and fracturing does not increase the specific yield of the basalt because porosity remains the same.

Similarly fractured basalt has high hydraulic conductivity as compared to the unfractured basalt. Weathered portion of basalt and top portion of the soil has high hydraulic conductivity.

Table 6 Aquifer Properties

Authors/ Department	**Transmissivity 'T' (m^2/day)**	**Specific Yield 'Sy'**
CGWB (1980)	VB 50-70	VB 0.01-0.04
Deolankar (1980)	FB 20-60 WB 90-200	FB 0.008-0.01 WB 0.02-.010
CGWB (1980)	VB 30- 300 FB 600-2077 WB 100-600	VB 0.02-0.03 FB 0.01-0.03 WB 0.015-0.05
Singhal (1991)	0.10-500	-
CGWB (1994)	22-73.60	0.015-0.06
Karanth (1999)	-	0.022-0.026
Saha and Agarwal (2006)	_	MB 0.0089-0.0103 VB* 0.0121
Naik and Awasthi (2006)	28-135	-
CGWB and GSDA (2009)	25-100	.02
Chatterjee and Purohit (2009)	-	0.01-0.025
Mohanta and shende (2010) [49]	JMB 3.73-21.30 JFB 1.49-33.75 WB 1.49-14.89 JVB 13.33-88.90	JMB 0.009-.062 JFB 0.006-0.085 WB .008-0.128 JVB 0.016-0.071

The permeability of this groundwater system is clearly observable in the form of inflows along well faces through the sheet joints of the vesicular-amygdaloidal basalt as well as through the vertical joints and fractures of the lower compact basalt. At many places water has been observed to flow just beneath the surface. This also indicates good amount of base flows present in lower region of watershed. Base flows have also been observed on the surface in the patches in the lower region of watershed. River continues to flow till the month of January even though rainfall occurs till September only. This shows that significant amount of water is moving out of the watershed through base flows.



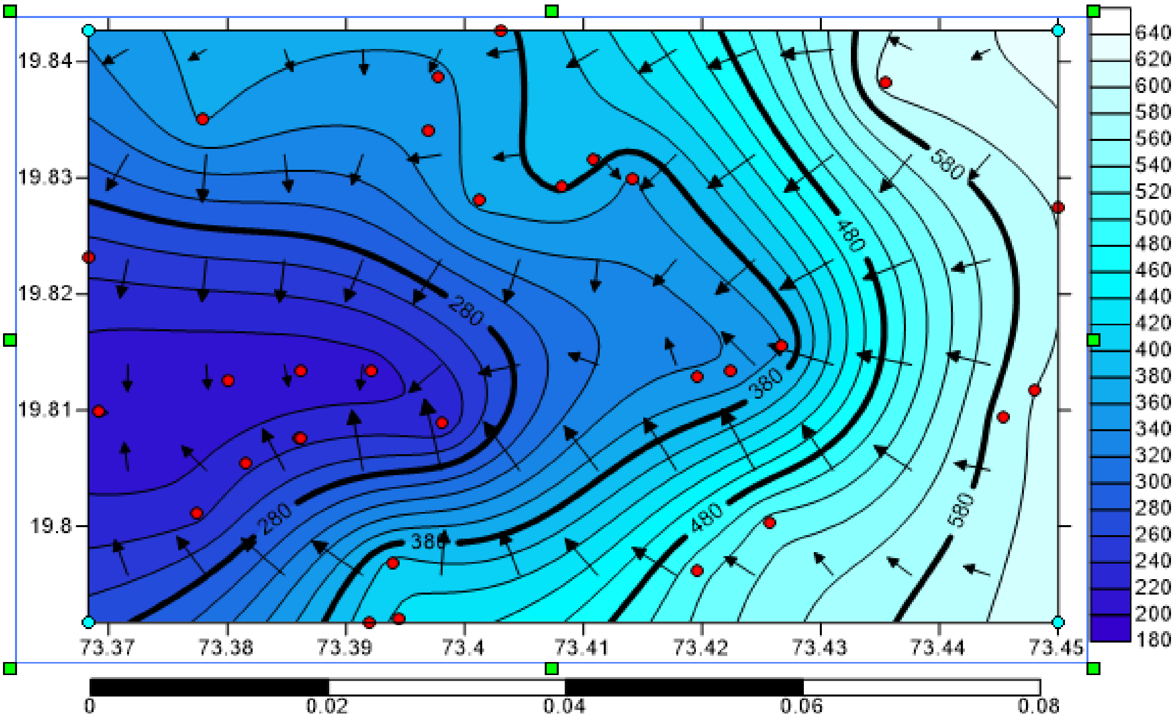
[50]Source:- Heath, R.C., 1983. Basic ground-water hydrology, U.S. Geological Survey Water-Supply Paper 2220, 86p.

Figure 22 Base flow Observed in the Region

The shallow groundwater system forms the only (relatively under tapped) source of non-monsoon water supply, essentially through the 50 odd wells in the area. Well diameter varies between 3 and 8 m. the maximum depth in watershed observed is 10m depth of wells generally varies between 6-8m. The upper part of the basalt (weathered portion) or the unconsolidated material that forms the overburden in portions along the stream channels is curbed or lined with masonry, in wells. Most wells have achieved a good penetration of the groundwater system and show a water table even in the peak summer period. The partially penetrating wells, especially at the upper elevations in the area run dry in the dry season. Therefore, one of the major improvements to the current scenario could be an intensive well deepening programme on all existing wells as well as sinking a few new wells at strategic locations for tapping groundwater from the groundwater discharge areas.

3.11 Water table in the region

In the watershed total 25 wells were selected for monitoring. Water levels were taken at regular interval. Reduced levels were calculated from the water level depth from ground and elevation data. This data was used to plot the water table contour map of the region. The water table contour map follows the regional topography. Pre monsoon and post monsoon water table map were plotted. This shows that the water table at the upper reaches were at greater depth. This can be verified if we observe contour line of 380m. During pre-monsoon all the wells water level have reached at their lowest point and some wells have dried up. During post monsoon period the 380 contour line has moved away from the wells, which means wells water level are at higher elevation. The difference between the contours of water table and elevation contours reduces as one moves down the topography. This again signifies the presence of base flow in the lower region of watershed. One of the important observation that comes out of the map is movement of water which is taking across the watershed. This means some water is getting transferred across the watershed boundaries. Both the Dholara and Nashera villages lie in the recharge zone of watershed whereas Shirasgaon and Adoshi lies in discharge zone of watershed. Both the Dholara and Nashera villages provide major opportunity for conservation measures. Hence recharge measures like trenching and conservation structures in upper locations can help in increasing the duration of base flows in lower region.



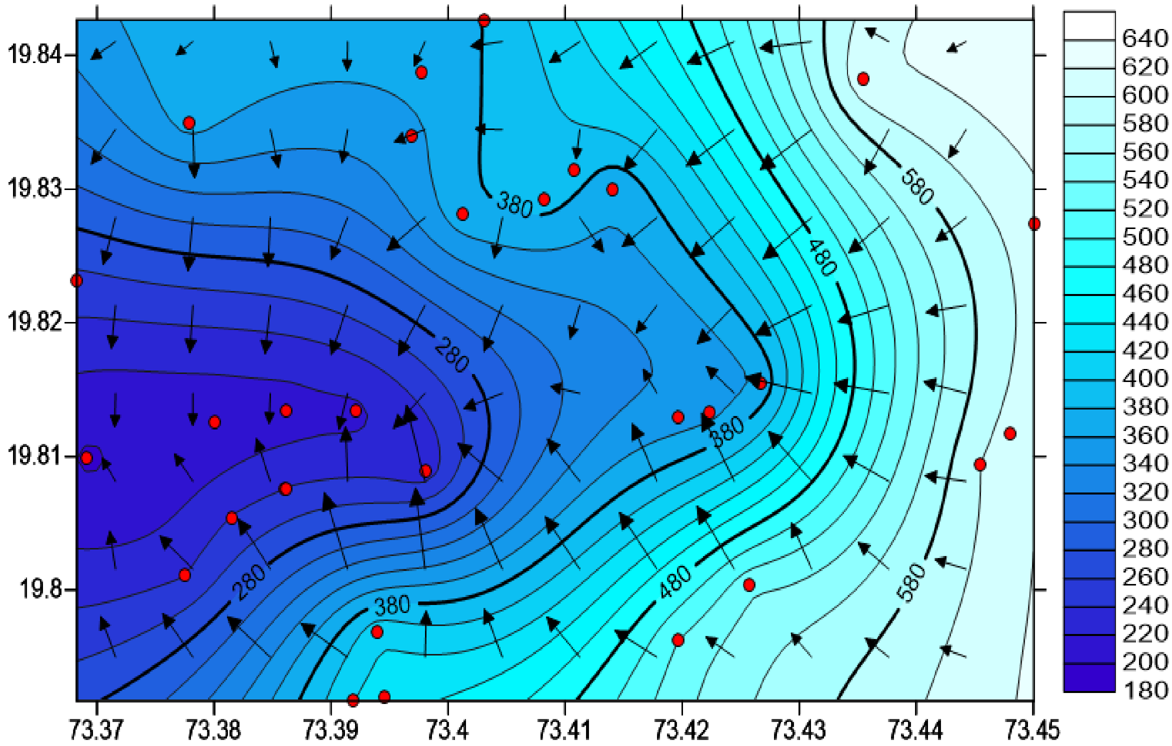


Figure 23 Groundwater Contour Map Pre And Post Monsoon

Time series of the reduced level of wells was also plotted for two region above 350m elevation wells and below 350m. Both the region forms the separate aquifer. Water table in the upper reaches of watershed shows higher fluctuation as compared to the lower region of the watershed. On closely observing the data one can clearly see that after the month of February all the wells have starting to show fall in water level. This clearly signifies the reduction of base flows in the upper reaches of watershed. Water level in the lower reaches of the watershed almost remains constant and does not show much fluctuation. This clearly indicates that base flow is present in the lower reaches of the watershed.

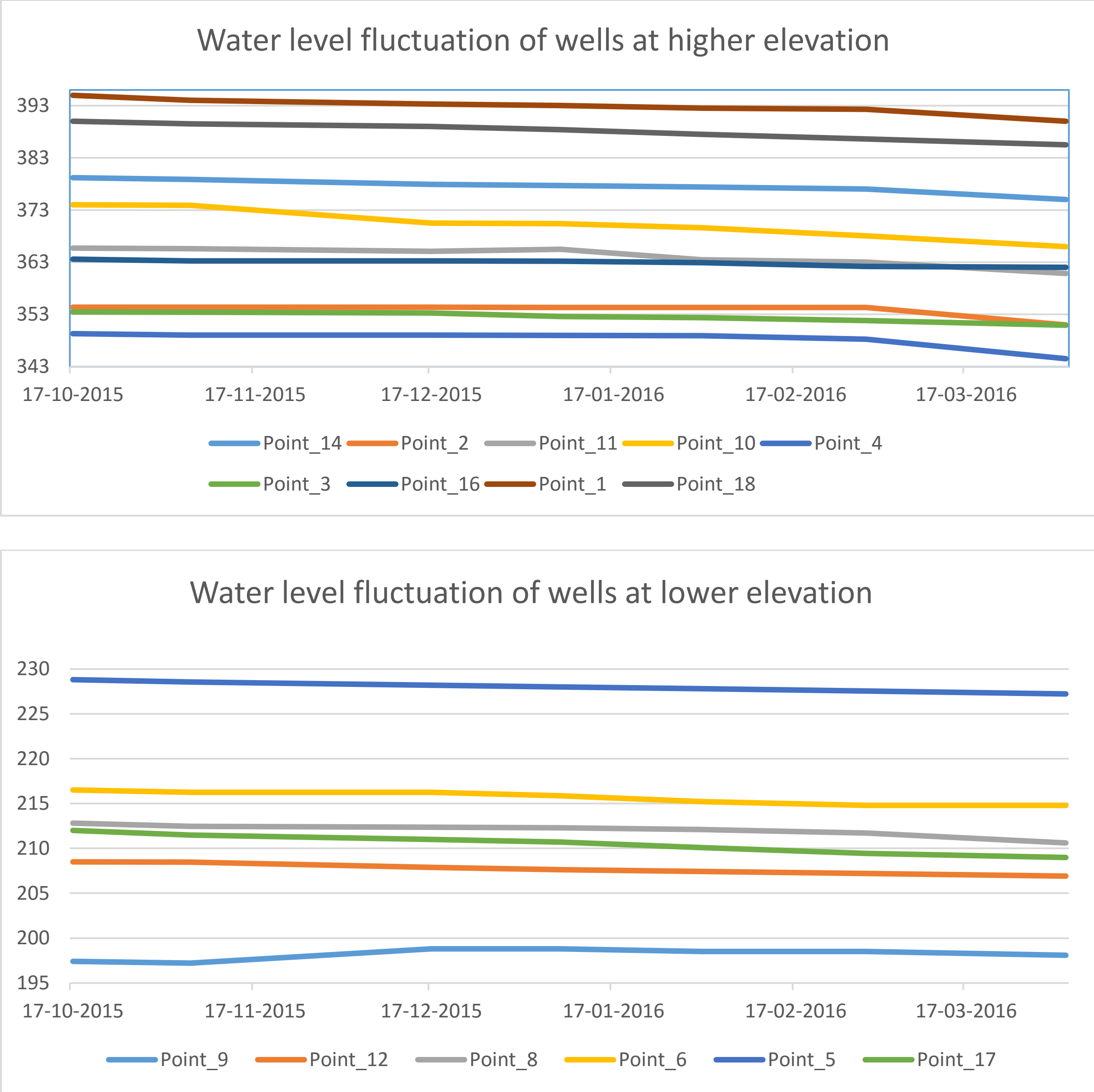


Figure 24 Water level Fluctuation

3.12 Role of AROEHAN in the region

AROEHAN (Activities Related to Organization of Education, Health and Nutrition) was a field work project initiated in 2006 by Nirmala Niketan College of social work, Mumbai. It started with the issue of malnutrition, but soon realised that the issue of malnutrition is not the only problem of poor health infrastructure, but is also closely linked with the issues of poor income levels of the people and lack of basic services like drinking water and education. Now AROEHAN works like an NGO and works on various issues like agriculture, education, drinking water, health, governance etc.

In 2010, under the Akshayjal programme, AROEHAN started efforts on the problem of drinking water. The project was funded by Bharat Petroleum Corporation Ltd. (BPCL). The first village chosen was Ikharichapada, as it was one of the most severely affected hamlets. In this intervention the NGO followed the approach of constructing subsurface bunds on the streams or drainage line in the area instead of following ridge to valley approach generally followed in the watershed intervention. After this intervention the water scenario in the village changed drastically. The water level in the well upstream of the area increased drastically during the water scarcity months. This made AROEHAN to do similar interventions in the other water scarce region of the Mokhada. AROEHEN also built number of wells in the region. It started doing stone pitching of the wells so that during the months of intense rainfall the walls of the wells do get damaged. As most of the wells are located in the streams. Most of the work on these structures is done by the local people. This creates the employment opportunities for these people. This also involves the participation of the people of the region and create awareness among the people for these structures. Ground water modelling can act as excellent tool to understand the effect of such type of interventions in the region.

Figure 25 Structures made by AROEHAN

Chapter 4 Methodology

Groundwater modelling is an important tool for prediction and management of groundwater. Groundwater modelling becomes all the more important since it can be used to see the efficiency of designed interventions in the given area. The effect of these structures may then be observed in small and large periods of time. Prediction of future groundwater level at current exploitation pace and increased rate can be easily made with these tools. This can help policy makers to take corrective measures at right time. Therefore, regional groundwater provides insight for its management.

However, there are some methodological challenges which have to be overcome in order to develop a robust and dependable groundwater model. Groundwater model development of any natural system is preceded by development of a conceptual model which is then converted into a numerical model. Soundness of conceptual model depends on the experience of modeller and how well he/she understands the study area. Benefits of building conceptual model is that it can be continuously updated as new information is obtained or interpretations are developed. Once the concepts are formulated, they can be translated into a mathematical frame work resulting into equations that describe the process. After running the numerical model it needs to be calibrated. Various tools are available which can be used to calibrate the same.

A conceptual model is a simplified representation of the region to be modelled. It includes the model domain, boundary conditions, sources, sinks and material zones. The purpose of building conceptual model is to simplify the field problem and organize the associated data so that the system can be analysed more readily. The simplifying assumptions are required partly because a complete reconstruction of field system is not feasible. There is rarely sufficient data to completely describe the system in full details. The conceptual model should therefore be kept as simple as possible while retaining sufficient capacity to adequately represent the physical elements of the hydrological behaviour.

4.1 Preparation of conceptual model

Preparation of conceptual model involves identification of the study area, deciding appropriate boundary conditions, creation of usually three dimensional model of hydrogeological system and estimation of sources and sinks[28]. In the present study, a methodology has been presented in which data for rainfall, groundwater table variations, hydro- geological zones and several Geographical Information System (GIS) tools have been used for development of conceptual groundwater flow model instead of lump sum value of average recharge for the study area normally used. One of the important sources, especially for the phreatic aquifer, is groundwater recharge. This number has to be decided carefully while calibrating the model. In the present study, while developing the conceptual groundwater flow model for Mokhada area, GIS has been extensively used for creation of database. Subsequently, the conceptual model so developed can be converted into a mathematical model such as 3-D modular finite difference based MODFLOW model [51]

4.2 Specific boundary conditions

In defining the study area, the modeler should be aware of the various groundwater system in the vicinity of the area. So, defining the model boundary becomes the first step before taking up any groundwater modeling exercise. Model boundary separates the study area and the surrounding environment [52]. Anderson and Woessner (1992) have defined boundary conditions as mathematical statements specifying the dependent variable (head) or the derivative of the dependent variable (flux) at the boundaries of the problem domain. They have also mentioned that regional groundwater divides are typically found near topographic high and may form beneath partially penetrating surface water bodies. In the present study, ridges have been identified as no flow boundary conditions which means no water is getting transferred across the boundary conditions. In reality our watershed is displaying different phenomenon which means there is outer interference happening across the watersheds. To check this assumption we assumed that there is no flow of water is taking place across the Adoshi watershed. Then we choose a smaller watershed inside the Adoshi watershed. This watershed was not given no-flow boundary, means water can flow across its boundary. After running the model we saw that net amount of water going in and out of Dholara watershed is negligible. So our assumption of no flow boundary can be taken as true. All the places in the watershed where there is constant amount of water is present e.g., lake, pond and storage or conservation structures should be represented as constant head or varying head boundary condition. Continuous amount of water is leaking and going out of these structures. To account for these changes such boundary condition is necessity. The location of the Adoshi bund where constant amount of water is present is used as specific head boundary condition. Most of the streams are lying in the lower elevation than their surrounding area, which means they are lying in recharge area and receives continuous amount of water from region at higher elevation. All these streams have been used as drain to remove the water from the system after rainfall stops. This condition is used to know about the amount of base flow getting out of the system. Then number of wells have been used as source of water extraction. In the current region very few people go for second crop. So, rate of extraction is not very high. To account for any inflow and outflow from a region or boundary wells can be used. If water is going out of the boundary then wells can be marked at boundary and negative extraction rate can be given to wells to account for water going out of system. Similarly if water is coming into the system from outer region, positive extraction rate can be given to account for inflows.

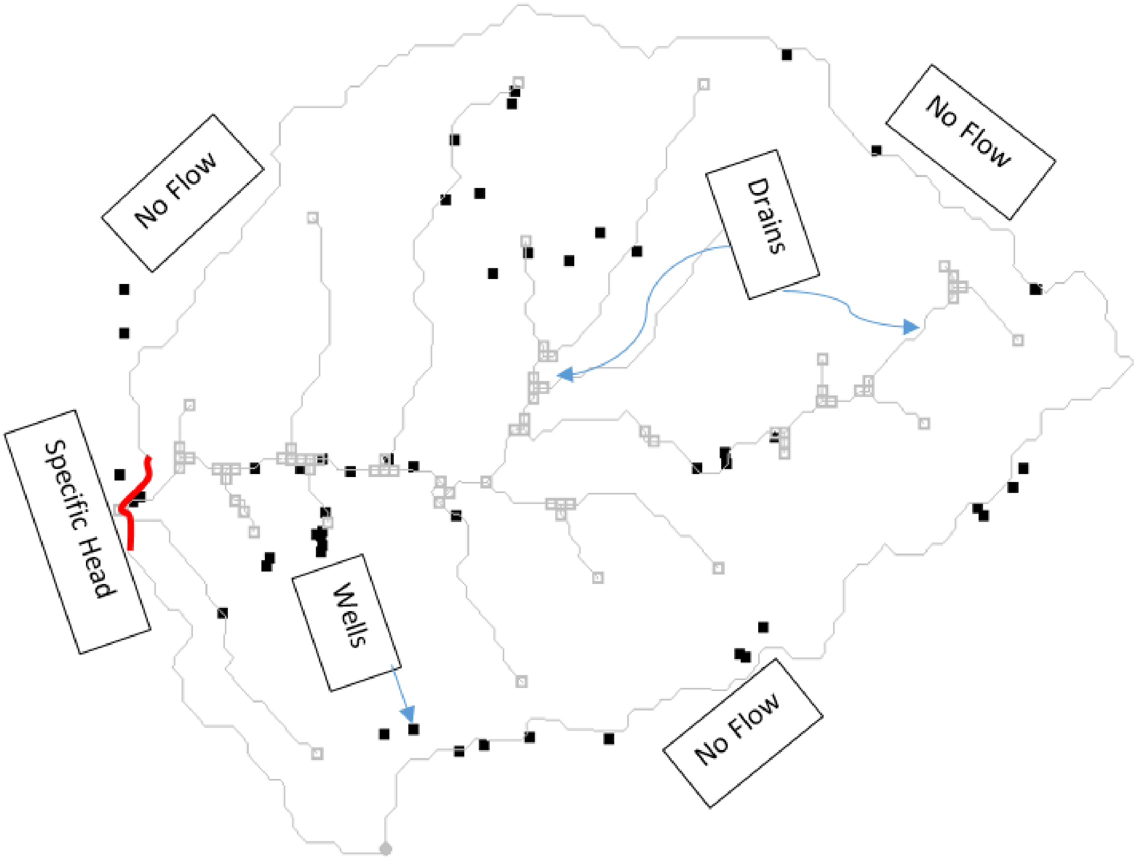


Figure 26 Description of conceptual model

While developing a groundwater model, not only spatial domain is discretized into cells, temporal domain is also discretized into time steps. The cell size is fixed generally while building a model. As terrain sometimes does not permit smaller cell size. Typically a year is digitized into 2 to 4 periods based on seasons with the requirement that during one time period, various stresses and parameters exhibit unique relationship or remain constant. In the present study time is discretized into two periods in a year, that is, monsoon and non-monsoon. Monsoon season is considered from middle of June to middle of October. Most of the rainfall occurs during this period. The remaining period is considered as non-monsoon where there is practically no recharge from rainfall.

4.3 Number and Elevation of layers

Understanding the geology of the area is first step while preparing a conceptual model. Lithologs of the area were not available which made it difficult to understand the hydrogeology of the area. The hydrogeological mapping of the area was done through field inspection which gave us some understanding regarding the physical framework of watershed. There are many studies which have been conducted in the Thane and Raigad Pune and Palghar district[38][37]. These all studies also gives essential inputs for understanding the regional geology, hydrogeology and aquifer level properties. This helped us in deciding the number of layers to be modelled in the watershed. Top and bottom elevation of each layer was decided based upon the understanding developed after analysing watershed as different groundwater system. Top layer was identified as a shallow unconfined aquifer whose thickness was decided by observing various well cross sections and weathering of various layers exposed to the atmosphere. Weathering up to 15m can be easily seen in the watershed. During various field visits and through google earth it has been observed that most of the first and second order streams are generally agriculture land reclaimed by farmers for paddy cultivation. Lower order streams are also highly weathered and some streams or narrow valleys are fractured controlled. This gave us an idea to model this zone around streams as separate zone whose thickness was kept 30m. Due to this another layer was formed whose thickness was 15m below the top layer. Now there were two layers of 15m thickness at top. From this layer to elevation 440m third layer was modelled. Layer from 440-390 was modelled as fourth layer. Based upon the analysis done in the previous chapter it was decided that there were two zones in the watershed which would be modelled as confined aquifers. Elevation of these zone were varying from 340-390m and 200-240m. These zones were combination of two layers which depicted highly sheet and rectangular jointing pattern. Elevation ranging from 340-240 was decided to be modelled as sixth layer which was highly compact in nature. From 200-160 eighth layer was modelled.

4.4 Land Use Land Cover Map

Land use land cover map of the area was prepared. For this landsat image was used. Semiautomatic plugin have been used in quantum GIS for classification of the area. The area has been divided into four parts vegetation, water, bare soil and built-up area. Vegetation includes all type of vegetation like trees, grassland. Built up area includes all types of concrete structures and households. 32.3 % area is under vegetation, 2.4 % area is under water bodies, 57.1 % area is under bare soil and 8 % area is built up area. This classification can be further refined by dividing the area into more number of classes. The landsat image which we have obtained is taken on the date of 10th May 2015. This is a pre monsoon image. This means most of bare soil includes land suitable for agriculture. Similarly post monsoon image can be obtained and classification can be performed on it. This can help us do change detection. This will help in predicting watershed behaviour.

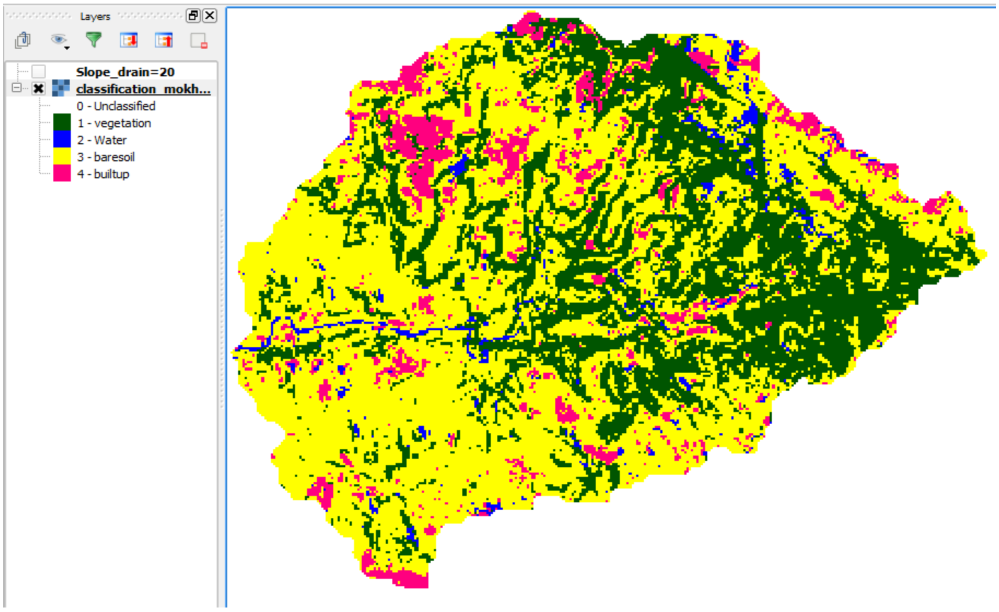


Figure 27 Land Use Land Cover Image

Table 7 Area under different LULC

Item	Area m^2	Percent
vegetation	13800600	32.3
Water	1026000	2.4
Soil	24379200	57.1
Built up	3484800	8.2
Total	42690600	100

4.5 Ground Elevation Image and DEM

Ground Elevation Map of the study area was prepared using Srtm remote sensing data. Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global (30m) resolution is freely available DEM which can be obtained from the USGS Earth explorer website http://earthexplorer.usgs.gov/. This DEM has been processed in QGIS to extract the important information. The area has been divide mainly into 5 parts. Outside the watershed 0 value, inside the watershed has been classified into 4 values 0-150,150-300,300-450 and 450-607. The elevation of watershed is varying from 180 to 607. Dark black lines are streams delineated in the area. Whereas light black lines are ridges in the area. This image help us to get an idea of elevation in the area, various transitions between the different zones. Ridges can be seen in transition zones only. DEM has been used to prepare the dataset required for preparing layers top elevation and bottom elevation. From DEM scatter points were extracted. Subtracting 15m and 30m from this data set gave us the elevation of second layer.

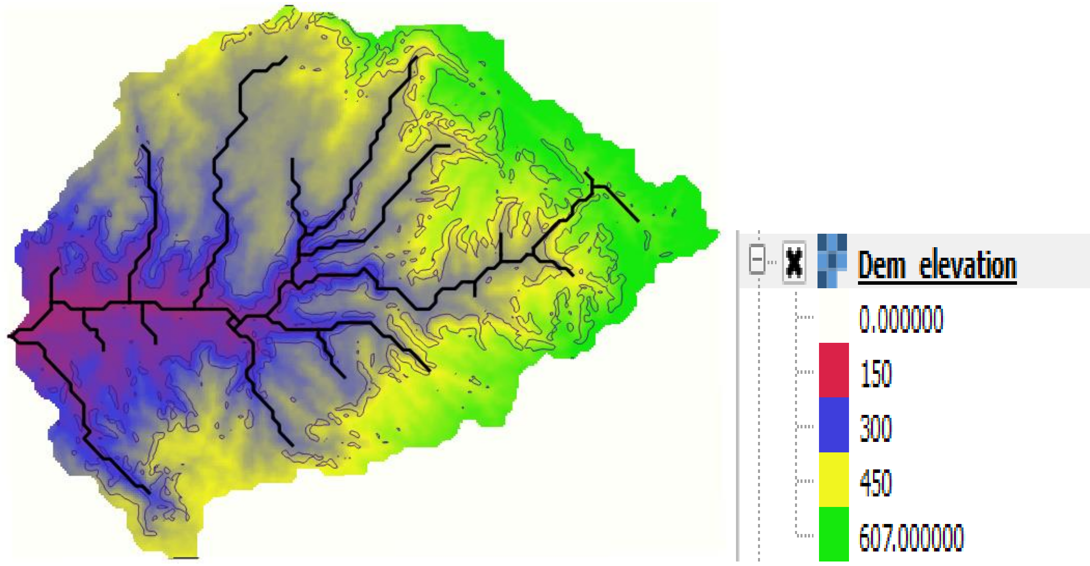


Figure 28 Elevation image

4.6 Location and selection of wells

To predict the water table fluctuation in the watershed we need to take the readings of water levels at various interval of time. For this we need to locate the wells at suitable locations so that we can monitor the wells at selected interval time. In our case this interval is selected as 30 days. Various wells have been located in the watershed with the help of the help of google earth and through field visits. These wells comes out to be around 60. Marking of wells have done with the help of GIS. It is very difficult to monitor all the wells in the watershed. GSDA also have two observation wells in the region. But GSDA monitors the wells only 4 times in a year. May, October, January and in March whereas we took readings more regularly. After looking in to the features of the watershed and location of wells we selected two streams one from Dholara and other from Nashera watershed meeting at Deobandh. These are two main streams which contribute most water to the river. Wells have been selected in the low elevation region and then in the higher elevation region. This is done to see the difference of water level fluctuation in different regions. In higher elevation region water levels fluctuate more rapidly than in the region with lower elevation. To account for these things in the modelling will require innovative approach.

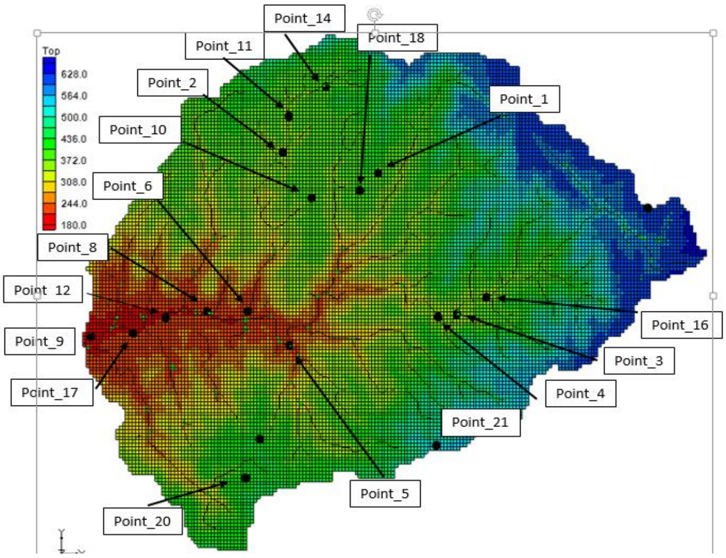


Figure 29 Well location

In the complete watershed total 18 wells were monitored regularly and their reduced level was calculated which is given in the following table. This well level data formed an important part of modelling as same data was used to calibrate the model at later stages. Level of both well data as well as level predicted by model were matched.

Table 8 Well Water Level Reading

Well	17-10-2015	06-11-2015	17-12-2015	08-01-2016	01-02-2016	29-02-2016	03-04-2016
Point_14	379.2	378.86	377.9	377.7	377.4	377	375
Point_2	354.4	354.38	354.36	354.34	354.32	354.3	351
Point_11	365.7	365.57	365.1	365.5	363.45	363	360.85
Point_10	374	373.9	370.5	370.4	369.6	368.05	366
Point_4	349.3	349.05	349	348.95	348.9	348.22	344.5
Point_3	353.5	353.46	353.24	352.6	352.4	351.8	350.9
Point_16	363.6	363.26	363.23	363.2	362.9	362.2	362
Point_1	395	394	393.3	393	392.5	392.28	390
Point_18	390	389.5	389	388.4	387.5	386.6	385.5
Point_20	415	414	413	411	409	407	
Point_21	518	517.5	517	516	515	513	512
Point_9	197.4	197.22	198.8	198.8	198.5	198.5	198.1
Point_12	208.5	208.48	207.88	207.64	207.44	207.2	206.9
Point_8	212.8	212.45	212.35	212.28	212.1	211.7	210.6
Point_6	216.5	216.25	216.25	215.86	215.2	214.8	214.8
Point_5	228.8	228.54	228.2	228	227.8	227.55	227.2
Point_17	212	211.5	211	210.7	210.1	209.45	209

Next, we tried to measure the discharge in the streams. There are two bandharas in the region which have pipes as outlet. We measured the discharge through these pipes. In Adoshi Bandhara there were 9 pipes. All pipes were of 60cm diameter. Discharge in these pipes were observed by filling a bucket and noting the time taken to fill the bucket. On 15/10/15 in Adoshi watershed 100000m3 discharge was observed. This value reduced to 10000m3 on 17/12/15. This value further reduced to 1000m3 on 8/1/16. Water levels in these pipes were also observed and given in table below. Similarly in Nashera there is one more bandhara with 2 pipes. One pipe was dry and other was flowing. It has the pipe diameter of 90cm. In Nashera on 15/10/15 15000m3 discharge was observed. This value reduced to 500m3 on 17/12/15. The pipe in this bandhara was at slope. At front end depth of water level was 8.5cm and at back end water level was 12.5cm. These values of discharge was used to calibrate the model.

Table 9 Water level reading in pipes

Item	Pipe 1	Pipe 2	Pipe 3	Pipe 4	Pipe 5	Pipe 6	Pipe 7	Pipe 8	Pipe 9
17/10/15	10cm	12cm	12cm	13 cm	10cm	3cm	10cm	6cm	3cm
6/11/15	5.5cm	5.3cm	5.1cm	5.8cm	4cm	2.5cm	6cm	5cm	0cm

Figure 30 Flow reading

Chapter 5 – Understanding basic modelling concepts

5.1 Need for technical analysis and modelling

As seen in the previous chapters, ground water budgeting methodology adopted by GSDA has some problems. This necessitate the need for the models which can more accurately give the water balance available in the region. With the help of model, future scenarios at same ground water extraction rate and increased extraction rate can be generated. Impact of various parameter on the ground water can be analysed. Future scenarios with various interventions like afforestation and contour trenching can be analysed. In the region there are many structures being constructed by the Aroehan. Understanding the impact of one structure will help in analysing the impact of many structures in the watershed.

5.2 Modelling

As the interventions being studied directly impact the groundwater flows, a groundwater-flow model is required to understand the situation thoroughly. Accordingly, it was decided to use GMS (Groundwater Modeling Software) which is a widely used groundwater software solution for developing, characterizing and visualizing groundwater models in 3D environment. GMS is basically a GUI (Graphical User Interface) layer over the actual groundwater equation solver, MODFLOW, which is a modular, 3D, finite difference flow model developed by United States Geological Survey (USGS).

The GMS along with MODFLOW is used for the current study. In order to use GMS, a thorough understanding of the science behind groundwater flow, and the physical and mathematical concepts on which the basic groundwater software i.e. MODFLOW is based, is required.

5.3 Science of groundwater flow

In this section, the basic groundwater flow equation will be derived, which forms the basis for groundwater modelling.

Some basic terms and terminologies:

Hydraulic head –

- The height of a column of water above datum is called hydraulic head or simply head or total head. In the study of groundwater, head is the elevation of water in a well, where mean sea level is used as a datum. Groundwater always flows in the direction of decreasing total head. It has got three components.

o Pressure head – It is measured from the bottom of the well to the top of the water level in the well

o Elevation head – It is measured from the mean sea level to the bottom of the well

o Velocity head – It represents the energy of a liquid due to its bulk motion, and is generally neglected in groundwater flow study as is negligible.

Groundwater flow zones –

While studying groundwater flow, the subsurface is divided into three zones as follows:

- Unsaturated or vadose zone: It is the upper zone, just below the earth's surface. Water in this zone is dominated by the forces of adhesion and cohesion. It contains water held by the soils and roots of the plants, and is also the link between water infiltrating in the ground and moving down to the saturated zone. The pressure of water in unsaturated zone is less than atmospheric.
- Capillary fringe: This area is actually contained in both, the unsaturated and the saturated zones, but the water in this zone is under the influence of surface tension i.e. it is the water which has risen from the saturated ground water region due to capillary action. The pressure here too is less than atmospheric pressure.
- Saturated or phreatic zone: Groundwater in this zone is fully saturated and is gravity driven. The water here is at pressure more than atmospheric pressure. Water table is the imaginary surface dividing unsaturated and capillary zones from saturated zone, at which the pore water pressure is equal to atmospheric pressure. Below water table, all the pores of soil or rock are fully saturated and pressure increases with depth.

Porosity –

- It is the measure of the void or empty spaces in a material, and is a fraction of the volume of voids over the total volume of the material
- It's value is always between 0 and 1, or is expressed as percentage
- Material can be soil, rock or anything which can have empty spaces; more the porosity of soil or rock, more easy is the water movement and storage

Hydraulic conductivity –

- It is the property of the plants, rocks or soils which describes the ease with which water can move through pore spaces or fractures
- It depends on the intrinsic permeability of the material and on the degree of saturation
- Its dimensions are [L/T]

Heterogeneity and Anisotropy –

If the hydraulic conductivity *K* is independent of position within a geologic formation, the formation is **homogeneous**. If *K* is dependent on position within a geologic formation, which is always the case in groundwater systems, the formation is **heterogeneous**. In a homogeneous formation, $K(x, y, z) = C$, *C* being constant; whereas in heterogeneous formation, $K(x, y, z) \neq C$

- If the hydraulic conductivity *K* is independent of the direction of measurement at a point in a geologic formation, the formation is **isotropic** at that point. If the hydraulic Conductivity *K* varies with the direction of measurement at a point in a geologic formation, the formation is **anisotropic** at that point. If an *x, y, z* coordinate system is set up in such a way that the coordinate directions coincide with the principal directions of anisotropy, the *K* values in the principal directions can be specified as K_x, K_y, K_z. At any point (*x, y, z*), an isotropic formation will have $K_x=K_y=K_z$, whereas an anisotropic formation will have $Kx \neq Ky \neq K_z$

Specific storage –

- It is the amount of water that a portion of an aquifer releases from storage, per unit volume of aquifer, per unit change in hydraulic head while remaining fully saturated

- Its dimensions are [L^{-1}]

Specific yield –

- It is the quantity of water, unit volume of an aquifer will yield by gravity, when fully saturated

- It is expressed as a ratio or as a percentage of the volume of the aquifer.

Continuity equation of groundwater flow –

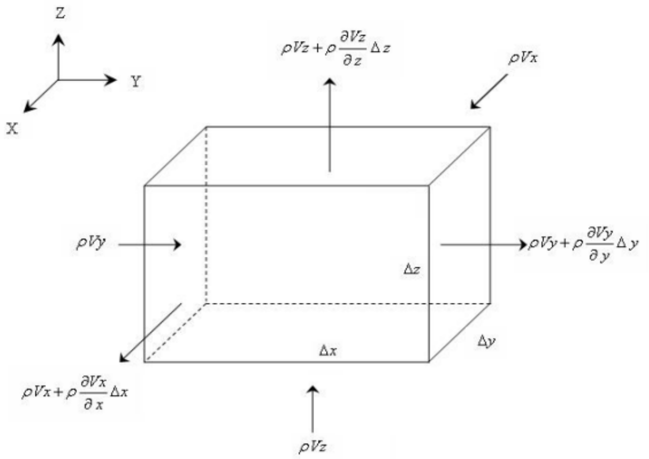


Figure 31 Continuity equation of groundwater flow

Consider the flow of ground water taking place within a small cube (of lengths Δx, Δy and Δz respectively the direction of the three areas) in a saturated zone where ρ is the density of water and V_x, V_y, V_z are the velocity components of water in *x, y* and *z* directions.

The total incoming water in the cuboidal volume should be equal to that going out. Thus, defining inflows and outflows as:

Inflows:

- **In x-direction:** $\boldsymbol{\rho v_x}(\Delta \boldsymbol{y}.\Delta \boldsymbol{z})$
- **In y-direction:** $\boldsymbol{\rho v_y}(\Delta \boldsymbol{x}.\Delta \boldsymbol{z})$
- **In z-direction:** $\boldsymbol{\rho v_z}(\Delta \boldsymbol{x}.\Delta \boldsymbol{y})$

Outflows:

- **In X-direction:** $\boldsymbol{\rho}\left(\boldsymbol{v_x} + \frac{\partial \boldsymbol{v_x}}{\boldsymbol{v_x}}\Delta \boldsymbol{x}\right)(\Delta \boldsymbol{y}.\Delta \boldsymbol{z})$
- **In Y-direction:** $\boldsymbol{\rho}\left(\boldsymbol{v_y} + \frac{\partial \boldsymbol{v_y}}{\boldsymbol{v_y}}\Delta \boldsymbol{y}\right)(\Delta \boldsymbol{x}.\Delta \boldsymbol{y})$
- **In Z-direction:** $\boldsymbol{\rho}\left(\boldsymbol{v_z} + \frac{\partial \boldsymbol{v_z}}{\boldsymbol{v_z}}\Delta \boldsymbol{z}\right)(\Delta \boldsymbol{x}.\Delta \boldsymbol{y})$

Thus, the net mass flow per unit time through the cube works out to:

$$\left[\frac{\partial \boldsymbol{v_x}}{\boldsymbol{v_x}} + \frac{\partial \boldsymbol{v_y}}{\boldsymbol{v_y}} + \frac{\partial \boldsymbol{v_z}}{\boldsymbol{v_z}}\right](\Delta \boldsymbol{x}.\Delta \boldsymbol{y}.\Delta \boldsymbol{z})$$

The conservation principle now requires that sum of the three quantities be zero. Thus,

$$\frac{\partial \boldsymbol{v_x}}{\boldsymbol{v_x}} + \frac{\partial \boldsymbol{v_y}}{\boldsymbol{v_y}} + \frac{\partial \boldsymbol{v_z}}{\boldsymbol{v_z}} = \boldsymbol{0}$$

This is referred to as the equation of continuity in groundwater flow.

5.3.1 Darcy's Law

The water flow just observed during the derivation of continuity equation is due to the difference in hydraulic / potentiometric head per unit length in the direction of flow. Henry Darcy, a French engineer was the first to suggest and derive a relation between the velocity as seen in the continuity equation and the hydraulic gradient.

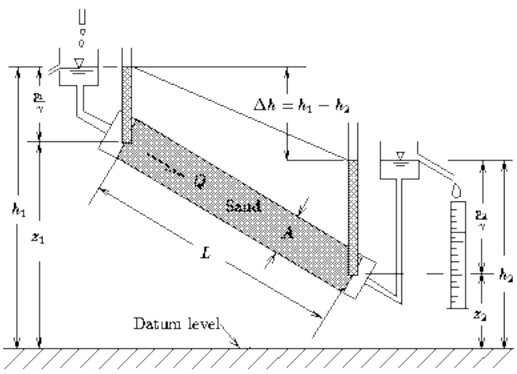


Figure 32 Darcy's Law

According to his experiments, the discharge Q passing through a tube of cross-sectional area A filled with a porous material is directly proportional to the difference of hydraulic head h between the two end points and inversely proportional to the flow length L.

Thus, $\boldsymbol{Q \propto A \cdot \frac{h_1 - h_2}{L}}$

He introduced the proportionality constant K *i.e. hydraulic conductivity* of the porous material, which finally makes the equation as,

$$\boldsymbol{Q = -KA\frac{dh}{dL}}$$

- Negative sign is introduced because the hydraulic head decreases in the direction of flow
- $\frac{dh}{dL}$ is known as the hydraulic gradient
- Dividing Q by, we get specific discharge, denoted by v, or the velocity of the fluid flow;

$$\boldsymbol{v = \frac{Q}{A} = -K\,\frac{dh}{dL}}$$

- It may be noted that this velocity v is not quite the same as velocity of fluid flowing through an open pipe, because it is defined as the total discharge per unit area of soil mass, not as the total discharge per unit area of pore space.
- Primarily, Darcy's Law holds was devised for saturated porous medium of soil. But it has been proved by Buckingham (1907) and Childs and Collis-George (1950) that Darcy's Law also holds true for unsaturated soils though with varying magnitudes of coefficient of permeability (K above) for different volumetric water contents (Fredlund D. G. Soild mechanics for unsaturated soils).

5.3.2 Basic differential equation of groundwater flow

Substituting Darcy's Law in the equation of continuity we get**,**

$$\boldsymbol{\frac{\partial}{\partial x}\left(K_x\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z\frac{\partial h}{\partial z}\right) = 0}$$

Here, hydraulic conductivities in the three directions are assumed to be different i.e. for anisotropic medium. If isotropic medium with constant hydraulic conductivity in all directions is considered, the equation becomes,

$$\boldsymbol{\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} + \frac{\partial^2 h}{\partial z^2} = 0}$$

This equation, also known as Laplace's equation (appears in many places in mathematical physics) is known as the basic equation governing the groundwater flow. The basic problem in all the groundwater models is to find the solution to this Laplace's equation.

As the conservation principle has been applied for deriving this equation, it means that no mass is gained or lost or there is no net inward flux or outward flux to or from this system. Thus, this equation is for the steady incompressible groundwater flow where heads don't change with time.

Now, if the heads change with time, the conservation principle cannot be applied. Hence, some mass will be gained or lost with time depending upon the heads. So there will be change in volumetric water content of the material. The net water stored depends on specific storage which is defined as,

$$\boldsymbol{S_s = \rho g(\alpha + n\beta)}$$

Where $\rho$the density of water is, α is the compressibility of material, n is the porosity of the material and β is the compressibility of water. The groundwater flow equation now becomes,

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right) - W = \frac{S_s}{K} \frac{\partial h}{\partial t} \quad \dots\dots\dots (\mathbf{1})$$

where W is the volumetric flux per unit volume. The above equation is the standard equation for transient flow or flow under non-equilibrium conditions, for heterogeneous and anisotropic porous material, where heads change with time.

Groundwater flow modelling is basically solving this equation for water table heads in a given region / aquifer, with given initial and boundary conditions along with external parameters like rain, lake river etc. The most popular groundwater flow equation solver is MODFLOW developed by United States Geological Survey (USGS) which is used in the present study.

GMS (Groundwater Modelling Software) is a 3D visual interface between MOFDLOW and the user, which helps in visualizing the solution given by the equation solver. It is licensed software developed by Aquaveo, an US company and costs around $ 5000. It is widely used groundwater software in developed countries and developing, characterizing and visualizing groundwater models in 3D environment.

In the present study GMS version 7.1 (trial license) with MODFLOW version 2000 are used.

5.4 Finite difference modelling - MODFLOW

MODFLOW is basically a computer program which numerically solves the three-dimensional groundwater flow equation (equation (1) above) for a porous medium by using finite difference method, wherein the continuous system described the equation (1) broken down into finite set of discrete points in space and time, and the partial derivatives are replaced by terms calculated from the differences in head values at these points. This process leads to systems of linear algebraic difference equations whose solution yields values of head at specific points and times.

The values obtained are approximates to the time-varying head distribution that would have been given by analytical solution of the partial differential equation of flow [51].

Thus, at the heart of MODFLOW lies spatial discretization of an aquifer system with a mesh of blocks called cells, the locations of which are described by rows, columns and layers.

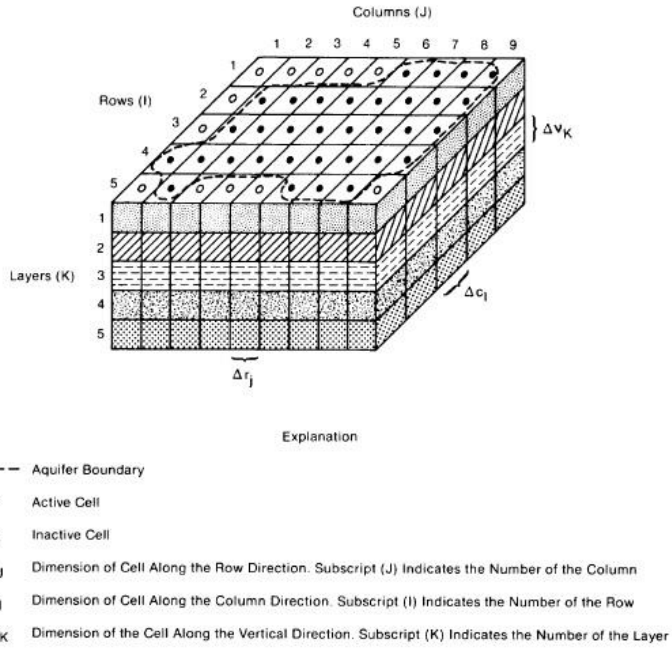


Figure 33 MODFLOW grid

5.4.1 Finite difference equation

The finite difference equation which forms the basis of MODFLOW, is derived by applying the continuity equation seen above i.e. the sum of all flows into and out of the cell must be equal to the rate of change in storage within the cell. Thus, assuming density of water as constant again, the continuity equation for the balance of flow in a cell will be,

$$\sum \boldsymbol{Q_i} = \boldsymbol{S_s} \frac{\Delta \boldsymbol{h}}{\Delta \boldsymbol{t}} \Delta \boldsymbol{V}$$

- **Q_i is the flow rate into the cell**
- **S_s is the specific storage; volume of water which can be injected per unit volume of aquifer material per unit of change in head**
- **ΔV is the volume of the cell and**
- **Δh is the change in head over a time interval Δt**

Now if a particular cell *i, j, k* is considered along with its six adjacent cells *i-1, j, k; i+1, j, k; i, j-1, k; i, j+1, k; i, j, k-1; and i, j, k+1,* the volumetric water discharge between through six faces of the cell can be obtained by applying Darcy’s law.

E.g. flow into the cell *i, j, k* in the horizontal direction from the cell *i, j-1, k* would be,

$$q_{i,j-1,k} = K_{i,j-1,k}\,.\,\Delta c_i \Delta v_k\,.\,\frac{h_{i,j-1,k} - h_{i,j,k}}{\Delta r_j}$$

- **$h_{i,j-1,k}$ and $h_{i,j,k}$ are heads at respective nodes, $K_{i,j-1,k}$ is the hydraulic conductivity along the row between the two cells, $\Delta c_i \Delta v_k$ is the area of the cell face normal to the flow direction and Δr_j is the distance between the cells.**

Similar equations can be written for the flow into the cell from remaining five faces. In addition, the flows into the cell from features or processes external to the aquifer, such as areal recharge, evapotranspiration, streams, drains or wells, additional terms are also to be considered. These flows may be dependent on the head in the receiving cell but independent of all other heads in the aquifer, or they may be entirely independent of head in the receiving cell. After considering all the flows and expressing the time derivative of head in terms of specific heads and times, the finite difference approximation for the cell *i, j, k* is obtained from the continuity equation

$$\begin{gathered} \textit{flow from six faces into cell } i,j,k + \\ \textit{external flows into or out of } i,j,k \\ = S_{s_{i,j,k}} \left(\Delta r_j \Delta c_i \Delta v_k\right) \frac{h_{i,j,k}^{m} - h_{i,j,k}^{m-1}}{t_m - t_{m-1}} \end{gathered}$$

- **$t_m - t_{m-1}$ is time interval and $h_{i,j,k}^{m}$ and $h_{i,j,k}^{m-1}$ are heads at respective time intervals. Time derivative of head is approximated using change in head at the node over time interval which precedes the time at which the flow is calculated. This is termed as backward difference approach.**

This equation is the basis for the simulation of partial differential equation of groundwater flow. The equation has seven heads, six for the six adjacent cells and one for the same cell from previous time step. These seven heads are unknown at the end of time step t_m. Thus, the equation cannot be solved independently. However, an equation of this type can be written for each active cell in the mesh; and, since there is only one unknown head for each cell, we are left with a system of "n" equations in "n" unknowns. Such a system can be solved simultaneously[51], [53].

For the simulation to start, two types of inputs are necessary:

Initial head distribution – The initial head distribution provides a value of $h_{i,j,k}^{1}$ at each point in the mesh i.e. it provides the values of head at the beginning of the first of the discrete time steps into which time axis is divided in finite-difference process. The first step is to find solution for $h_{i,j,k}^{2}$ which marks the end of first step and so on**.**

Boundary conditions – The groundwater flow equation is solved by solving the boundary value problem. Boundary value problem is a differential equation with additional constraints, called boundary conditions. In MODFLOW, the boundary conditions can be set at the beginning, by entering the status of certain cells in the mesh in advance. There are three kinds of boundary conditions:

- Known head or constant head – the head for some cells is specified in advance, and this head remains constant throughout the simulation
- Known flow – the flow into or out of particular cell is known beforehand e.g. withdrawal of water from well per day
- No flow – These are the cells for which no flow into or out of the cell is permitted, in any time step in the simulation

5.4.2 Iterative method

Each time step in the simulation in MODFLOW starts by arbitrarily assigning a trial value or estimate for the head at each cell at the end of that step. A procedure for calculation is then started which alters these estimated values, producing a new set of head values which are in closer agreement with the system of equations. These new, or interim, head values then take the place of the initially assumed heads, and the procedure of calculation is repeated, producing a third set of head values. This procedure is repeated successively, at each stage producing a new set of interim heads which more nearly satisfies the system of equations. Each repetition of the calculation is termed as iteration. Finally the changes made by the succeeding stages become very small, and this smallness is utilized in determining when to stop the iteration also termed as closure criterion or convergence criterion.

Thus, during a MODFLOW simulation, series of iterations form one time step, series of time steps form one stress period and user can enter multiple stress periods each with specific stress data like monsoon period data, post-monsoon period data etc [53].

5.4.3 Packages

The modular structure of MODFLOW consists of a Main program and a series of highly independent sub-routines called modules. The modules are in turn grouped into packages. Each package deals with the specific feature of hydrologic system which is to be simulated, such as simulation of a well, simulation of a lake, simulation of an underground barrier structure, simulation of stream, simulation of drains, rains etc. [53].

Chapter 6 Modelling of Mokhada watershed

We now build the conceptual model and then the numerical model for the area selected for the study purpose. The watershed has been delineated using GRASS in QGIS. Streams have been identified. Separate shapefiles have been prepared for both watershed boundary and streams. Both the shapefiles were then imported in to GMS. It has been assumed that watershed boundary coincides with the aquifer boundary in the area (but more about this, later). Various wells have been identified in the region and the shapefile for the same has been made in QGIS. This shapefile was also imported into GMS.

The model was to simulate a full hydraulic year, i.e., from the start of the monsoon on June 1 to the end of the season on May 31st. This was done as a steady state computation resulting in the state S, and a transient computation which would carry on from S and evolve as the season progresses. The monsoon was modeled as a steady state computation since the daily rainfall in Konkan is fairly regular. Thus the state S above was to denote the steady state at the end of the monsoon. The transient state began with the cessation of monsoon, on October 15.

6.1 Building of conceptual model for steady state

For the present study 23 coverages have been made. These coverages are boundary condition, (hydraulic conductivity, specific yield, specific storage and vertical conductivity), recharge rate wells, drains, zone budget and observation data. Total number of layers in 3d model was decided to be eight. Eight coverages of aquifer properties and 8 coverages for zone budget were prepared. Two separate coverages were made around the drains so that they could be treated and manipulated separately, e.g., for making the zones around drains more conductive. In boundary coverage the boundary of the watershed has been selected as a no-flow boundary. For the first time the model was run in steady state with values taken from literature for various layers. The values have been given in the following table. For the hydraulic conductivity, the value of k has been selected as 0.2 m/day for the first layer. Similarly values for the other layers have been given in the table below. The conductivity values of various layers were taken from the literature based upon their relative capacity to transmit, store and accumulate water with respect to each other. Vertical hydraulic conductivity was selected to be half of the horizontal hydraulic conductivity. The recharge rate has been selected as 0.005m but was modified later. In wells and drain coverage data has been imported from the shapefiles. Extraction rate for wells are very low since there is very less extraction, which is mostly for domestic purpose.

The modeling of surface water and groundwater interactions is always critical. The streams which have been delineated in the QGIS have been used as drains in the GMS. Conductance value of 1000 m2/d/m was used with the drain elevation as the elevation of the cell. Thus, in effect, the head at the drain cell was clamped above at its elevation. Excess water coming into the cell would be "drained" off instead of raising the hydraulic head. The outlet of watershed was modelled as a specific head due to the presence of the bund where is a constant water level. So it has been given specified head value of 195m. The specified head boundary was taken as the elevation of the bund. Specified head was mentioned in the boundary coverage.

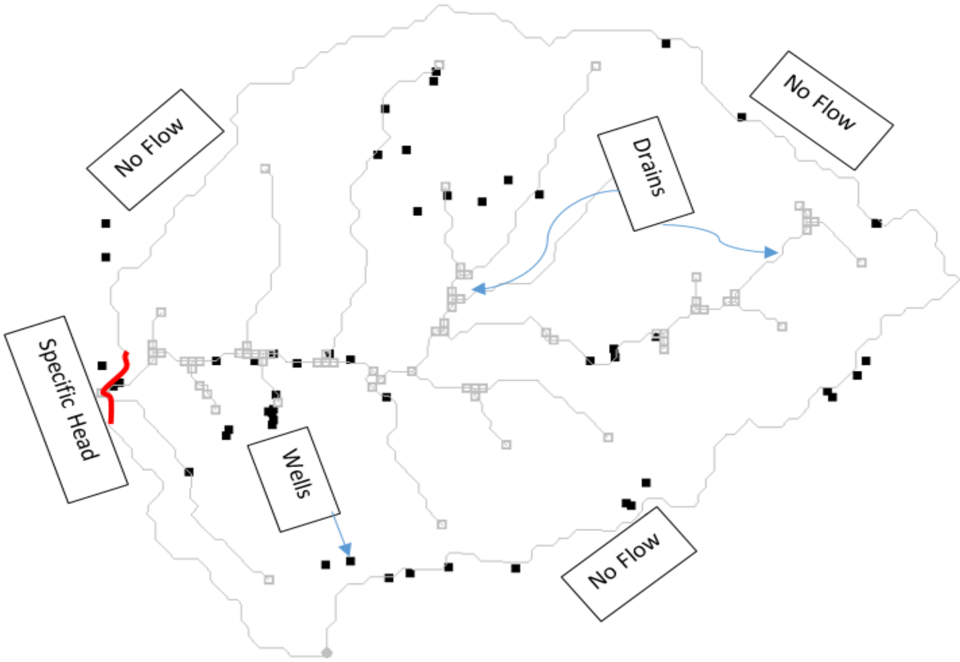


Figure 34 Boundary Conditions

Table 10 Initial aquifer properties

Layer	**HK m/day**	**VANI HK/VK**	**Recharge meters**	**Conductance** m2/d/m
1	0.2	2	0.003	1000
2	0.01	2		
3	0.0005	2		
4	0.008	2		
5	0.05	2		
6	0.0001	2		
7	0.05	2		
8	0.0001	2		

6.2 Building of 3D Model

After preparation of conceptual model 30*30m cell size grid was generated. Then the conceptual model was mapped to the 3d grid. All the values which were given as input to the conceptual model were mapped to the individual grid cells. Elevation data has been prepared from DEM. DEM has been directly imported to GMS and has been given as input to the GMS. A new raster was prepared for the bottom elevation by subtracting 15m thickness from the top elevation. This has been given as input to bottom elevation of top layer. Another raster was prepared by subtracting 30m from the top layer. This was given as input to the second layer bottom elevation. Since this model is eight layer model rest of the layers have been given constant elevation at 440m, 390m, 340m, 240m, 200m and 160m. Elevation of top layer is preserved at all the places. At this point the conceptual model is ready and can be converted to numerical model.

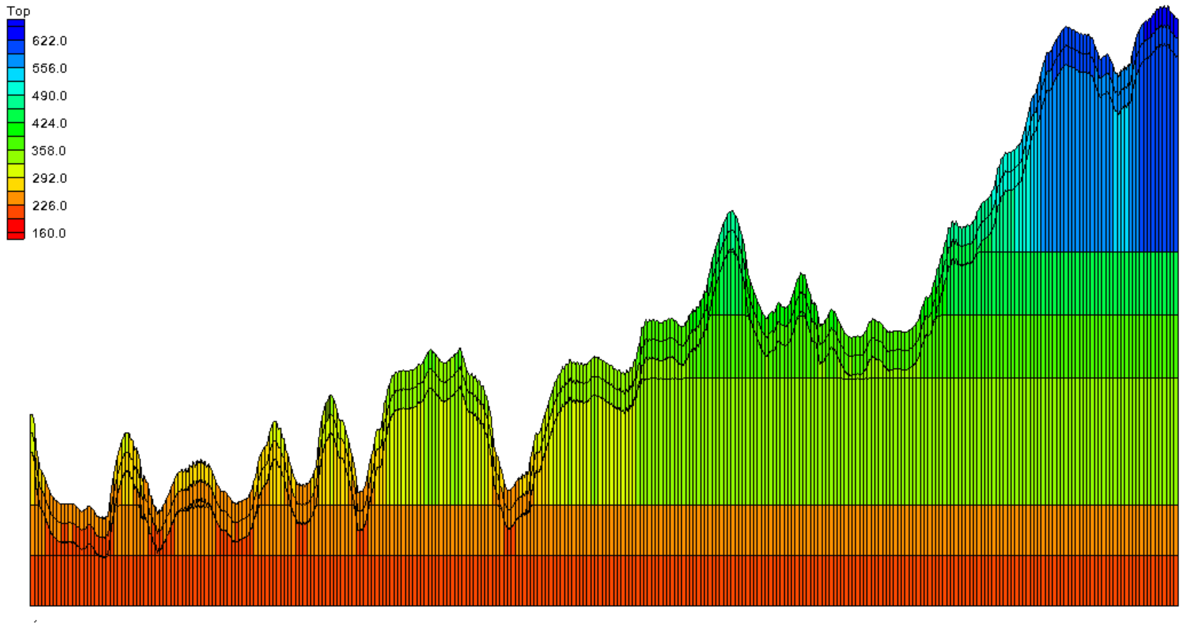
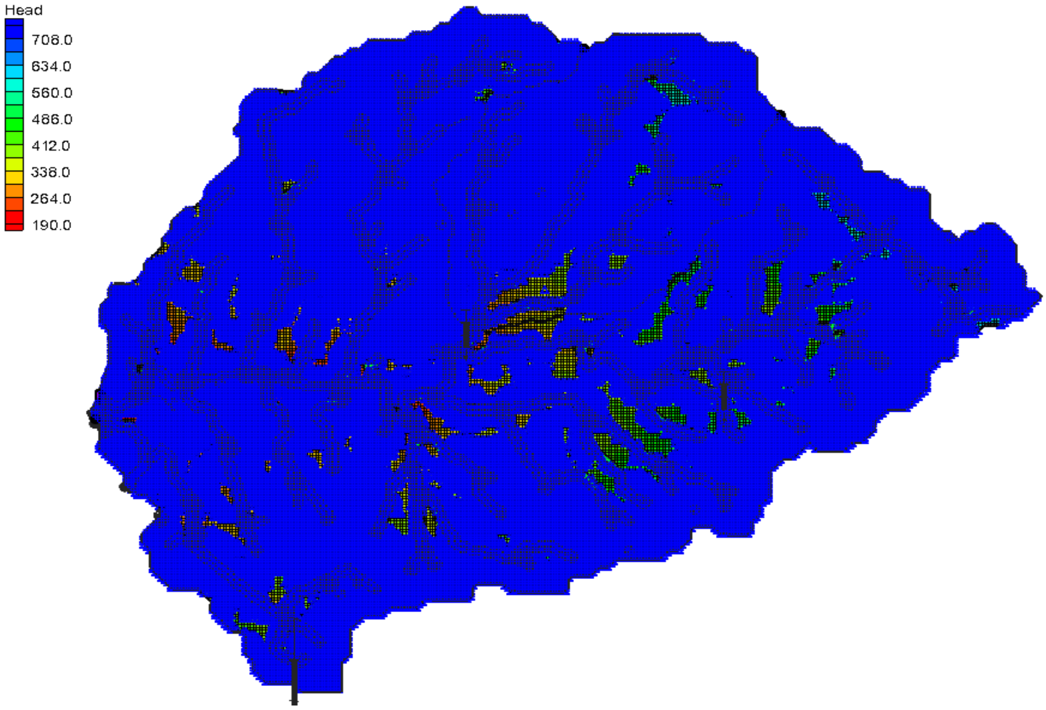


Figure 35 Top and bottom elevation of various layers of Adoshi watershed

6.3 Running the model

After 3d grid model was ready, check simulation was run on the model to view problems in the cell properties, drain conductance and layer elevation. After fixing errors related to all these problems model was ready to run. Starting heads for the model were kept same as top elevation. First the model was run in steady state. The model gives the output head as shown in the figure.



Number of selected cells: 0 (data for all cells is displayed below)

	Flow In	Flow Out
Sources/Sinks		
CONSTANT HEAD	0.0	-111.1360047912
WELLS	0.0	-140.0
DRAINS	0.0	-213533.2432221
RECHARGE	213784.20326233	0.0
Total Source/Sink	**213784.20326233**	**-213784.3792269**
Zone Flow		
FLOW RIGHT FACE	0.0	0.0
FLOW FRONT FACE	0.0	0.0
FLOW LOWER FACE	0.0	0.0
FLOW LEFT FACE	0.0	0.0
FLOW UPPER FACE	0.0	0.0
FLOW BACK FACE	0.0	0.0
Total Zone Flow	**0.0**	**0.0**
TOTAL FLOW	**213784.20326233**	**-213784.3792269**
Summary	**In - Out**	**% difference**
Sources/Sinks	**-0.17596457203**	**-0.000082309402**
Cell To Cell	**0.0**	**0.0**
Total	**-0.17596457203**	**-0.000082309402**

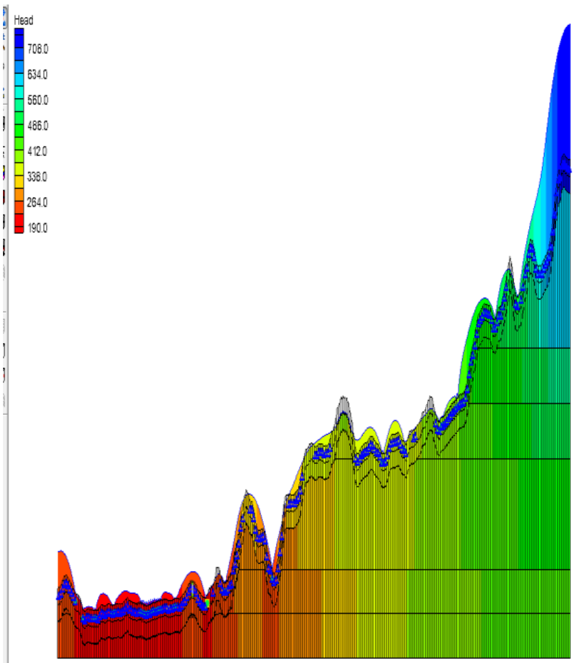
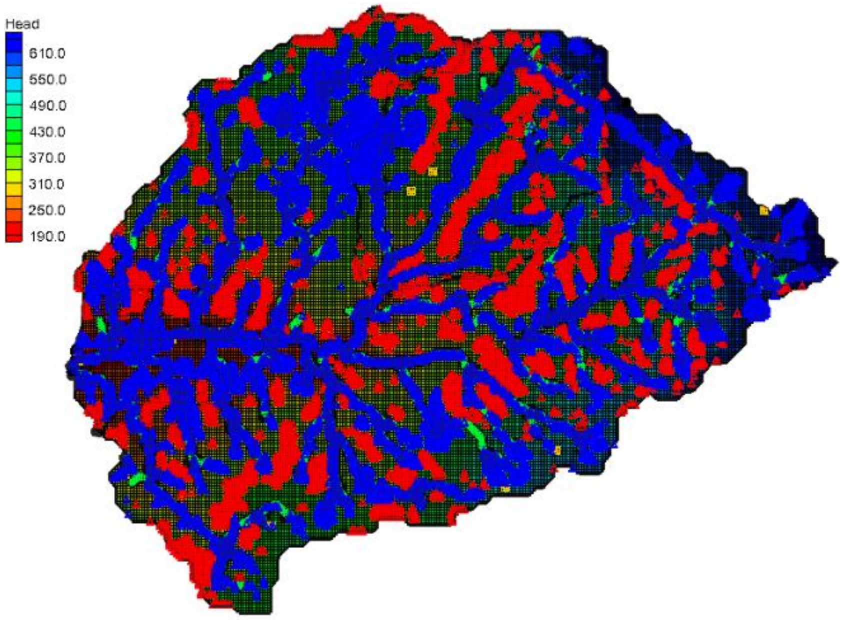


Figure 36 Head distribution and flow budget of Mokhada watershed

6.3 Problems with the model

Since the model converged but there were some problems with the simulation. We have kept the recharge rate is very high. We see the resulting head in the image above and can easily find that the head values vary between 708m to 180 m. But the top elevation was only 650m which means cells are getting flooded. Blue colour in the image represents the flooding. The main reason for this was high recharge rate. Drains in the result were also removing 213533m3 of water from the watershed which is far from the observed value of 100000m3. This value of water removed from drains was approximately equal to the recharge rate. This gave us the idea of reducing the recharge rate. After number of trials value of recharge rate was reduced to 0.001m. This reduced the flooding in the model but value of flow coming out of drains was reduced to 42579m3. There was considerable difference between the observed value and value given by the drain. Drain conductance was also changed but did not produce desirable results. Reducing the drain conductance led to increase in head at places which are far from drain. Increasing drain conduction reduced the head at far places. So one value 100 of drain conductance was fixed and we did not change it further.



Flow Budget

Cells | Zones | USGS ZONEBUDGET

Number of selected cells: 0 (data for all cells is displayed below)

	Flow In	Flow Out
Sources/Sinks		
CONSTANT HEAD	0.0	-37.60991808996
WELLS	0.0	-140.0
DRAINS	0.0027227401733	-42579.53703284
RECHARGE	42756.84634757	0.0
Total Source/Sink	**42756.849070311**	**-42757.14695093**
Zone Flow		
FLOW RIGHT FACE	0.0	0.0
FLOW FRONT FACE	0.0	0.0
FLOW LOWER FACE	0.0	0.0
FLOW LEFT FACE	0.0	0.0
FLOW UPPER FACE	0.0	0.0
FLOW BACK FACE	0.0	0.0
Total Zone Flow	**0.0**	**0.0**
TOTAL FLOW	42756.849070311	-42757.14695093
Summary	**In - Out**	**% difference**
Sources/Sinks	**-0.297880620143**	**-0.000696682728**
Cell To Cell	**0.0**	**0.0**
Total	**-0.297880620143**	**-0.000696682728**

Figure 37 Change in recharge rate

Finally the value was fixed at .003m which gave us the closest result of 128055m3 to the observed value but again flooding was considerably increased in the model. Then it was decided to change the value of hydraulic conductivity. Value of hydraulic conductivity of top layer was changed to .5 yet it did not reduce the flooding by much but it did not had any impact on amount of water draining out of system. Now we could fix the value of recharge rate and could change the value of hydraulic conductivity. The value of recharge rate was further reduced to .0025m which was closely matching the observed value. Hydraulic conductivity of the all the layers were increased considerably this led to dryness of the top layer of watershed.

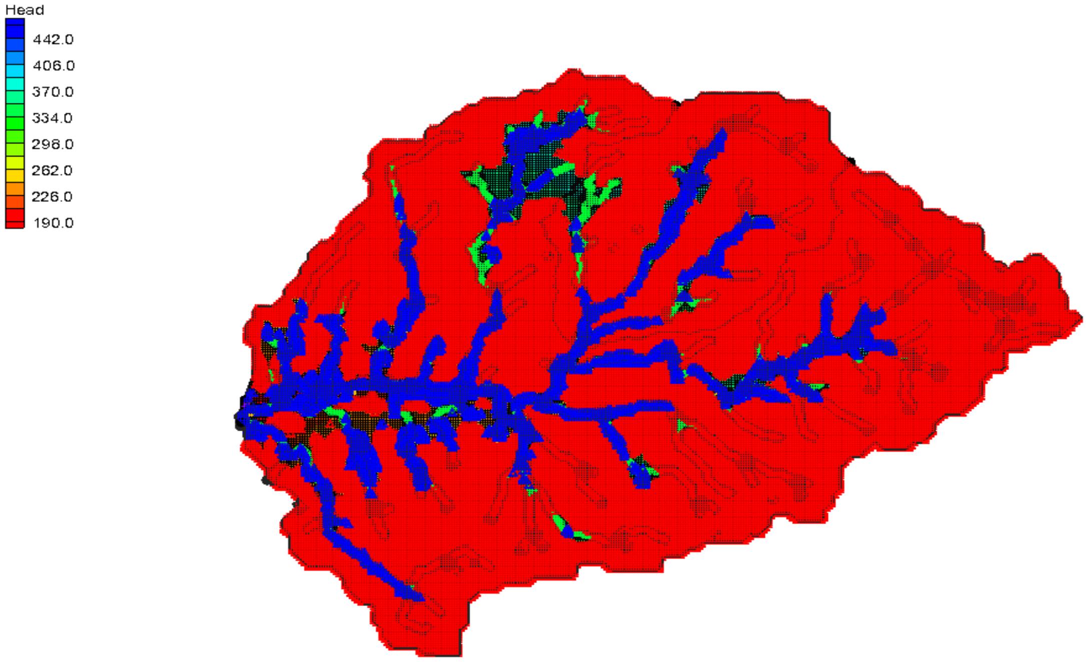


Figure 38 Change in hydraulic conductivity

After several such calibration loops, a set of values were reached at which both flow and initial head levels of well-matched considerably. At this point values were fixed and model was finally calibrated for steady state. Following graph shows the observed value and computed head value at the well location. Most of the values are completely falling on the line. One or two points are offset to the line due to local geology conditions.

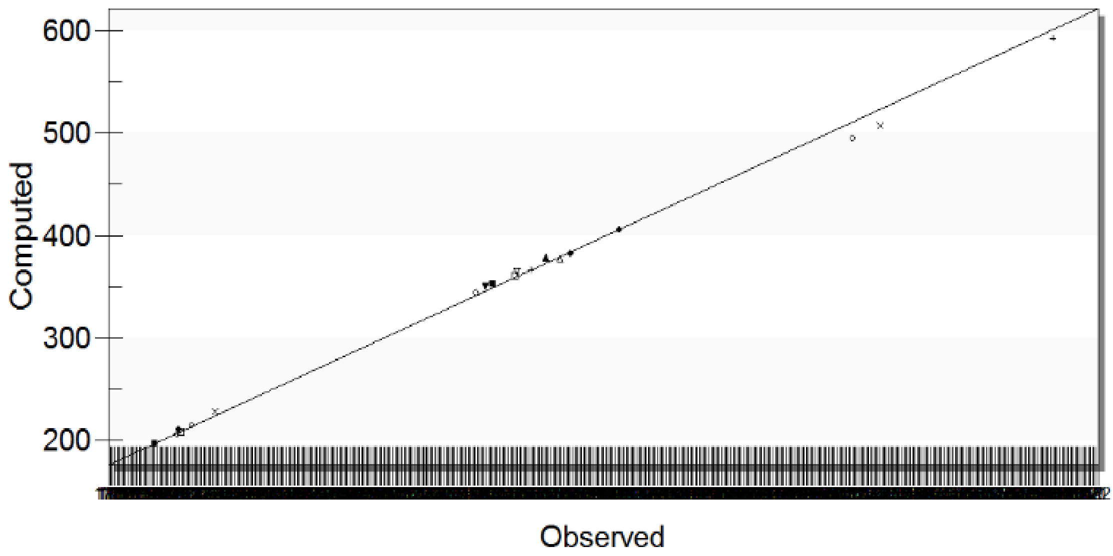


Figure 39 Computed and observed head value

We now come to the transient state. This involves computing the hydraulic head movements and matching them with the observed wells data. By looking at the elevation and slope map and comparing with the head distribution we see that because of hilly terrain water table at certain places is falling very fast. More over at these places thickness of soil is very less. All these places which do not allow any water to infiltrate and have high slope have dried up shown by red colour. Most of the blue colour is in the streams which actually have water till December. At few places where there is flat agriculture land and have flat slope is holding some water because of high thickness of soil at these places.

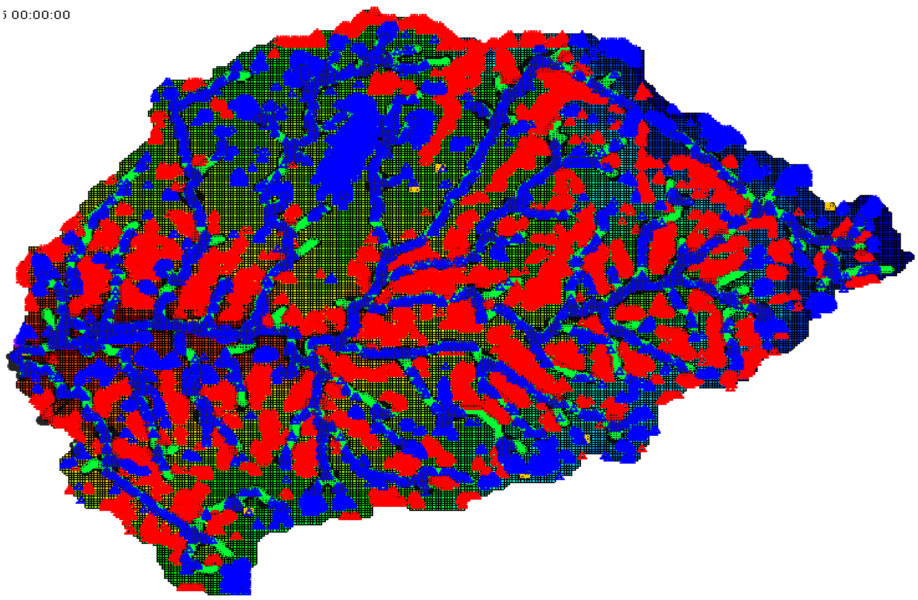


Figure 40 Head after steady state

6.4 Calibrating the model in transient state

From the calibration experience of steady state model it was decided to first analyse the sensitivity of various parameters. It was easier to calibrate the transient state model after checking the sensitivity of various parameters. Recharge rate in the model was fixed in steady state so it was not changed during transient calibration. Value of recharge rate in transient mode was kept 0 because during transient period there was no rain fall. For this purpose two stress periods were used, one for monsoon and other for non-monsoon. The model was run for total 228 days for non-monsoon period. Time step for this was fixed as one day. For calibrating the model it was decided to first match the observed water level readings. Second step was to match the flows in the region with observed values in the region.

After fixing the transient objectives we decided to analyse impact of various parameters on simulation. From the table given below following conclusions were drawn. There were mainly two parameters, viz., hydraulic conductivity and specific yield which impacted the flows and head level in the region. Change in specific yield values did not impact the initial head values or head set up in steady state. However it led to increase of daily base flows in transient state. Heads of the region were fell at lower pace with increasing specific yields. Higher head values were obtained at the end of transient state after increasing the specific yield. Change in value of hydraulic conductivity also had an impact on both head values and flows in the region. Higher hydraulic conductivity value led to heads going down at a faster pace. Whereas this value does not have any impact on the initial flow on the steady state but it impacted the daily flows in transient state. Increased value of Hk for first layer reduced the head values as well as flows. Reduction of Hk value for the first layer led to increase in head values and flows also increased substantially. This phenomenon was different in rest of the layers as increase in Hk value of other layers led to reduction in head and increase in flow. Change in vertical anisotropy or increase in vertical hydraulic conductivity of the layer led to increase in reduction of head and increase in flow[54].

Figure 41 Parameter Sensitivity

	wells	Starting head	Intermediate head	Closing head	Flow	Nashera	Dholara
Model	Point_1	392.42	386.4	382.19	15921	2711	2991
	Point_10	376.86	370.79	366.5			
	Point_8	211.53	210.97	210.88			
	point_4	346.56	345.67	345.38			

Sy=.03	Point_1	392.42	388	384.12	20772	3858	3951
	Point_10	376.86	372	368.25			
	Point_8	211.53	211.01	210.92			
	point_4	346.56	345.86	345.49			
sy=.01	Point_1	392.42	383.79	379.85	12552	1938	2360
	Point_10	376.86	367.39	361.84			
	Point_8	211.53	210.94	210.82			
	point_4	346.56	345.53	345.34			
Hk=.4	Point_1	389.48	383.26	379.65	14284	2332	2643
	Point_10	373.83	367.84	363.43			
	Point_8	346.58	345.66	345.4			
	point_4	211.55	210.96	210.86			
Hk1=.1	Point_1	435	425	416.3	41527	7896	8578
	Point_10	417.6	406	395.17			
	Point_8	215.9	212.9	211.49			
	point_4	349.5	347.62	346.57			
Hk2=.01	Point_1	394.25	388.17	384.04	15860	2829	2955
	Point_10	377.88	371.57	367.33			
	Point_8	211.53	210.96	210.87			
	point_4	346.56	345.67	345.37			
Hk2=2	Point_1	392.14	386.1	381.92	16671	2471	2640
	Point_10	375.14	368.99	364.11	drain	conductive	
	Point_8	211.41	211.03	210.87			
	point_4	346.25	344.49	343.85			
hk7=.03	Point_1	392.12	386.37	382.21	18513	3084	3490
	Point_10	376	369.88	365.28			
	Point_8	211.53	211	210.93			
	point_4	346.57	345.76	345.48			
hk5=.05	Point_1	390.75	384.68	379.85	17731	3073	3547
	Point_10	376.06	369.87	365.08			
	Point_8	211.53	210.96	210.87			
	point_4	346.56	345.78	345.47			
Sy=.01	Point_1	392.42	387.44	383.74	22386	4186	4282
	Point_10	376.86	371.15	367.13			
	Point_8	211.53	211.05	210.94			
	point_4	346.56	345.88	345.53			
VANI=1	Point_1	392.1	386.48	382.35	17831	3085	3433
	Point_10	376.28	370.19	365.73			
	Point_8	211.53	210.98	210.89			
	point_4	346.56	345.73	345.45			

To calibrate the model it was decided to match the water levels of wells. After the heads were stabilized in the steady state the model was converted into transient state. Slopes of the head did not match for many wells. For, these wells, our predicted heads fell much faster than what was observed. During the trial and error it was observed that wells could be represented into two groups, viz., wells in drains i.e., close to streams, and non-drain wells i.e., away from streams. These two groups could not be matched simultaneously. In other words, if transient water levels of non-drain wells were matched then drain well water level were in error.

So it was decided to calibrate the model in the three steps. First the heads of non-drain wells were calibrated. Values of specific yield and specific storage were taken based upon the literature reviewed and their relative ability of zones modelled to hold water in the layers. Top layer was given higher specific yield because it forms the highly weathered and shallow unconfined aquifer. Reducing the conductivity values of the bottom layers have led to reduction in flow and increase in head. Then flows in both the Nashera and Adoshi were calibrated. The flows in the region were brought within 15% of starting value. Further reducing the flow was disturbing the calibration of calibration of non-drain well. Then we tried to match the heads in drain wells. Reducing the specific yield value have also led to reduction in flows and increase in head gradient. This third process was bit difficult as the system was governed by numerous boundaries conditions and properties. Since drains were located at the lowest elevation in the region which meant until and unless water in the nearby region reduced heads in the drains would not be reduce by much. To calibrate this, a new zone around the drain was created in the top layer.

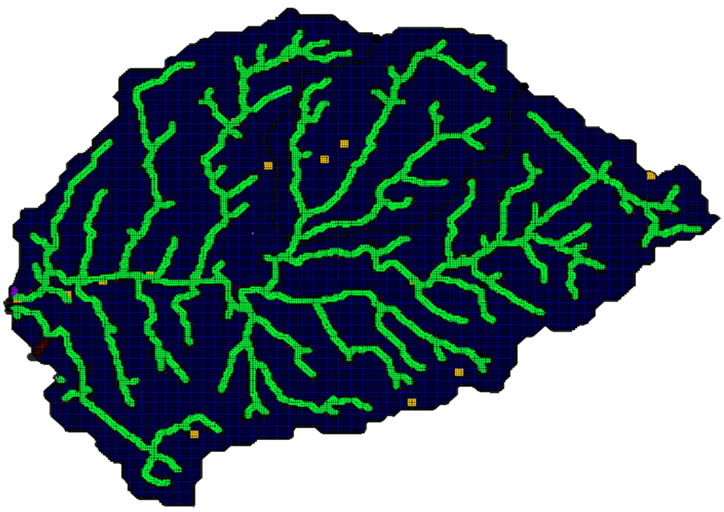


Figure 42 Drain Zone

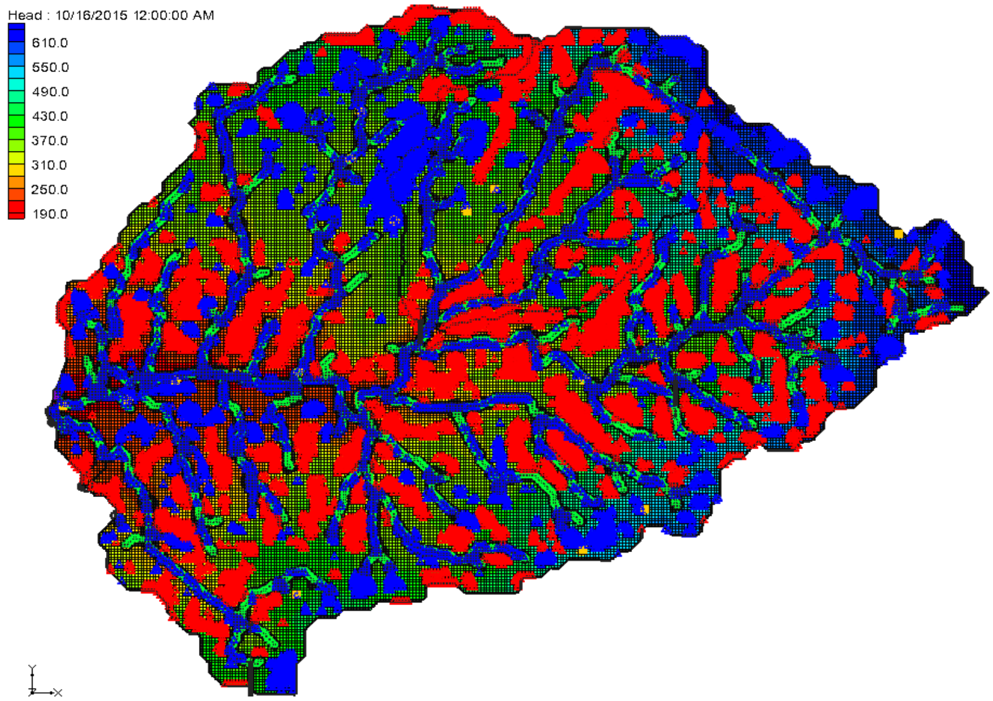
Conductivity of this zone around drains was increased to find the appropriate head distribution throughout the watershed. After number of simulations it was concluded that this does not improve the calibration of drain wells. Another attempt of deepening the thickness of the conductive layer near the drains was tried. This was done by creating in the second layer. Outer part of this zone was given properties of lower conductivity and inner part was given properties of top layer conductive zone. This did improve the calibration but full calibration of drain wells was not achieved. Similarly conductivity, specific yield and specific storage values of various layers were altered to improve the calibration in the model. This whole process of calibration was based on trial and error method. Based upon the calibration achieved following values were fixed.

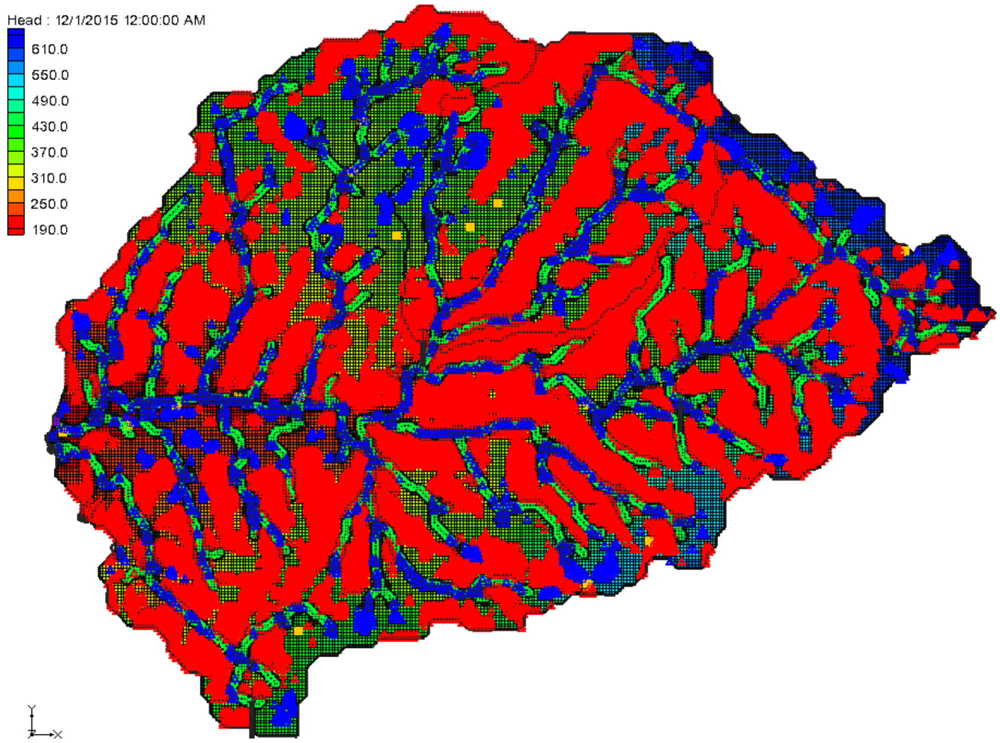
Figure 43 Aquifer Properties of Model

Layer	**HK** m/day	**SY**	**SS**	**VANI HK/VK**	**Recharge meters**	**Conductance** m2/d/m
1	0.35	0.02	0.0013	2	0.0025	100
2	0.05	0.001	0.00006	2		
3	0.001	0.001	0.00003	2		
4	0.001	0.001	0.00006	2		
5	0.01	0.005	0.0004	2		
6	0.001	0.001	0.00006	2		
7	0.01	0.01	0.0003	2		
8	0.001	0.001	0.00006	2		
1 Drain zone	2	0.015	0.001	1		
2 Drain zone	0.05	0.01	0.0006	1		

In the following images head distribution in the transient state is given. Most of the flooding happens in the drains and areas which are completely flat. This matches field observations. Because of less gradient water is moving slowly in these area and is prone to seeping out. As the propery of the complete layers are kept constant it is difficult to account for these variations which are present on ground. Four different time steps 16/10/15, 12/1/15, 2/1/16 and 31/5/16 have been shown in the following images. During the early months head falls at considerable pace. Once the top layer has become dry there is reduction in the rate of fall of head.

This completes the model-building phase. Thus, what achieved was (i) a matching of well heads, field observations of flooding and initial stream flow in the steady state, and (ii) heads in non-drain wells, stream flows and behaviour of flooding with field observations.


Head : 10/16/2015 12:00:00 AM
610.0
550.0
490.0
430.0
370.0
310.0
250.0
190.0
Y
X


Head : 12/1/2015 12:00:00 AM
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490.0
430.0
370.0
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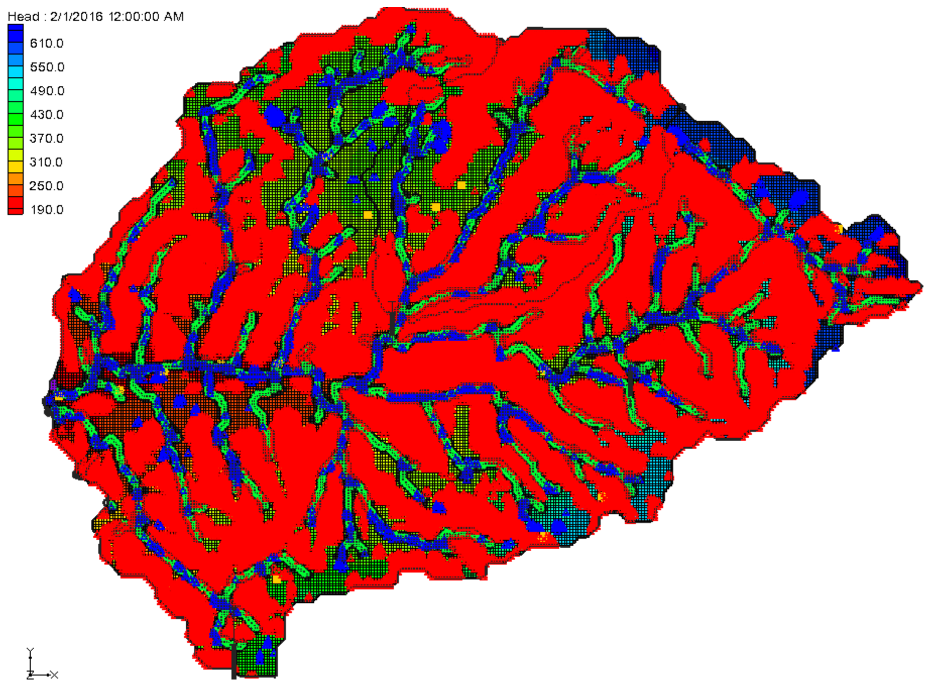
Y
X



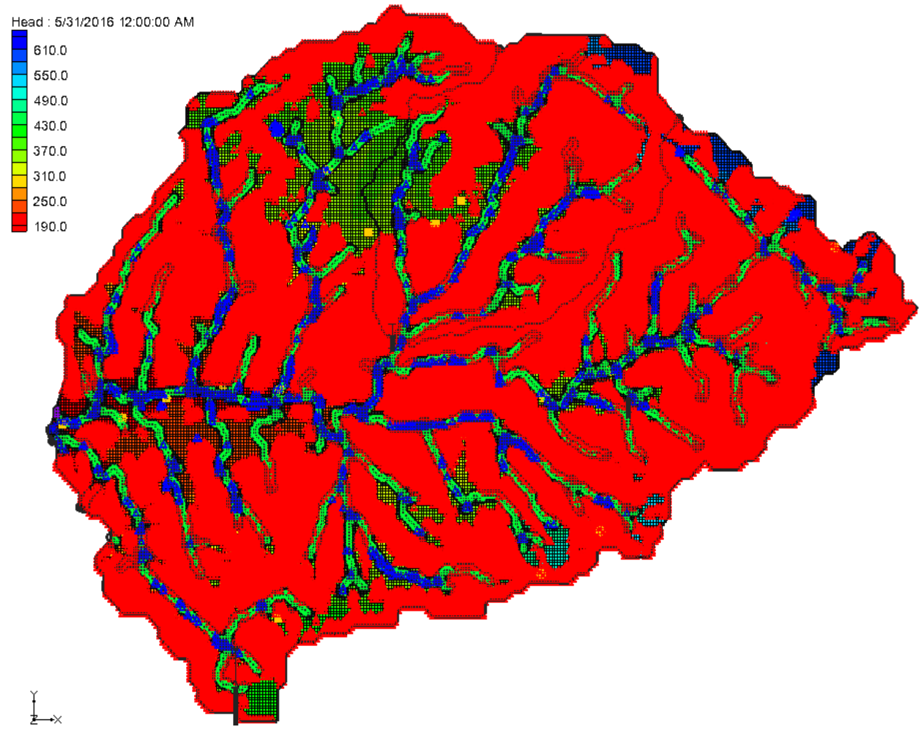


Figure 44 Head distribution in transient state

Chapter 7 Result and Discussion

The model yields considerable insights into 4 major areas which we list here.

(i) It offers a comparison between typical (GSDA or CGWB) assessment methods and what the model depicts.

(ii) It offers a seasonal understanding on the availability of ground-water and the factors and possible interventions which impact it.

(iii) It offers an insight into the availability of water for agriculture and drinking, esp. the post-monsoon months.

(iv) Some insights into the technical aspects of modeling hilly regions. These are in the modeling of boundary conditions and the device of drains in MODFLOW.

7.1 Comparison of GSDA and Model Data

As per GSDA methodology water balance of the area has been calculated by both the methods i.e. rainfall infiltration method and water fluctuation method. The values of rainfall, infiltration, specific yield have been taken according to values used in the WF-15 watershed. Our study area falls in this watershed. 5% of total recharge has been assumed as base flow. Water table fluctuation method gives more amount of natural discharge. So our data will be compared to these values. According to GSDA 70mm of water is getting infiltrated into the area which is calculated from the infiltration coefficient.

Table 11 Water balance by GSDA methodology for study area

Rainfall Infiltration Method

Name	Area ha	Rainfall m	Infiltration	Total recharge m3	Natural discharge m3 (Base flow) 5%
Adoshi Watershed	42730000	2	3.5%	2991100	149555
Dholara	7740000	2	3.5%	541800	27090

Water Table Fluctuation Method

Name	Area ha	Specific yield	Water fluctuation	Total Recharge m3	Natural discharge m3 (base flow) 5%
Watershed	42730000	.015	7m	4486650	224332.5
Dholara	7740000	.015	7m	812700	40635

Total amount of storage released by model including the water which is going through the constant head is 7653028 m3. Most of this water is getting out of the system through drains and this number is equal to 7704800m3. This means most of the water which is entering the top layers is almost getting out through drain as base flow. Where as in case of GSDA only 5% of total recharge 4486650m3 in the area is getting out. This base flow figure comes out to be 224332m3. This means most of the water is still inside ground. If we distribute the total amount of water which is draining out of the drains over the whole watershed the figure comes out to be 180.3mm. This tells us that large amount of water is entering into the ground and if layers are completely saturated which is real scenario they are likely to release more amount of water as base flow which is predicted by our model.

Table 12 Water balance predicted by Model

Steady state

Name	Recharge m3	Drain out m3	Constant head m3
Dholara	19369	19806	
Complete Model	87522	86886	72

Transient state

Name	Storage released m3	Drain out m3	Constant head m3
Dholara	1429796	1496735	
Complete Model	6208268	6208065	14964

7.2 Net water available at the end of monsoon

Water balance of top layer of thickness 15m was calculated. The total amount of water available at the start of the simulation in the given layer was 6989240m3. The amount of available water was reduced to 3210771m3. Most of the water from this layer which is 3778469m3 is contributed to the drains as base flows. After contributing this much amount of water still substantial amount of water is left in the layer 3210771m3. During the end of month of

November there is still 50 lakh m3 of water present in the top layer. This water can be easily utilized for Rabi crop. As most of the dug wells in the region are dug at the depth less than 10m substantial amount of water is untapped in the region which can be used by deepening of the wells. In the watershed it has been observed that there are considerable amount of base flows present in the lower reaches. This has been proved by the model but these numbers are missing from GSDA calculation. Even if we provide protective irrigation of 50cm in Rabi season over a period of 3-4 months over the complete watershed second crop can be easily taken. The amount of agriculture area calculated from the BHUVAN satellite image comes out to be 13km2. This agriculture land area is 1/3th of the actual watershed which is calculated from the BHUVAN satellite data this makes even more availability of water for the crops. Most of the areas which show good amount of water availability coincide with the agricultural area.

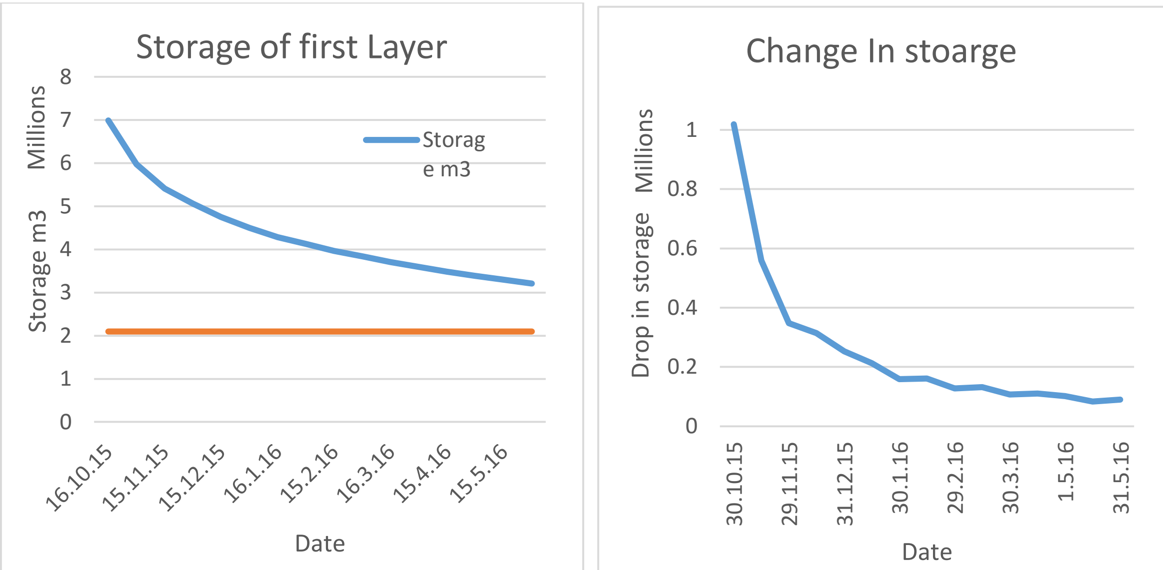


Figure 45 Water availability of First layer

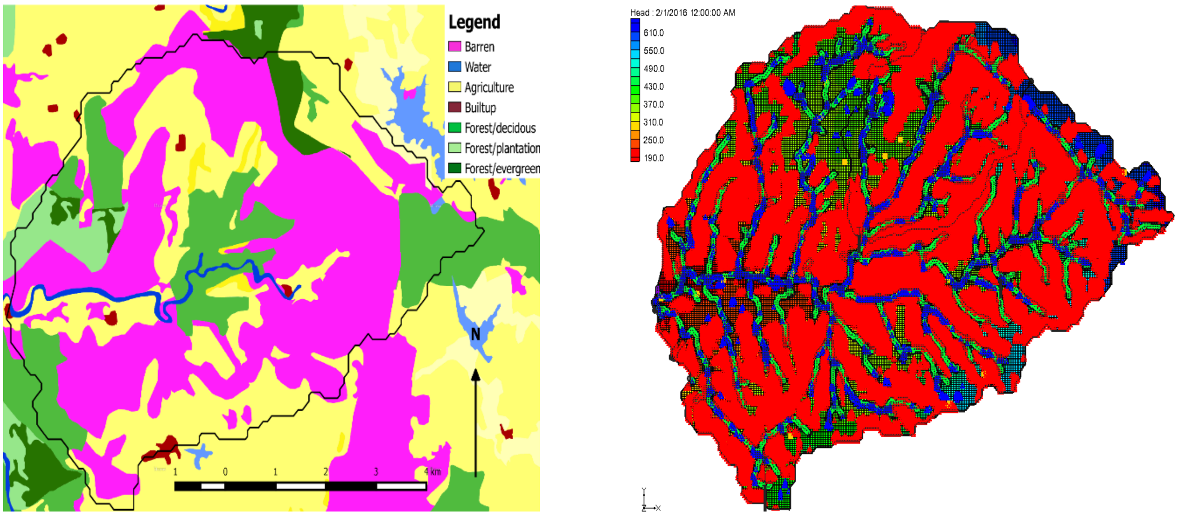
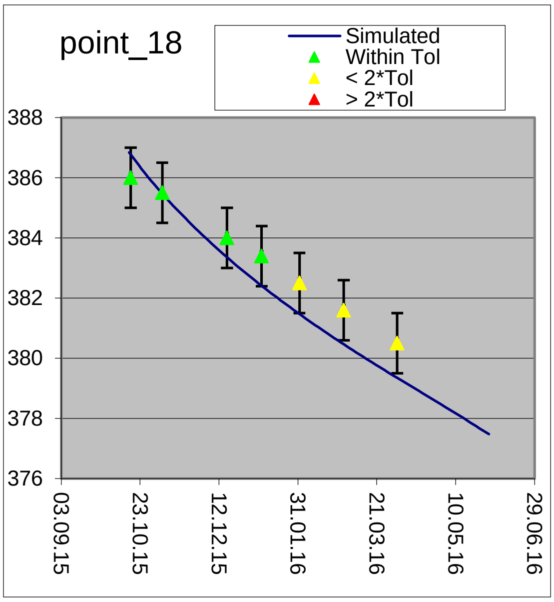
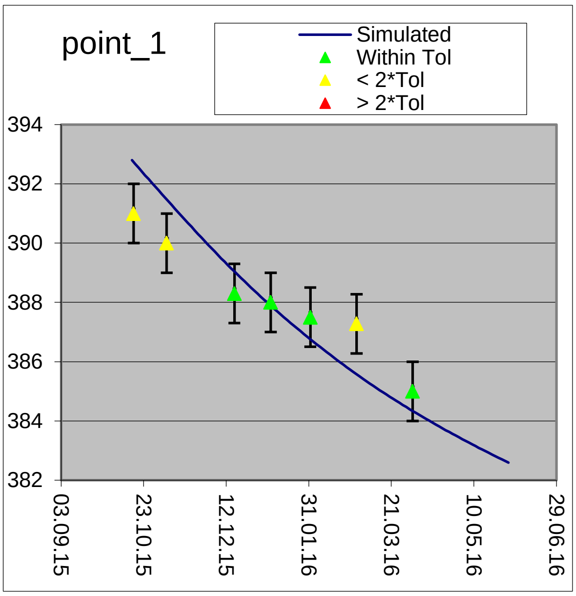


Figure 46 Agriculture land and water availability

7.3 Calibration result for Non-Drain wells

Total 6 wells were calibrated which were not falling in the any of streams. Result of matching of these wells with the actual observation has been shown in the following graphs. If the simulated head is falling within 1m of the observed value than that reading has been marked with green sign. If head is falling with in 2m of observed value then that reading has been marked with yellow colour. Otherwise head value has been marked as red colour. Well number 18, 1, 20, 17,12and 10 are non-drain wells. They show extremely good fit with the observed reading in the watershed. All these wells water level are fairly predicted by Model. Well number 21 is lying on the boundary of the watershed. This well is also a non-drain well but due to local geological conditions and interference from other side of boundary it seem that some flows are entering into this well, due to which water level in this well is not falling as quickly as it should.





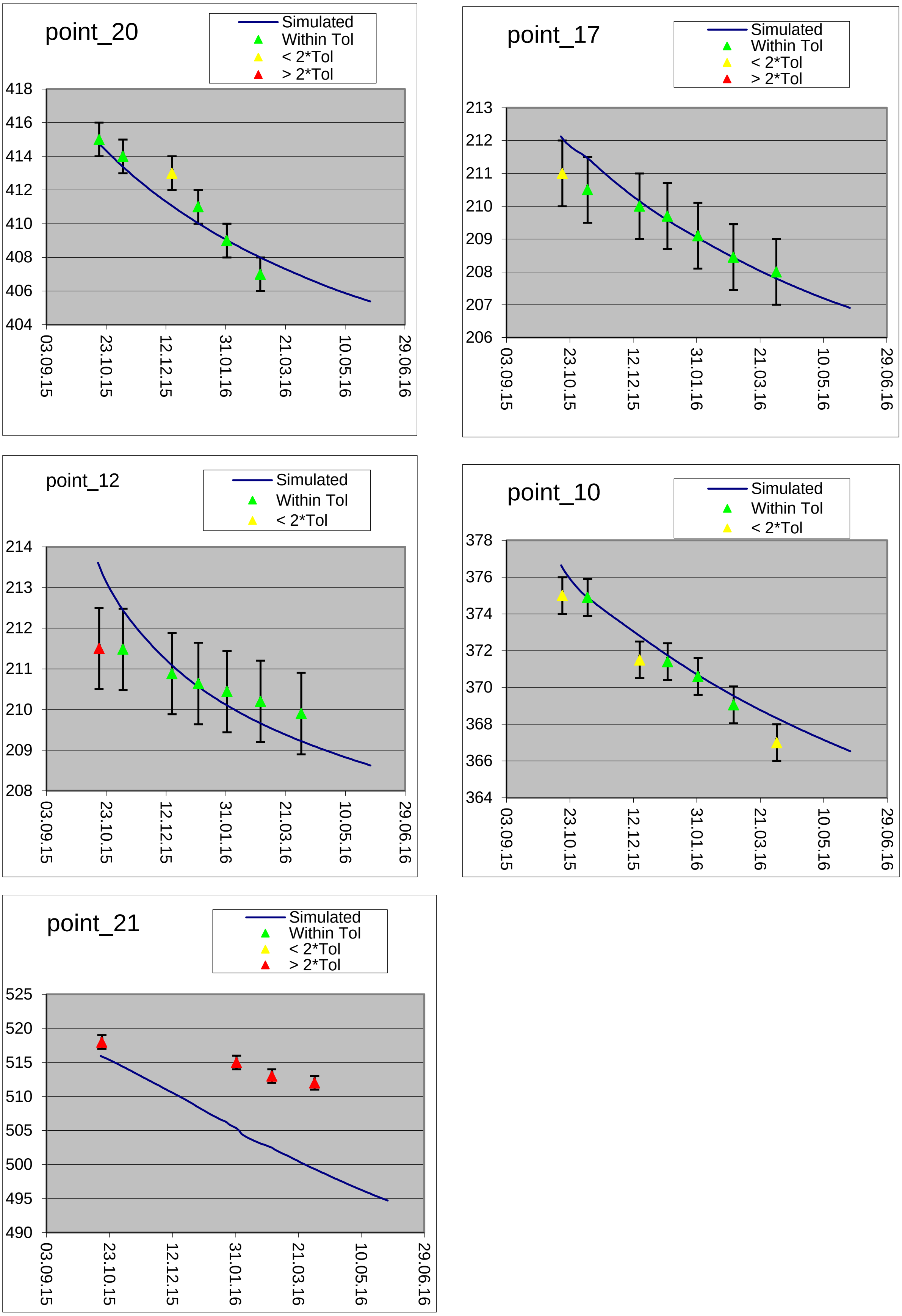
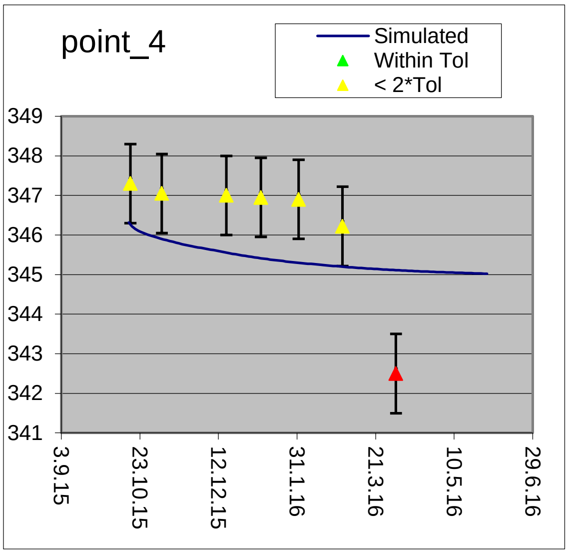
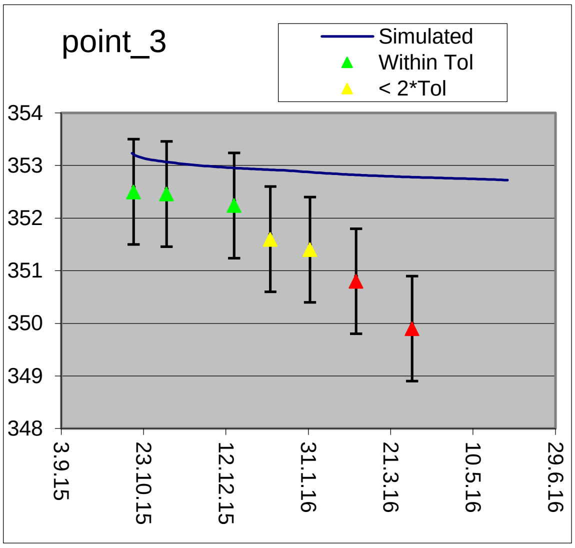


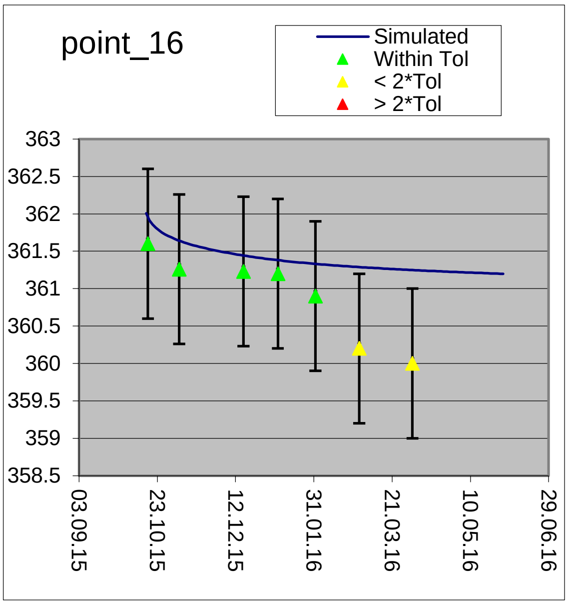
Figure 47 Calibration of Non-drain wells

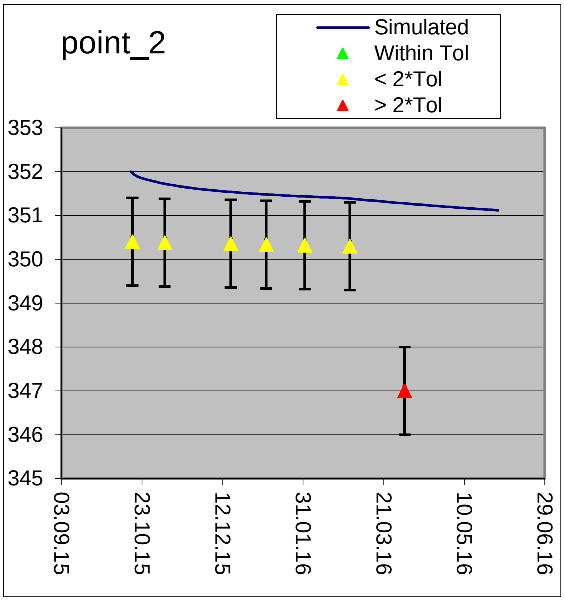
7.4 Calibration result for Drain Wells

Calibration result of drain wells is shown in the following graphs. Well number 2, 3, 4, 5, 6, 8, 9, 11,14and 16 all are drain wells. They all are present in the streams. There is continuous inflow to these wells. After February there is fall in water table is observed. There are two reasons for this. Base flows in the streams are reduced. Extraction rate from wells have increased. The water level predicted by the model is within the limits till the month of February. But after the month of February model fails to capture the sudden fall in the well water levels. Calibration achieved is not as accurate as in the case of non-drain wells. There are two reasons for this. First, two boundary conditions at one place are interfering with each other because wells and drains are in same cell. At many places in the streams cells are getting dried up. Due to this water which should have extracted is within the system. This water is preventing the water table to fall in the drain wells.









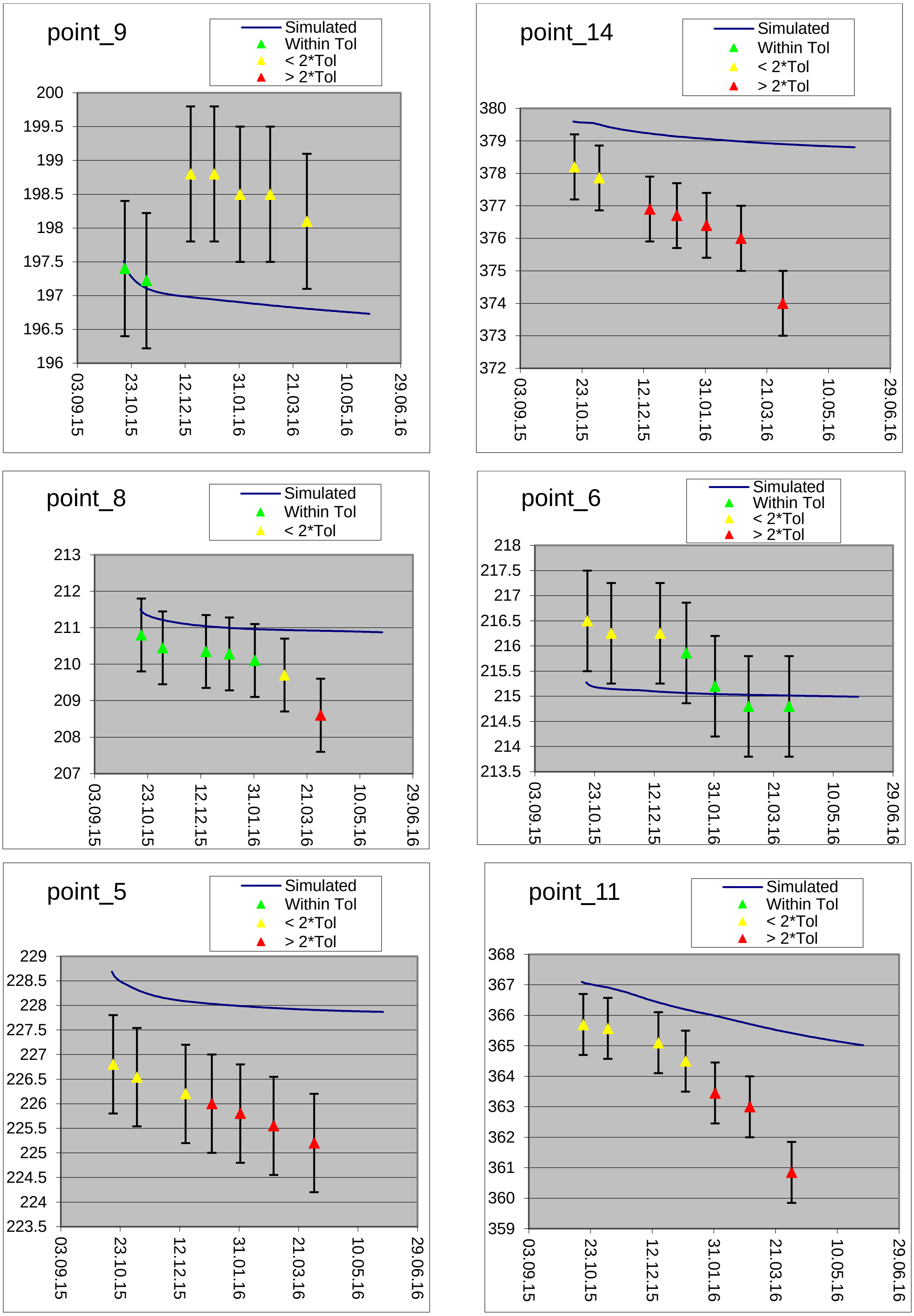


Figure 48 Calibration of Drain wells

7.5 Calibration result of flows

During the field visits it was observed that even after the river had stopped flowing there were considerable amount of base flows present in the area. This was observed in the patches along the river streams, along the walls of wells and in river pockets. But we cannot calculate this flow. So for model one assumption is made that if the flow at the final day is 15% of initial flow then it is considered as within the limit. While calibrating the model for flows this assumption was kept in mind. Flows for both the Adoshi and Nashera watershed were calibrated and were within the limits. The observed reading is red in colour and is not matching the predicted value. The reason for this value is explained. Value in the graph is negative since drains are removing water from aquifer.

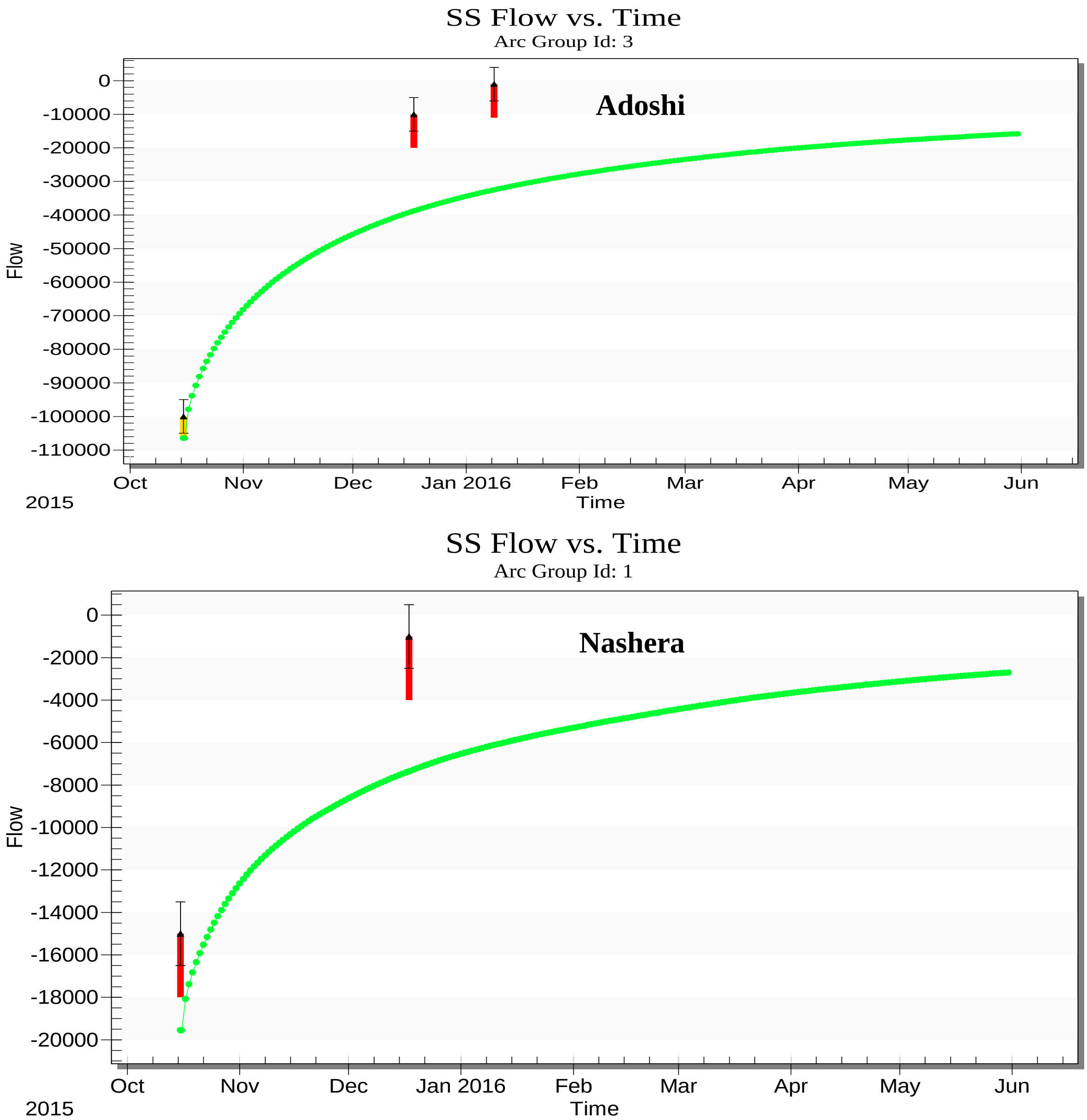


Figure 49 Calibration of Flows

7.5 Interaction of different layers

To completely understand the model it is required to analyse the interaction of water within layer with other layers. For this purpose first interaction of top layer is analysed with second layer. Then interaction of top 30m is analysed with remaining six layers. Interaction of complete Dholara region is analysed with the remaining region for complete eight layers. This helped in understanding the flows across the watershed. The assumption made regarding no flow across watershed was checked while analysis the flow across the Dholara watershed. It was also seen that first two layers are contributing maximum amount of water to drains as base flows. In the following image top two layers are shown similarly there are total 8 eight layers in the model with two zones.

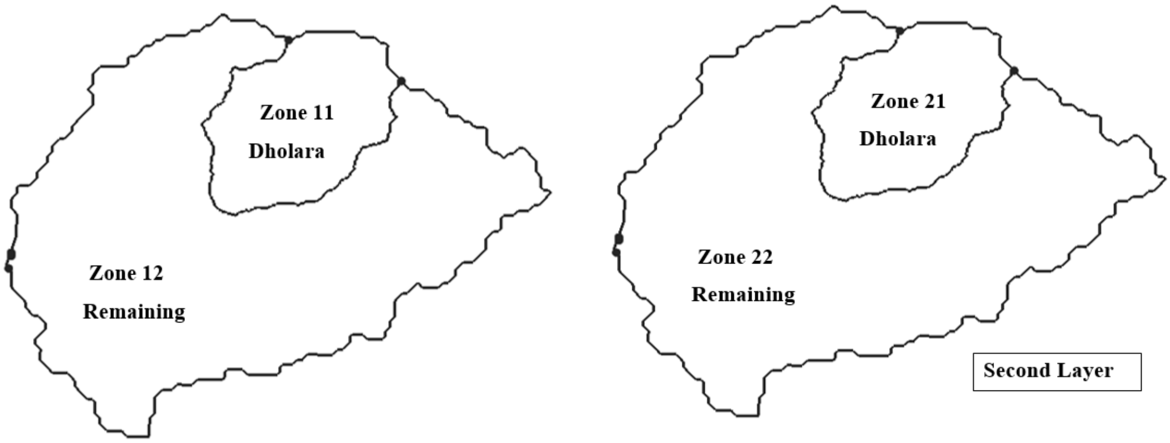


Figure 50 Dholara and Remaining Region

7.5.1 Interaction of top layer

It is important to see the interaction of water within the layer and with the other layers. First only top layer of 15m thickness is analysed. Total amount of water coming into Dholara watershed (Zone 11) from remaining region (Zone 12) comes out to be 34859m3. Total water going out to remaining region is 16045m3. This means there is net inflow of 18814 m3 of water from outer region to the Dholara region of watershed. Second layer of thickness 15m of Dholara region (Zone 21) is also contributing 970960m3 of water to Zone 11 whereas top layer contributing 342825m3 of water to Zone 21. There is net inflow of 628135m3 of water coming from layer below. The amount of storage released by the top layer comes out to be 829095. Total amount of water flowing through drains is1495413m3. This concludes that first there is huge amount of water is flowing as base flow second ample amount of water contributed by second layer as base flow to the streams.

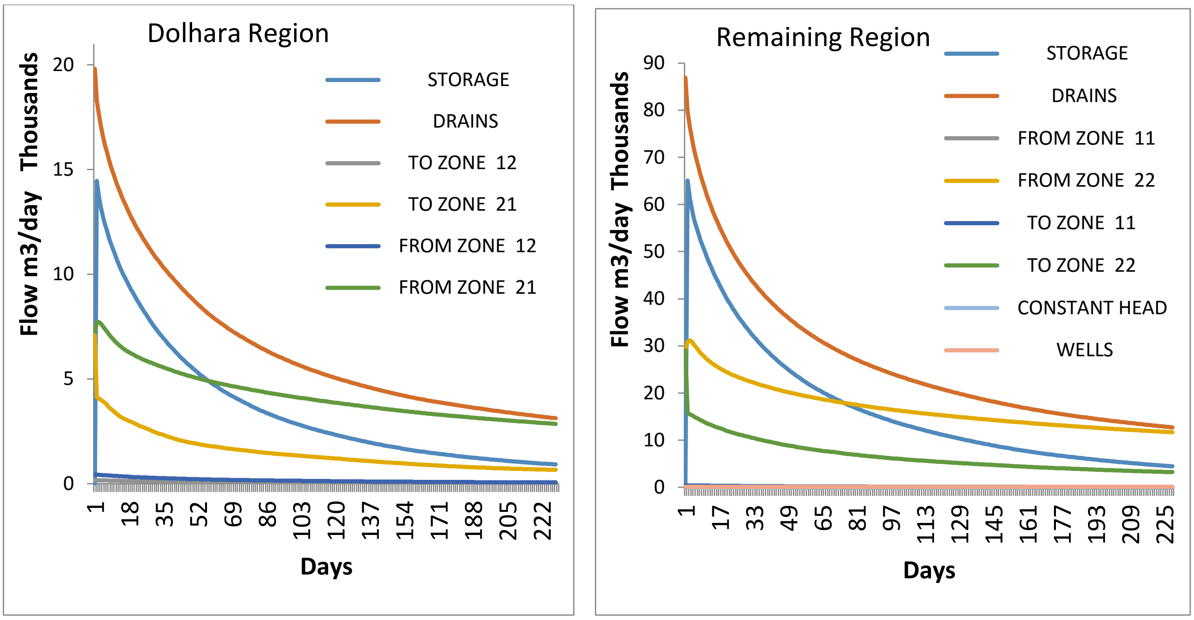


Figure 51 Interaction of Dholara region with Remaining Region

Table 13 Water balance of Dholara Region Top layer

RECH	STORAGE ZONE 11	ZONE 12 to 11	ZONE 21 to 11	TOTAL IN	DRAIN ZONE 11	ZONE 11 to 12	ZONE 11 to 21	TOTAL OUT
19369	829095	34859	970960	1854283	1495413	16045	342825	1854283

Table 14 Water balance of Remaining Region Top layer

RECH	STORAGE Zone 12	ZONE 11 to 12	Zone 22 to 12	Total IN
87522	3821662	16045	3875067	7800297

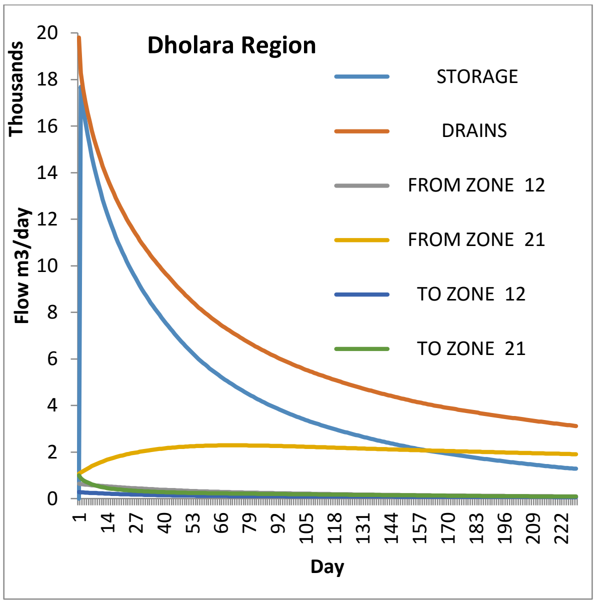
DRAIN ZONE 12	CONST HEAD ZONE 12	TO ZONE 12 to 22	TO ZONE 12 to 11	wells	TOTAL OUT
6195250	13808	1525629	34859	30751	7800297

7.5.2 Interaction of top 30m Dholara Region with Remaining Region

Top layer of 15m and second layer of 15m is considered as one layer of 30m. Total water coming in from the Remaining region is 55743m3. Total water going out comes out to Remaining region is 25792m3. There is net inflow of 29951m3 towards the Dholara region. The total amount of water going to bottom region of Dholara watershed is 48967m3. Total amount of water coming out of Region is 473040m3. Net contribution done by the bottom Region(remaining six layers) is 424073m3. Total amount of water going out through drains comes out to be 1495413m3. Where as storage released region is 1022020m3. Even though the contribution done by the bottiom region has reduced but still it is contributing 473393m3 of water to streams as base flows.

Table 15 Water balance of Dholara Region top two layers

RECH	STORAGE ZONE 11	12 to 11	21 to 11	TOTAL IN	DRAIN ZONE 11	11 to 12	11 to 21	TOTAL OUT
19369	1022020	55743	473040	1570173	1495413	25792	48967	1570174



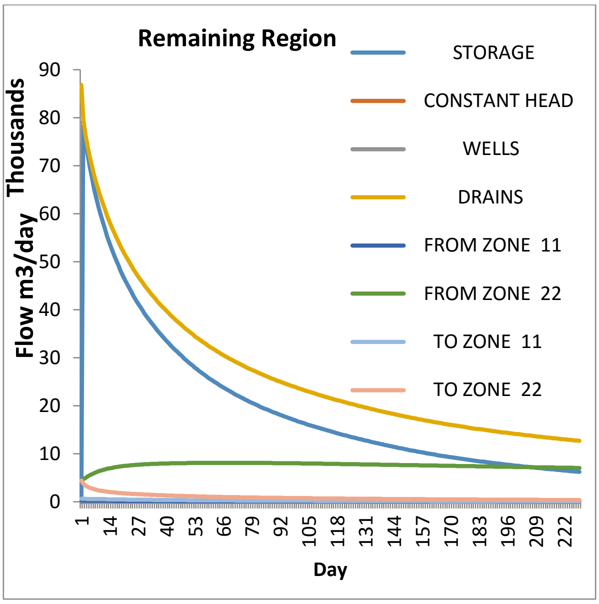


Figure 52 Interaction of Dholara Region with Remaining Region (six Layers)

Table 16 Water balance of Remaining Region top two layers

RECH	STORAGE IN ZONE 12	FROM ZONE 11 to 12	FROM ZONE 22 to 12	Total IN
87522	4653258	25792	1740280	6506852

DRAIN ZONE 12	CONST HEAD ZONE 12	FROM ZONE 12 to 22	From ZONE 12 to 11	wells	TOTAL OUT
6191250	14945	210164	55743	30751	6502853

7.5.3 Interaction of Dholara with Remaining Region for eight layers

Total water coming into the Dholara region comes out be 108327m3. Whereas total water going out of the region is 62088m3. There is net inflow of 46239 m3 of water to whole Dholara region. Most of the water in the region is due to storage released by the zone. This concludes that there is very small net inflow to the Dholara region from the remaining zone. The assumption made regarding no flow boundary condition across Adoshi watershed can be held true.

Table 17 Water balance for Dholara watershed eight layers

RECHARGE	STORAGE IN ZONE 11	FROM ZONE 12 to 11	TOTAL IN	DRAIN ZONE 11	FROM ZONE 11 to 12	TOTAL OUT
19369	1429807	108327	1557505	1495413	62088	1557505

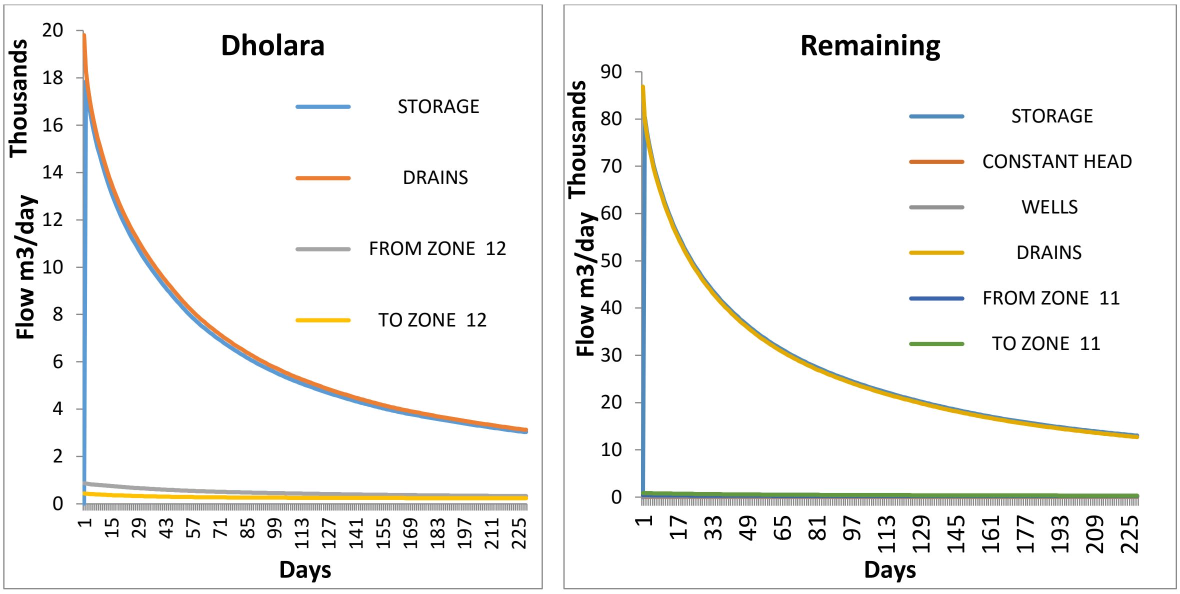


Figure 53 Interaction of Dholara and Remaining Region complete model

Table 18 Water balance of Remaining Region eight layers

RECH	STORAGE ZONE 12	ZONE 11 to 12	Total IN	DRAIN ZONE 12	CONST HEAD ZONE 12	ZONE 12 to 11	wells	TOTAL OUT
87522	6199700	62088	6349311	6195250	14964	108327	30751	6349311

7.6 Impact of increasing the specific yield of layer 1 to .03

The model was run again after increasing the specific yield of top layer from 2% to 3% to see the impact of the increase in specific yield. The storage capacity of layer increases from 829095m3 to 1194575m3. Flows in the drain also increased from 1495413m3 to 1798170m3. By increasing the specific yield base flows in the region increased substantially. The flow in drains also increased from 6195250m3 to 7512698m3 for remaining zone. Impact of increased specific yield can be observed in the graphs plotted below. The amount water released through storage and water draining out had increased. Due to increase of base flow water level in the wells have increased. It can be observed in the graph plotted for the wells number point 10 and

20 that heads in the wells have improved significantly. Improvement have observed in all the wells. Same thing can also be observed with the table on parameter sensitivity (table 34).

Table 19 Water balance after increasing specific yield Dholara Region

RECH	STORAGE ZONE 11	ZONE 12 to 11	ZONE 21 to 11	TOTAL IN	DRAIN ZONE 11	ZONE 11 to 12	ZONE 11 to 21	TOTAL OUT
19369	1194575	43270	1002059	2259273	1798170	18313	442790	2259273

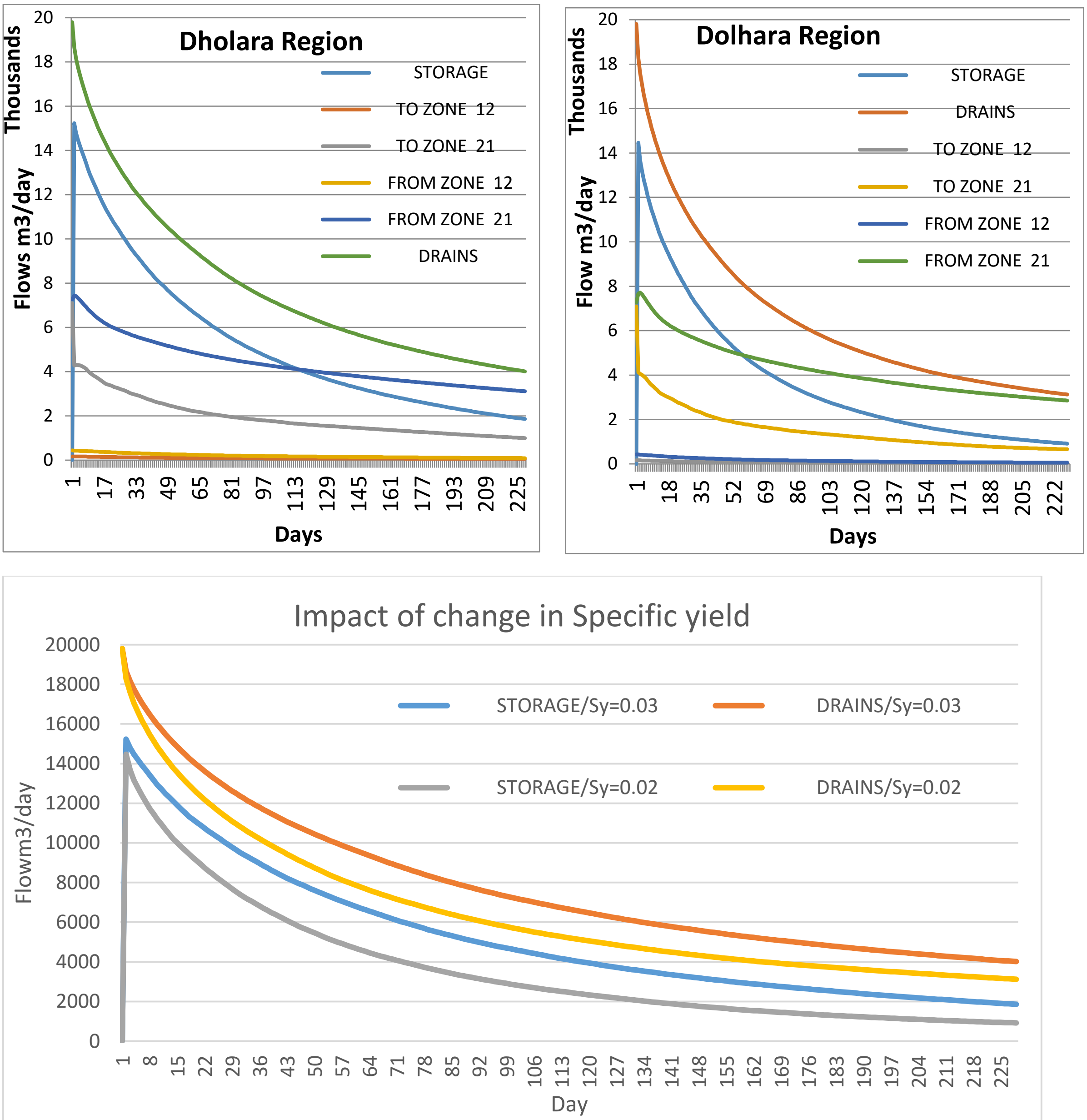


Figure 54 Impact of increased specific yield Dholara region

Table 20 Water balance after increasing specific yield Remaining Region

RECH	STORAGE IN ZONE 12	FROM ZONE 11 to 12	FROM ZONE 22 to 12	Total IN
87522	5470587	18313	3971732	9548155

DRAIN ZONE 12	CONST HEAD ZONE 12	FROM ZONE 12 to 22	From ZONE 12 to 11	wells	TOTAL OUT
7512698	15193	1945583	43270	31411	9548155

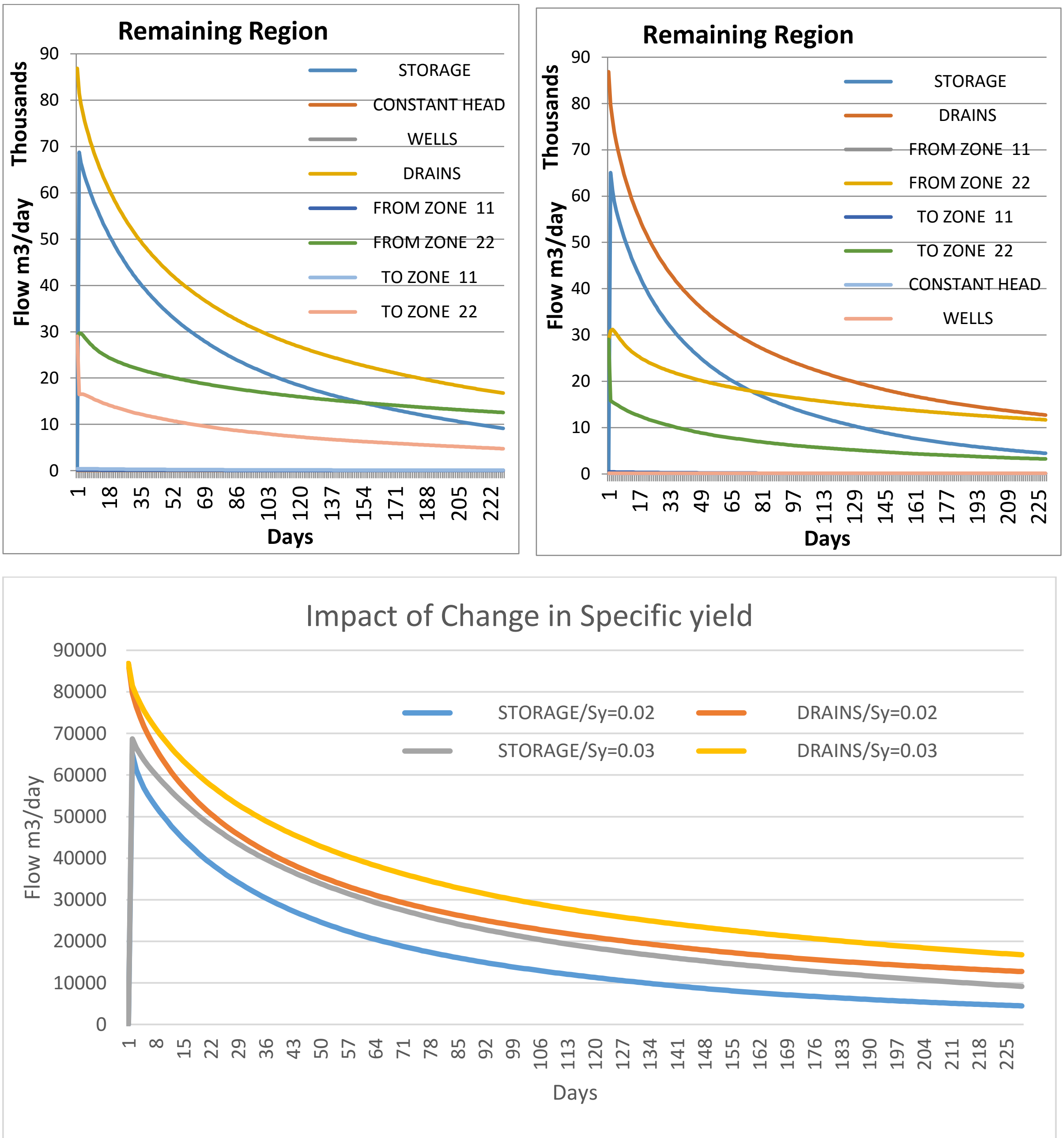


Figure 55 Impact of increased specific yield Remaining region

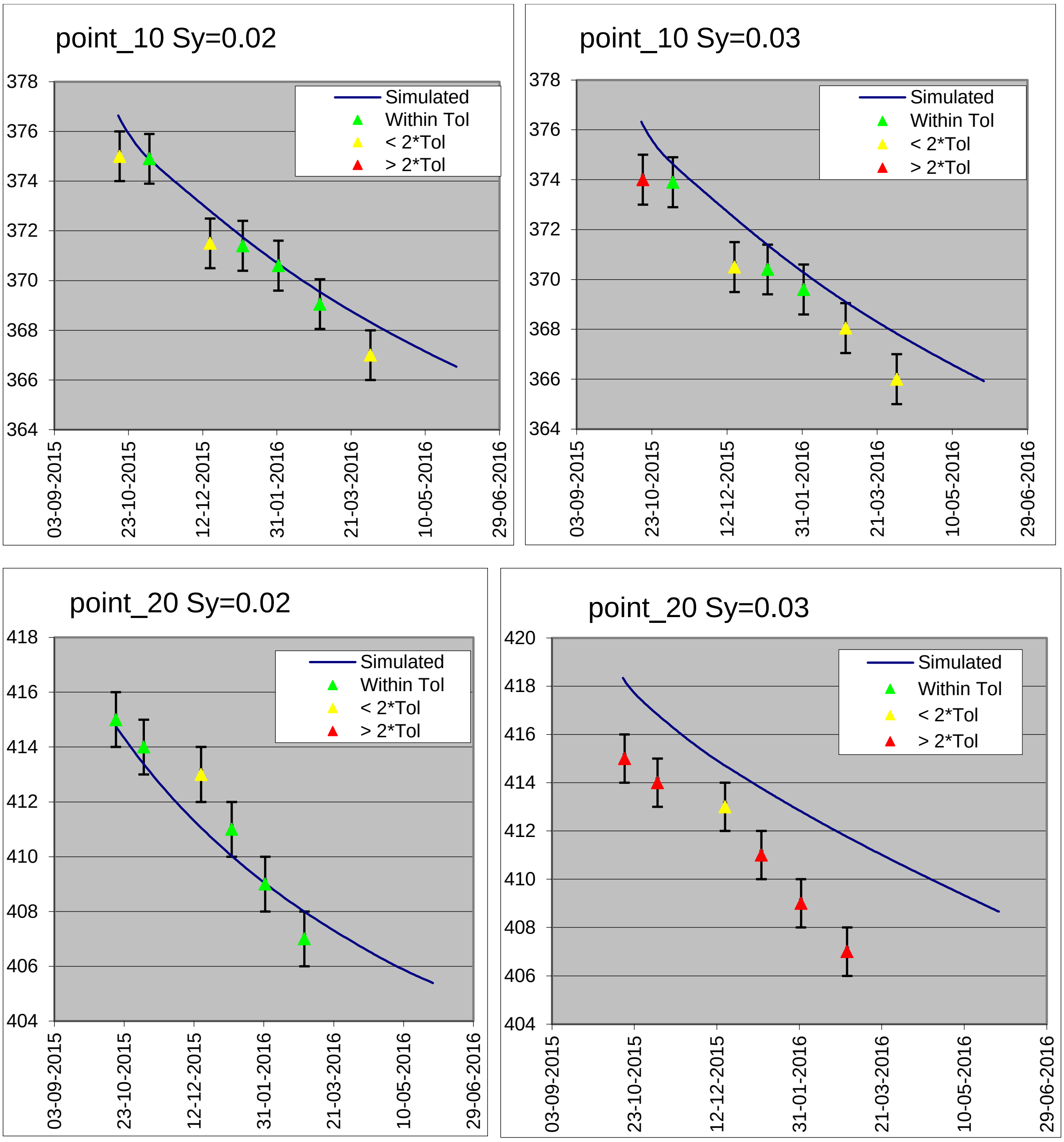


Figure 56 Impact of specific yield on head

7.7 Impact of timing of monsoons duration

After analysing the rain fall data it was observed that there was dry spell of 20 days before the last rainfall. Around the 60mm rainfall happened on 14-15 October. This rainfall was sufficient to recharge the aquifers again. It is also observed that rainfall generally arrives in second week of June. Duration of monsoons is getting shorter. To simulate this scenario model was run for extra 45 days. This can predict the severity of situation. Decision makers can easily plan for different future scenarios. From the following graphs it can be observed that the storage of top layer has gone significantly down in those 45 days. Second observation is that water removed by the drains in the region has reduced significantly. This means there is hardly any water coming to wells. This is likely to impact the drinking water scenario in a watershed. During the period of 45 days extra 6.8 lakh m3 of water has been removed from the model. Heads in the region have fallen considerably during the month of May.

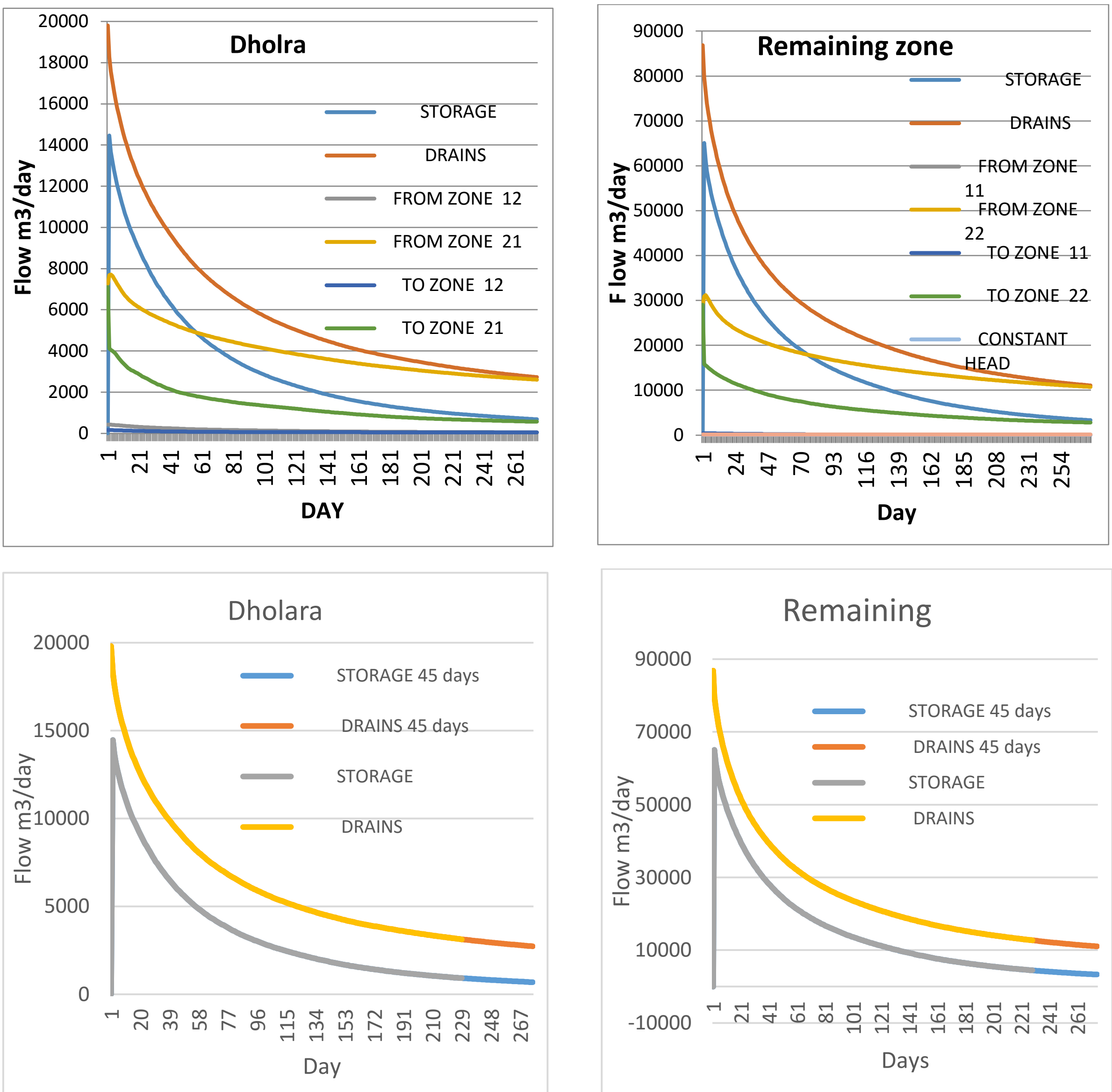


Figure 57 Impact of Monsoons duration

RECH	STORAGE 11	FROM ZONE 12	FROM ZONE 21	Total IN	TO ZONE 12	TO ZONE 21	DRAIN	TOTAL OUT
19369	865460	37241	1096112	2018182	18154	370735	1629285	2018174

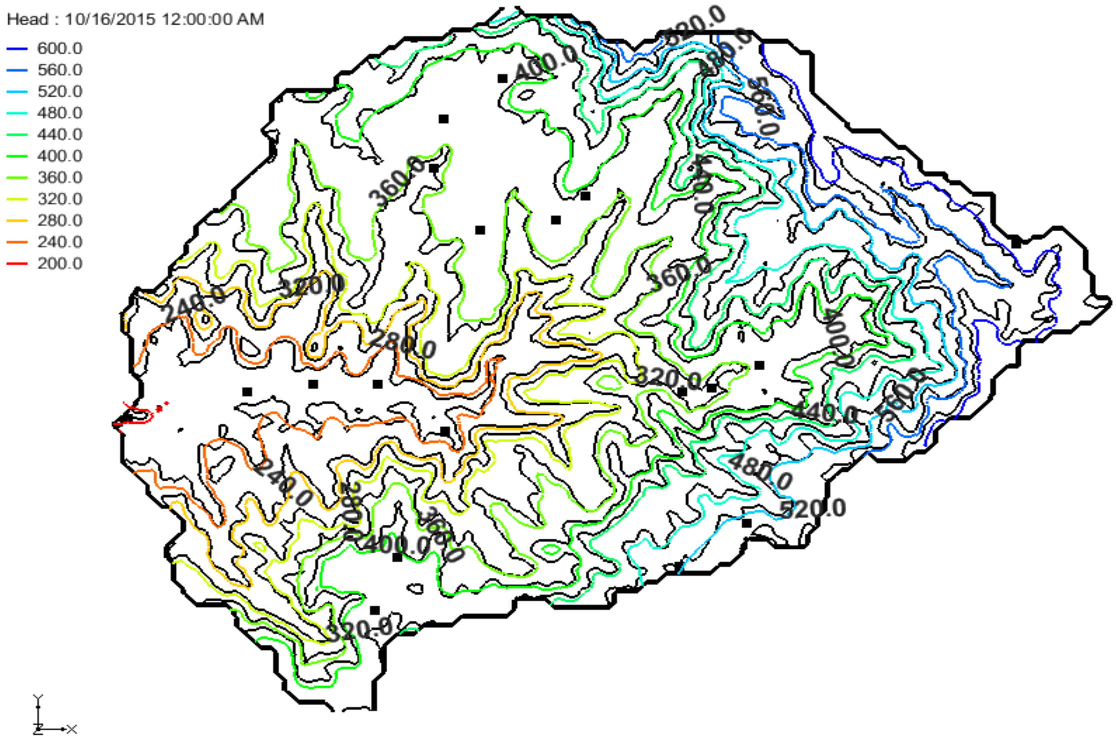
RECHARGE	STORAGE 12	FROM ZONE 11	FROM ZONE 22	Total IN

87522	3997664	18154	4388997	8492337

DRAIN	CONSTANT HEAD	TO ZONE 11	TO ZONE 22	WELLS	Total
6739141	15828	37241	1663488	36639	8492337

Contour Map generated by the model

After running the model for 228 days water levels can be predicted by the model at any day with in eight months. Following maps generated by Modflow shows the reduction of water level during period of six months. Both the contour maps fairly following the natural topography. This also shows that water is not flowing across the contours. At the places of lower elevation of area around 240m contour there is very less change observed in the water level, whereas above elevation of 360m significant changes can be observed in the water level.



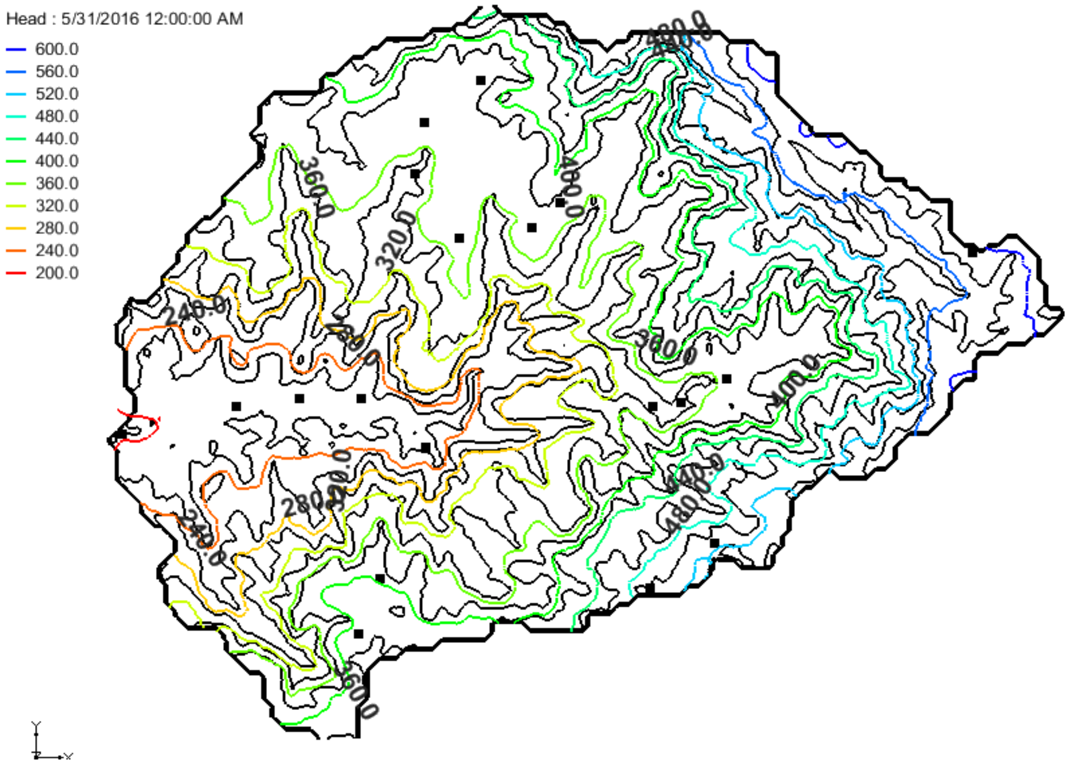


Figure 58 Water level contour maps generated by model

Conclusion

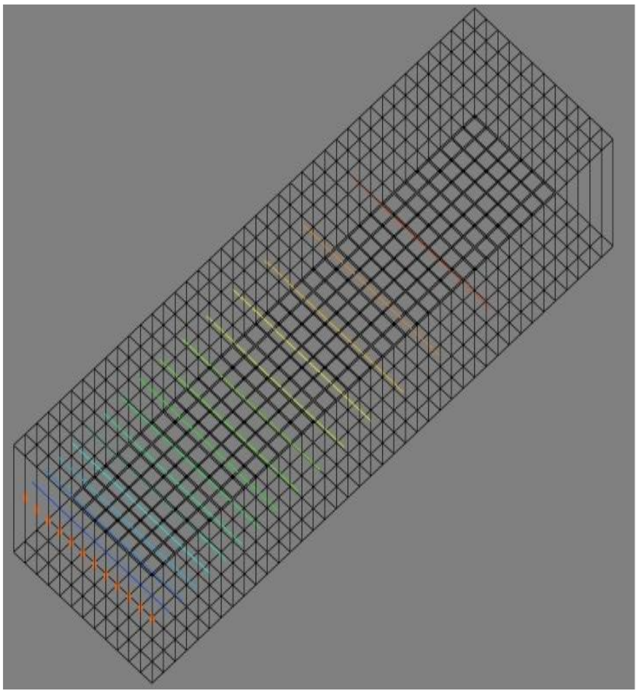
The current model is fairly predicting the behaviour of watershed. It proves that water balance estimation done by GSDA is not correct. It gives the new water budget which is in line with the various field observations. The model can be used to predict the water balance of villages. It can also predict the amount of flows coming from the other areas. Based upon this water balance cropping pattern in the area can be decided. The model predicts the amount of water availability at different time steps of simulation. It also highlights the areas where water availability is more. In such areas during November or December based upon the water availability rabbi crop can be sown. The model predicts that water is available in top layer of thickness 15m and most of wells have average depth of 6-7m. This means that intensive well deepening in the region can be done in upper reaches of watershed. There are significant amount of base flows present in the lower reaches of watershed. New wells can be dug in such areas. Impact of increased specific yield proves that afforestation is the best way to improve the storage, accumulation and duration of base flows in the region. Impact of duration of monsoon's helped in predicting the scarcity situation during the month of May. There is insignificant amount of water getting transferred across ridge boundary. Natural ridge boundary in the region can be assumed as no flow boundary condition. Same model can be scaled up to WF-15. This can help GSDA make water budget based upon new technique on the existing watershed units. This model further provides the scope of improvement in modelling aquifers in hard rock terrain. Drains were successfully used to estimate the amount the base flows in the region. New approaches while modelling can further enhance the scope of modelling such type of multiple aquifer system.

Annexure

Getting acquainted with GMS

Building a simple model

We started GMS with simple grid model. A grid of dimensions 12 m x 40 m x 20 m was created with 12 x 40 x 1 cells i.e. a single layer model. The grid had only one layer and the thickness of the layer was kept uniform. Boundary conditions – GMS automatically treats all the border cells as no-flow cells i.e. the boundary of the system. There will be no flow out from or into these boundary cells. The other boundary condition was entered as constant heads on one face of the grid as shown in the plan view of the grid in figure below.



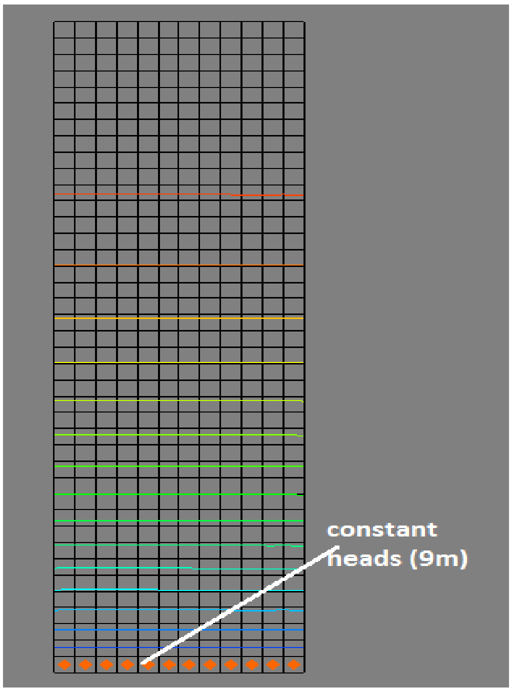


Figure Simple model grid

The Recharge package (RCH1) was chosen and recharge rate was set as 0.01 m/d. Recharge package was applied to all the cells on the top layer. It meant that the infiltration after rainfall into the system would be 0.01 m/d per cell. This would be the flow into the system. Hydraulic conductivity was set to be 5 m/d for each cell.

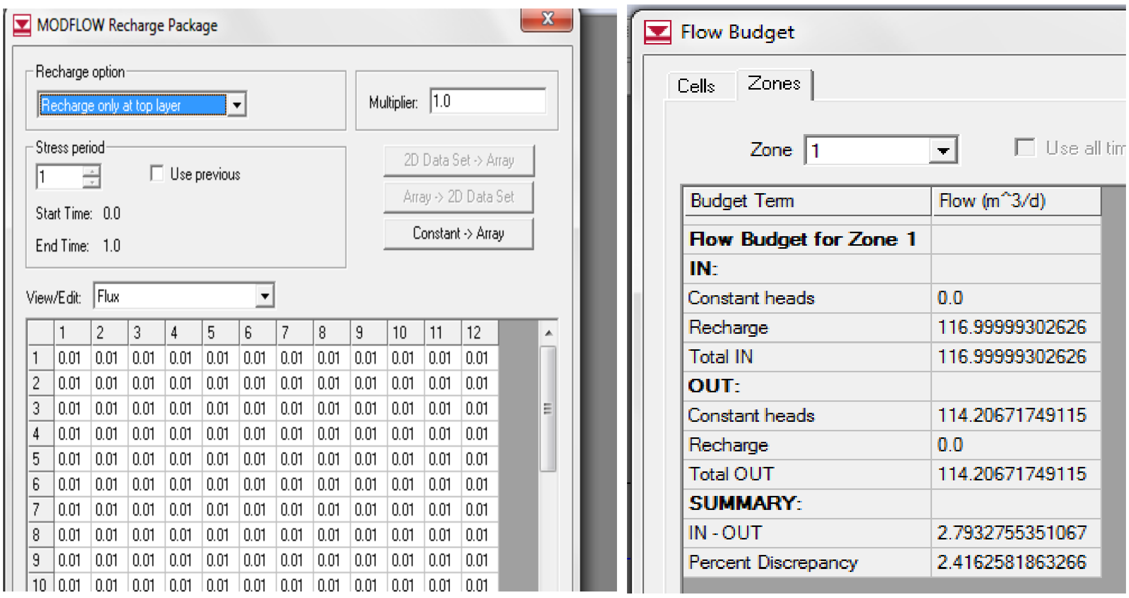


Figure Recharge package and flow budget

The model was run in the steady state i.e. with only one stress period. The system will come to equilibrium condition with input recharge and constant heads given. The following was the head distribution in space.

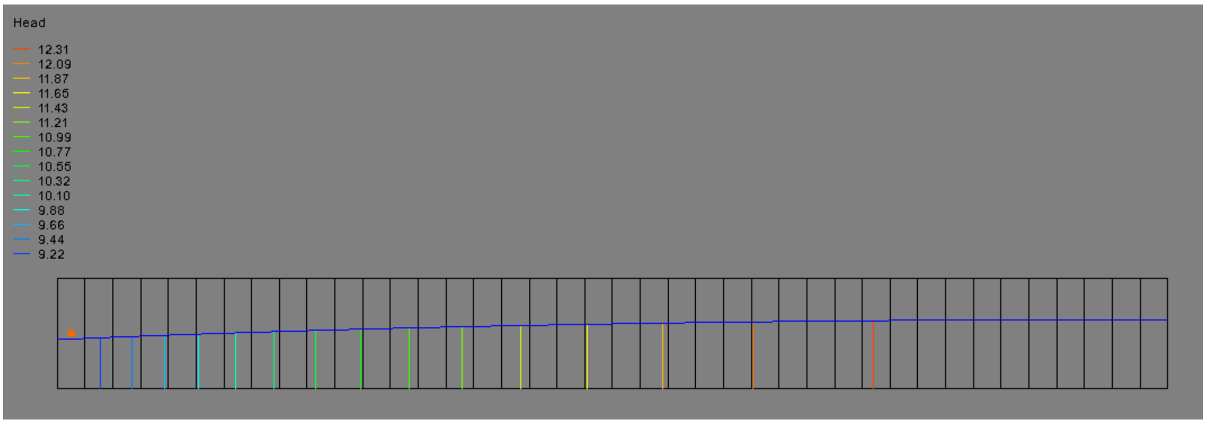


Figure Head distribution

The values of sources sinks i.e. the net quantity of water coming into the system and flowing out of the system can be observed by looking at the flow budget, As seen in the figure, the recharge is 116.99 and the constant heads out is 114.20 with around 2.4% discrepancy in finite difference approximation.

Next step – Drain, Well, Barrier

The next step was getting acquainted with packages for simulating drains and wells. The model was created using grid with elevations. The grid was 60 m x 20 m in x – y and with variable layer thickness, with top decreasing from 60 m to 10 m. Bottom was kept 0 m throughout. The elevations were entered for simulating a hilly terrain to understand groundwater flow through such terrain.

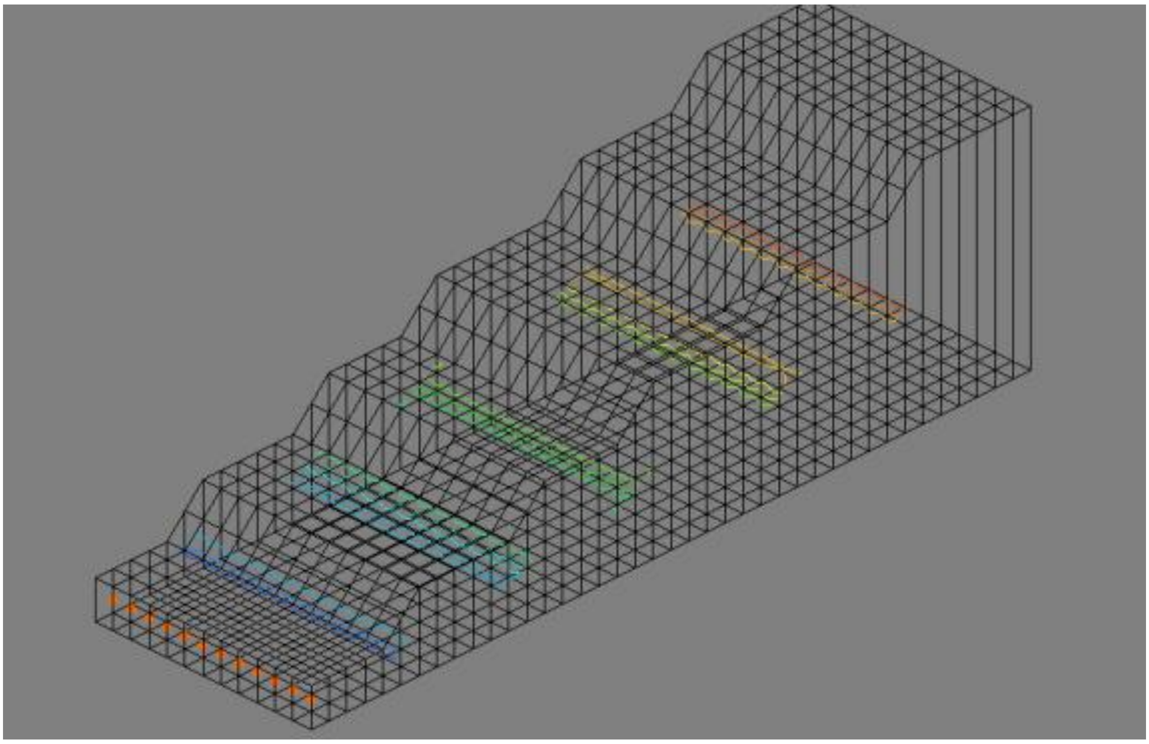


Figure Varying Elevation grid

A well and a barrier were added and the effects were studied. Boundary conditions other than the default no-flow condition, constant heads were entered on the lower elevation face with value as 4m. Recharge rate was 0.06 m/d and horizontal hydraulic conductivity was kept as 5 m/d. Horizontal anisotropy was kept at default value of 1 m/d for all cells (i.e. the conductivity values along all directions are same at each cell).

A well was introduced using Well package at some cell in the grid. The well package requires the discharge from the well (or withdrawal). The withdrawal rate was entered as -20m3/day. Negative sign is because water will be flowing out of the system. The model was run and it was found that the head values near the well show a dip due to withdrawal. It was also found that calculated heads are higher than elevations of some cells. This water was getting lost and was not considered in the flow budget. To count for this water, drains are to be put on cells where the heads will be higher than the cell elevations. This puts the water lost from the system back to system. In realistic scenario, drains can be compared with groundwater oozing out on the surface, thus creating springs. Or alternatively put, drains are like water logged areas created due to higher head than the surface elevation.

Understanding barrier effects

The Horizontal Flow Barrier (HFB1) package was used for introducing barrier between cells. The barrier acts like a low conductivity film between the faces of two cells. The important characteristic of barrier is the hydraulic characteristic with which the barrier-property of the barrier can be adjusted i.e. hydraulic characteristic of 1 means no barrier in flow, while hydraulic characteristic of 0 means no flow will be possible between those two cells. Barrier in this example was downstream to the well at elevation 10. Barrier is an important feature in this current study as it works as a sub-surface bund. When the effect of barrier was studied, it was found that the heads above the barrier changed slightly positively. The well head was increased from 11.9m to 12.4m due to barrier. The effect of change was close to the barrier. But no change in overall flows (constant heads out – 450.82 m3/d) suggested that no extra water was harvested due to barrier. The flows only got regulated due to the barrier.

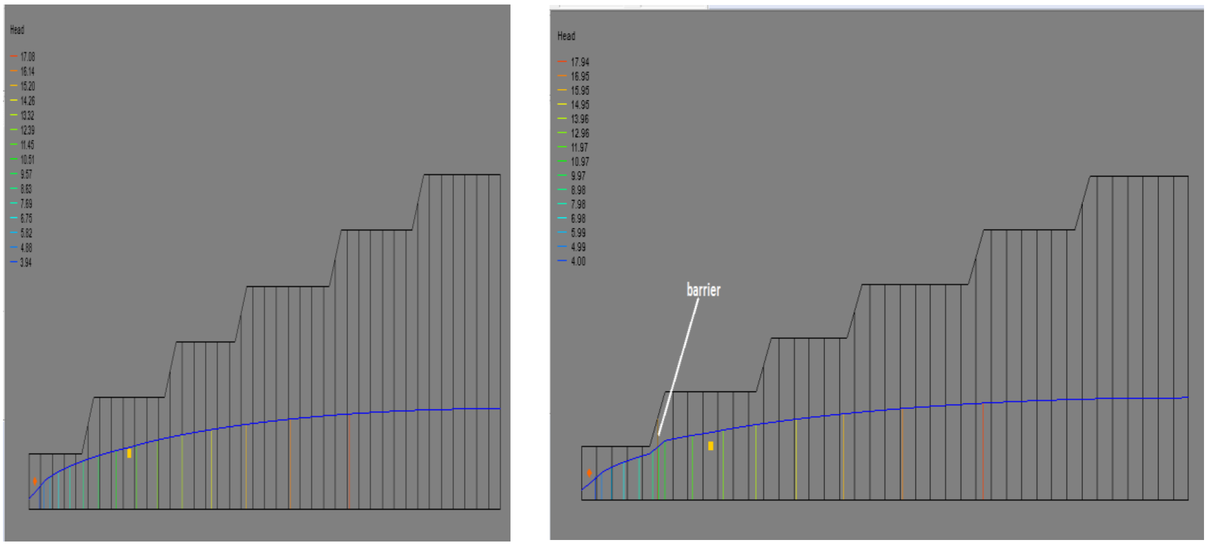


Figure Effect of barrier

Modelling a hypothetical watershed

A groundwater model for a medium-sized basin is shown in Figure. The basin encompasses 72.5 square kilometres. It is in a semi-arid climate, with different recharge zones. Most of the precipitation is lost through evapotranspiration. The recharge which reaches the aquifer eventually drains into a small stream at the center of the basin. This stream drains to the north and eventually empties into a lake with elevation 304.8 m. Three wells in the basin also extract water from the aquifer. The perimeter of the basin is bounded by low permeability crystalline rock. There are ten observation wells in the basin. There is also a stream flow gauge at the bottom end of the stream. In the MODFLOW we have tried to build a conceptual model. This model has 3 three coverages namely recharge zone, hydraulic conductivity and

Source/sink. The area has been divided into 5 different recharge zones and hydraulic conductivity zones as shown in figure below.

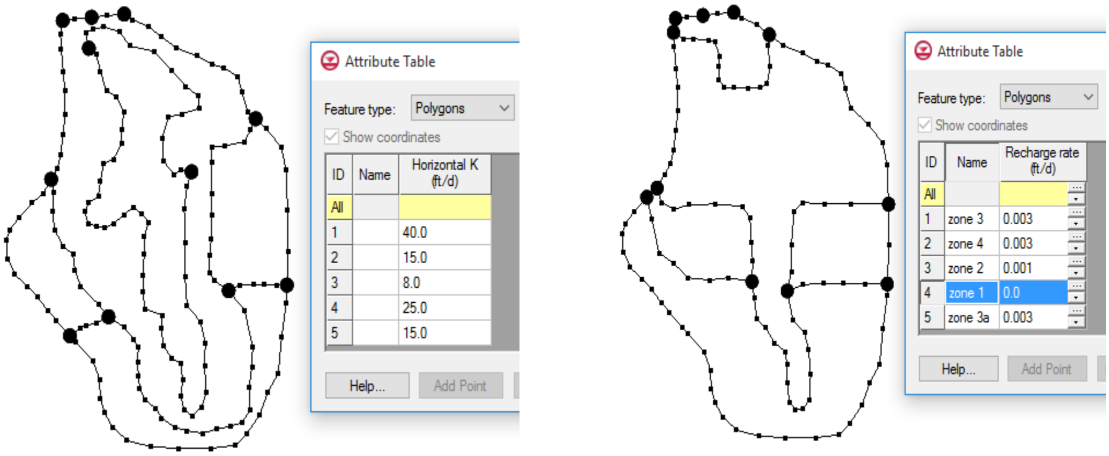


Figure Zones of hydraulic conductivity and recharge rate

Then in the source and sink coverage packages like drain, well and specific head has been used . the red color arc represents the specific head boundary condition. Black color arc represents no flow boundary condition. Blue color arc represents drain. Yellow dots represents the wells in the watershed. For drains we must specify the bottom elevation which can be manually inputted or through the elevation surface.

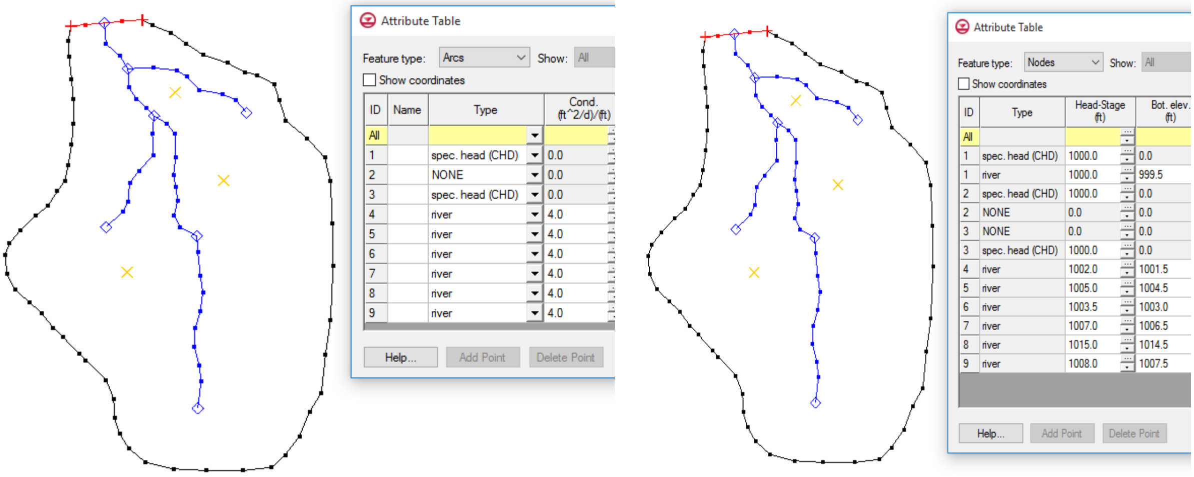


Figure Different boundary conditions

After building all the coverages and specifying all the boundary conditions our conceptual model is ready. Then we have to convert our model into grid. For this a grid frame is selected which will fit our conceptual model. Then after that the grid frame is converted to 3d grid. From this grid new modflow command is initiated. Then all the coverages are mapped to this grid. After that cells which are lying inside the coveregs are activated by going to feature objects and activating the coverages. Elevation data can be entered in the model number ways. We can directly add the elevation data through DEM, raster TIN. We can import the text file containg the elevation readings and the coordinates. We also manually add the elevation data. The follwing figure shows the the elevation readings of top and bottom layer.

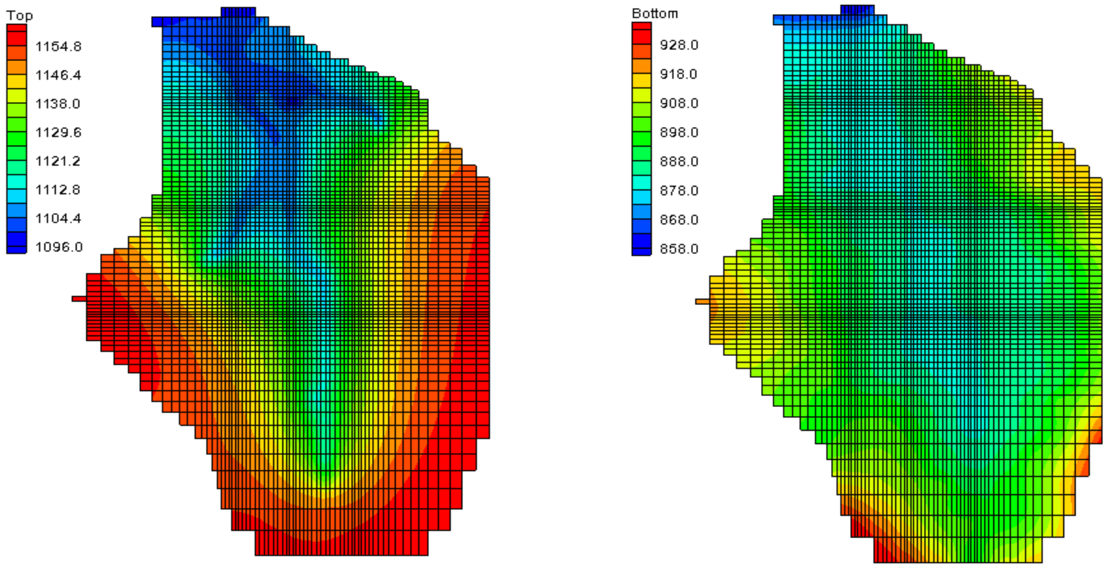
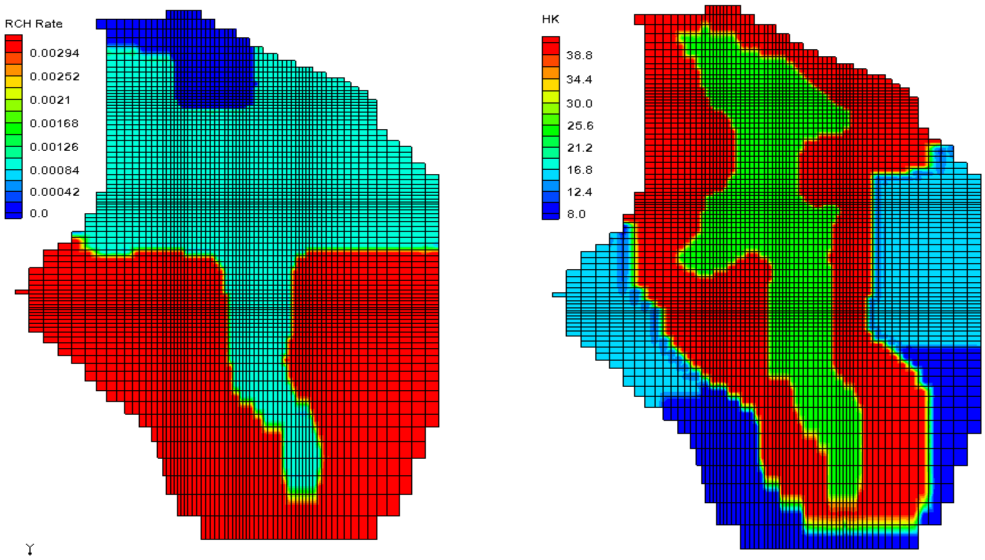


Figure Top and bottom elevation of watershed

In the figure below we can see the recharge rate and hydraulic conductivity values have been mapped to 3d grid. This exactly the way we have input the data in the conceptual model.



After entering all the values now the model is ready to run. Before running the model we would like to check for errors. With the help of run check we can see if there are any errors or not. Then we can run the modflow. After doing the number of iterations modflow will converge and will give us the head value over the entire watershed.

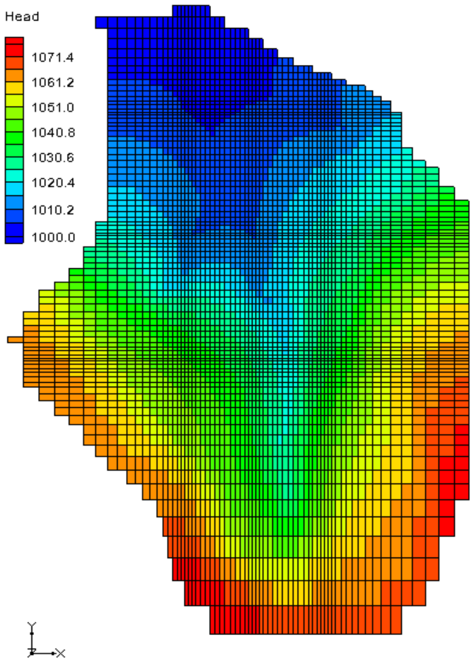


Figure Distribution of head

Till now we have run our model in steady state conditions. Now we need to run our model in transient state. When entering the time values associated with transient data, MODFLOW requires that the time be entered as scalar time values relative to a time value of zero at the beginning of the simulation. Furthermore, the times must be compatible with the time unit selected for the model. This approach can be time-consuming since transient data must be converted from a date/time format to relative time format. The strategy used in GMS for managing transient data makes it possible to enter all time values using a simple date/time

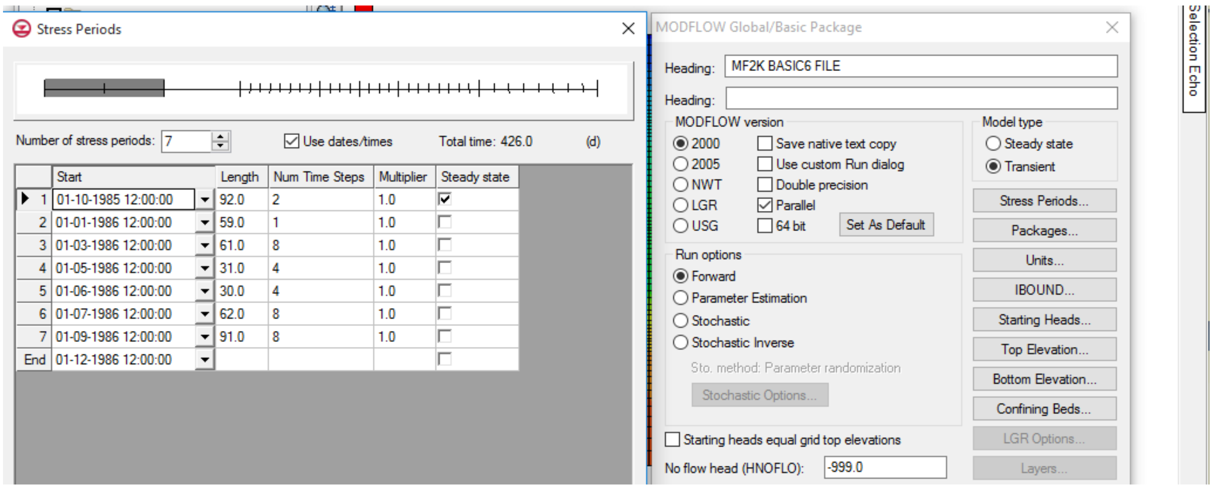


Figure Model in transient state

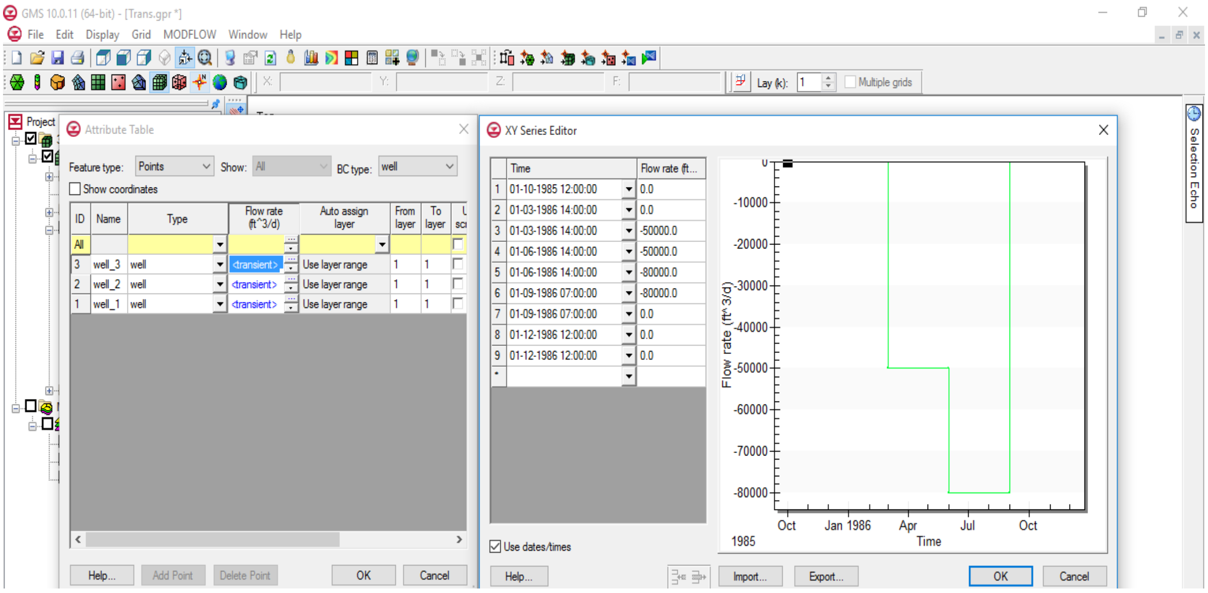
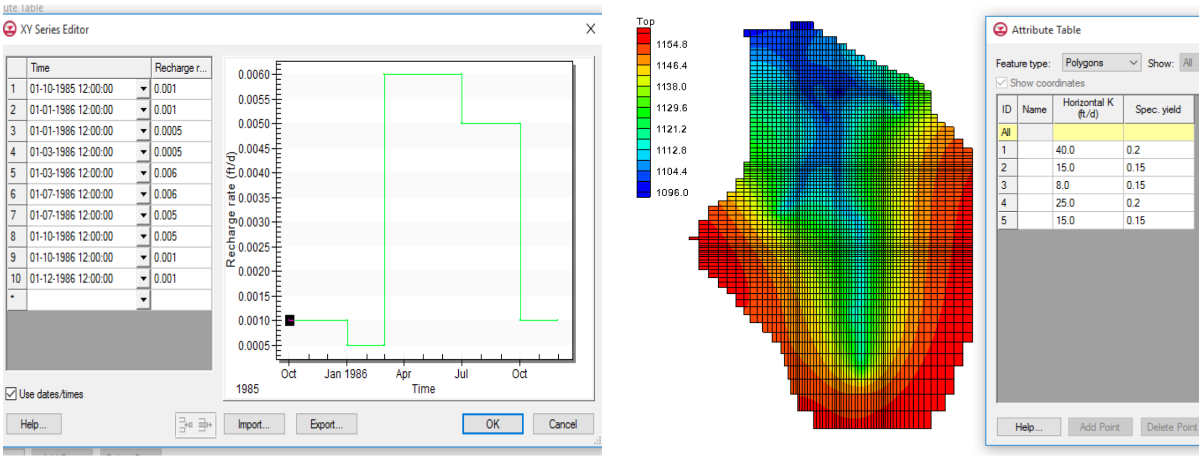


Figure entering transient data

format. Transient data are entered in the conceptual model using date/time values. The time at the beginning of the first MODFLOW stress period is the reference time. This represents the date/time corresponding to time=0.0 in the simulation. When the model is converted from the conceptual model to the grid model, the time values in the conceptual model are automatically mapped to the appropriate time values corresponding to the MODFLOW stress periods. When the MODFLOW model is saved to disk, the date/time values are converted to the appropriate relative time values. In addition to ease of use, another advantage of the transient data strategy used in GMS is that both the spatial and temporal components of the conceptual model are defined independently of the discretization used in both the grid spacing and the stress period size. The user can change the stress period spacing and regenerate the model from the conceptual model in seconds.

We can manually add the transient data or we can import the text file containg the transient data. As we have to run the model in transient there is one more parameter which needs to be addedd which is specific yield.



An important part of any groundwater modeling exercise is the model calibration process. In order for a groundwater model to be used in any type of predictive role, it must be demonstrated that the model can successfully simulate observed aquifer behavior. Calibration is a process wherein certain parameters of the model such as recharge and hydraulic conductivity are altered in a systematic fashion and the model is repeatedly run until the computed solution matches field-observed values within an acceptable level of accuracy. Units in the following figure are in meters. Ten observations well have been used to calibrate the model. In following image we can see computed heads and observed head. There is huge difference in these values. In the left image we are observing some symbols in the watershed. The center of the target corresponds to the observed value. The top of the target corresponds to the observed value plus the interval and the bottom corresponds to the observed value minus the interval. The colored bar represents the error. If the bar lies entirely within the target, the color bar is drawn in green. If the bar is outside the target but the error is less than 200%, the bar is drawn in yellow. If the error is greater than 200%, the bar is drawn in red.

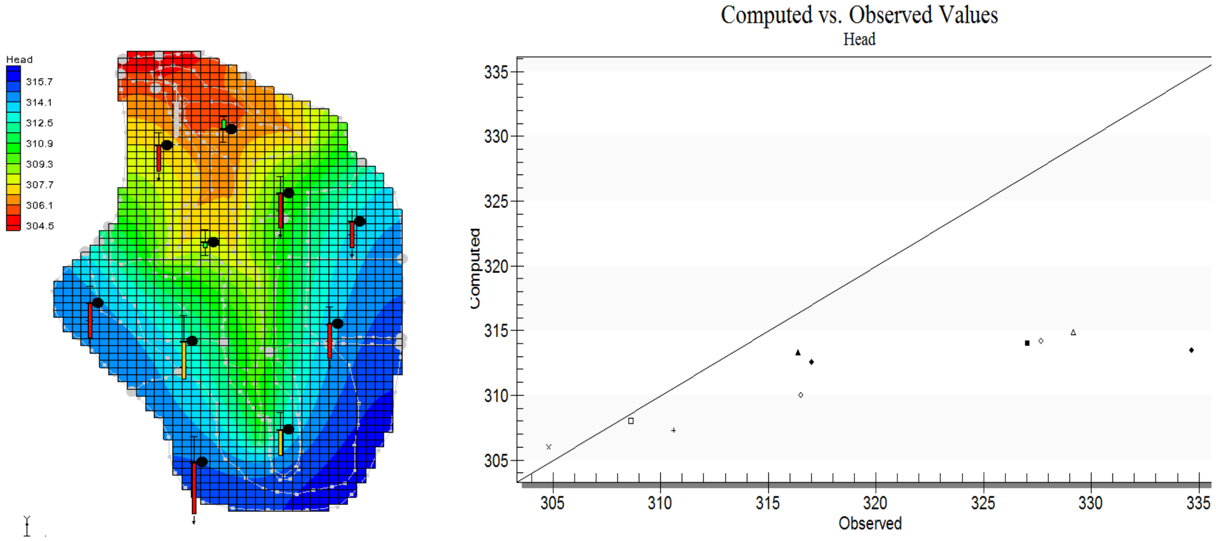


Figure Error in the model before calibration

This means we have to alter some values to get the accurate prediction from our model. We have to change the values of hydraulic conductivity, recharge rate so that our model starts giving more accurate results. We may have to change the zones of hydraulic conductivity and recharge zones. After altering some values of rechrage rate and hydraulic conductivity we arrive at a stage when our model starts giving accurate results.

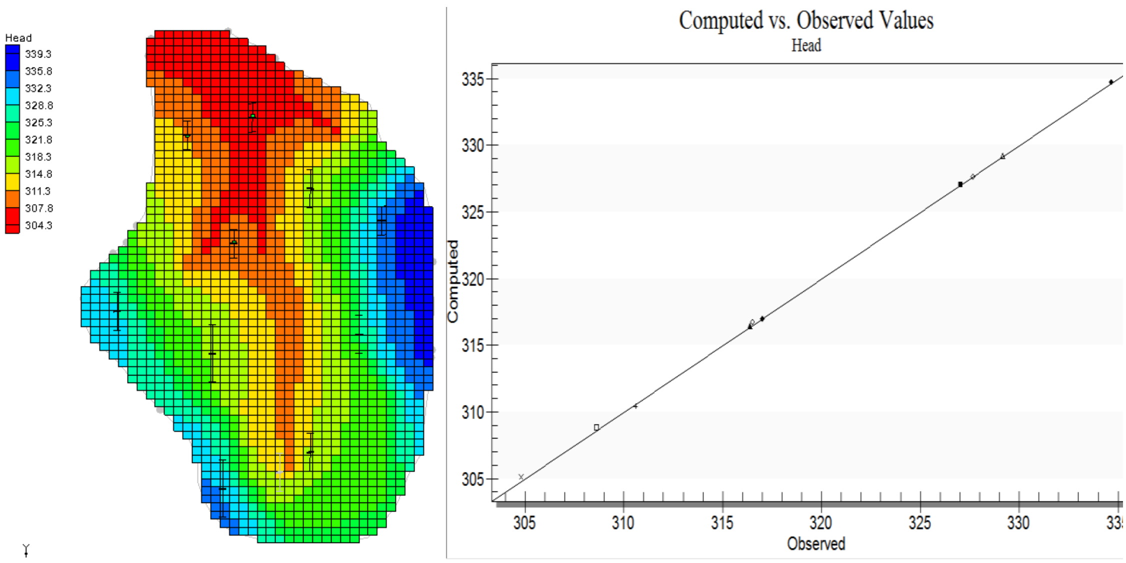


Figure Error in model after calibration

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