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On

Understanding, Analysing and Modelling Watershed Interventions

Submitted in Partial Fulfillment of the Requirement for the Degree of

M.Tech (Technology and Development)

By

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Certificate

This is to certify that the seminar report titled **"Understanding, Analysing and Modelling Watershed Interventions"** prepared by Hemant Khanderao Belsare is approved for submission at Centre for Technology Alternatives for Rural Areas (CTARA), IIT Bombay, Powai.

3rd Dec 2012

Signature of Project Guide

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Declaration

I hereby declare that the report entitled "**Understanding, Analysing and Modelling Watershed Interventions**" submitted by me, for the partial fulfilment of the degree of Master of Technology to CTARA, IITB is a record of the seminar work carried out by me under the supervision of Dr. Milind Sohoni, Head, CTARA.

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

3rd Dec 2012

Signature of the Candidate

Acknowledgement

I would like to express my sincere gratitude towards **Prof. Milind Sohoni** for his valuable guidance and support for literature, critical review of report and above all the moral support he provided to me at all the stages of work. I also thank Prof. T. I. Eldho of Civil Engineering Department for his keen interest and valuable support.

Date: 3rd December 2012

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Abstract

The report focusses on one specific watershed intervention i.e. subsurface bunds for extending life of drinking water well, done by NGO AROEHAN in a small hamlet of Ikharichapada in Mokhada block of Thane district, Maharashtra for solving the drinking water problem of the hamlet. Beginning with the understanding of the technical aspects of the intervention and learning the basics of modelling watershed interventions, a conceptual model for the Ikharichapada scenario is developed on the basis of key observations and data obtained from field visits.

The results clearly show the effectiveness of downstream subsurface bunds in raising the water storage in the watershed, thus proving to be good water harvesting structures. This model will now be further refined in the next stage of this study and will be verified through monitoring and observations on field. The model will help in predicting the impacts of such interventions and will help in arriving to the best solutions which will further help in implementation and replication of such interventions in other neighbouring regions with similar topography and climate. This will strengthen the technical base of the NGO and will help them in solving the critical issue of drinking water in Mokhada.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter 1 – Introduction

1.1 Background

The Water Group at Centre for Technology Alternatives for Rural Areas (CTARA), Indian Institute of Technology, Mumbai has been working on various issues related to rural drinking water for past several years. The group is doing work at different levels, like research, implementation, evaluation and monitoring, policy interventions etc. Some of the issues touched are construction of check-dam in small hamlet in Karjat block of Maharashtra, analysis of various multi-village and single-village rural drinking water schemes in Thane and Raigad districts of Maharashtra, study of behaviour of observation wells and analysis of tanker-fed villages in Thane district etc. During all these years, Water Group has worked hand-in-hand with government institutions like Maharashtra Jeevan Pradhikaran (MJP), Minor Irrigation (MI) departments, Groundwater Survey and Development Agency, Maharashtra etc. as well as with NGOs and local people.

A need was felt to gain understanding of watersheds and watershed development programmes, with the bigger aim to understand the role of watershed development in the ultimate solution to water problem in the country and to assess its role in solving the most critical drinking water problem.

A study was carried out in this direction by Dharmvir Kumar of CTARA under guidance of Prof. Milind Sohoni, CTARA, IITB and Prof. T. I. Eldho, Civil Engineering, IITB in 2009 which tried to understand various situations of groundwater flow arising in practice (e.g. contour trenches or lake problem etc.) and tried to model those using MODFLOW.

In May and June 2012, the author had done field stay as a part of curriculum at CTARA in a small hamlet Ikharichapada in Mokhada block of Thane district, Maharashtra during which the author got an opportunity to closely observe the watershed intervention done by the local NGO, AROEHAN to solve the drinking water problem of the hamlet.

The current report will help in understanding the role of watershed management in solving the critical issue of water, especially drinking water, with prime focus on predictability and effectiveness of watershed structures.

1.2 Understanding Watershed Development scenario in India in brief–

In order to understand the watershed development in detail, it is important to study how the history of watershed development programmes has shaped its current discourse.

The first large-scale government watershed programme in India was launched in 1962-63, called as Soil Conservation Works in the Catchments of River Valley Projects (RVP). This was a purely technical intervention and was specifically introduced for checking siltation in reservoirs (Joshi, et. al, 2004).

The first area development programme, the Drought Prone Areas Development programme (DPAP), which was later implemented exclusively on watershed-basis, was launched in 1973-74 by Central Government in many parts of the country following the severe drought of 1972. This programme was specifically launched to tackle special problems faced by fragile areas which were constantly affected by the drought conditions. It started with 74 projects in 13 districts of India. The coverage kept on increasing, and it reached to about 972 blocks of 182 districts in 16 states till 2004-05. This programme proved to be a model for other watershed-based area development programmes (Rural Development Report, NIC, Chapter 20).

Maharashtra has always had a lot to contribute to evolution of watershed management discourse in the country. In 1972, a major step of including drought-proofing works like construction of water harvesting structures, contour bunding etc was taken on a large scale through Employment Guarantee Scheme (EGS). In 1974, Vilasrao Salunkhe carried out one of the first experiments in people-centred watershed development (*Pani Panchayat*) in Naigaon. It was followed by two more success stories of genuine people's participation in watershed development carried out in Ralegan Siddhi and Adgaon. But these instances, along with few other instances in the country like Sukhomajri, Haryana remained isolated for a long time, and were not seriously considered at the policy level.

During the same time, research projects were also taken up by institutes like Central Soil and Water Conservation Research and Training Institute (CSWCRTI) and Central Research Institute for Dryland Agriculture (CRIDA) to validate soil and water conservation technologies and demonstrate the benefits of watershed activities to farming community. In 1980s, Indian Council of Agricultural Research (ICAR) launched 47 model research watersheds on the same lines. Apart from government institutes many NGOs also started working in watershed development. Few pilot projects funded by the World Bank were also initiated. All these projects and experiments emphasised on building assets or structures helpful in reduction of soil runoff like vegetative bunding, contour bunding etc. or structures for increasing groundwater storage like nala bunds etc. This was the prime era when the technical discourse on watershed development was developed (Joshi et. al, 2004).

During the same time, programmes like Desert Development Programme (DDP), National Watershed Programme for Rainfed Areas (NWDPRA) and Integrated Wasteland Development Programme (IWDP) were launched. Although all these programmes, along with the DPAP, had a positive impact in creating durable public assets, their overall impact in effectively containing the adverse effects of drought was not found to be very encouraging (NIC Report). Though the common objective of all these programmes was improving socio-economic conditions of people living in backward areas, all programmes had been following different guidelines and norms. A study was carried out by a technical committee constituted under Ministry of Rural Development (MoRD) under chairmanship of Prof. Hanumantha Rao in 1993 for studying the impacts of watershed development programmes all over the country. It was learnt that for proper implementation of such programmes, focus must be shifted on public participation, their involvement, their technical capacity to operate and maintain the assets post-implementation, equity in distribution of benefits etc. As a result of the study, a common set of operational guidelines was evolved for watershed development programmes in India. The guidelines brought all the area development programmes like DPAP, DDP and IWDP under one common umbrella. Also, 50% of the funds available for the schemes such as Jawahar Rozgar Yojana (JRY) and Employment Assurance Scheme (EAS) were earmarked for watershed development activities (Joy, 2004).

The guidelines, among others, talked about following points –

- Equitable distribution of benefits
- People’s participation in watershed activities along with their contribution for operation and maintenance
- Institutional setup (Watershed Committee, Watershed Association, Project Implementation Agency etc.) and role of Panchayati Raj Institutions (PRI):
- Employment generation through watershed works
- Training to watershed users on technical aspects of soil and water conservation

The guidelines also mentioned about the criteria for taking up the watershed projects which were based on the presence of large population of SC/ST, preponderance of wastelands / common lands, poverty, presence of acute shortage of drinking water etc (DoLR, 1994).

The guidelines brought change in the way evaluation and monitoring of watershed projects was done under various programmes like DPAP, DDP and IWDP. The new project evaluation criteria had people’s participation, setup of proper institutions and committees, increase in income generation etc. among others as the main criteria for success. The guidelines played a major role in institutionalization of watershed development.

Since 1994, large number of projects was undertaken in various parts of India. Various studies were done for the impact assessment of these projects and various conditions for success were examined and evolved (Joshi et. al, 2004). As a result of the studies, the guidelines have been revised in the year 2001, and then subsequently in the year 2003 (Hariyali guidelines) and 2008.

The guidelines of 2001 and 2003 gave more stress on the role of PRIs, included forest areas under the watershed development activities, gave more stress on water harvesting measures for agriculture as well as drinking water, suggested strong ‘entry-point’ activities in order to ensure public participation and contribution and tried to develop robust ‘exit strategies’ in order to ensure equity and sustainability of assets (DoLR, 2001) (DoLR, 2003).

The main objective of 2008 guidelines was to have unified perspective across all the ministries, departments, schemes and projects related to watershed development. National Rainfed Areas Authority (NRAA) set up in 2006 has been given a major role in planning and preparing strategies related to watershed development activities at State and District levels. This was done with the special objective of giving more attention towards rainfed areas which form 85 million ha out of the total 142 million ha of net cultivated area and have suffered neglect in the past resulting into poverty, water scarcity, rapid depletion of groundwater table and high rates of soil erosion and land degradation (DoLR, 2008).

In 2008, the DPAP, DDP, NWDPRA and IDWP programmes were brought under one single umbrella of Integrated Watershed Management Programme (IWMP) whose main objective of restoring ecological balance by harnessing, conserving and developing degraded natural resources such as soil, water etc. was not very different from earlier objectives. Only some minor changes in the criteria for selection of watersheds, expenditure norms, funding patterns and institutional setup are made (Kerr, 2002).

Today there is large number of watershed projects taken-up in various parts of the country. These projects mainly consist of two types of interventions; technical interventions which form the core part of watershed development such as Continuous Contour Trenches, afforestation, terracing, contour bunds, check dams, percolation tanks, nala bunds, underground dams, farm ponds, etc. and social interventions which have evolved with time in order to ensure success and sustainability of the technical interventions as well as to ensure key developmental perspectives such as equity in distribution of benefits, people's participation etc (Samuel, 2004).

Considerable amounts of expenditures on watershed development programmes have been made all over the country at central as well as state levels. An NWDPRA report tells that total expenditure till 2006 has been Rs. 3034.66 lakhs which has been spent on 11876 micro-watersheds covering total area of around 94.028 lakh ha. The expenditure since 2007 (till 2011 - target) is Rs. 1044.37 lakhs spent on total area of 11.778 lakh ha (DAC, 2011).

Looking at this big picture, it becomes necessary to understand the role and impact of watershed programmes.

Impact of watershed development programmes in India

Over the last 25 years the discourse on watershed development has been evolved as a result of various impact assessment and evaluation studies taken up by government agencies or technical committees responsible for revision of guidelines, government research institutes like

There has been large number of studies done on assessment of impacts of the watershed development programmes in India in last 20 odd years. The studies are done by government agencies or government technical committees which were responsible for revision of guidelines, studies done by government research institutes like ICRISAT (Singh, 2008), NIRD (Sharma, 2010) etc and studies done by NGOs (Joy, 2004) and individual academicians (Kerr, 2002).

It has been shown by various studies that the success of a watershed project not only depends on quality of assets being created but also on socio-cultural and political factors such as public participation, decision making process followed in designing projects, sense of ownership and capacity of people, prevalent social stratification and power relations in villages etc. Accordingly, over the years, many activities not directly related to soil or water conservation works have been incorporated in watershed projects. These external activities like building schools or roads in villages, strengthening medical facilities, or tackling social issues like gender inequality, caste discrimination etc for bringing people together, setting up village level institutions and self help groups for proper administration and decision making in watershed projects in order to ensure equity and public participation, providing training and building technical capacity for proper operation and maintenance of assets in order to ensure sustainability and providing employment for income generation can be termed as input activities which are expected to deliver better outputs from watershed projects.

Consequently, the criteria for evaluation of watershed projects included input variables like number of village watershed committees created, participation of women, employment generated, capacity building trainings undertaken in addition to direct output variables like increase in groundwater, reduction in soil runoff etc. Following are some of the important parameters used in impact assessment studies:

- Output parameters
  - Impact on land, water and biomass
    - Direct impacts
      - Increase in water storage capacity
      - Reduction in runoff
      - Reduction in soil loss
      - Status and quality of water harvesting structures
      - Groundwater increase
      - Increase in stream / spring flow period
    - Indirect impacts
      - Increase in net sown area
      - Gross cropped area
      - Irrigation options
      - Fuelwood and fodder availability
      - Number of livestock owned
  - Impact on socio-economic conditions

        - Cropping pattern (one or two crops annually)
        - Equity in distribution of benefits
- Input parameters
    - Income and employment generation
    - Gender sensitivity
    - Establishment of local level institutions like Watershed Committees, User groups etc.
    - Capacity building and people's participation
    - Number of capacity building trainings

The results of impact assessment studies are quite varied. Some government studies have shown that there has been reduction in soil loss, increase in storage capacity, rise in groundwater and rise in income and employment generation and have concluded that watershed development programmes in general have been successful (Khalid, 2001) (Singh, 2008). Many analyses which have considered direct impacts as parameters have shown that there has been in increase in groundwater, increase in stream / spring flow period and reduction in run-off (Samuel, 2004) (Palinasmi, 2004) though some show otherwise (NIRD). But it is also argued that most of the studies have failed to use rigorous benchmarks for comparing values beforehand and after and have merely relied on the recall and perception of the respondents of the change or impact (Joy, 2004).

Also, even after this success of watershed development programmes, the drought prone areas in the country have not reduced proportionately i.e. watershed programmes have failed to make most drought-prone regions drought-proof apart from the few success stories. (Sharma, 2004a)

It can be seen that in recent years, the focus has been shifted from output-side variables like quality, durability and effectiveness of assets to entry-point activities and exit strategies, but it can be argued that giving more stress on input-side parameters alone would not be sufficient in ensuring the success of watershed projects. For example, construction of most of the soil and water conservation measures is done largely to generate employment, and hence very less attention is given on the effectiveness and quality of the measures. This results in local acceptance of measures only for gaining employment which further results in preponderance of sub-standard and non-effective assets in the name of employment generation (Kerr, 2002).

Secondly, there is complete lack of any protocol or guidelines for estimating the effectiveness of the asset or structure being put in place. At the local level, if there is a low cost mechanism or a low cost model to quantify and estimate the results of the watershed intervention, it will prove much effective in planning and cost estimation of the project and at the same time will lead to more scientific approach to creating assets.

Another important aspect missing throughout the discussion related to watershed development programme design is of neglect towards drinking water problem. Although mentioned in all the guidelines, the problem of drinking water is not addressed effectively by the watershed development programmes across the country (Kakade, 2001). Most of the programmes have historically been looked upon as a measure for water resource development for improved irrigation and crop production. The drinking water issue which can be surely solved through watershed approach, especially in state like Maharashtra where 80% of the rural drinking water comes from groundwater (as mentioned on the website of Groundwater Survey and Development Agency – GSDA: **www.gsda**.maharashtra.gov.in/**)**

1.3 Objectives of this study –

Keeping the above issues on agenda, it has been felt that there is a need of some protocol for evaluating and predicting the technical soundness of assets and structures at the local level. Especially in some parts of Western Ghats (Thane and Raigad districts) where there is acute drinking water scarcity in spite heavy rainfall, this kind of protocol would prove to be effective in solving the drinking water problem.

One step in this direction is to study and understand the intervention done in Ikharichapada in Mokhada by NGO AROEHAN. The development of protocol would require following:

- understanding of basic concepts of watershed and watershed modelling,
- to understand the local terrain and study the specific watershed intervention in Ikharichapada using groundwater flow modelling
- to understand working of watershed programmes at policy level in order to disseminate the protocol for wider application in other similar areas.

The scope of current report is limited only to understanding basic concepts of watershed management and groundwater flow modelling and to develop a conceptually correct model of

Ikharichapada intervention based on key observations and secondary data, which would be further refined and developed into a more accurate model.

Chapter 2 – Understanding technical aspects about Watersheds

2.1 What is watershed? –

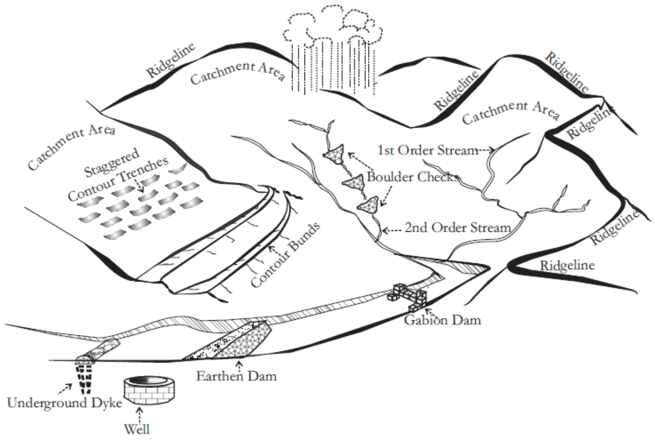


Figure 2-1: Watershed (source – SPS, 2006)

Watershed is the hydro-geological unit of area from which the rain water drains through a single outlet. When rain falls on the mountains, it flows down through small streams. Many such streams join to form bigger streams, which in turn join to form rivulets, which join to form rivers and so on. The entire area which supplies water to a stream or rivulet or a river at a particular point in its flow is called the watershed or catchment area or drainage basin of that particular point. The top of the watershed is called hill or ridge portion. The ridge-line partitions one watershed from another, or can be said to be the boundary of the watershed. All the droplets of rain within the watershed will flow from ridge portion through different drainage lines to the valley portion of the watershed and will be drained out of the watershed through a common exit point (SPS, 2006) (see fig. 2-1)

Watersheds can vary from few hectares to thousands of square km. Following table shows the classification of watersheds by its area.

Table 1 : Classification of watersheds (source: FES, 2008)

Category	Number of watersheds in India	Size ranges (in thousand hectares)
Regions	6	25000 – 100000
Basins	35	3000 – 25000
Catchments	112	1000 – 3000
Sub-catchments	500	200 – 1000
Watersheds	3237	50 – 200
Sub-watersheds	12000	10 – 50
Milli-watersheds	72000	1 – 10
Micro-watersheds	400000	0.5 – 1

A watershed is always characterized by the rainfall it receives and its ability to hold it within the watershed against draining it through the outlet. The main factors deciding this are land cover, vegetation, soil types, geographical terrain, geology of the watershed (having its characteristic hydro-geological properties), land use, cropping pattern etc.

Water, after entering the watershed as rainfall, can take many forms, such as surface flows through rivers, streams etc., surface storage in lakes, ponds, dams etc., groundwater flows through underground channels and springs or groundwater storage in shallow aquifers. This water may flow out of the watershed through single outlet as surface runoff or it may leave watershed through evaporation from surface water bodies, evapo-transpiration from plants, crops and soil, baseflow (i.e. flow of water beneath earth surface), consumption by humans and animals or leakage to deep aquifers.

Watershed development refers to any measures or interventions done at watershed level for conservation of natural resources like soil, forests, water or measures taken for changes in land use, water use or cropping pattern in order to increase the net water stored within the watershed.

2.2 Watershed interventions –

Watershed interventions can be made independently at different points in the watershed in a location specific manner, but while thinking of holistic watershed development, interventions are generally planned according to ridge-valley principle. In this approach, the ridge area is treated first with proper interventions followed by the smallest drain, moving on to larger and larger drains arresting the runoff at each point. Finally after reaching valley by following the streams, interventions can also be made at farm level. At each level, there are specific interventions which depend on the location in the watershed. Broadly, all the interventions can be classified into ridge area treatment and drainage line treatment. These are described as below:

2.2.1 Interventions in the Ridge Area –

These are the interventions carried out in the upper catchments of the watershed, with the main aim of soil conservation. This helps in the reducing soil runoff at the origin. The main types of ridge area interventions are:

Protection and plantation of grasses, plants, shrubs and trees native to the area –

These interventions are done at locations having high slopes i.e. slopes greater than 25%, where there is high probability of soil runoff and erosion (SPS, 2006).

Contour trenching –

It is a simple, low cost method of checking the surface runoff as well as soil erosion in the upper catchments where the slopes are between 10% and 25%. The contour trench is a pit dug along a contour line i.e. imaginary line joining points of same elevation. Thus, contour trenching means successive trenches of fixed length, width and depth along contour lines which will create small water pockets during rainfall and will make slow down the velocity of runoff, thus resulting into more infiltration of water into soil (SPS, 2006).

Contour bunds –

Contour bunding is also simple, low cost method of checking the surface runoff and soil erosion in the ridge area. Contour bunds are generally constructed in that part of the ridge area where the slopes are less than 10%. As against pits or trenches in contour trenches, here steps of soil are created along contour lines which will block the surface runoff from ridge to valley and will also help in reducing soil erosion (SPS, 2006).

2.2.2 Drainage line interventions –

These interventions are done along the drainages i.e. small streams, big streams or even rivers with the main objective of reducing the velocity of runoff through drainage line or for impounding water by creating water storage structure. Along with slowing down the runoff out of the watershed, the drainage line treatment also helps in enhancing recharge or infiltration of water into ground. Few examples of drainage line treatment are as follows:

Loose boulder checks –

Boulder checks or gully plugs are loose rock structures or small dams on small drainage lines (mostly in the upper catchments) having catchment area of not more than 50 ha. Apart from reducing the runoff velocity, loose boulder checks also reduce soil erosion by trapping the silt in the upper catchments. They are generally constructed in series one below the other across small streams thus helping to increase the duration of the stream flow and enhancing infiltration of surface runoff by creating small (1 to 2 ha) water pockets (SPS, 2006).

Gabion structures –

They are similar to loose boulder checks, but are constructed across bigger streams and have their own catchment area at least 5 ha. Also, these structures are constructed on flatter regions as against loose boulder checks. The flatter the upstream slope, the more will be the storage. Along with slowing down the runoff these structures also help in temporary water storage if the bed is impermeable enough. These structures are generally reinforced with wire mesh for stable embankments and strength against strong currents (SPS, 2006).

Underground dykes or subsurface bunds –

These are underground dams which obstruct the flow of sub-surface water and divert them to nearby wells by creating catchment area underground. They are suitable in areas where impermeable strata (such as hard rock) are found at shallow depths below the surface. Subsurface bunds will be effective only if the sub-surface flows are considerable and continue long after the surface flows cease to exist. They must be built perpendicular to the overall direction of drainage line and should not be built where the drainage line slope is very high (SPS, 2006).

Water harvesting structures: Earthen dams / Check dams –

These are most important structures of any watershed programme and are built on the main stream of the watershed. There can be two types of dams; for water storage and for percolation. These two types of dams have different aims.

- Percolation dams are primarily built for enhancing recharge and are built in the upper parts of the catchment area. The water stored in these dams percolates to the wells and tubewells located in the lower part of the catchment (SPS, 2006).
- Storage dams are primarily built for the purpose of storing water during monsoon season which can be used for drinking or for irrigation in post monsoon period. Such dams are useful in regions which are poor in groundwater resources and have low capacity of recharge / infiltration (SPS, 2006).

Chapter 3 – Watershed interventions in Ikharichapada, Mokhada

3.1 About Ikharichapada –

Ikharichapada is a small and remote hamlet in Aase Gram Panchayat (G.P.) of Mokhada tehsil / block in Thane district. Mokhada is the most backward tribal block in Thane district and is located at the north-east tip of Thane district. It borders Nashik district on the east, Gujarat state on the north, Jawhar block of Thane district on the west and Shahapur block of Thane district on the south.

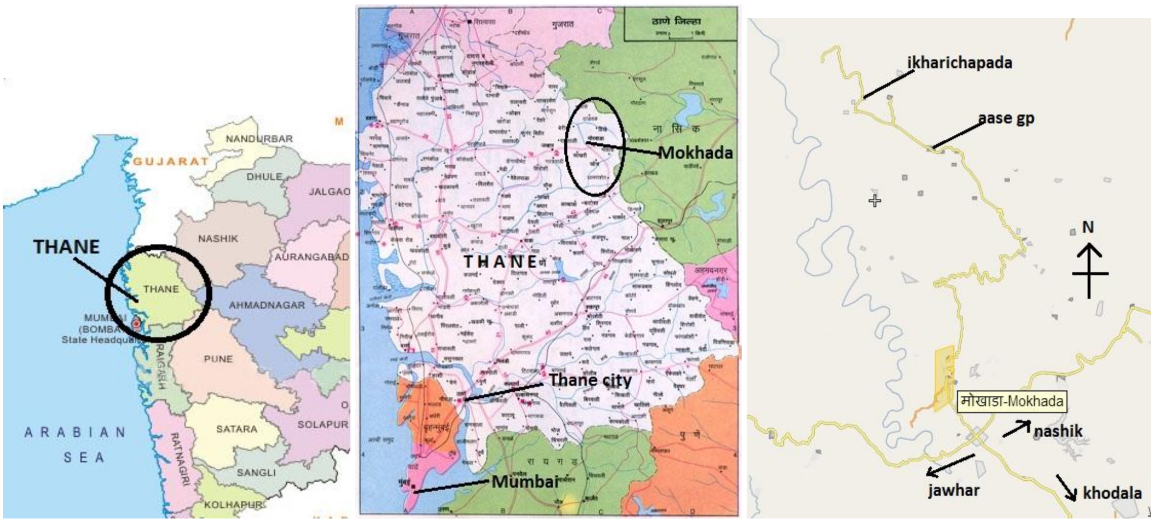


Figure 3-1: Ikharichapada location

According to the census of 2001, the total population of the tehsil is 67,319 of which more than 92% are tribal. The non-tribal population resides only in and around the tehsil town Mokhada and comprises of traders and government officials. In villages, 100% population is tribal. This region (along with neighbouring regions of Jawhar, Wada and Vikramgad blocks) suffers from large number of developmental problems like poverty, malnutrition, water scarcity and lack of basic infrastructure etc.(http://aroehan.blogspot.in/2009/03/aroehan.html)

Table 2: Lat-Long Ikharichapada

Ikharichapada	Latitude	Longitude
	20.0277°	73.3116°

The hamlet Ikharichapada of Aase G.P. is situated at the north-eastern tip of Mokhada tehsil and is only few km away from Nashik district and Gujarat state borders (but not connected by roads). The population of the hamlet is around 200 and all the inhabitants are from *Warli* tribal community.

All the villagers depend on subsistence rain-fed agriculture with main crops being paddy, *nachni* and *varai*. There is no mechanization in agriculture and the farm produce is not sold in the market. The yearly incomes of these people vary from Rs. 5,000 to Rs. 15,000.

Geography, Geology and Climate of the region –

As Mokhada block is situated in the northern tip of Western Ghats, the region is hilly and mountainous with undulating slopes. 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 firstly due to hilly terrain because of which most of the rainwater runs off quickly; the elevation in Aase G.P. alone (which is the largest of the G.P.s geographically and covers 19 small and scattered hamlets) varies from 150 m to 400 m from mean sea level, and secondly due to hard rock geology of the region, which does not allow large groundwater storages.

Thus, all 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 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.

3.2 Watershed interventions in Ikharichapada - Akshayjal programme of AROEHAN –

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.

3.2.1 Drinking water scenario of Ikharichapada before intervention –

In Ikharichapada, the primary source of drinking water is a well which is around 50 m from the hamlet. The well supplies water up to March, when people from surrounding villages start coming to fetch water from this well (as wells in their villages go dry). Suddenly due to increased burden, the well starts emptying fast and with the inflows to the well through springs getting weaker and weaker, the well eventually goes dry before end of March, after which people have to literally trek kilometres of hilly terrain to just get few pots of drinking water. Following table shows drinking water scenario for Ikharichapada hamlet before intervention:

Table 3: Drinking water scenario, Ikharichapada, pre 2010

Name of the source	**Type of the source**	**Active / Inactive**	**Dimensions**	**Distance from the hamlet**	**Dries in**
Mothi well	Open dug well	Active (primary source)	11.7m x 6.2m	50m	March
Jalswarajya well	Open dug well	Inactive (poor water quality)	5.2m x 3.5m	50m	March
Pond		Active (not for drinking)	32m x 35m	50m	March
Waal River		Active	-	5km	-

3.2.2 The intervention (2010) –

Dr. Ajit Gokhale of Natural Solutions, a Mumbai based consultancy providing technical help for *Akshayjal*, after studying the well condition and the surrounding region decided to go for sub-surface bunds (or underground dams, or underground dykes) across the stream in which the well was located, in order to extend the life of the well.

3.2.3 The approach –

The approach followed by Natural Solutions was not the conventional *ridge to valley* approach generally advised in watershed interventions. The intervention suggested was a drainage line intervention on the main stream in the watershed in which the primary drinking water well was situated.

The basic idea was to obstruct the sub-surface flows which used to exist till January i.e. long after the surface flows cease to exist. This would push the water below the surface backwards into the stream, thus creating an underground dam which would increase the local water table and would extend the life of the well.

Simply put, sub-surface bunds are impermeable barriers made of clay or concrete or reinforced concrete or stone masonry or steel sheets or clay covered with plastic sheets constructed 2 to 6 m below ground till hard rock is found. In basaltic regions like Mokhada, the hard rock is shallow and thus is more suited for such structures.

Accordingly, two locations downstream to the well were decided where the sub-surface bund made of cement concrete would be constructed. These locations were decided through series of questions to local people about the life of the springs *upwelling* out of the terrace bunds of the fields in the stream.

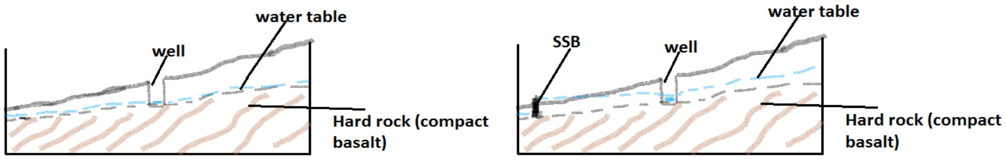


Figure 3-2: Downstream subsurface bund

At the same time, a sub-surface bund upstream to the well was also planned. This bund would work similar to a surface bund. That is, it would slow down the sub-surface runoff, thus extending the life of stream flow underground. This too, would contribute in extending the life of the well.

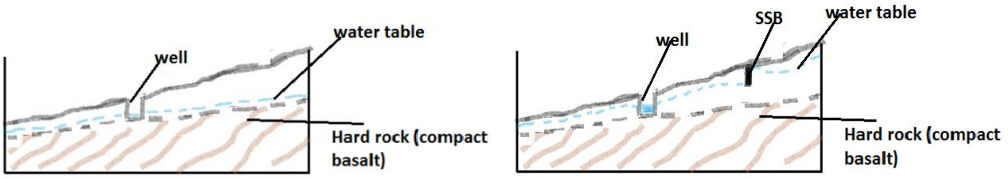


Figure 3-3: Upstream subsurface bund

Innovative structures, called cordons were also suggested along with sub-surface bunds. These are tank-like impoundment structures having capacity of 1000 litres to 4000 litres, built around springs in order to make water collection easier. They can be built independently or at the same location as that of sub-surface bunds.

Following map shows all the interventions done in Ikharichapada:

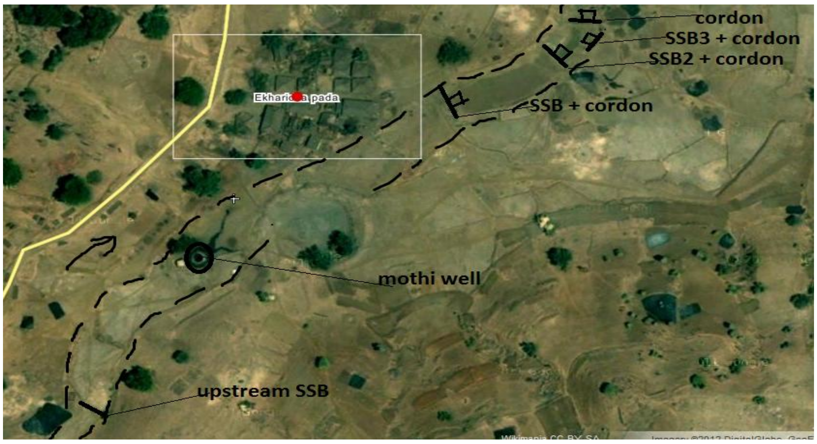


Figure 3-4: Interventions in Ikharichapada

3.2.3 Impact of the interventions –

During the field stay in Ikharichapada in May, June 2012, author, along with Mr. Vishal Mishra, a fellow student at CTARA, did a survey in Ikharichapada and neighbouring hamlets of Dapti-1, Dapti-2, Dhamni and Dhamodi in order to assess the impact of the interventions. According to the survey, the water level in the Mothi well has increased considerably due to the interventions.

In the 1st year after intervention, the well did not go dry till the end of dry season i.e. till monsoon started. In the 2nd year of intervention, the well got dry, but in May 2nd week, which is far *after* than March.

Also, according to the survey, in the 2nd year, demand for water was increased due to brick making as well as due to burden of more people from neighbouring hamlets on the well. This was the reason ascribed by the NGO for the well getting dry earlier than last year.

Also, during the field stay, a senior geologist Mr. Himanshu Kulkarni did the geological survey and quick impact analysis of the interventions, according to whom the downstream sub-surface bunds would be very less effective in increasing the water levels in the well. Thus, whatever effect the intervention had on the well water level was due to upstream subsurface bund only.

Based on the success of the interventions according to local people, the NGO AROEHAN is planning to replicate the same interventions in other stressed villages of Mokhada. Hence, thorough impact assessment of the interventions is required.

Chapter 4 – Understanding basic modelling concepts

4.1 Need for technical analysis and modelling –

- As seen in the previous chapter, the results of the interventions done in Ikharichapada although positive are variable. This makes scientific explanation of the impacts difficult which in turn makes it hard to predict the results in future.
- If only a single village, with fixed number of people, had depended on the well in Ikharichapada, with their consumption remaining constant over time, then it would have been possible to calculate the net increase in the water in the well, which would have made it easy to do cost – benefit analysis of the intervention. But such an ideal case is rarely encountered, and as seen in the previous chapter, the demand increased a lot in two years due to increase in burden. Thus, just a simple water balance approach will be inadequate to analyze the actual impact of the intervention.
- In order to replicate such interventions in neighbouring villages it is necessary to know the individual impacts of upstream and downstream bunds. At the same time, the distance of bunds from the well, number of bunds, hydraulic characteristics of the bunds etc. have impacts on the net increase in water harvested. Hence an analysis which can give the best possible solution needs to be developed.

Considering all the above points, and taking into account the fact that AROEHAN is looking forward to carry out similar interventions in the whole Mokhada block, it was found apt to do a technical analysis of the intervention in Ikharichapada by developing a watershed model for understanding the functioning of sub-surface bunds, its impact on groundwater flows and its impacts on the well.

4.2 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. It is licensed software developed by Aquaveo, an engineering services company developing groundwater modelling softwares, costing around US $5000.

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 version 7.1 along with MODFLOW version 2000 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.

4.3 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.
  - Pressure head – It is measured from the bottom of the well to the top of the water level in the well
  - Elevation head – It is measured from the mean sea level to the bottom of the well
  - 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 a constant; whereas in a 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 $K_x \neq K_y \neq K_z$

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 –

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

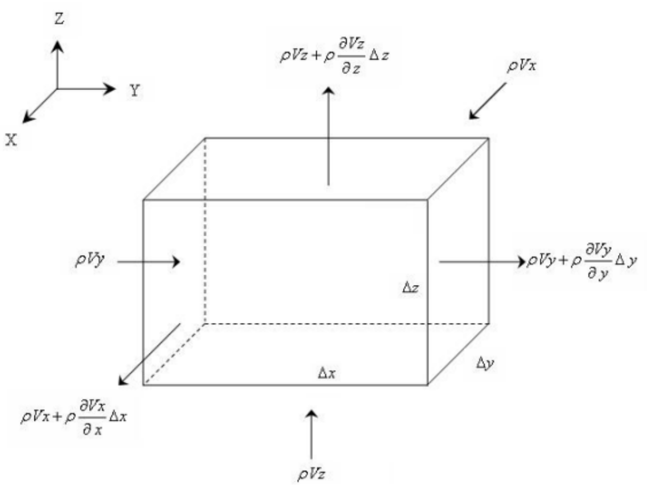


Figure 4-1: Continuity equation of groundwater flow

where ρ is the density of water and is considered to be identical along three directions i.e. water is considered as incompressible;

V_x, V_y, V_z are the velocity components of water in x, y and z directions.

Since water has been considered incompressible, 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: $\rho v_x(\Delta y.\Delta z)$

In y-direction: $\rho v_y(\Delta x.\Delta z)$

In z-direction: $\rho v_z(\Delta x.\Delta y)$

Outflows:

In X-direction: $\rho\left(v_x+\frac{\partial v_x}{v_x}\Delta x\right)(\Delta y.\Delta z)$

In Y-direction: $\rho\left(v_y+\frac{\partial v_y}{v_y}\Delta y\right)(\Delta x.\Delta y)$

In Z-direction: $\rho\left(v_z+\frac{\partial v_z}{v_z}\Delta z\right)(\Delta x.\Delta y)$

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

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

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

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

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

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.

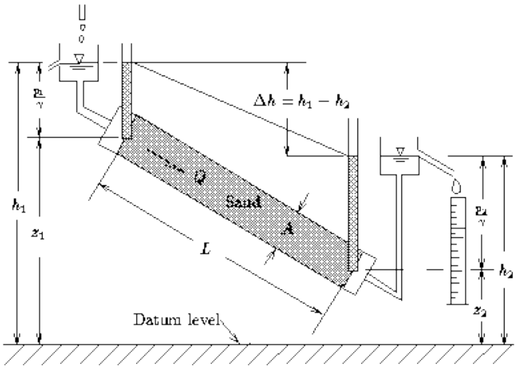


Figure 4-2: Darcy's experiment of conductivity

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

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

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

- Negative sign is introduced because the hydraulic head decreased 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;

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

- But 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.

Basic differential equation of groundwater flow –

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

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

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,

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

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 porosity of the material. The net water stored depends on specific storage which is defined as,

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

Where ρ is the density of water, 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,

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

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.

4.4 Basics of 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 (Rumbough, 1995).

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.

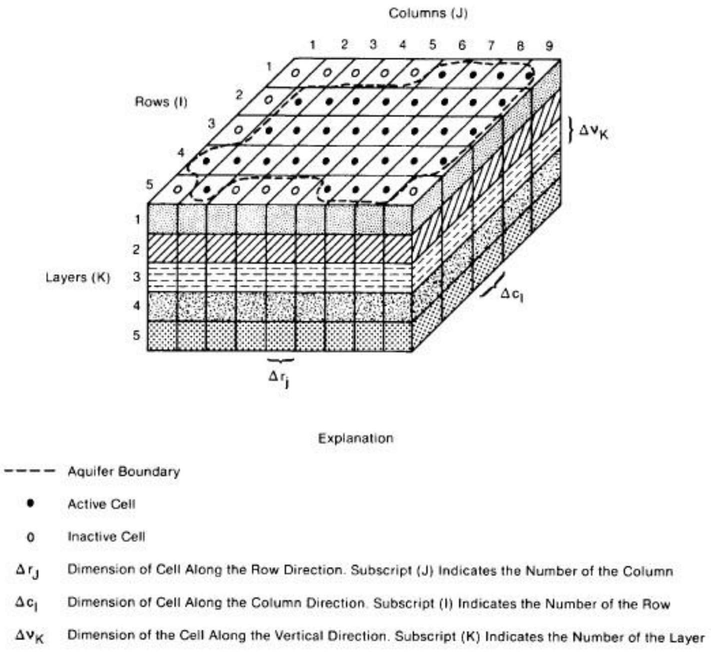


Figure 4-3: MODFLOW grid

4.4.1 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,

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

- 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

$$flow\ from\ six\ faces\ into\ cell\ i,j,k +$$

$$external\ flows\ into\ or\ out\ of\ i,j,k$$

$$= S_{s_{i,j,k}} \left(\Delta r_j \Delta c_i \Delta v_k\right) \frac{h_{i,j,k}^{m} - h_{i,j,k}^{m-1}}{t_m - t_{m-1}}$$

- $t_m - t_{m-1}$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 (Rumbough, 1995).

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

4.4.2 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 (Rumbough, 1995).

4.4.3 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. (Rumbough, 1995)

4.5 GMS: Groundwater Modeling Software –

GMS is one of the several, and at the same time, one of the most widely used graphical user interfaces to MOFLOW. GMS is known for the ease of use and its ability to simulate more complex groundwater scenarios. Primarily, two approaches can be used to construct MODFLOW simulation in GMS: the grid approach which involves working directly with the 3D or 2D grid and applying model parameters like hydraulic conductivity, specific yield, layer dimensions etc. and sources / sinks like recharge rates, well withdrawal data etc on a cell-by-cell basis. The conceptual model approach allows the user to use lines, polylines, arcs, polygons etc. and to import GIS (Geographical Information System) data into GMS in order to create more realistic scenarios. The conceptual model is finally converted to grid internally and the same logic is used to solve the simulation and the results are again converted back to conceptual frame and given back to the user. In the following chapter, GMS will be used to construct a conceptual model in order to understand the watershed intervention done at Ikharichapada.

4.5.1 Getting acquainted with GMS – Starting with a simple model

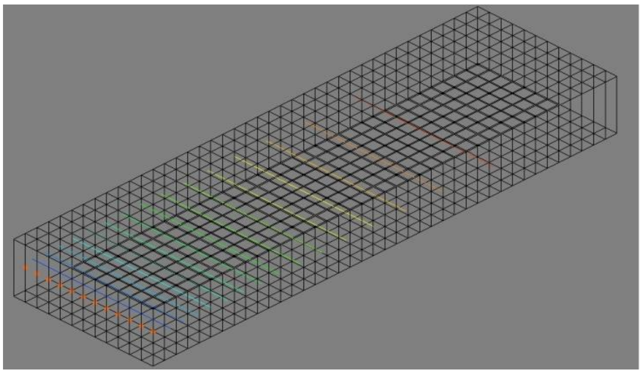


Figure 4-4: Simple grid example

A simple grid approach was followed. 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.

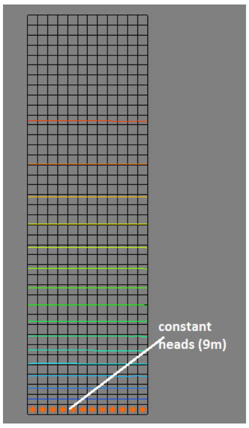
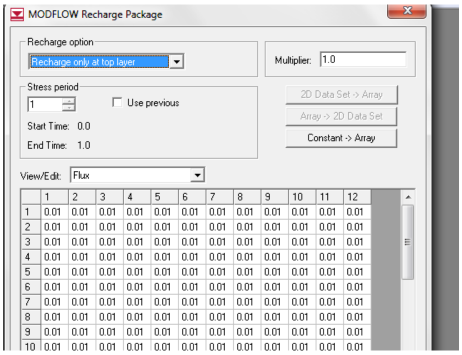


Figure 4-5: Constant Heads

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. 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. 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.



Recharge option: Recharge only at top layer

Multiplier: 1.0

Stress period: 1 ☐ Use previous

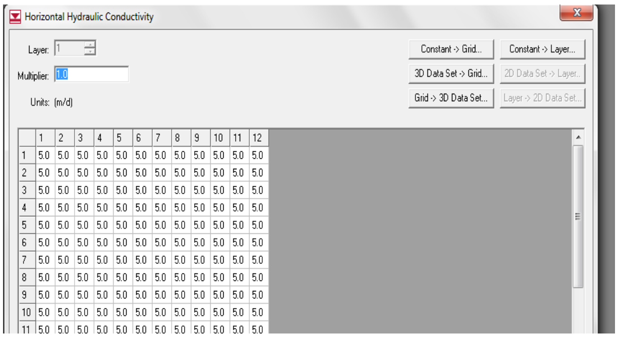
Start Time: 0.0

End Time: 1.0

View/Edit: Flux

	1	2	3	4	5	6	7	8	9	10	11	12
1	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
2	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
3	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
4	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
5	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
6	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
7	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
8	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
9	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
10	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01

Figure 4-6: Recharge rates



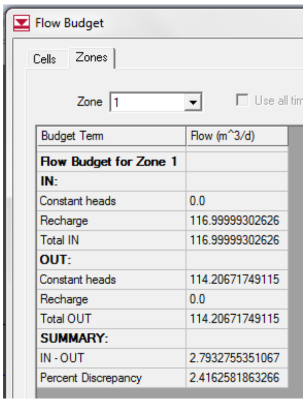
Layer: 1

Multiplier: 1.0

Units: (m/d)

	1	2	3	4	5	6	7	8	9	10	11	12
1	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
2	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
3	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
4	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
5	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
6	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
7	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
8	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
9	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
10	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
11	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0

Figure 4-5: Hydraulic Conductivity



Zone: 1

Budget Term	Flow (m^3/d)
Flow Budget for Zone 1	
IN:	
Constant heads	0.0
Recharge	116.99999302626
Total IN	116.99999302626
OUT:	
Constant heads	114.20671749115
Recharge	0.0
Total OUT	114.20671749115
SUMMARY:	
IN - OUT	2.7932755351067
Percent Discrepancy	2.4162581863266

Figure 4-8: Flow Budget

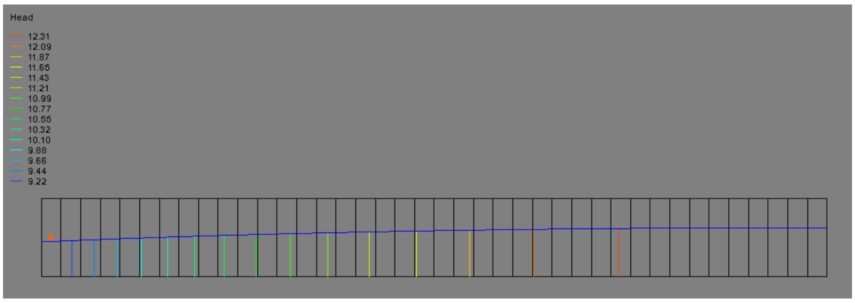


Figure 4-7: Output heads

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 follows:

As seen in the figure, the recharge is 116.99 m^3/d and the constant heads out is 114.20 m^3/d with around 2.4% discrepancy in finite difference approximation.

4.5.2 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.

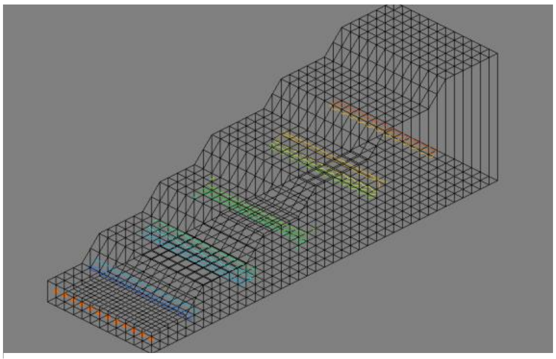


Figure 4-8: Model with varying elevations

The elevations were entered for simulating a hilly terrain to understand groundwater flow through such terrain. A well and a barrier were added and the effects were studied.

Boundary conditions used –

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 -20m^3/d. 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 –

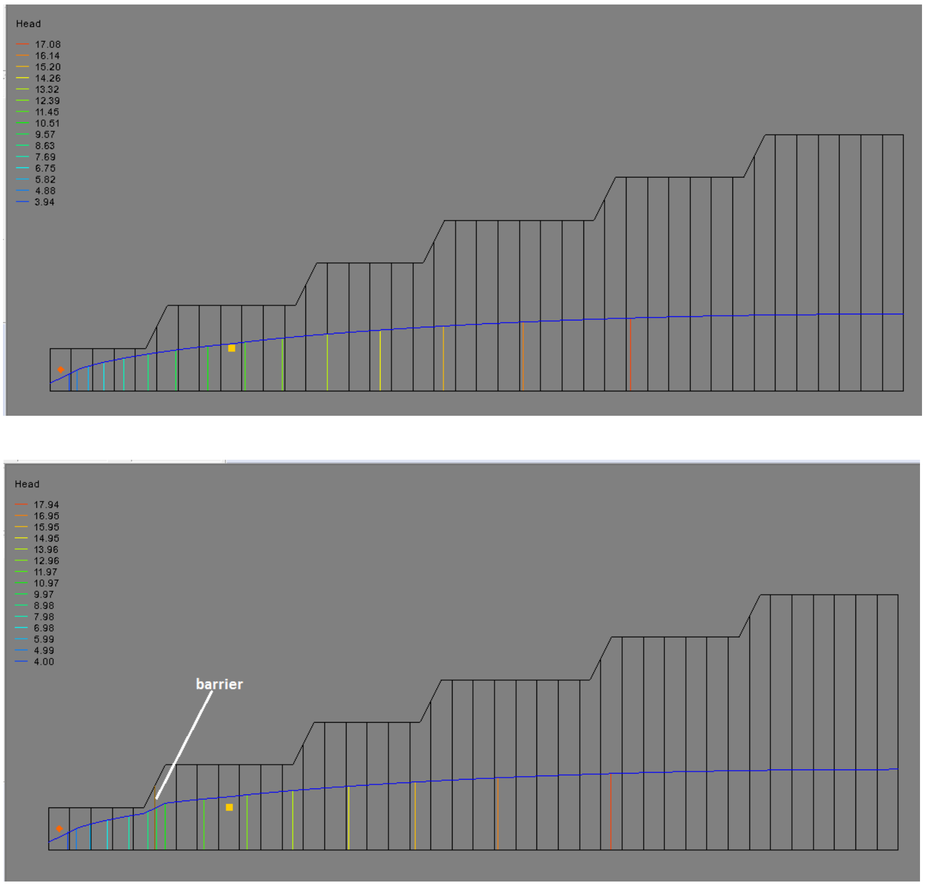


Figure 4-9: Barrier effects

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. The 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 m^3/d) suggested that no extra water was harvested due to barrier. The flows only got regulated due to the barrier.

4.5.3 Modelling a hypothetical watershed

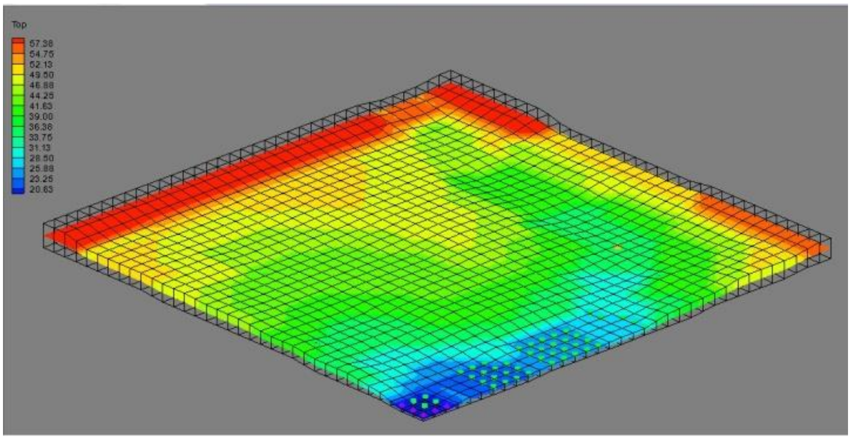


Figure 4-11: Hypothetical Watershed

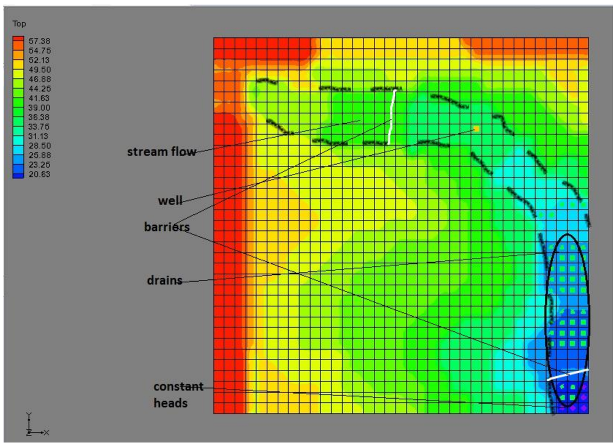


Figure 4-10: Modelling hypothetical watershed

After knowing the basics of GMS and its packages, it was decided to create a hypothetical watershed in grid approach. The grid is 35 x 35 x 1 cells with dimensions as 700 m x 700 in x – y plane with variable thickness across the watershed. The thickness of the layer was given such that the grid is thick in the hilly areas and tapers towards the outlet of watershed, as is the scenario in Ikharichapada. The watershed would have topography similar to Ikharichapada with one main stream, terraced fields along the stream, one or two other small streams meeting the main stream downstream to the well.

The basic objective was to move closer to the real scenario by giving realistic elevation values and thickness of the layer, understanding the behaviour of the various base flows in the watershed, understanding the different conductivity zones for different types of materials and the effect of barrier on the overall flows and heads in the watershed.

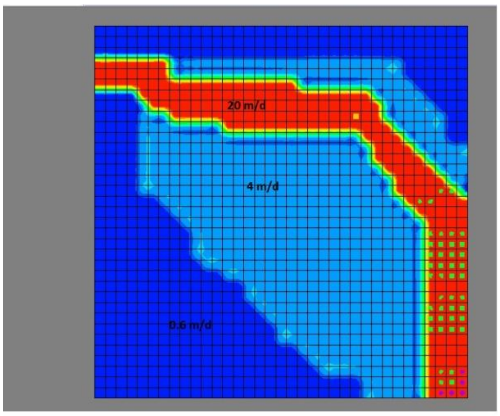


Figure 4-12: Hydraulic conductivity

Three zones of different hydraulic conductivity were delineated; as the stream bed has terraced farms and contains clay, the stream bed was given high conductivity, zone around the stream has vesicular amygdaloidal basalt is given medium conductivity, and the high hills have compact basalt with low conductivity.

High conductivity region *(m/d)*	Medium conductivity region *(m/d)*	Low conductivity region *(m/d)*
20	4	0.6

Recharge – The recharge was set as .0018 m/d i.e. 1.8 mm/d which means that 1.8 mm per day will be infiltrated in the whole watershed. The total area of the watershed is 700 m x 700 m = 490000 m^2. Thus the net recharge into the watershed per day is 490000 x 0.0018 = 882 m^3. If we consider infiltration rate to be 6% in western ghat area with basaltic hilly terrain, then it means that the rainfall per day is 30 mm, which means 900 mm per month or around 2700 mm per rainy season, which matches with the real data.

Specific yield – As the terrain is all basaltic, very low specific yield i.e. 3% or 0.03 is considered (Deolankar, n.a.).

Stress periods – The model will be run in steady state to obtain the equilibrium conditions during the rainy season, and then will be run in transient state for next 200 days of dry season to see the effects of recharge.

Table 4: Parameters for Hypothetical watershed

Parameter	Steady state	Transient state
Recharge	.0018 *m/d*	0
Well discharge	-4 m^3/d	-12 m^3/d
Constant heads	16.8 *m*	Gradually decreases from 16.8 *m* to 14.8 *m* at the last time step

Results –

The flows i.e. constant heads flowing out, drains flowing out and recharge, which gets converted into storage after stress period 1 were studied. Also, four points in the watershed were chosen and heads at those points were compared for all the interventions at fixed times in the stress period. The plots are shown below.

It was found that there is no change in flows out of the watershed after intervention of upstream bund.

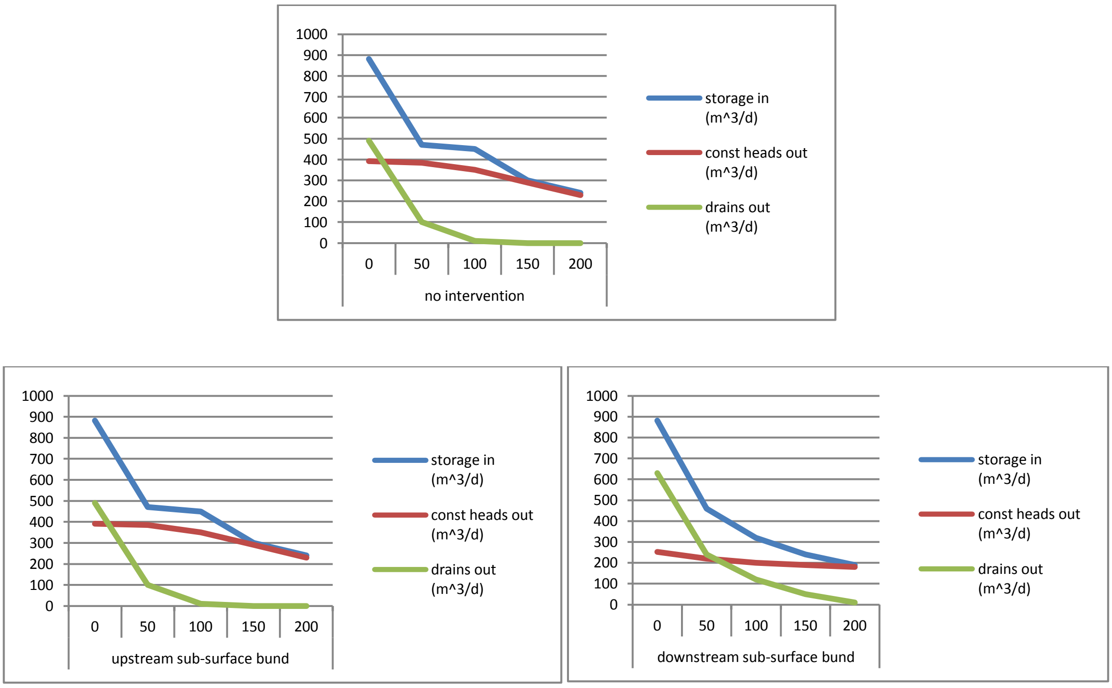


Figure 4-13: Results - Hypothetical watershed

But in case of downstream bund, the drains i.e. the springs or upwelling of water remains active till the end of stress period 2 i.e. till time step 200. But the increase in drains is compensated by decrease in constant heads i.e. the sub-surface flow out of the watershed is decreased while surface flow has increased.

Also, the storage curve, which gives the rate of decrease in storage per day or the area under this curve gives the total water flown out of the watershed and which is the addition of water flowing out as constant heads and water flowing out of the system as drains, tells that there is a slight increase in net water storage in case of downstream subsurface bund (as the area under curve in case of downstream bund is slightly less than that of upstream bund).

Chapter 5 – Ikharichapada conceptual model

All the previous models helped in learning about various packages used in GMS. The next step was to move closer to Ikharichapada scenario and develop a model which would be conceptually correct and would help in explaining the functioning of the watershed under various conditions.

The model thus constructed would be like a system of variables in which there would be some known variables coming directly from simple key observations in the field (like location of the well, well depth, well levels at different times, locations and durations of various springs in the watershed etc.) and secondary data (like water withdrawal from the well per day, elevation and contour data of the watershed, latitude-longitude values of all points in the watershed, specific yield and specific storage values of different types of basalt etc.). Along with some known variables, the model will have more than one unknown variables (like geological formations, thickness of different geological layers, hydraulic conductivity values of different regions in the watershed etc.) whose values will be adjusted through series of iterations and refinements to the model, so as to meet the conditions (in the current scenario) as observed in the field. This is how the conceptual model is built.

5.1 Key observations

The key observations are the data obtained from the summer field work of June, May 2012 by author and Mishra, V. and through individual field visits during and post monsoon and interviews with the NGO volunteers and local people. Those are as follows:

- Positions of wells, subsurface bunds, stream etc.
- Location of springs and water logging in fields and its duration
- Life of springs before and after the interventions
- Water levels in the well at different times

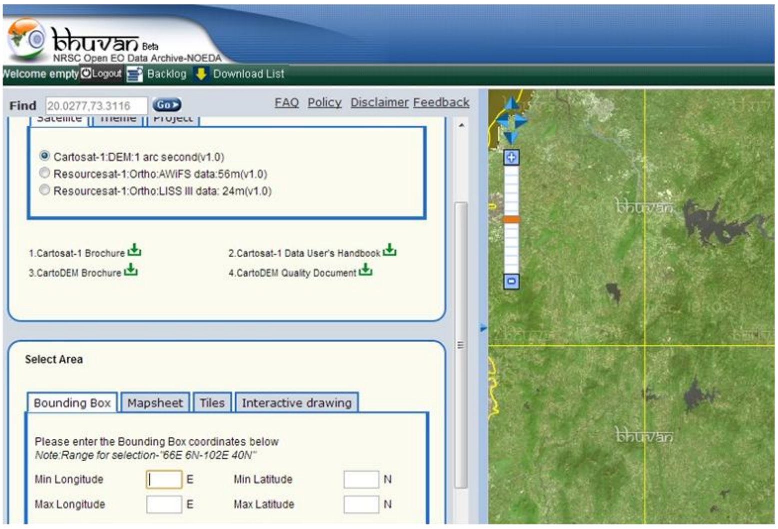
And the following was the data obtained:

Table 5: Key Observations

No.	Observation
1	The well is 10m deep and is located within the stream The well is 10m deep and is located within the stream
2	The water level in the well is just 2m below surface during monsoons
3	The dependence on well is less in monsoon (about 6 cum/day) and increases as the dry season progresses (at the end of dry season, withdrawal is almost 12 cum/day)
4	The fields downstream to the well are water logged during monsoon
5	The springs downstream to well (just close to the outlet of watershed) used to exist till late-December or early-January before intervention; after intervention they continue till March
6	The watershed tapers towards the outlet; thick in highly elevated areas and thins out in the direction of stream flows
7	Three layers: topmost soil layer, followed by slightly porous vesicular amygdaloidal basalt, followed by impermeable compact basalt layer
8	Constant heads were set at 61.5m at the outlet of the watershed in the steady state i.e. just below the surface which gradually was reduced to 54.8m at the end of simulation i.e. just 0.2m above bottom layer, as is the case in summer.

5.2 Secondary Data

Similarly, some important data like elevations and latitude-longitudes of all points in the watershed, contour data, rainfall data of Mokhada, specific yield and specific storage values of basalt etc. were obtained through different sources.



Find 20.0277,73.3116

● Cartosat-1:DEM:1 arc second(v1.0)
○ Resourcesat-1:Ortho:AWiFS data:56m(v1.0)
○ Resourcesat-1:Ortho:LISS III data: 24m(v1.0)

Please enter the Bounding Box coordinates below
Note:Range for selection-"66E 6N-102E 40N"

Min Longitude ☐ E Min Latitude ☐ N
Max Longitude ☐ E Max Latitude ☐ N

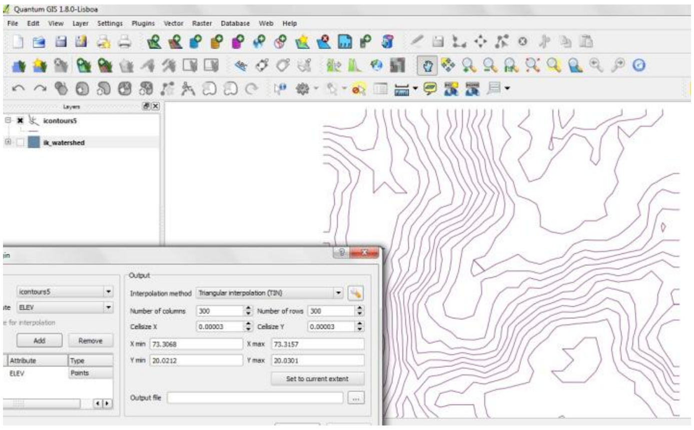
Figure 5-1: Getting DEM from Bhuvan

Elevation and Position data –

The Digital Elevation Model (DEM) data was obtained from Bhuvan i.e. a geo-portal website of Indian Space Research Organization (ISRO) available at http://bhuvan.nrsc.gov.in/. DEM is the digital model or three dimensional representation of terrain's surface and is acquired through India's *Cartosat* satellite with *1 arc second* resolution.

The DEM from ISRO geo-portal is received as an image (of TIFF format), which was manipulated in Geographical Information System (GIS) software, Quantum GIS (QGIS). The above DEM was used to extract contour data in QGIS. The resolution of the contour data was 5m.

This contour image was loaded into GMS and watershed boundary was delineated. This boundary would act as no-flow boundary i.e. there would be no inflow or outflow through this boundary except at the outlet.



icontours5
ELEV

Attribute	Type
ELEV	Points

Interpolation method: Triangular interpolation (TIN)
Number of columns: 300
Number of rows: 300
Cellsize X: 0.00003
Cellsize Y: 0.00003
X min: 73.3068
X max: 73.3157
Y min: 20.0212
Y max: 20.0301
Output file:

Figure 5-2: QGIS - Contour data to TIN file

Then the contour image was matched with Wikimapia image of Ikharichapada with the help of latitude-longitude positions of points to mark the well and subsurface bunds.

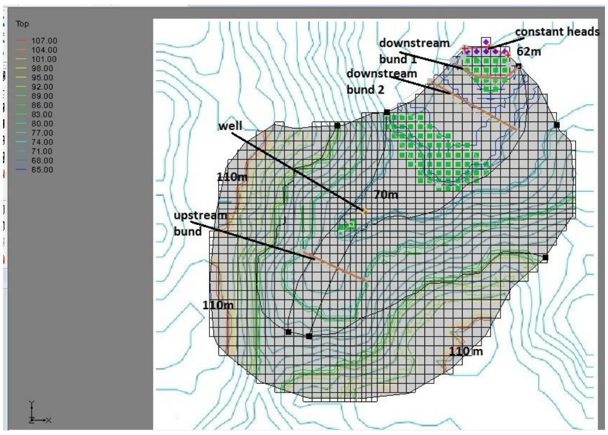


Figure 5-3: Ikharichapada watershed

For getting elevation data, the contour file was converted to Triangulated Irregular Network (TIN) file in QGIS by interpolation method. TIN file is a vector-based representation of 3D surface made up of irregularly distributed nodes and lines with three dimensional coordinates (x, y and z) which are arranged in a network of non-overlapping triangles. This TIN file was superimposed over the contour image in GMS to get elevations of all the points in the watershed.

Due to some irregularities in the TIN file the elevations were inconsistent with the contour image at some locations. Hence the TIN file was tweaked and manipulated so as to match the contour data and then was used to import the elevations of the top layer in GMS.

Thus, the model now had realistic watershed boundaries, exact location of well, streams, hills etc. and realistic elevations of top layer. The internal representation of this model contained 1319 cells in the grid. The grid had only one layer, each cell with surface area of about 305.9866 sq m. The total surface area of the watershed was 403.5964 sq km.

Rainfall data for Mokhada block was obtained from rain gauge installed in Central Water Commission Office, Mokhada during the summer field-stay. Average rainfall for last 10 years was 2724.24 mm.

The infiltration rate or the recharge rate required for the model was assumed to be 4-5% of the total rainfall i.e. 0.0022 m/d. Thus every cell would receive 22 mm/d of water. Thus, the whole watershed would receive 887.9128 cum/day through discharge.

Regarding geological data, it was decided to refer to Prof. S. B. Deolankar's study on potential of Deccan Basalts as aquifers which gives hydrogeological properties like specific yield and specific storage for different types of basalt (vesicular basalt, weathered basalt, compact basalt etc.)

Table 6: Rainfall data - Mokhada

Year	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	Average
Rainfall (mm)	2376.4	2428.2	3379.2	3320	3205.4	2512.3	2822.3	1987.6	2429.4	2781.6	2724.24

5.3 Other Assumptions and Constraints

The main assumption was that only one geological layer was considered. The whole subsurface was considered as homogeneous and isotropic.

The thickness of the layer varied from 37m in the highly elevated areas to 8m in the outlet area of the watershed i.e. tapering towards the outlet.

Due to only one layer, the barrier package which was applied for simulating subsurface bunds had to be applied for the whole depth of the cell while in reality the subsurface bunds are only around 4-6 m below ground.

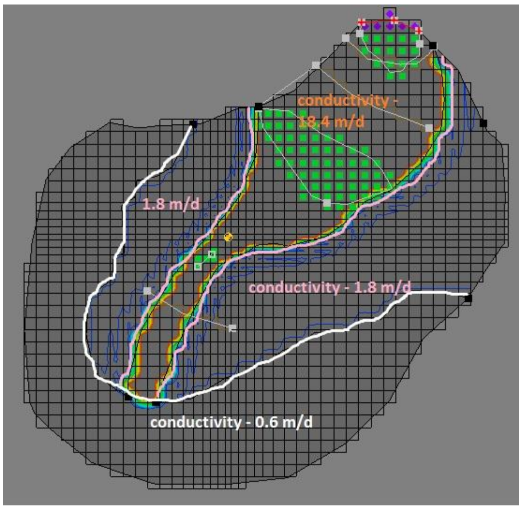
Leakage characteristic of barrier package used for subsurface bunds (0.04) – means barrier was considered almost leak-proof.

Unsaturated zone groundwater flow cannot be simulated easily using MODFLOW as Darcy's Law is not applicable as it is in case of flow through unsaturated zone. Hence, it was not considered in this model.

Three conductivity zones – high (along the stream bed), medium (in the vesicular basalt region i.e. medium elevations) and low (in the compact basalt region i.e. high elevations)

Table 7: Hydraulic Conductivity Zones - Ikharichapada

High conductivity region *(m/d)*	Medium conductivity region *(m/d)*	Low conductivity region *(m/d)*
18.4	1.8	0.6



5.4 Running the model –

Model was run in steady state to obtain equilibrium conditions just after monsoon, and then was run in transient state for 249 days of dry period. The stress periods for the model were as follows:

Table 8: Stress period parameters - Ikharichapada

Stress period	Type	No. of days	Period
1	Steady state	1	30th Sep 2012 – 1st Oct-2012
2	Transient state	249	2nd Oct 2012 – 7th Jun 2013

Values for stress periods

Table 9: Values for Stress periods - Ikharichapada

Parameter	**Steady state**	**Transient state**
Recharge	.0022 m/d	0
Well discharge	-6 m^3/d	Starts with -6m^3/d and increases gradually till -12m^3/d till 7th Jun 2013
Constant heads	61.5 m	Gradually decreases from 61.5m to 54.8m in the last time step

Model scenarios

Six different scenarios were simulated by running the above model (refer to fig):

Table 10: Scenarios for Ikharichapada model

Scenario no.	**Description**	**Short form used**
1	With no intervention	No bund
2	With only downstream sub-surface bund just near the outlet of watershed (at elevation 62m)	Only ds 1
3	With only downstream sub-surface bund upstream of the downstream bund and downstream of well (at elevation 65m)	Only ds 2
4	With both downstream sub-surface bunds	Both ds
5	With only upstream sub-surface bund, i.e. upstream of the well (at elevation 75m)	Only us
6	With all three sub-surface bunds	All bunds

5.5 Results –

The models were run in steady state with the above values (i.e. recharge = 0.0022 m/d) for getting equilibrium conditions of monsoon, and then were run in transient state to notice the change in heads and flows after the monsoon i.e. recharge was stopped. The changes in all the six models / scenarios were studied for understanding the impacts.

5.5.1 Impact on well –

The well elevation is 70m. As per the field survey the water in the well is at 1m to 2m depth from the surface i.e. the well is almost full. This condition was met in the steady state run. In the transient state, the interventions started playing their role and following were the findings.

Table 11: Well water levels - Ikharichapada

Scenario	Well heads as on 1st-Oct 2012 (m)	Well heads as on 7th-Jun-2013 (m)	Change in heads (m)	Net increase over 'no bund' condition (m)
No bund	68.19	61.82	-6.36	0
Only ds 1	68.19	63.55	-4.64	1.72
Only ds 2	68.20	63.06	-5.15	1.21
Both ds	68.20	64.38	-3.83	2.53
Only us	68.13	61.92	-6.21	0.15
All bunds	68.15	64.5	-3.65	2.71

Thus, the well heads drop gradually throughout the dry period, but more or less for different interventions. If the net head increase over "no bund" condition is seen i.e. how much head has increased due to the intervention at the end of dry season, then the impact of each intervention on the well can be easily quantified. In this case, it is see that the maximum impact is when all the three bunds are in action. But the impact of only upstream bund is very less, in fact minimum of all the interventions.

Also, between the two downstream bunds, the down-most downstream bund, which is close to the outlet of the watershed, has more impact on the well than the downstream bund closer to the well and farer from the outlet. But the difference in these impacts is not as much as difference between downstream and upstream bunds.

This shows that, *in this situation* the downstream bunds are more effective in obstructing the flow and creating a catchment like situation underground, and the well falls in this catchment area.

The above table only shows the impact on the well in the last time step of simulation. It will be interesting to see how the well heads change with respect to time over the dry period. Following graph shows this:

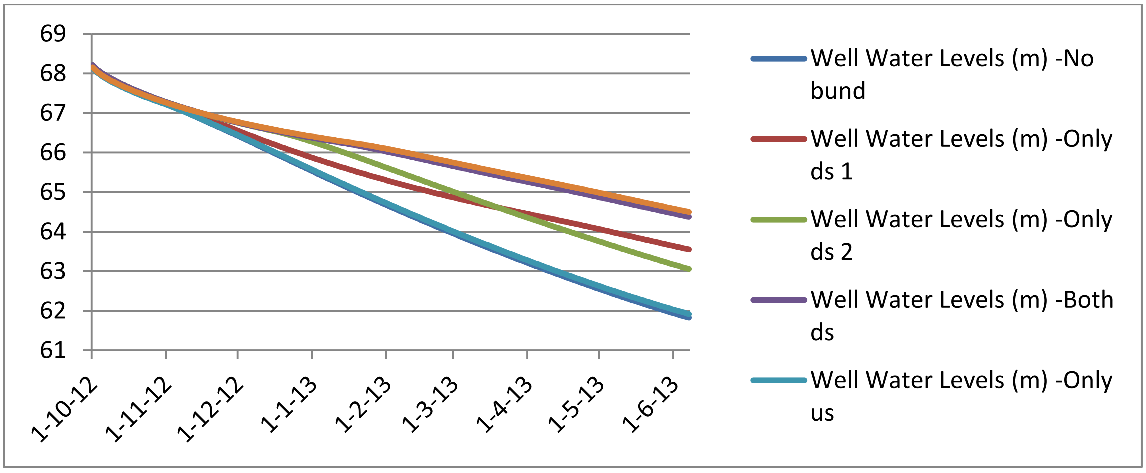


Figure 5-4: Well water levels

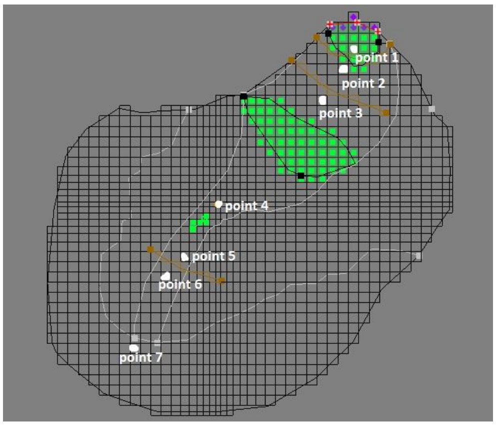
The interesting thing in the above graph is the crossing of trends between effects of downstream bund 1 and downstream bund 2 which occurs in mid-March. This may mean that the catchment created by downstream bund 2 i.e. the one which is closer to the well and is at just higher elevation (by 3m) than downstream bund 1 empties the water a little earlier than the catchment of downstream bund 1. This means that the effect of downstream bund 1 lasts longer than downstream bund 2.

5.5.2 Impact on other points in watershed:

It will be more interesting to see the effects of all the interventions at different points in the watershed. Following points were considered:

Table 12: Points in watershed - Ikharichapada

Point no.	Description and elevation
1	Closes to the outlet at elevation 62m
2	Between downstream bund 1 and downstream bund 2 at elevation 65m
3	Between well and downstream bund 2 at elevation 65m
4	Well at elevation 70m
5	Between well and upstream bund at elevation 75m
6	Just above upstream bund at elevation 75m
7	Farthest from the outlet at elevation 85m



The plots for all the points were studied. The most interesting points were point 2 and point 3 i.e. the point between both downstream bunds and the one between well and downstream bund 2. The plots clearly explain the picture of underground dams created due to both the bunds.

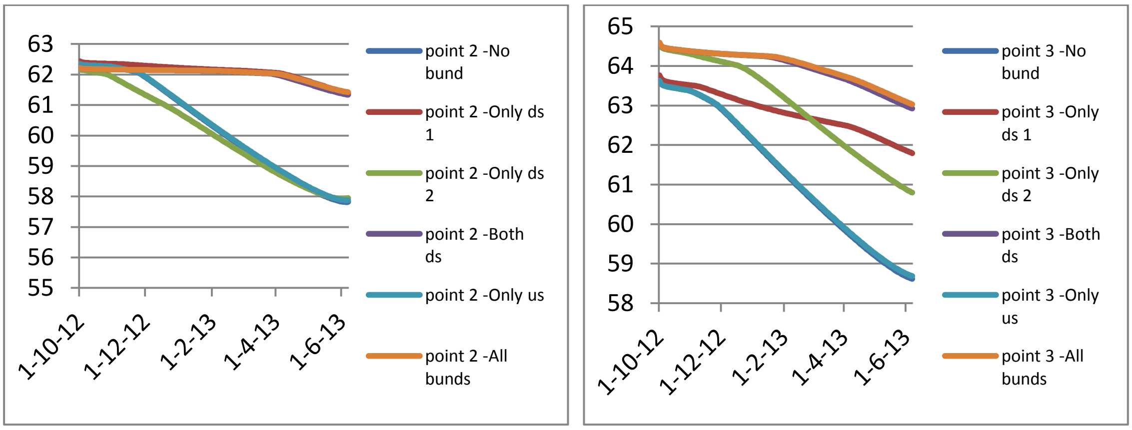


Figure 5-5: Head comparison for points 2 and 3

It is clearly seen that the graph downstream bund 1 and downstream bund 2 again cross. The explanation for this is the same; the zone of influence of downstream bund 2 is less than that of downstream bund 1. That is, the temporary storage space created by downstream bund 1 is more than that of downstream bund 2 and hence more water is obstructed by downstream bund 1 i.e. the bund closer to the outlet. This fact is clearly seen in the graph for point 2. The heads are constantly high till the ends of March after which they start dropping, although not much.

Following are the plots for points 5, 6 and 7; point 5 between upstream bund and well, 6 just above upstream bund and 7 far above upstream bund.

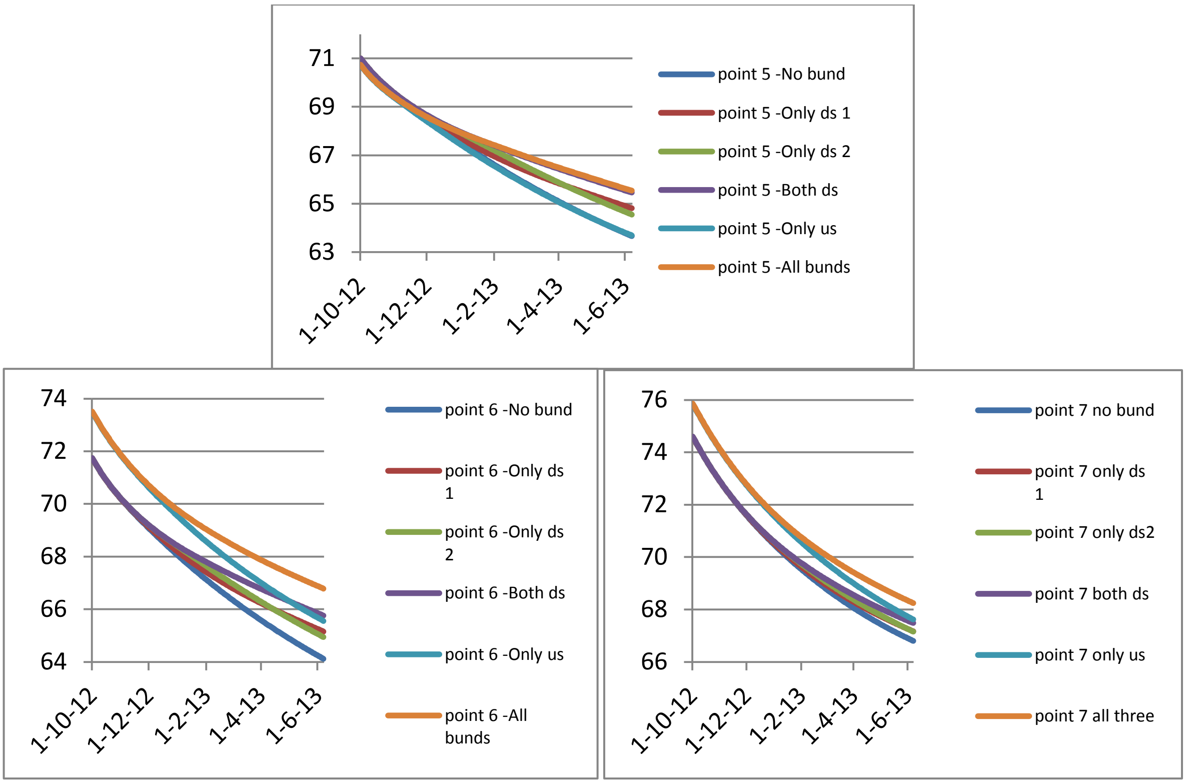


Figure 5-6: Head comparison for points 5, 6 and 7

Plots for point 5 show that this point comes in the shadow region of the upstream bund. As the upstream bund starts obstructing the flows, the heads at this point start reducing and finally at the end of the dry season, the head at this point are less than the head in “no bund” scenario.

For points 6 and 7, the heads are high on day 1 due to the temporary storage created by the upstream bund and in the scenario of only upstream bund, these points end up with higher heads than all other scenarios except the “all three bunds” scenario. This tells two things: firstly, the effect of upstream bund on these points is positive and secondly the zone of influence of both downstream bunds combined is so large that it reaches the farthest point in the stream too.

One thing coming out of these plots is that the main duty of slowing down the groundwater flows in order to extend the life of well is not well performed by the upstream bund. The upstream bund works in exactly similar fashion as that of downstream bunds. Hence only the points upstream of upstream bund will be benefited.

5.5.3 Impact on net water storage –

The flow budget i.e. output from GMS simulation for each scenario and for all days was studied. The flow budget contains the term, rate of change of storage into the system per day.

The 1st day i.e. 1st Oct 2012 shows the steady state output i.e. no storage. This state gives the equilibrium conditions prevailing in monsoon. These conditions are the starting conditions for the coming dry period. This steady state gives value of recharge based on recharge rate entered and the total area of the watershed. This total recharge becomes the storage for the transient state i.e. dry period. This storage reduces as the time progresses. The rate of decrease of the storage for all the scenarios was plotted and is as follows:

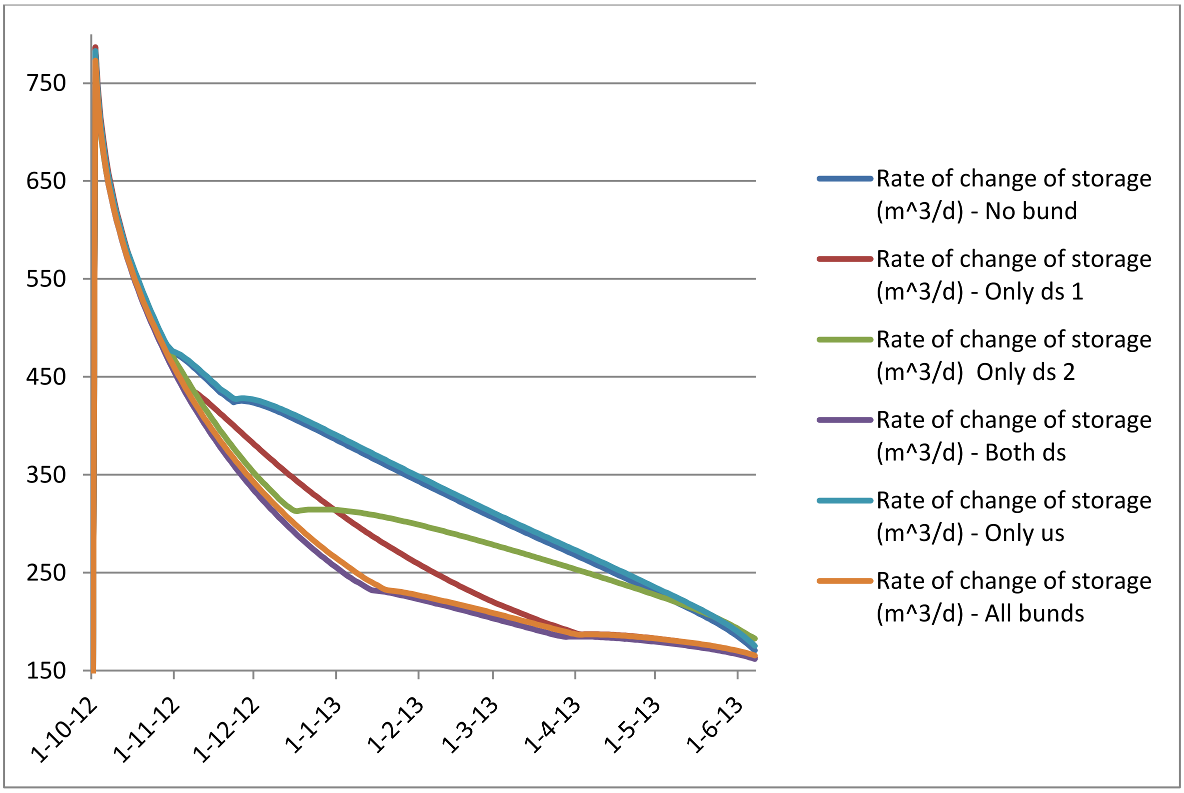


Figure 5-7: Comparison - Rate of change Storage In

The area under each curve is the net storage of water flown out of the watershed for that particular intervention. That means, the lower the area, lesser is the amount of water lost i.e. more effective intervention and larger the area under curve, more is the water lost, less effective is the intervention.

Thus, it is clearly observed that the upstream bund is as good as no bund or no intervention. It does not help in increasing the net water storage. It just regulates the water in watershed with respect to space and time, and the effects are not good for the well as it falls in its shadow region.

The maximum water harvested or stored is when both the downstream bunds are in action. In that also, the downstream bund closer to outlet proves to be more effective than the one farer from outlet.

The above results were quantified as follows:

$$Total\ area\ of\ watershed = 403596.4\ m^2$$

$$Total\ no.of\ cells\ in\ watershed\ model = 1319$$

$$Average\ area\ of\ each\ cell = 305.9866\ m^2$$

$$Net\ water\ stored\ in\ each\ cell$$
$$= Average\ area\ of\ each\ cell\ \times height\ of\ water\ column\ at\ that\ cell$$

This net water stored for all cells at time step 1 minus the net water stored for all cells at the last time step would give the total amount of water lost. These were calculated for all the scenarios and were compared. Then considering the “no bund” scenario as the base condition, the net increase in water storage in other scenarios was calculated. The results are shown in following graph:

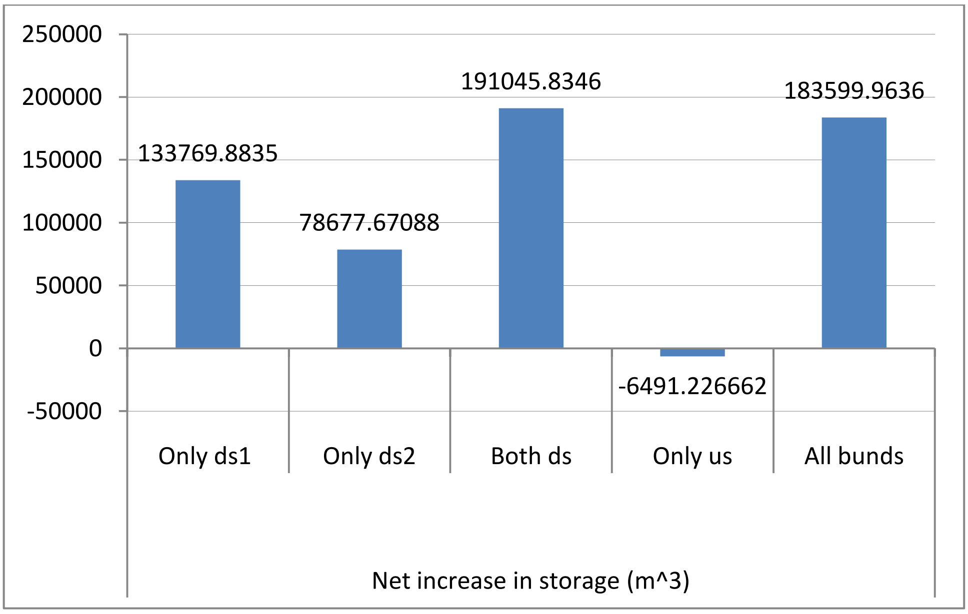


Figure 5-8: Comparison - Net increase in storage

The above graph shows the total amount of water increased in the watershed due to that particular intervention. It can be seen that in case of upstream bund, there is actually a decrease in total amount of water stored.

One important point to be noted is about the significance of the barrier properties. The barrier i.e. subsurface bund used in the model had hydraulic characteristic of 0.04 (0 meaning completely impermeable, 1 meaning no barrier). The value of 0.04 is quite low. This means the barrier is almost leak-proof. The effect of this on the total water stored in the watershed would be pretty high. In real scenario, even if the barrier is made of cement concrete there will be leakages from around the barrier, which are not considered here for now. This will be taken care of in future work.

Chapter 6 – Conclusions

With the help of key observations on field like location of springs and water-logging, no-flow boundaries, well withdrawal rates etc. and secondary data like contour and elevation data of the terrain, rainfall data, specific yield, specific storage, porosity for vesicular and compact basalts, a conceptually correct groundwater flow model of the Ikharichapada watershed was developed in GMS after series of refinements, iterations and adjustments in order to find values of unknown variables like hydraulic conductivity and thickness of layers for matching the on-field conditions.

The model was run for different scenarios of watershed interventions of sub-surface bunds. The model showed that in the current scenario, the water level in the well has risen, which matches with the field data. Thus, the model with its constraints and approximations showed that the interventions done in Ikharichapada are successful.

The model in its current form cannot justify the variation in rise of water in the well for the last two years i.e. two years post intervention as the model has assumed only single homogeneous subsurface layer which is not the case in reality. The model needs to be further refined to match the on-field conditions in order to predict the effectiveness of the intervention more accurately.

Regarding the individual effects of the bunds, downstream subsurface bunds seem to be more effective in increasing the net storage of water in watershed as well as extending the life of well, while the upstream subsurface bunds proved to be far less effective (in fact had negative impact) on the well.

Such a conceptual model can be useful in modelling other watershed interventions like contour trenches, check dams etc.

Chapter 7 – Future Work

The conceptual model developed in this stage of the project will be verified by actual observations and monitoring on the field. The main parameters required to be verified are:

Soil conductivity in the stream bed – This can be done in-situ with the help of Augerhole method as well as in laboratory by putting soil samples under various hydraulic experiments.

Shifting to multiple layers – Measurements would be carried out using Electrical Resistivity surveys or advanced method like Multi-electrode Resistivity Imaging to get information regarding geological layers, their thickness and their hydrogeological properties.

Verification and monitoring of the constant heads condition at the outlet – This would be done by digging trial pits or boreholes. Similar trial pits or boreholes should be dug at few other points to monitor heads throughout the dry season

Monitoring of well water levels – This will be done by local trained people.

Barrier properties – The actual hydraulic characteristic of the barrier needs to be calculated i.e. the effectiveness of the subsurface bund and its quality should be taken into account. Currently the hydraulic characteristic was taken as 0.04 which means the bund is almost leak-proof. The bund material (i.e. cement concrete) needs to be checked for its leak-proof behaviour, and at the same time, the chances of water getting diverted due to the bund need to be checked.

Once the field observations are obtained, the model will be refined to run for the exact situations and will give more accurate results. One more watershed in the same region will be chosen (where the watershed intervention is planned by the NGO AROEHAN) and the model will be applied to that watershed to verify whether the planned intervention is effective or not.

Towards larger objective –

Based on the overall process of developing a conceptual model and then refining it to match with the field conditions, a simple and easy-to-follow protocol can be developed for replicating such analysis for some other water harvesting structures.

This protocol can be used to assess and evaluate technical soundness of unit watershed interventions like trenches, bunds, check dams etc. In order to develop such a protocol, a framework for technical analysis needs to be developed which may consist of low cost softwares, models and practices which can be effectively used by regional agents including government officials and local engineers.

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