A report on

MODELING OF ARSENIC TRANSPORT IN GROUNDWATER USING MODFLOW

Submitted in the partial fulfilment of the requirements for the award of degree of

MASTER OF TECHNOLOGY
(Environmental Engineering)

by

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2015-2016

ACKNOWLEDGEMENTS

Any accomplishment requires the efforts of many people and this work is no exception. I appreciate the contribution and support which various individuals have provided for the successful completion of this study. It may not be possible to mention all by name but the following were singled out for their exceptional help.

First and foremost, I would like to express my deepest gratitude to my project supervisor ***Prof. S.K. Singh****, Department of Environmental Engineering, Delhi Technological University, for his valuable guidance, support, motivation and encouragement during the project work, without which the completion of the work would have been impossible.*

I am highly obliged and pay my gratitude to the ***Central Groundwater Board (CGWB)****, Kolkatta;* ***State Water Investigation Directorate (SWID)****, Kolkata and* ***Public Health Engineering Department (PHED)****, Kolkata for providing me the required data without which this work would have been impossible.*
I am grateful to ***Mr. S.K. Sinha*** *and* ***Mr. Rajesh Chandra****, Central Ground Water Board, Faridabad for their generous help and inspiring guidance during the study.*

I would like to thank my family members for supporting and helping me at every step of life. Their sincere blessings and wishes have enabled me to complete my work successfully. I am also thankful to my friends Sparsh Jain and Sourabh Batra for their unconditional support and motivation during this work. Above all thanks to the God, for the blessings that has been bestowed upon me in all my endeavors.

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CERTIFICATE

This is to certify that Ms. SHUCHITA GARG, M. Tech. student in the Department of Environmental Engineering has submitted a project report on "MODELING OF ARSENIC TRANSPORT IN GROUNDWATER USING MODFLOW" in partial fulfillment of the requirement for award of degree of Master of Technology in Environmental Engineering, during the academic year 2015-16.

It is a record of the student's research work prepared under my supervision and guidance.

Professor S. K. Singh
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Declaration of Originality

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I declare that this is the true copy of my/our report, including all revisions, as approved by my advisor and supervisor, and that this report has not been submitted for any other degree to any other University or Institution.

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Abstract

Groundwater plays an important role in India’s economy. According to World Bank study, the contribution of groundwater to India’s GDP is estimated to be 9%. This resource has gained importance as a source of drinking water and food security. Dependence on this resource has also increased due to its availability and less risk to pollution than the surface water.

Groundwater development has been intensive in alluvial areas of Indo Gangetic plains. This intensive development in many areas has given rise to a number of problems including social and public health. One such grave problem is arsenic menace in groundwater of Gangetic plains in West Bengal. The arsenic pollution in West Bengal has been described as world’s biggest calamity.

Numerical modeling has emerged as an effective tool for managing groundwater resources and predicting future responses, especially when dealing with complex aquifers systems and heterogeneous formations. Groundwater flow models solve for the distribution of heads, whereas solute transport models solve for concentration of solute as affected by advection, dispersion and chemical reactions. A MODFLOW and MT3D model has been simulated to understand the movement of water and Arsenic in English Bazar block of Malda district, West Bengal. A 3-dimensional groundwater flow and contaminant transport model has been developed considering semi-confined unconfined aquifer system.

Reduction of iron oxyhydroxide (FeOOH) and release of its sorbed arsenic load to solution is an important mechanism by which Arsenic enters groundwater. In the Bengal Basin of Bangladesh and West Bengal (India), it is the main mechanism by which arsenic pollutes groundwater.

Arsenic is present in very high concentrations in certain pockets of the study area with respect to average concentration of the panchayat. These high concentration pockets have been taken as the point source of arsenic for the study area. Simulation was performed for the movement of arsenic for every 120 days for a stretch of 1080 days. The time concentration outputs of the model were recorded by observation wells placed at a distance of 1000 m for all the localized pockets. Distribution of arsenic in the different soil layers were presented in the form of contour maps for the study area at the end of every year for a time period of three years. It was observed that the distribution of arsenic in the sand and coarse sand layers was more uniform in comparison to the sandy clay layer. Arsenic concentration recorded at observation boreholes showed a marginal increase over time for the coarse sand layer. It is known that the potential aquifers in the study domain are present in the depth range of 44 - 69 m and 73 -89 m where coarse sand and gravel is encountered. Therefore, even marginal rise in arsenic concentration for the bottom most layer might be a major cause of concern for people surrounding high arsenic concentration pocket areas. Areas along the flow direction are at much greater risk to the rise in arsenic concentration than the lateral ones.

Keywords: arsenic contamination, groundwater, contaminant transport, English Bazar block, West Bengal

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Chapter 1 INTRODUCTION

1.1 OVERVIEW OF GROUNDWATER

Groundwater is one of the important elements of environment which is indispensable for life. It is an essential natural resource for secure and economic provisioning of drinking water. Groundwater plays a vital role in the well-being of a human. It is used for various purposes like - domestic, agricultural, industrial etc.

Groundwater may be visualized as occurring in a subsurface reservoir, the boundaries of which are formed by adjacent less permeable or impermeable geological materials. The reservoir may be open everywhere to the land surface (unconfined), or it may be capped in large part by impermeable or relatively impermeable geological materials (confined).

Groundwater plays a crucial role as a decentralized source of drinking water for millions rural and urban families. According to some estimates, it accounts for nearly 80 per cent of the rural domestic water needs, and 50 per cent of the urban water needs in India. Groundwater is generally less susceptible to contamination and pollution when compared to surface water bodies. Also, the natural impurities in rainwater, which replenishes groundwater systems, get removed while infiltrating through soil strata. But, in India, where groundwater is used intensively for irrigation and industrial purposes, a variety of land and water-based human activities are causing pollution of this precious resource. Increasing demand for water, a growing use of pesticides and fertilizers, atmospheric deposition and numerous point sources of contamination constitute a threat to the quality of groundwater. Over-exploitation of groundwater is causing aquifer contamination in certain instances, while in certain others its unscientific development with insufficient knowledge of groundwater flow dynamic and geo-hydro chemical processes has led to its mineralization.

1.2 GROUNDWATER CONTAMINATION

The instance of groundwater contamination and quality of groundwater has become key issues since last few decades. Widespread usage of pesticides, fertilizers, toxic chemicals in industry and in manufactured products has magnified the toxicity for plants, animals and society. Contaminants that can dissolve in groundwater will move along with the water, potentially to wells used for drinking water. A combination of moving groundwater and a continuous source of contamination can, therefore, pollute very large volumes and areas of groundwater. The presence and the transport of contaminants constitute a potential threat to human health and ecosystem.

1.3 GROUNDWATER REMEDIATION

Groundwater remediation is a process for cleaning up or containing contamination. The technologies that are used to remediate groundwater are designed in such a way that it minimizes its impact on environmental or human receptors by treating air, water or soil pathways through a chemical or mechanical process. To prevent human health and/or the environment from the risk of chemical exposure, remediation technologies are used.

Chemicals can be removed through remedial technologies from the air, soil or water pathways in either of the two ways

(1) The process in which a chemical is broken down into a less toxic chemical. Example: enhanced bioremediation and thermal oxidation.

(2) The process where the toxicity of a chemical is reduced to a level so that it no longer poses a threat to the environment or humans. Example: soil-vapor extraction, pump-treat methods, air-stripping etc.

1.4 GROUNWATER MODELING

A groundwater model is a mathematical tool designed to represent a simplified version of the chemical, physical and biological processes taking place in a real field site. It is usually, a computer-based approximation of observed groundwater behavior. Groundwater modeling requires the development of a good and simplified geometry, aquifer properties and source / sink terms of the system as is achievable.

Groundwater models are imperative in the study of groundwater flow and contaminant transport. To setup a groundwater transport model, the first part of modeling involves the development of a groundwater model that adequately simulates the groundwater flow observed in long term monitoring. The second phase of model development involves the pairing of groundwater flow model with contaminant transport model.

1.5 ARSENIC CONTAMINATION OF GROUNDWATER

The alarming rate at which arsenic contamination in groundwater has been observed over the last few years is becoming a matter of great concern. Arsenic contamination is a worldwide health problem due to its toxicity and the fact that it occurs at unhealthful levels in water supplies, particularly groundwater, in more than 70 countries (Ravenscroft et al., 2009).

Arsenic contamination of drinking water is a worldwide problem due to its damaging effects on health. These effects range from skin ailments to serious and dangerous diseases such as cancer. Continuing exposure to arsenic can cause damage to the human cardiovascular, gastrointestinal, dermal, hepatic, pulmonary, renal, neurological, reproductive system and respiratory systems (ATSDR, 2000; Mandal and Suzuki, 2002). The regulatory limit of arsenic was set at 50ppb for Bangladesh, India, UK and USA, but the adverse effects of continuous arsenic exposure led WHO to lower their recommended limit to 10ppb.

1.6 OBJECTIVES OF THE STUDY

The Present study has the following objectives:

- To simulate water and arsenic movement using a 3D solute transport model.
- To study variation of hydraulic heads in the groundwater of English Bazar Block, Malda district, West Bengal using MODFLOW.
- To study distribution and movement of arsenic in the groundwater of English Bazar Block, Malda district, West Bengal using MT3D.

Chapter 2 LITERATURE REVIEW

2.1 GROUNDWATER CONTAMINATION

Ground water contamination is the presence of certain pollutants in ground water that are in excess of the prescribed limits. The commonly observed contaminants include arsenic, fluoride, nitrate and iron, which are geogenic in nature. Other contaminants include bacteria, phosphates and heavy metals which are a result of human activities including domestic sewage, agricultural practices and industrial effluents. The sources of contamination include pollution by landfills, septic tanks, leaky underground gas tanks, and from overuse of fertilizers and pesticides.

We are well aware that groundwater is one of the important elements of environment which is indispensable for life. Despite groundwater's important function to society, adequate protection is not provided to these resources (*Foster et al. 2002*). Slow movement of water through the ground means that residence times in groundwater are generally longer than surface water. Thus, once groundwater gets polluted, it can remain so for several decades, or even for hundreds of years until they can be cleaned if cleaning was actually possible. Cleaning and restoring contaminated groundwater pose many technical problems and is very expensive. Also, finding an alternative source of water supply is not always possible (*Lindström et al. 1995*).

Vulnerability assessment provides a basis for initiating protective measures for important groundwater resources and will normally be the first step in a groundwater pollution hazard assessment and quality protection, when the interest is at the municipal or provincial scale (*Foster et al. 2002*).

All groundwater resources are not valued equally, and thus the protection of any groundwater resource depends on multiple factors. The actual use of groundwater, its potential for future supply, other alternatives for water supply and its importance for other ecosystems and landscapes being a few of them (*Scharp et al. 1997).*

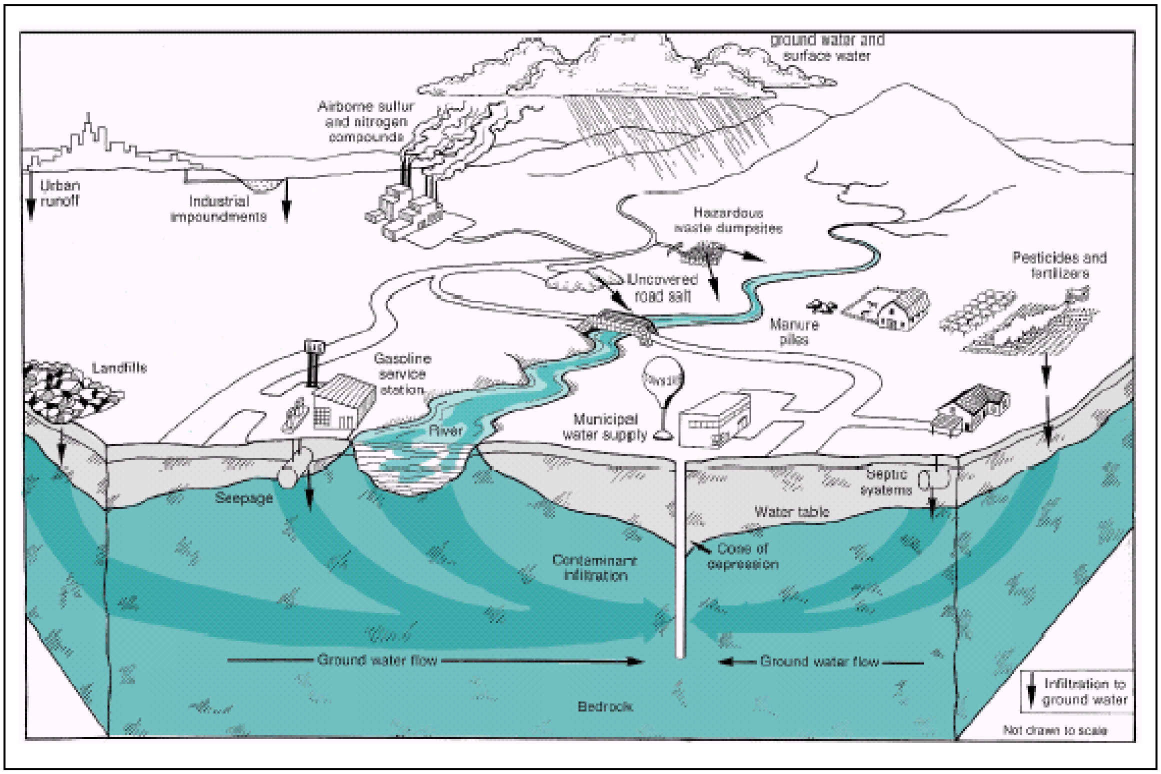

Figure 2.1 Groundwater contamination through various processes

The ideal way to prevent groundwater contamination is by controlling potential contaminants, so that they don’t come in contact with groundwater at all.

2.2 ARSENIC CONTAMINATION OF GROUNDWATER

2.2.1 Arsenic - General Information

Arsenic is a natural constituent of the earth’s crust and is the 20th most abundant element. The average concentration of arsenic in the continental crust is 1–2 mg/kg（Taylor and McLennan, 1985). Arsenic (As) is a metalloid element (atomic number 33) with one naturally occurring isotope of atomic mass 75, and four oxidation states (-3, 0, +3, and +5). In the aqueous environment, the +3 and +5 oxidation states are most prevalent, as the oxyanions arsenite (H_3AsO_3 or $H_2AsO_3^-$ at pH ~9-11) and arsenate ($H_2AsO_4^-$ and $HAsO_4^{2-}$ at pH ~4-10) (Smedley and Kinniburgh, 2002). Arsenic is widely distributed in nature and principally occurs in the form of inorganic or organic compounds. In soils, arsine gases may be generated by fungi and other related micro-organisms. Different forms of arsenic have different toxicities, with arsine gas being the most toxic form of the inorganic oxyanions, arsenite are the most toxic forms and arsenate, the less toxic forms. Arsenite is more toxic (approximately ten times) than the arsenate due to the former’s ability to react with sulfhydryl groups thereby increasing the residence time (Nagarnaik et al., 2002).The organic (methylated) arsenic forms are considered least toxic.

Table 2.1 Physical Properties of Arsenic

Physical Properties	Values
Molecular Weight	74.92
Valence	3, 5
Boiling Point	Sublimes at 612 °C
Melting Point	817.0 °C at 28 atm
Vapour Pressure	1.0mm Hg at 372 °C
Density / Specific Gravity	5.727 at 14 °C

Exposure to inorganic compounds may occur in a number of ways through certain industrial effluents, pesticides, chemical alloys and combustion of fossil fuels, wood preservative agents, occupational hazards in mining and dissolution in drinking water. The most commonly found arsenic compounds in drinking water are arsenate or arsenite. Although the anthropogenic source of arsenic contamination is increasingly becoming important, it should be noted that the recent episode of extensive arsenic contamination of groundwater in Bangladesh and West Bengal is of geological origin, transported by rivers from sedimentary rocks in the Himalayas over tens of thousands of years, rather than anthropogenic.

2.2.2 Global scenario

Arsenic contamination is a worldwide health problem due to its toxicity and the fact that it occurs at unhealthful levels in water supplies, particularly groundwater, in more than 70 countries (Ravenscroft et al., 2009) of six continents. High Arsenic concentrations have been reported from USA, China, Chile, Columbia, Bangladesh, Taiwan, Mexico, Argentina, Poland, Brazil, Zimbabwe, Canada, Hungary, Japan and India. Among the various countries in different parts of the world affected by groundwater Arsenic contamination, the largest population at risk is in Bangladesh followed by West Bengal in India (Mahan and Pittman, 2006).

Reliable information on arsenic vulnerability and health effects are seldom available, but it is clear that in many nations of the world, arsenic in drinking water has been observed at concentrations greater than the WHO guideline value i.e. 10 µg/L (0.01 mg/l) or the prevailing national standards. The major issue of arsenic contaminated water is to find out the level of contamination and it is not so easy because of no colour, no odour and no taste even in the highly contaminated water.

2.2.3 Arsenic Contamination of Groundwater in India

The presence of arsenic in groundwater in India is one of the most serious health hazard. In India, arsenic is of geological nature. It is mostly believed that rocks containing arsenic eroded from the Himalayas and deposited in the Gangetic plains, which later got buried in the sediments over thousands of years. These arsenic-bearing sediments form parts of the aquifers that are presently being tapped for water resources. Arsenic may be released in the groundwater by reduction of the iron oxy-hydroxides by reducing microorganisms.

The "Committee on Estimates 2014-15", that reviewed the occurrence of high arsenic content in ground water witnessed that 68 districts in 10 states are affected by high arsenic contamination in groundwater. These states are Punjab, Haryana, Bihar, Uttar Pradesh, Jharkhand, Chhattisgarh, Assam, Manipur, West Bengal and Karnataka.

As per the information furnished by Ministry of WR, RD & GR, presence of high arsenic in ground water has been reported from various districts of States as indicated below:

Table 2.2 Arsenic Concentration in Different districts of India

S. No.	**Name of the State**	**Districts partly affected by arsenic in ground water** **(above 0.05 mg/L)**
1	Assam	Sivsagar, Jorhat, Golaghat, Sonitpur, Lakhimpur, Dhemaji, Hailakandi, Karimganj, Cachar, Barpeta, Bongaigaon, Goalpara, Dhubri, Nalbari, Nagaon, Morigaon, Darrang and Baksha.
2	Bihar	Begusarai, Bhagalpur, Bhojpur, Buxar, Darbhanga, Katihar, Khagaria, Kishanganj, Lakhisarai, Munger, Patna, Purnea, Samastipur, Saran and Vaishali
3	Chhattisgarh	Rajnandgaon
4	Haryana	Ambala, Bhiwani, Faridabad, Fatehabad, Hissar, Jhajjar, Jind, Karnal, Panipat, Rohtak, Sirsa, Sonepat and Yamunanagar
5	Jharkhand	Sahibgunj
6	Karnataka	Raichur and Yadgir
7	Manipur	Vishnupur, Thoubal

8	Punjab	Mansa, Amritsar, Gurdaspur, Hoshiarpur, Kapurthala and Ropar
9	Uttar Pradesh	Bahraich, Balia, Balrampur, Bareilly, Basti, Bijnor, Chandauli, Ghazipur, Gonda, Gorakhpur, Lakhimpur Kheri, Meerut, Mirzapur, Muradabad, Raebareli, Santkabir Nagar, Shajahanpur, Siddharthnagar, Unnao, Sant Ravidas Nagar
10	West Bengal	Bardhaman, Hoogly, Howrah, Malda, Murshidabad, Nadia, North -24 Parganas and South -24 Parganas

2.2.4 Arsenic in Ground Water of West Bengal

In terms of arsenic concentration and areal coverage, Bengal basin is one of the major arsenic affected region in the world (**Henke** 2009). The occurrence of high Arsenic in ground water was first reported in 1978 in West Bengal in India. The most affected areas are on the eastern side of Bhagirathi river in the districts of Malda, Murshidabad, Nadia, North 24 Parganas and South 24 Parganas and western side of the districts of Howrah, Hugli and Bardhman (*Ahamed et al., 2006).* Arsenic in ground water is confined mainly in the aquifers upto 100 m depth. The deeper aquifers are free from Arsenic contamination. At present about 162.6 lakh people (35.48% of the total population of the state) live in the risk zone of potential threat in terms of Arsenic related diseases.

Based on the Arsenic concentrations found in the 19 districts of West Bengal, these districts have been classified into three categories: Severely affected, mildly affected, and Arsenic safe (*Sengupta et al., 2009).*

Nine districts (Malda, Murshidabad, Nadia, North-24 Parganas, South-24 Parganas, Bardhaman, Howrah, Hoogly and Kolkata), were more than 300 µg/L Arsenic concentrations were found in tubewells are categorized as severely affected. The five districts (Koch Bihar, Jalpaiguri, Darjeeling, North Dinajpur and South Dinajpur) where the contaminated tube wells show Arsenic concentrations mostly below 50 µg/L (only a few above 50 µg/L but none above 100 µg/L), termed as mildly affected. The rest five districts (Bankura, Birbhum, Purulia, Medinipur East and Medinipur West), where all the recorded concentrations were below 10 µg/L termed as unaffected or Arsenic safe.

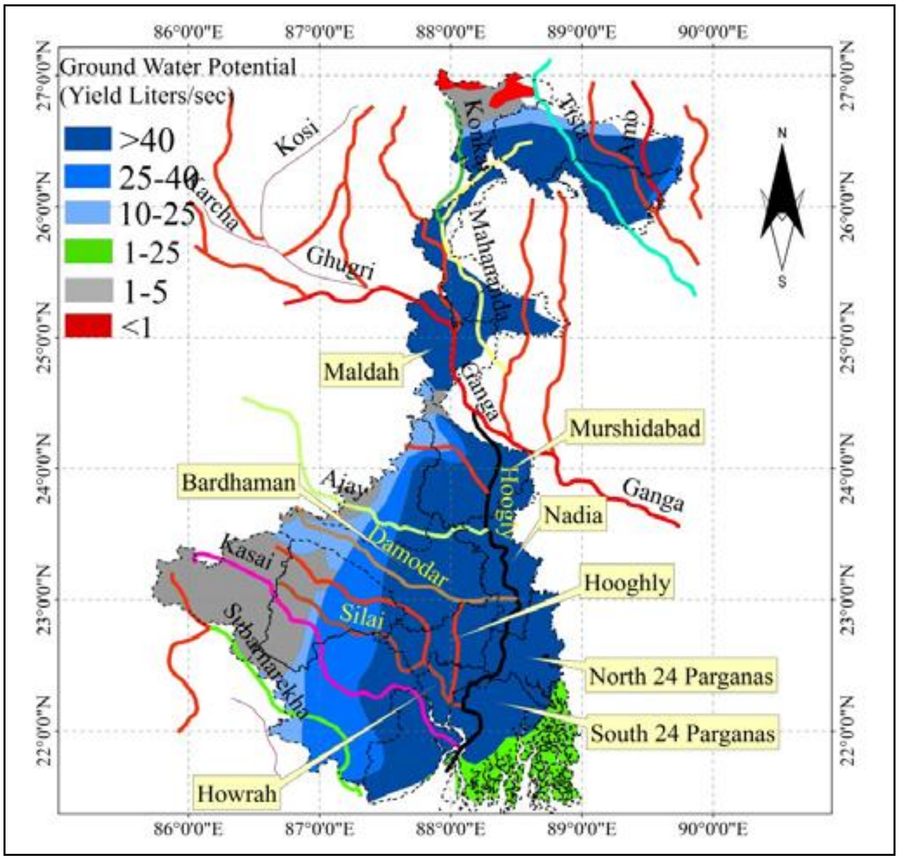

Fig. 2.1 Arsenic exposed districts in West Bengal (Source: Arsenic Mitigation Report, 2015)

Table 2.3 Arsenic Concentration in Different districts of West Bengal

Districts	**Arsenic Concentration in mg/L**
South 24 Parganas	0.06-3.20
North 24 Parganas	0.06-1.28
Malda	0.05-1.434

Nadia	0.05-1.00
Murshidabad	0.05-0.90
Burdwan	0.10-0.50
Howrah	0.09
Hooghly	0.6

Source: Planning Commission of India (2007)

Table 2.4 Arsenic Concentration in blocks of Malda district, West Bengal

District	Name of Blocks affected with High Arsenic	Maximum Value of Arsenic in mg/L
Malda	English Bazar	0.945
	Kaliachak- I	0.747
	Kaliachak- II	0.917
	Kaliachak- III	1.045
	Manickchak	0.944
	Ratua - I	0.894
	Ratua – II	0.333

Source: Ground Water Quality in Shallow Aquifers of India (2010)

Table 2.5 Extent & Magnitude of Arsenic Problem in West Bengal

S. No.	Physical Parameters	West Bengal
1.	Area in sq. km.	88,750
2.	Population in million (up to December 2005)	80.2
3.	Total number of districts (no. of district surveyed)	19(19)
4.	Total number of water samples analysed	1,40,150
5.	% of samples having arsenic > 10 µg L^{-1}	48.1

6.	% of samples having arsenic > 50 µg L^{-1}	23.8
7.	No. of severely arsenic affected districts	9
8.	No. of mildly arsenic affected districts	5
9.	No. of arsenic safe districts	5
10.	Total population of severely arsenic affected 9 districts in million	50.4
11.	Total area of severely arsenic affected 9 districts in sq. km.	38,861
12.	Total number of blocks/ police station	341
13.	Total number of blocks/ police station surveyed	241
14.	Number of blocks / police station having arsenic >50µgL^{-1}	111
15.	Number of blocks / police station having arsenic >10µgL^{-1}	148
16.	Total number of village	37910
17.	Total number of village surveyed	7823
18.	Number of villages/Paras having arsenic above 50 µgL^{-1}	3417
19.	People at risk of drinking arsenic contaminated water >10 µgL^{-1} (in million)	9.5
20.	People at risk of drinking arsenic contaminated water >50 µgL^{-1} (in million)	4.6
21.	No. of districts surveyed for arsenic patients	9
22.	No. of districts where arsenic patients found	7
23.	People screened for arsenic patients including children (preliminary survey)	96,000
24.	No. of adults screened for arsenic patient	82,000
25.	Number of registered patients with clinical manifestations	9,356 (11.0%)

26.	No. of children screened for arsenic patient	14,000
27.	No. of children showing arsenical manifestation	778 (5.6%)
28.	Total hair, nail, urine analysed	39624
29.	Arsenic above normal/toxic level in hair, nail and urine samples	91%, 97% and 92%

Source: Sengupta et al. (2009)

2.2.5 Harmful Effects of Arsenic

Consumption of arsenic affected water for longer period of time gives rise to different health issues which may vary from general to severe. The toxic effect of arsenic species depends mainly on their chemical form, route of entry, age, sex, doses and duration of exposure. Contaminated food or drinking water is the major cause behind arsenic toxicity. In the initial stage, the symptoms of arsenic poisoning are non-specific and are general in nature like nausea/vomiting and limb pain. With the increase in exposure over time the health issues became more prominent like thickening and pigmentation (black and white) of skin. In severe cases the symptoms like keratosis and carcinoma of skin develop. Sometimes, when the severity of the problem increases, internal organs like kidney and liver also get adversely affected. The last stage is the development of cancer and amputation of body parts.

2.2.6 Determining Exposure to Arsenic

Urine can be tested for arsenic up to a week after the exposure. Arsenic can also be measured in hair and fingernails within a few months of exposure. The results of arsenic urine tests may be misleading if seafood, marine fish or ocean-derived vitamin supplements have been taken in the past five days. If a person suspect's high arsenic exposure, tests that monitor the functioning of the liver and kidneys should be done. A doctor can carry out these tests on blood samples.

2.2.7 Sources of Arsenic in Ganga–Brahmaputra Aquifers

The hypotheses about the sources of arsenic in the Bengal Delta Plain are as follows:

1. It is transported by the river Ganga and its numerous tributaries from the Rajmahal trap which is situated in the western segment of the basin (Saha et al. 1991, Acharyya et al. 2000).
2. It is conveyed through the north Bengal tributaries of Bhagirathi and Padma Rivers from the eastern Himalayas (Ray et al. 1999).
3. It is mainly transported through the fluvial sediments from the Himalayas (McArthur et al. 2004). This is the most accepted hypothesis at present.

2.2.8 Theories of Arsenic Mobilization

Among few hypotheses proposed to explain the possible mechanism of arsenic groundwater contamination, most scientists have settled down to two hypotheses: (i) oxidation of arsenopyrite or arsenic rich pyrite in soil strata, and (ii) reductive dissolution of arsenic from soils. However, based on arsenic geochemistry, three hypotheses describing probable mechanisms of Arsenic mobilization in groundwater specially, with reference to Holocene aquifers like in West Bengal and Bangladesh, have been suggested (Bose and Sharma, 2002). These are:

i. Mobilization of arsenic due to the oxidation of As-bearing pyrite minerals: Insoluble As-bearing minerals, such as Arsenopyrite (FeAsS), are rapidly oxidized when exposed to atmosphere, releasing soluble As (III), sulfate (SO_4^{2-}), and ferrous iron (Fe^{2+}). The dissolution of these As-containing minerals is highly dependent on the availability of oxygen and the rate of oxidation of sulfide. The released As (III) is partially oxidized to As (V) by microbial mediated reactions. The chemical reaction is given by:

$$FeAsS + 13\,Fe^{3+} + 8\,H_2O \rightarrow 14\,Fe^{2+} + SO_4^{\,2-} + 13\,H^+ + H_3AsO_4\ (aq.)$$

ii. Dissolution of As-rich iron oxyhydroxides (FeOOH) due to onset of reducing conditions in the subsurface: Under oxidizing conditions, and in the presence of Fe, inorganic species of

As are predominantly retained in the solid phase through interaction with FeOOH coatings on soil particles. The onset of reducing conditions in such environments can lead to the dissolution of FeOOH coatings. Fermentation of peat in the subsurface releases organic molecules (e.g., acetate) to drive reducing dissolution of FeOOH, resulting in release of Fe^{2+}, As^{+3}, and As^{+5} present on such coatings. The chemical reaction is given by:

$$8FeOOH - As_{(s)} + CH_3COOH + 14\ H_2CO_3 \rightarrow 8\ Fe^{2+} + As_{(d)} + 16\ HCO^{3-} + 12\ H_2O$$

Where, $As_{(s)}$ is sorbed As, and $As_{(d)}$ is dissolved As.

iii. Release of As sorbed to aquifer minerals by competitive exchange with phosphate (H_2PO^{4-}) ions that migrate into aquifers from the application of fertilizers to subsurface soil.

The second mechanism involving dissolution of FeOOH under reducing conditions is considered to be the most probable reason for excessive accumulation of As in groundwater.

2.2.9 Technological Options to combat arsenic menace

Technological options to combat arsenic menace, in groundwater, to ensure supply of arsenic free water, in the affected areas, can be one of the followings or a combination of all:

i) In-situ remediation of arsenic from aquifer system,

ii) Ex-situ remediation of arsenic from tapped groundwater by arsenic removal technologies,

iii) Use of surface water source as an alternative to the contaminated groundwater source,

iv) Tapping alternate safe aquifers for supply of arsenic free groundwater.

2.2.10 Mitigation measures taken by the government to combat the problem

To combat the situation, Government of India set up Arsenic Task Force and Department of drinking water Supply. The following types of w ork have so far been undertaken for arsenic mitigation.

a) New Hand Pump fitted in deeper aquifer,
b) Set up Arsenic Treated Units (ATU),
c) Ring wells at upper aquifer,
d) Piped Water Supply Schemes with pond water as resource,
e) Surface water based Piped Schemes.

Efforts by Government of West Bengal-

a) All the arsenic affected villages to be covered by piped water supply schemes.
b) Attempts are made to cover the affected areas with surface water wherever available.

Some Surface water based piped schemes with river as source in west Bengal are-

a) For Malda district with river Fulhar and Bhagirathi as source.
b) For South and North 24 Parganas river Hooghly as source.
c) For Murshidabad river Bhagirathi as source.

i) **Arsenic Removal Plant (ARP) Fitted directly with Hand Pump**: This has been developed by PHED, Govt. of West Bengal. Due to this Plant around 250,000 population in the arsenic affected districts viz., Murshidabad, South 24 Parganas, Malda are benefitted.

ii) **Arsenic Removal Plant for piped water supply scheme:** There are three such plants constructed by the Government of West Bengal out of State Action Plan as on 31st March 2002 at Sujapur, Kaliachak block of Malda district, Dhaititha, Basirhat block of North 24 Parganas district.

2.3 APPLICATIONS OF MODFLOW

Majumdar et al. (2002) used MODFLOW, MT3D and MODPATH in the Nadia district of West Bengal to conceptualize the groundwater flow domain, to determine groundwater flow paths and groundwater velocities, to study arsenic transport in the flow domain, and to study the well captures zones for the study area.

Abu-El-Sha'r W. Y. & Hatamleh R. I. (2007) used MODFLOW and MT3D as a management tool for the Azraq basin in Jordan. Five suggested scenarios of pumping with different abstraction rates have been explored by using MODFLOW to simulate the flow system, and MT3D to predict the transport of total dissolved solids given in terms of Electric Conductivity.

Surinaidu et al. (2014) used MODFLOW 2005 to estimate the groundwater inflows into Srirampur underground coal mines located in Adilabad district of Andhra Pradesh at different mine development stages to design an optimal groundwater withdrawal schemes for dewatering mine pits for safe mining.

Renganathan et al. (2015) used Visual MODFLOW to assess groundwater contamination in unsewered area of Alandur, Chennai. This study aims to find out the prevailing groundwater contamination issues due to improper disposal of domestic waste. Visual Modflow was used to find out the flow direction and to estimate the groundwater contaminant movement. Nitrate was taken as pollutant parameter to study the groundwater contamination.

Duriez, S. (2005) simulated a groundwater contaminant transport model for the Wockatz site, in eastern Göteborg, using Groundwater Modelling System (GMS) software. Groundwater modeling was carried out for the particular scenario where the upper layer of contaminated filling material was replaced by clean soil with more or less the same hydraulic characteristics.

Ehteshami et al. (2014) used PMWIN 5.3 to simulate the flow and transport of contamination in Mashhad aquifer. Simulation techniques were used to assess the magnitude of the groundwater contamination with nitrate. Collected field data were used to calibrate and verify the model to predict groundwater status. The simulated and observed measured data showed that the model was able to predict the ground water quality changes within the aquifer.

Mondal, N.C. & Singh, V.S. (2009) carried out modelling of pollutant migration in Tannery belt, Dindigul by applying Visual MODFLOW. The study involves construction of mass transport model for understanding the behavior of pollutant migration. The study concluded that the migration phenomenon is mainly through advection rather than dispersion.

Calderon and Bentley (2007) studied the groundwater flow system and effects of groundwater development using numerical groundwater flow model (Visual MODFLOW), for Leon-Chinandega, unconfined aquifer located in the agricultural plain in northwest Nicaragua. The study involves simulation of groundwater flow using transient and steady-state numerical models. The study results indicated that pumping induces decrease in base flow and depleting river discharge, which becomes critical during dry periods, when irrigation is highest. Transient state model results indicated that the response time of the aquifer is about one hydrological year. The study reveals that numerical groundwater flow model can be a useful tool for management of water resources.

Molykutty et al (2005) developed a regional mass transport model for upper Palar river using Visual MODFLOW. In this study, the groundwater flow model was developed to find out the hydraulic heads and velocity of flow of groundwater in the basin. The concentration of TDS in the groundwater for various scenarios was presented using mass transport model.

Gurunadha Rao and Gupta (2000) studied the contamination of groundwater in one of the water supply wells near Sabarmati railway bridge due to Duff-nala stream of Shahibaug on the eastern periphery of the river, sewage discharge from slum pocket on the western periphery and another sewage discharge from hutments south of the French well. In this study, combined groundwater flow and mass transport model under two different scenarios were constructed using Visual MODFLOW software and groundwater velocities using porosity values in the MODPATH program. Mass Transport Model (MT3D) was used to determine contaminant migration from sources towards the French well. The model results confirmed the migration of contaminants towards the well.

El Fakharany et al. (2013) used Visual MODFLOW and MT3D models as a management tool for forecasting the future changes in groundwater levels and quality of the south-eastern part of the Nile Delta aquifer. Three suggested scenarios of pumping with different abstraction rates for years 2000 through 2030 were explored by Visual MODFLOW (version 3.0) and MT3D models. MT3D was used to investigate the mass transport of total dissolved solids, SO_4, Na, Cl, Fe, Mn, Al and NO_3.

Chapter 3 GROUNDWATER PROPERTIES & MECHANISMS AFFECTING SOLUTE TRANSPORT IN GROUNDWATER

3.1 GROUNDWATER PROPERTIES

Groundwater is characterized both by its vertical and its horizontal distribution. Vertically, groundwater is divided in two main parts: saturated and unsaturated (or vadose) zone. These two parts are generally separated by the water table. The horizontal distribution of subsurface water depends on several parameters that are characteristics from the porous medium and groundwater. These parameters determine the rate and the direction of groundwater flow.

3.1.1 Porosity

The porosity of a medium is the proportion of the non-solid volume to the total volume of material, and is defined by the ratio:

$$\Theta = \frac{Vp}{Vm} \tag{3.1}$$

Where

θ = porosity of the medium

V_p = the non-solid volume (pores and liquid) [L^3]

V_m = the total volume of material, including the solid and non-solid parts [L^3]

In the saturated zone, which occurs beneath the water table, the porosity is a direct measure of the water contained per unit volume. Porosity is a fraction between 0 and 1, typically ranging from less than 0.01 for solid granite to more than 0.5 for peat and clay. It averages about 0.25 to 0.35 for most aquifer systems (Wikipedia, 2005).

3.1.2 Hydraulic Conductivity, Transmissivity and Intrinsic Permeability

Hydraulic conductivity, K [L.T^{-1}], is a property of the soil that 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.

Transmissivity, T [L^{2}.T^{-1}], is a measure of how much water an aquifer can transmit horizontally. It depends on the aquifer's saturated hydraulic conductivity, K_s, and on the saturated thickness of the aquifer b.

$$T = K_s \times \mathrm{b} \tag{3.2}$$

Because of their high porosity and permeability, sand and gravel aquifers have higher hydraulic conductivity than clay or unfractured granite aquifer. Sand or gravel and gravel aquifers would thus be easier to extract water from, because of their higher transmissivity, than clay or unfractured granite aquifers (Wikipedia, 2005). Typical values for aquifers would be 10^{-4} m.s^{-1} for sand, 10^{-6} m.s^{-1} for silt and 10^{-7} cm.s^{-1} for clay (Bedient *et al*, 1999).

Permeability is a measure of the ability of soil to transmit fluids through it. The intrinsic permeability k [L^{2}] of a soil is a property of the medium only, independent of fluid properties. It can be related to hydraulic conductivity K by:

$$K = k\left(\frac{\rho g}{\mu}\right) \tag{3.3}$$

Where

μ = dynamic viscosity [M.L^{-1}.T^{-1}]

ρ = fluid density [M.L^{-3}]

g = the gravitational constant [L.T^{-2}]

3.1.3 Storage Coefficient

The storage coefficient *S* is defined as the volume of water that an aquifer releases from or takes into storage per unit surface area per unit change in piezometric head. For a confined aquifer, values of *S* fall in range of 0.00005 to 0.005, indicating that large pressure changes produce small changes in the storage volume. The storage coefficient for an unconfined aquifer typically ranges from 0.07 to 0.25 (Bedient *et al*, 1999).

3.1.4 Groundwater Flow

The first experimental study of groundwater flow was performed by Henry Darcy in 1856 (Fetter, 1998). He found that, for a one-dimensional flow, the flow rate of water through porous media is proportional to the cross-sectional area and to the head loss along the path, and inversely proportional to the length of the flow path. Darcy's law can be expressed as:

$$Q = -KA\frac{dh}{dl} \tag{3.4}$$

Where

Q = volumetric discharge of water [L^3.T^{-1}]

K = hydraulic conductivity [L.T^{-1}]

A = cross sectional area [L^2]

$\frac{dh}{dl}$ = gradient of hydraulic head [$L.L^{-1}$]

3.1.5 Flow Nets

Darcy's law was originally derived for one dimension, but because many groundwater problems are really two- or three-dimensional, graphical methods are available for the determination of flow rate and direction. A specified set of streamlines and equipotential lines can be constructed for a given set of boundary conditions to form a flow net in two dimension, as shown on Figure 3.1 (Bedient *et al*, 1999).

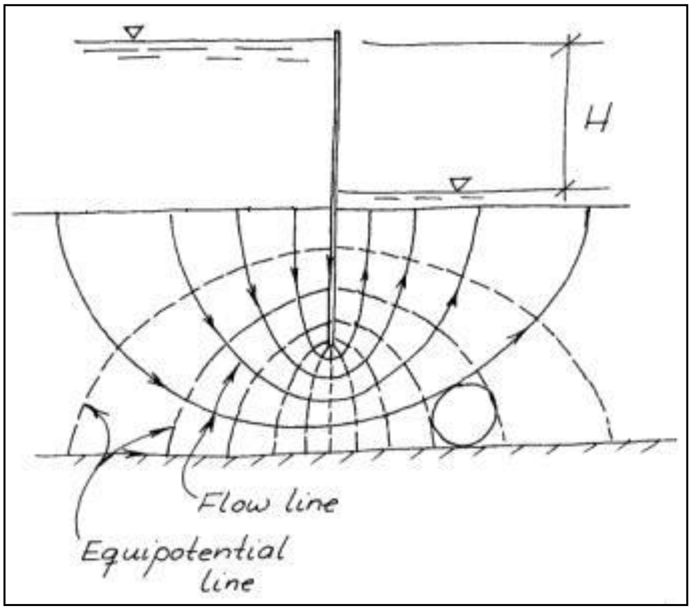

Fig. 3.1 Example of flow net (source: Broms, 1992).

3.2 CONTAMINANT TRANSPORT PROCESSES IN SATURATED MEDIA

The mechanisms which decide the movement of the contaminant in the aquifer are known as transport mechanisms. The most important mechanism affecting solute transport is Advection, Diffusion, Dispersion, Sorption and Biodegradation.

3.2.1 Transport by Advection

Advection is defined as the movement of a solute with the flowing groundwater. The mass flux of dissolved contaminant that is being transported depends on its concentration in groundwater and on the quantity of groundwater flowing. For a one-dimensional flow normal to a cross-sectional area of porous media, this quantity of groundwater equals the average linear velocity times the effective porosity. Thus, for a one-dimensional flow, the mass flux F_x [$M.T^{-1}.L^{-2}$] is given by the following equation:

$$Fx = v_x n_e C \tag{3.5}$$

Where

v_x = average linear velocity [$L.T^{-1}$]

n_e = effective porosity

C = solute concentration [$M.L^{-3}$]

The average linear velocity v_x is the rate at which the flux of water across the unit cross-sectional area of porous media occurs. It is given by the following equation:

$$v_x = \frac{K}{n_e}\frac{dh}{dl} \tag{3.6}$$

Where

K = hydraulic conductivity [L.T^{-1}]

dh / dl = hydraulic gradient [L.L^{-1}]

The average linear velocity is thus equal to the Darcy velocity divided by the effective porosity associated with the porous medium through which water can flow.

3.2.2 Transport by Diffusion

Molecular diffusion describes the movement of a solute in water from an area of higher concentration to an area of lower concentration. Diffusion occurs as long as a concentration gradient exists, even if the fluid is not moving, causing spreading and random motion. The mass of fluid diffusing follows the Fick's first law, which is, in one dimension, given by:

$$F = -D_d \frac{dC}{dx} \tag{3.7}$$

Where

F = mass flux of solute per unit area [M.T^{-1}.L^{-2}]

D_d = diffusion coefficient [L^{2}.T^{-1}]

C = solute concentration [M.L^{-3}]

dC / dx = concentration gradient [M.L^{-3}.L^{-1}]

Values of D_d are specific for each pollutant and are, among others, temperature-dependent.

If the concentrations are changing with time, Fick's second law applies, which is, in one dimension:

$$\frac{\partial C}{\partial t} = D_d \frac{\partial^2 C}{\partial x^2} \qquad (3.8)$$

Where,

$\partial C / \partial t$ is the change in concentration with time [$M.L^{-3}.T^{-1}$].

Since diffusion cannot proceed as fast in porous media as in water because of mineral grains, an effective diffusion coefficient D * [$L^2.T^{-1}$] has been introduced:

$$D^* = \omega D_d \qquad (3.9)$$

Where

ω is the tortuosity coefficient. Tortuosity allows to take into account the effect of the shape of the path followed by water through porous media.

3.2.3 Dispersion Process

3.2.3.1 Mechanical dispersion

Mechanical dispersion is the transport of a solute resulting from minor differences in groundwater velocity as it flows through heterogeneous porous media. When solutes in groundwater get in contact with water that does not contain a solute, mixing occurs along the flow path, resulting in a dilution of the solute at the advancing edge of flow. Mechanical dispersion can be broken down in two complementary dispersions: longitudinal dispersion (see Figure 3.3), which is the mixing that occurs along the direction of the flow path, and transverse dispersion, which is the mixing in directions normal to the flow path. Assuming that mechanical dispersion follows Fick's law for diffusion and that the amount of mechanical dispersion is a function of the average linear velocity, a coefficient of mechanical dispersion has been introduced. This coefficient is defined by:

Coefficient of longitudinal mechanical dispersion = $a_i v_i$ (3.10)

Where

v_i = average linear velocity in the principal direction of flow i [L.T^{-1}]

α_i = dynamic dispersivity in the principal direction of flow i [L]

and

Coefficient of transverse mechanical dispersion = $a_j v_i$ (3.11)

Where

v_i = average linear velocity in the principal direction of flow i [L.T^{-1}]

α_j = dynamic dispersivity in j direction [L]

Dynamic dispersivity is a property of the medium.

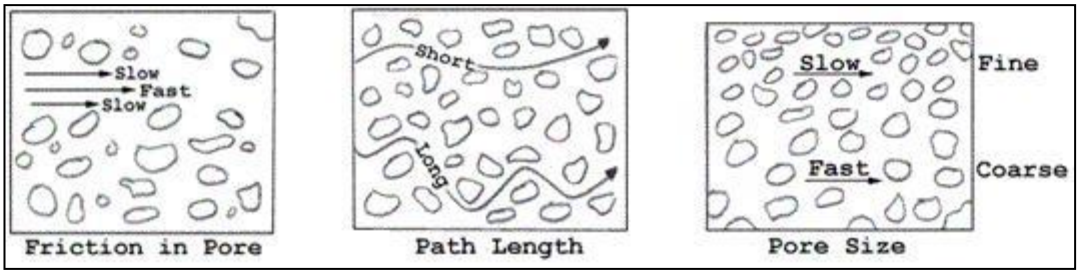

Fig. 3.2 Factors causing longitudinal mechanical dispersion (source: Cunningham, 2004).

3.2.3.2 Hydrodynamic Dispersion

Hydrodynamic is a combination of diffusion and mechanical dispersion in flowing groundwater. The hydrodynamic dispersion coefficient was introduced and defined as follows:

$$D_L = \alpha_L v_i + D^* \tag{3.12a}$$

$$D_T = \alpha_T v_i + D^* \tag{3.12b}$$

Where,

D_L = longitudinal hydrodynamic dispersion coefficient $[L^2.T^{-1}]$

D_T = transverse hydrodynamic dispersion coefficient $[L^2.T^{-1}]$

α_L = longitudinal dynamic dispersivity [L]
α_T = transverse dynamic dispersivity [L]

3.2.4 Linear or Non-linear Sorption

Sorption is defined as the association of a dissolved or gaseous contaminant with a solid material (Bedient *et al*, 1999). The term of sorption encompasses two more specific processes known as adsorption and absorption. Adsorption is the association of a contaminant with the surface of a solid particle. Absorption is the association of a contaminant within a solid particle. Sorption processes also include chemisorption and ion exchange. Chemisorption occurs when the solute is incorporated on solid particle surface by a chemical reaction. Cation exchange can occur when a cation is attracted to the region close to a negatively charges clay mineral-surface and held there by electrostatic forces. Anion exchange can occur at positively charged sites of iron and aluminum oxides sand the broken edges of clay minerals (Fetter, 1998). The reverse process of sorption is desorption. It is the dissociation of a sorbed molecule and its return to the aqueous or gaseous phase.

The condition of equilibrium is assumed to be existing between the solution-phase and solid -phase concentrations. As the sorption reaction is fast enough, it is generally assumed that it can be treated instantaneously as compared to groundwater velocity. The sorption isotherm is the functional relationship between the dissolved and sorbed concentrations. The integration of sorption isotherm into the transport model is generally through the use of the retardation factor.

Three types of sorption isotherms are considered in the MT3D transport model. These include Linear, Freundlich and Langmuir sorption isotherms.

The linear sorption isotherm assumes that the sorbed concentration ($\overline{C}$) is directly proportional to the dissolved concentration (C):

$$\overline{C} = K_d C \qquad (3.2.10)$$

Where

K_d is called the distribution coefficient [L^3M^{-1}]

The retardation factor is defined as

$$R = 1 + \frac{\rho_b}{\theta}\frac{\partial \overline{C}}{\partial C} = 1 + \frac{\rho_b}{\theta} K_d \qquad (3.2.11)$$

The Freundlich isotherm is a non-linear isotherm which is expressed as:

$$\overline{C} = K_f C^a \qquad (3.2.12)$$

Where

K_f is the Freundlich constant [L^3M^{-1}]^a

a is the Freundlich exponent [-].

Both *K* and *a* are empirical coefficients. When *a* is equal to 1, the Freundlich isotherm is equivalent to the linear isotherm. The retardation factor for the Freundlich isotherm is defined as:

$$R = 1 + \frac{\rho_b}{\theta}\frac{\partial \overline{C}}{\partial C} = 1 + \frac{\rho_b}{\theta} a K_f C^{a-1} \qquad (3.2.13)$$

Langmuir isotherm is another non-linear sorption isotherm, expressed as

$$\overline{C} = \frac{K_l \overline{S} C}{1 + K_l C} \tag{3.2.14}$$

Where

K_l is the Langmuir constant [L^3M^{-1}]

$\overline{S}$ is the total concentration of sorption sites available [MM^{-1}]

The retardation factor defined for the Langrnuir isotherm is then

$$R = 1 + \frac{\rho_b}{\theta} \frac{\partial \overline{C}}{\partial C} = 1 + \frac{\rho_b}{\theta} \left[\frac{K_l \overline{S}}{(1 + K_l C)^2} \right] \tag{3.2.15}$$

3.2.5 Biodegradation

Biodegradation of contaminants refers to complete conversion of a contaminant to mineralized end products (i.e. CO_2, H_2O and salts) through metabolism by living organisms. In groundwater system, the organisms that carry out this process are bacteria indigenous to the aquifer. In some cases, metabolic activity does change the chemical form of the contaminant but does not result in the mineralization. This processes are then called biotransformation.

Chapter 4 MODELING OF GROUNDWATER CONTAMINATION

4.1 INTRODUCTION TO GROUNDWATER MODELING

Groundwater modeling has become an integral part of many groundwater exploitation, protection, and remediation projects in the past few years. As computer hardware and software continue to be improved and become more affordable, the role of models in highly quantitative earth sciences is increasing accordingly. For proper interpretation and usage of any groundwater model, it is essential that its limitations are clearly understood. Apart from technical limitations, such as accuracy of computations (hardware / software), the following is true for any model:

- It is based on numerous assumptions regarding the real natural system being modeled,
- Hydrologic and Hydro-geologic parameters used by the model are always just an approximation of their actual field distribution which is difficult to be determined with 100% accuracy,
- Theoretical differential equations describing groundwater flow are replaced with systems of algebraic equations which are more or less accurate.

A groundwater model is a mathematical tool designed to represent a simplified version of the physical, chemical and biological processes taking place in a real field site. A groundwater-modeling component consists of a groundwater quantity model and a groundwater quality model. The groundwater quantity model is used to simulate groundwater movement in an aquifer. The groundwater quality model requires the output of the groundwater quantity model to simulate pollutant movement in the ground water system.

4.2 USE OF GROUNDWATER MODELS

Groundwater models can be used as:

1. **Predictive tools**: Here, the models are used to determine future conditions or the effect of a planned action on existing conditions in the subsurface. Predictive models are by far the largest group of models built in hydro-geologic practice.
2. **Interpretive or Research tools**: In this, the models are used for understanding system dynamics and processes.
3. **Generic or Screening tools**: Here, the models are used for the purpose of developing management principles and procedures. These models generally incorporate uncertainty in aquifer parameters.

4.3 DEVELOPING A GROUNDWATER MODEL

A groundwater flow model can be developed with the help of the following steps:

1. Develop a **Conceptual Model** based on the physical, chemical and biological processes, which will be governing the behavior of the system.
2. Translate the conceptual model into **Mathematical Model** i.e. a set of partial differential equations and an associated set of boundary conditions.
3. If the mathematical model is solved by analytical methods, the solution is **Analytical Model**. It is possible only for simple geometric, homogeneous aquifers and simple boundary conditions.
4. If the mathematical model is solved by numerical methods, the solution is **Numerical Models**.
5. If the numerical model is implemented by a computer program, it is the **Computer Model**.

Anderson and Woesser (1992) propose a modeling protocol that can be summarized as follows:

Step 1**:** Establishing the purpose of the model.

Typical objectives may include:

(a) To test a hypothesis about a given aquifer system.
(b) Understanding physical, chemical or biological processes.
(c) To design remediation systems.
(d) To predict impact of a proposed stress on the ground water system.
(e) Resource management.

Step 2**:** Developing a conceptual model of the system.

These may include the following steps:

(a) Define hydro-geologic features of interest (e.g. aquifer). The conceptual model may combine several geologic formations into a single unit or may subdivide a single formation into aquifers and confining units.

(b) Define the flow system, sources and sinks of water in the system. Sources or inflows may include recharge from infiltration, recharge from surface water bodies, or artificial recharge of groundwater. Sinks or outflows may include spring flow, base flow to streams, evapotranspiration, and pumping. Defining the flow system involves determining the direction of groundwater flow and the hydrologic interaction between the different modeled units.

(c) Define the transport system, sources and sinks of chemicals in the system. The conceptual model has to include a representation of the time variant chemical source concentration, mass or volume of spill, and the chemical / biological processes affecting those chemicals.

Step 3**:** Selecting the governing equation and a computer code. Both of these should be verified. Verification of the governing equation exhibits that it describes the physical, chemical and biological processes occurring. Code verification can be achieved by comparing the model results to an analytical solution of a known problem.

Step 4**:** Designing the model. This step comprises selection of a grid design, time parameters, initial and boundary conditions, and developing estimates of model parameters.

Step 5**:** Calibrating the design model. Calibration refers to the process of determining a set of model input parameters that approximates field measured heads, flow and/or concentrations. The purpose of calibration is to establish that the model can reproduce field-measured values of the unknown variable. It is noted that calibration is quite subjective and in many cases does not yield a unique set of parameters that reproduce field conditions.

Step 6**:** Determining the effect of uncertainty on model results. This is sometimes referred to as a sensitivity analysis. This is done by varying the model parameters individually within a range of possible values and noting down the results.

Step 7**:** Verifying designed and calibrated model. This step involves testing the models ability to reproduce another set of field measurements using the model parameters that developed in the calibration process.

Step 8**:** Predicting results based on calibrated model.

Step 9**:** Determining the effects of uncertainty on the model prediction.

Step 10**:** Presenting modeling design and results.

Step 11**:** Post auditing and redesigning the model as necessary.

4.4 TYPES OF ERROR

There are two main types of error.

4.4.1 Computational Error

These types of errors happen due to numerical approximation procedures which are used in solving the governing equations. Their estimation is done either by applying continuity equation or the principle of conservation of mass.

4.4.2 Calibration Error

This type of error occurs because of model assumptions and limitations in parameter estimation. The evaluation of these errors can be quantified by comparing the model’s predicted values with the observed values.

4.5 DRAWBACKS AND USEFULNESS OF THE MODELING

The main drawback of a model is that it requires large amount of data and it is too expensive to assemble and run. Also, models aren’t always correct. But for some people, model is a boon as it performs complex analysis and makes informed decisions. Furthermore, these models allow effective use of the available data and is essential for analyzing and evaluating the implications of proposed course of action at the field scale.

4.6 APPLYING NUMERICAL MODELS TO FIELD SITES

A good field data is necessary when a model is being used for simulating existing flow and/or contaminant conditions at a site or when it is used for predictive purposes. However, an attempt to model a system with inadequate data may be advantageous because it may serve as a method for identifying those areas where detailed field information needs to be collected.

Chapter 5 PROCESSING MODFLOW FOR WINDOWS (PMWIN)

5.1 INTRODUCTION

Processing Modflow was originally developed for a remediation project of a disposal site in the coastal region of North Germany. It was designed as a pre and postprocessor for the groundwater flow model MODFLOW. PMWIN offer a totally integrated simulation system for modeling groundwater flow and transport processes with MODFLOW-88, MODFLOW-96, PMPATH, MT3D, MT3DMS, MOC3D, PEST and UCODE. It comes complete with a professional graphical pre and postprocessor.

5.2 PACKAGES UNDER PMWIN

A brief summary of the various packages under PMWIN is given below:

5.2.1 MODFLOW

MODFLOW (*McDonald and Harbaugh, 1988*) supports the simulation of the effects of wells, rivers, reservoirs, drains, head-dependent boundaries, time-dependent fixed-head boundaries, cut-off walls, compaction and subsidence, recharge and evapotranspiration. In addition to these standard packages of MODFLOW-96, PMWIN includes the unique Density package for taking into account the density driven flow rates into flow models.

5.2.2 PMPATH

The PMPATH (*Chiang and Kinzelbach, 1994, 1998*) uses a semi-analytical particle tracking scheme to calculates and animates the particle tracking processes simultaneously and provides various on-screen graphical options including head contours, drawdown contours and velocity vectors. Both forward and backward particle tracking schemes are allowed for steady-state and transient flow fields.

5.2.3 MT3D

The MT3D (*Zheng, 1990*) uses a mixed Eulerian-Lagrangian approach to simulate changes in concentration of single species miscible contaminants in groundwater considering advection, dispersion and simple chemical reaction. The chemical reactions included in the model are limited to equilibrium controlled linear or non-linear sorption and first-order irreversible decay or biodegradation.

5.2.4 MT3DMS

The MT3DMS (*Zheng and Wang, 1998*) is a further development of MT3D. The abbreviation MS denotes the Multi- Species structure for accommodating add-on reaction packages. MT3DMS includes three major classes of transport solution techniques, i.e., the standard finite difference method; the particle tracking based Eulerian-Lagrangian methods; and the higher-order finite-volume TVD method. Up to 30 different species can be simulated with PMWIN.

5.2.5 MOC3D

The MOC3D (*Konikow, Goode and Homberger, 1996*) transport model uses the method of characteristics to compute changes in concentration of a single dissolved chemical constituent over time that are caused by advective transport, hydrodynamic dispersion (including both mechanical dispersion and diffusion), mixing or dilution from fluid sources, and mathematically simple chemical reactions, including decay and linear sorption represented by a retardation factor.

5.2.6 PEST and UCODE

The PEST (*Doherty, Brebber and Whyte, 1994*) and UCODE (*Poeter and Hill, 1998*) assist in data interpretation and in model calibration. If there are field or laboratory measurements, PEST and UCODE can adjust model parameters and/or excitation data in order that the discrepancies between the pertinent model-generated numbers and the corresponding measurements are reduced to a minimum. The following model parameters can be automatically calibrated: (1) horizontal hydraulic conductivity or transmissivity; (2) vertical leakance; (3) specific yield or confined storage coefficient; (4) pumping rate of wells; (5) conductance of drain, river, stream or head-dependent cells; (6) recharge flux; (7) maximum evapotranspiration rate; and (8) inelastic storage factor.

5.3 MODFLOW

MODFLOW, a modular three-dimensional finite difference groundwater flow model developed by the U. S. Geological Survey simulates saturated flow in three dimensions. MODFLOW is probably the most widely used, tested and verified model today because of its versatility and an open structure.

The “original” version of MODFLOW-88 was developed by Michael G. McDonald and Arlen W. Harbaugh in 1988. MODFLOW-88 and MODFLOW-96 can simulate the effects of wells, rivers, drains, head-dependent boundaries, recharge and evapotranspiration. Since the publication of MODFLOW numerous investigators have developed various codes. These codes are called packages, models or sometimes simply programs. Packages are integrated with MODFLOW, each package deals with a specific feature of the hydrologic system to be simulated, such as wells, recharge or river. Models or programs can be stand-alone codes or can be integrated with MODFLOW. A standalone model or program communicates with MODFLOW through data files. The advective transport model PMPATH, the solute transport model MT3D, MT3DMS and the parameter estimation programs PEST and UCODE use this approach. The solute transport model MOC3D is integrated with MODFLOW. This code uses MODFLOW as a function for calculating flow fields.

MODFLOW is coded in FORTRAN and requires a specific data input format. The major inputs required for running MODFLOW are:

- Model grid size and aquifer's thickness
- Horizontal and vertical hydraulic conductivity of the soil of the model area
- Recharge to aquifers (area and point source)
- Ground water boundary conditions

Boundary conditions for the modeled area could be established with a prior knowledge of the area. The types of boundary conditions MODFLOW uses are:

- Constant head boundary, e.g., a river or a reservoir
- No flow boundary, e.g., an impermeable layer such as mountain bedrock
- Constant flux, e.g., a constant flux of water, such as a stream inlet or ground water recharge from neighboring aquifers.

The major outputs from MODFLOW are the predicted ground water elevation or head for each grid cell in the model along with a water budget (mass balance) for each grid cell. These two outputs can be used as inputs to run MT3D.

A step-by-step explanation of the various parameters under MODFLOW package is given below:

5.3.1 Grid

MODFLOW uses the block-centered grid (Fig. 5.1) in which the model calculates the head at the center of each cell i.e. the node. It is assumed that hydraulic and hydrogeological properties are uniform over the extent of a cell so that the cell is represented by the node.

In MODFLOW the origin of the grid is in the upper left corner of the grid and the layers are numbered from top down. An aquifer system is discretized into a mesh of blocks, or cells, the locations of which are described in terms of rows (I), columns (J), and layers (K) as illustrated in Fig. 5.2.

The grid mesh can be uniform, when all the cells have same dimensions, and custom, when cell sizes varies. Although the uniform grid is preferred from a mathematical standpoint, it will often be necessary to design a custom grid. A rule of thumb when designing a custom grid is that the size of a cell, in all three directions (row, column, layer), cannot be more than 1.5 times larger (smaller) than the size of the adjacent cells. This is necessary in order to preserve the mathematical stability of the numerical solution.

5.3.2 Layer Type

There are four basic types of layers in MODFLOW:

- **Type 0:** This layer type is used to simulate confined conditions (layers / aquifers) in which transmissivity of each cell remains constant for the entire simulation time. For transient simulations this layer type requires the confined storage coefficient, which is used to calculate the rate of change in storage.

- **Type 1:** This layer type is used strictly for unconfined conditions and is valid for the first (uppermost) layer only. It requires specific yield for transient conditions. Transmissivity of the layer varies as saturated thickness of the aquifer changes during simulation.

- **Type 2:** This layer type is used when the aquifer alternates between confined and unconfined. However, it is assumed that the saturated thickness remains everywhere a high fraction of the layer thickness so that recalculation of transmissivity is not necessary. In transient simulations it is needed to specify both the storage coefficient for fully saturated confined conditions, and the specific yield for unconfined flow. If the layer completely desaturates, vertical leakage from above ceases.

- **Type 3:** This layer type is also used for confined unconfined transitions. It includes varying transmissivity, which is recalculated at each iteration using hydraulic conductivity and new saturated thickness. Confined storage coefficient and specific yield are both needed for transient simulations. Vertical leakage from above terminates when the layer is completely dry.

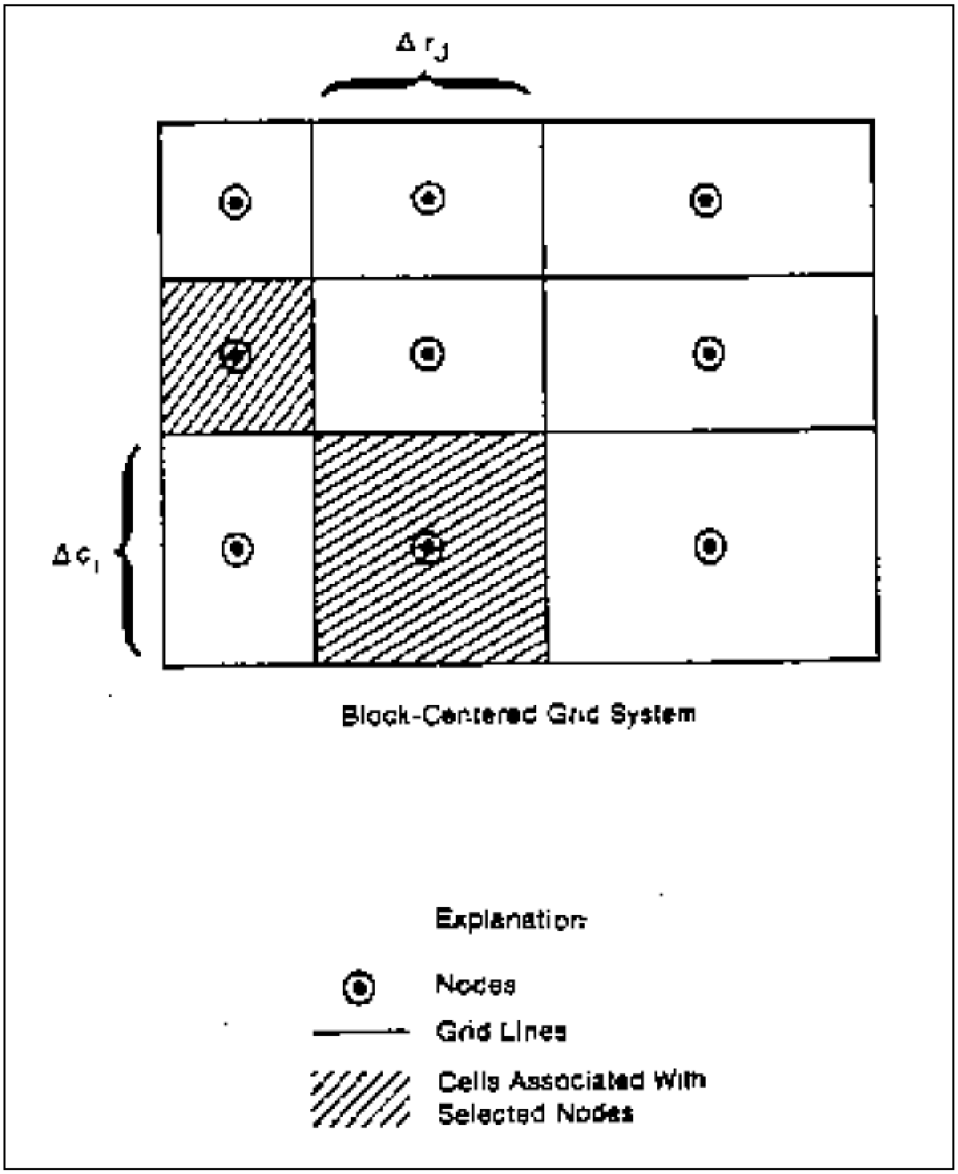

Fig. 5.1 Diagram showing Block Centered Grid System (after McDonald and Harbaugh, 1988)

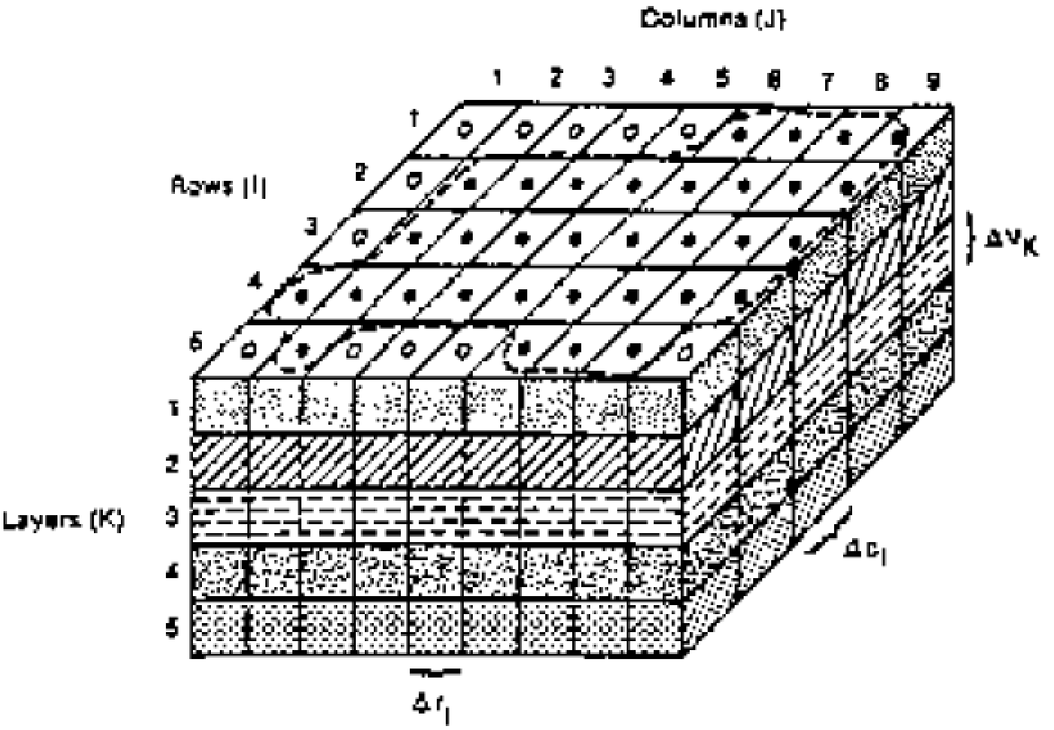

Fig. 5.2 Spatial discretization of an aquifer system (after McDonald and Harbaugh, 1988)

- - - - -	Aquifer Boundary
•	Active Cell
o	Inactive Cell
Δr_j	Dimension of cell along the row direction. Subscript (j) indicates the number of the column
Δc_i	Dimension of cell along the column direction. Subscript (i) indicates the number of the row
Δv_k	Dimension of cell along the vertical direction. Subscript (k) indicates the number of the layer

5.3.3 Boundary Condition

(1) IBOUND (MODFLOW)

An IBOUND array is required by the flow model MODFLOW. Three types of boundary conditions are possible in IBOUND

- An active cell denoted by 1, in which the hydraulic head is calculated by the model and are free to vary with time.
- A fixed-head cell denoted by -1, in which the hydraulic head is kept fixed at a given value such as aquifer contacts with major surface water features.
- An inactive cell denoted by 0, in which no flow into or out of the cell occurs during the entire time of simulation.

(2) ICBUND (MT3D)

An ICBUND array is required by the transport models MT3D and MT3DMS.

- An active concentration cell denoted by 1, in which the concentration varies with time and is calculated by the model.
- A constant concentration cell denoted by -1, in which the concentration is constant.
- An inactive concentration cell denoted by 0, in which no transport simulation takes place at such cells.

5.3.4 Layer Top and Bottom

The elevation of the layer top and bottom is required to calculate aquifer transmissivity, vertical leakance or confined storage coefficient.

5.3.5 Time

Time parameters are specified when modeling transient (time dependent) conditions. They include time unit, the length and number of time periods, and the number of time steps. During one time (stress) period all model parameters associated with boundary conditions and various stresses remain constant. A time period is further divided into time steps that are useful for analyzing changes in hydraulic head and drawdown. Time steps do not have to be of same length.

5.3.6 Initial Hydraulic Heads

MODFLOW requires initial hydraulic heads at the beginning of a flow simulation. For transient flow simulations, the initial heads must be the actual values. For steady-state flow simulations, the initial heads are starting guessed values for the iterative equation solvers. The heads at the fixed-head cells must be the actual values while all other initial heads can be set arbitrarily.

5.3.7 Horizontal Hydraulic Conductivity and Transmissivity

In MODFLOW the horizontal hydraulic conductivity is the conductivity along the grid rows. The hydraulic conductivity is required for layers of type 1 and 3 (unconfined conditions), and transmissivity is required for layers of type 0 and 2 (confined conditions). Most MODFLOW processors like PMWIN Pro can calculate transmissivity for a layer of any type by multiplying hydraulic conductivity with layer thickness derived from layer top and bottom elevations.

5.3.8 Vertical Hydraulic Conductivity and Leakance

For quasi-3D models with more than one layer and for full 3D models, MODFLOW requires the input of the vertical leakance between two layers. Processors such as PMWIN Pro can calculate the vertical leakance for each layer from the layer thickness and the vertical hydraulic conductivity. Unless accurately determined from pumping tests, the vertical hydraulic conductivity is usually assumed and/or calibrated.

5.3.9 Storage Terms

Confined storage coefficient for confined layers (layer type 0, 2, and 3) and specific yield for unconfined layers (layer type 1, 2, 3) are required only for transient simulations. The confined storage coefficient (S) is the product of the layer thickness (b) and specific storage (S_s)

$$S = b.S_s \tag{5.3.1}$$

5.3.10 Effective Porosity

The volume percentage of a rock or soil sample that consists of interconnected pores through which water can flow is the effective porosity. It is used by transport models, for example PMPATH, MOC3D, MT3D to calculate the average velocity of the flow through the porous medium.

5.3.11 MODFLOW Packages

(i) Density Package

In the Density Package developed by Schaars and Van Gerven (1997), the water density of a “density-layer” may differ from cell for cell. During a flow simulation the density-dependent flows will be adapted into the system of flow equations by correcting the hydraulic heads to equivalent fresh water heads (or reference density heads).

(ii) Drain Package

The Drain Package simulates both closed and open drains. It is one of the best tools to model springs since the inflow into the drain ceases when the head in the aquifer drops below drain elevation.

(iii) Evapotranspiration Package

The Evapotranspiration Package simulates the effects of plant transpiration and direct evaporation in removing water from the saturated groundwater regime. This package shows a linear variation in the water table elevation accounting for the user specified maximum and minimum (zero) depth of evapotranspiration.

(iv) General Head Boundary Package

The General Head Boundary Package is used for transient simulations of constant head boundaries since it allows the user to change the head from one time period to another. It can be used to simulate permanent surface water features.

(v) Horizontal Flow Barrier Package

The Horizontal-Flow Barrier Package developed by Hsieh and Freckleton (1993), simulates thin low-permeability geologic features, such as vertical faults or slurry walls that impede the horizontal flow of groundwater. These geologic features are approximated as a series of horizontal-flow barriers conceptually situated on the boundaries between pairs of adjacent cells in the finite-difference grid.

(vi) Interbed Storage Package

The Interbed Storage Package developed by Leake and Prudic (1991), calculates the water volume released from storage and simulates elastic and inelastic compaction of compressible fine-grained beds in an aquifer due to groundwater extraction. The term “interbed” is used to denote a poorly permeable bed within a relatively permeable aquifer. This package is used only for transient simulations.

(vii) Recharge Package

The Recharge Package is typically used to simulate areal infiltration from precipitation or irrigation. It can also simulate local recharge to ponds. It is flexible in assigning vertical flux to different layers along the vertical.

(viii) Reservoir Package

The Reservoir package developed by Fenske, Leake and Prudic (1996) can simulate leakage from reservoirs where the reservoirs are much greater in area than the area represented by individual model cells. More than one reservoir can be simulated using this package.

(ix) River Package

The River Package simulates the flow between an aquifer and a surface water feature in both directions. It includes riverbed conductance for simulating fine sediment clogging of a river channel. It should not be used for intermittent streams since there is no adjustment for the stream flow and stage once it drops below the channel bottom.

(x) Streamflow Routing Package

The Streamflow Routing Package developed by Prudic (1989), simulates interaction between an aquifer and a surface stream accounting for the flow rate in the stream. Flow into or out of the stream stops when the stream dries out. It requires intensive data preparation and more data input than any other package.

(xi) Time-Variant Specified-Head Package

The Time-Variant Specified-Head Package developed by Leake and Prudic (1988) is used in transient simulations and allows constant head cells to take on different head values for each time step during a simulation time period.

(xii) Well Package

The Well Package simulates both extraction and recharge wells. Negative cell values for the “Recharge rate of the well” are used to indicate pumping wells, while positive cell values indicate injection wells. It assumes full penetration of the layer.

(xiii) Block-Centered Flow 2 Package

The Block-Centered Flow 2 Package developed by McDonald, Harbaugh, Orr and Ackerman (1992) allows the simulation of a rising water table into unsaturated (dry) model layers. A typical application is the simulation of the recovery of over stressed aquifer, such as after heavy pumpage, either through artificial recharge or the reduction of stress.

5.3.12 Model Run

After the model parameters are assigned to each cell, to run the model the user must choose one of the solving packages. PMWIN Pro supports the following packages (solvers) for solving systems of simultaneous linear equations:

- The Direct Solution (DE45) package,
- The Preconditioned Conjugate-Gradient 2 (PCG2) package,
- The Strongly Implicit Procedure (SIP) package,
- The Slice-Successive Over relaxation (SSOR) package, and
- Geometric Multigrid Solver (GMG) package.

The number of model runs during calibration will depend on the quantity and quality of available data, desirable accuracy of the model results.

5.4 MATHEMATICAL MODEL OF MODFLOW

The three-dimensional movement of groundwater of constant density through porous earth material may be described by the partial differential equation:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)+W=S_s\frac{\partial h}{\partial t} \qquad (5.4.1)$$

Where,

K_{xx}, K_{yy}, K_{zz} are the values of hydraulic conductivity along the x, y and z coordinate axes, which are assumed to be parallel to the major axes of hydraulic conductivity [LT^{-1}];

h is the potentiometric head $[L]$;

W is the volumetric flux per unit volume and represent sources and / or sinks of water, with $W<0.0$ for flow out of the ground-water system, and $W>0.0$ for flow in [T^{-1}]

S_s is the specific storage of the porous material [L^{-1}]

t is the time $[T]$

A solution to equation (5.4.1) in an analytical sense, is an algebraic expression giving h(x,y,z) such that, when the derivatives of h with respect to space and time are substituted in equation (5.4.1), the equation and its initial and boundary conditions are satisfied. Except for very simple systems, analytical solution of equation (5.4.1) are rarely possible, so various numerical methods must be employed to obtain approximate solutions.

MODFLOW uses one such numerical method i.e. Finite Difference Method, wherein the continuous system described by equation (5.4.1) is replaced by a 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. The process leads to systems of simultaneous linear algebraic difference equations; their solution yields values of head at specific points and times. These values constitute an approximation to the time varying head distribution that would be given by an analytical solution of the partial difference equation of flow.

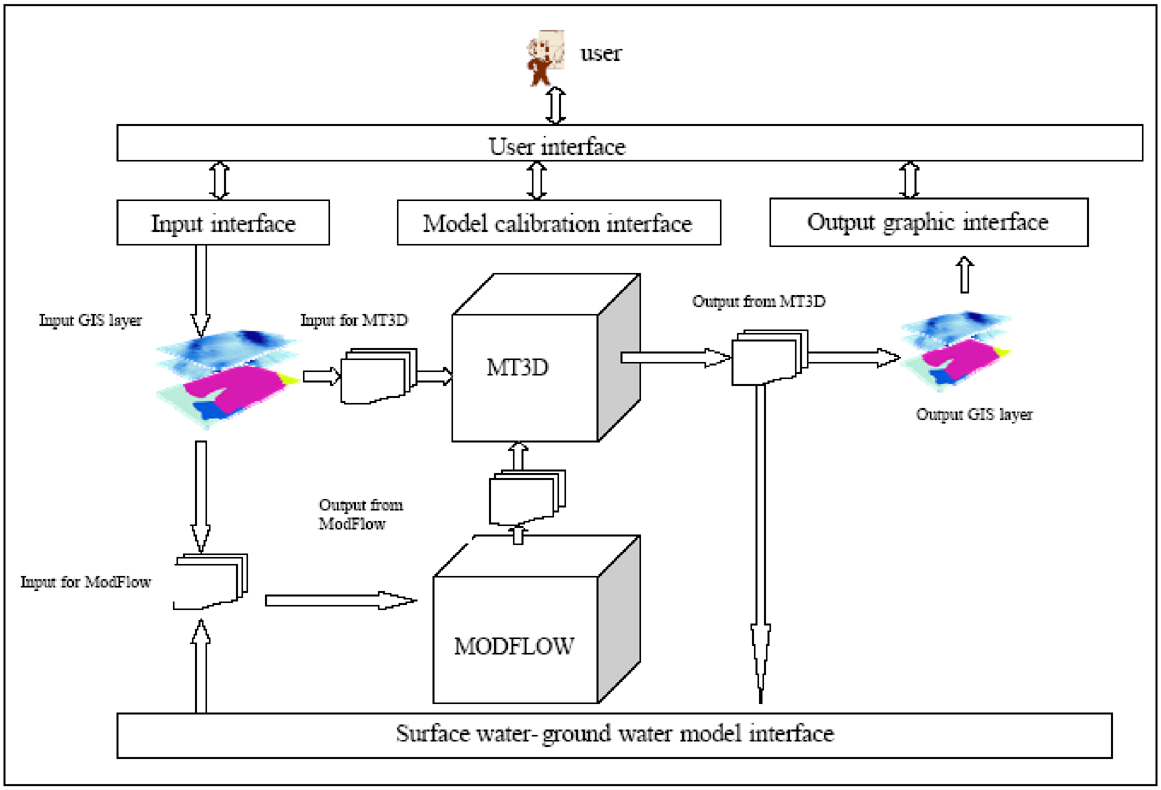

Fig. 5.3 Schematic structure of the ground water modeling component.

5.5 MT3D

MT3D, a Modular Three-Dimensional Transport Model developed by the U.S Geological Survey uses a mixed Eulerian-Lagrangian approach to the solution of the three-dimensional advective-dispersive-reactive transport equation. MT3D is based on the assumption that changes in the concentration field will not affect the flow field significantly. This allows the user to construct and calibrate a flow model independently. After a flow simulation is complete, MT3D simulates solute transport by using the calculated hydraulic heads and various flow terms saved by MODFLOW.

Currently, MT3D accommodates the following spatial discretization capabilities and transport boundary conditions:

- Confined, unconfined variably confined/unconfined aquifer layers;
- Solute transport effects of external sources and sinks such as wells, drains, Inclined model layers and variable cell thickness within the same layer;
- Specified concentration or mass flux boundaries;
- The rivers, areal recharge and evapotranspiration.

MT3D can be used to simulate changes in concentration of single species miscible contaminants in groundwater considering advection, dispersion and some simple chemical reactions. The chemical reactions included in the model are limited to equilibrium controlled linear or non-linear sorption and first-order irreversible decay or biodegradation.

Like the MODFLOW model, the MT3D model consists of a main program and a large number of highly independent subroutines, called modules, which are grouped into a series of "packages". Each of these packages deals with a single aspect of the transport simulation.

The major input required for running MT3D are:

- Ground water head and water mass budget generated by MODFLOW,
- Model grid size and aquifers thickness,
- Hydraulic parameters (such as conductivity) of the aquifer material,
- Effective soil porosity at each model cell,
- Advection numerical solver parameters,

- Soil dispersion and diffusion effect parameter (longitudinal dispersivity, horizontal/ transverse dispersivity, vertical dispersivity and diffusion coefficient),
- Pollutant loading source location, type and rate.

The major output form MT3D is an unformatted file of pollutant concentrations for the model grid cells at a specified time.

A step-by-step explanation of the various parameters under MT3D is given below:

5.5.1 Initial Concentration

The initial concentration at each active cell is required at the beginning of a transport simulation.

5.5.2 Advection Package

The Advection Package solves the concentration change due to advection with one of the four schemes included in the package:

- Method of characteristics (MOC)
- Modified method of characteristics (MMOC)
- Hybrid method of characteristics (HMOC)
- Upstream finite difference method.

5.5.3 Dispersion Package

The Dispersion Package solves the concentration change due to dispersion with the explicit finite difference method. This package requires:

- Longitudinal dispersivity of the aquifer,
- The ratio of the horizontal transverse dispersivity to the longitudinal dispersivity
- The ratio of the vertical transverse dispersivity to the longitudinal dispersivity

- Effective molecular diffusion coefficient.

5.5.4 Chemical Reaction Package

The Chemical Reaction Package solves the concentration change due to chemical reactions. Currently, the chemical reactions include linear or nonlinear sorption isotherms and first order irreversible rate reactions (radioactive decay or biodegradation).

5.5.5 Sink & Source Concentration Package

The Sink & Source Concentration Package solves the concentration change due to fluid sink/source mixing with the explicit finite difference method. Point sources include wells, general-head boundary cells, fixed-head cells, rivers and streams. Recharge is the only areally distributed source whereas evapotranspiration is the only sink whose concentration can be specified.

5.6 MATHEMATICAL MODELING OF MT3D

The governing advective-dispersive-reactive solute transport equation in three dimensions underlying in the transport model MT3D can be describe by the partial differential equation:

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x_i}\left(D_{ij}\frac{\partial C}{\partial x_j}\right) - \frac{\partial}{\partial x_i}(v_i C) + \frac{q_s}{\Theta}C_s + \sum_{k=1}^{N} R_k \qquad (5.6.1)$$

Where

C is the concentration of contaminants dissolved in groundwater [ML^{-3}]

t is time [T]

x_i is the distance along the respective Cartesian coordinate axis [L]

D_{ij} is the hydrodynamic dispersion coefficient [L^2T^{-1}]

v_i is the seepage or linear pore water velocity [LT^{-1}]

q_s is the volumetric flux of water per unit volume of aquifer representing sources (positive) and sinks (negative) [T^{-1}]

C_s is the concentration of the sources or sinks [ML^{-3}]

θ is the porosity of the porous medium dimensionless

$\sum_{k=1}^{N} R_k$ is the chemical reaction term [$ML^{-3}T^{-1}$]

Chapter 6 MATERIALS AND METHODS

6.1 THE STUDY DOMAIN

In the present study, the domain is restricted to the English Bazar Block, lying between latitude 24°50N to 25°05N and longitude 88°00E to 88°10E (Fig. 6.1) in Malda district, West Bengal, with areal extent of about 265 km^2. The block can be divided into two parts, namely the municipal part covering an area of about 13.5 km^2 in the eastern and central part of the block and the non-municipal area covering about 251.5 km^2 distributed in 135 villages with a population density of 11, 846 persons/km^2 in municipal and 899 persons/km^2 in non-municipal area. The municipal area is urbanized whereas the non-municipal area is rural in nature.

The area is drained by the Ganga (known as Bhagirathi), the Mahananda and the Kalindri rivers. The Bhagirathi flows in a south-easterly direction and demarcates the western and southwestern boundaries of the block. River Mahananda flanks the north-eastern boundary of the block whereas river Kalindri flows in the northern part of the block.

The maximum concentration of arsenic found in the groundwater of English Bazar block is 0.945 mg/L. The groundwater of western part of the municipal area has arsenic concentration above 0.05 mg/l. On the other hand the entire municipal area has arsenic concentration below the detection level.

The demand of potable water of the block is about 33.9 million litre per day (mld). Apart from this, groundwater is being extensively used for agricultural purpose. Sikdar and Chakraborty (in press) indicated that arsenicals used as fertilizer, pesticides in mango orchards and multi-cropped agricultural land, wood preservative and arsenic pumped out along with groundwater for irrigation may be the possible sources of arsenic in groundwater. High abstraction of groundwater could lead to downward infiltration of arsenic rich water used for agricultural purpose from the surface, and then horizontal movement of arsenious water within the aquifer towards the fresh water zones. These conditions would lead to pollution of uncontaminated zones of aquifer.

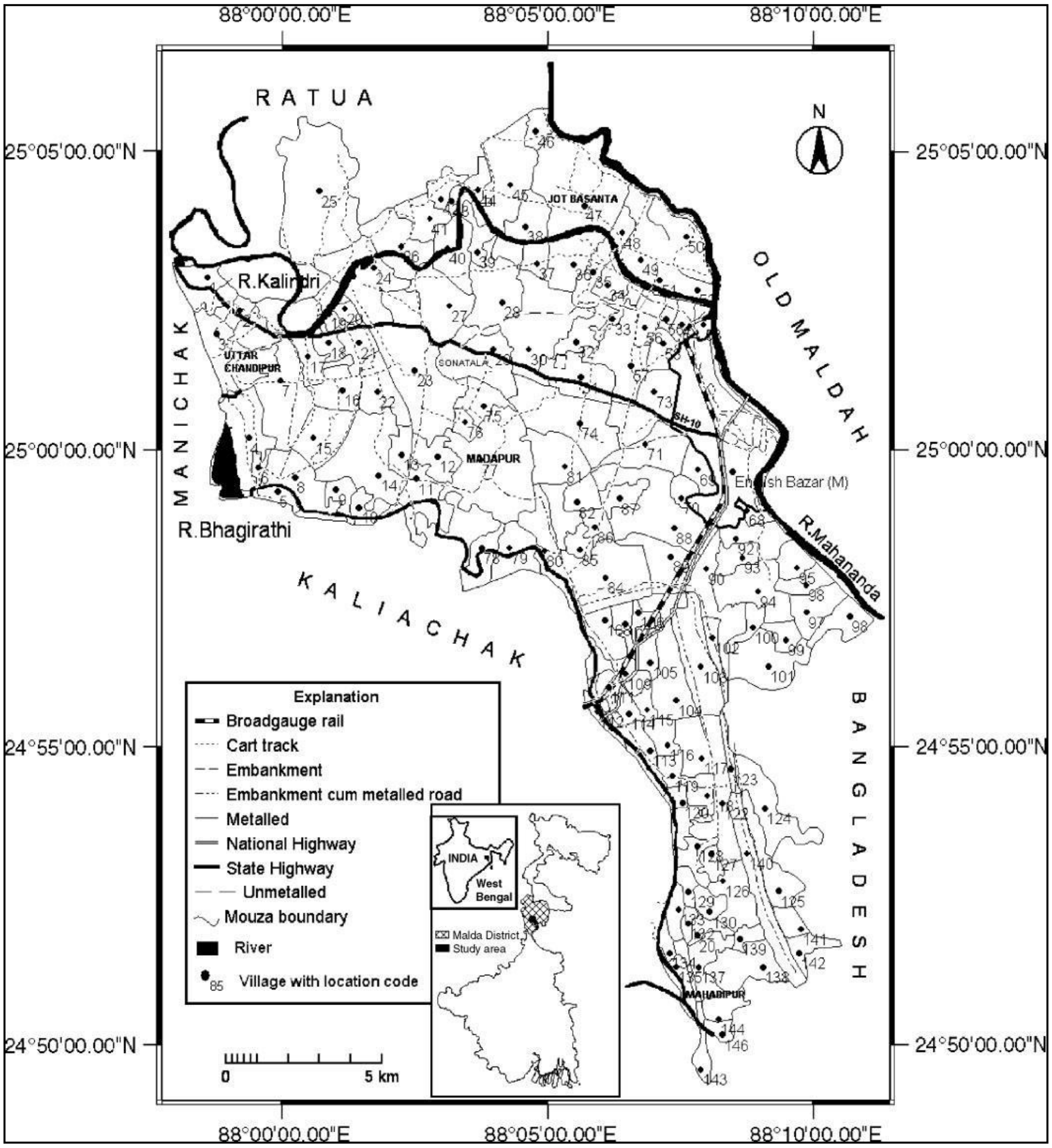

Fig. 6.1 Location map of the study area

6.2 Surface Water Hydrology

The area is characterised by humid tropical climate, which may be due to its proximity to the Bay of Bengal. The rainfall begins around the middle of the June with the onset of monsoon. The average annual rainfall in the area is 1545.5 mm. On average, there are 76 rainy days in a year. The maximum precipitation occurs during the period from June to September.

Table 6.1 Distribution of rainfall in different seasons for Malda district

Rainfall	Normal RF(mm)	Normal Rainy days (number)	Normal Onset (specify week and month)	Normal Cessation (specify week and month)
SW monsoon (June-September):	1163.8	57	1st week of June	2nd week of October
NE Monsoon(October-December):	167.0	6	-	-
Winter (January- February)	214.7	13	-	-
Summer (March-May)	-	-	-	-
Annual	1545.5	76	-	-

The mean annual temperature is 25°C. The temperatures attains its peak in the months of April – May to go up to 43°C. January is the coldest month and the minimum temperature during this winter month ranges between 5 to 9°C. Maximum and minimum temperatures normally vary between 38.6°C and 7.8°C during summer and winter respectively.

The district shows humid tropical climate condition with high relative humidity prevails in the air throughout the year and it ranges between 54 to 84% recorded at 8:30 am. The recorded lowest and highest normal potential evapotranspiration of Malda district are 61.2 mm during the month of December and 187.6 mm in the month of May. The total potential evapotranspiration of the district is 1363 mm.

The area is drained by the Ganga (known as Bhagirathi), the Mahananda and the Kalindri. The Bhagirathi demarcates the western and southwestern boundaries of the block and flows in a south-easterly direction. The Mahananda, which flanks the north-eastern boundary of the block, is next in importance. The other river, in the northern part of the block is Kalindri (Figure 6.1). All the rivers in the area are mature and meander characteristically. The Mahananda River receives groundwater all along its western bank and therefore is a gaining or effluent river. The Kalindri River receives water from the north and southeast and also behaves as an effluent river. The Bhagirathi River is perhaps a losing or influent river as the flow lines are either parallel to it, or moving away from it. Mahananda is perennial whereas Kalindri becomes dry during summer. People towards both western and southern parts of the area are using water from Mahanada mainly for irrigation purpose for almost entire year. Apart from the rivers, there are number of typical ox-bow lakes along the abandoned channel courses.

6.3 Groundwater Hydrology

Groundwater occurs under unconfined condition in a thick (108 - 117 m) zone of saturation within the alluvial sediments. At the upper part of the sedimentary column there is a mixture of silt, clay and fine sand of thickness up to 20 m. Below, there is a thick sandy horizon comprising fine to coarse material, at places gravelly. Several promising saturated granular zones are present in the depth span of 15 - 120 m below ground level (bgl). Generally, tubewells with drilling depths at 70 - 104 m bgl have been constructed. However, the maximum depth is 121 m in the municipal area. Potential aquifers occur in the depth range of 44 - 69 m and 73 -89 m where coarse sand and gravel is encountered. The discharge of the wells ranges from 215–218 m^3 hr^{-1} with drawdown varying from 1.5 – 4.7 m. Transmissivity and hydraulic conductivity of the aquifers are computed by pumping to be 758–2969 m^2 day^{-1} and 25–99 m day^{-1}, respectively (CGWB, 2001). The usual trend of groundwater table fluctuations in a calendar year is a declining trend from January to April, a rising trend from May to July, and then declining again from August onwards. Moreover, analysis of monthly water level fluctuations for all the wells within the study area during the year 2010 to 2015 shows that the water levels in most of these wells follow an identical trend between August and April.

6.4 LITHO LOGS AND ARSENIC LEVELS OF THE STUDY AREA

The area consists of a continuous clayey silt bed varying in thickness from a thin veneer to about 20m at the top followed by sand of various grades mixed with gravels and carbonate nodules. The thickness of the clayey silt bed is thin in the western side and attains its maximum thickness in the eastern side. There are several clay lenses splitting the sand body into a multi-layered sequence at various depths. The sand shows coarsening downward sequence. The sand is highly micaceous and often tends to be silty. The continuity in the sequence of sand, which forms the aquifer material, is broken by the occasional occurrence of clay lenses of limited lateral extent.

Fifteen litho-logs were provided by the Public Health Engineering Department (PHEP), West Bengal for the study area. The maximum depth of available logs is of 120.34m at Itakhola Mauza II, while the minimum one goes upto 95m deep at Lalapur. None of these logs, however, reach the basement rock. The thickness of each lithological unit changes abruptly and there is no distinct aquifer - aquitard system. A tabular form of the available lithologs are given in Appendix. These available litho logs were simplified to get a litho log for the entire study area.

The figure below shows the sub-surface lithological correlations of arsenic affected areas in Malda District.

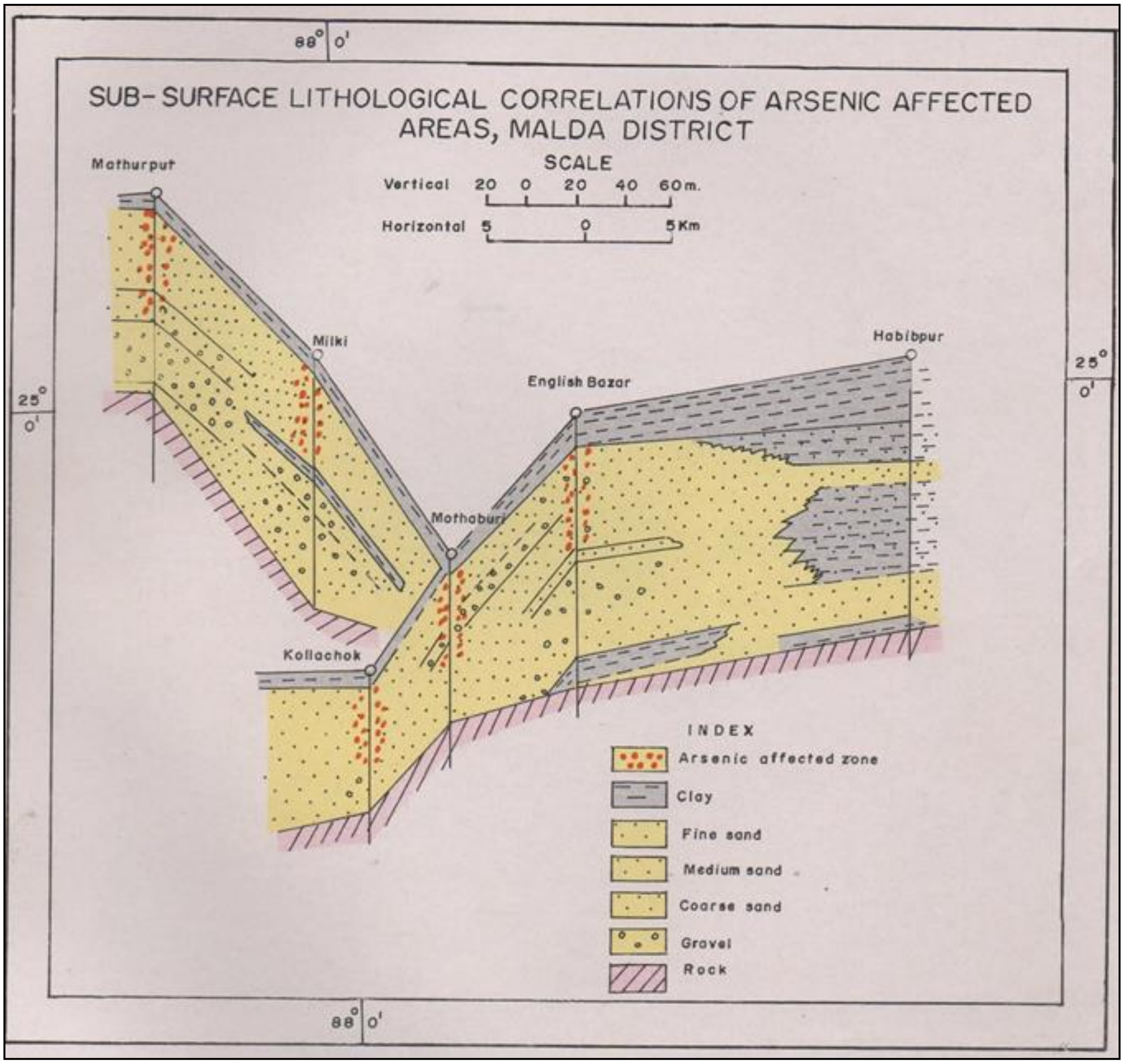

Fig. 6.2 Sub-Surface Lithological Correlations of Arsenic Affected Areas, Malda District (Source: CGWB)

Arsenic in groundwater with concentration beyond 0.05 mg/l, is found to occur within the depth span of 16 m to 57 m. The distribution of arsenic affected tubewells along with the concentration range has been shown in the figure below.

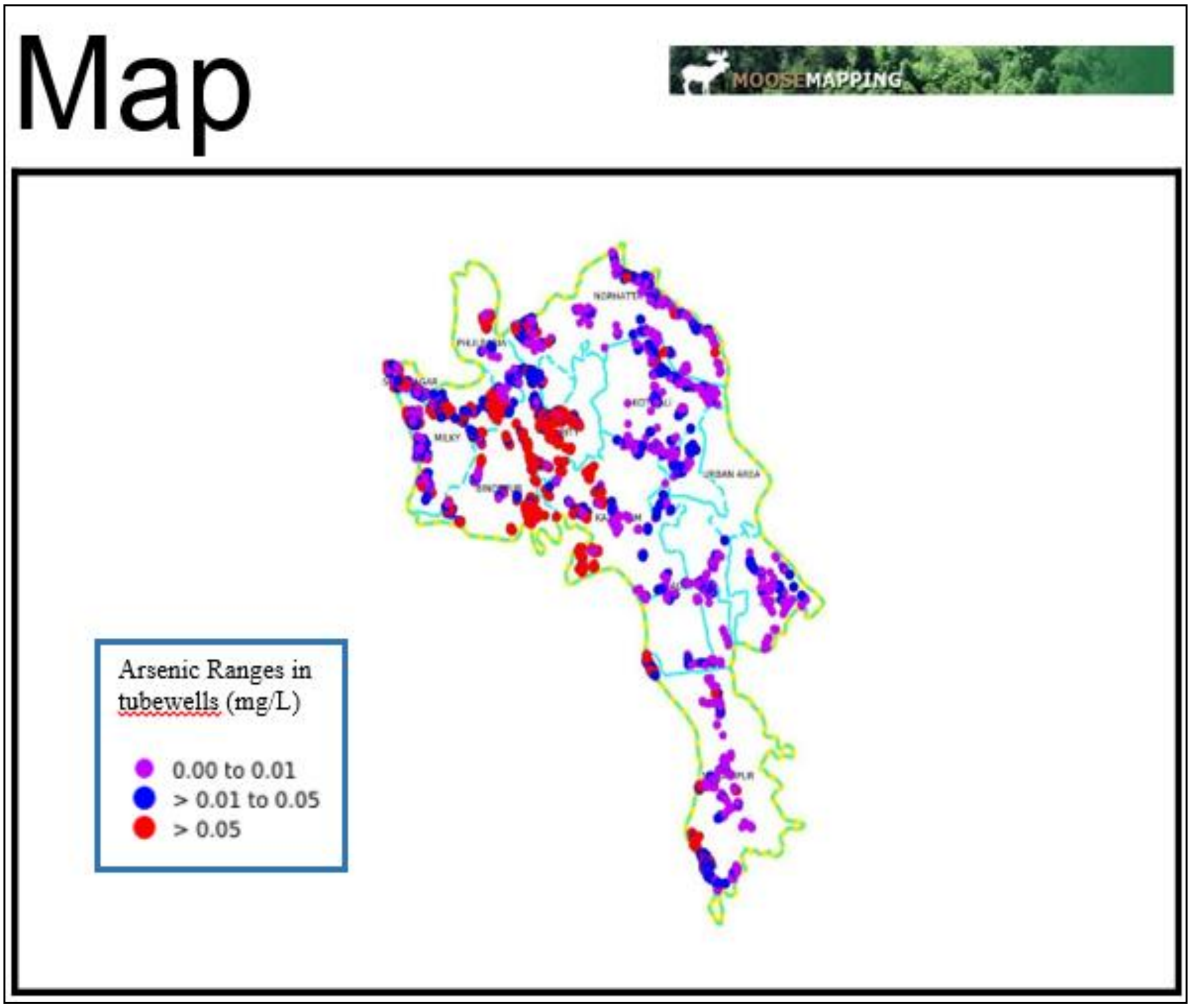

Fig. 6.3 Arsenic affected tubewells in English Bazar (Source: www.whphed.gov.in)

The spatial distribution of arsenic in groundwater within the study area shows that the concentration broadly decreases from west to east.

Maximum arsenic concentration observed in different panchayat's of English Bazar block has been tabulated for the year 2015.

Table 6.2 Maximum Arsenic concentration observed in English Bazar block (Year 2015)

Panchayat Name	Village Name	Habitation Name	Type Of Source	Lab Testing Date	Maximum Concentration Observed
AMRITY	NIAMATPUR	BORO MOHANPARA	Deep Tubewell	31/07/2015	0.63 mg/l
BINODPUR	SATTARI	KAGMARI	Deep Tubewell	01/07/2015	0.60 mg/l
JADUPUR-I	BARACHAK	GOPI NATH PUR	Deep Tubewell	01/07/2015	0.27 mg/l
JADUPUR- II	MAHESHPUR(P)	JHARATALA COLONY	Deep Tubewell	01/07/2015	0.04 mg/l
KAZIGRAM	HARISHPUR	HORISH PUR	Deep Tubewell	01/07/2015	0.69 mg/l
KOTWALI	SAHAZALALPUR	KATWALI	Deep Tubewell	03/07/2015	0.12 mg/l
MAHADIPUR	BADULYABARI	KHIRKI	Deep Tubewell	04/07/2015	0.95 mg/l
MILKY	BASUDEBPUR	BHAGBANPUR	Deep Tubewell	04/07/2015	0.48 mg/l
NORHATTA	ITAKHOLA	ITAKHOLA	Deep Tubewell	07/07/2015	0.23 mg/l
PHULBARIA	NAGHARIA	BAKUL MATH	Deep Tubewell	08/07/2015	0.25 mg/l
SOVANAGAR	UTTAR CHANDIPUR	SOVANAGAR	Deep Tubewell	09/07/2015	0.90 mg/l

(**Source**: www.indiawater.gov.in)

6.5 GROUNDWATER FLOW MODELING USING MODFLOW & SOLUTE TRANSPORT MODELING USING MT3D

The groundwater quantity-modeling component used here is MODFLOW and the pollutant transport component is MT3D. MODFLOW and MT3D used in this study is part of the software Processing Modflow for Windows (PMWIN). The combined hydrologic and water quality model requires the compilation of considerable data sources to accurately capture the dynamical processes prevalent within the hydrologic systems. Unfortunately the data available for the model domain was not sufficient and some aquifer properties had to be assumed. These assumptions might have created some unavoidable discrepancies in the results.

The first part of the modeling involves developing a groundwater model to adequately simulate flow condition in the aquifer using MODFLOW. The three-dimensional model domain is a 21 km by 30 km area situated in Malda district of West Bengal. For formulating MODFLOW model for English Bazar block which has area of 265.5 km^2, 42 columns and 60 rows mesh size was selected depending upon the shape of the block. Each cell has 500.0 m length and 500.0 m width. As there is a maximum limit on the nodes of grid possible in this educational issue of PMWIN, the overall grid size would not be reduced further. A three-layer system of sandy clay, sand and coarse sand has been assumed. The custom grid is shown in Fig. 6.4.

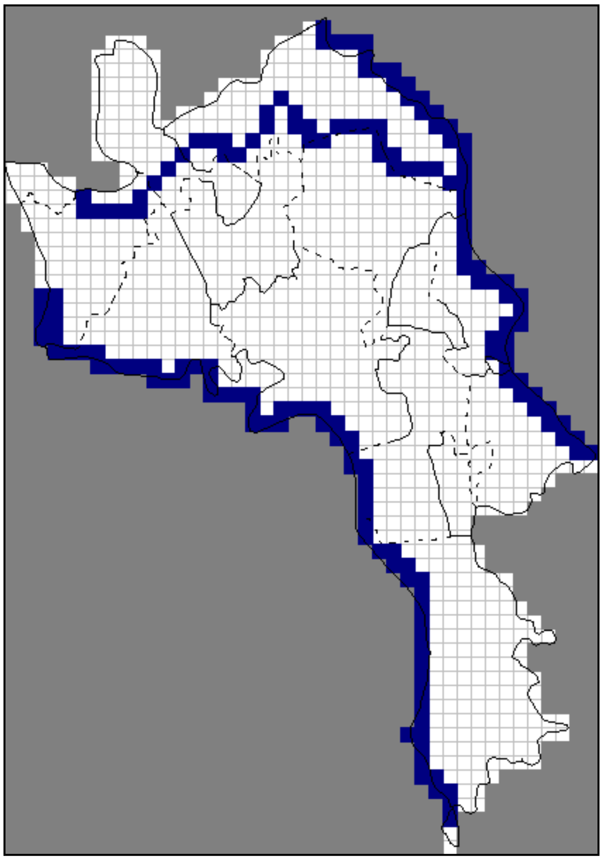

Fig. 6.4 Custom grid of the model

The top layer of the model, which is a sandy clay group, has its lower bound at 15 m from the ground surface. The second layer i.e. the sand layer is 20m deep while the third layer, which is a coarse sand group is 60m in depth. These values are obtained from the simplified litho logs of the sub basin. All the three layers are assumed to be semi-confined. The Hydraulic parameters of these three layers are given in Table 6.2.

The first step of the groundwater flow modelling was to build some realistic piezometric map of the field for some fixed dates (depending on the available data). In order to achieve a realistic interpolation of the groundwater level in the field, several intrinsic data had to be known: the head of several points spread all over the field, the recharge of the area and the hydraulic conductivity of the different layers. Since these data are partly assumed or interpolated, they would have to be adapted in order to calibrate the model on a realistic situation.

Constant-head boundaries were applied to the Mahananda, Bhagirathi and Kalindri, rivers flowing within the model domain. The cells falling under the study domain were provided with variable head boundaries. The highest flood level of Kalindri river is 26.5m while that of Mahananda river is 23.5 m. Data for Bhagirathi river could not be obtained and was assumed as 30m.

The initial values of aquifer parameters were taken from the literature. The value of porosity (n) was assumed to be 0.2 (Harvey, 2002; JICA, 2002). BGS/DPHE (2001) suggested that the K values for Gangetic sediments could vary from 10 to 100 m/d. In their site-specific model of Faridpur, they classified the sediment as sandy silt (K= 4 m/d), fine sand (8 m/d), medium sand (25 m/d), and coarse sand (46 m/d). For the present model, uniform initial K_x and K_y (K_z = 1/10 of K_x) values of 4 m/d, 25 m/d and 40 m/d for sandy clay, sand, and coarse sand, respectively.

Satisfactory results were obtained for steady state flow simulation with these data as input parameters.

The transient period was divided into monsoon and non-monsoon period of 120 days and 240 days respectively. The input parameters considered during transient period flow simulation varied accordingly. The total annual ground water recharge for English Bazar block is 8789.15 ham. Net recharge during monsoon months is 5897.34 ham while net recharge during non-monsoon months 2891.73 ham. Existing gross ground water draft for all uses is 3746.52 ham for the study area (Source: CGWB). Recharge was assumed to be distributed uniformly in the entire study area. It was assumed that the draft is confined to the non-monsoon period only and there is zero draft during monsoon months. A uniform distribution of wells in the whole model domain was assumed for simulation of draft. It is assumed that 50% of all the pumping of water is from the course sand aquifer, while 30% and 20% are from the sand and sandy clay layer respectively. The MODFLOW package was run and the simulated hydraulic heads for the 3 layers was obtained in the form of a contour map at the end of non-monsoon period and monsoon period for a time period of 1080 days.

Table 6.3 Parameters used for simulation of MODFLOW and MT3D

S. No.	Parameters	Unit	Values
1.	Horizontal Hydraulic Conductivity for Sandy Clay	m/day	4
2.	Horizontal Hydraulic Conductivity for Sand	m/day	25
3.	Horizontal Hydraulic Conductivity for Coarse Sand	m/day	40
4.	Vertical Hydraulic Conductivity for Clay	m/day	0.4
5.	Vertical Hydraulic Conductivity for Sand	m/day	2.5
6.	Vertical Hydraulic Conductivity for Coarse Sand	m/day	4.0
7.	Effective Porosity	-	0.25
8.	Evapotranspiration Rate	m/day	$3.734\text{x}10^{-3}$
9.	Recharge Rate during monsoon	m/day	$1.8545\text{x}10^{-3}$
10.	Recharge Rate during non-monsoon	m/day	$4.454\text{x}10^{-4}$
11.	Pumping Rate of Well for 1st layer (non-monsoon)	m^3/day/m^2	$-3.8734\text{x}10^{-5}$
12.	Pumping Rate of Well for 2nd layer (non-monsoon)	m^3/day/m^2	$-5.81\text{x}10^{-5}$
13.	Pumping Rate of Well for 3rd layer (non-monsoon)	m^3/day/m^2	$-1.9367\text{x}10^{-4}$
14.	Pumping Rate of Well during monsoon	m^3/day/m^2	0

15.	$\frac{Horizontal\ Transverse\ Dispersivity}{Longitudinal\ Dispersivity}$	-	0.1
16.	$\frac{Vertical\ Transverse\ Dispersivity}{Longitudinal\ Dispersivity}$	-	0.01
17.	Effective molecular diffusion coefficient	m^2/day	0.0864

The second part of the modeling involves the three-dimensional transport of solute in the study area. The arsenic pollution problem was conceptualized considering point sources at localized pockets as the probable source.

Arsenic in groundwater with concentration beyond 0.05 mg/l is found to occur within the depth span of 16 m to 57 m and thus it was assumed that there is no initial arsenic concentration for the top soil layer while for the second and third layers the vertical variation in the concentration of arsenic is zero i.e. same concentration was applied for both the layers. A simplified table recording the panchayat's under the study domain with the respective average arsenic concentration is given in Table 6.4.

Table 6.4 Initial concentration of arsenic in different panchayat's of English Bazar block

Panchayat Name	**Arsenic Concentration (μg/m^3)**
AMRITY	124803
BINODPUR	128906
JADUPUR-I	50930
JADUPUR-II	4720
KAZIGRAM	52478

KOTWALI	13221
MAHADIPUR	36482
MILKY	45923
NORHATTA	10522
PHULBARIA	42093
SOVANAGAR	59405

(**Source:** www.indiawater.gov.in)

10 localized pockets of high concentration arsenic in the study area have been assumed as the source of arsenic in the study area. These localized pockets are selected based on maximum observed arsenic concentration in different panchayat's of the study area. The locations of these point source are given in Table 6.5.

Table 6.5 Location of high arsenic concentration pockets in the study area

Borehole No.	**Panchayat Name**	**Distance in X-direction**	**Distance in Y-direction**	**Arsenic concentration (μg/m^3)**
1	PHULBARIA	10200	28200	250000
2	BINODPUR	12800	20700	600000
3	AMRITY	14000	22700	630000
4	KAZIGRAM	16700	20200	690000
5	JADUPUR I	21300	13800	270000
6	KOTWALI	20600	24000	120000
7	NORHATTA	17740	29240	230000

8	MILKY	9820	23230	480000
9	JADUPUR II	25760	15800	40000
10	MAHADIPUR	22280	9260	950000

The average concentration observed were taken as the base concentration for each panchayat. The localized zones of high arsenic concentration were taken as point source of arsenic for that panchayat. Fig. 6.5 shows the customized grid of the model after the application of initial arsenic concentration in the study area.

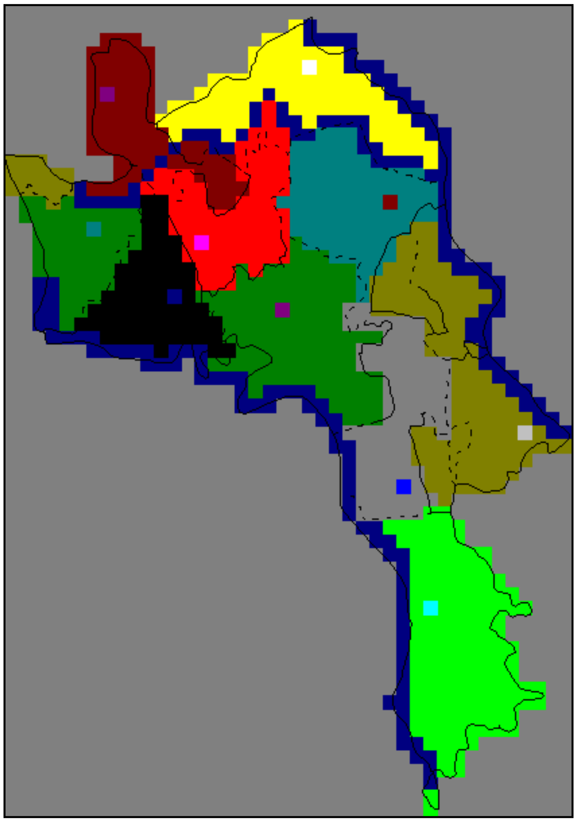

Fig. 6.5 Custom grid of the model showing base concentration of each panchayat along with high concentration arsenic pockets

To record arsenic concentration in the study area, 10 observation wells were placed at a distance of 1000 m from high arsenic concentration pockets. The locations of these observation wells are given in Table 6.6.

Table 6.6 Location of observation wells in the study area

Borehole No.	Panchayat Name	Distance in the X-direction	Distance in Y-direction
1.	PHULBARIA	10200	29200
2.	BINODPUR	11800	20700
3.	AMRITY	15000	22700
4.	KAZIGRAM	17700	20200
5.	JADUPUR I	21300	14800
6.	KOTWALI	20600	23000
7.	NORHATTA	18740	29240
8.	MILKY	10820	23230
9.	JADUPUR II	24760	15800
10.	MAHADIPUR	23280	9260

MODFLOW solves for the distribution of hydraulic head within the model domain and, from these results, the velocity components of flow are calculated. MT3D uses the velocity values as inputs to solve the transport equation. The transport advection term is solved by particle tracking (Lagrangian approach) and the dispersion term is solved using a finite-difference method (Eulerian approach).

The kinetics of geo-chemical processes of Arsenic though play a crucial role in time and space distribution of concentration, but from the available information it is difficult to establish any trends of chemical kinetics. Hence simulation of contaminants' transport has been done considering advective-dispersive phenomena.

The apparent longitudinal dispersivity α_L is scale dependent and can be estimated by the following relationship (Xu and Eckstein formula, 1995): $\alpha_L = 0.83(\log L)^{2.414}$, where L is the length of the cell. Since the length of a cell is 500m, thus the longitudinal dispersivity has been estimated to be 9.12 m. The dispersivity value has been assumed to be constant for all the cells. Other parameters considered in MT3D runs were as follows (Majumdar et. al, 2002)

- transverse horizontal dispersivity: 10% of longitudinal dispersivity;

- transverse vertical dispersivity: 1 % of longitudinal dispersivity; and

- molecular diffusion: $1.0 \times 10^{-6}\ m^2s^{-1}$.

Chapter 7 RESULTS AND DISCUSSION

The model used, Processing Modflow for Windows (PMWIN), offers a totally integrated simulation system for modeling groundwater flow and transport. The program MODFLOW simulated three-dimensional groundwater flow and revealed the variation of hydraulic heads in the study area. MT3D, a modular 3D solute transport model for MODFLOW for simulation of advection, dispersion and chemical reaction, simulated the movement of arsenic and revealed the impact of localized pockets of high concentration arsenic in the study area and at observation wells placed at a distance of 1000 m distance from these pockets. The results of MODFLOW were compiled in the form of contour maps showing the spatial distribution of hydraulic head. The results of MT3D were compiled in the form of concentration time graphs for observation wells kept at a distance of 1000 m from the localized source. Also contour maps showing the spatial distribution of arsenic concentration for different durations have been plotted.

7.1 VARIATION OF HYDRAULIC HEADS

MODFLOW was used to simulate the groundwater flow in the study area. The resultant contour maps depicting the variation of hydraulic head in the three layers are enclosed in this dissertation.

7.1.1 Variation of Hydraulic Heads in the Sandy Clay Layer

Fig. 7.1 to Fig 7.7 illustrates the variation of hydraulic heads in the sandy clay layer of the study area. The groundwater contour map indicates that the dominant groundwater flow directions are E’ly, NE’ly and N’ly which is consistent with the flow pattern observed in the study area. Fig. 7.1 shows the hydraulic head distribution for sandy clay layer after steady state analysis. Fig. 7.2, 7.4 and 7.6 shows the hydraulic head distribution for the sandy clay layer at the end of pre-monsoon period for three consecutive years observed during MODFLOW analysis. Fig. 7.3, 7.5

and 7.7 shows the hydraulic head distribution for the sandy clay layer at the end of monsoon period for three consecutive years observed during MODFLOW analysis.

Variations in hydraulic heads can be clearly seen during the end of monsoon and non-monsoon period. Groundwater table observations at site shows a declining trend during the non-monsoon period and a rising trend during the monsoon period. The same can be observed from the hydraulic head contours formed for the sandy clay layer in the contour maps given below. The hydraulic head shows a large variation near the river i.e. the value of hydraulic gradient is high near the river and the variation becomes less towards the middle, only to increase again, thus giving a concave look. This high hydraulic gradient near the river may be due to more relative recharge from the river at places near to it. But the aquifer material being sandy clay, which has a low hydraulic conductivity in comparison to other two layers, could not distribute the recharge uniformly. This may be the reason why a sharp concave contour is formed.

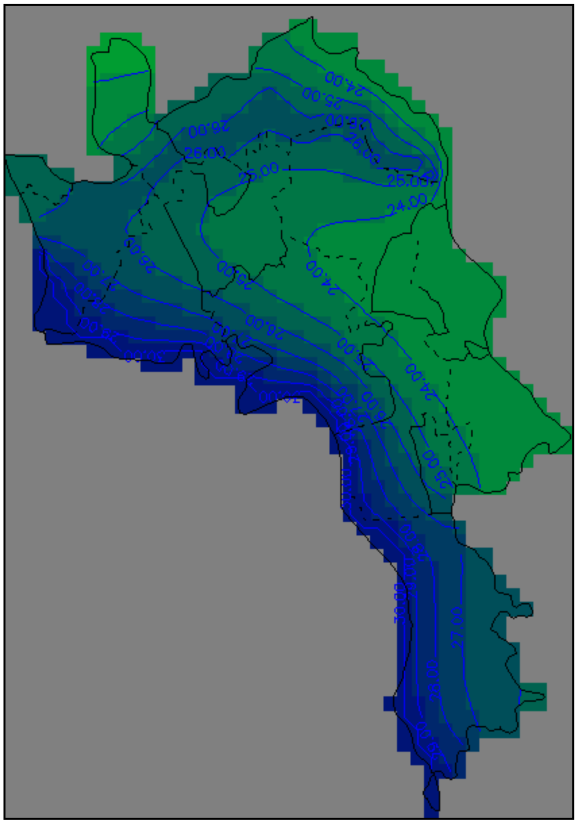

Fig. 7.1 Steady state head distribution for sandy clay layer

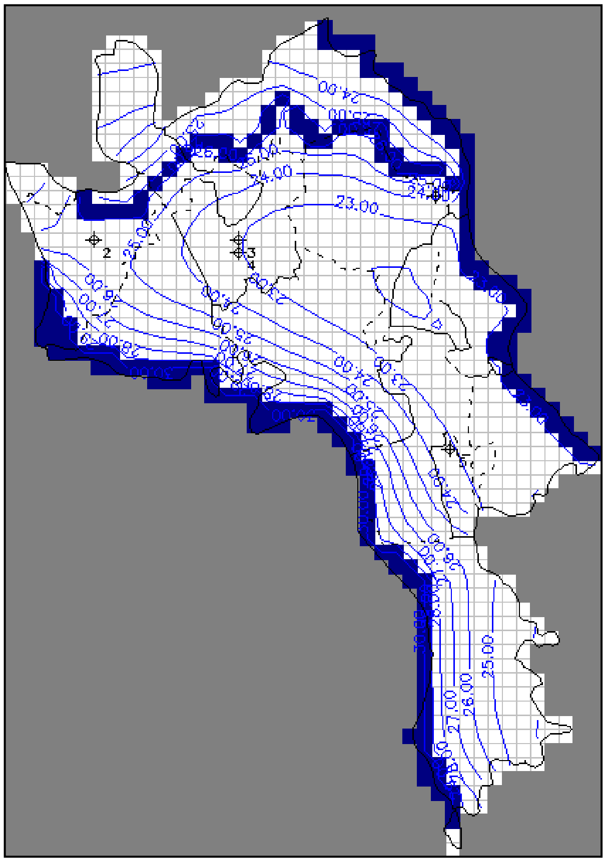

Fig. 7.2 Head distribution for sandy clay layer at the end of first pre-monsoon period (240 days)

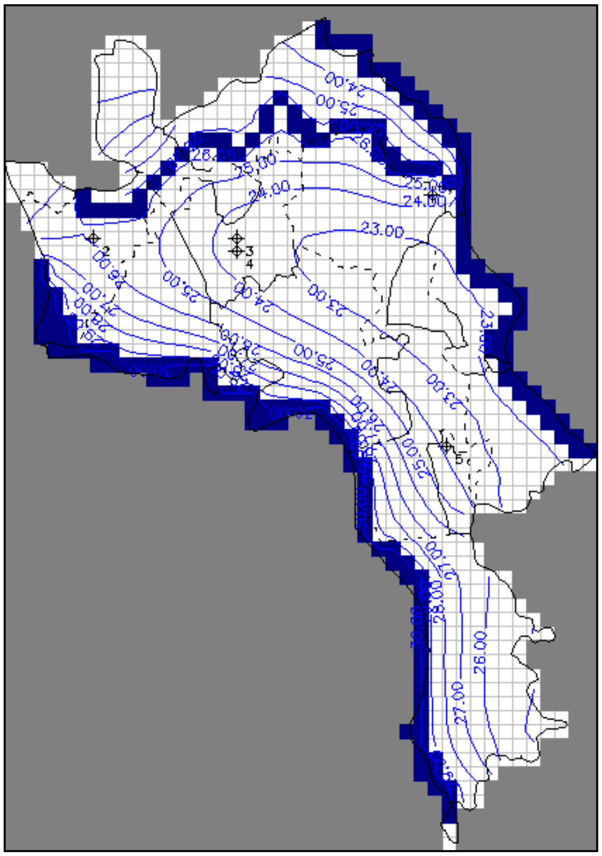

Fig. 7.3 Head distribution for sandy clay layer at the end of first monsoon period (360 days)

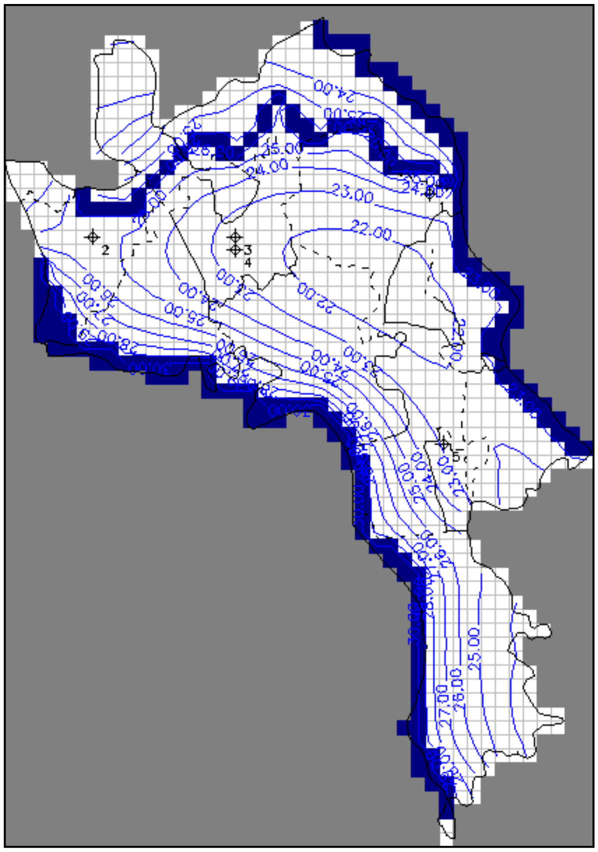

Fig. 7.4 Head distribution for sandy clay layer at the end of second pre-monsoon period (600 days)

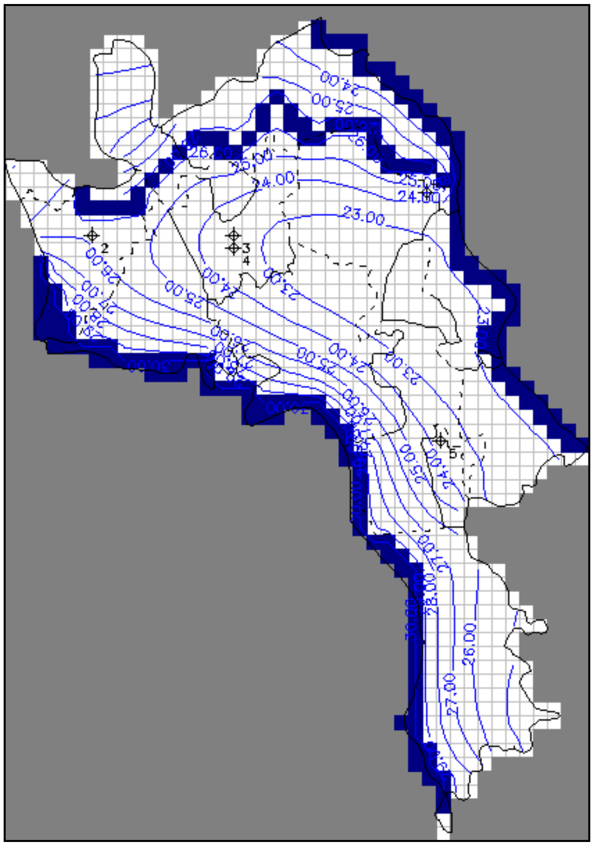

Fig. 7.5 Head distribution for sandy clay layer at the end of second monsoon period (720 days)

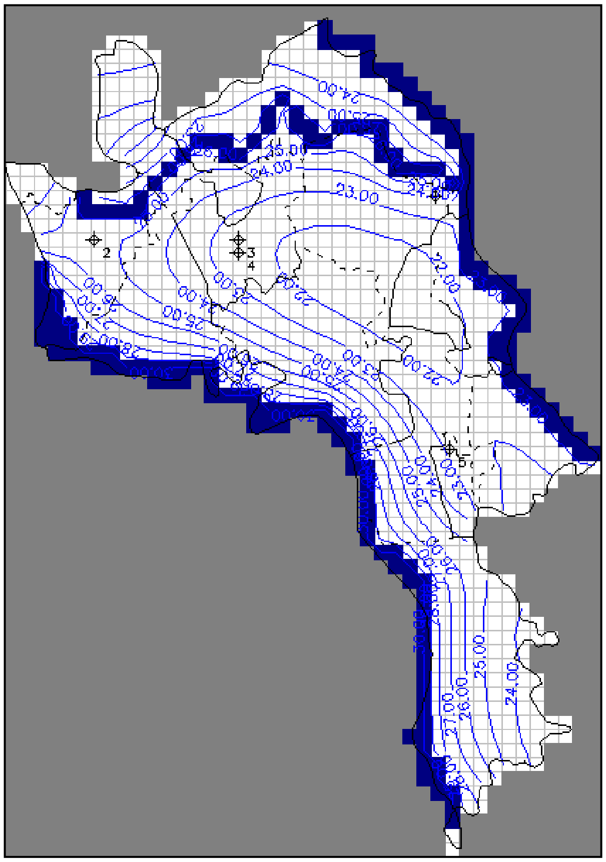

Fig. 7.6 Head distribution for sandy clay layer at the end of third pre-monsoon period (960 days)

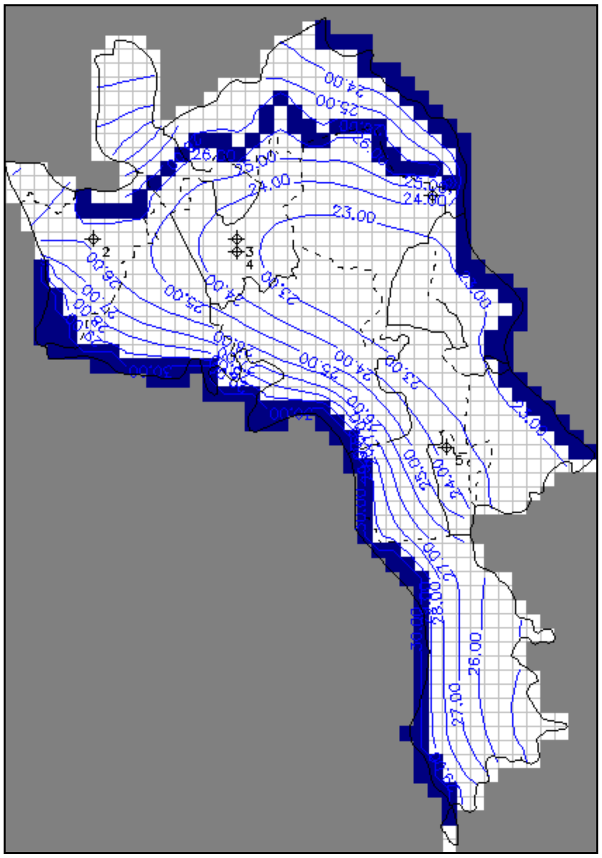

Fig. 7.7 Head distribution for sandy clay layer at the end of third monsoon period (1080 days)

7.1.2 Variation of Hydraulic Heads in the Sand Layer

Fig. 7.8 to Fig 7.14 illustrates the variation of hydraulic heads in the sand layer of the study area. The groundwater contour map indicates that the dominant groundwater flow directions are E'ly, NE'ly and N'ly which is consistent with the flow pattern observed in the study area. Fig. 7.8 shows the hydraulic head distribution for the sand layer after steady state analysis. Fig. 7.9, 7.11 and 7.13 shows the hydraulic head distribution at the end of pre-monsoon period for three consecutive years observed during MODFLOW analysis. Fig. 7.10, 7.12 and 7.14 shows the hydraulic head distribution at the end of monsoon period for three consecutive years observed during MODFLOW analysis. Variations in hydraulic heads can be clearly seen during the end of monsoon and pre-monsoon period. Groundwater table observations at site shows a declining trend during the non-monsoon period and a rising trend during the monsoon period. The same can be observed from the hydraulic head contours formed for the sand layer in the contour maps given below. The hydraulic head shows a gradual variation in comparison to the top sandy clay layer in the whole of the study area giving a smooth concave look.

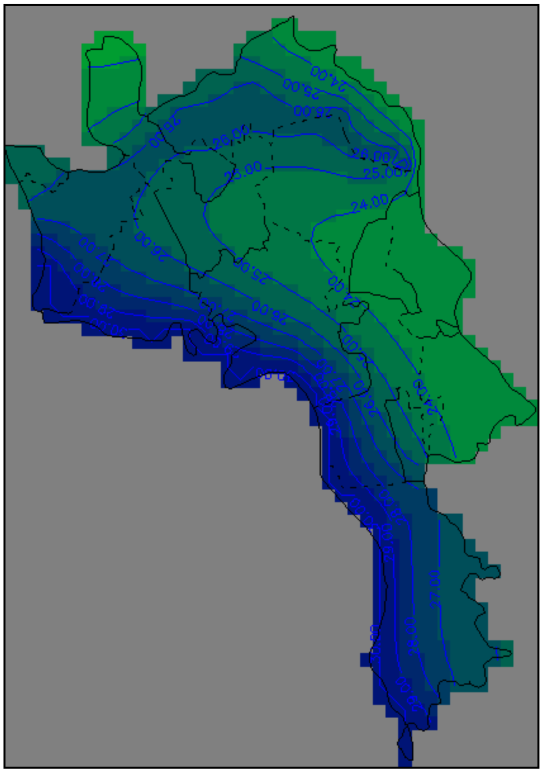

Fig. 7.8 Steady state head distribution for sand layer

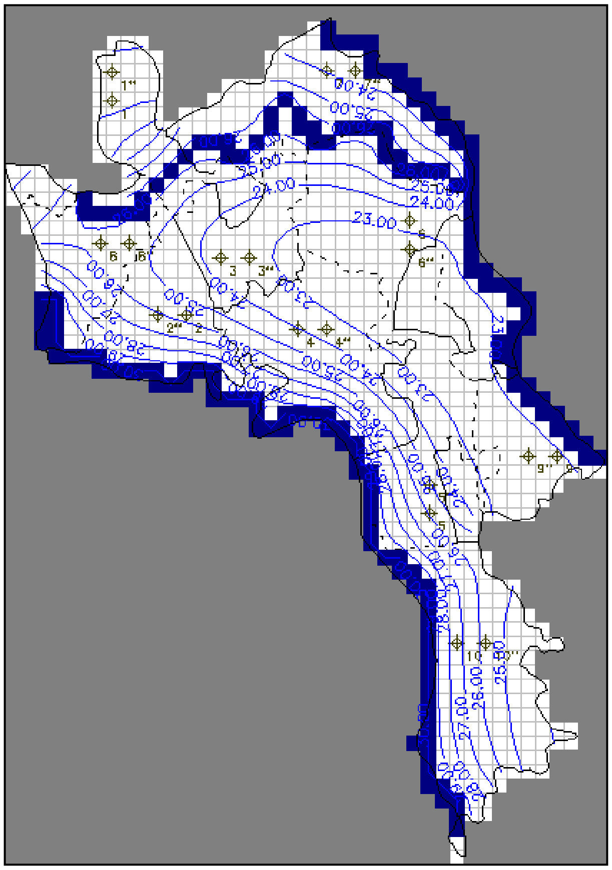

Fig. 7.9 Head distribution for sand layer at the end of first pre-monsoon period (240 days)

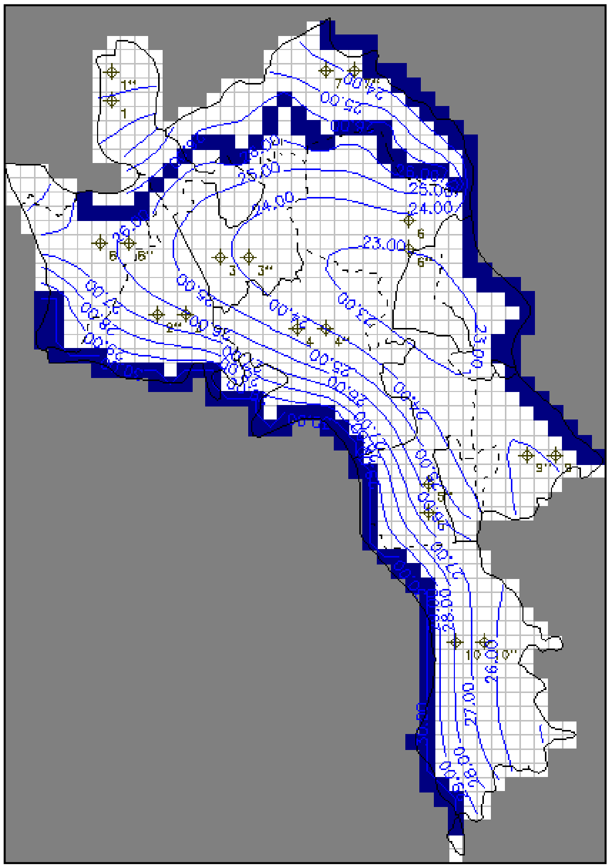

Fig. 7.10 Head distribution for sand layer at the end of first monsoon period (360 days)

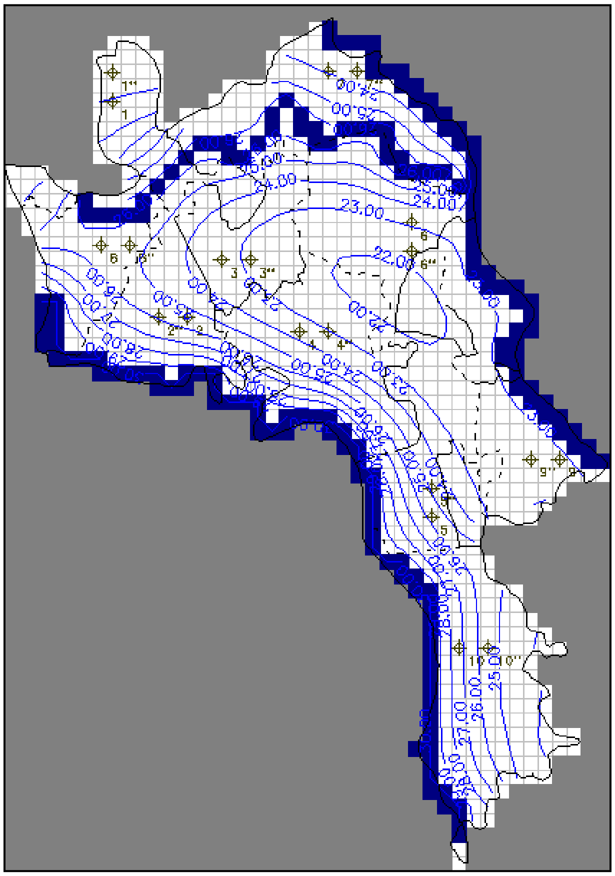

Fig. 7.11 Head distribution for sand layer at the end of second pre-monsoon period (600 days)

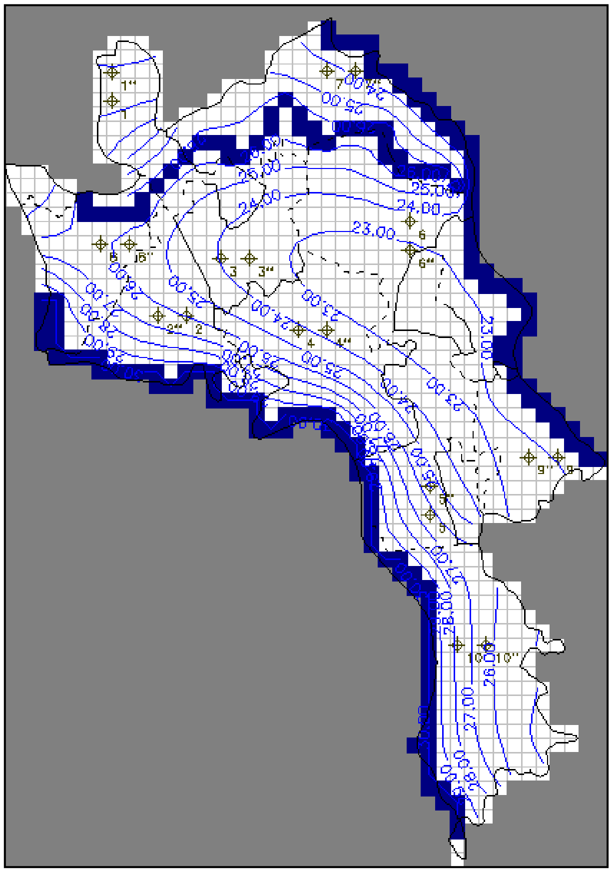

Fig. 7.12 Head distribution for sand layer at the end of second monsoon period (720 days)

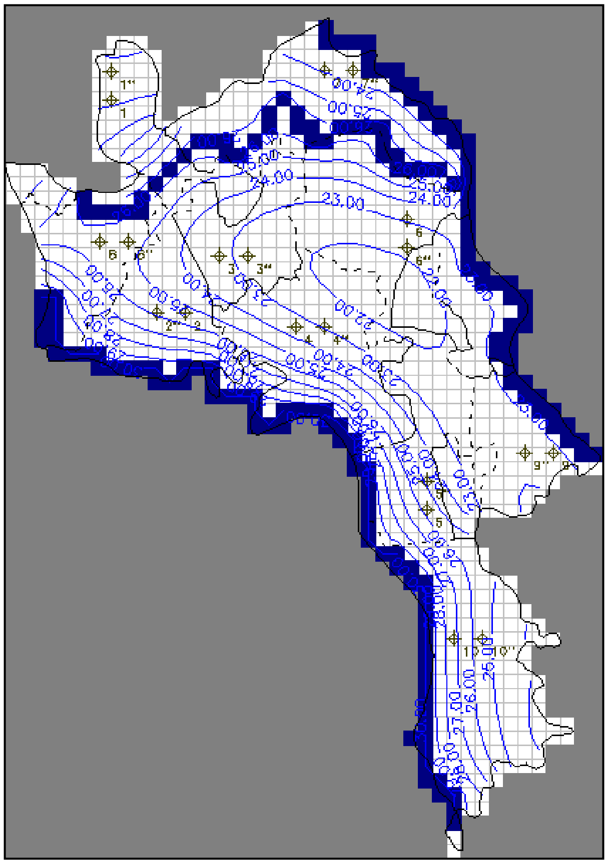

Fig. 7.13 Head distribution for sand layer at the end of third pre-monsoon period (960 days)

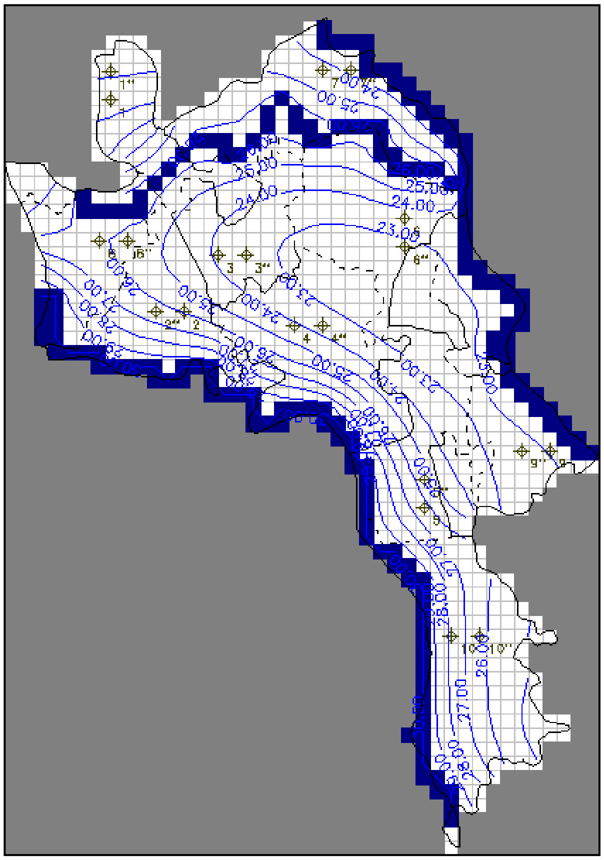

Fig. 7.14 Head distribution for sand layer at the end of third monsoon period (1080 days)

7.1.3 **Variation of Hydraulic Heads in the Coarse Sand Layer**

Fig. 7.15 to Fig 7.21 illustrates the variation of hydraulic heads in the coarse sand layer of the study area. The groundwater contour map indicates that the dominant groundwater flow directions are E'ly, NE'ly and N'ly which is consistent with the flow pattern observed in the study area. Fig. 7.15 shows the hydraulic head distribution for coarse sand layer after steady state analysis. Fig. 7.16, 7.18 and 7.20 shows the hydraulic head distribution for coarse sand layer at the end of pre-monsoon period for three consecutive years observed during MODFLOW analysis. Fig. 7.17, 7.19 and 7.21 shows the hydraulic head distribution for coarse sand layer at the end of monsoon period for three consecutive years observed during MODFLOW analysis. Variations in hydraulic heads can be clearly seen during the end of monsoon and pre-monsoon period. Groundwater table observations at site shows a declining trend during the non-monsoon period and a rising trend during the monsoon period. The same can be observed from the hydraulic head contours formed for the coarse sand layer in the contour maps given below. The hydraulic head in the coarse sand layer is marginally higher at all points than the above sand layer. It shows a gradual variation in the whole of the study area giving a smooth concave look.

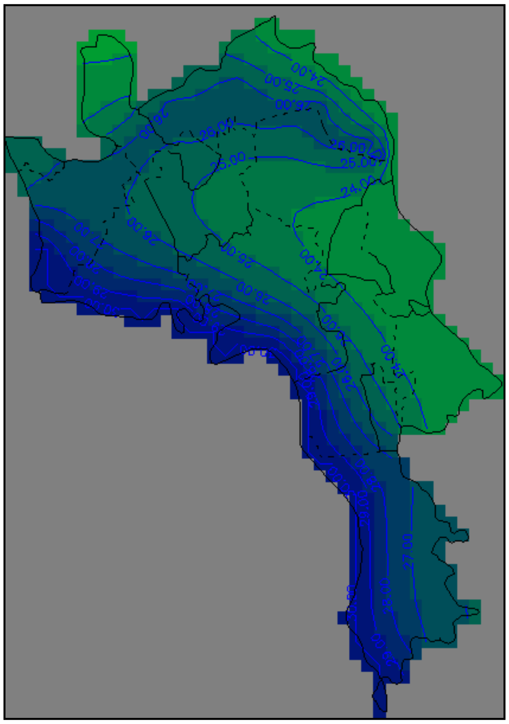

Fig. 7.15 Steady state head distribution for coarse sand layer

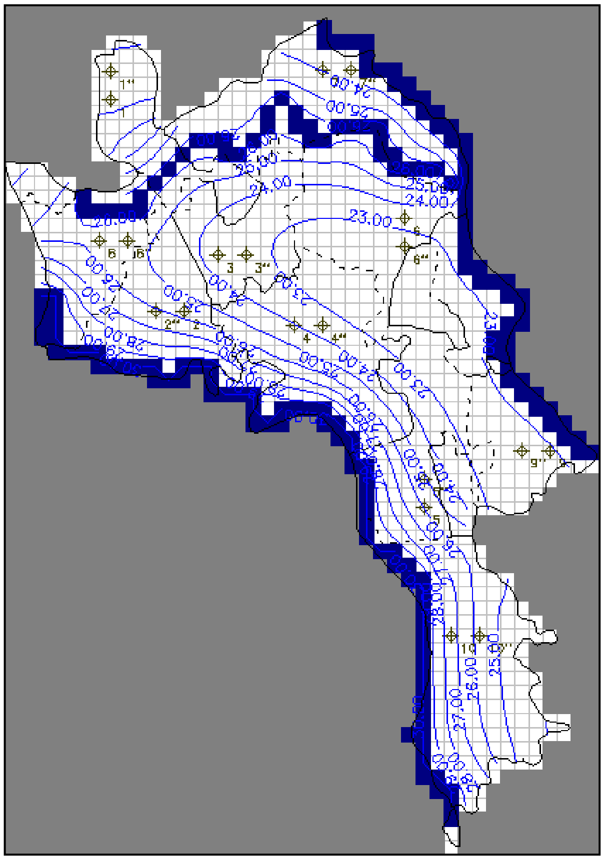

Fig. 7.16 Head distribution for coarse sand layer at the end of first pre-monsoon period (240 days)

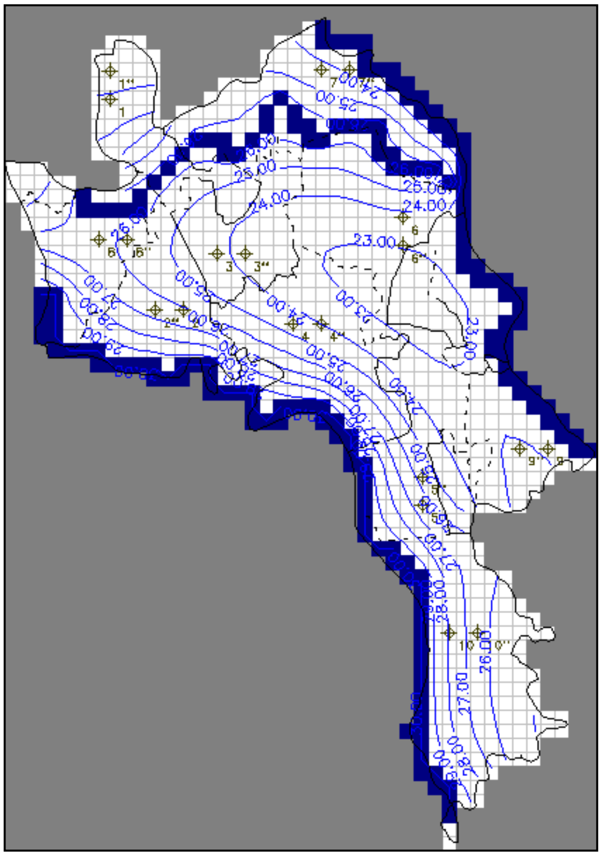

Fig. 7.17 Head distribution for coarse sand layer at the end of first monsoon period (360 days)

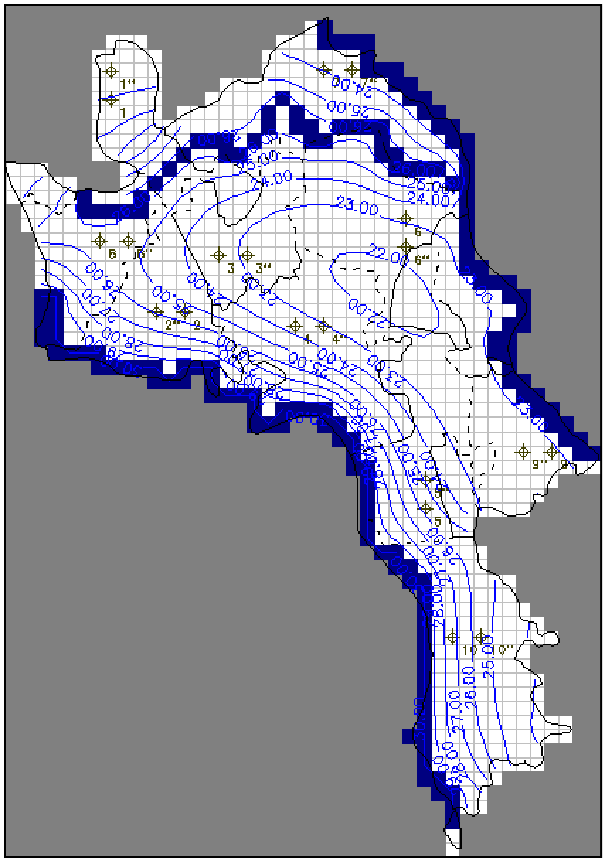

Fig. 7.18 Head distribution for coarse sand layer at the end of second pre-monsoon period (600 days)

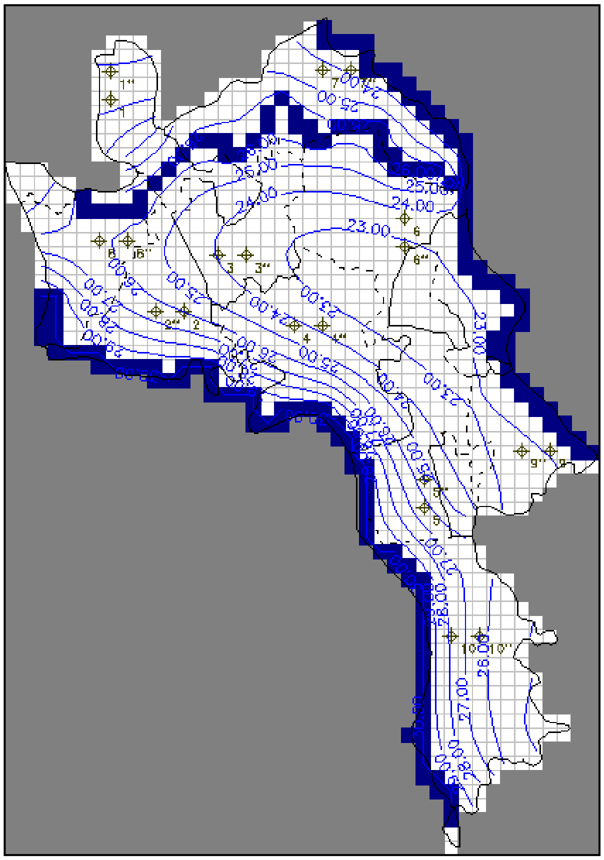

Fig. 7.19 Head distribution for coarse sand layer at the end of second monsoon period (720 days)

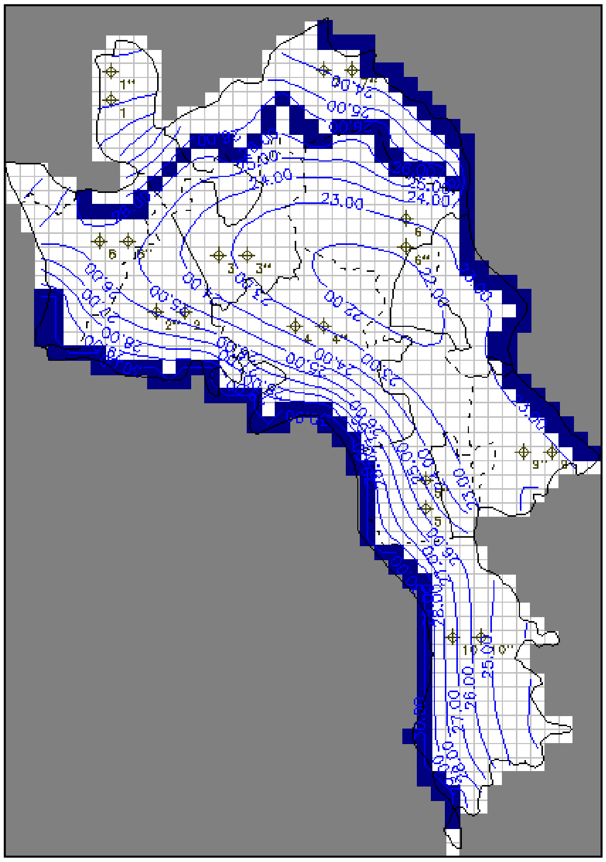

Fig. 7.20 Head distribution for coarse sand layer at the end of third pre-monsoon period (960 days)

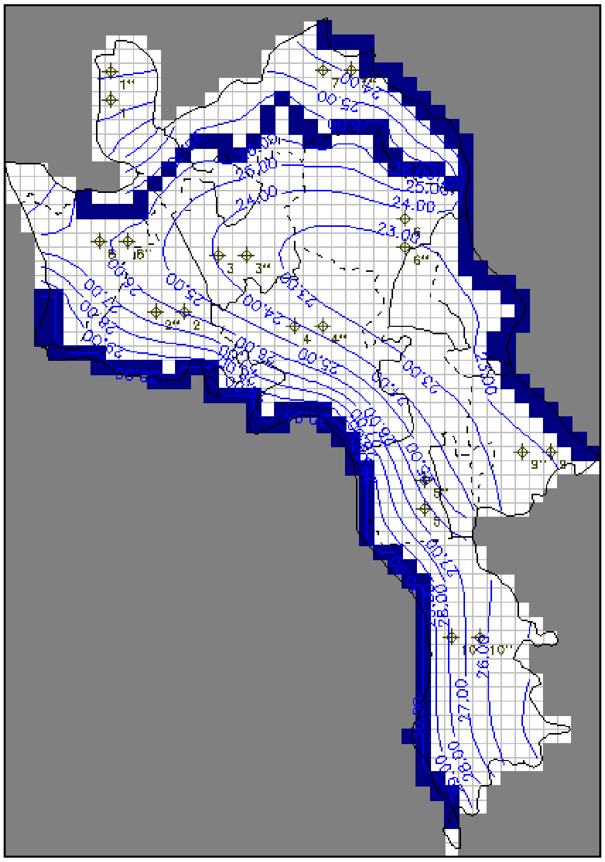

Fig. 7.21 Head distribution for coarse sand layer at the end of third monsoon period (1080 days)

7.2 DISTRIBUTION OF ARSENIC IN THE STUDY AREA

7.2.1 Concentration-Time curves

Ten pockets of maximum arsenic concentration have been used as the source of pollutants in the flow domain. The resultant concentration-time outputs for three years of simulation were recorded at a distance of 1000 m for all ten localized pockets. These are shown in Fig 7.22 to Fig. 7.31. The figures exhibit the arsenic concentration distribution in all the three layers of the soil media over time. The time period is divided into 10 equal time steps of 120 days each.

It is observed that the concentration in the sandy clay layer rises from its initial concentration of zero assumed at the starting of time. It seems that the arsenic concentration from sand layer is getting redistributed in the layers above and below to it. Arsenic concentration shows a marginal change with time in the bottom most layer i.e. coarse sand layer. As we know that potential aquifers in the study domain are found in the depth range of 44 - 69 m and 73 -89 m where coarse sand and gravel is encountered, the bottom most layer i.e. the coarse sand layer in our analysis is the most important layer for consideration. Even marginal rise in arsenic concentration for the bottom most layer will prove to be a major cause of concern for people residing in these areas. Increase in arsenic concentration at observation points is dependent on the location of observation wells in the study area. Areas along the flow direction are at much greater risk to rise in arsenic concentration than the lateral ones.

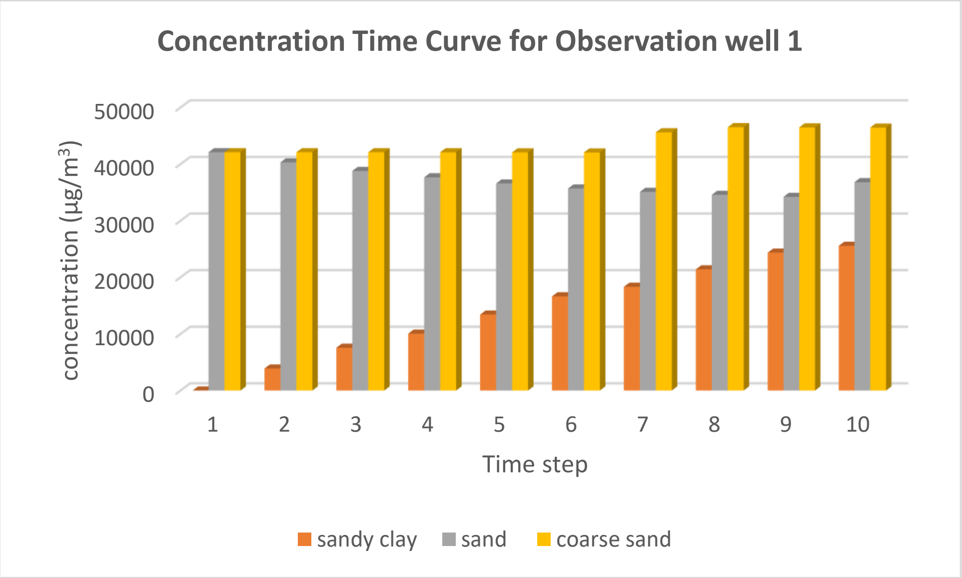

Fig. 7.22 Computed concentration for transient flow condition at 1000m away from the source point (Nagharia village, Phulbaria)

Percentage increase in arsenic concentration (for coarse sand layer) over a period of 3 years is 10.35%.

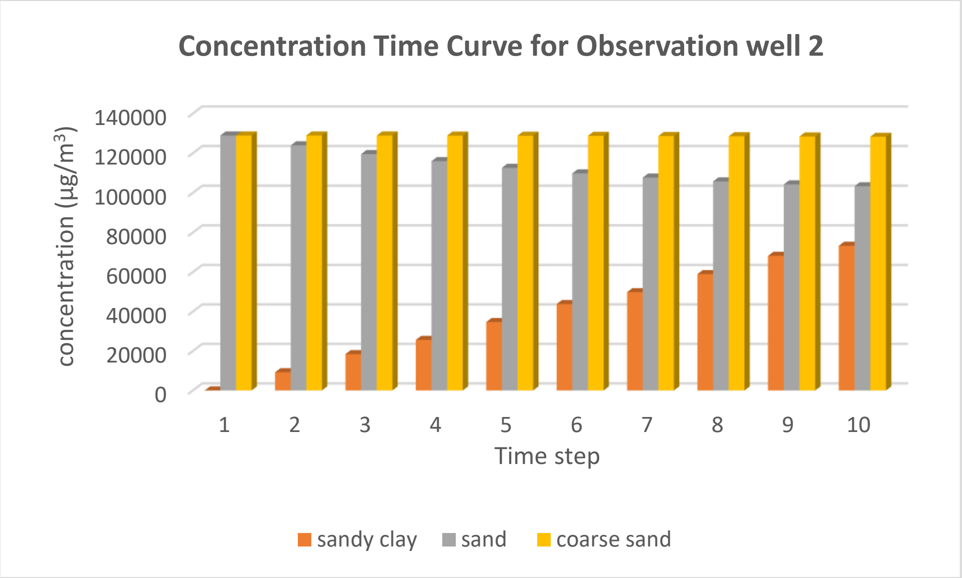

Fig. 7.23 Computed concentration for transient flow condition at 1000m away from the source point (Sattari village, Binodpur)

Percentage decrease in arsenic concentration (for coarse sand layer) over a period of 3 years is 0.50%.

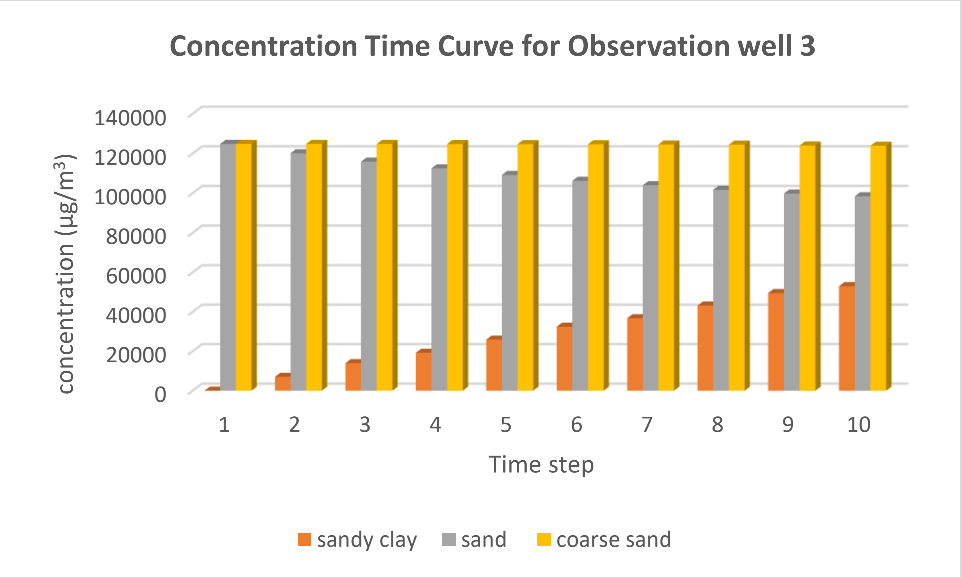

Fig. 7.24 Computed concentration for transient flow condition at 1000m away from the source point (Niamatpur village, Amrity)

Percentage decrease in arsenic concentration (for coarse sand layer) over a period of 3 years is 0.76%.

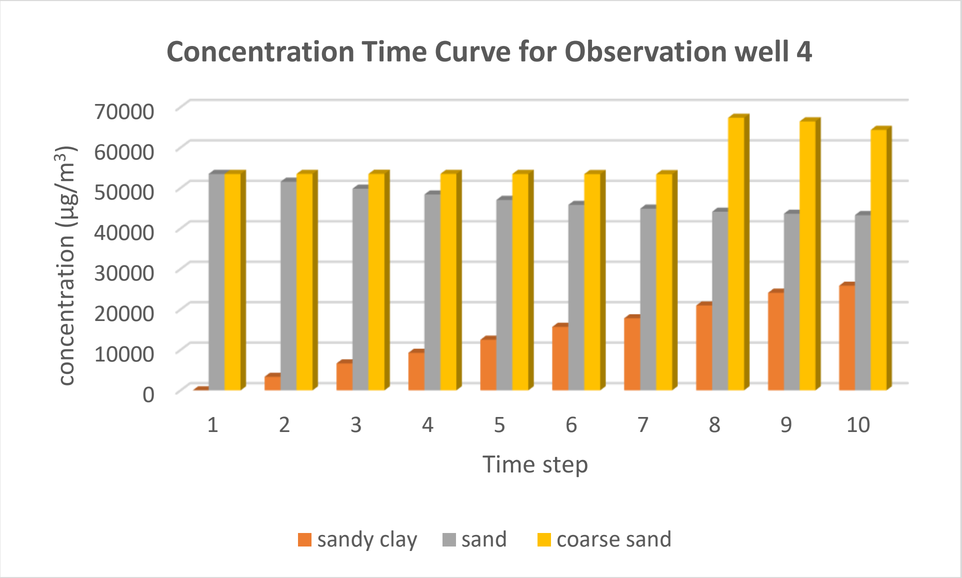

Fig. 7.25 Computed concentration for transient flow condition at 1000m away from the source point (Harishpur village, Kazigram)

Percentage increase in arsenic concentration (for coarse sand layer) over a period of 3 years is 20.35%.

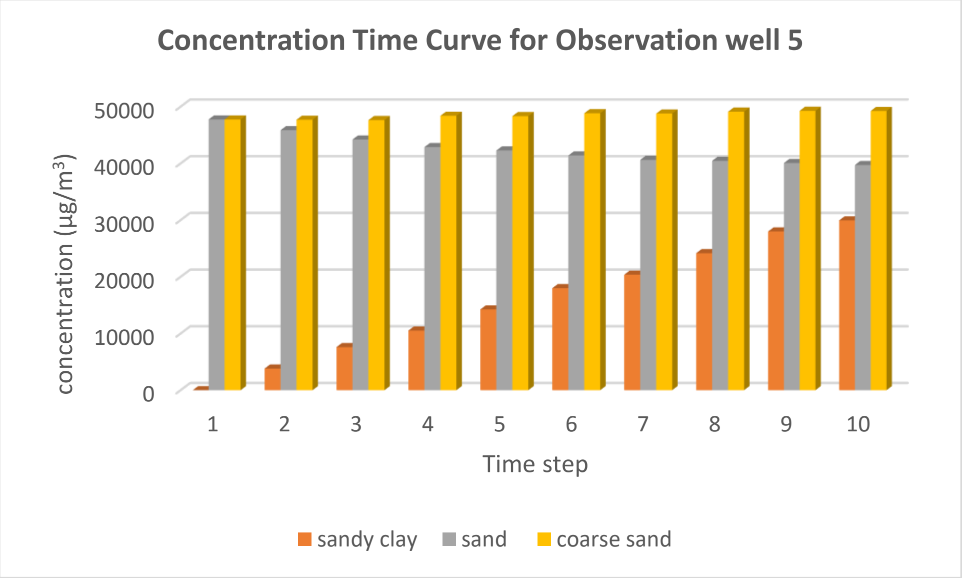

Fig. 7.26 Computed concentration for transient flow condition at 1000m away from the source point (Barachak village, Jadupur I)

Percentage increase in arsenic concentration (for coarse sand layer) over a period of 3 years is 3.13%.

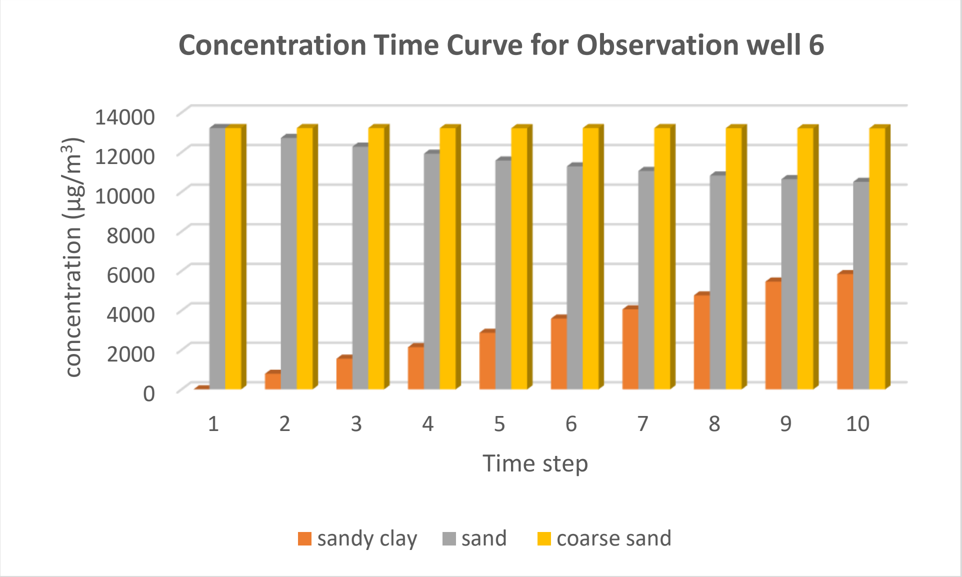

Fig. 7.27 Computed concentration for transient flow condition at 1000m away from the source point (Sahazalalpur village, Kotwali)

Percentage decrease in arsenic concentration (for coarse sand layer) over a period of 3 years is 0.14%.

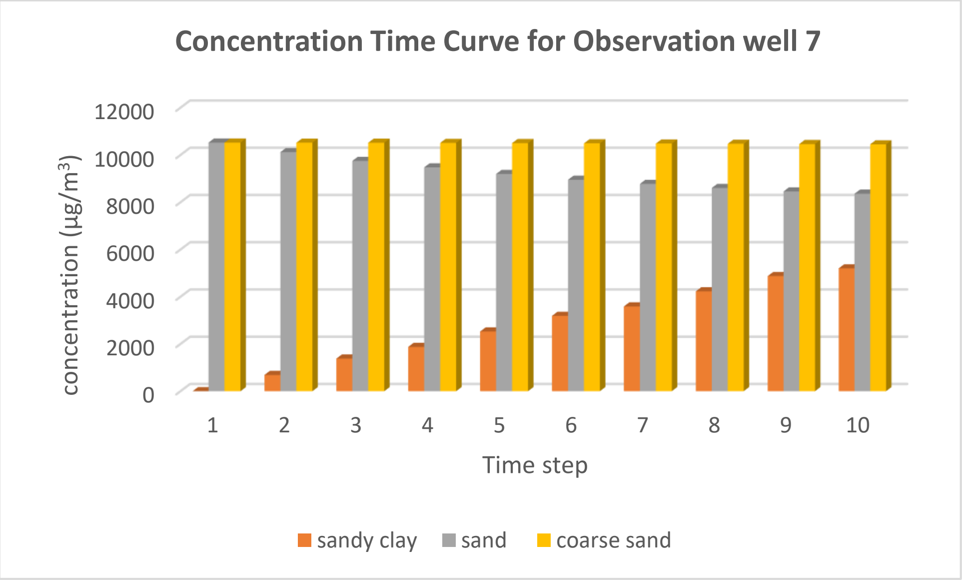

Fig. 7.28 Computed concentration for transient flow condition at 1000m away from the source point (Itakhola village, Norhatta)

Percentage decrease in arsenic concentration (for coarse sand layer) over a period of 3 years is 0.69%.

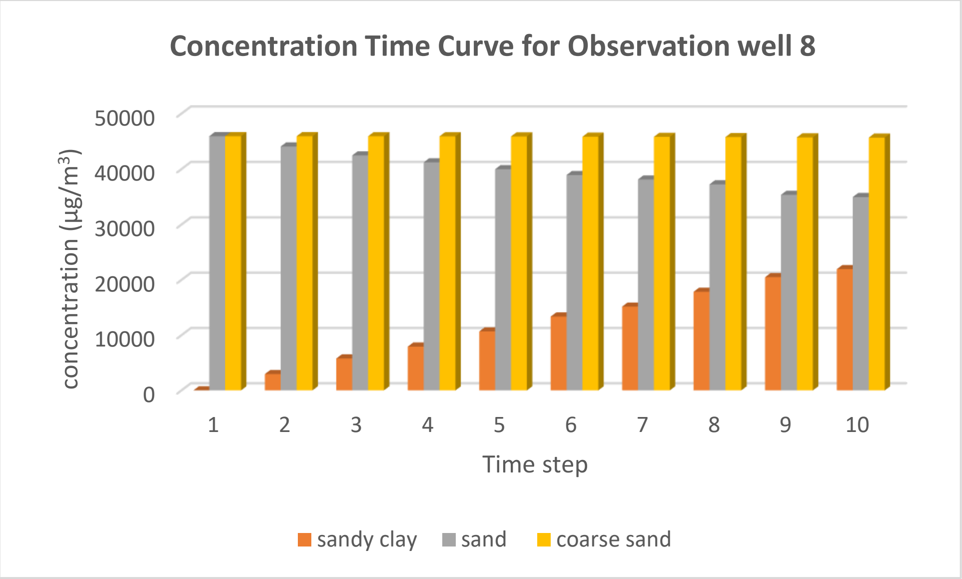

Fig. 7.29 Computed concentration for transient flow condition at 1000m away from the source point (Basudebpur village, Milky*)*

Percentage decrease in arsenic concentration (for coarse sand layer) over a period of 3 years is 0.56%.

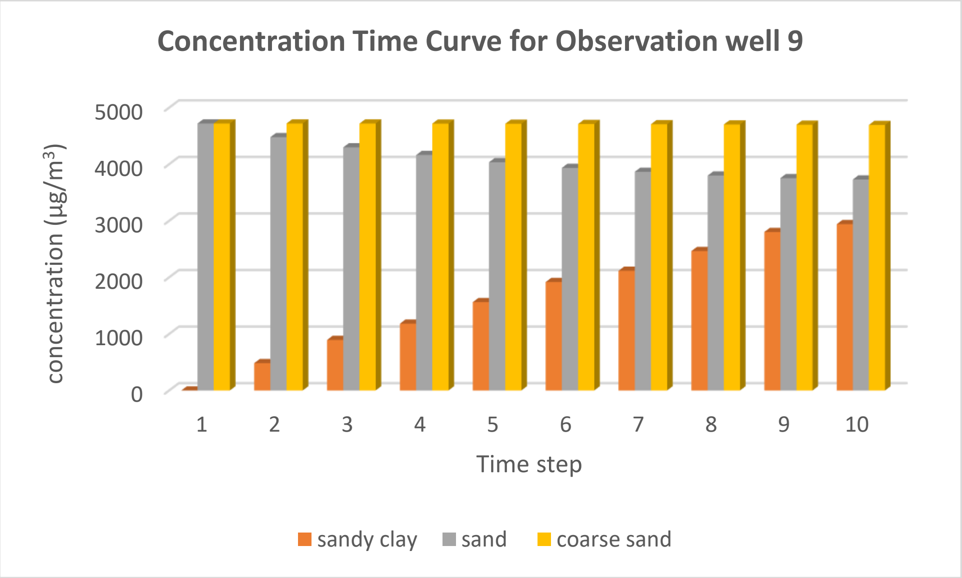

Fig. 7.30 Computed concentration for transient flow condition at 1000m away from the source point (Maheshpur village, Jadupur II)

Percentage decrease in arsenic concentration (for coarse sand layer) over a period of 3 years is 0.54%.

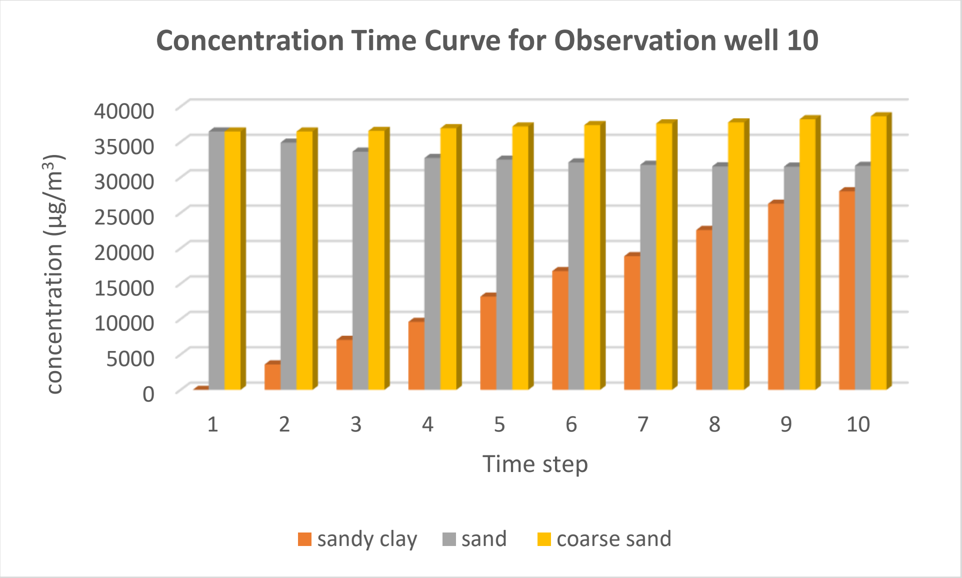

Fig. 7.31 Computed concentration for transient flow condition at 1000m away from the source point (Badulyabari village, Mahadipur)

Percentage increase in arsenic concentration (for coarse sand layer) over a period of 3 years is 5.89%.

7.2.2 Distribution of Arsenic in the Sandy Clay Layer

Fig. 7.32 (a) illustrates the distribution of arsenic in the clay layer of the study area at the start of time i.e. 0 days. Fig. 7.32 (b) illustrates the distribution of arsenic in the clay layer of the study area after 360 days. Fig. 7.32 (c) illustrates the distribution of arsenic in the clay layer of the study area after 720 days. Fig. 7.32 (d) illustrates the distribution of arsenic in the clay layer of the study area after 1080 days.

It was observed that arsenic concentrations in the clay layer increased from its base concentration of 0µg/m^3 assumed at the start of time. The concentration of arsenic increased at almost all nodes of the study domain with time from its base concentration. But the distribution of arsenic in the sandy clay layer was not uniform. The spatial distribution of arsenic in groundwater within the study area shows that the concentration broadly decreases from west to east. Binodpur and Amrity areas recorded maximum concentration of arsenic after a period of three years.

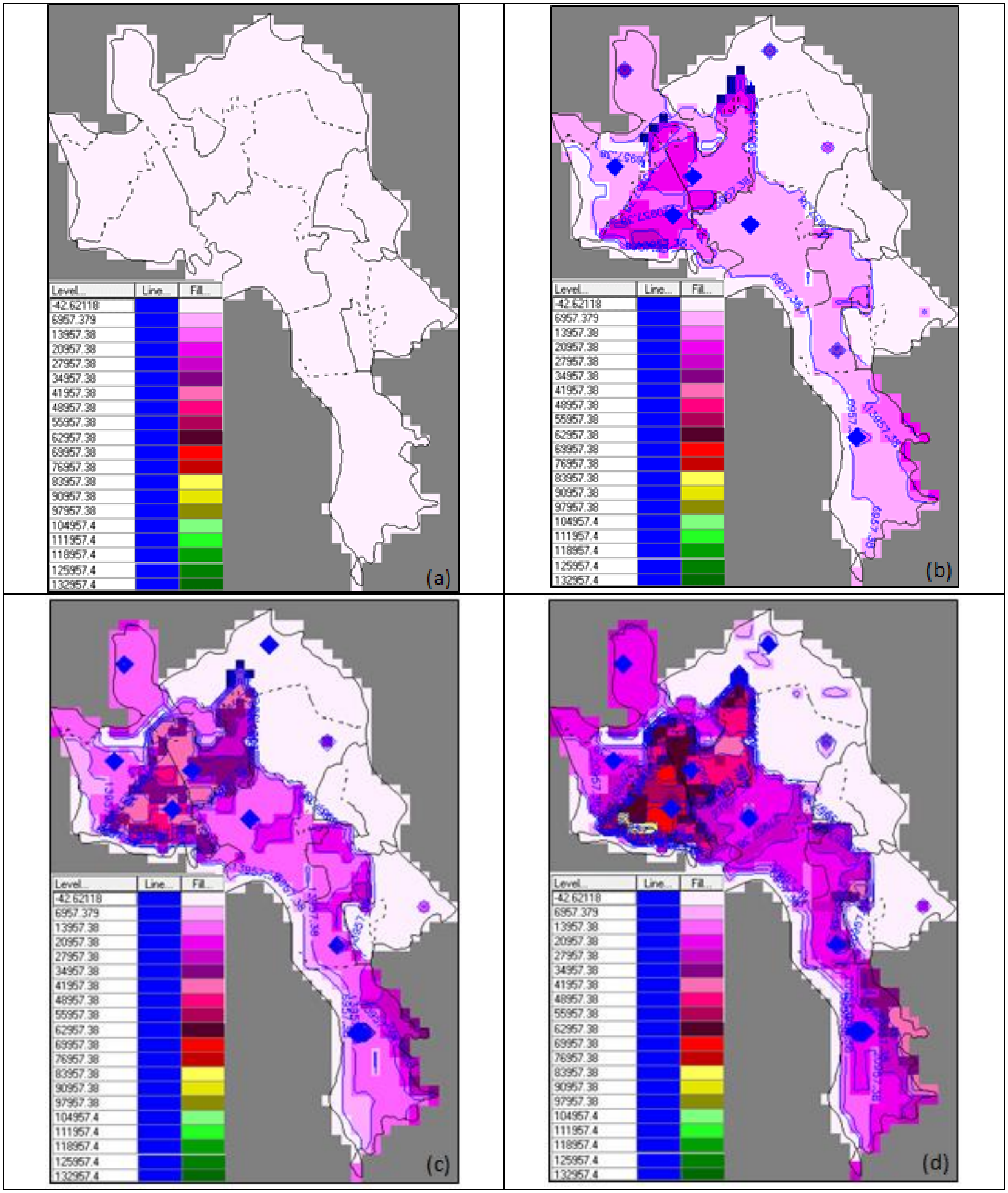

Fig. 7.32 Distribution of Arsenic in the Sandy Clay Layer at 0 days (a), after 360 days (b), after 720 days (c) and 1080 days (d)

7.2.3 Distribution of Arsenic in the Sand Layer

Fig. 7.33 (a) illustrates the distribution of arsenic in the sand layer of the study area at the start of time i.e. 0 days. Fig. 7.33 (b) illustrates the distribution of arsenic in the sand layer of the study area after 360 days. Fig. 7.33 (c) illustrates the distribution of arsenic in the sand layer of the study area after 720 days. Fig. 7.33 (d) illustrates the distribution of arsenic in the sand layer of the study area after 1080 days.

The arsenic concentrations in the sand layer drops marginally at all nodes from its initial defined concentration. This might be due to the fact that initial arsenic concentration were applied to the top of sand layers and coarse sand layers while zero concentration was assumed for the sandy clay layer. The high concentration gradient created between the first and the second layers i.e. sandy clay and clay layers, might have caused the movement of arsenic from sand layer to sandy clay layer. The spatial distribution of arsenic in groundwater within the study area shows that the concentration broadly decreases from west to east. Binodpur and Amrity areas recorded maximum concentration of arsenic after a period of three years.

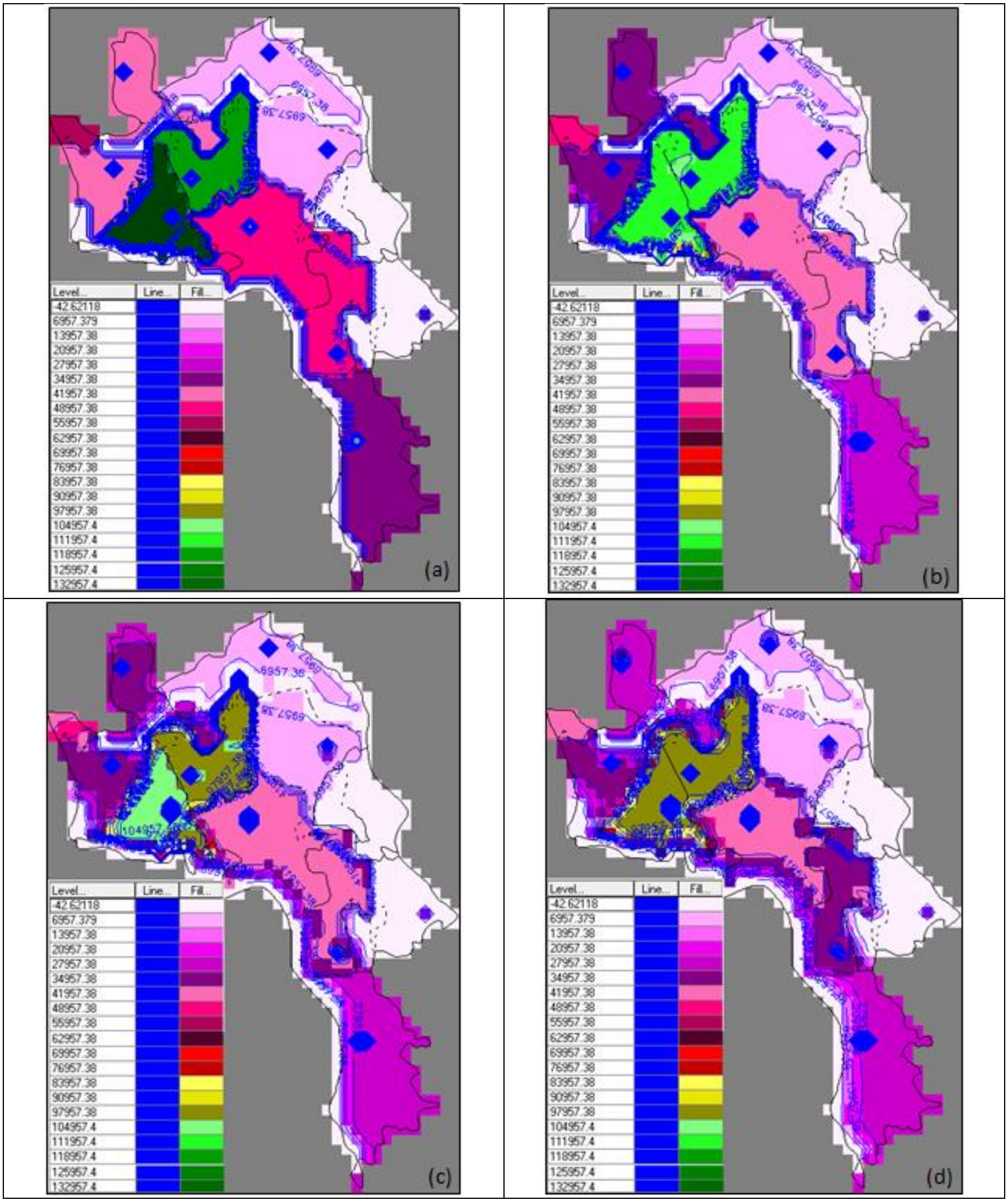

Fig. 7.33 Distribution of Arsenic in the Sand Layer at 0 days (a), after 360 days (b), after 720 days (c) and 1080 days (d)

7.2.4 Distribution of Arsenic in the Coarse Sand Layer

Fig. 7.34 (a) illustrates the distribution of arsenic in the coarse sand layer of the study area at the start of time i.e. 0 days. Fig. 7.34 (b) illustrates the distribution of arsenic in the coarse sand layer of the study area after 360 days. Fig. 7.34 (c) illustrates the distribution of arsenic in the coarse sand layer of the study area after 720 days. Fig. 7.34 (d) illustrates the distribution of arsenic in the coarse sand layer of the study area after 1080 days.

The arsenic concentrations in the coarse sand layer rises marginally at all nodes from its initial defined concentration. We are well aware that the potential aquifers in the study domain are found in the depth range of 44 - 69 m and 73 - 89 m where coarse sand and gravel layer is encountered. Therefore, even marginal rise in arsenic concentration for the coarse sand layer might be a major cause of concern for people in these areas. Areas along the flow direction are at much greater risk to the rise in arsenic concentration than the lateral ones. The spatial distribution of arsenic in groundwater within the study area shows that the concentration broadly decreases from west to east. Binodpur and Amrity areas recorded maximum concentration of arsenic after a period of three years.

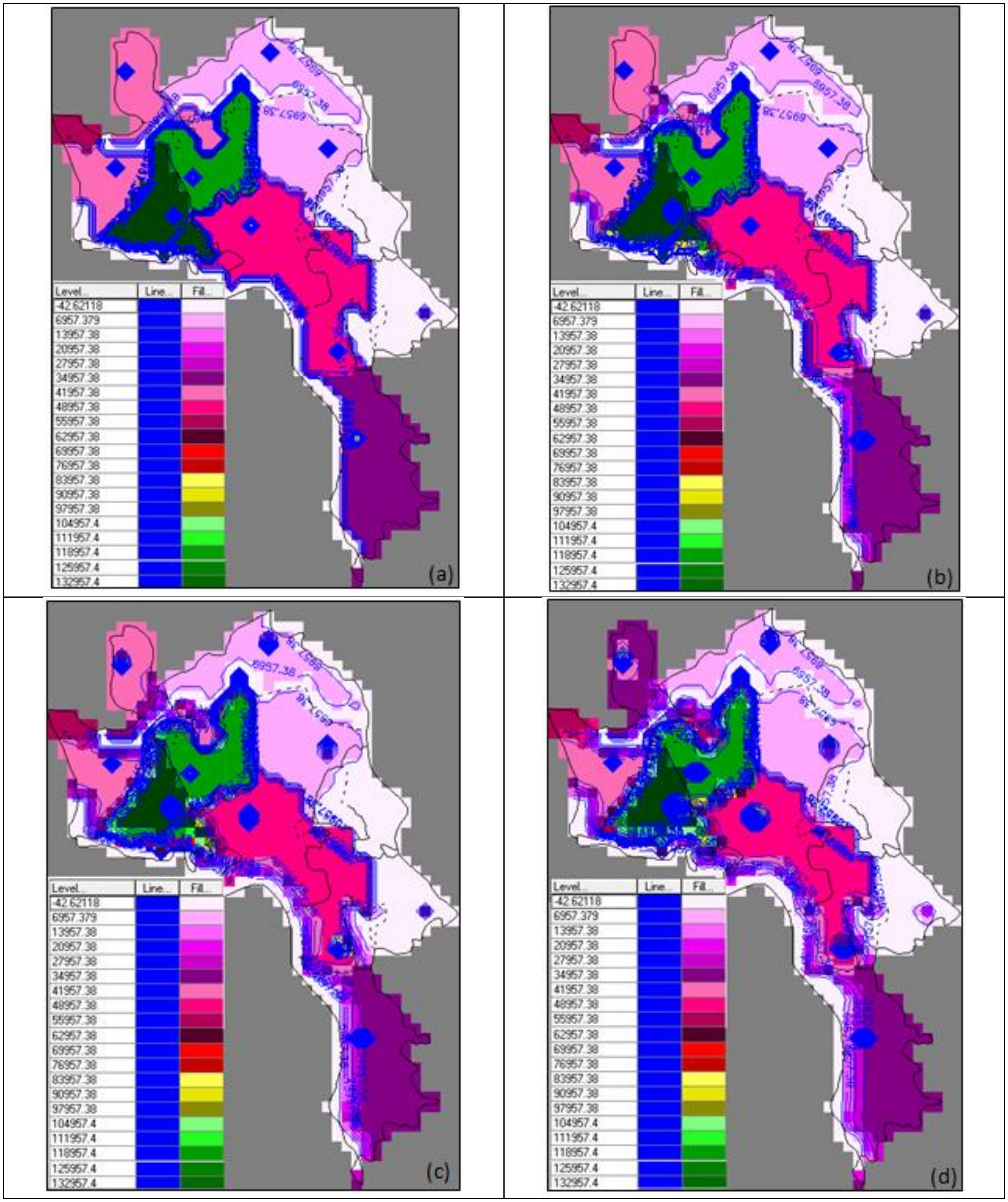

Fig. 7.34 Distribution of Arsenic in the Coarse Sand Layer at 0 days (a), after 360 days (b), after 720 days (c) and 1080 days (d)

CONCLUSION

From the study the following conclusions were made:

- Arsenic pollution of groundwater is one of the World's worst hit disasters affecting humans. Millions of people still drink arsenic contaminated water in countries like India, Bangladesh etc. due to limited availability of other reliable source of drinking water. Long-term exposure to excessive levels of arsenic causes changes in skin pigments and hyperkeratosis; promotes the development of ulcerations of skin; and accelerates the risk of cancer in liver, bladder, kidney and skin.

- Microbial reduction of iron oxyhydroxide (FeOOH) and release of its sorbed arsenic load to solution is the main mechanism by which arsenic enters the groundwater. Shallow aquifers are relatively more prone to contamination by arsenic than deep aquifers.

- MODFLOW was successfully used to simulate three-dimensional groundwater flow and it revealed the variation of hydraulic heads in the study area. MT3D simulated the movement of arsenic in the study area for a stress period of 1080 days and revealed the impact of high arsenic concentration pockets in the study area.

- The hydraulic heads contour map for the sand layer and the coarse sand layer is a gradual concave curve and the hydraulic heads contour map for the sandy clay layer is a sharp concave curve with steep hydraulic gradient in the periphery and gentler slope towards the center.

- There is a spatial and temporal variation in the concentration of arsenic due to the presence of high arsenic concentration pockets in the study area. The concentration of arsenic increases in the study area with time. Arsenic distribution is not uniform for the sandy clay layer whereas it is much more evenly distributed in the coarse sand layer.

- The potential aquifers in the study domain are found in the depth range of 44 - 69 m and 73 -89 m where coarse sand and gravel is encountered and thus even marginal rise in arsenic concentration for the bottom most layer might be a major cause of concern for people surrounding high arsenic concentration pocket areas. Areas along the flow direction are at much greater risk to the rise in arsenic concentration than the lateral ones.

LIMITATIONS OF THE STUDY

One of the weaknesses of the modelling is that no quantitative validation of the modelling could be done, due to the lack of data. This is why it is necessary to carry out more investigations and sampling campaigns, in order to both build a more accurate model, and to check the validity of the model. More head data are required not only during the same year to get a more accurate annual variation model, but also on several years to check if the variation is more or less the same every year. It is obviously necessary to get more concentration data: more scattered sampling spots are required in order to have a better representation of the whole area, and for these points, regular samplings should be done and analyzed in order to be able to visualize the true transport pattern of the contamination. Finally, it would be interesting to get more geological data, so that an observed soil distribution could be used instead of assumptions and unconditional material set generation. Soil distribution and characteristics were assumed, based on typical values. Those parameters might have a significant influence on flow modelling. The time frame of this project and the lack of input data did not allow to investigate this modelling as much as it could be, but it provide a good basis for further studies.

APPLICATIONS OF THE STUDY

The study deals with simulation of water and arsenic movement using a 3D solute transport model. The hydraulic heads of the groundwater in the study area were studied to understand the direction of flow of groundwater. It was assumed that high arsenic concentration pockets in the study area served as the source of arsenic for the area under consideration. The temporal and spatial distribution and movement were studied.

The results of this study will be useful to individuals, municipalities, and regulators who all have an interest in maintaining safe drinking water supplies. An understanding of the mechanisms controlling arsenic contamination will be useful in modifying well construction methods and placing new wells to prevent contamination and in designing mitigation measures for already contaminated wells.

This study will be useful in understanding the difference in the movement of arsenic in soil. From this a mitigation scheme can be chopped out to control the spread of arsenic. This study can also be manipulated to locate safe drinking water wells in the arsenic polluted groundwater in the study area. This can be done by locating areas and aquifer layers having permissible (least) arsenic in the groundwater.

FUTURE SCOPE OF WORK

Simulations of these types can be used as a tool to elicit and discern the detailed structure of evolving solute plumes that occur in realistic aquifer systems and to validate predictions of their large-scale behavior.

Future simulations on similar lines with experimentally determined hydraulic parameters of the aquifer will be very helpful in determining the arsenic polluted areas. Such similar models can also be applied to other regions of the world where there is contamination of the groundwater with other pollutants.

This model can be further developed to simulate movement of multi-species contaminants. Additional work can be carried out in systems characterized by different physical boundaries.

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APPENDIX

LITHO LOGS OF THE STUDY AREA

1. SAHAJALPUR MOUZA-I

Unit	Lithology	Depth (m)	Thickness (m)
1.	Grey Clay	0.00-9.14	9.14
2.	Clay Mixed with Silt	9.14-15.24	6.1
3.	Grey Clay	15.24-18.28	3.04
4.	Fine Sand Yellowish	18.28-24.382	6.1
5.	Whitish fine Sand	24.38-30.48	6.1
6.	Medium Sand Whitish	30.48-33.52	3.04
7.	Sandy Loam	33.52-36.57	3.05
8.	Clayey loam	36.57-39.62	3.05
9.	Whitish fine Sand	39.62-48.76	9.14
10.	Whitish Medium Sand	48.76-51.81	3.05
11.	Whitish fine Sand	51.81-54.86	3.05
12.	Whitish Medium Sand	54.86-60.96	6.1
13.	Whitish Fine Sand with Silt	60.96-64.08	3.12
14.	Whitish Fine Sand	64.08-70.14	6.06
15.	Whitish Medium Sand	70.14-79.24	9.1
16.	Whitish Coarse Sand	79.24-85.34	6.1
17.	Whitish Medium Sand	85.34-91.44	6.1
18.	Grey Clay	91.44-106.44	15
19.	Whitish Fine Sand	106.44-119.44	13

2. SAHAJALPUR MOUZA-II

Unit	Lithology	Depth (m)	Thickness (m)
1.	Grey Clay	0-3.05	3.05
2.	Silty Grey Clay	3.05-9.14	6.09
3.	Grey Silty Clay	9.14-12.19	3.05
4.	Very Fine Sand	12.19-15.24	3.05
5.	Very Fine Sand mixed with silt	15.24-18.28	3.04
6.	Very Fine Sand	18.28-24.38	6.1
7.	Fine Sand	24.38-27.43	3.05
8.	Whitish Fine Sand	27.43-30.48	3.05
9.	Whitish Medium Sand	30.48-33.52	3.04
10.	Whitish Coarse Sand	33.52-42.67	9.15
11.	Whitish Sandy Loam	42.67-45.72	3.05
12.	Whitish Fine Sand With mica	45.72-51.8	6.08
13.	Whitish Medium Sand	51.8-60.96	9.16
14.	Whitish Fine Sand	60.96-64	3.04
15.	Whitish Medium Sand	64-67.05	3.05
16.	Whitish Medium Sand	67.05-91.44	24.39
17.	Silty Grey Clay	91.44-106.68	15.24
18.	Fine Sand	106.68-119.52	12.84

3. JOT BASANTA-I

Unit	Lithology	Depth (m)	Thickness (m)
1.	Grey Clay	0-15.24	15.24
2.	Yellowish Fine Sand mixed with mica	15.24-21.33	6.09
3.	Yellowish fine to medium sand mixed with mica	21.33-27.43	6.1
4.	Whitish medium Sand	27.43-36.57	9.14
5.	Whitish Medium to fine Sand	36.57-39.62	3.05
6.	Yellowish Medium Sand	39.62-51.81	12.19
7.	Yellowish fine to medium sand mixed with mica	51.81-57.91	6.1
8.	Whitish Fine Sand	57.91-64	6.09
9.	Whitish Fine to medium Sand	64-67.05	3.05
10.	Whitish medium Sand	67.05-79.24	12.19
11.	Whitish Fine Sand	79.24-82.29	3.05
12.	Whitish medium Sand	82.29-97.53	15.24
13.	Grey Clayey Sand	97.53-119.53	22

4. JOT BASANTA-II

Unit	Lithology	Depth (m)	Thickness (m)
1.	Sandy loam Greyish	0-6.096	6.096
2.	Grey Clay	6.096-15.24	9.144
3.	Yellowish Medium Sand	15.24-18.28	3.04
4.	Yellowish Fine Sand	18.28-21.33	3.05
5.	Yellowish Medium Sand	21.33-30.48	9.15
6.	Whitish medium Sand	30.48-39.62	9.14
7.	Yellowish Medium Sand	39.62-42.67	3.05
8.	Yellowish medium to fine Sand	42.67-51.81	9.14

9.	Yellowish Fine Sand	51.81-57.91	6.1
10.	Whitish medium Sand	57.91-60.96	3.05
11.	Whitish fine Sand	60.96-67.05	6.09
12.	Whitish medium Sand	67.05-88.39	21.34
13.	Whitish fine Sand	88.39-91.44	3.05
14.	Grey Clay	91.44-119.53	28.09

5. NAGARIA-I

Unit	Lithology	Depth (m)	Thickness (m)
1.	Sandy Clay	0-14.73	14.73
2.	Fine Sand	14.73-48.83	34.1
3.	Coarse Sand	48.83-55.05	6.22
4.	Fine Sand	55.05-64.3	9.25
5.	Coarse Sand	64.3-101.27	36.97
6.	Fine Sand	101.27-120	18.73

6. NAGARIA-II

Unit	Lithology	Depth (m)	Thickness (m)
1.	Fine Sand	0-20.91	20.91
2.	Medium Sand	20.91-42.53	21.62
3.	Medium Sand	42.53-92.2	49.67
4.	Coarse Sand	92.2-95.32	3.12
5.	Fine Sand	95.32-120	24.68

7. RAMCHANDRAPUR MAUZA-I

Unit	Lithology	Depth (m)	Thickness (m)
1.	Greyish Silty Soil	0-3.05	3.05
2.	Greyish Silty Loam	3.05-9.14	6.09
3.	Greyish Fine Sandy Loam	9.14-12.19	3.05
4.	Greyish Fine sand mixed with clay	12.19-15.24	3.05
5.	Whitish medium sand	15.24-27.43	12.19
6.	Whitish medium sand mixed with clay	27.43-39.62	12.19
7.	Whitish fine sand	39.62-42.67	3.05
8.	Very fine sand mixed with clay	42.67-45.72	3.05
9.	Whitish medium to fine sand	45.72-48.76	3.04
10.	Whitish medium sand	48.76-60.96	12.2
11.	Silty soil	60.96-73.15	12.19
12.	Grey very fine sand	73.15-94.18	21.03
13.	Grey clay	94.18-118.56	24.38

8. RAMCHANDRAPUR MAUZA-II

Unit	Lithology	Depth (m)	Thickness (m)
1.	whitish fine sand	0-6.1	6.1
2.	grey sieve sand mixed with clay	6.1-9.144	3.044
3.	grey sieve sand	9.144-12.19	3.046
4.	fine sandy loam mixed with clay	12.19-15.24	3.05
5.	grey very fine sand	15.24-18.28	3.04
6.	grey very fine sand mixed with clay	18.28-24.38	6.1
7.	grey fine sand	24.38-30.48	6.1
8.	whitish fine sand	30.48-36.57	6.09

9.	whitish very fine sand	36.57-42.67	6.1
10.	whitish fine sand	42.67-45.72	3.05
11.	whitish medium sand	45.72-54.86	9.14
12.	whitish medium coarse sand	54.86-57.91	3.05
13.	whitish coarse sand	57.91-60.96	3.05
14.	milky white fine sand	60.96-67.05	6.09
15.	silty soil	67.05-73.15	6.1
16.	grey very fine sand	73.15-94.48	21.33
17.	grey clay	94.48-119.56	25.08

9. LAKSHMI GHAT-I

Unit	**Lithology**	**Depth (m)**	**Thickness (m)**
1.	Grey Sandy Clay	0-6.096	6.096
2.	Grey Fine Sand	6.096-15.24	9.144
3.	Grey medium to fine Sand	15.24-33.528	18.288
4.	Grey Fine Sand	33.528-48.76	15.232
5.	Medium to Fine Sand	48.76-57.91	9.15
6.	Whitish Medium Sand	57.91-67.05	9.14
7.	Grey Medium Sand	67.05-70.1	3.05
8.	Whitish Medium Sand	70.1-79.24	9.14
9.	Whitish Coarse Sand	79.24-85.344	6.104
10.	Grey medium Sand	85.344-88.392	3.048
11.	Grey Fine Sand Mixed with Clay	88.392-97.53	9.138

10. LAKSHMI GHAT-II

Unit	Lithology	Depth (m)	Thickness (m)
1.	Grey Sandy Clay	0-6.096	6.096
2.	Grey Fine sand	6.096-15.24	9.144
3.	Grey medium to Fine Sand	15.24-33.52	18.28
4.	Grey Fine sand	33.52-48.76	15.24
5.	Medium to fine Sand	48.76-57.91	9.15
6.	whitish Medium sand	57.91-67.05	9.14
7.	Grey Medium sand	67.05-70.1	3.05
8.	whitish Medium sand	70.1-79.24	9.14
9.	Whitish Coarse Sand	79.24-85.34	6.1
10.	Grey Medium Sand	85.34-88.392	3.052
11.	Grey Fine Sand Mixed with Clay	88.392-97.53	9.138
12.	Clayey Loam	97.53-119.33	21.8

11. ITAKHOLA MAUZA-I

Unit	Lithology	Depth (m)	Thickness (m)
1.	Sandy Clay	0-3.05	3.05
2.	Clay	3.05-9.14	6.09
3.	Sandy Clay	9.14-12.19	3.05
4.	Pebbles	12.19-18.29	6.1
5.	Sandy Clay	18.29-24.38	6.09
6.	White Sand	24.38-36.58	12.2
7.	White Coarse Sand	36.58-48.67	12.09
8.	Clayey Coarse Sand	48.67-57.91	9.24
9.	Red Sand	57.91-70.1	12.19

10.	Red Coarse Sand	70.1-73.15	3.05
11.	Red & White Sand	73.15-76.2	3.05
12.	White Coarse Sand	76.2-85.34	9.14
13.	Sandy Clay	85.34-105.34	20
14.	White Sand	105.34-119.34	14

12. ITAKHOLA MAUZA-II

Unit	Lithology	Depth (m)	Thickness (m)
1.	Sandy loam	0-3.05	3.05
2.	Yellowish Clay	3.05-6.1	3.05
3.	Clayey Loam	6.1-9.14	3.04
4.	Sandy loam	9.14-12.19	3.05
5.	Clayey Loam	12.19-15.24	3.05
6.	Clay Mixed With Gravels	15.24-18.28	3.04
7.	very Fine Sand mixed With mica	18.28-24.38	6.1
8.	fine Sand mixed With mica	24.38-27.43	3.05
9.	Whitish Fine Sand	27.43-33.52	6.09
10.	fine Sand mixed With mica	33.52-36.57	3.05
11.	Whitish Medium Sand	36.57-42.67	6.1
12.	Yellowish Coarse Sand	42.67-45.72	3.05
13.	Yellowish Medium Sand	45.72-48.76	3.04
14.	Sandy Clay	48.76-54.86	6.1
15.	Medium Sand mixed with Clay	54.86-57.91	3.05
16.	Very Fine Yellowish Sand	57.91-60.96	3.05
17.	Medium yellowish Sand	60.96-76.2	15.24
18.	Yellowish Medium Sand	76.2-85.34	9.14
19.	Clay Mixed With Gravels	85.34-105.34	20

20.	very Fine Sand mixed With clay	105.34-120.34	15

13. BARACHAUK MAUZA-I

Unit	Lithology	Depth (m)	Thickness (m)
1.	Grey Sandy Clay	0-6.096	6.096
2.	Grey Silty Clay	6.096-15.24	9.144
3.	Fine Grey Sand	15.24-18.28	3.04
4.	Grey fine to medium Sand	18.28-21.33	3.05
5.	Grey Medium Sand	21.33-36.57	15.24
6.	whitish Medium to fine Sand	36.57-39.62	3.05
7.	Whitish Medium Sand	39.62-54.86	15.24
8.	whitish Coarse Sand	54.86-64.08	9.22
9.	Grey Clay	64.08-73.15	9.07
10.	Grey Stiff Clay	73.15-79.2	6.05
11.	Whitish fine Sand	79.2-82.22	3.02
12.	Whitish Medium Sand	82.22-88.39	6.17
13.	Whitish fine Sand	88.39-97.53	9.14
14.	Grey Sandy Clay	97.53-106.33	8.8
15.	Grey Fine Sand	106.33-119.52	13.19

14. BARACHAUK MAUZA-II

Unit	Lithology	Depth (m)	Thickness (m)
1.	Clay Grey Sticky	0-9.14	9.14
2.	Sand Fine Grey	9.14-12.19	3.05
3.	Sand Fine Grey mixed with clay	12.19-15.24	3.05
4.	Sand Fine Grey	15.24-30.48	15.24

5.	Sand Fine Grey to medium Grey	30.48-39.62	9.14
6.	Sand fine Grey	39.62-42.67	3.05
7.	Sand fine to medium grey	42.67-54.86	12.19
8.	Sand fine Grey	54.86-67.06	12.2
9.	Clay Mixed With Silt	67.06-87.04	19.98
10.	Grey Clay	87.04-97.05	10.01
11.	Medium Sand Whitish	97.05-109.05	12
12.	Clayey Loam	109.05-118.95	9.9

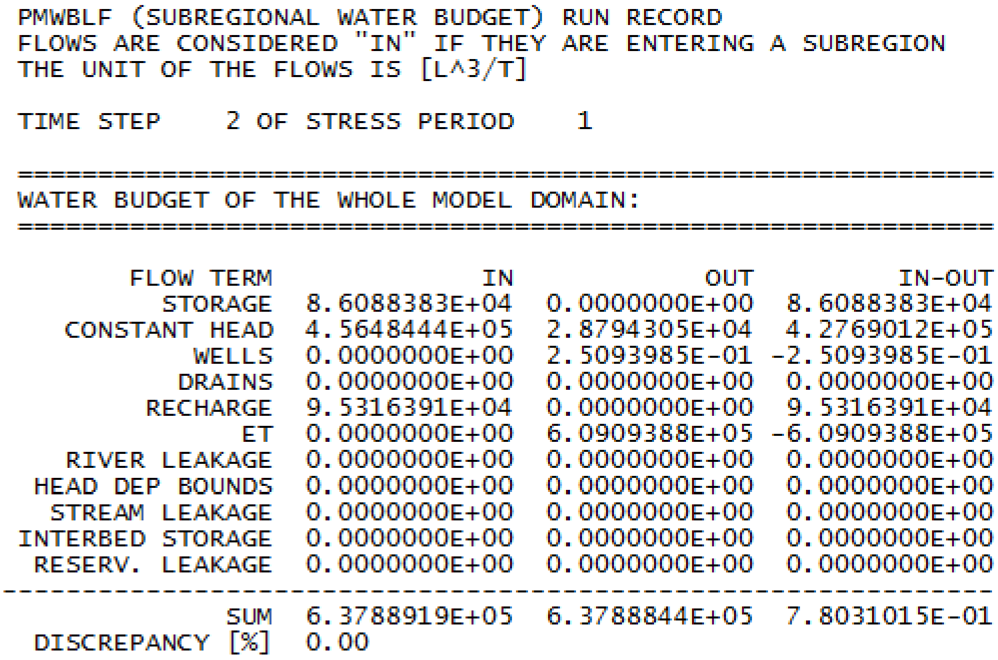
15. LALAPUR

Unit	**Lithology**	**Depth (m)**	**Thickness (m)**
1.	Surface Soil Clay	0-3	3
2.	Very Fine Sand with Silt	3-15	12
3.	Fine Sand Grey	15-30	15
4.	Fine Sand with hard Formation	30-33.5	3.5
5.	Fine Sand Grey	33.5-36.58	3.08
6.	medium Sand Grey	36.58-39.6	3.02
7.	Fine Sand Grey	39.6-45.13	5.53
8.	Fine Sand Yellow	45.13-48.78	3.65
9.	Very Fine Sand grey	48.78-57.82	9.04
10.	Fine Sand Grey	57.82-70.12	12.3
11.	Fine to medium Sand Grey	70.12-85.36	15.24
12.	Medium to Coarse Sand Greyish	85.36-90.51	5.15
13.	Very Fine Sad Greyish	90.51-95	4.49

GROUNDWATER RESOURCES OF ENGLISH BAZAR BLOCK (Source: CGWB)

Name of Ground water Assessment Unit	**Name of Ground water Assessment Sub- Unit**	**Recharge from rainfall in ham**		**Recharge from other sources in ham**		**Total Annual Ground Water Recharge in ham**	**Existing Gross Ground Water Draft for All uses in ham**
		Monsoon	**Non-monsoon**	**Monsoon**	**Non-monsoon**		
ENGLISH BAZAR	Command	0.00	0.00	0.00	0.00	0.00	0.00
	Nom-Command	5530.96	1805.58	366.38	1086.23	8789.15	3746.52
	Poor Ground Water Quality	0.00	0.00	0.00	0.00	0.00	0.00

WATER BUDGET



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PMWBLF (SUBREGIONAL WATER BUDGET) RUN RECORD
FLOWS ARE CONSIDERED "IN" IF THEY ARE ENTERING A SUBREGION
THE UNIT OF THE FLOWS IS [L^3/T]

TIME STEP    2 OF STRESS PERIOD    1

==============================================================
WATER BUDGET OF THE WHOLE MODEL DOMAIN:
==============================================================

       FLOW TERM              IN             OUT          IN-OUT
         STORAGE  8.6088383E+04  0.0000000E+00  8.6088383E+04
   CONSTANT HEAD  4.5648444E+05  2.8794305E+04  4.2769012E+05
           WELLS  0.0000000E+00  2.5093985E-01 -2.5093985E-01
          DRAINS  0.0000000E+00  0.0000000E+00  0.0000000E+00
        RECHARGE  9.5316391E+04  0.0000000E+00  9.5316391E+04
              ET  0.0000000E+00  6.0909388E+05 -6.0909388E+05
   RIVER LEAKAGE  0.0000000E+00  0.0000000E+00  0.0000000E+00
  HEAD DEP BOUNDS  0.0000000E+00  0.0000000E+00  0.0000000E+00
  STREAM LEAKAGE  0.0000000E+00  0.0000000E+00  0.0000000E+00
INTERBED STORAGE  0.0000000E+00  0.0000000E+00  0.0000000E+00
  RESERV. LEAKAGE  0.0000000E+00  0.0000000E+00  0.0000000E+00
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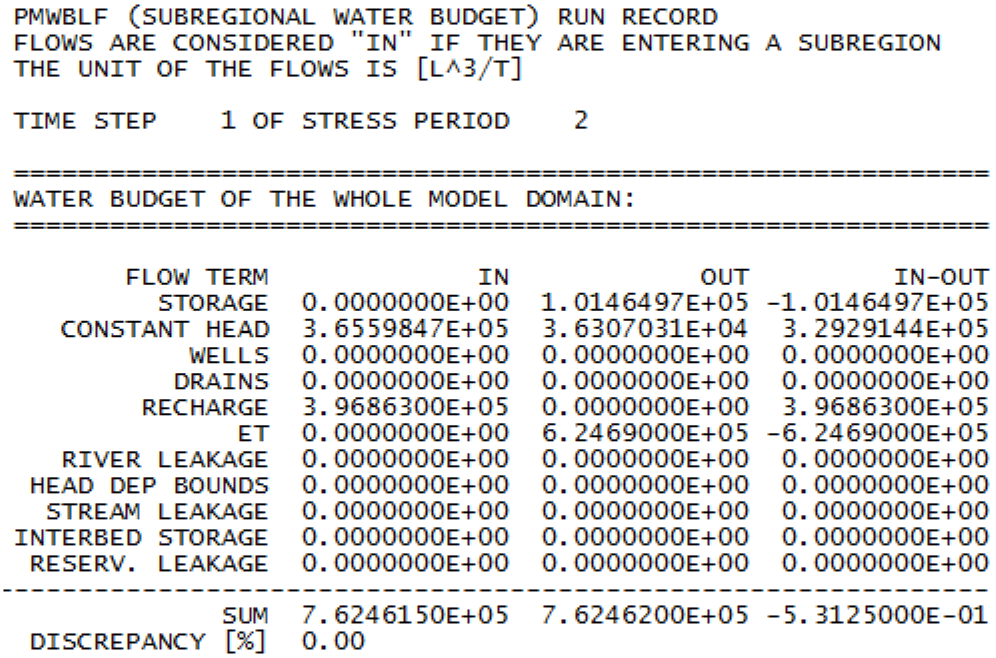

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PMWBLF (SUBREGIONAL WATER BUDGET) RUN RECORD
FLOWS ARE CONSIDERED "IN" IF THEY ARE ENTERING A SUBREGION
THE UNIT OF THE FLOWS IS [L^3/T]

TIME STEP    1 OF STRESS PERIOD    2

============================================================
WATER BUDGET OF THE WHOLE MODEL DOMAIN:
============================================================

       FLOW TERM             IN             OUT          IN-OUT
         STORAGE  0.0000000E+00  1.0146497E+05 -1.0146497E+05
   CONSTANT HEAD  3.6559847E+05  3.6307031E+04  3.2929144E+05
           WELLS  0.0000000E+00  0.0000000E+00  0.0000000E+00
          DRAINS  0.0000000E+00  0.0000000E+00  0.0000000E+00
        RECHARGE  3.9686300E+05  0.0000000E+00  3.9686300E+05
              ET  0.0000000E+00  6.2469000E+05 -6.2469000E+05
   RIVER LEAKAGE  0.0000000E+00  0.0000000E+00  0.0000000E+00
  HEAD DEP BOUNDS  0.0000000E+00  0.0000000E+00  0.0000000E+00
  STREAM LEAKAGE  0.0000000E+00  0.0000000E+00  0.0000000E+00
INTERBED STORAGE  0.0000000E+00  0.0000000E+00  0.0000000E+00
  RESERV. LEAKAGE  0.0000000E+00  0.0000000E+00  0.0000000E+00
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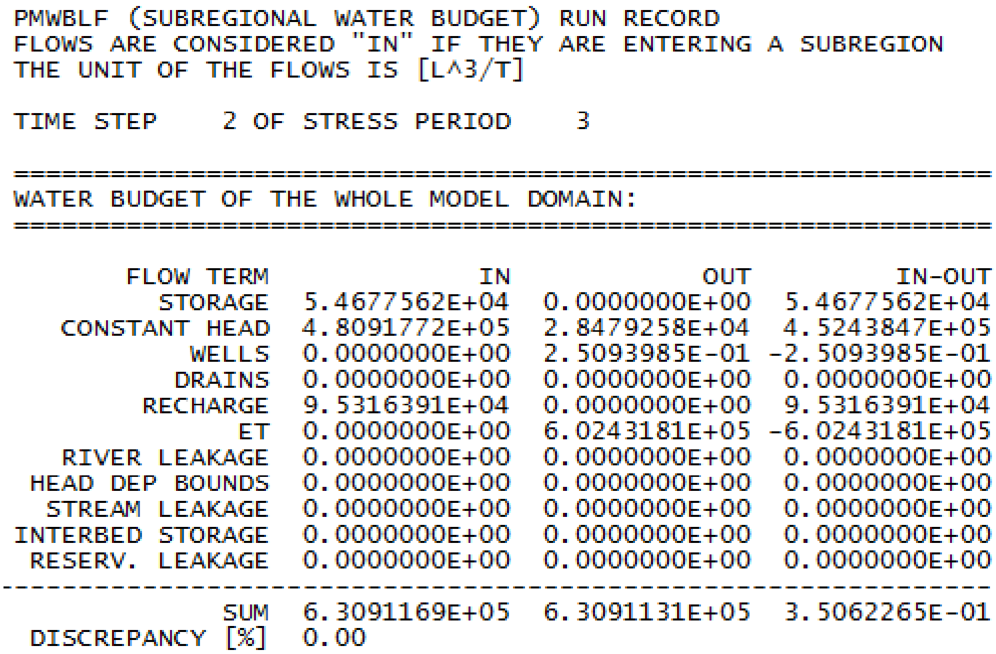

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PMWBLF (SUBREGIONAL WATER BUDGET) RUN RECORD
FLOWS ARE CONSIDERED "IN" IF THEY ARE ENTERING A SUBREGION
THE UNIT OF THE FLOWS IS [L^3/T]

TIME STEP    2 OF STRESS PERIOD    3

============================================================
WATER BUDGET OF THE WHOLE MODEL DOMAIN:
============================================================

       FLOW TERM             IN             OUT          IN-OUT
         STORAGE  5.4677562E+04  0.0000000E+00  5.4677562E+04
   CONSTANT HEAD  4.8091772E+05  2.8479258E+04  4.5243847E+05
           WELLS  0.0000000E+00  2.5093985E-01 -2.5093985E-01
          DRAINS  0.0000000E+00  0.0000000E+00  0.0000000E+00
        RECHARGE  9.5316391E+04  0.0000000E+00  9.5316391E+04
              ET  0.0000000E+00  6.0243181E+05 -6.0243181E+05
   RIVER LEAKAGE  0.0000000E+00  0.0000000E+00  0.0000000E+00
  HEAD DEP BOUNDS  0.0000000E+00  0.0000000E+00  0.0000000E+00
  STREAM LEAKAGE  0.0000000E+00  0.0000000E+00  0.0000000E+00
INTERBED STORAGE  0.0000000E+00  0.0000000E+00  0.0000000E+00
  RESERV. LEAKAGE  0.0000000E+00  0.0000000E+00  0.0000000E+00
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  DISCREPANCY [%]  0.00
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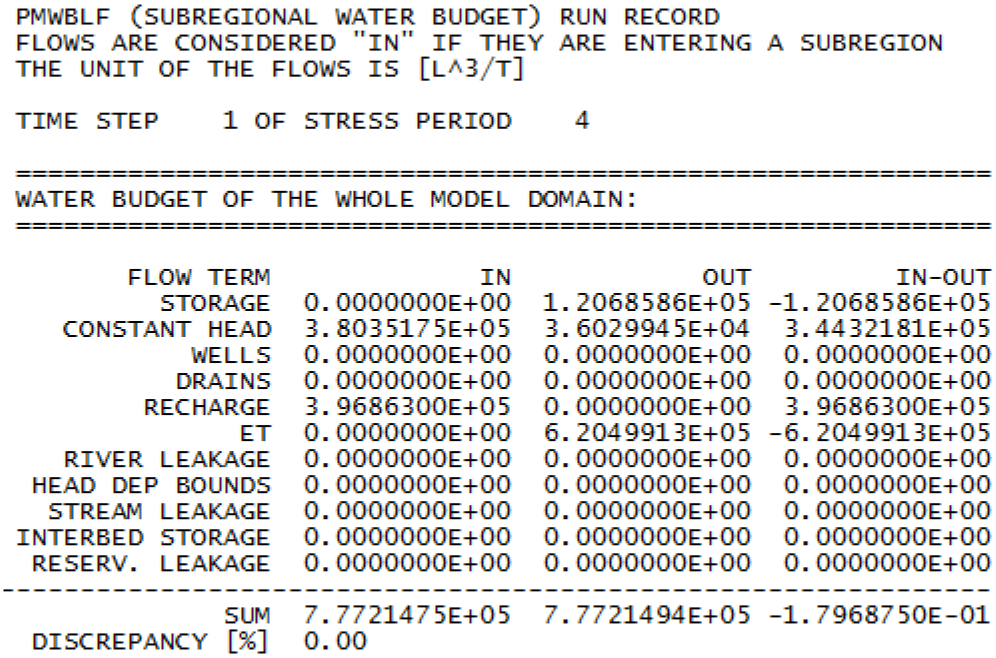

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PMWBLF (SUBREGIONAL WATER BUDGET) RUN RECORD
FLOWS ARE CONSIDERED "IN" IF THEY ARE ENTERING A SUBREGION
THE UNIT OF THE FLOWS IS [L^3/T]

TIME STEP    1 OF STRESS PERIOD    4

==============================================================
WATER BUDGET OF THE WHOLE MODEL DOMAIN:
==============================================================

       FLOW TERM               IN             OUT          IN-OUT
         STORAGE  0.0000000E+00  1.2068586E+05 -1.2068586E+05
   CONSTANT HEAD  3.8035175E+05  3.6029945E+04  3.4432181E+05
           WELLS  0.0000000E+00  0.0000000E+00  0.0000000E+00
          DRAINS  0.0000000E+00  0.0000000E+00  0.0000000E+00
        RECHARGE  3.9686300E+05  0.0000000E+00  3.9686300E+05
              ET  0.0000000E+00  6.2049913E+05 -6.2049913E+05
   RIVER LEAKAGE  0.0000000E+00  0.0000000E+00  0.0000000E+00
 HEAD DEP BOUNDS  0.0000000E+00  0.0000000E+00  0.0000000E+00
  STREAM LEAKAGE  0.0000000E+00  0.0000000E+00  0.0000000E+00
INTERBED STORAGE  0.0000000E+00  0.0000000E+00  0.0000000E+00
 RESERV. LEAKAGE  0.0000000E+00  0.0000000E+00  0.0000000E+00
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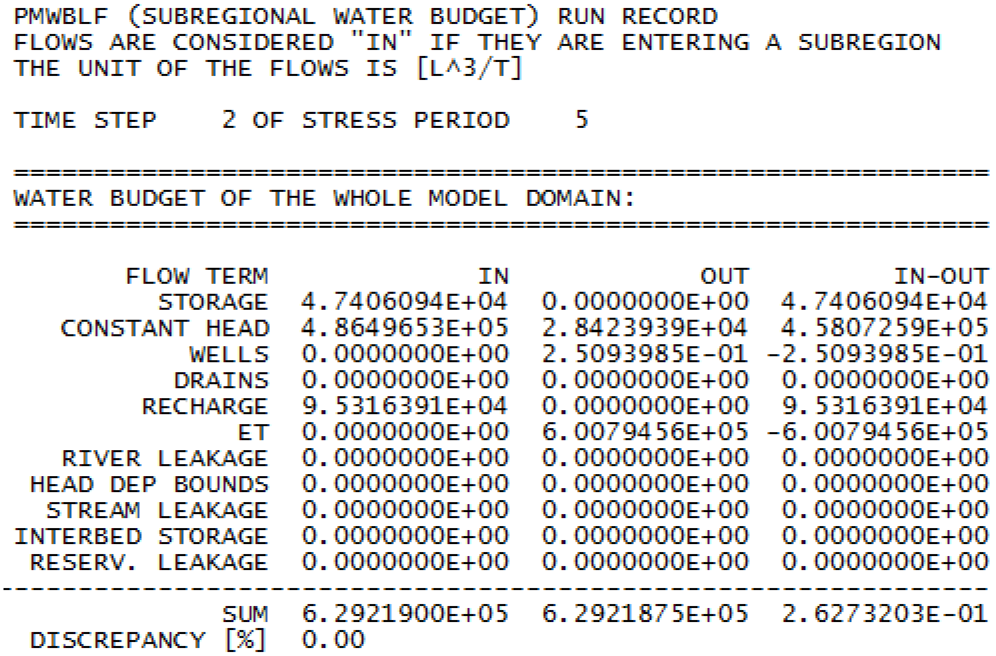

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PMWBLF (SUBREGIONAL WATER BUDGET) RUN RECORD
FLOWS ARE CONSIDERED "IN" IF THEY ARE ENTERING A SUBREGION
THE UNIT OF THE FLOWS IS [L^3/T]

TIME STEP    2 OF STRESS PERIOD    5

==============================================================
WATER BUDGET OF THE WHOLE MODEL DOMAIN:
==============================================================

       FLOW TERM               IN             OUT          IN-OUT
         STORAGE  4.7406094E+04  0.0000000E+00  4.7406094E+04
   CONSTANT HEAD  4.8649653E+05  2.8423939E+04  4.5807259E+05
           WELLS  0.0000000E+00  2.5093985E-01 -2.5093985E-01
          DRAINS  0.0000000E+00  0.0000000E+00  0.0000000E+00
        RECHARGE  9.5316391E+04  0.0000000E+00  9.5316391E+04
              ET  0.0000000E+00  6.0079456E+05 -6.0079456E+05
   RIVER LEAKAGE  0.0000000E+00  0.0000000E+00  0.0000000E+00
 HEAD DEP BOUNDS  0.0000000E+00  0.0000000E+00  0.0000000E+00
  STREAM LEAKAGE  0.0000000E+00  0.0000000E+00  0.0000000E+00
INTERBED STORAGE  0.0000000E+00  0.0000000E+00  0.0000000E+00
 RESERV. LEAKAGE  0.0000000E+00  0.0000000E+00  0.0000000E+00
---------------------------------------------------------------
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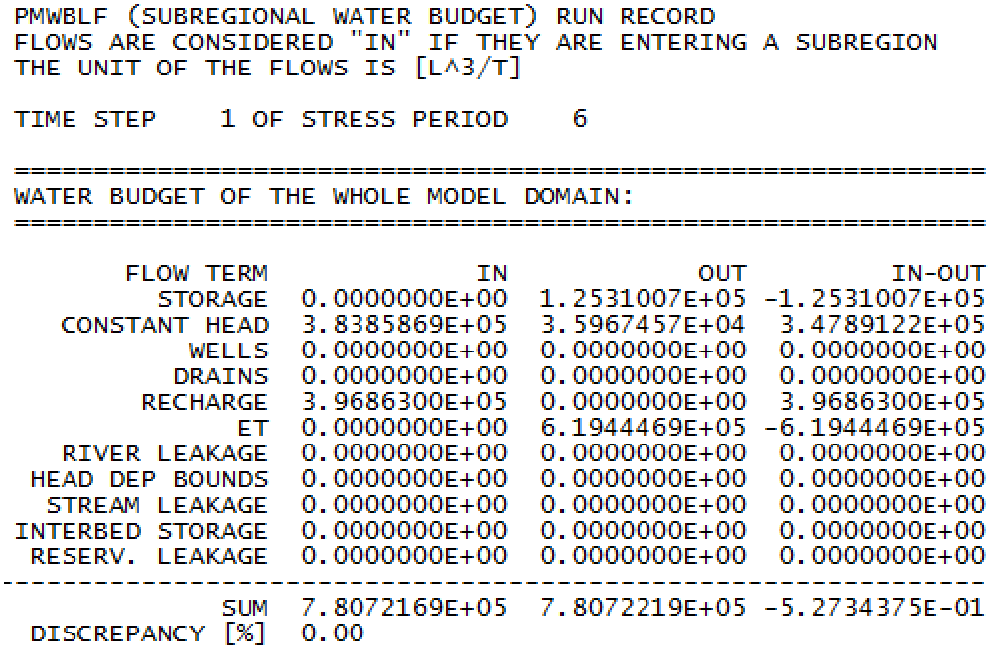

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PMWBLF (SUBREGIONAL WATER BUDGET) RUN RECORD
FLOWS ARE CONSIDERED "IN" IF THEY ARE ENTERING A SUBREGION
THE UNIT OF THE FLOWS IS [L^3/T]

TIME STEP    1 OF STRESS PERIOD    6

=============================================================
WATER BUDGET OF THE WHOLE MODEL DOMAIN:
=============================================================

       FLOW TERM             IN            OUT         IN-OUT
         STORAGE  0.0000000E+00  1.2531007E+05 -1.2531007E+05
   CONSTANT HEAD  3.8385869E+05  3.5967457E+04  3.4789122E+05
           WELLS  0.0000000E+00  0.0000000E+00  0.0000000E+00
          DRAINS  0.0000000E+00  0.0000000E+00  0.0000000E+00
        RECHARGE  3.9686300E+05  0.0000000E+00  3.9686300E+05
              ET  0.0000000E+00  6.1944469E+05 -6.1944469E+05
   RIVER LEAKAGE  0.0000000E+00  0.0000000E+00  0.0000000E+00
 HEAD DEP BOUNDS  0.0000000E+00  0.0000000E+00  0.0000000E+00
  STREAM LEAKAGE  0.0000000E+00  0.0000000E+00  0.0000000E+00
INTERBED STORAGE  0.0000000E+00  0.0000000E+00  0.0000000E+00
 RESERV. LEAKAGE  0.0000000E+00  0.0000000E+00  0.0000000E+00
--------------------------------------------------------------
             SUM  7.8072169E+05  7.8072219E+05 -5.2734375E-01
 DISCREPANCY [%]  0.00
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