RIVER-AQUIFER INTERACTION IN LITTLE JAMUNA RIVER CATCHMENT IN THE NORTHWEST REGION OF BANGLADESH

A Thesis Submitted by

GAUTAM KUMAR BISWAS

IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE DEGREE OF MASTER OF SCIENCE IN WATER RESOURCES DEVELOPMENT

BUET

July, 2008

INSTITUTE OF WATER AND FLOOD MANAGEMENT
BANGLADESH UNIVERSITY OF ENGINEERING AND TECHNOLOGY
DHAKA, BANGLADESH

BANGLADESH UNIVERSITY OF ENGINEERING AND TECHNOLOGY
INSTITUTE OF WATER AND FLOOD MANAGEMENT

The Thesis titled '**River-Aquifer Interaction in Little Jamuna River Catchment in the Northwest Region of Bangladesh**' submitted by Gautam Kumar Biswas, Roll No: MF 0428010. Session: April 2004, has been accepted as satisfactory in partial fulfillment of the requirement for the degree of Master of Science in Water Resources Development.

BOARD OF EXAMINERS

Mashfiqus Salehin

Dr. Mashfiqus Salehin
Associate Professor
Institute of Water and Flood Management
Bangladesh University of Engineering and Technology
Dhaka

Chairman
(Supervisor)

Mozzammel Hoque

Dr. M. Mozzammel Hoque
Professor
Institute of Water and Flood Management
Bangladesh University of Engineering and Technology
Dhaka

Member

Dr. Anisul Haque
Professor and Director
Institute of Water and Flood Management
Bangladesh University of Engineering and Technology
Dhaka

Member
(Ex-officio)

Dr. Mohammed Ali Bhuiyan
Professor
Water Resource Engineering
Bangladesh University of Engineering and Technology
Dhaka

Member
(External)

July 2008

CANDIDATE'S DECLARATION

It is hereby declared that the thesis on 'River-Aquifer Interaction in Little Jamuna River Catchment in the Northwest Region of Bangladesh' has been performed by me and neither this thesis nor any part of it has been submitted elsewhere for the award of any degree or diploma.

Counter Signature

Dr. Mashfiqus Salehin
(Supervisor)
Associate Professor
Institute of Water and Flood Management
Bangladesh University of Engineering and Technology

Signature of the Candidate

Gautam Kumar Biswas
Roll No: MF 0428010
Session: April, 2004

DEDICATED

TO

MY PARENTS (Raman Krisna Biswas & Ranuka Biswas)

AND

ELDER BROTHER (Suranjit Kumar Biswas)

ACKNOWLEDGEMENT

First of all, the author would like to express all his devotion and reverence to Almighty, most merciful beneficent creator who has enables the author to complete the project thesis for the fulfillment of the degree of Masters of Science in Water Resources Development.

The author would like to express his sincere and heartiest gratitude to his supervisor Dr. Mashfiqus Salehin, Chairman of the Board of Examiners and Associate Professor, Institute of Water and Flood Management (IWFM), Bangladesh University of Engineering and Technology (BUET), for his constant guidance, valuable advice, generous help and constructive discussion to carry out this research. Dr. Salehin took personal interest in all the major and minor details of this research work and offered a helping hand whenever needed. The author considers himself to be proud to have worked with him.

The author is deeply grateful to Dr. Anisul Haque, Professor and Director, Dr. M. Mozzammel Hoque, Professor, IWFM, BUET and the other members of the Board of Examiners for their valuable suggestions regarding the study. All of them provided valuable suggestions in improving the thesis work.

The author expresses his profound respect and deepest sense of gratitude to all of his respected teachers of IWFM, BUET for their fruitful advices in different times and valuable teachings under different courses that have helped to reach the author study at this stage.

The author offers his sincere thanks to Mr. M. A. Baten, Principal Scientific Officer, IDS Sections and Mr. Saiful Alam, Senior Scientific Officer, WARPO; Mr. Sajadul Karim, Superintending Engineer, Processing & Flood Forecasting Circle, BWDB, Mr. Mohiuddin, Project Director, S&M Project, and Mr. M. Hasan, Chief Geologist, BADC; Malik Fida Abdullah Khan, Division Head, Database/IT Division, CEGIS, and Dr. Motin Uddin Ahmed, Professor, Department of Geology, Dhaka University for providing valuable information, all the necessary data in regarding his work and their co-operation suggestions throughout the research period.

The author wishes to express special thanks to Arpana Rani Datta, Assistant Professor, and Dr. Saiful Islam, Assistant Professor, IWFM, BUET for help in using GIS Arc View, Bflow program. The author expresses his sincere and profound gratitude to all the individuals and institutions that provided him support, advice, and inspired him during the completion of this study.

A special mention of gratitude goes to all the friends, and in particular S.M. Imrul Hasan, Salim, Shakhar who endless helped encouraged, and gave the author moral support and valuable advice in all the way to continue this study.

Finally, the author is profoundly indebted to his elder brother named Suranjit Kumar Biswas for his forbearance in detailing with all the impudent demands by the author in relation to this study which they satisfied promptly and even enthusiastically!

GAUTAM KUMAR BISWAS

ABSTRACT

One of the major recent concerns in the Northwest region of Bangladesh is drying up of a large number of rivers and small water bodies, which has a direct impact on the ecology and the environment. Small rivers such as Punorvoba, Little Jamuna, Dhepa, Tulai and Goveshari that used to be perennial in nature some twenty years ago are now reported to be completely drying out in the dry season. Clearly an improved understanding of the river and groundwater is needed to explain the change in surface water availability, and to assess the response of stream flow to fluctuations or change in groundwater level. In this study, Little Jamuna river catchment in the Northwest region was selected as the study area.

The study followed a techno-social approach to characterize the surface water and ground water systems and their interactions in the study area. Technical analysis mainly included a variety of analytical approaches, e.g. lithological analysis, hydrograph analysis, flow duration curve, baseflow separation, trend analysis and correlation regression analysis. Two social investigation methods were conducted in the study area: the first one involved a questionnaire survey with a view to finding out people's perception about the status of stream flow depletion and its possible causes, impacts and mitigation measures, and the second method involved purposive interviews along a 17.5 km stretch along the Little Jamuna river with the chief objective of characterizing the spatial variation in stream and aquifer system and their interaction.

There have been substantial reductions in stream flow in the dry irrigation months, with reduction of flows ranging from 40% to 70% over a period of 30 years. At the same time, there has been a marked decreasing trend in the dry season minimum groundwater levels. There is direct connection between the river and underlying aquifer. The interaction between river and groundwater is the strongest close to the river, reflected in a high correlation coefficient of 0.814 at a distance of 2 km. It was found that there is a lag time in the response between the groundwater and surface water. Strong river-aquifer interactions were found even at greater distances after a lag-time of 2 to 3 months. This was reflected in a high correlation coefficient of 0.760 at 8 km from the river after a lag time of 3 months. Hence it is important to recognize the delayed response between groundwater level and river in analyzing the interaction between

surface water and groundwater, and hence consider the effect of irrigation pumping on stream flow depletion even in areas relatively far from the river.

There has been a sharp declining trend in the baseflow of the river, with baseflow declining by 50% to 90% in the dry season months of January to April over a period of 30 years. Rainfall distribution was not found to have played any major role in affecting groundwater levels and hence stream flow. It is the irrigation development that have affected gradual lowering of the groundwater level, which in turn caused reduction of base flow and hence stream flow in the dry season months.

The problem of river drying up had started since 1990-91; however, recent trend has been the start of the problem in earlier part of the dry season. The flow depletion of rivers and reduction in water bodies have had negative impacts on the environmental ecosystem, with many of the local fish species started to disappearing, and the migratory birds getting lower in number.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

BADC	Bangladesh Agricultural Development Corporation
BMD	Bangladesh Metrological Department
BMDA	Barind Multipurpose Development Authority
BUET	Bangladesh University of Engineering and Technology
BWDB	Bangladesh Water Development Board
CA	Catchment area
DAE	Department of Agricultural Extension
DPHE	Department of Public Health Engineers
DSSTW	Deep Set shallow tube well
DTW	Deep Tube well
DTWNOP	Deep Tube well Non- operated
FMTW	Force Mode Tube well
GIS	Geographic Information System
HYV	High Yielding Varieties
IWFM	Institute of Water and Flood Management
l/s	Liter per second
LLP	Low Lift Pump
Mha	Million hectares
MOP	Manually Operated Pump
MOPU	Manually Operated Pumping Unit
MPO	Master Plan Organization
NCA	Net Cultivable Area
NGO	Non-governmental Organization
PA	Planning Area
PWD	Public Works Department Datum
RL	Reduced Level
sdf	Stream depletion factor
STW	Shallow Tube well
TRAD	Traditional pumping units
VDSSTW	Very Deep Set Shallow Tube well
WARPO	Water Resources Planning Organization

Chapter One

INTRODUCTION

1.1 General

Groundwater and surface water are often managed as isolated components of the hydrologic system, yet they interact in a variety of physiographic settings (Sophocleous, 2000). The nature of the interaction between the surface water and groundwater is very important from the perspective of resource development and management, salt water intrusion, and groundwater contamination. The nature of interaction is also important because the discharge of sewage and untreated industrial effluent to the surface water bodies is a common practice in Bangladesh (Ahmed and Burgess, 1995). In many regions groundwater and surface water resources are hydraulically connected, and most surface water features such as rivers, lakes, dams and wetlands generally interact with groundwater (Winter et al., 1998). The hydrologic relation between stream and aquifers is generally complex, and often vary temporally and spatially over different scales. The exploitation of, or quality of one resource, can therefore affect the other. Depending on the nature of hydraulic connection between the surface water and groundwater systems, surface water bodies can lose water recharging the aquifer, with contaminated surface water affecting groundwater quality. Conversely, surface water bodies can gain water from groundwater system as baseflow, and may get affected by groundwater pollution, if any. Anthropogenic activities like pumping of groundwater can deplete surface water, withdrawal of surface water can deplete groundwater, flood control activities can significantly reduce recharge to the groundwater systems, and human activities can be a significant source of the degradation of the water resources quality. Reduced quantity and quality of water resources can lead to water management problems and threaten environmental integrity.

1.2 Rationale of the Study

One of the major concerns of late in the Northwest region of Bangladesh is drying up of a large number of rivers and small water bodies, which has a direct impact on the ecology and the environment. The major significant impacts reportedly having already taken place include loss of different kinds of aquatic habitats and fish diversity, reduction of migratory birds, and hampering of navigation. Small rivers (e.g. Punorvoba, Little Jamuna, Dhepa, Tulai and Goveshari) that used to be perennial in nature some twenty years ago are now reported to be completely drying out in the dry season. Bigger rivers like Teesta, Dharala, Korotoa, Atrai, and Tangon are reduced significantly in the dry season than before as reported by BWDB and BADC personnel. Ahmed (1994) and Ahmed and Burgess (1995) reported drying of rivers and beels in the Barind Tract area. One general opinion about the reason behind the stream flow depletion is that the groundwater level has been lowered resulting in less base flow contributions or rivers loosing water to aquifer during dry season.

Clearly an improved understanding of the river and groundwater is needed to explain the change in surface water availability, to assess the response of stream flow to fluctuations or change in groundwater level, and to balance different uses of water with water supply needs and the need to maintain steam habitat for fish, aquatic biota, and wildlife. The National Water Resources Plan Organization (WARPO) of Bangladesh emphasizes implementation of a range of structural and non-structural measures designed to improve efficiency of resource utilization through conjunctive use of all forms of surface water and groundwater for irrigation and urban water supply. However, before the conjunctive management can take place, it is imperative to develop a proper understanding of the basic principles and relationships guiding groundwater and surface water interactions.

In this study, Little Jamuna river catchment in the Northwest region (MPO catchment no. 33) has been selected as the study area. Because ground water is the major water source in that part of the country, and the potential apparently exists for pumping-induced streamflow reduction to impact downstream users, a good understanding of stream-aquifer relations is essential to effectively manage water resources in the Little Jamuna river catchment.

1.3 Objectives of the Study

The overall aim of this research project is to develop a greater understanding of the interaction between river and groundwater systems in the study area. The specific objectives of this research were:

i. To investigate hydraulic connection between river and underlying aquifer, i.e. to assess behavior of steam flow in response to fluctuations and vice versa;

ii. To analyze the long-term effect of irrigation development on the groundwater levels and the corresponding impacts on the river flow.

1.4 Organization of the Thesis

Chapter two introduces the basic principles along with a comprehensive description of surface water–groundwater interaction processes. Chapter three is devoted to a review of past studies on surface water–groundwater interactions in many parts of world along with Bangladesh. It also provides descriptions of tools and techniques typically used in assessing surface water-groundwater interaction. Chapter four concentrates on the general description on the study area with special emphasis on the hydrometeorology and hydrogeology that are of utmost importance in understanding both surface water and underlain aquifer characteristics and relating their interaction. Chapter five discusses the methodology adopted in the study. It gives an assessment of the availability and quality of surface and subsurface data. It also contains a description of the computer programs used for baseflow analysis and a short description of field survey. Chapter six presents the results of the hydrologic analysis and field survey methods. The inferences drawn from the results and some congruent recommendations are included in Chapter Seven.

Chapter Two

BASIC PRINCIPLES OF SURFACE WATER – GROUNDWATER INTERACTION

2.1 Introduction

Surface water and ground water interact within a dynamic hydrologic system consisting of aquifers, streams, reservoirs, and floodplains (Priest et al., 2003) These systems are interconnected and form a single hydrologic entity that is stressed by natural hydrologic and climatic factors and by anthropogenic factors. The interaction between surface water (e.g., stream, lakes, and wetland) and groundwater systems take place at many places throughout the landscape and is governed by the positions of the water bodies with respect to groundwater flow systems, geologic characteristics of their beds, and their climatic settings (Winter et al., 1998; Sophocleous, 2002). Therefore surface water and groundwater are in continuous dynamic interaction. The groundwater component of river flow derives from continuous and intermittent flows from aquifers that drain to the river under varying degrees of hydraulic connection (UNESCO, 1980).

2.2 Basic Concepts of Interaction Process

Groundwater and surface water interact in a wide variety of landscapes from alpine to coastal (Winter, 1998). Within these landscapes, ground-water systems range in scale from local to regional, and the types of surface water include streams, lakes, wetlands, and oceans. The most common image of the interaction of groundwater and surface water is that of the interaction of streams with a contiguous alluvial aquifer. Flow system in groundwater can be of different sizes and depths, and they can overlie on another. Groundwater moves along flow paths of varying lengths from areas of recharge. Water from precipitation infiltrates the ground and percolates to the groundwater table. Local flow systems have shorter and shallower flow paths starting from the water table in the uppermost unconfined aquifer to the discharge areas, and may have travel times on the order of days to a few years depending on the length of flow paths. These systems have the greatest interaction with surface water. The longest and deepest flow paths having may have travel times on the order of decades to millennia.

Recharge to or discharge from groundwater is the cause for continual change in the position of the water table. Changing meteorological conditions strongly affect seepage patterns in surface water beds, especially near the stream shore-line (Winter et al., 1998). Therefore, the transfer of water between the surface and subsurface may be usefully defined in two ways, first according to whether they are processes of recharge or discharge, and second whether they are natural or determined by human action. Recharge to groundwater storage may occur whenever the stage in a surface water body is above the adjacent groundwater table, provided the underlying bed of the water body comprises permeable or semi-permeable strata. This type of groundwater recharge may be seasonal or continuous. In the area where rivers cut through the overlying semi-permeable beds, there is groundwater movement to and from the rivers but the amount is small compared with vertical recharge from rainfall and flooding during the rainy season (MPO, 1986). This recharge through natural process may occur by infiltration of rain or flood water or infiltration from rivers and/or beels; through artificial process, it may occur by return flows from surface water and groundwater irrigation, leaking water distribution systems or leaking sewers. Groundwater discharge through natural process may occur by capillary rise from shallow water tables, baseflow to rivers and beels and direct flow to the sea. Discharge from pumped wells is only artificial process.

2.3 Interaction between River and Aquifer

2.3.1 Types of Interaction between River and Aquifer

The important factors that determine the direction and magnitude of flux across the river-aquifer interface are the relation of river stage to the adjacent groundwater level and the distribution of hydraulic conductivities of river bed sediments. For groundwater to discharge into a stream channel, a connection must exist, and the hydraulic head in the underlying aquifer must exceed the hydrostatic head in the overlying surface water. Conversely, the loss of surface water to the underlying aquifer requires that the elevation of the water table in the vicinity of the stream is lower than the elevation of the stream-water surface. Rivers generally interact with groundwater in three basic ways (Winter et al., 1998): i) streams gain water from inflow of groundwater through the streambed (connected gaining stream); ii) they lose water to groundwater by outflow through the streambed (losing stream); or iii) they do both, gaining in some reaches and losing in other reaches (connected-gaining-losing stream), or both gain and lose in the same reach at different times. For groundwater to discharge into a stream channel, the elevation of the groundwater surface adjacent to the stream must be higher than the elevation of the river stage (Figure 2.1a). Conversely, for surface water to seep to groundwater, the elevation of the river stage must be higher than the adjacent near stream groundwater elevation (Figure 2.1b). In both cases, there must be permeable material that will allow this hydraulic head to move water. Losing streams can be connected to the groundwater system by a continuous saturated zone (Figure 2.1b). Losing reaches can also be occurred when the saturated sediments surrounding the channel sediments are physically detached from the groundwater table by a partially saturated or an unsaturated zone (Figure 2.1c). The rate of this water loss is a function of the depth of water, the hydraulic gradient towards the groundwater, and the hydraulic conductivity of the underlying alluvium. The channel system can be hydraulically connected to the aquifer, or have a leaking bed through which water can infiltrate to the subsurface. The extent of this interaction depends on physical characteristics of the channel system such as cross section and bed composition. Streams commonly contain a silt layer in their beds which reduces conductance between the stream and the aquifer.

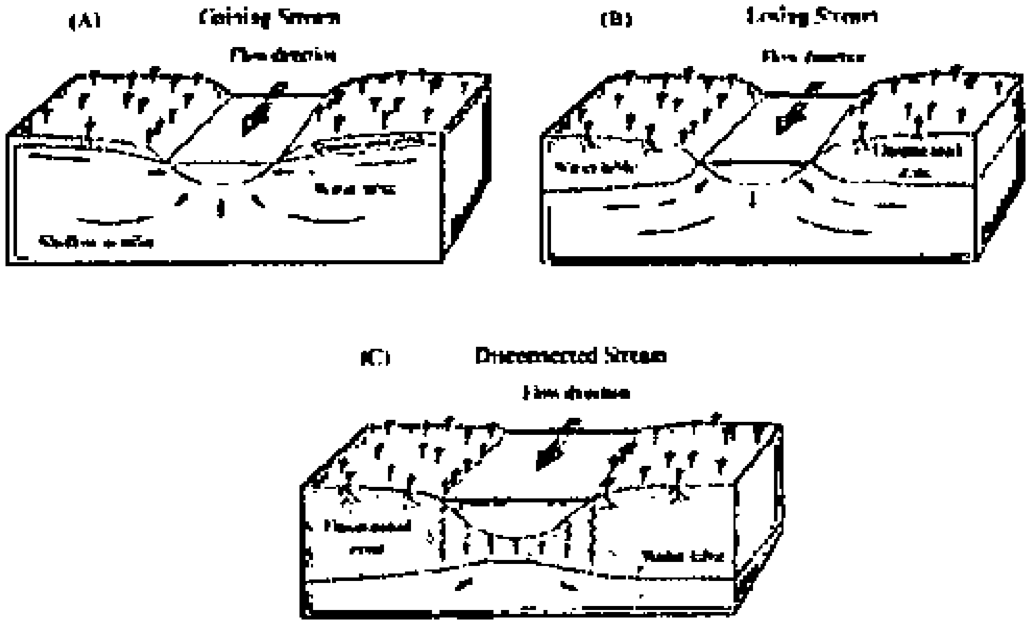


Figure 2.1 Schematic diagrams illustrating (a) hydraulically connected-gaining stream, (b) hydraulically connected-losing stream, (c) hydraulically disconnected-losing stream (Source: Winter et al., 1998)

From a hydrogeomorphological point of view, four types of interactions between streams and groundwater can be conceptualized (Xu et al., 2002) as:

i) *Constantly losing or gaining streams*: This type may occur in the upper catchment where the regional groundwater level is constantly below the stream stage as shown in Figure 2.2 (1a). It may also be found in places where permeability of stream bed materials are such that the amount of water lost from streams is limited. Constantly gaining streams may also exist where streams are fed by groundwater from confined aquifers (case 1b of Figure 2.2).

ii) *Intermittent streams*. This type may be found in the middle course where groundwater discharges towards the stream during dry periods, while the river recharges aquifers during floods. The baseflow component would have a cutoff under the peak flow time as in case 2 of Figure 2.2.

iii) *Gaining streams with or without storage*: This type is often observed in the lower course where groundwater levels may be consistently higher than the river stage. The baseflow component would increase in either an S curve or a straight line, depending on the presence of bank storage. As shown in Figure 2.2, the three possible cases are: 3a for porous media without bank storage, 3b for fractured media without bank storage and 3c for fractured media with storage.

iv) *Interflow-dominant streams*. This type may occur in the upper catchment where interflow may be the dominant component of stream hydrographs. If the regional groundwater level is below the stream stage, traditional separation techniques would give an indication of the magnitude of interflow contribution. It may also be complicated by geological structures in some cases.

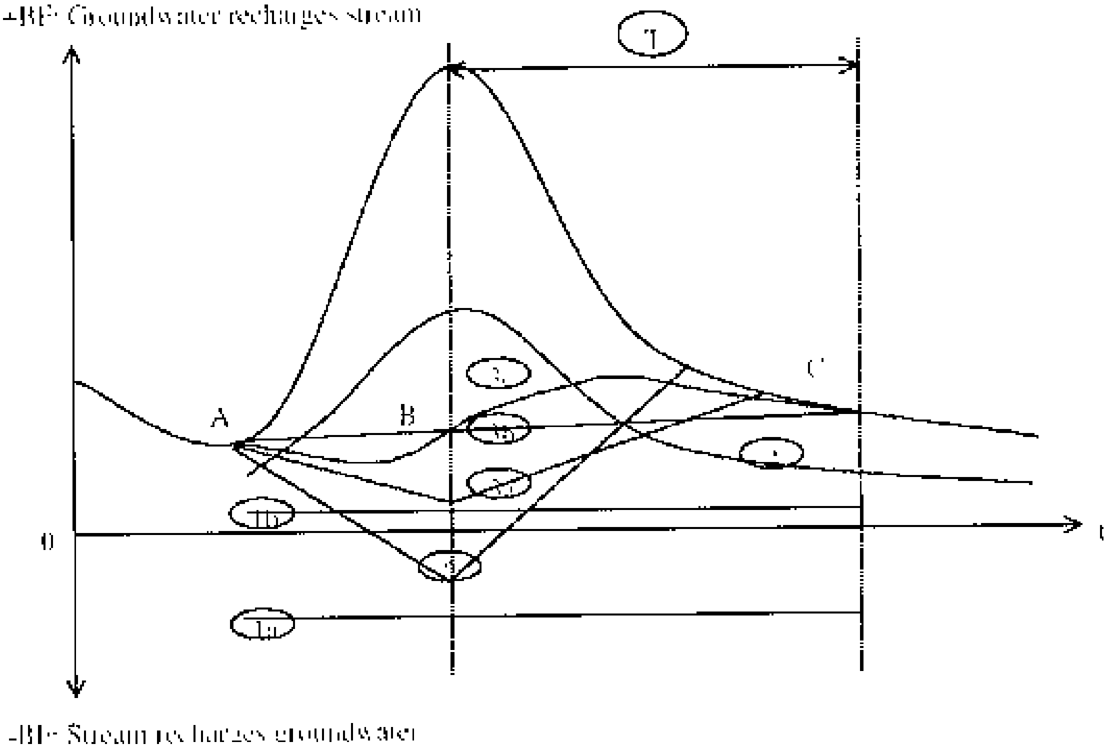


Figure 2.2 Typical scenarios of the interaction between groundwater and steams

A connected, variably gaining-losing river reach is in direct hydraulic connection with the underlying aquifer and alternates between being a gaining and losing river. Where the river is gaining or losing will depend on the relative differences between the groundwater and river stage elevations. These relationships may change seasonally with varying climatic regime, with natural erosion-deposition processes in river beds, and from changes in the water table in response to surface water and/or groundwater extraction. In a system which initially loses water at or before the start of raintall event, the infiltration of rain water and flood water in wet months may recharge the underlying aquifer to a level higher than the river stage transforming the stream onto a gaining one. When the groundwater component ceases in the next dry season after the water table returns to a level that is below the base of the river, and the stream becomes losing again. Groundwater pumping can also cause the hydraulic gradients to fluctuate during the irrigation season by lowering the water table and reversing flow directions such that a gaining stream becomes a losing stream. In some instances, the groundwater and river may become disconnected for varying periods which might occur during the irrigation season from groundwater extraction resulting in a lowered groundwater table

One of the most commonly used forms of groundwater comes from unconfined shallow water table aquifers. These aquifers are major sources of drinking and irrigation water. They also interact closely with streams, sometimes flowing (discharging) water into a stream or lake and sometimes receiving water from the stream or lake. An important feature of rivers that are disconnected from groundwater is that pumping of shallow groundwater near the stream generally does not affect the flow of the stream near the pumped wells (although unsaturated zone storage of water may play a role in maintaining some degree of connectivity). Conversely, pumping groundwater from a connected aquifer-river system will impact on the local stream flow hydrology, reducing water availability for surface water users and riverine ecosystems.

2.3.2 Factors Affecting River-Aquifer Interaction

The relation between stream elevation and water table elevation can be highly transient depending on variations in the rates of groundwater and surface water withdrawal and recharge. These rates are affected by changes in season, and by human activities (agricultural development, irrigation systems, construction of reservoirs, etc). The factors affect on river-aquifer interaction are discussed below in details.

Seasonal variation of hydraulic gradient: Flow between aquifers and rivers alternates in direction seasonally. Water levels in many aquifers follow a natural cyclic pattern of seasonal fluctuation, typically rising during the summer and rainy season due to greater precipitation and recharge, then declining during the winter and spring owing to less recharge and greater evapotranspiration. The magnitude of fluctuations in water levels can vary greatly from season to season and from year to year in response to varying climatic conditions.

In a variably gaining-losing type of reach, a river will generally initially loose water at the start of a rainfall event when runoff processes dominate. During wet periods and flood events the infiltration of rain water and stream flow through the base of the river contributes recharge to the underlying aquifer and eventually, the groundwater elevation may become higher than that of the river stage. At this point the flow gradient will be reversed in the near stream area, and seepage to the riverbed will occur in the form of baseflow (REM 2002, Ward 1975). When the baseflow component ceases, after the water table returns to a level that is below the base of the river, the river channel dries out until the next rainfall-runoff-recharge event takes place.

In Bangladesh, a humid, floodplain country, rivers receive a substantial contribution of their lean flows through groundwater discharge along the courses. On the other hand, rivers at high water levels typically recharge the aquifers by reversing the lateral gradients of groundwater flow. It has been estimated that in case of Ganges river, the yearly horizontal recharge is in the amount of 14.5 million cubic meters, which is equivalent to the discharges of 55 deep tube wells (Rahman and Chowdhury, 2003).

Geology or geomorphology: Geology exercises a strong control over the transfer of water between rivers and aquifers Geomorphology of the surrounding land,, bank storage and sediments in the riverbed affect the hydraulic gradient of surface water and groundwater levels. Fine sediments are deposited in the riverbeds and banks in many rivers and these sediments can cause significant resistance to the flow of water between the river and aquifer (Younger et al., 1993)

Degree of connectivity: The exchange rate between the river and the aquifer will also depend on the degree of penetration of the river into the aquifer. If the river is not perched, but sediments have accumulated in the riverbed, or the river only slightly penetrates into the aquifer, than the hydraulic communication between the river and aquifer may be limited, while for a fully penetrating river is more likely to have greater hydraulic connection with the aquifer.

In Bangladesh, flow between aquifers and rivers alternates seasonally, and the exchange is significantly controlled by the geology. Ahmed and Burgess (2003) and Ravenscroft (2003) summarize the geomorphology and geology of the rivers and other surface water bodies in Bangladesh. Rivers in Bangladesh have various degrees of penetration into the upper aquifer; those of Holocene floodplains have a good hydraulic continuity and those on Pleistocene terraces have no simple genetic connection with the underlying aquifer. However, in Barind Tract area, rivers like Atrai, Little Jamuna and Mahananda cut through the Barind clay into the underlying aquifer allowing direct recharge. The river Atrai and little Jamuna are good examples of variably gaining-losing streams, being effluent during the wet season and influent during the dry season.

Courses of many rivers are, however, fault controlled, and presumably fault planes in these river beds play a role in the interaction with the aquifer. Rivers surrounding the Capital City, Dhaka partially penetrate the aquifer system

Baseflow of rivers originates predominantly from the saturated zone, the shallow groundwater reservoir, which in most cases is unconfined. Discharge from this groundwater reservoir exfiltrates through river banks and the bottom of river beds. This discharge has a relatively fast response to rainfall due to the mobilization of "old", pre-event groundwater (Chapman and Maxwell, 1996; Herrmann, 1997) stored within a short distance to the river, by percolating rainwater increasing the level and hydraulic head of the groundwater reservoir

Withdrawal of groundwater by pumping: Groundwater pumping can also cause the hydraulic gradients to fluctuate during the irrigation season by lowering the water table and reversing flow directions such that a gaining stream becomes a losing stream. In an example of an aquifer system located near a river, under natural conditions the recharge to the water table is equal to the groundwater discharge to the stream. Introducing a pumped bore will result in the reduction of water stored within the aquifer and in the development of a cone of depression (Figure 2.3). The volume of water that is removed from storage through pumping is no longer available as stream discharge. If the bore is pumped at an even greater rate the cone of depression will expand towards the river and induce the movement of stream water into the aquifer resulting in induced recharge. Essentially this situation results in reversing the groundwater-stream gradients such that a groundwater discharge site, where the stream was once gaining, is changed into a groundwater recharge site, where the stream looses water to the underlying aquifer replenishing aquifer storage during pumping. This is a simple but compelling example of the interactions between groundwater and river systems (Ivkovic and Croke, 2004). The response time for groundwater pumping to impact river flows in a hydraulically connected groundwater-river system is a function of the aquifer diffusivity and the distance of the bore to the river. Commonly, the natural hydraulic connection between river and aquifer is exploited by near-river installation of wells designed to draw down groundwater levels below the river level and induce recharge by surface water (Larkin and Sharp, 1992).

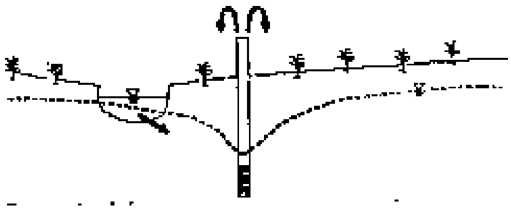


Figure 2.3 Schematic showing seepage of river water to aquifer induced by the intersection of the cone of depression of a pumping well with the river (Source: Salehin, 2005)

Critical factors for water management are the timing, location, and volume of streamflow depletions, which depend on 1) the degree to which the river and aquifer are interconnected, 2) the distance between the river and the pumping source, 3) the rate of pumping, and 4) the physical characteristics of the streambed and the aquifer. While the impact of groundwater pumping on streamflow may be limited in partially penetrating rivers or in rivers with clogged less permeable sediment beds, stronger hydraulic connection in a fully penetrating stream is more likely to allow for significant streamflow depletion by groundwater pumping. The rate of stream depletion associated with pumping from a given location is normally proportional to the rate of ground water pumping rate. Aquifer physical characteristics also affect the timing and magnitude of stream depletion. Aquifer layering, water transmission, and storage properties may have a strong influence on the direction and rate of propagation of pumping effects. Highly transmissive aquifers with limited water storage capacity will transmit effects more rapidly than aquifers of lower permeability or higher storage capacity.

The distance between a surface water body and a pumping location strongly affects the timing and degree that pumping will impact stream depletion (Figure 2.4). Pumping near an interconnected surface water body will have a nearly immediate impact on the surface water source. The impact may be nearly equal to the rate of ground water pumping. At greater distances, the effects of pumping will be attenuated and distributed over longer time periods and may be shared with other hydraulically connected surface water bodies.

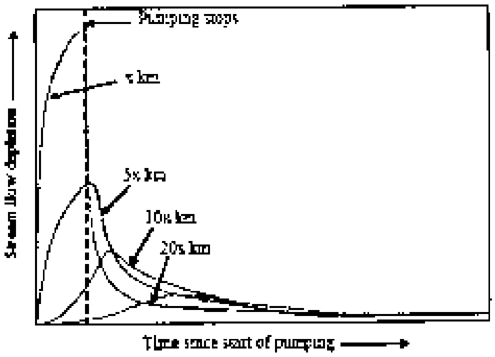


Figure 2.4 Schematic showing stream flow depletion due to pumping for different pumping locations from the stream (Source: Salehin, 2005)

The lag effect

An important consideration in streamflow depletion analysis is the 'lag effect', i.e., the time lag between the time when water is pumped from the groundwater and the time the depletion is observed in streams. In many ground water systems, surface water supplies are ultimately depleted by an amount of water equal to the volume pumped and consumptively used. The effects of pumping on surface water supplies may be distributed over years, or even decades, depending on the size and properties of the aquifer. Johnson et al. (1993) demonstrate how the stream depletion effects for 30 years of continuous pumping from the Snake River Plain aquifer, North America's second-largest aquifer, persist for decades after pumping ceases (Figure 2.5). In reality, it is not easy to observe the impacts of wells on streamflow. Often, variations in precipitation, pumping patterns and stream flow are such that only after many years can the impacts on stream flow be observed.

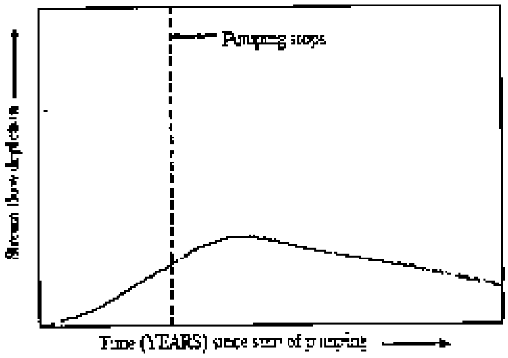


Figure 2.5 Schematic showing time lag in years between groundwater pumping and streamflow depletion observed (Source: Salehin, 2005)

Generally, only the shallowest aquifers in an alluvial aquifer system will be in direct hydraulic connection with a river. However, if vertical flow components exist between a connected shallow aquifer-river system and a deeper underlying aquifer, then there is the potential for the river and the deeper aquifer to interact with each other (Ivkovic et al., 2005). For example, pumping from a deeper aquifer may result in a downward hydraulic gradient that reduces the water level in the shallow aquifer. Reduced groundwater levels in the shallow aquifer may alter the nature of the groundwater-river interactions by changing the direction of flux or the hydraulic connection between the two systems.

2.4 Infiltration and Percolation Process

The infiltration-percolation is the process in which aquifer gets vertically recharge. Rain water and/or flood water in the wet season also infiltrate through the pervious soil cover and ultimately reach the shallow water table by deep percolation or gravity drainage thus recharging the shallow aquifer (Figure 2.6). Vertical infiltration-percolation process may also take place from irrigation water in the dry season. The time it takes the recharged flood water to return to the river by groundwater flow may be weeks, months, or years (Winter et al., 1998).

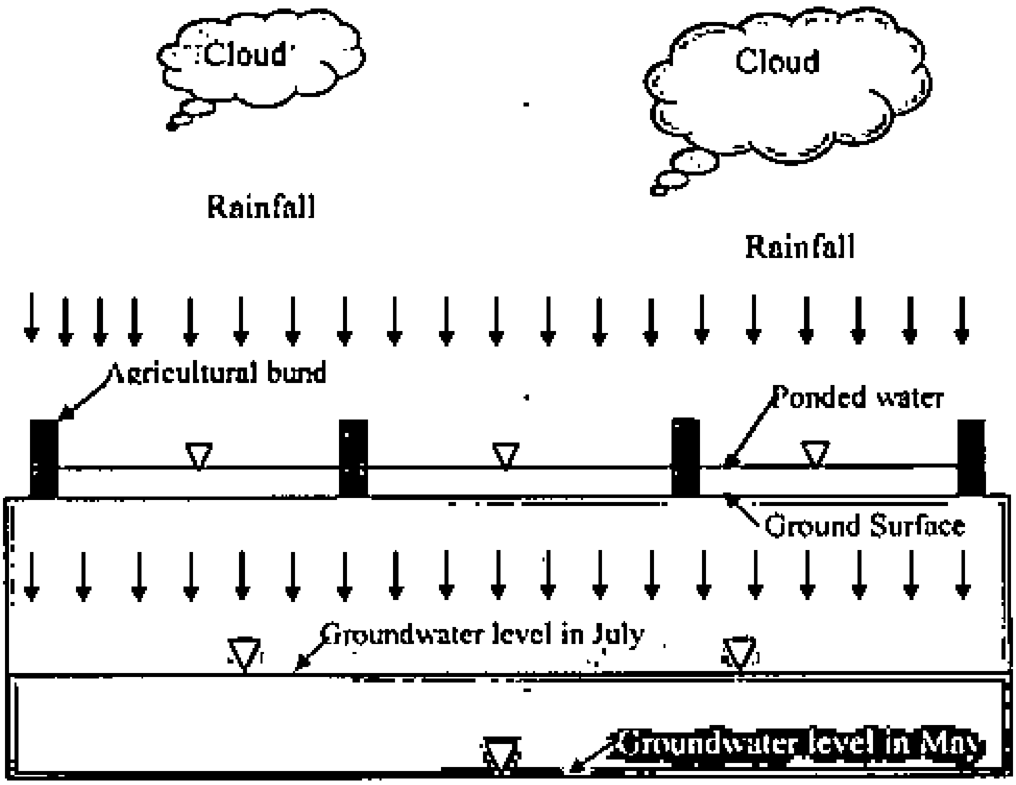


Figure 2.6 Schematic diagram of infiltration-percolation process illustrating rise in water table due to vertical recharge by percolation during wet season (Reproduced from Rahman and Chowdhury, 2003)

Water infiltrating through the unsaturated zone is from direct precipitation, from overland flow, and from leakage through streambeds. Flow in the unsaturated zone generally is assumed downward in response to gravity. However, poorly permeable strata (for example, a clay layer) can create barriers to downward flow that can limit the amount of water reaching the underlying saturated zone.

Flooding of low-lying lands is, in a sense, the most visible and extreme example of the interaction of surface water and groundwater (Winter et al., 1998). During flooding, recharge to groundwater is continuous; given sufficient time, the water table may rise to the land surface and completely saturate the shallow aquifer. Under this condition, an extended period of drainage from the shallow aquifer takes place after the flood waters recede.

In Bangladesh, recharge of groundwater mainly takes place by rainfall and flooding. Groundwater recharge conditions are advantageous with much of the country flooded and/or under rice cultivation during the monsoon. Out of the total area of 14.40 Mha, almost six Mha are subject to annual flooding in depths ranging from 30 cm to over 2 meters. The shallow aquifer of Bangladesh has, in general, good to reasonable transmission and storage properties. Therefore, in many areas the aquifer or soil profile fills up almost to the ground surface at the end of the wet season (Rahman and Chowdhury, 2003; Ravenscroft, 2003).

2.5 Interaction between Aquifer and Lakes or Wetlands

The hydraulic properties of stream and lake beds control the interactions between surface water and groundwater system (Sophocleous, 2002). The hydrologic regime of a lake is strongly influenced by the regional groundwater flow system in which it is located. This interaction plays a critical role in evaluating the water budget for the lake. Lakes can receive groundwater or lose water to the shallow aquifer throughout their entire bed, or receive groundwater through some parts of the bed and lose water through other parts. Because of the huge surface area, evaporation generally has a much greater effect on lakes than on river levels. Variation of water level in lakes is not a rapid as it is in streams. Bed sediments in lakes generally consist of less permeable organic deposits, which can affect the spatial distribution of lake-aquifer interactions.

An important aspect of groundwater-surface water interchange is that surface water in stream, lakes, and wetlands repeatedly interchanges with nearby groundwater (Winter et. al., 1998)

Wetlands may interact with groundwater similar to lakes. Many wetland sites are associated with the discharge of groundwater to the surface, in the form of localized springs or diffuse seepage. Unlike lakes, wetlands may not be sited in the lowest depressions; they can be present on slopes, drainage divides, or along streams, especially slow moving streams (Winter et al., 1998). Seasonal change in groundwater levels in the wetland soils and in underlying or adjacent aquifers can bring about a complex pattern of water movement and storage. The groundwater component of the water budget may be a great significance to the survival of the wetland Riverine wetlands although complex receive groundwater discharge; depend primarily on the river for water supply. Periodic water level changes in wetlands thus can result in complex interaction process with groundwater.

The rivers and beels are thought to be sources of recharge to the aquifer (BWDB, 1990; MPO, 1985; Ahmed, 1994; MMI/HTS, 1992; Khan, 1991). In Bangladesh, a large number of bills (small perennial lakes) occur in the down-faulted depressions in the northeast region, which apparently persist because of groundwater discharge (Ravenscroft, 2003). Ahmed and Burgess (1995) studied the behavior of bills in the Barind Tract area in the northwest region, and found that the contribution of bills to the underlying aquifers is localized and is active only during the wet season. Some of the bills become zones of discharge from the aquifer towards the end of the dry season. There has been a recent tendency of some of the beels drying out, which is thought to be a result of aquifer over-exploitation.

Chapter Three

ASSESSMENT METHODS OF STREAM-AQUIFER INTERACTION

3.1 Introduction

The current study used a number of analytical techniques to examine the interaction between surface water and groundwater. There exist a variety of techniques to investigate the interaction process, including field experiments, analytical techniques and numerical models. While many of the applications used one or two methods, some studies employed a combination of methods (e.g. Oxtobee and Novakowski. 2001; Mosner. 2002) A comprehensive review of the assessment methods are provided in this Chapter.

3.2 Field Methods

Several field methods are used to determine the interaction of surface water and groundwater on the basis of investigation criteria. A common field technique to establish the predominant direction of flux between river and groundwater is employing piezometers at several locations at different direction. This way vertical hydraulic gradient and direction of water interchange can be established. The exchange flow paths can be delineated by properly selecting the locations of piezometers in the alluvial aquifers (Wondzell and Swanson, Wroblicky et al., 1998). Knowing the head difference (Δh) between stream and aquifer allows the calculation of flux q, between the two systems using Darcy,s law:

$$q = k\Delta h \qquad (3.1)$$

Where, k is the leakage coefficient or conductance of stream bed, expressed as the hydraulic conductivity of stream bed divided by its thickness (Rushton and Tomlinson, 1979). The above linear relation can be used for aquifer discharge and river recharge as it implies a similar mechanism for the two processes, the sign of q determining the direction of the flux. In many cases. the linear relation may not represent the true picture. The rate of recharge can be smaller than the rate of discharge because of increased resistance to the passage of water when volume of recharge water increases

(Rushton and Tomlinson, 1979) Non-linear and a combination of linear and non-linear relations were proposed by Rushton and Tomlinson (1979). Another field method commonly used is the direct measurement of seepage rate and flux using seepage meters or flux chambers (Belanger and Montgomery, 1992). To determine groundwater flux using the piezometers, the hydraulic conductivity of the sediments needs to be estimated or determined, as well as the cross-sectional area of the flux. The drum method represents a direct measurement of the flux.

Field methods have found extensive application, some of which are reviewed here. Carey (2001) studied groundwater and surface water interaction for the Sammamish river in Washington, USA and used Mini-piezometer set-up to determine whether groundwater is flowing into or out of the river at selected locations during the low flow conditions. Anderson (2003) conducted an assessment of groundwater and surface water interaction in the Warm Springs canal in Frenchglen, Oregon, USA. Two common field techniques were used to evaluate stream and groundwater exchange. Mini-piezometer probes were installed at several locations to define the vertical hydraulic gradient and direction of water interchange. Flux chambers drums were installed to estimate the groundwater seepage rate and flux. Donato (1998) studied on surface-water and ground-water relations in the Lemhi River Basin, East-Central Idaho. The main objectives of the study were to carry out seepage measurements to determine seasonal distributed gains and losses in the Lemhi River and to estimate annual ground-water underflow from the basin to the Salmon River. Nish and others (1998) estimated stream-aquifer flux from streamflow measurements, and groundwater head distributions along the reach of the San Pedro River in Cochise County, Arizona, USA. Lee and Swancar (1994) used field data from piezometer nests as well as modeling to study the complex interaction of the lakes with groundwater and the effect of groundwater pumping from the aquifer in the karst terrane of Florida.

3.3 Chemical Methods

Conducting tracer tests is also a commonly used technique to investigate transient and complex groundwater flow patterns near surface water bodies (Meigs and Bahr, 1995). Commonly used environmental tracers are naturally occurring dissolved constituents such as anions and cations, stable isotopes of oxygen and hydrogen, radio isotopes such as tritium and radon, and physical properties of water such as temperature. Environmental isotopes are being used with greater frequency for studies of the interaction of groundwater and surface water. Use of cations and anions can be helpful in determining the sources of water to streamflow during storms in small watersheds Stable isotopes of oxygen and hydrogen can give better indication of the mixing of water from different sources areas since waters from different sources have different isotope compositions (Winter et al., 1998; Ahmed and Burgess. 2003). Radio isotopes are good indicators of water ages or residence times, i.e the time that water has spent in the groundwater systems. They can be used to identify significant groundwater input to a stream and stream water loss to groundwater as a result of abstraction of groundwater. Temperature can be a useful parameter in identifying gaining and losing reaches of a stream. Sediment temperature and stream temperature are markedly different in gaining reaches while diurnal fluctuations of stream temperature are strongly reflected in sediment temperature in losing reaches (Winter et al.. 1998). Some examples of the applications of chemical methods are mentioned below:

Otz et al. (2003) investigated the extent to which lakes and surface water interact with the underlying aquifer in Triassic Piora, Switzerland. In this study, the authors used seven dye tracing tests and found that the direction of groundwater flow in the aquifer is from the valley area to stream areas.

Stauffer (1985) used solute tracers to estimate groundwater flow into lakes. Krabbenhoft et al. (1994) used environmental isotopes for understanding the interaction of lakes and groundwater. Alpers and Whittemore (1990) also used environmental isotopes to gain insight into the role of groundwater in the hydrology of two lakes in northern Chile, and Herczeg et al. (1992) did the same for Lake Tyrrel, in Australia.

3.4 Analytical Methods

Much of the literature on the interaction of surface water with groundwater in alluvial aquifers was concerned with analytical solutions to 1-dimensional flow of groundwater to fully penetrating streams (Rorabaugh. 1964, Glover, 1964; Hall, 1968). This approach is still being used today to estimate groundwater recharge from streamflow hydrographs (Bevans, 1986), and automated computer-based techniques for using these analytical methods were recently developed. Numerous analytical solutions were developed over the years to consider a wide variety of theoretical and field conditions, and analytical solutions are still being developed. A range of analytical methods are in use. A good example of this is study by Ivkovic and Croke (2004) characterizing who developed a framework for the spatial and temporal interactions between groundwater and surface water systems in the Namoi catchment in Australia through several analysis methods including analysis of groundwater and stream hydrographs, analysis of flow duration curves, baseflow filtering techniques and analysis of piezometers transects and flow nets. In addition to the analytical studies, the use of numerical models to evaluate the interaction of groundwater and surface water has become commonplace over the past 25 years. Recently, improved numerical methods for simulating the interconnection of groundwater and surface water have been developed, especially with respect to simulating the surface water component

3.4.1 Hydrograph Separation Technique / Baseflow Separation

Hydrograph separation is the process of separating a plot of stage or discharge vs. time, known as a stream hydrograph, into baseflow and surface runoff components. Baseflow comprises the groundwater contribution to total stream flow. Hydrograph separation is an established technique for quantifying groundwater contribution to annual streams. Clearly, it is not appropriate to apply such a technique to an ephemeral stream fed only seasonally by melt water, or a stream that was only actively flowing after major precipitation events.

Hydrograph separation or recession analysis of stream flow hydrographs has been used for a long time and continues to find its application in many studies. Determination of groundwater baseflow from recession analysis of stream flow hydrographs commonly referred to as hydrograph separation also has a long history (Hall, 1968). There are many techniques that can be used for base flow separation. Methods for separating streamflow hydrographs into components of base flow and direct runoff have been available for many years (Hall, 1968). The common separation methods are either *graphical* (IH, 1978) which tend to focus on defining the points where baseflow intersects the rising and falling limbs of the quickflow response, or involve *filtering* where data processing of the entire stream hydrograph derives a baseflow hydrograph.

Graphical Method

Graphical methods are commonly used to plot the baseflow component of a flood hydrograph event, including the point where the baseflow intersects the falling limb (Figure 3.1). Stream flow subsequent to this point is assumed to be entirely baseflow, until the start of the hydrographic response to the next significant rainfall event. These graphical approaches to partitioning base flow vary in complexity and include:

(i) An empirical relationship for estimating the point along the falling limb where quickflow has ceased and all of the stream flow is baseflow.

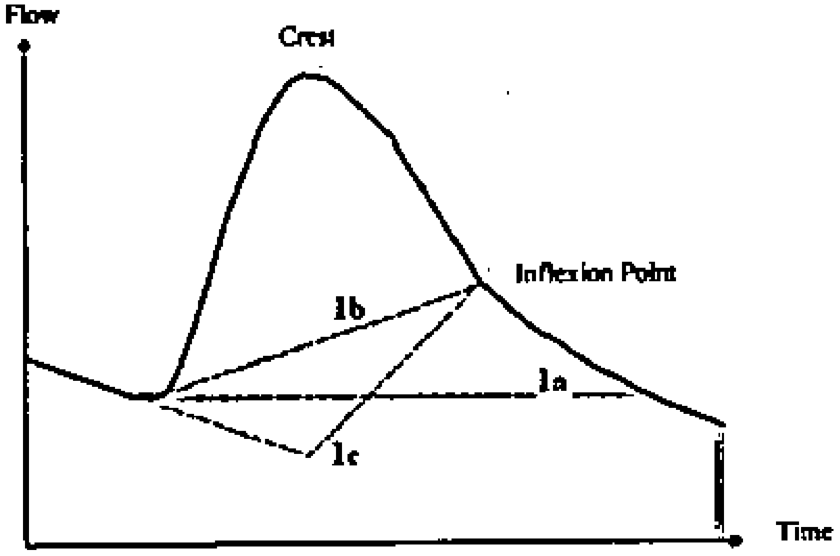
$$N = 0.827A^{0.2} \qquad (3.2)$$

where N is the number of days between the storm crest and the end of quickflow, and *A* is the area of the catchment in square kilometres (Linsley et al., 1975). The value of the exponential constant (0.2) can vary depending on catchment characteristics such as slope, vegetation and geology.

(ii) The *constant discharge method* assumes that baseflow is constant during the storm hydrograph (Linsley et al., 1958). The minimum stream flow immediately prior to the rising limb is used as the constant value

(iii) The *constant slope method* connects the start of the rising limb with the inflection point on the receding limb. This assumes an instant response in baseflow to the rainfall event.

(iv) The *concave method* attempts to represent the assumed initial decrease in baseflow during the climbing limb by projecting the declining hydrographic trend evident prior to the rainfall event to directly under the crest of the flood hydrograph (Linsley et al., 1958). This minima is then connected to the inflection point on the receding limb of storm hydrograph to model the delayed increase in baseflow



(1a) Constant discharge method

(1b) Constant slop method and

(1c) Concave method

Figure 3.1 Graphical baseflow separation techniques

Digital filter methods for baseflow separation

Digital filtering methods have recently become commonplace in hydrograph separation (Lyne and Hollick, 1979; Chapman, 1991; Nathan and McMahon, 1990; Arnold et al., 1995; Arnold and Allen, 1999; Eckhardt, 2004). The digital filter method was originally used in signal analysis and processing processing to separate high frequency signal from low frequency signal (Lyne and Hollick, 1979). This method has been extende in baseflow separation. River runoff analysis can be considered analogus to the electronic signal analysis. High frequency waves can be associated with the direct runoff, and low frequency waves can be associated with the baseflow (Eckhardt, 2004). Thus, filtering direct runoff from baseflow is similar to signal analysis and processing (Eckhardt, 2004). The digital filter method has no physical meaning, but it removes the subjective aspect from manual separation, and aims to generate an objective and easily automated index that can be related to the baseflow response of a catchment. Filtering techniques are fast, consistent, and reproducible (Arnold et al., 1995).

Examples of continuous hydrographic separation techniques based on processing or filtering the data record include:

(i) Increasing the base flow at each time step, either at a constant rate or varied by a fraction of the runoff (Boughton, 1988);

(ii) The *smoothed minima technique* which uses the minima of 5 day nonoverlapping periods derived from the hydrograph (IH, 1980; FREND, 1989). The baseflow hydrograph is generated by connecting a subset of points selected from this minima series. The HYSEP hydrograph separation programme uses a variant of this called the *local-minimum method* (Sloto and Crouse, 1996);

(iii) The *fixed interval method* discretises the hydrographic record into increments of fixed time (Pettyjohn and Henning, 1979). The magnitude of the time interval used is calculated by doubling (and rounding up) the duration of quickflow. The baseflow component of each time increment is assigned the minimum streamflow recorded within the increment;

(iv) The *sliding-interval method* assigns a baseflow to each daily record in the hydrograph based on the lowest discharge found within a fixed time period before and after that particular day (Pettyjohn and Henning, 1979);

(v) *Recursive digital filters*, which are routine tools in signal analysis and processing, are used to remove the high-frequency quickflow signal to derive the low-frequency baseflow signal (Nathan and McMahon, 1990).

3.4.2 Correlation Regression Process

Statistical methods have been used recently to study problems related to the interaction of groundwater and surface water. For example, Adamowski and Feluch (1991) proposed a new nonparametric regression model to investigate the relation between fluctuations in groundwater levels and time series of streamflow. They determined that the nonparametric method resulted in more accurate predictions than those obtained from parametric regression. In another study involving time-series analysis, Niestle and Reusing (1990) compared Autoregressive Moving Average and Fractional Gaussian Noise models to assess their reliability for the analysis of drought risk of the Nile River at Aswan, Egypt. River discharges were converted to water levels, which were then used as input to a simulation model of the interaction of the Nile River with groundwater.

Operation of Rain Gauge and Groundwater Monitoring Networks for the Imperial Valley Water Authority, by Scott et al. (2002), presents hydrogeologic and hydro-meteorologic information gathered from the rain gauge and observation well networks in the Imperial Valley. They found that groundwater level decline was a result of irrigation season pumpage during the highest crop water demands. The study also shows the importance of the timing of precipitation to maintain groundwater levels. Statistical analysis of the relationship between groundwater levels and precipitation showed a one- to two-month lag from the time rainfall is received at the surface of the earth to the time that it is observed in groundwater levels. For wells near the Illinois River, only a one-month lag exists between river stage and groundwater level response.

3.4.3 Flow Duration Curve

Streamflow variations at a station can be characterized by constructing flow-duration curves, which represent the percentage of time stream flows were equaled or exceeded during a selected period (Searcy, 1959; Dingman, 1994). A flow duration curve is one of the most informative means of displaying the complete range of river discharges, from low flows to flood events (Smakhtin, 2001). Low-flow information is particularly useful in determining the probably adequacy of a stream for water supply or for receiving waste discharges. Inclusion of flow duration curves, an essential component of low-flow analysis, with the other hydrologic data help to define the relationship between groundwater and surface water at the site in question. The longer the period selected for the flow duration analysis, the more representative the flow duration curve will be of long-term conditions at the station. Flow duration curves may be constructed with the flow on the logarithmic scale and per cent of time-probability on a linear scale. The percentage of time that flows did not occur is also calculated to assist with characterizing river reaches; in particular, to assist with distinguishing gaining from variably gaining-losing river reaches. Figure 3.2 shows a schematic example of flow duration curves.

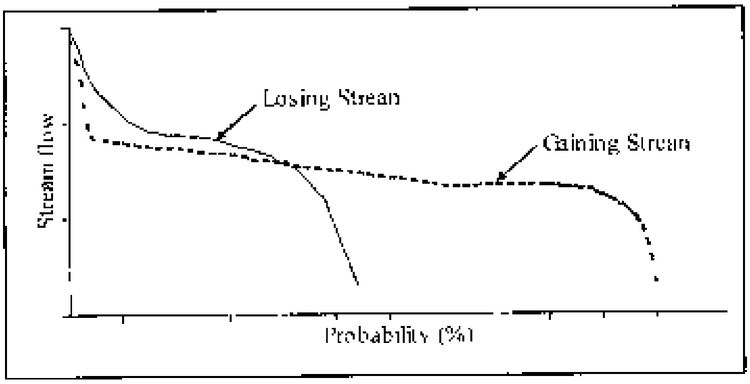


Figure 3.2 Schematic showing flow duration curves illustrating river-aquifer interactions

A connected variably gaining-losing reach may be reflected in the steep slope of the curve, while a flat slope may indicate a gaining stream.

3.4.4 Analytical Solution of Transient Effects of River on Groundwater Flow

Development of analytical solution to one-dimensional groundwater flow in estimating interaction between fluctuating river and groundwater levels and estimating groundwater recharge from streamflow hydrographs has a long history. The one-dimensional flow system is described by the governing equation for linear, non-steady flow in a confined aquifer:

$$\frac{\delta h}{\delta t}=\frac{T}{S}\frac{\delta^2 h}{\delta x^2} \qquad (3.3)$$

Where, T and S are transmissivity and storativity of the aquifer, respectively, h is rise or fall of piezometric head in the aquifer, x is the distance from aquifer-surface body intersection, and t is time. The aquifer is represented as a semi-infinite, horizontal aquifer of uniform thickness. The water level in the river fluctuates and causes a corresponding fluctuation in the piezometric head within the aquifer. The solution to this governing equation for different boundary conditions has been developed over the years by several authors (Ferris, 1951; Cooper and Rorabaugh, 1963; Pinder et al., 1969; Hall and Moench, 1972). However, the solutions are based on many simplifying assumptions, e.g. (1) stream fully penetrates the aquifer, (2) the stream and the aquifer are hydraulically connected, (3) the aquifer is homogeneous, isotropic, semi-infinite in extent and of constant thickness, and (4) flow in the aquifer is only horizontal. The solutions are derived for confined conditions, although satisfactory results for unconfined conditions are also obtained if the location of computed head is sufficiently far enough from the surface water intersection so that it is unaffected by vertical components of flow and the ranges in fluctuation at the computed location is only a small fraction of the saturated thickness of the formation.

3.4.5 Analytical Solution for Computing Streamflow Depletion

The depletion of streamflow by pumping groundwater from the contiguous alluvial aquifer has been a major impetus to studies of the interaction of groundwater and surface water. Several analytical methods are available for computing groundwater drawdowns and stream depletion caused by steady, constant pumping (Theis, 1941; Hantush, 1965). The solutions generally employ image well theory to calculate depletion consider an unclogged streambed in an infinitely long and straight stream. Jenkins (1968) created a series of dimensionless curves and tables of volumes and rates of stream depletion. He introduced a 'stream depletion factor' (sdf) term, which is a time scale based on aquifer parameters and the perpendicular distance from the stream to the well (a_w):

$$sdf = a_w^2 S / T \qquad (3.4)$$

The solutions are based on many simplifying assumptions such as i) The aquifer is isotropic, homogeneous, and semi-infinite; (ii) Transmissivity remains constant. (iii) The stream is of constant temperature, represents a straight boundary, and fully penetrates the aquifer; (iv) Water is released instantaneously from storage; (v) The pumping rate is steady during any rate of pumping, (vi) The well is screened through the full saturated thickness of the aquifer. When the assumptions made in the above solutions are too restrictive, more sophisticated methods must be employed. In a complex system, sdf can be considered an effective value of $a_w S/T$. This value is dependent upon the integrated effects of irregular impermeable boundaries, stream meanders, areal variation of aquifer properties, distance from the stream, and imperfect connections between the stream and aquifer.

A recent paper on this problem (Wallace et al., 1990) was concerned with comparing a dimensionless volume of stream depletion over a pumping cycle with maximum rate of stream depletion at a practical state of dynamic equilibrium. Dimensionless plots of equations developed by applying superposition principles to analytical solutions for steady continuous pumping were used in the study.

When the assumptions made in the above solutions are too restrictive, more sophisticated methods must be employed. Spalding and Khaleel (1991) established relationships between the degree of stream penetration and streambed resistances for values of extended flow lengths and retardation coefficients. They evaluated relative effects of various simplifying assumptions and methods used in the analytical solutions and found that stream flow depletion differed from the numerical model by 20% if partial penetration is ignored and 45% if clogging resistances are ignored.

Fox (2004) studied the development of analytical solutions for predicting the effects of pumping wells on adjacent streams and rivers. The objective of this research was to evaluate the predictive performance of recently proposed analytical solutions for unsteady stream depletion using field data collected during a stream/aquifer analysis test at the Tamarack State Wildlife Area in eastern Colorado. He used stream/aquifer analysis test and falling head parameter test. Analytical solutions are evaluated based on a comparison of measured aquifer properties from prior aquifer investigations and measured streambed conductivity in the backwater stream using in-situ falling head parameter tests against the estimated parameters from the Hunt (1999), Butler et al. (2001), Fox et al. (2002) and Hunt (2003) analytical solutions.

John Harker (1999) developed a simple mathematical model which provides an estimate of the reduction in groundwater flow into a wetland caused by pumping. This tool is based on a new well function which incorporates leakage between the aquifer and the wetland and is a generalisation of the Theis equation.

Zarriello and Ries (2000) incorporated an analytical technique (STRMDEPL) for calculating the effects of pumped wells on streamflow depletion. The authors assessed the interrelated effects of surface-water and ground-water withdrawals on streamflow, and to develop sound management practices to protect these resources.

Zhang (1992) developed solutions for transient flow in an aquifer-aquitard system that considers storativity in a confined layer in response to abrupt changes in water level, uniform changes in water level, and steady rates of seepage from a river. From these equations, he determined groundwater levels for aquifer and aquitard, as well as rates and total volume of seepage from the river. Transient conditions were also of interest to Rastogi (1991), who determined seasonal groundwater flow to a river reach bounded by two reservoirs, where the water-table aquifer was underlain by an impermeable bed. The objective was to determine the amount of groundwater that could be developed from this aquifer system that was receiving seepage from the upstream reservoir, losing seepage to the downstream reservoir, and receiving seepage from the river.

3.5 Numerical Methods

A numerical model of river aquifer interactions generally requires simulation of the surface water and groundwater by employing numerical solutions of equations for surface water routing and groundwater flow. Coupling between two models is also required, and most models use a simple Darcy calculation based on head differences between the surface water and groundwater (winter. 1995). However, Numerical modeling has been the primary tools for analyzing the interaction of groundwater and surface water since the mid-1960s. Because of rigid boundary conditions and simplifying assumptions. analytical models generally can be applied only to simple one-dimensional problems, which may not be adequate for many studies. Complex systems do not lead themselves to analytical solutions. particularly if the types of stresses acting on the system change with time. Numerical models allow for analysis of more complicated systems with or without groundwater withdrawals without many of the simplifying assumptions, and these have been the primary tool for analyzing surface water-groundwater interaction for many years.

Earlier versions of models such as MODFLOW by McDonald and Harbaugh (1984) of U.S. Geological Survey used stream stage as boundary conditions. Later the surface-water model and the groundwater model were combined for an integrated calculation of a more realistic nature by incorporating a streamflow routing routine, called the "Stream Package", in MODFLOW (Prudic, 1989). Its use, however, is limited to steady flow in rectangular channels. Swain and Wexler (1996) combined USGS models MODFLOW and BRANCH into a new groundwater/surface water interaction model, called "MODBRANCH. The streamflow and groundwater equations were coupled using a leakage term at the sediment-water boundary. Coupling of unsteady river flow solver with other groundwater flow model such as MIKE-SHE developed by Danish Hydraulic Institute (DHI, 2000) has also been made. MIKE-SHE and MIKE-11 were applied in a basin in the northwest region of Bangladesh to examine aquifer-river interaction and assess safe withdrawal from the aquifer without environmental degradation (SWMC, 2000)

3.6 Artificial Neural Networks

Artificial neural networks (ANNs) are a recent innovation in water resources technology which has potential for use in river-aquifer interaction studies. An ANN is a set of highly interconnected mathematical processing elements which are capable of representing non-linear multivariate mapping functions between input and output data sets. The forms of the mapping functions are determined through 'training' the ANN using sets of input and output data. Their use in the UK within a water resources context has been largely pioneered by the Newcastle team (Rao and Jamieson, 1997; Rao and O'Connell, 1999). Within the field of river-aquifer interaction studies, ANN's have the potential to represent the relationships between groundwater abstraction data and river low depletion using data from numerical models and from field observations where available.

3.7 Surface water - Groundwater Interaction Studies in Bangladesh

Ahmed (1994), Ahmed & Burgess (1995) conducted the study using chemical and isotopic evidences to determine the interaction between surface water and groundwater system in Northwest region of Bangladesh Ahmed (1994) conducted a study to estimate baseflow of the river Atrai in NW Bangladesh estimated base flow components for the period 1980 to 1990 using software from the Institute of Hydrology, UK. The estimate shows that baseflow on the river varies from 32 to 62% where the annual discharges varied from 31,700 to 72,076 cumecs.

Saleh (1985) developed an analytical model called, Watershed Irrigation Potential Estimation (WIPE) model, to simulate groundwater movement in a watershed in the North-West Bangladesh. He found that, beyond 2000 m from the river, the flux from the water table to the river was negligible and the water table profile of the watershed was not affected by the water level in the river. Hoque (1986), Khan and Mawdsley (1986), and Michael (1986) also dealt the problem of stream-aquifer system, although their main emphasis was on the theme of conjunctive use of surface and groundwater. Faisal (1988) studied the effect of river stage on the groundwater table at different distances by simple linear regression and estimated the characteristic distance beyond which the groundwater table is no more affected by the river stage.

SWMC (1996) used MIKE-SHE to model the interaction between the surface water and groundwater in order to introduce the modelling system and demonstrate the capabilities in some areas of data shortage with limited time. In this study, the model reproduced the groundwater levels and surface water flows and levels, and clearly showed the interaction between surface water and groundwater. SWMC (2000) carried out a study to examine the interaction between surface water and groundwater in the Atrai river basin, Northwest region of Bangladesh using coupled MIKE II-MIKE SHE modeling system. The result of this study are the river is in direct contact with the aquifer, and generally river contributes to aquifer from the month of March to November and the gets flow from aquifer from December to February. IWM (2005) carried out the study using Integrated MIKE 11 – MIKE SHE modeling system to explore the modern technique with the view to increase agricultural production in Thakurgaon District through optimum utilization of available water resources, to address irrigation adoption based on groundwater zoning for an efficient planning and management of the water resources and also to conduct the assessment of groundwater availability and potential for future expansion.

Chapter Four

STUDY AREA

4.1 Introduction

Master Plan Organization (MPO) set hydrologic catchment area (CA) level and planning area (PA) level all over the country on the basis of hydrological characteristics for analysis of problem, assessment of resources and identification of development opportunities. The selected catchment (catchment no. 33) is shown in Figure 4.1. In Bangladesh, almost 193 catchments were considered for the identification of project type, formulation and prioritization of investment program, computation of incremental food production etc.

4.2 Area and Location

The study area covers parts of eight thanas named Akkelpur, Badalgachhi, Naogaon sadar, Mohadevpur, Raninagar, Atrai, Adamdighi and Dhupchanchia within hydrological catchment area No NW-33 in the Northwest region of Bangladesh. The total area of selected eight thanas is 1886 sq. km among which catchment no NW-33 occupies an area of 839 sq. km. including river area (BBS, 2001). Table 4.1 shows the thanas and districts along with the percentage of area covered from each thana within the study area.

The study area lies between 24°37'48" and 24°58'48" North latitudes and between 88°48'36" and 89°10'12" East longitudes. The area is bounded on the north by Khatlal thana of Joypurhat district, on the east by Kahalu and Nandigram thana of Bogra district, on the south by the Atrai river and on the west by Niamotpur and Manda thana of Naogaon district. Hydrologically, the study area named Little Jamuna catchment (Catchment no. 33) is bounded on the north by Catchment no. 24 and 27, on the east Catchment no. 28 and 34, on the south by Catchment no. 25 and 39 and on the west by Catchment no. 25

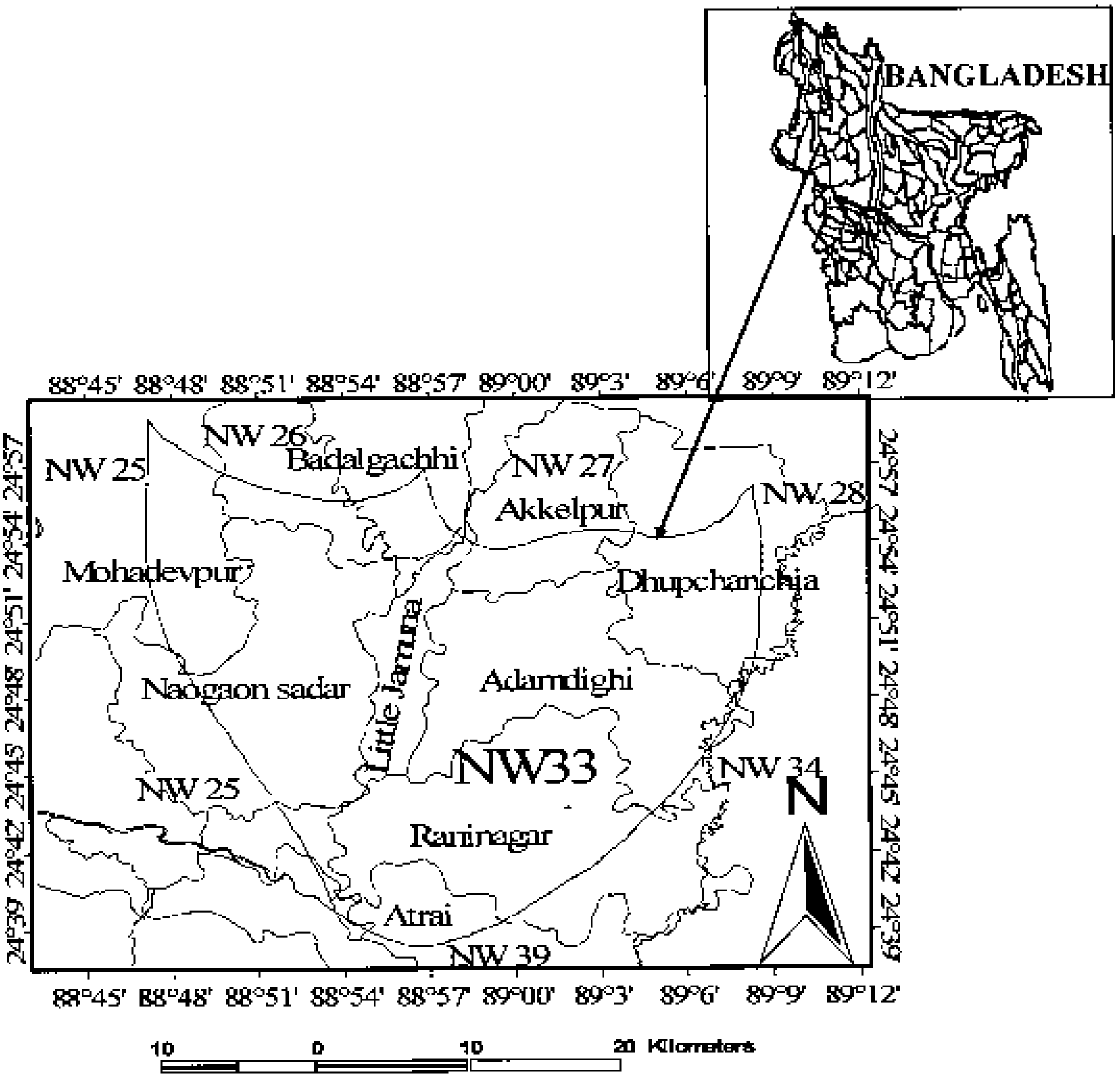


Figure 4.1 Location of the Study Area

Table 4.1 List of thana along with covered area in the study area

SL. No.	District	Thana	Area of Thana in Study Area (%)	Area of Thana in Study Area (km^2)
1	Bogra	Adamdighi	100	183
2	Bogra	Dupchanchia	55	90
3	Joypurhat	Akkelpur	21	35
4	Naogaon	Atrai	16	35
5	Naogaon	Badalgachi	35	78
6	Naogaon	Mohadevpur	24	90
7	Naogaon	Naogaon sadar	85	238
8	Naogaon	Raninagar	35	90
Total Area of the Study Area (km^2)				**839**

4.3 River Systems

The term 'Little' is used to differentiate the river from the mighty 'Jamuna' river. The Ichamoti river is originated from Chatianagar beel under Khansama thana of Dinajpur district and flows through Birampur thana and renamed as Icha-Jamuna. Flowing through Panchbibi and Badalgachi, the Icha-Jamuna river is met with Tulsiganga at Naogaon sadar and renamed as Little Jamuna. The Tulsiganga acts as a tributary of Little Jamuna. This Tulsiganga river originates from Dhanpara beel under Nawbabganj thana of Dinajpur and flow through Birampur, Hakimpur, Panchbibi, Khatlal, Akkelpur and met with Little Jamuna at Naogaon sadar. The river Little Jamuna falls with Atrai river flowing through Naogaon sadar, Raninagar, Atrai and Bagmara thana (BWDB, 2005). The river system in the study area is shown in Figure 4.2. Nagar river originates from Karatoya and flows to the boundary of the study area at Adamdighi and meets Atrai at Raninagar thana. The total length of Little Jamuna river is about 120 km. There is a river stage and flow measurement station in the Little Jamuna river situated at Naogaon town (as shown in the Figure 4.2).

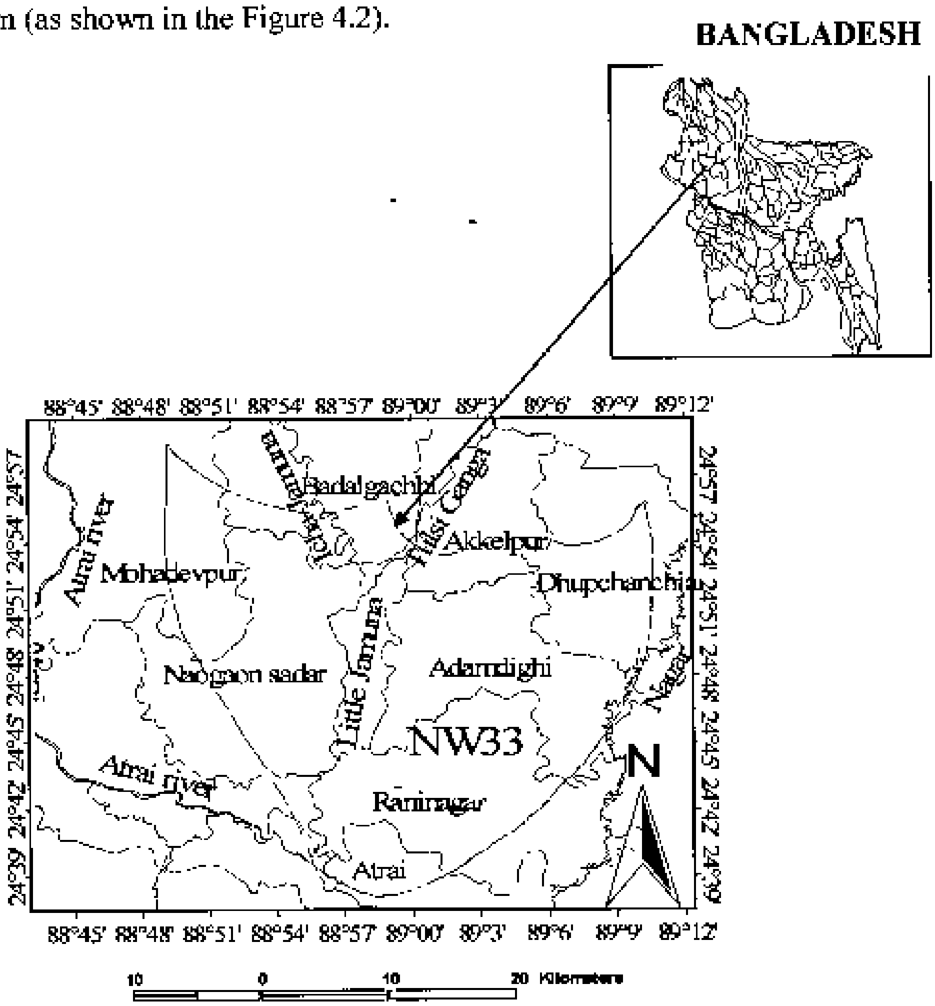


Figure 4.2 River Systems in the Study Area

4.4 Static Water Systems

In the study area, there are some important static water bodies. Notable Beels are Betgari, Kaigari, Subeel, Nuruler Beel, Poradaha beel, Keshpathar, Kalidaha, Padma, Garai, Sattarail, Arulia Demradaha, Sara, Gobarchapa, Mahichbaran, Ziadaha, Bahuar beel, Ramchandrapur, and Kokira, Kachiar beel. Adamdighi, Sangshar, Badla, Sil Kawrer Dighi, Shahar Dighi, Kuldighi, Khadash Dighi are also notable water bodies During dry season, the static water bodies are considered as the important sources from which water is used for various purposes. Static water bodies may play an important role for supplying of water in the dry season. These beels are the major source of fish for local people. But the depths of these beels are very shallow and most of them are now completely dry and used as a crop field in the dry season. Some of them are used as regular agricultural field. The beels in the Barind Tract of northwest Bangladesh play a localized role in the interaction between surface water and groundwater (Ahmed and Burgess, 1995).

4.5 Climatic Factors

The study area lies in the monsoon region of the summer dominant hemisphere. The tropic of cancer lies south of this region The climate of the area is generally warm and humid. Based on rainfall, humidity, temperature and wind pressure the weather condition is classified into four types, such as, (a) pre-monsoon, (b) monsoon, (c) post-monsoon and (d) winter. Some of the important climatic parameters are described below.

4.5.1 Temperature

The temperature varies between 44°C to 6°C; the climate is dry apart from the monsoon season from mid June to mid October. Its average temperature ranges from 35°C to 25°C in the hottest season and 9°C to 15°C in the coolest season. The coldest months, December and January, average about 10.72°C; occasional freezing temperatures occur during this time. During the warmest months of July and August, the average temperature is about 27.28°C Generally this region is rather hot and is considered semi-arid. In summer, some of the hottest days experience a temperature of about 45°C or even more. In winter it falls to about 5°C in some places of the study area So this older alluvium region experiences extremes that are clearly in contrast to the climatic condition of the rest of the country.

4.5.2 Rainfall

The tropical monsoon climate of Bangladesh results in an annual rainfall of about 2300 mm across the country as a whole, but rainfall over the Little Jamuna river floodplain is much less (Ahmed and Burgess. 2003). Annual rainfall varies between 1400 to 1700 mm; about 1500 mm annually that is much lower than the national average. Rainfall is concentrated into the wet season between May and July. and little rainfalls occur during six dry months of the year between October and March. Rainfall varies from place to place as well as year to year For instance, the rainfall recorded in 1981 was about 1.738 mm, but in 1992 it was about 798 mm only. There are six rainfall stations in this area namely Atrai, Mohadevpur, Badalgachhi, Dhupchanchia. Adamdighi and Naogaon. Daily rainfall data are available at these stations mostly from 1961 to 2003. The lowest annual average rainfall of 572 mm is observed at Adamdighi in 1999, whereas, the highest annual average rainfall of 2352 mm at Naogaon in 1987. Table 4.2 shows the mean monthly rainfall in the study area.

Table 4.2: Mean monthly rainfall in mm (Source of data: BWDB)

Station Name	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Annual
Adamdighi	40.4	138.3	282.3	272.9	283.1	238.4	127.2	11.3	1.5	9.7	10.2	17.4	1432.7
Dhupchanchia	64.1	178.7	309.1	329.2	276.8	280.1	158.1	11.7	1.3	9.8	15.6	27.2	1661.7
Badalgachhi	35.8	137.7	274.6	303.4	276.7	269.6	153.1	11.8	2.0	10.2	17.3	19.1	1511.3
Naogaon	49.7	135.8	295.9	310.2	295.2	262.4	131.0	12.3	1.7	7.8	16.5	21.9	1540.4
Mohadevpur	76.1	189.2	298.7	338.9	297.2	279.5	177.3	13.2	3.6	15.9	18.2	26.5	1734.3
Atrai	31.5	125.1	279.6	298.5	231.2	253.7	119.1	8.9	1.2	6.4	11.2	17.2	1383.6

4.6 Geology and Geomorphology

Northwest region is divided into three units. These are Recent Alluvial Fan, Barind Pleistocene, and Recent Floodplain. The Little Jamuna catchment area is located southeast of Barind Tract: the catchment includes recent alluvial floodplain and some parts of the East Barind Tract. Barind tract is one distinct physiographic feature of

Bangladesh. The East Barind Tract is at an elevation of 30 m while the West Barind tract is at an elevation of 50 m (Ahmed and Burgess. 2003).the poorly permeable clay ground surfaces of both regions are drained by a network of 'Kharies' (drainage channels) which carry floodwater during the monsoons but rapidly become dry following the onset of the dry season. The Little Jamuna together with other rivers such as Mohananda. Atrai. Punarbhaba and Siba dissect the Barind Tract in to a number of blocks. These morphologic units are separated by long, narrow bands of Recent Alluvial Each of these rivers has its own floodplain within the tract and is generally restricted in width to few kilometers. The Barind unit is comparatively at 15m to 25m higher elevation than the adjoining floodplains.

Barind Tract, the largest Pleistocene terrace of the country, is made up of the Pleistocene alluvium. also known as older alluvium of mostly red and brownish clay. The clay cover of barind Tract varies considerably in thickness. The clay reaches to a maximum thickness of 40 m in the north-west in high (West) Barind to a thickness of few meters in the south-east. The alluvial sediments of the river floodplain consist of sequence of sediments varying from clay to medium sands. The sandy section of the unit serves as producing aquifer in those parts. The thickness of the unit reaches upto 100 m (drilled depth) in the floodplains. Naogaon, Atrai area are within interstream deposits areas whereas Mohadevpur, Badalgachhi, Akkelpur, Dhupchanchia, Adamdighi and Raninagar area are within the older alluvial deposits. All the deposits are riverine, stratified and heterogeneous in nature (SWMC, 2000).

4.7 Aquifer System and Properties

Most aquifers in Bangladesh exhibit either leaky or unconfined responses over the time period of main concern (Peter, 2004) A number of hydrogeological studies have been carried out in and around the study area (Alam et al.. 1990; Ali, 1993; Ahmed. 1994; Ahmed and Burgess, 1995, Begum et. al., 1997; Azad and Bashar, 2000; Haque et al., 2000; Shams, 2002). The available literature (BGS, 2001) reported that the aquifers in the area occur in two broad horizons, the shallow aquifer and the deep aquifer. Most of the people of the area meet their demands of irrigation and domestic water supply by tapping these shallow aquifers. Except some part of the Flood Plain area, the aquifers over most of the region are sandwiched between upper silt and clay aquitard and lower silt and clay aquitard (Shams, 2002). The aquifer (Dupi Tila) material is composed of a sequence of medium to coarse-grained sands with occasional gravels. The thickness of this layer ranges from 5 meters to more than 70 meters (Begum et al., 1997). According to Ahmed (1994), groundwater in this shallow aquifer flows from north to south with localized outflow into the major rivers with a head gradient of 1:1000.

SWMC (2000) analyzed the subsurface formations in the Atrai basin and classified them into four groups: (i) upper aquitard; (ii) upper aquifer; (iii) lower aquitard; and (iv) lower aquifer. The material like clay, silt, very fine sand and fine sand were considered as aquitard and other sandy materials like medium and coarse sand and gravels were taken as aquifer. Geometry of aquifer covers the thickness of aquifer and depth to top of main aquifer. The average thickness of aquifer is 50 m or more and the maximum can be as such as 80 m or more. Maximum, minimum and average thickness of the geological layers in the Atrai basin is given in Table 4.3. The thickness gradually decreases from North-west to South-east. The thickness of upper aquifer is undulating from North-west to South-east. Some assumptions were applied in defining the lower aquitard and lower aquifer because of insufficient data over depth in many of the borelogs.

Table 4.3 Maximum, minimum and average thickness of the geological layers (Source: SWMC, 2000)

Geological Layer	Thickness (m)		
	Maximum	Minimum	Average
Upper Aquitard	53.00	4.25	16.50
Upper Aquifer	87.00	35.75	53.50
Lower Aquitard	87.00	4.50	35.50
Lower Aquifer	50.00	50.00	50.00

Along the Atrai, the clay is overlain by a thin section of alluvium. The Atrai and Mohananda cut through the Barind across clay, and this contributes to direct recharge (Ravenscroft, 2003; Khan, 1991). In most parts of east of Little Jamuna and West of Mohananda, the Barind clay is missing. In these recent alluvial parts, the aquifer behaves like an unconfined aquifer. The Dupi Tila aquifer is in hydraulic contact with the alluvial sediments that makes out the majority of the sediments in the Little Jamuna river catchment.

Aquifer Properties

Aquifers in Bangladesh are recharged by vertical percolation of rain and flood water (Ahmed and Burgess, 1995) The aquifers of the Little Jamuna Floodplain demonstrate piezometric recovery subsequent to pumps being turned off at the end of the irrigation season, before the onset of the monsoon rains, confirming the significance or vertical leakage (Ahmed, 1994). Transmissivity values range from 1500 m^2/day to 3000 m^2/day, averaging 2300 m^2/day (see Table 4.4). Higher transmissivity occur in the northern part (2500-3000 m^2/day), and lowest transmissivity occur in the southern part (1500 m^2/day) (Majumder, 1998).

The storage coefficient is the fraction of water released from a unit volume of aquifer because of reduces water pressure or dewatering. The long term storage characteristics used to define the seasonal storage volumes are defined by specific yields representative of the fully unconfined aquifer. Specific yields of the upper aquifer in the study area is mostly 0.1 (see Table 4.4), indicating a close to unconfined characteristic of aquifer.

Table 4.4 Aquifer properties (Source of data, WARPO: Specific yield information is from SWMC, 2000)

Geocode	District	Thana	Vertical hydraulic conductivity (cm/s)	Transmissivity (m^2/day)	Specific yield
53813	Joypurhat	Akkelpur	0.2	2500	0.1
51006	Bogra	Adamdighi	0.2	2500	0.1
51033	Bogra	Dhupchanchia	0.3	3000	0.1
56406	Naogaon	Badalgachhi	0.1	2500	0.05
56460	Naogaon	Naogaon sadar	0.02	2000	0.1
56485	Naogaon	Raninagar	0.1	1500	0.1

4.8 Existing Groundwater Irrigation Development

The study area is dominated by agricultural land with discrete households. The main crop in this area is paddy, which includes Boro, High Yield Variety (HYV) Aman and transplanted Aman. Extensive irrigation mainly through shallow and deep tube well is common in the area. The main use of groundwater in the study area is for irrigation. Groundwater is also abstracted by hand tube wells and dug well for drinking purpose. This volume is insignificant compared to abstraction rates for irrigation (SWMC, 2000).

There is extensive abstraction of groundwater in the study area mainly by shallow tube well (STW), deep-set shallow tube well (DSSTW), very deep-set shallow tube well (VDSSTW) and deep tube well (DTW). Manually operated pumps or MOPs (non-mechanized hand tube well, traditional pumps, rower pumps, bamboo tube wells etc) for irrigation had created great enthusiasm among the farmers for low cost, simple technology and easy operation. But presently, most of the hand tube wells are no more in use for irrigation in dry season following lowering of groundwater level and goes out of order due to long use. For this, numbers of manually operated pumps have declined substantially. The area under dry season irrigation from groundwater has grown rapidly since 1986-87, after low growth during the mid-1980s period of regulation and controls. Both numbers and total areas under STWs have increased rapidly, and the STW irrigated area has grown by an average of 12.5% per annum in the 15 years up to 1997-98 (NWMP, 2000). At peak irrigation period groundwater scarcity posses some problem for STWs. Due to lowering of static water level it is not possible to lift water by STWs. This has led to use of deep tubewells, which has increased in the study area over the years.

Chapter Five
METHODOLOGY

5.1 Introduction

In order to understand the interaction between surface water and ground water systems, the important features in each system need to be examined. The study followed a techno-social approach to characterize the surface water and ground water systems and their interactions in the study area. Technical analysis mainly included a variety of analytical approaches, e.g lithological analysis, hydrograph analysis (through comparison of rainfall, ground water level and river stage time series), flow duration curve, baseflow separation, trend analysis and correlation regression analysis. Two social investigation methods were conducted in the study area. The first one involved a questionnaire survey (using structured questionnaire) in 4 thanas in the study area, with a view to finding out people's perception about the status of stream flow depletion and its possible causes, impacts and mitigation measures. The second method involved purposive interviews (with semi-structured questionnaire) conducted along a 17.5 km stretch along the Little Jamuna river with the chief objective of characterizing the spatial variation in stream and aquifer system and their interaction.

5.2 Data Collection

Data required for the study include rainfall, river water level and discharge, groundwater level from observation wells, irrigation, borelog data. These data were collected from different types of sources such as BWDB, WARPO, BMDA, BADC, DAE, BMD, DPHE, IWM, and IWFM Library in BUET. In addition to this, data were collected from field offices as and when required. The hydro-meteorological data collected are not continuous, there are quite a few gaps in the data. The periods for data collection along with missing data are summarized in Appendix-A.

5.2.1 Rainfall

There are 6 rainfall stations namely Naogaon, Badalgachhi, Adamdighi, Dhupchanchia, Atrai and Mohadevpur within the study area. Historical rainfall for the period of 1961-2003 of these stations was collected from BWDB. The locations of the rainfall, river water level and discharge stations are shown in Figure 5.1. Among the 6 rainfall stations, data of only 4 stations, namely Naogaon, Badalgachhi, Adamdighi and Dhupchanchia, were processed for analysis. Rainfall stations along with data status are listed in Appendix-A.

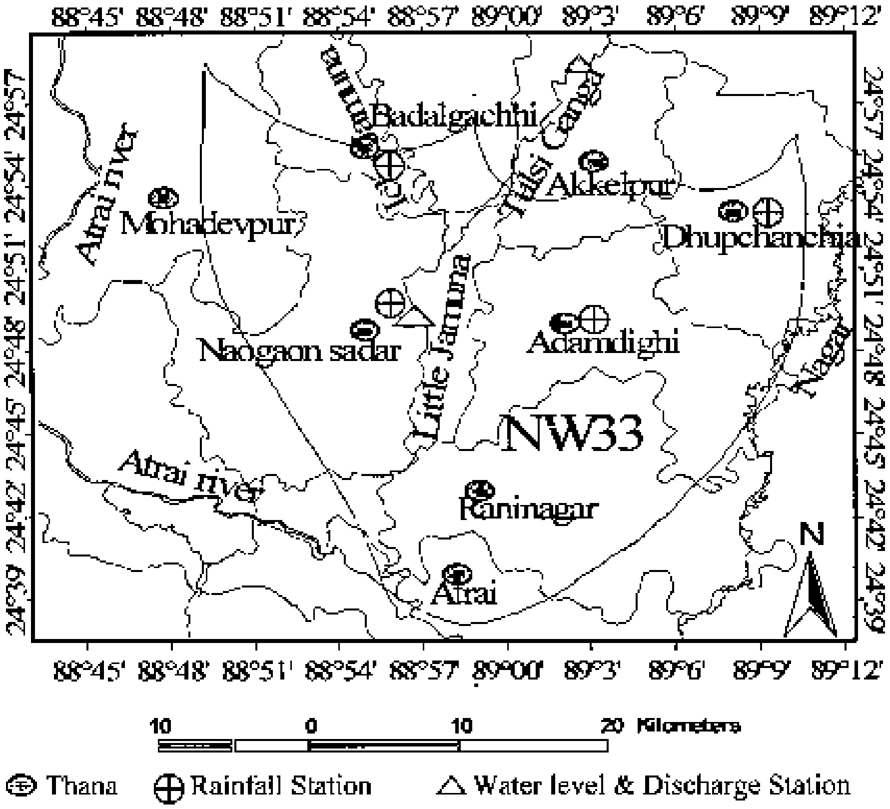


Figure 5.1 Location of rainfall, water level and discharge gauge stations

5.2.2 River Water Level and Discharge

River water levels for the period of 1964-2003 of existing two stations namely Naogaon (133) and Sonaimukhi (325) of BWDB were collected from WARPO database and BWDB. Sonaimukhi water level station is upstream and far from the selected study area and was used mainly to interpolate water level at different locations in the Little Jamuna river. River water discharge data for the period of 1965-1992 of Naogaon (133) station of BWDB were from WARPO database and BWDB. Among these discharge data, some data are missing in each every year. Besides, there is no daily discharge data from 1993 to date. For the analysis of the present study, discharge data was generated for the period of 1993-2003 using a rating curve equation, $Q = 0.0000166 * (WL - 3)^{6\ 4103}$, which was estimated by fitting a line through the discharge versus water level plots of 1990-1993 (see Figure 5.2). It should be noted here that this may have involved some uncertainty and error. However, when the discharge versus water level plots for the four years are compared (Figure 5.2), it is seen that there was not any significant shift in the rating curve.

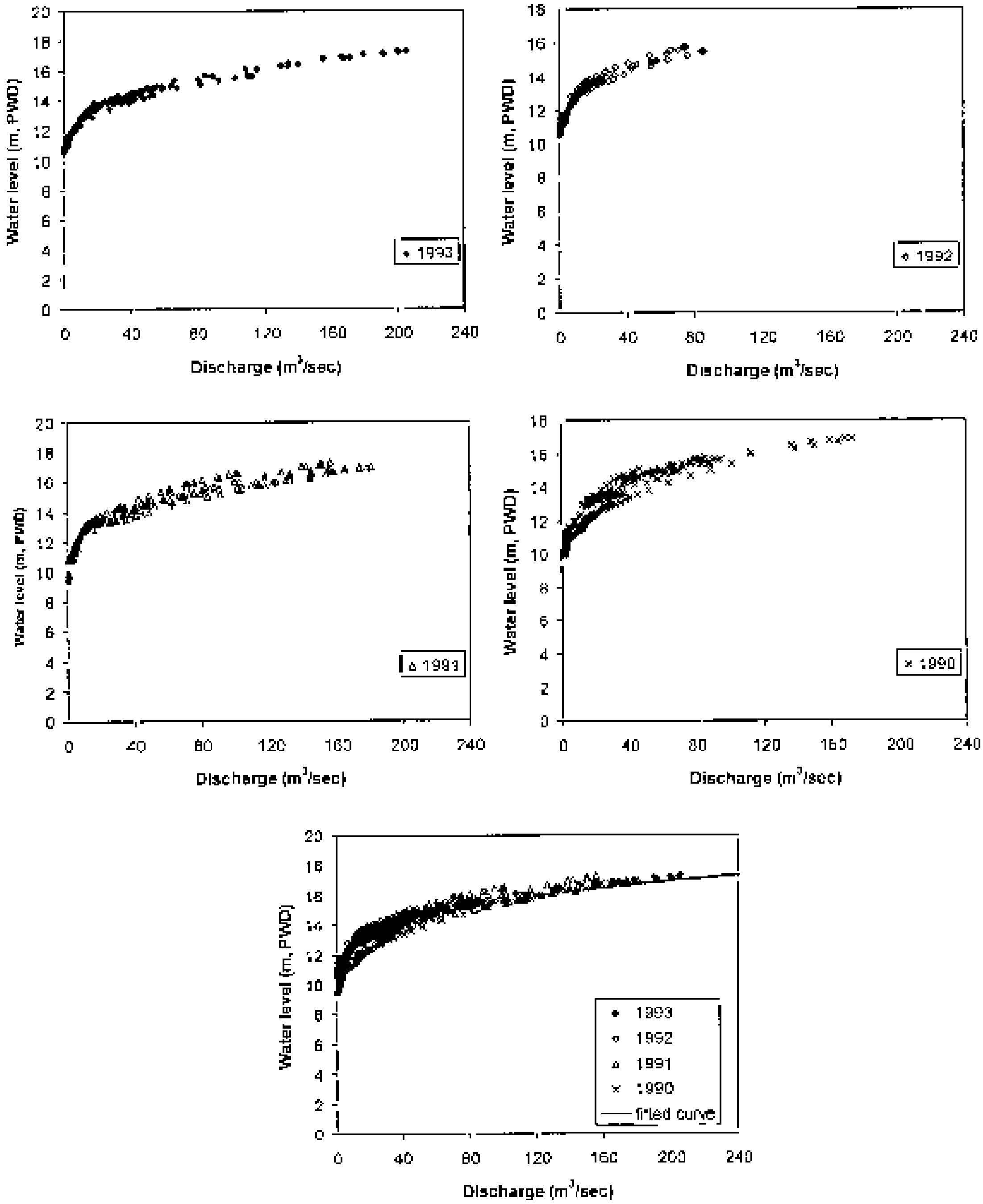


Figure 5.2 Fitted rating curve equation for generating discharge data for the period 1993-2003 [$Q = 0.0000166 * (WL - 3)^{6.108}$]

5.2.3 Groundwater Level

Weekly depths of ground water level data from the fixed measuring stations were collected for a period of about 30 years. These data were collected from WARPO, BWDB and local office of BMDA and BADC. BWDB maintains all the groundwater observation wells. The frequency of measurement is generally once a week. The locations of the groundwater observation wells are presented in the Figure 5.3. It was found that piezometer well and dug well were installed in same location and some data are missing and poor in quality and quantity in a few observation wells, which were later discarded. The locations together with specification of the observation wells are given in Appendix-B.

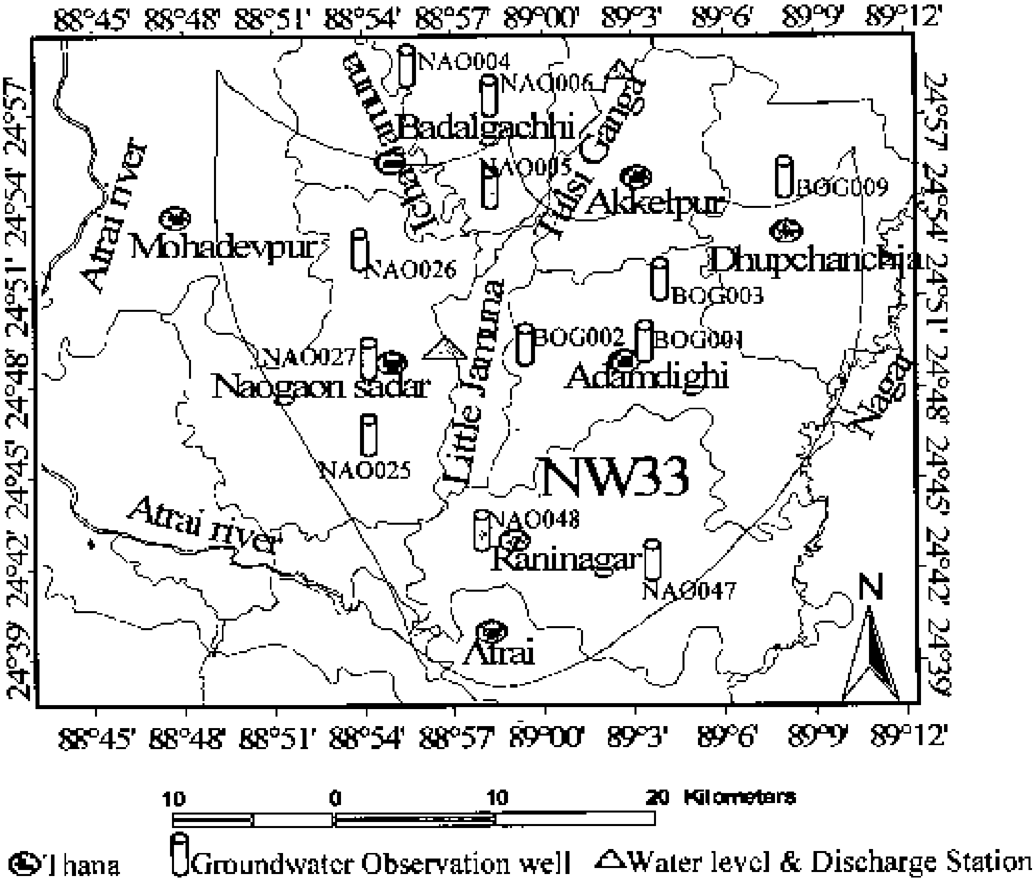


Figure 5.3 Location of groundwater observation wells

It is essential to mention the concept of groundwater depth and level before analyzing the groundwater data. In the data sheet reduced level (RL) of parapet, parapet height (PH) and groundwater depth below measuring point (h) are given. The groundwater level is calculated by the equation, $Groundwaterlevel = RL - h$. The concept of groundwater depth and level were shown through a sketch (Figure 5.4). It is to be mentioned that the minimum groundwater depth occur during wet season while the maximum groundwater depth occur during dry season.

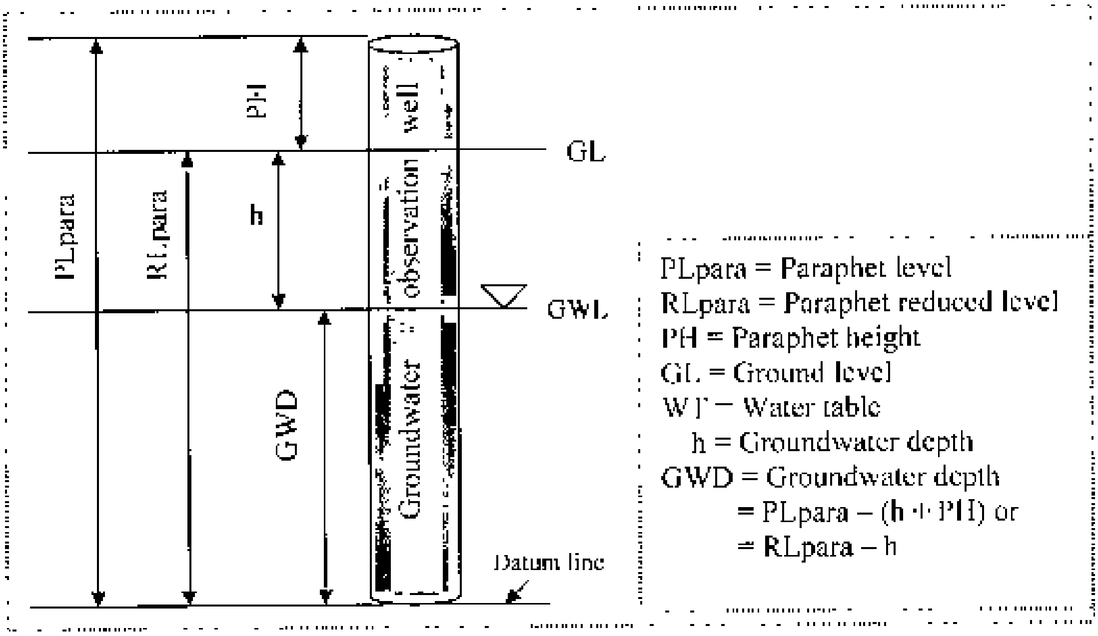


Figure 5.4 Schematic diagram of groundwater depth and level

5.2.4 Borelog Data

There are 61 borelog stations in and around the study area. These borelog data were collected from WARPO and BWDB database. Among 61 borelog only 46 borelog are installed within the study area. Most of the boreholes are located in the west-central part of the study area and in some part of the area no borelog data are available. The locations of boreholes are shown in Figure 5.5, and borelog data status in and around the study area are presented in Appendix-C.

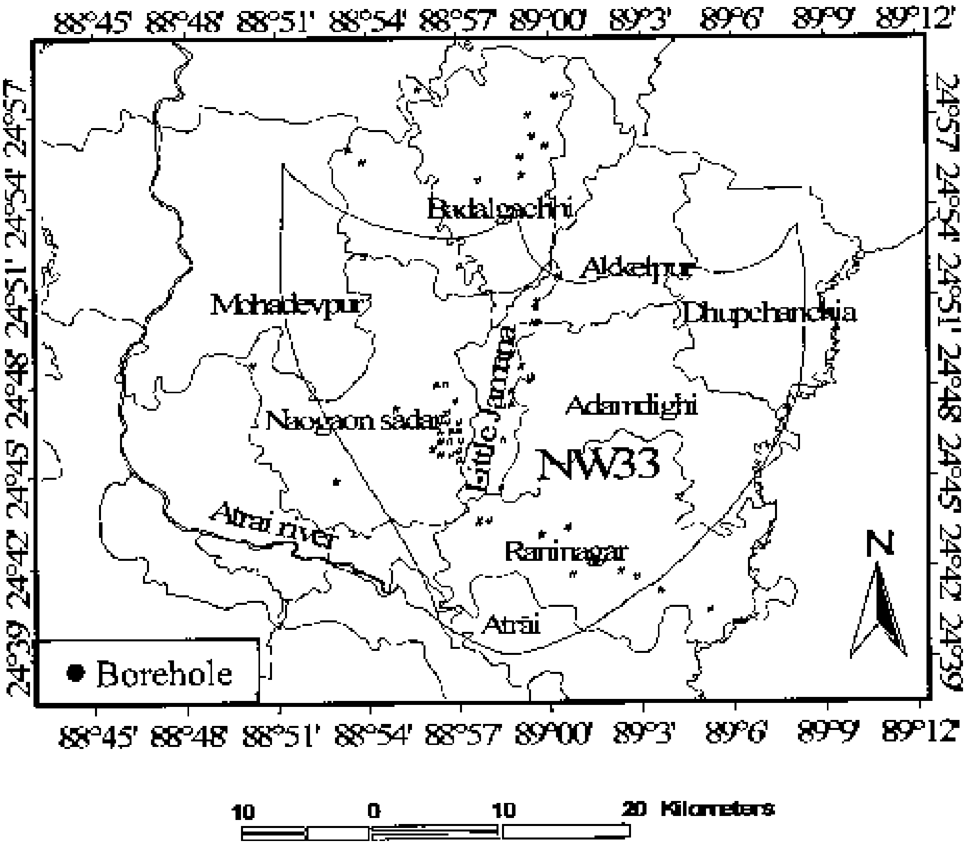


Figure 5.5 Location of boreholes in and around the study area

5.2.5 Irrigation Development Data

Thana wise irrigation data from 6 thanas, namely Naogaon, Badalgachhi. Raninagar, Adamdighi, Dhupchanchia and Akkelpur within the study area have been collected from WARPO, BADC, DAE and field office of BMDA in the form of no. of STW, DSSTW, VDSSTW, DTW, FMTW, LLP, MOPU, TRAD, DTWNOP along with net cultivable area (NCA) in hectares. From secondary sources along with field survey, pumping rate of STW was found to be 0.5 cusec and that of DTW 2 cusec. Depth of STW is about 40 to 60 meters and that of DTW 100 to 120 meters. From BADC source, discharge capacity of STW is about 14 l/s and of DTW is about 4 times that of STW. The number of STWs considered in the study includes the number of STW, DSSTW and VDSSTW, and the number of DTWs includes FMTW and DTW also. Thana wise irrigation data status collected mainly from secondary sources are enlisted in Appendix-D.

5.2.6 Field Survey

Two social investigation techniques were employed. One questionnaire survey was conducted using structured questionnaires in 4 thanas, named as Naogaon, Badalgachhi, Raninagar and Adamdighi in the study area, with a view to finding out people's perception about the status of stream flow depletion and its possible causes, impacts and mitigation measures A number of 60 randomly selected respondents were chosen (15 from each thana) in areas (or villages near the Little Jamuna river). Since the purpose of the survey was to look into the history of availability of stream flow and groundwater, all of the respondents chosen were local permanent residents with age above 50. The second method involved purposive interviews with the help of a semi-structured questionnaire with 35 selected respondents (one for each 1/2-km distance) over a 17.5 km stretch along the Little Jamuna river with the chief objective of characterizing the spatial variation in stream and aquifer system and their interactions. The respondents in this second survey were also were aged 50 years or above.

The questionnaires used in the questionnaire survey and purposive interviews are given in Appendix-E and Appendix -F, respectively. In addition to the questionnaire surveys, a number of purposive interviews were conducted with local officials of BMDA, BWDB, BADC, DPHE and NGOs.

5.3 Data Analysis

5.3.1 Analysis of Lithology

Borelog data were processed according to depth of same soil properties. According to similarity in soil types or homogeneity in soil properties, the soil layers were grouped into 8 major layers as Pure Sand, Graveliferous Sand, Silty Sand, Pure Silt, Sandy Clay, Sand Clay Silt Mixed, Silty Clay and Pure Clay (see Appendix-G).

More than 60 lithologic logs were visually analyzed and treated in three dimensional environment using software Rockworks 2004 (RockWare, 2004). Rockware software has long been the standard in the petroleum, environmental, geotechnical and mining industries for subsurface data visualization because of popular tools such as maps, logs, cross-sections, fence diagrams, solid models and volumetrics. The well organized layers with borehole_id, longitude, latitude in decimal, elevation, depth with homogenous soil type and total depth of lithologs are input into the three dimensional environment Rockworks 2004. In the Rockworks 2004 software program, longitude and latitude were converted into Northing and Easting value. After the identification of the locations of boreholes and processing borelog data, lithological columnar sections were drawn. In order to represent the vertical distribution of different sub-surface formations a datum has been considered 106.75 m below PWD covering the maximum depth of borehole information. To observe the vertical distribution of different formations of the effective study area, twelve representative vertical cross-sections (shown in Figure 5.6) along east-west (6 profiles) and north-south (6 profiles) directions were prepared. The east-west profiles are oriented at latitude of 24°51', 24°49', 24°47', 24°45', 24°43', and 24°41'; whereas the north-south profiles are oriented at 88°52', 88°54', 88°56', 89°00', 89°02', and 89°04' respectively.

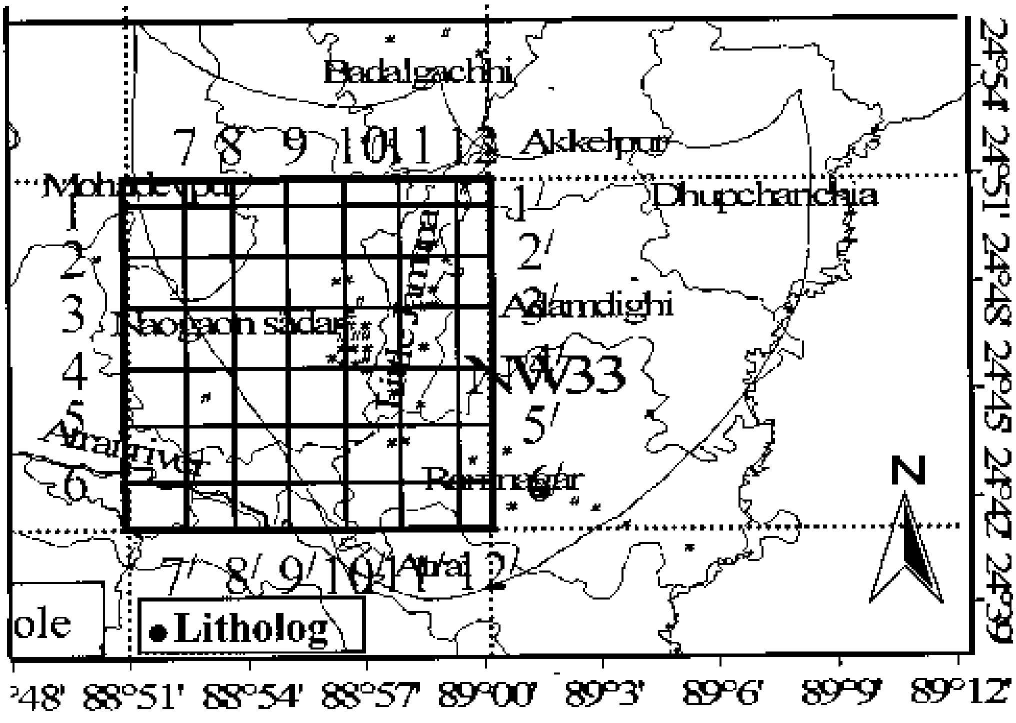


Figure 5.6 Representative twelve cross-sectional profiles in the study area

5.3.2 Time Series Analysis

The historical time series data of river water level and discharge, and groundwater levels were visually checked for presence of trends, if any. Daily river water levels and discharge for the period of 1964-2003 of Naogaon (133) gauge station were processed for yearly mean, maximum and minimum, yearly dry period (November-May) mean, yearly flood period (June-October) mean water level and discharge data set, respectively for trend analysis. The groundwater levels were processed for yearly minimum.

5.3.3 Analysis of Relationships between Hydro-Meteorological Parameters

Visual comparison of time series data: Time series data of rainfall, river water level, and groundwater levels were compared to see the relationship (e.g. change in one parameter in response to the change in other parameter) between rainfall and river water level, rainfall and groundwater level and river water level and groundwater level.

Correlation Regression Analysis: Correlation regression analysis was performed between monthly total rainfall and monthly mean river water level, monthly total rainfall and monthly mean groundwater level, and monthly mean river water level and monthly mean groundwater level. Monthly groundwater level measurements in each well were correlated with total monthly precipitation at the nearest rain gauge(s) and the Little Jamuna River stage. The correlation regression analysis was repeated for lagged time series data to investigate the time delay in response, if any, of any parameter to the change in the other parameter.

Irrigation development and Monthly river stage were also correlated with total monthly precipitation by simple correlation regression analyses. Best-fit equations were calculated based on linear regressions and coefficients of determination (R^2) and correlation coefficients (R) were calculated.

5.3.4 Baseflow Analysis

Baseflow separations from the hydrographs were performed using digital filtering technique. In this study, the digital filter BFLOW was used. A brief description of BFLOW is given below.

BFLOW

The BFlow program separates baseflow from streamflow by passing a filter over the streamflow records, three consecutive times: forwards, backwards and forwards again. Each consecutive pass of the filter over the streamflow is output, producing three time series estimates of baseflow. The user can then select the optimum pass based upon previously selected estimates of baseflow from the catchment in question.

The filter is as follows:

$$q_t = \alpha * q_{t-1} + \frac{(1+\alpha)}{2}(Q_t - Q_{t-1})$$

where

q_t = filtered direct runoff at the t time step

q_{t-1} = filtered direct runoff at the t-1 time step

α = filter parameter (0.925)

Q_t = total stream flow at the t time step

Q_{t-1} = total stream flow at the t-1 time step

The filter parameter 0.925 was determined by Nathan and McMahon (1990) and Arnold et al. (1995), to replicate manual separation techniques. Baseflow is then calculated by:

$$b_t = Q_t - q_t$$

5.3.5 Analysis of Irrigation Data and Its Effect on Surface Water and Groundwater Interaction:

Thana wise groundwater withdrawal/used for irrigation in a year or irrigation water was calculated from the following formula

$$Irrigation water, Mm^3\,(\mathrm{STW}) = \frac{(\# STW \times 0.5cusec) \times 10hr/d \times 105d/yr \times 0.02832m^3/ft^3}{10^6}$$

$$Irrigation water, Mm^3\,(\mathrm{DTW}) = \frac{(\# DTW \times 2cusec) \times 10hr/d \times 105d/yr \times 0.02832m^3/ft^3}{10^6}$$

Correlation regression analysis between irrigation development and groundwater level (dry season irrigation months of January, February, March and April) and stream flow were conducted. In this case, irrigation development data was irrigation water volume in Mm^3 calculated by the equations given above.

Chapter Six

RESULTS AND DISCUSSION

6.1 Introduction

The objectives of the study, as outlined in Chapter one, was to investigate the behavior of stream flow in response to groundwater level fluctuations and vice versa, and to analyze the long-term effect of irrigation development on groundwater levels and the corresponding impacts on the river flow. This chapter presents the results and analysis from a number of analytical and social investigation tools employed in this respect.

6.2 Conceptual Hydrogeologic System

The analysis of lithologic information from borelog data by Rockworks software are presented in Figure 6.1. The dimensions and specific locations of the slices are illustrated in Figure 5.6. The subsurface geology of the study area investigated was studied up to 106.75 m on the basis of lithological logs of covering the area. The lithologic panel diagrams as shown in Figure 6.1 are very useful in predicting three-dimensional distribution of the sub-surface formations. This diagram represents an overall view of the sub-surface geological formations delineating the major aquifer zones. It is noted here that analysis of lithology of the area using information from only 61 non-uniformly distributed borelogs may not provide a one hundred percent accurate picture. Nevertheless, it is expected to provide reasonable indicative delineation of the three-dimensional lithological distribution.

There are confining sandy clay layers (upper aquitard) in the north-west of the study area, with the thickness of the clay varying from 2 to 13 m. However, as Figure 6.1 demonstrates, the lithology of the study area is mostly dominated by sandy soil alluvium, with most of the area without any significant confining clay layer. The upper sandy aquifer extends upto 70 m depth. Although the lower aquitard (silty clay, sand-clay-silt mix) is shown to be generally located at a depth below the upper aquifer (i.e. below roughly 70 m), there is uncertainty as there are possibilities of errors due to a low number of borelogs with sufficient depths. Hence, the location and thickness of the lower aquitard could not be resolved with certainty from the above analysis.

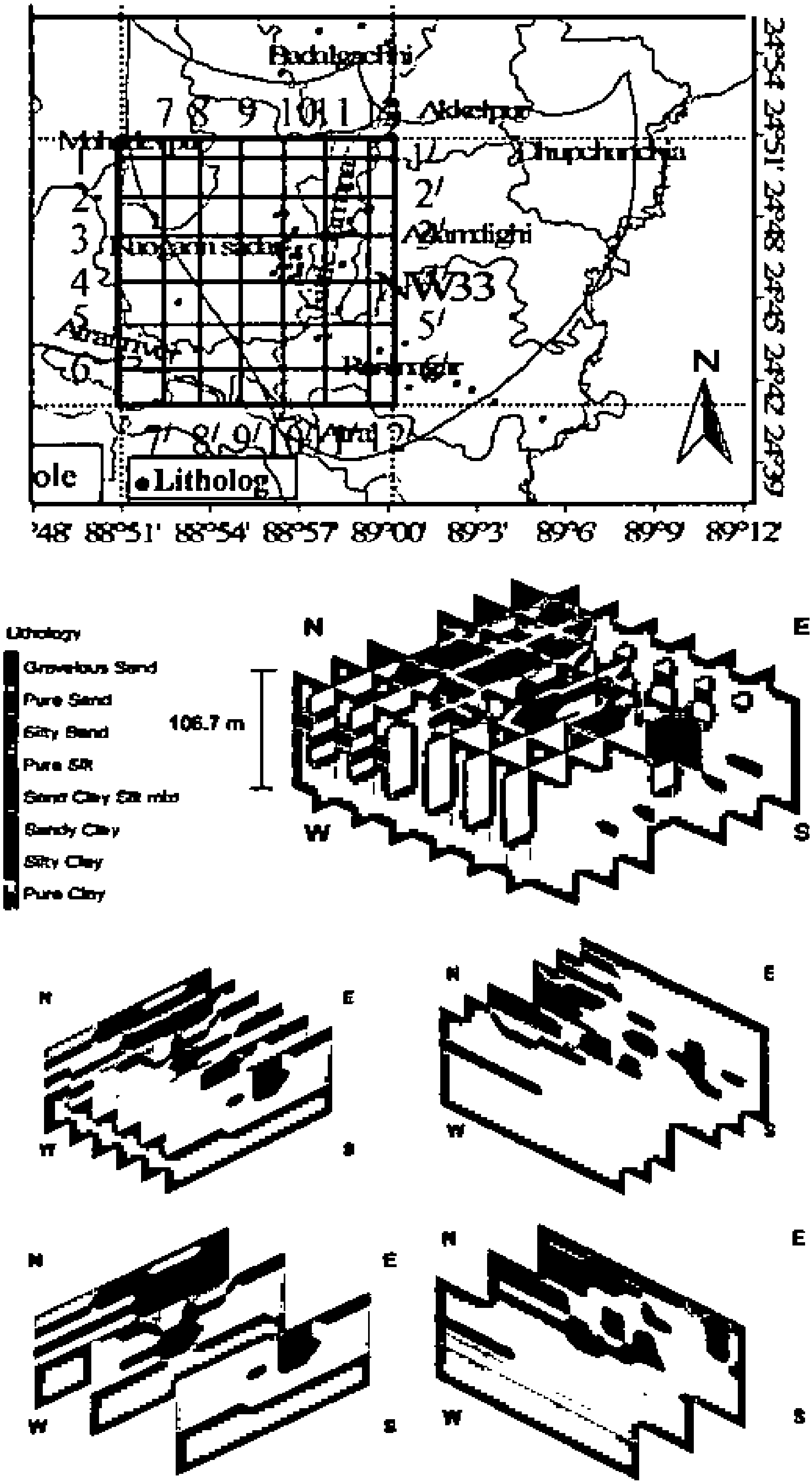


Figure 6.1 Subsurface lithologic panel diagrams (upto 106.75m) of study area

Connectivity between Little Jamuna river and aquifer

The finding that most of the floodplain aquifer adjacent to the river do not have any significant confining clay layer indicate that there is direct connection between the river and the underlying aquifer in the floodplain alluvium. There is also a sufficient indication that there is hydraulic connection between the floodplain aquifer and the upper aquifer in areas underlain by the clay aquitard. It may be mentioned here that similar observations were also made by Ahmed (1994) about the hydrogeology of the Little Jamuna river. All of the observations wells are located in the upper aquifer. The hydraulic connection between the upper aquifer and the lower aquifer could not be directly established because of low depth lithologic data available. However, literature (e.g. Rahman and Roehrig, 2006; Ahmed, 2004) suggests that all the layers are leaky in nature and thus interconnected. The fact that hand-tube wells get frequently affected by the deep-tube wells (discussed in a later section) indicates that there are good possibilities of hydraulic connections between the upper and lower aquifer. A conceptual hydrologic flow system (Figure 6.2) is prepared based on groundwater level, surface water level and lithological data of the Little Jamuna river catchment.

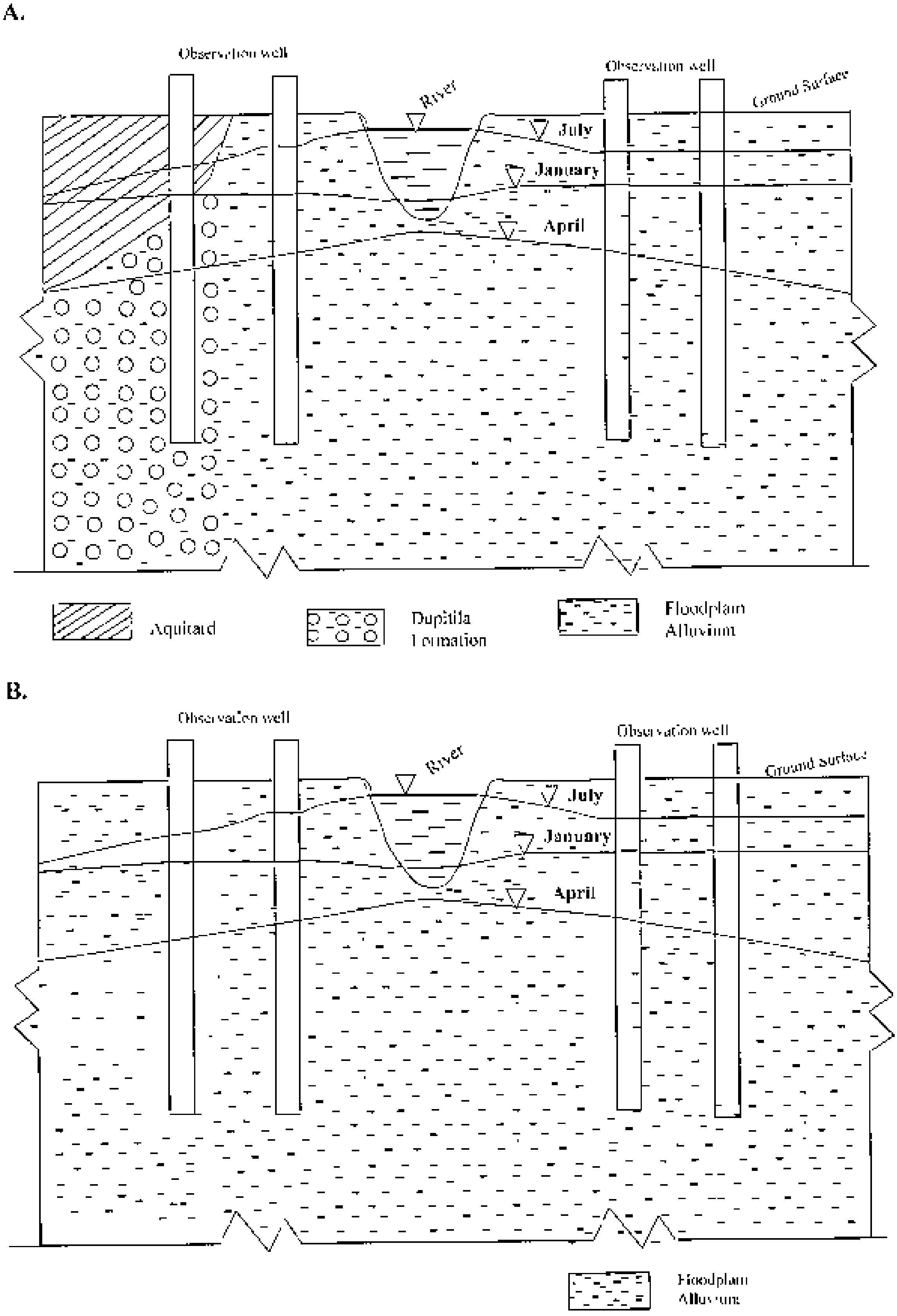


Figure 6.2 Schematic diagram of the conceptual hydrologic flow system in Little Jamuna river catchment in the northwest region of Bangladesh: (A) a cross-section in extreme north and (B) a cross-section in south.

6.3 Analysis of Time Series of Surface Water Level and Discharge

Figures 6.3 and 6.4 present the water level hydrograph and flow hydrograph of Little Jamuna river at Naogaon, respectively. It is observed that surface water level fluctuated from 10 m to 14 m in mid sixties but it fluctuated more relatively recently and the range was from 5.5 m to 15.5 m. It means that in dry season water level remains low and in wet season it remain high. Figure 6.5 shows that there is apparently no trend in the maximum water level, while there is some declining trend in the yearly mean water level and strong declining trends in the yearly minimum water level

There are strong decreasing trends in the river flow in dry season months, as seen in Figure 6.6. The figure includes both original flow data and rating curve generated flow data (as explained in Section 5.2.3). Analysis with both original and generated data shows similar trends in flows. Hence, interpretation of results is made for the entire data period (including generated data) from early 1970's till early 2000's. Flows in January, February, March and April have decreased by roughly 40%, 50%, 70% and 70%, respectively from 1974 to 2003.

In the months of March and April, the flows have declined considerably, and decreased to zero or near zero flow in some years from around 1990. Flows in the month of February, in recent years, have declined to very low flows. Apparently, the problem of very low flow (or no flow) is gradually extending from March-April to February. The flow in January has decreased considerably; however, it has not gone down to zero so as to cause drying up of river in this month. However, given the declining trend of flows, the problem of low flow may well extend to even January in the coming years.

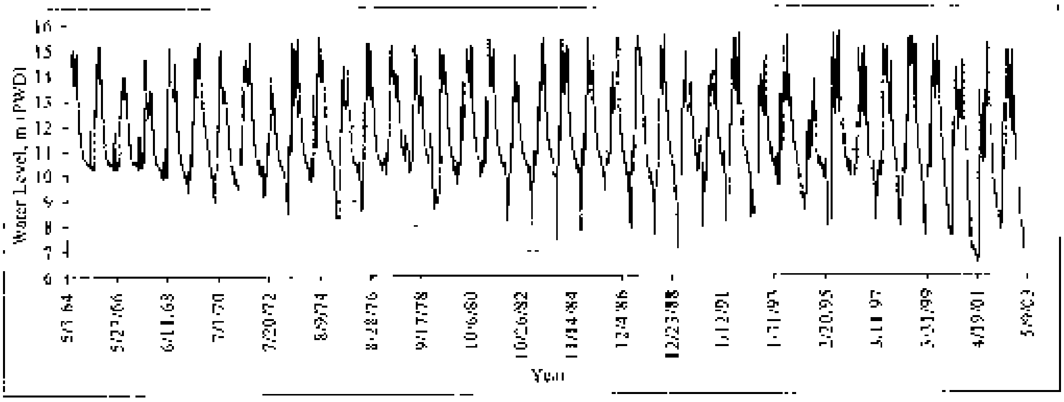


Figure 6.3 Water level fluctuations in Little Jamuna river at Naogaon station

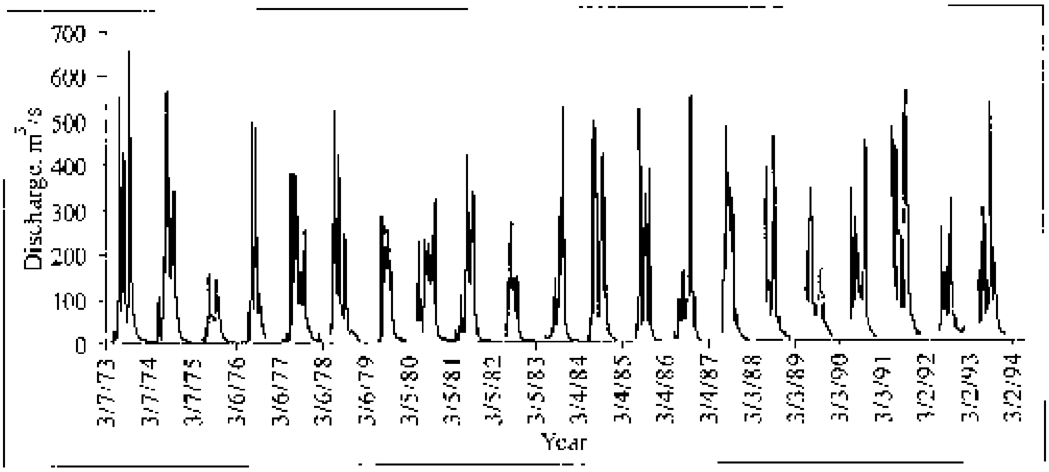


Figure 6.4 Water flow fluctuations in Little Jamuna river at Naogaon station

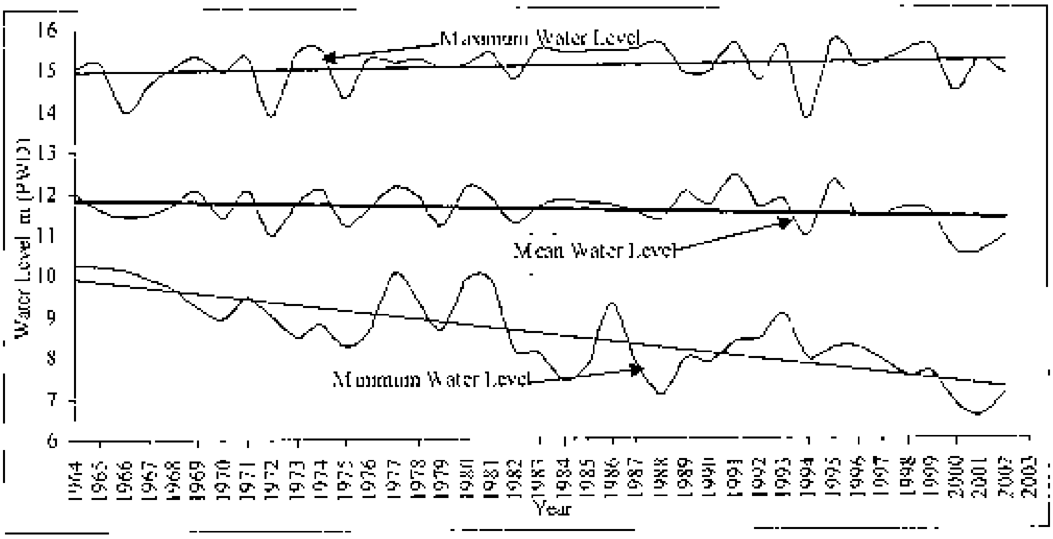


Figure 6.5 Maximum, mean and minimum water level fluctuations in Little Jamuna river at Naogaon station

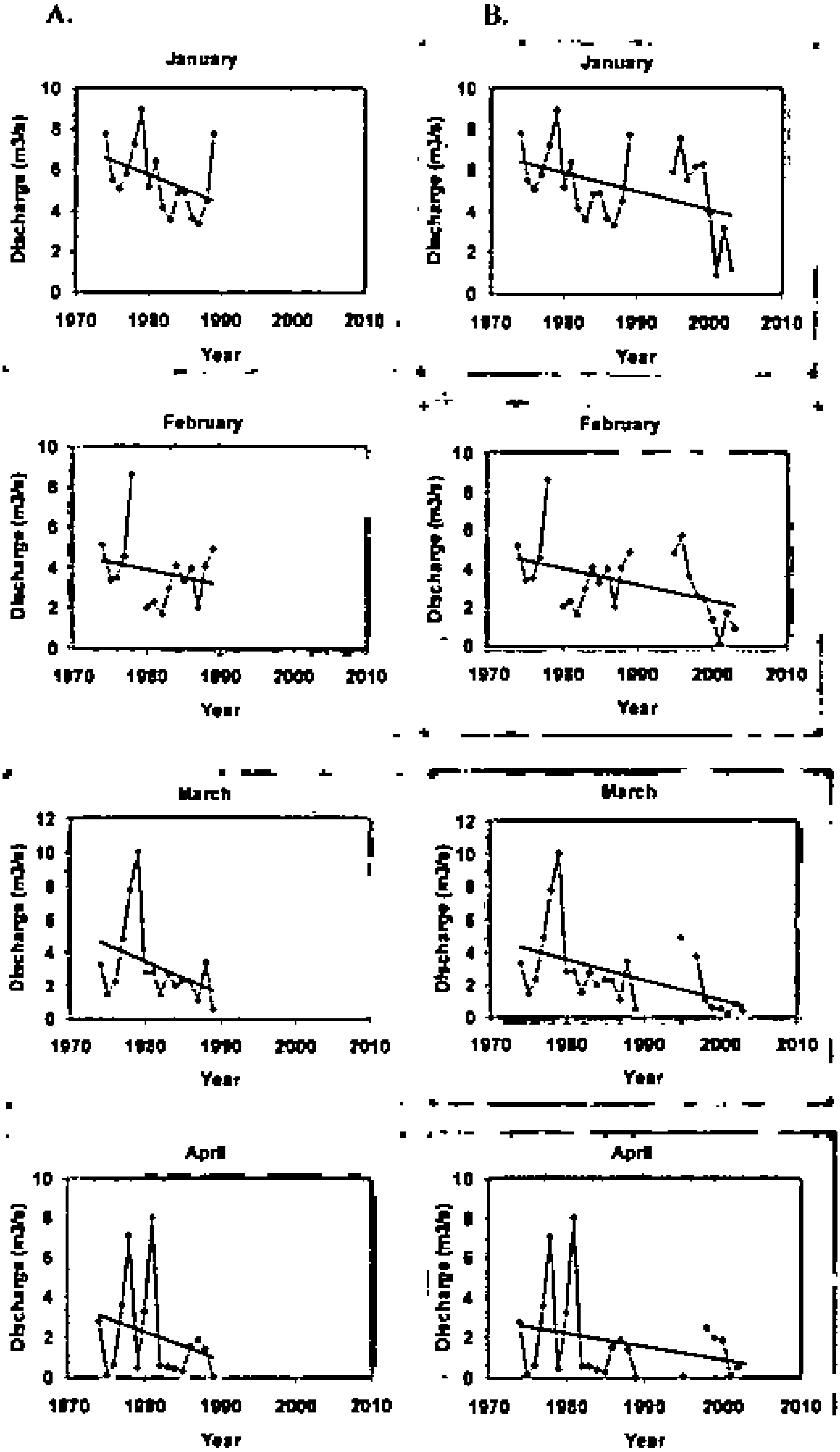


Figure 6.6 Trends in flows of Little Jamuna at Naogaon for dry season months: (A) without and (B) with generated flow data after 1993

6.4 Trend in Groundwater Level

Groundwater level fluctuation

The groundwater level in the Little Jamuna river catchment aquifer fluctuates seasonally in response to recharge from precipitation, discharge from pumping, evapotranspiration, interaction with surface-water features, and periods of reduced precipitation and drought. Water level is highest during the month of September and October and lowest during the month of March and April. Generally, recharge begins in July and August, and the water level rises quickly in response to precipitation. During the month of January and February, the water level declines in response to increased agricultural water use (pumping) and evapotranspiration. These factors also contribute to decreased water-level response to precipitation by reducing infiltration. Seasonal groundwater level fluctuations range from 4 m to nearly 15 m (Figures 6.7-6.10) in different wells in the study area.

Although the recovery is found more or less good at most of the wells, overall there seems to be decreasing trends in groundwater levels over the years. Linear regression lines drawn through the time series of the groundwater levels in different wells show decreasing trends in many of the wells; some of them are strong.

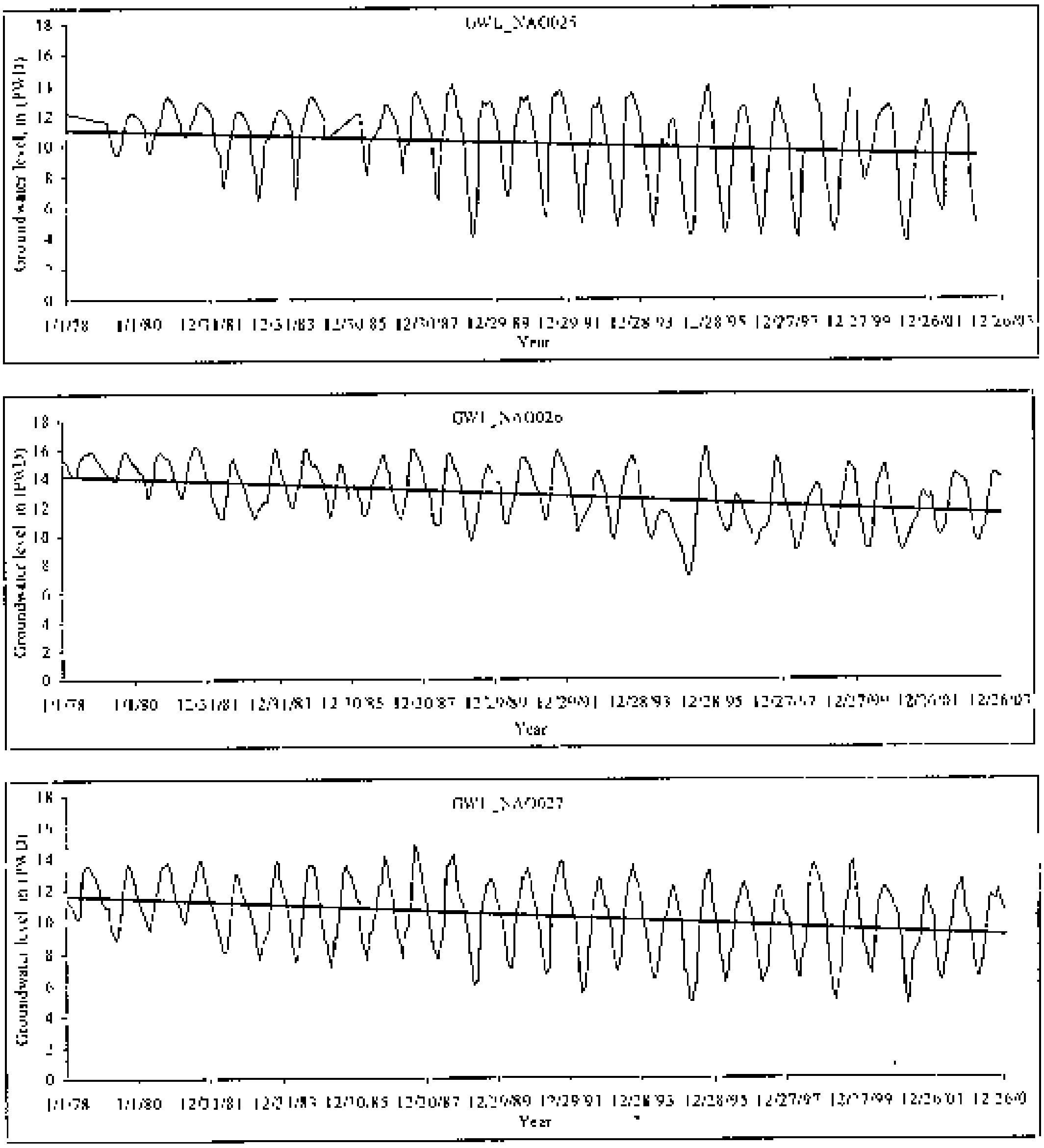


Figure 6.7 Groundwater level fluctuation in piezometer wells in Naogaon Sadar in the Little Jamuna river catchment aquifer.

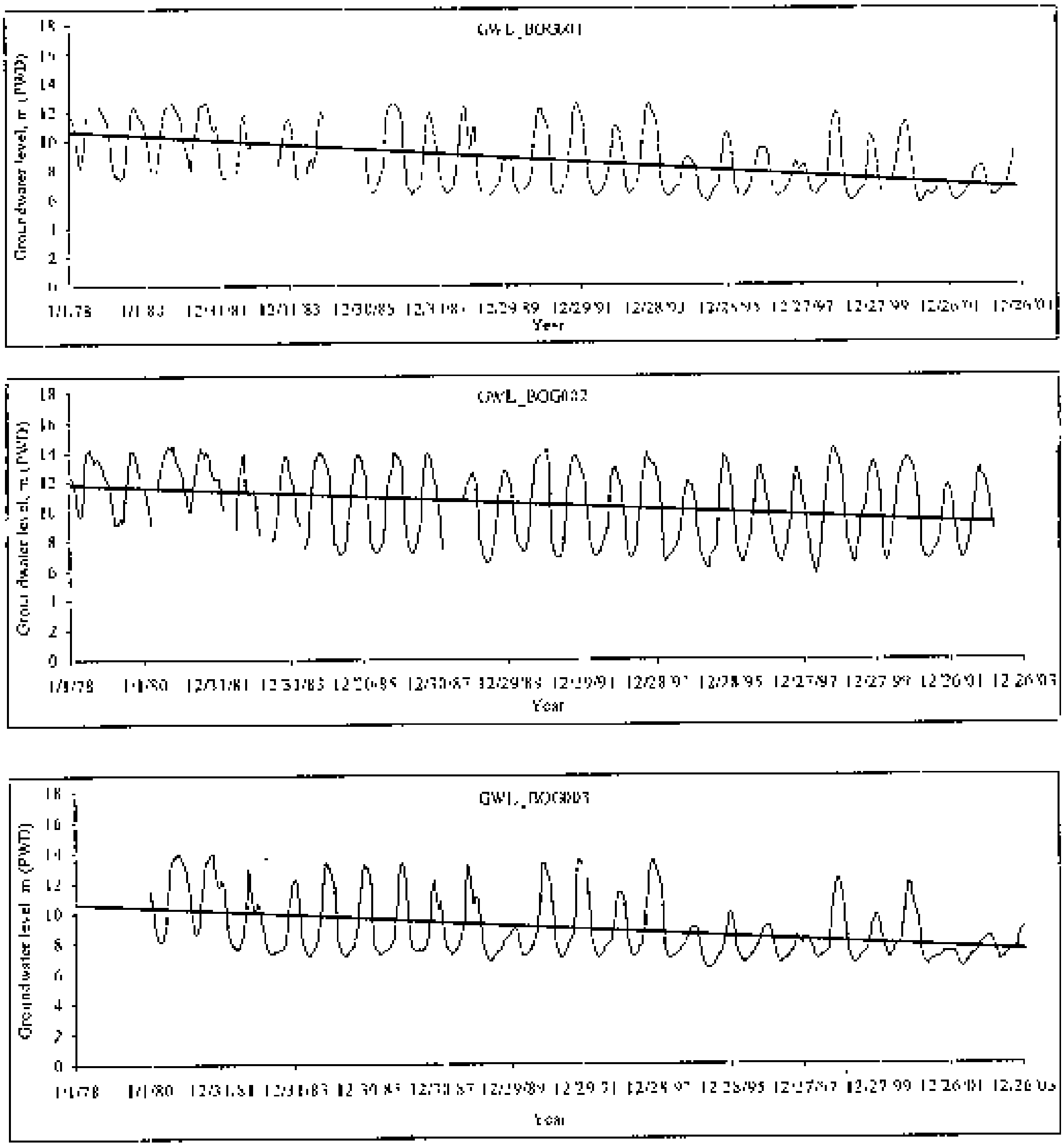


Figure 6.8 Groundwater level fluctuation in piezometer wells in Adamdighi the Little Jamuna river catchment aquifer

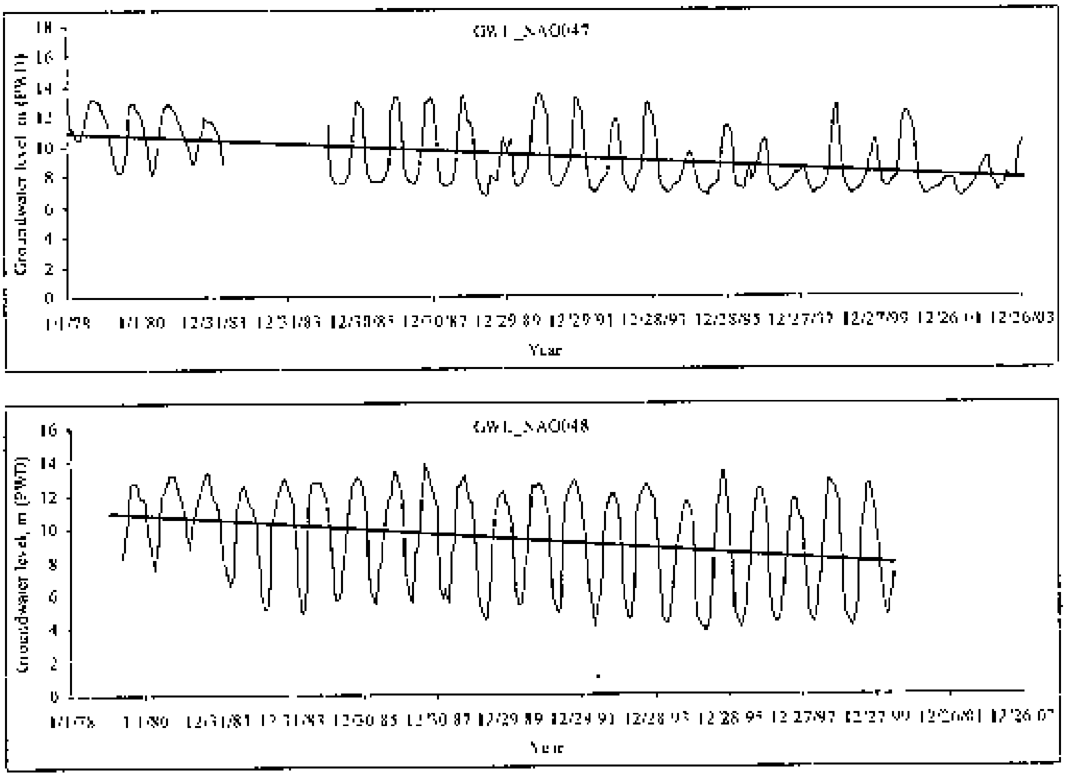


Figure 6.9 Groundwater level fluctuation in piezometer wells in Raninagar in the Little Jamuna river catchment aquifer.

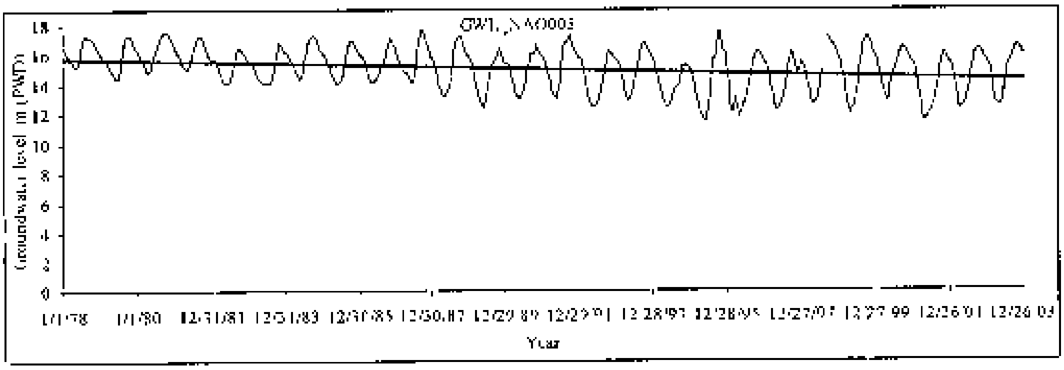


Figure 6.10 Groundwater level fluctuation in piezometer wells in Badalgachhi in the Little Jamuna river catchment aquifer.

Trends in minimum groundwater level

The time series plots in Figures 6.7-6.10 indicate that the minimum groundwater level has been historically declining over the last 25 years. This is further illustrated in Figures 6.11-6.14, which present the trends in yearly minimum groundwater levels at various locations. There are marked decline in groundwater levels in NAO025, NAO026 and NAO027 at Naogaon sadar; BOG001 and BOG002 at Adamdighi;

NAO047 and NAO048 at Raninagar; and NAO004 and NAO005 at Badalgachi. On the other hand, there is a little change in BOG003 at Adamdighi and NAO006 at Badalgachi

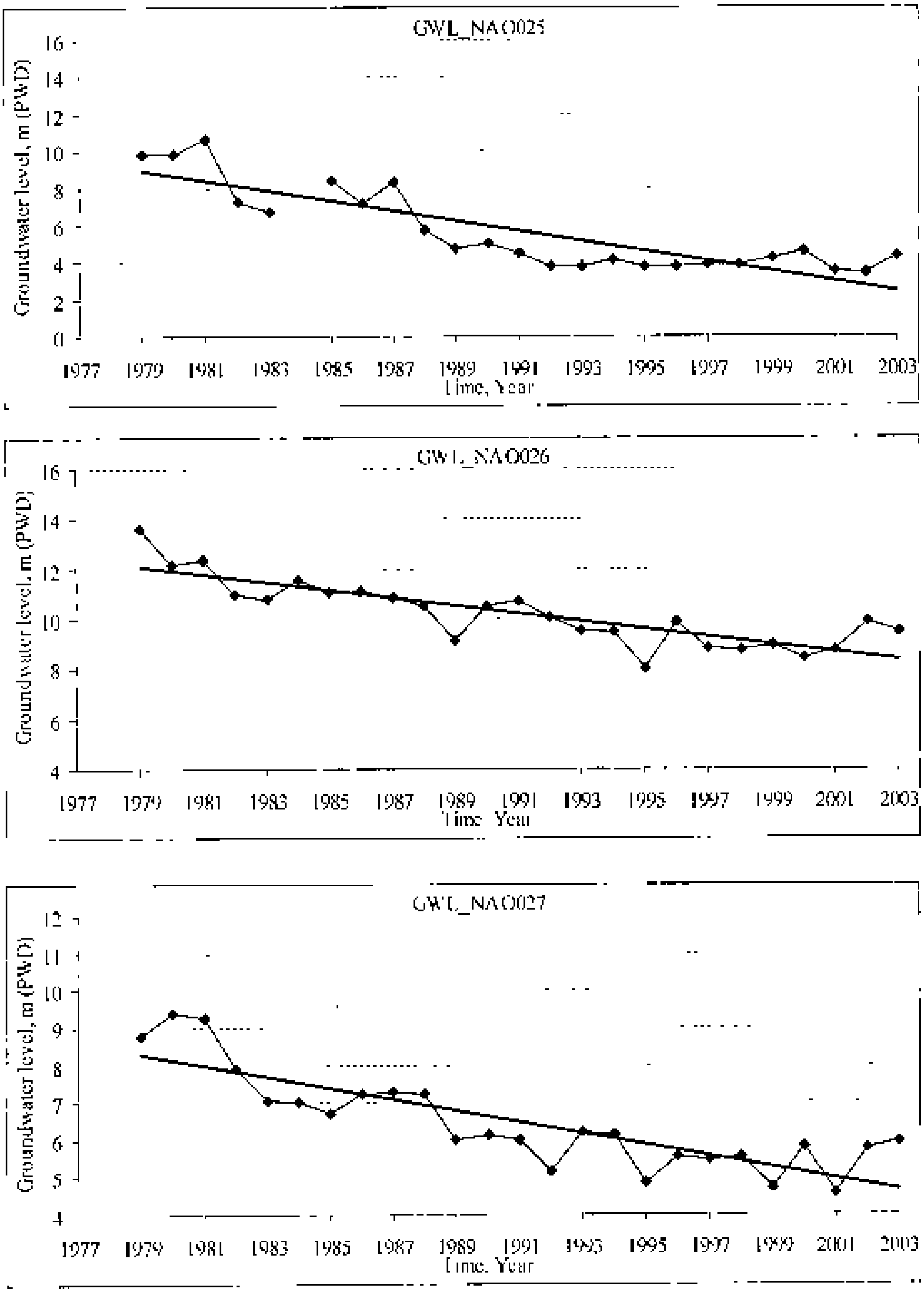


Figure 6.11 Time series of minimum groundwater level in Naogaon Sadar in the Little Jamuna river catchment aquifer

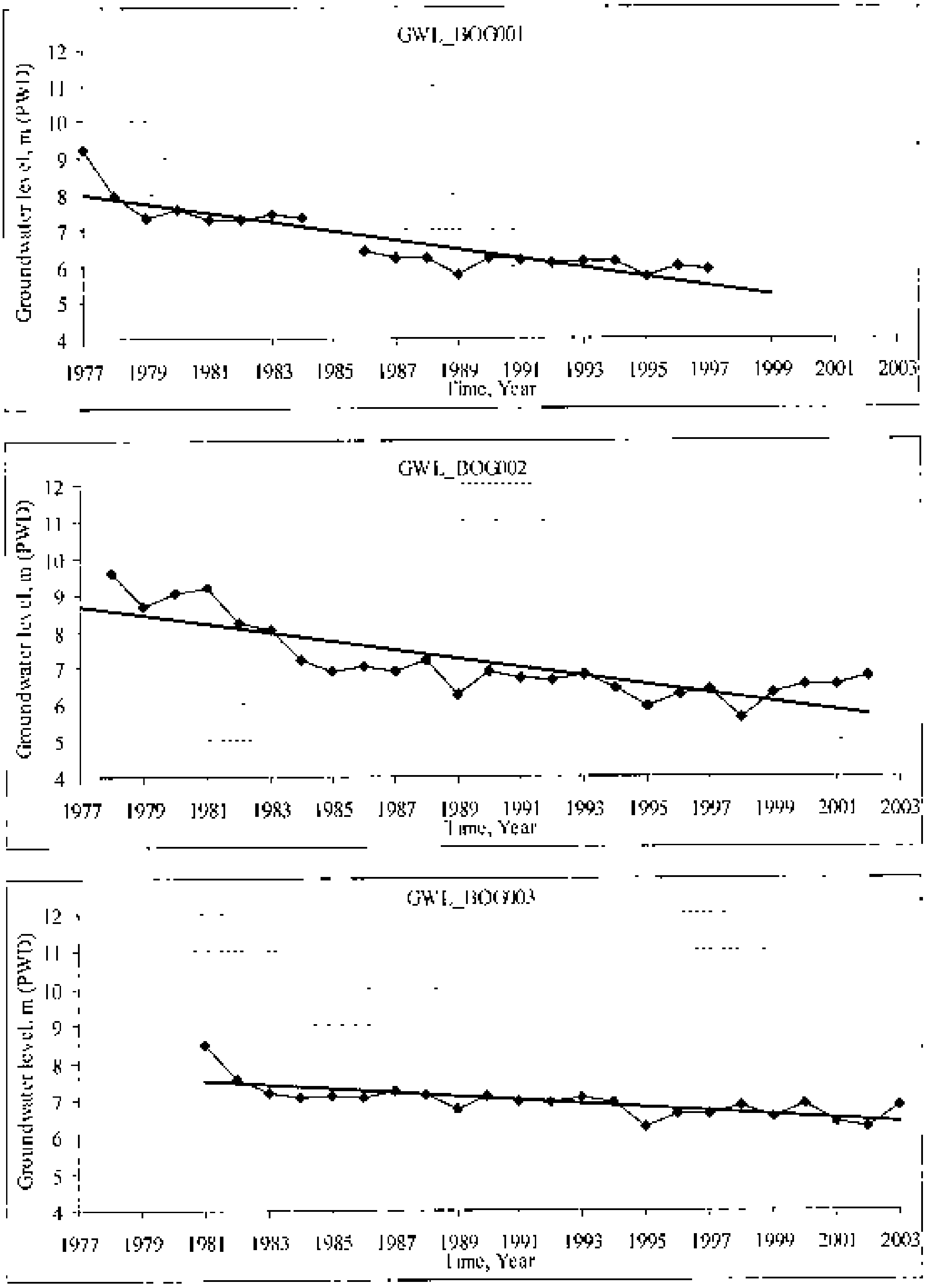


Figure 6.12 Time series of minimum groundwater level in Adamdighi in the Little Jamuna river catchment aquifer.

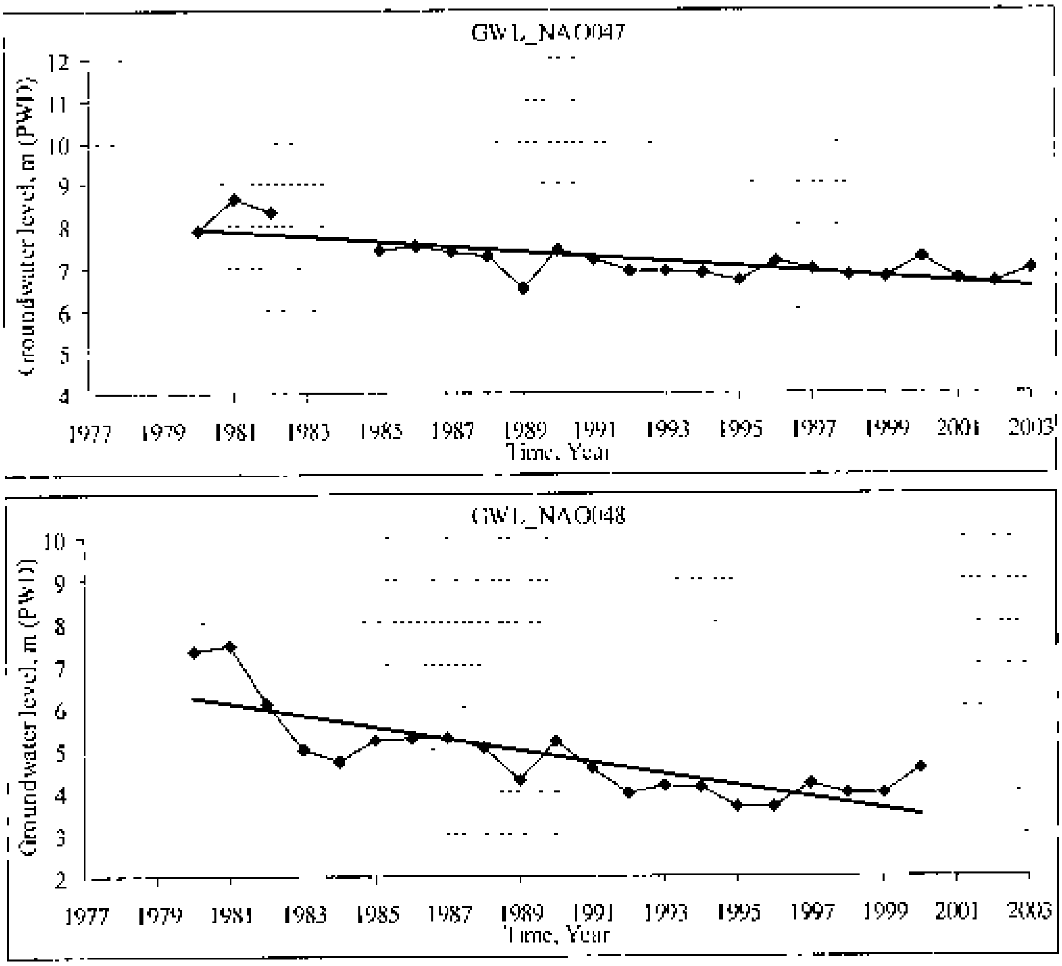


Figure 6.13 Time series of minimum groundwater level in Ramnagar in the Little Jamuna river catchment aquifer.

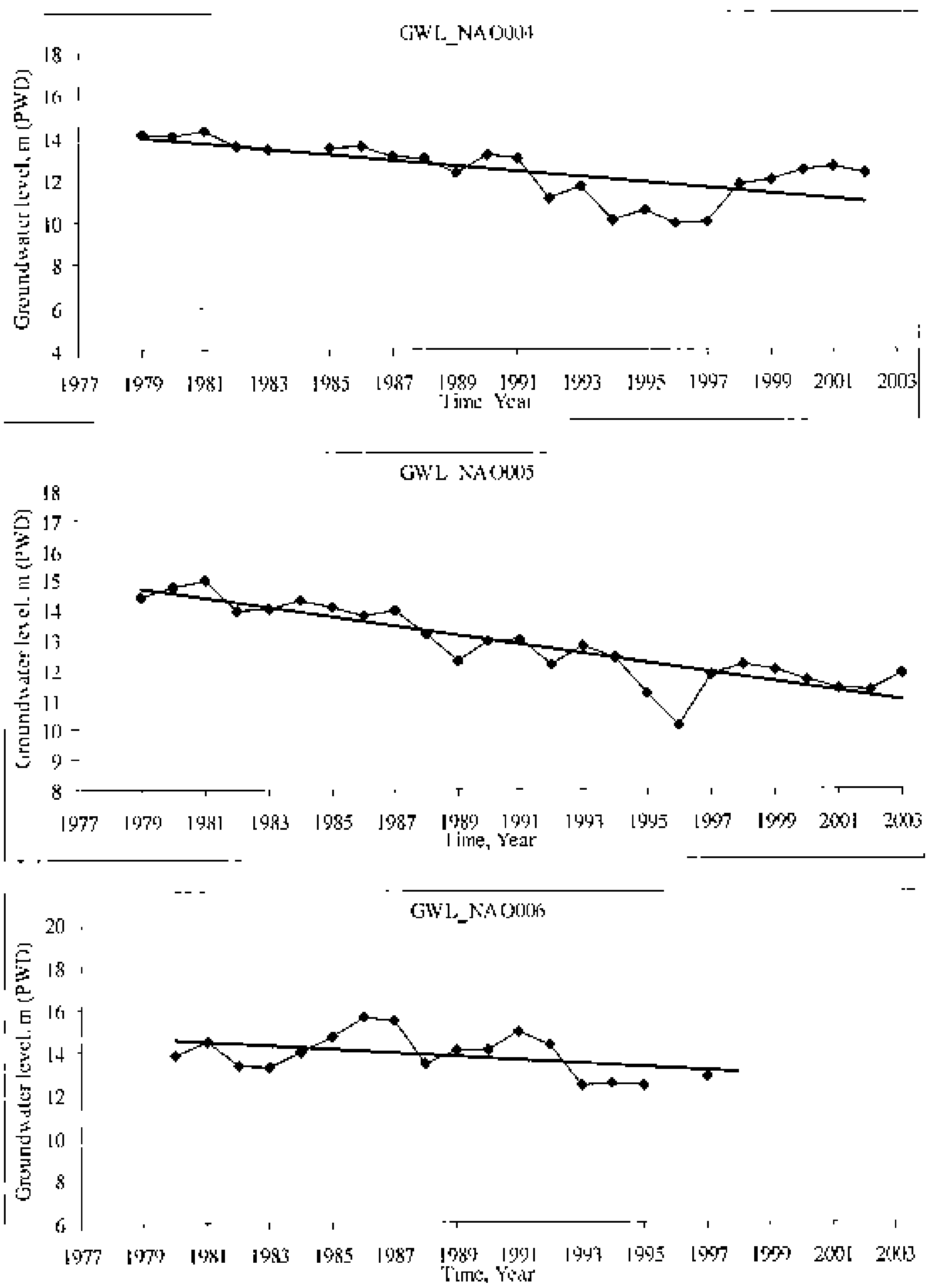


Figure 6.14 Time series of minimum groundwater level in Badalgachhi in the Little Jamuna river catchment aquifer.

6.5 Relation between Rainfall and Groundwater Level

Comparison of patterns:

Precipitation patterns are compared with groundwater levels in various observation wells in the Little Jamuna River Catchment, which are shown in Figure 6.15 and Appendix-H. There is a marked similarity in pattern in variation of the two parameters. It is observed that rainfall affects the groundwater level fluctuation of respective place after some period of occurrence. When it rains, it infiltrates into the ground resulting the recharge to the groundwater level. It takes some time for the rain water to reach and affect the groundwater reservoir through lithological strata of different characteristics; it takes some time to affect the groundwater level. Infiltration would be higher in gravelous or sandy layers and relatively low with the increase in clay and silt content.

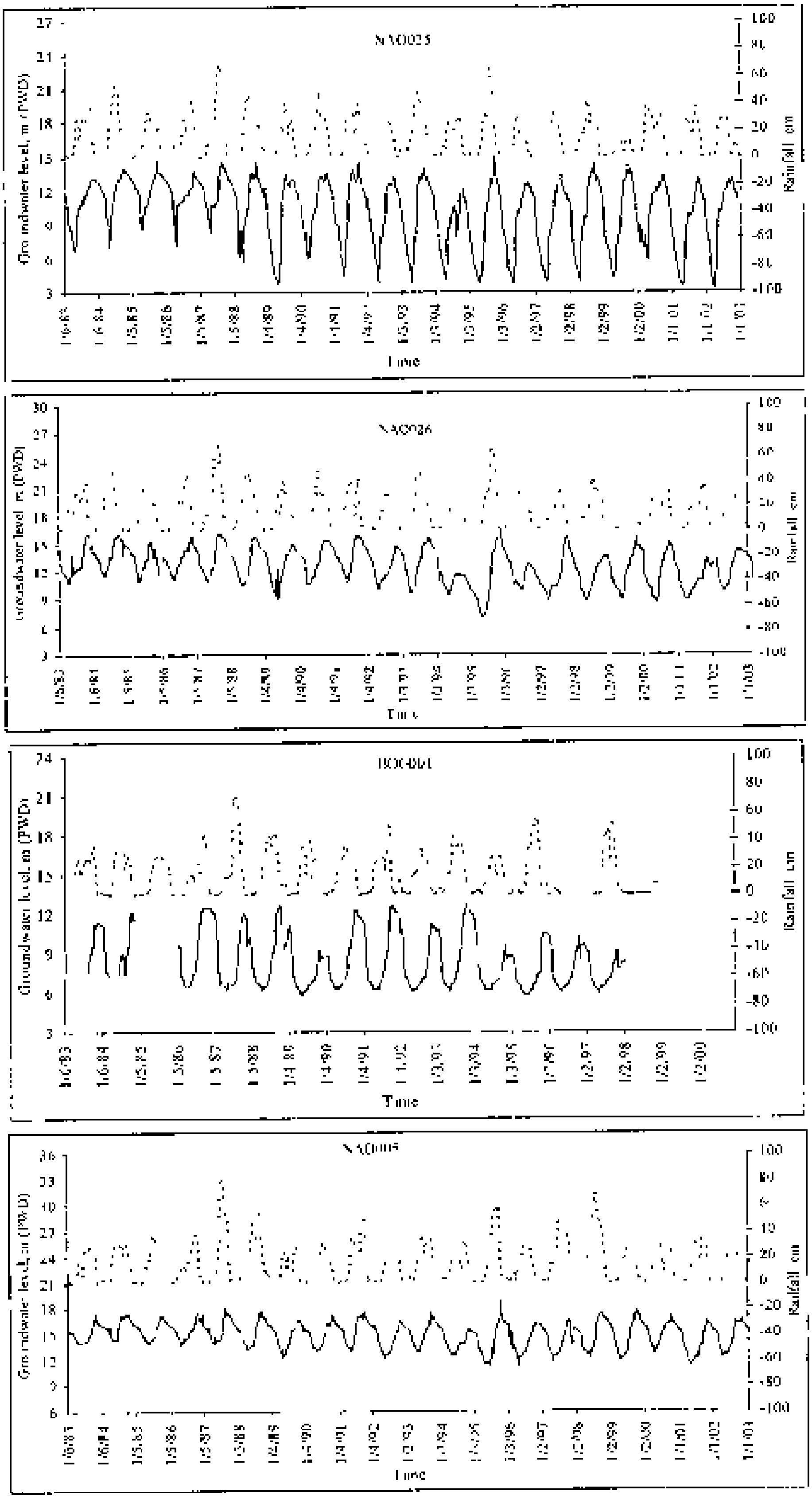


Figure 6.15 Distribution of rainfall and groundwater level in the study area

Regression Analysis:

Monthly total rainfall at nearest rain gauge was correlated with monthly groundwater level measurements in each well. The fluctuation pattern in groundwater levels agrees well approximately with the varied pattern of rainfall. However, the correlation coefficient of groundwater and rainfall is not so large as shown in Table 6.1 The highest coefficient of determination (R^2) was 0.1594 (R = 0.40) and the lowest was 0.002 (R = 0.045). The variation in the correlation coefficients is due to the variability in groundwater recharge, which differs spatially because of heterogeneity in lithology..

Table 6.1 Correlation coefficient value of rainfall and groundwater level

Rainfall station	Groundwater well ID	Methods	R^2	R
Badalgachhi, 152	NAO004	Linear	0.1594	0.40
		Exponential	0.0685	0.26
	NAO005	Linear	0.0092	0.096
		Exponential	0.0024	0.049
	NAO006	Linear	0.0024	0.049
		Exponential	0.0047	0.068
Naogaon sadar, 191	NAO025	Linear	0.1562	0.40
		Exponential	0.1155	0.34
	NAO026	Linear	0.0184	0.135
		Exponential	0.0040	0.063
	NAO027	Linear	0.1378	0.37
		Exponential	0.0901	0.30
Adamdighi, 151	BOG001	Linear	0.0047	0.068
		Exponential	0.0055	0.074
	BOG002	Linear	0.0095	0.097
		Exponential	0.0057	0.075
	BOG003	Linear	0.0427	0.21
		Exponential	0.0613	0.247
Dhupchanchhi, 169	BOG009	Linear	0.0034	0.058
		Exponential	0.0002	0.045

Lag Regression Analysis

It is expected that change in groundwater level will not respond to the rainfall immediately; there is supposed to be a lag in the response of groundwater levels. To examine the timing of the delay in groundwater response to a single previous month's rainfall, the total precipitation for each month was "lagged" for a period from one to four months and correlated to the observed groundwater level measurement for the month of the prescribed lag period. Best-fit equations were calculated based on linear and exponential regressions. The results for all the wells are summarized in Table 6.2.

Results of lagged correlation between rainfall and observation well in Naogaon and Adamdighi are presented in Figure 6.16 and Figure 6.17 (other Figures are given in Appendix- I).

The lag period with the highest coefficient of determination is marked with an asterisk. The correlation between rainfall and groundwater level improves significantly when groundwater response to rainfall is lagged by different time periods. For most piezometer wells, the best correlations occur for a 2-month or 3-month lag in precipitation; that is, the groundwater level response follows precipitation by two to three months (Table 6.2). Piezometer wells with the best correlation to a 2-month lag in precipitation include NAO025, NAO027, and NAO004. Piezometer wells with the best correlation to a 3-month lag in precipitation include NAO026, NAO005, NAO006, BOG001, BOG 002 and BOG009. Piezometer well BOG003 correlated best with a 4-month lag. The highest coefficient of determination (R^2) is found to be 0.6913 ($R = 0.83$) at 3 months lag compared to the correlation of determination (R^2) of 0.0057 ($R = 0.075$) at the same location at zero lag and the highest coefficient of determination (R^2) of 0.1594 ($R = 0.40$) among all the locations at zero lag.

Table 6.2 Results of groundwater level lag regression analysis

Coefficients of determination, R^2, for rainfall (Y) v.s lagged groundwater level (X)							
Thana St. ID	Well_ID	Methods	0-Month lag	1-Month lag	2-Month lag	3-Month lag	4-Month lag
Badalgachhi, 152	NAO004	Linear	0.1594	0.4760*	0.4345	0.2533	0.0870
		Exponential	0.0685	0.3367	0.4845*	0.3953	0.1817
	NAO005	Linear	0.0092	0.2185	0.3662	0.3692*	0.2223
		Exponential	0.0024	0.1192	0.3479	0.4607*	0.3843
	NAO006	Linear	0.0024	0.0661	0.1335	0.1421*	0.1234
		Exponential	0.0047	0.0303	0.1362	0.1975*	0.1781
Naogaon sadar, 191	NAO025	Linear	0.1562	0.3727	0.4325*	0.3329	0.1352
		Exponential	0.1155	0.3689	0.4908*	0.4179	0.1785
	NAO026	Linear	0.0184	0.1840	0.3838	0.4077*	0.2533
		Exponential	0.0040	0.1237	0.3172	0.3891*	0.2763
	NAO027	Linear	0.1378	0.4240	0.5079*	0.4011	0.1486
		Exponential	0.0901	0.3804	0.5771*	0.3159	0.2368
Adamdighi 151	BOG001	Linear	0.0047	0.0789	0.2664	0.3285*	0.2924
		Exponential	0.0055	0.0786	0.3113	0.4252*	0.3939
	BOG002	Linear	0.0095	0.2071	0.4288	0.5303*	0.3168
		Exponential	0.0057	0.2045	0.5213	0.6913*	0.4504
	BOG003	Linear	0.0427	0.0230	0.1942	0.3685	0.4035*
		Exponential	0.0613	0.0234	0.2068	0.1965	0.4560*
Dhupchachi, 169	BOG009	Linear	0.0034	0.0768	0.1480	0.1823*	0.1429
		Exponential	0.0002	0.0512	0.1216	0.1541*	0.1377

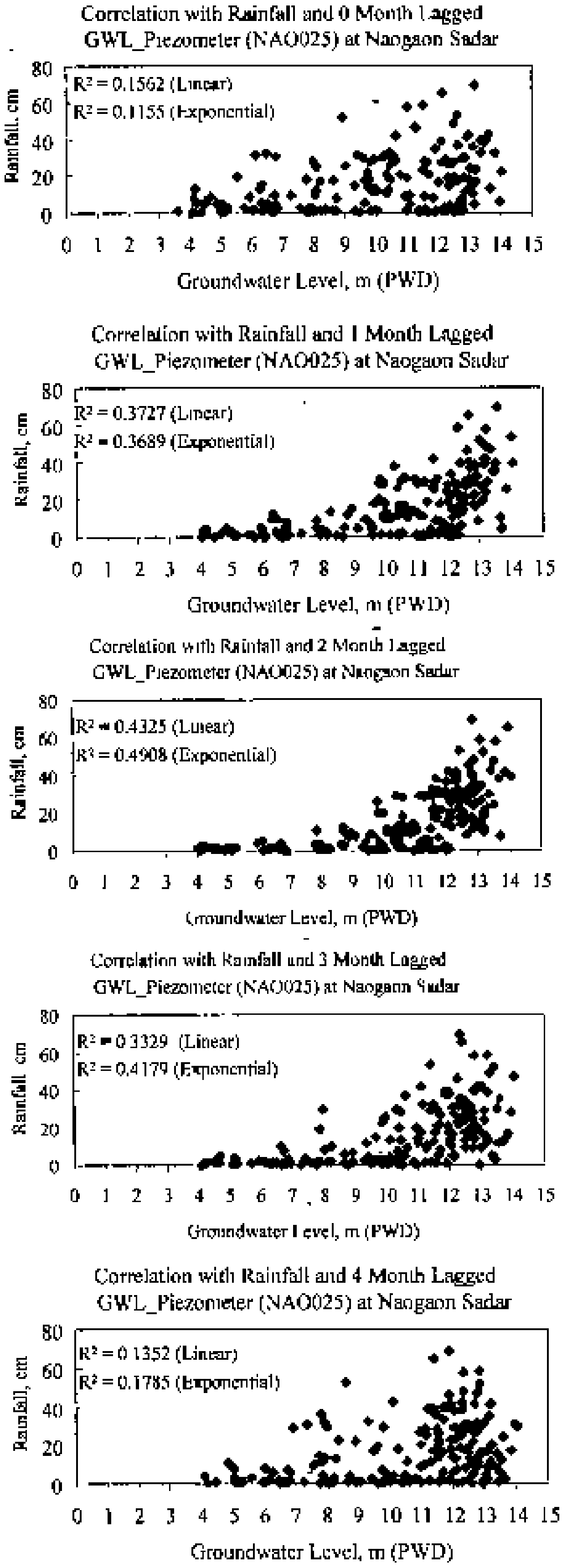
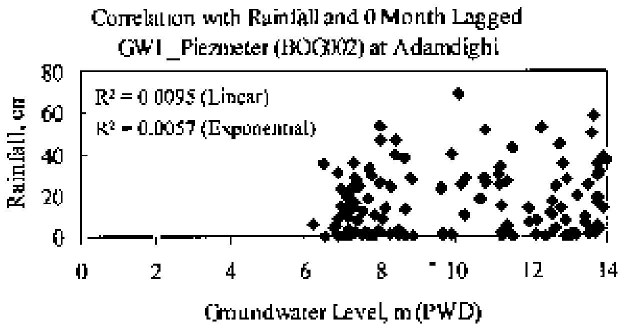
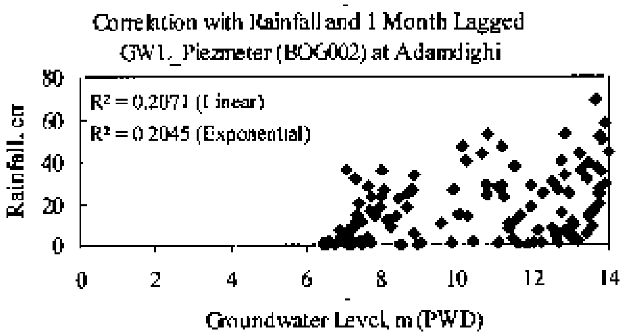
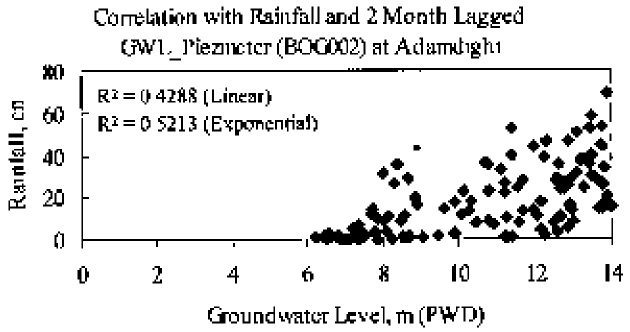
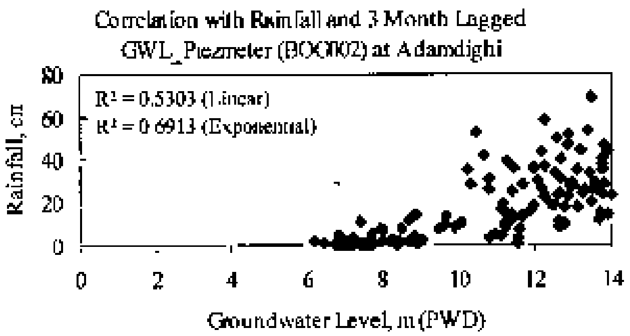


Figure 6.16 Best-fit linear and exponential correlation for lagged rainfall versus groundwater level in observation well no NAO025 in Naogaon sadar.









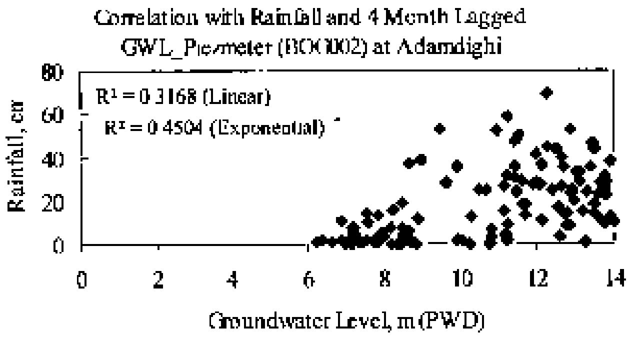


Figure 6.17 Best-fit linear and exponential correlations for lagged rainfall versus groundwater level in observation well no BOG002 in Adamdighi.

These results indicate that groundwater levels are influenced by precipitation falling two to three months prior to the groundwater observation wells. This gives an indication of the length of time required for precipitation falling on the earth's surface to reach the water table within the Little Jamuna river catchment area.

6.6 Relation between Rainfall and Surface Water Level and Discharge

Comparison of Pattern

Stream discharge and stage data to monthly precipitation data are compared for the study area in order to evaluate how Little Jamuna River responded to precipitation trends. From Figure 6.18, it is observed that at the time of rainfall occurrence, surface water level and flow show fairly quick response. The graph indicates that monthly precipitation totals and river Little Jamuna flow and stage at Naogaon Station often followed similar patterns. As expected, periods of low discharge and stage were clearly related to periods of low precipitation.

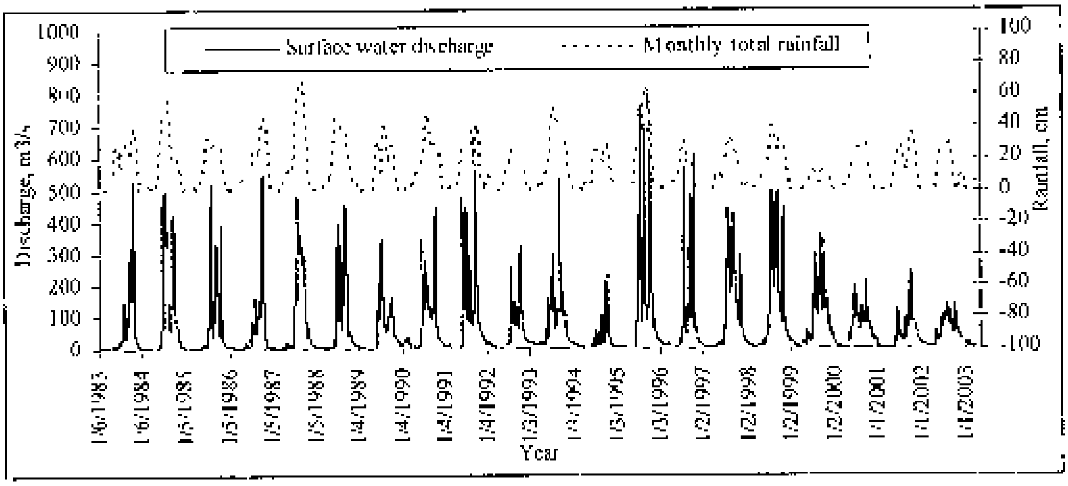


Figure 6.18 Distribution of rainfall and surface water discharge in the study area

Regression analysis

Correlation regression analysis was carried out between rainfall and river stage. Rainfall shows a good correlation with river water level in the study area. The best-fit linear correlation regressions for rainfall versus surface water level are shown in Figure 6.19 and correlation coefficients of those results are listed in Table 6.3.

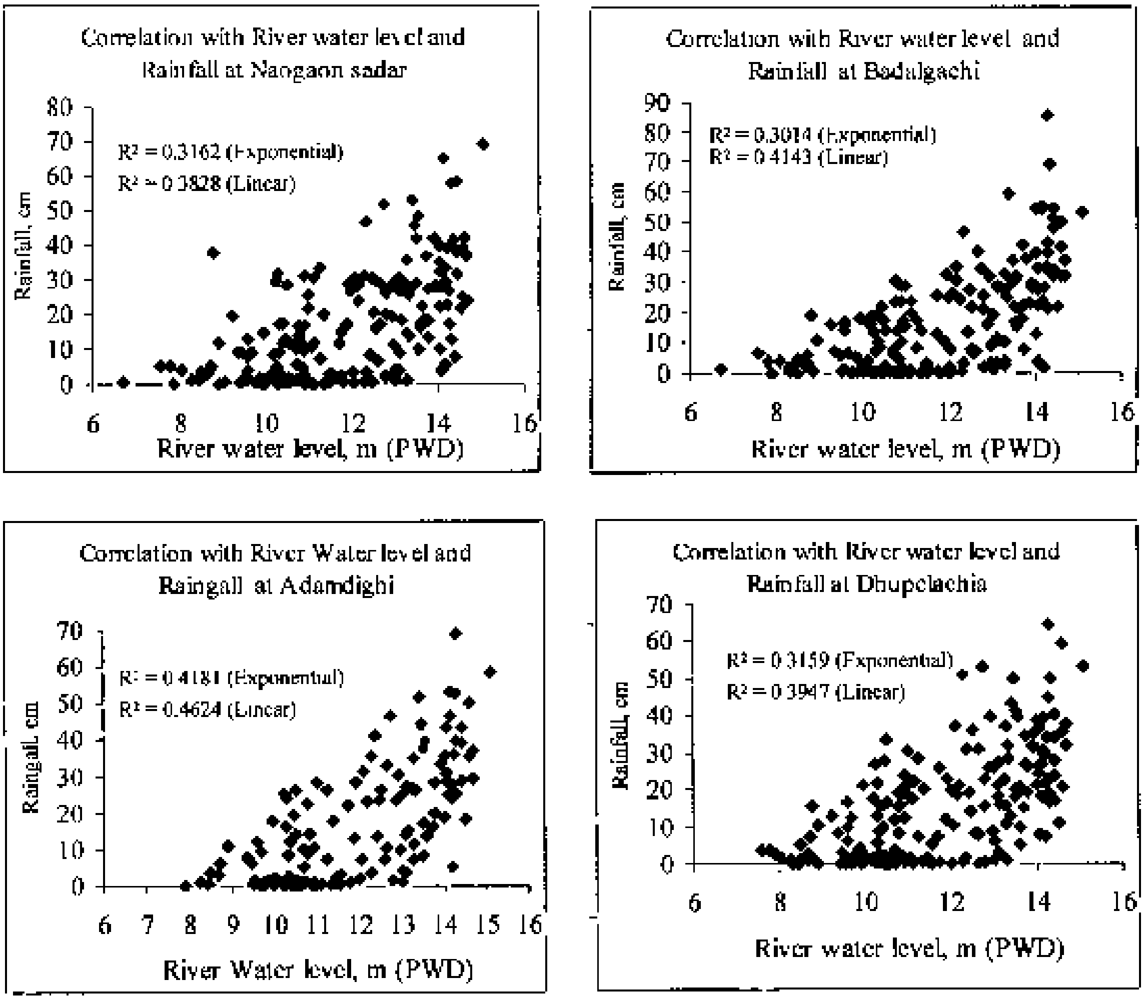


Figure 6.19 Best-fit linear correlations for rainfall versus surface water level in study area

Table 6.3 Results of linear and exponential correlation for rainfall versus surface water level in the study area

Thana	Rainfall Station ID	Methods	R^2	R
Naogaon sadar	191	Linear	0.3828	0.619
		Exponential	0.3162	0.562
Badalgachhi	152	Linear	0.4143	0.644
		Exponential	0.3014	0.549
Adamdighi	151	Linear	0.4624	0.680
		Exponential	0.4181	0.645
Dhupchachia	169	Linear	0.3947	0.628
		Exponential	0.3159	0.562

6.7 Relationship between Surface water Level and Groundwater Level

Comparison of Pattern:

The relationship between surface water and groundwater was evaluated by comparing hydrographs of groundwater level data with graphs of stream stage. The analysis was based on the period from 1978 through 2001. The results are in shown in Figures 6.20-6.23. It is observed that peak in a groundwater level hydrographs and the peak in a river water level hydrographs do not rise at the same time in many of the wells. There is a lag time between them.

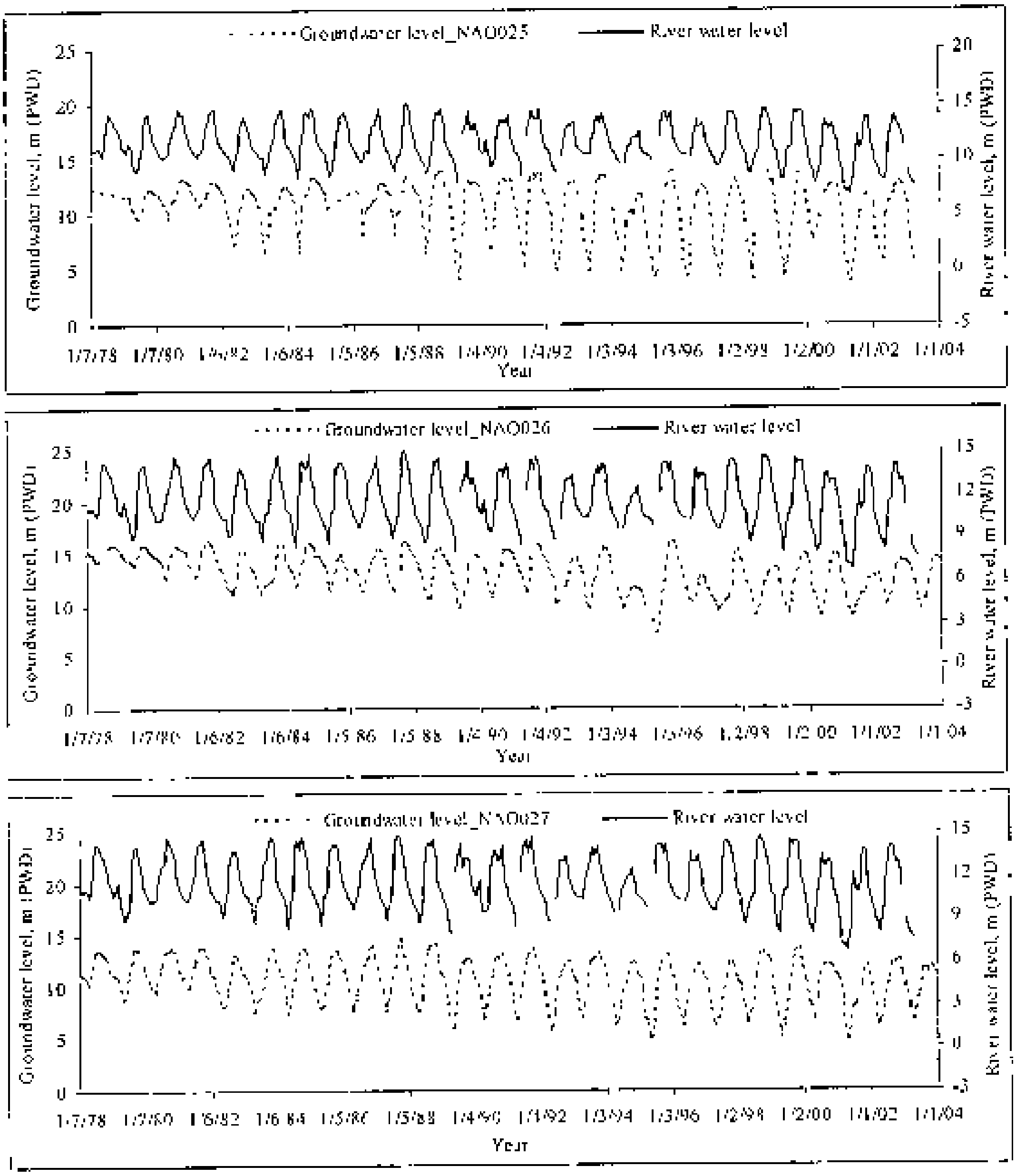


Figure 6.20 Distribution of Surface water level and groundwater level in observation well in Naogaon sadar in the study area.

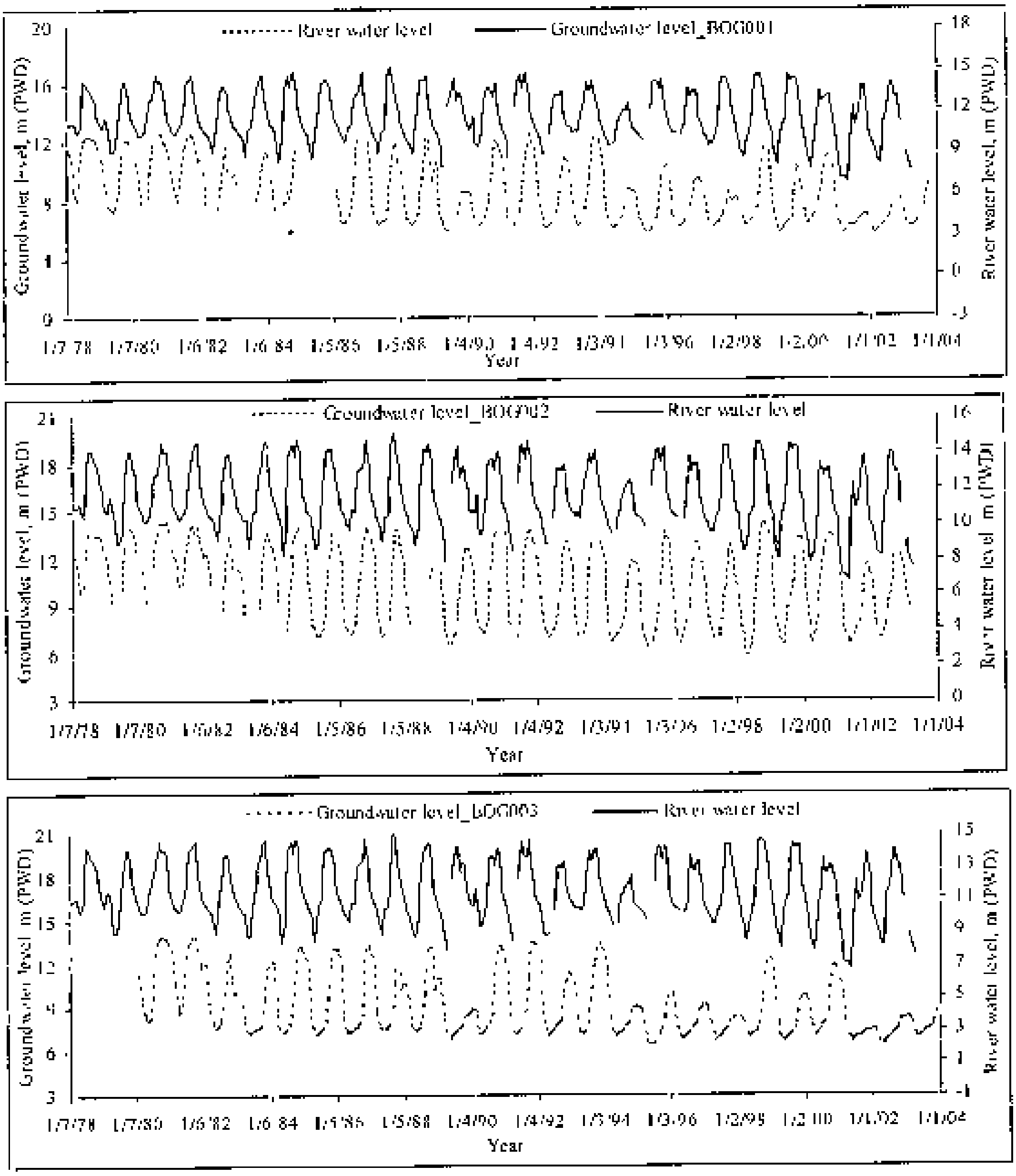


Figure 6.21 Distribution of Surface water level and groundwater level in observation well in Adamdighi thana in the study area.

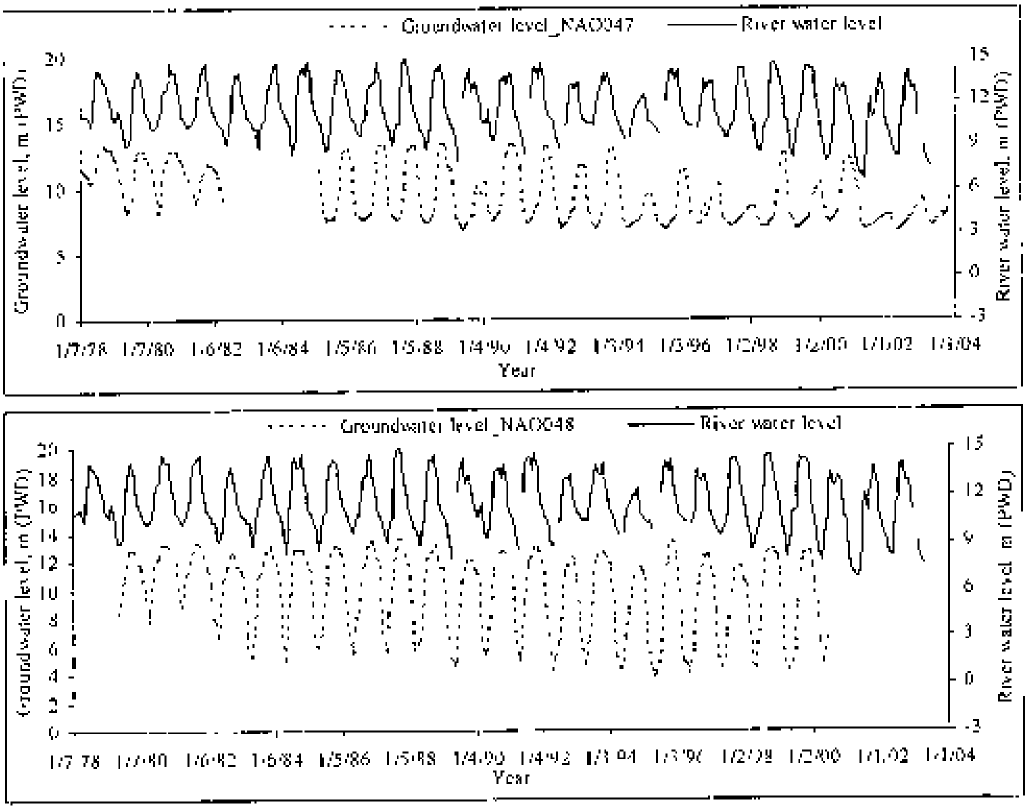


Figure 6.22 Distribution of Surface water level and groundwater level in observation well in Raninagar thana in the study area.

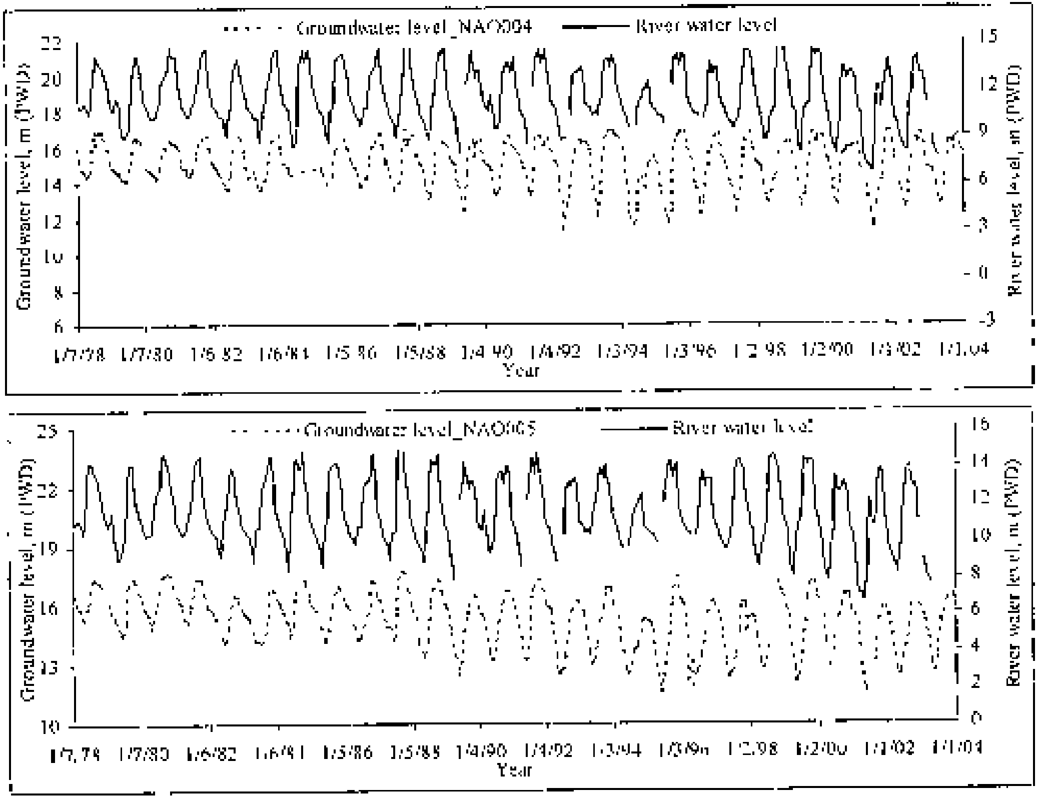


Figure 6.23 Distribution of Surface water level and groundwater level in observation well Badalgachi thana in the study area.

Regression Analysis

Groundwater level measurements in each well were correlated with river stage by linear and exponential regression analysis. Groundwater levels at a few wells showed strong correlations with river stage, while correlations were not that strong in other wells (as shown regression at zero month in Table 6.4. It is to be noted here that the response between groundwater and surface water may not be immediate. The extent of response and the response time depend on a number of factors including distance between the river and the groundwater well, degree of hydraulic connectivity and the transmissivity of the aquifer materials. These are well illustrated in Chapter Two.

Lag Regression Analysis

To examine the timing of the delay in groundwater response to a single previous month's river water level for each month was "lagged" for a period from zero to four months and correlated to the observed groundwater level measurement for the month of the prescribed lag period. Best-fit equations were calculated based on linear and exponential regressions. The lag period with the highest coefficient determination is marked with an asterisk. The groundwater level lag regression analysis was performed with river stage data for wells with within 6 kilometers (perpendicular distance) of the Little Jamuna River (wells NOA004, NAO048, NAO025, NAO027, NAO005, and BOG002) and another 4 wells located more than 6 kilometers from the river (wells NAO006, NAO026, BOG001, BOG003 and BOG009) to see how far inland the river may have an influence. The resulting correlation plots are presented in Figures 6.24-6.26 (others are in Appendix-J), and results of such an analysis are summarized in Table 6.4.

Table 6.4 Results of groundwater level lag regression analysis

Coefficients of determination, R^2 (%), for river stage (Y) v s lagged groundwater level (X)								
Thana	Well_ID	Distance from river (km)	Methods	0 Month	1-month lag	2-month lag	3-month lag	4-month lag
Naogaon sadar	NAO025	5	Linear	0.470	0.5087*	0.2817	0.0652	0.2099
			Exponential	0.494	0.5239*	0.2748	0.0565	0.0050
	NAO026	6	Linear	0.242	0.4257*	0.3966	0.2099	0.0372
			Exponential	0.255	0.4388*	0.4056	0.2110	0.0364
	NAO027	5	Linear	0.517	0.6104*	0.3909	0.1131	0.0002
			Exponential	0.529	0.6192*	0.3922	0.1107	0.0004
Badalgachi	NAO004	2	Linear	0.662*	0.6213	0.2859	0.0354	0.0274
			Exponential	0.634*	0.6097	0.2804	0.0324	0.0298
	NAO005	3	Linear	0.361	0.6179*	0.5376	0.2596	0.0369
			Exponential	0.366	0.6272*	0.5481	0.2622	0.0361
	NAO006	6	Linear	0.224	0.3633*	0.3022	0.1472	0.0298
			Exponential	0.229	0.3754*	0.3009	0.1367	0.0232
Adamdighi	BOG001	7	Linear	0.208	0.3770	0.4013*	0.2661	0.0684
			Exponential	0.222	0.3810	0.3951*	0.2572	0.0664
	BOG002	4	Linear	0.334	0.6170*	0.6034	0.3140	0.0417
			Exponential	0.339	0.6118*	0.5908	0.3030	0.0395
	BOG003	8	Linear	0.044	0.2933	0.5514	0.5769*	0.2715
			Exponential	0.052	0.2981	0.5374	0.5515*	0.2586
Ranınagar	NAO048	4	Linear	0.586	0.7136*	0.4850	0.1509	0.0006
			Exponential	0.602	0.7188*	0.4703	0.1351	0.0020

The importance of the distance between rivers and groundwater observation well and the delayed response between them are clear from the results presented. The nearest well (NAO004, 2 km) showed a strong correlation with almost no lag time while the correlation for the same observation well declined with increased lag times.

For other observation wells, with distance equal to or greater than 3 kms, the strongest correlation where found with lag time 1 month or more. This illustrates the delay in response between the two parameters. For example, strongest correlation for well NAO027 was found for lag period of 1 month (Figure 6.25), while the same for well BOG003 was found for lag period of 3 months (Figure 6.26).

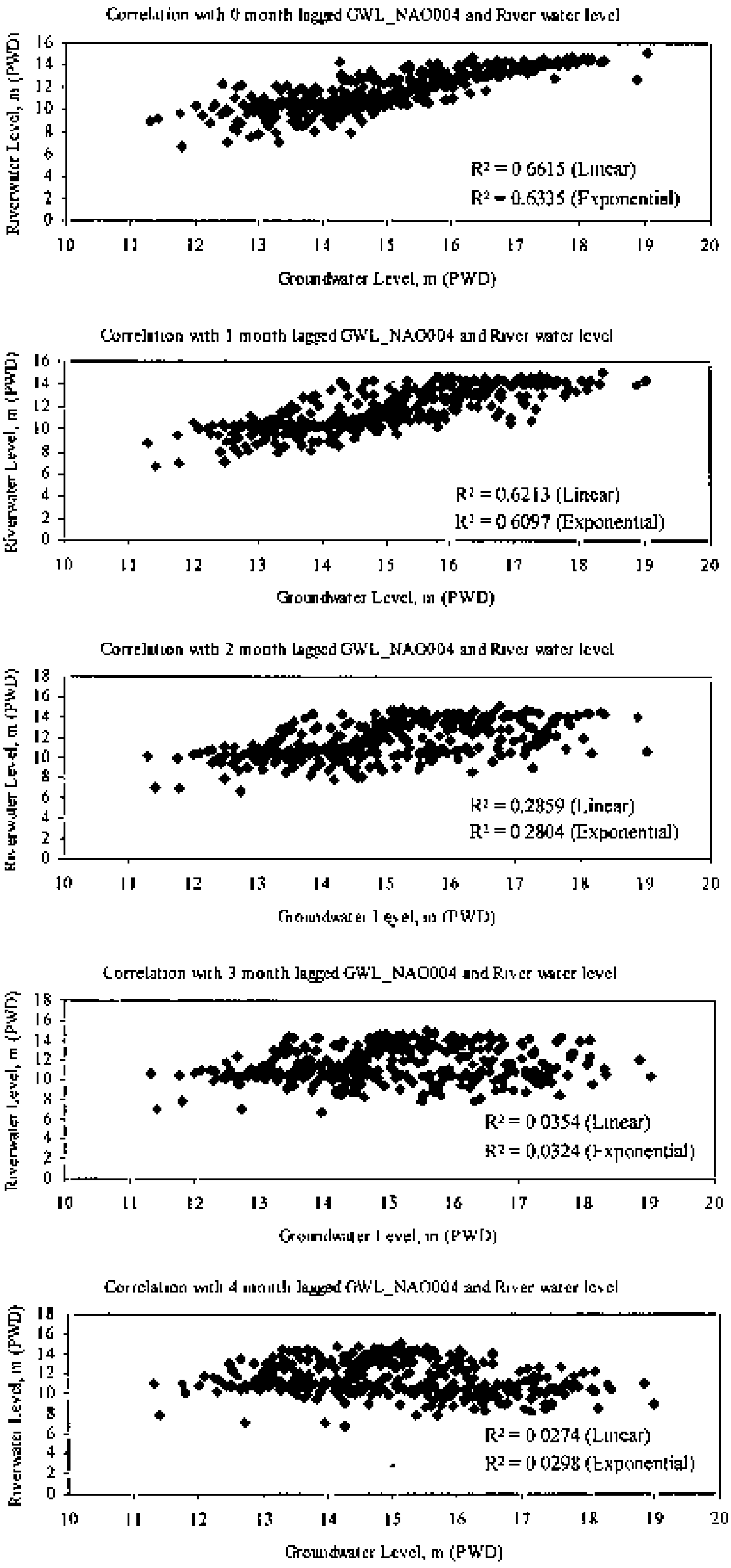


Figure 6.24 Best-fit linear and exponential correlation for 0 to 4-month lagged groundwater level in observation well no NAO004 in Badalgachi.

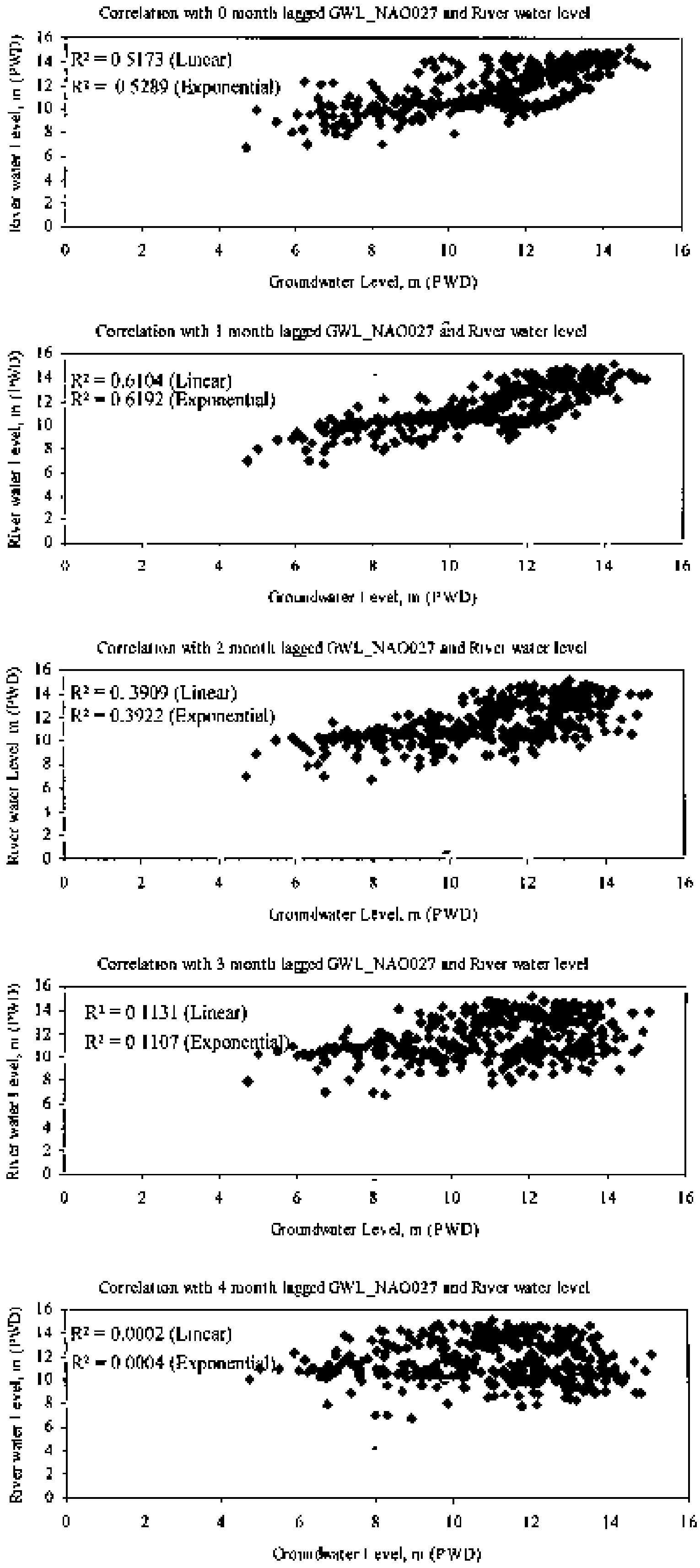


Figure 6.25 Best-fit linear and exponential correlation for 0 to 4-month lagged groundwater level in observation well no NAO027 in Naogaon.

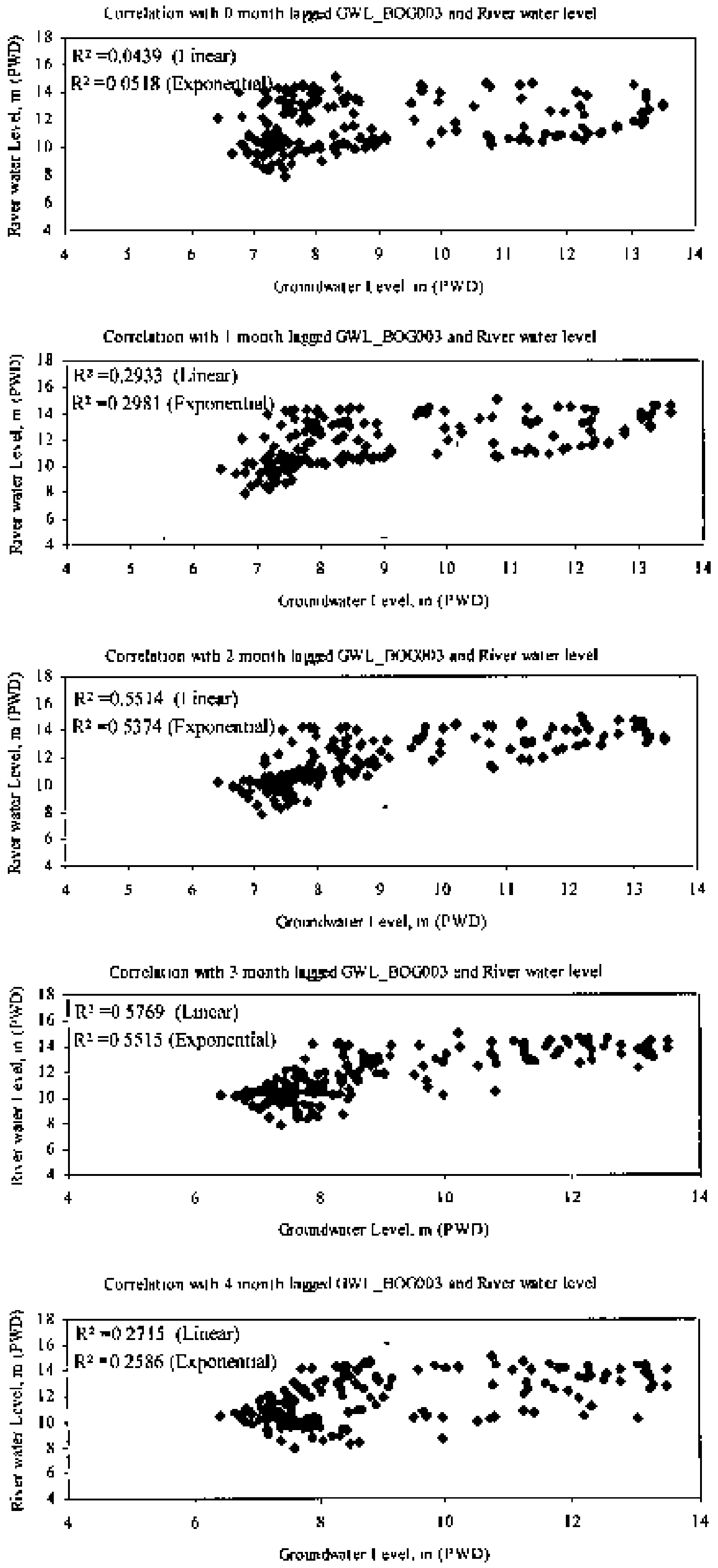


Figure 6.26 Best-fit linear and exponential correlation for 0 to 4-month lagged groundwater level in observation well no BOG0003 in Adamdighi.

Table 6.5 summarizes the maximum correlations for the groundwater observation wells with different lag periods. The table also shows the distance of the wells from the Little Jamuna river. With no lag times, the correlation decreases sharply with a more or less linear trend with increasing distance (Figure 6.27). However, the maximum correlation does not show as sharp decrease with distance (Figure 6.28). In a few case, for example the station BOG003 which is 8 km away from the river, the maximum correlation (found for 3 month-lag period) is significantly higher than those for 4 other wells BOG001, NAO006, NAO026, NAO025 which are 7, 6, 5 and 5 km away from the river.

Table 6.5 Maximum correlation between lagged groundwater level and river water level

Well_ID	Distance from river, km	Maximum, R^2	Maximum, R	Lagged Time
NAO025	5	0.5087	0.713	1-Month
NAO026	6	0.4257	0.652	1-Month
NAO027	5	0.6104	0.781	1-Month
NAO004	2	0.6620	0.814	0-Month
NAO005	3	0.6179	0.786	1-Month
NAO006	6	0.3633	0.603	1-Month
BOG001	7	0.4013	0.633	2-Month
BOG002	4	0.6170	0.785	1-Month
BOG003	8	0.5769	0.760	3-Month
NAO048	4	0.7136	0.845	1-Month

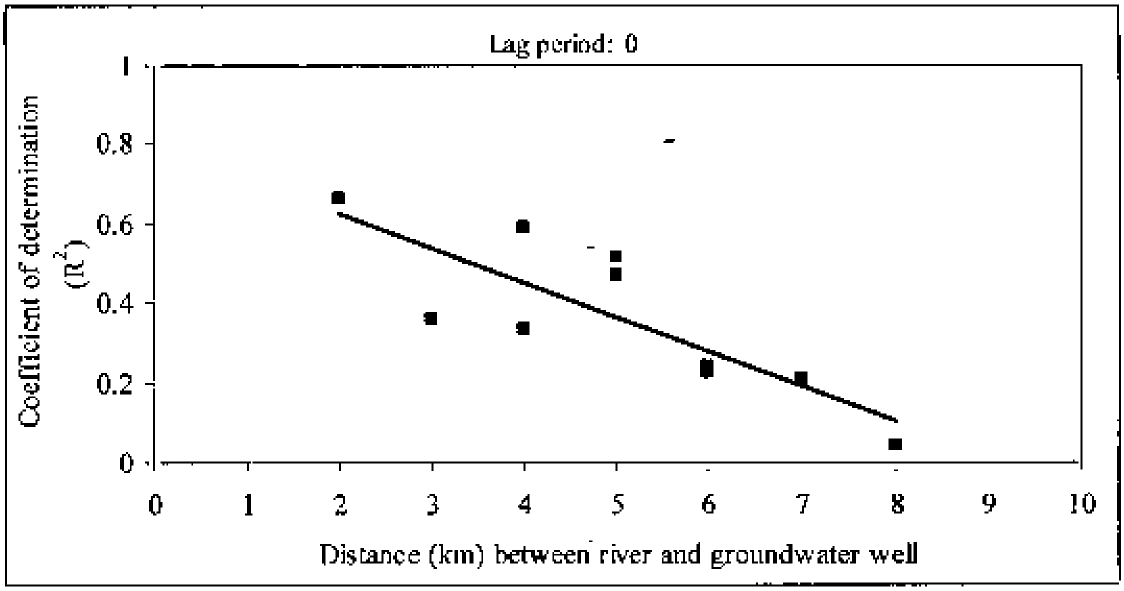


Figure 6.27 Change in correlation with zero lag time with distance

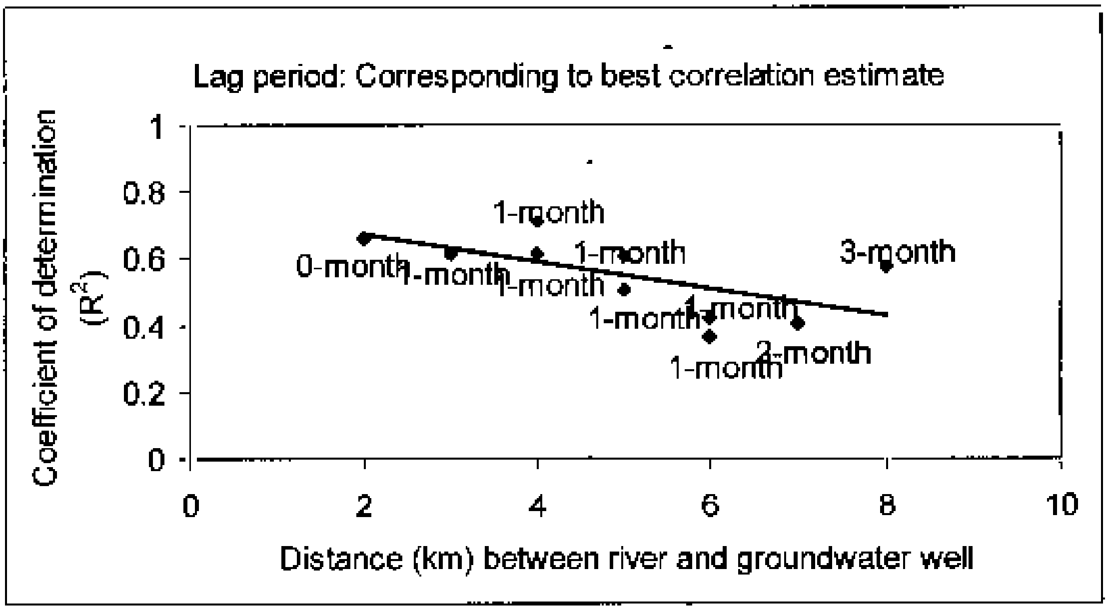


Figure 6.28 Change in maximum correlation among different lag times with distance

This illustrates the importance of consideration of delayed response between groundwater level and river in analyzing the interaction between surface water and groundwater. As we have already seen, river and groundwater are correlated, meaning that significant lowering of groundwater by irrigation pumping is expected to affect the river water. It is thus important to consider the effect of irrigation pumping even in areas relatively far from the river.

6.8 Baseflow Separation

Mean base flow was computed from continuous records of daily mean discharge at Naogaon long-term streamflow gaging station in the study area using the BFlow digital baseflow filter. Table 6.6 shows the average stream flow, baseflow and basefow index (BFI) (percent of base flow of total flow) percent for the months from January to April. Stream flow in Little Jamuna river is dominated by base flow in these dry months, especially in January and February, with baseflow contributing from 47% to 76% of total stream flow during the period.

Table 6.6 Estimates of mean monthly stream flow and base flow at Naogaon station in Little Jamuna river for 1974-2003 using BFlow baseflow filter.

Year	January			February			March			April		
	Stream flow (m^3/s)	Baseflow (m^3/s)	BFI (%)	Stream flow (m^3/s)	Baseflow (m^3/s)	BFI (%)	Stream Flow (m^3/s)	Baseflow (m^3/s)	BFI (%)	Stream flow (m^3/s)	Baseflow (m^3/s)	BFI (%)
1974	7.810	6.486	83.05	5.275	4.151	78.70	3.246	2.071	63.79	2.935	1.976	67.32
1975	5.518	4.322	78.33	3.448	2.732	79.23	1.431	0.759	53.06	0.145	0.117	80.53
1976	5.078	4.438	87.38	3.533	2.816	79.69	2.227	1.397	62.70	0,664	0.403	60.61
1977	5.718	5.107	89.32	4.569	4.053	88.72	4,717	3.444	73.01	3.484	1.568	45.00
1978	7.419	5.978	80.57	8.653	4.741	54.79	7.465	5.484	73.46	7.006	5.198	74.20
1979	8.904	5.972	67.07	21.396	9.987	46.68	9.440	4.724	50.05	0.530	0.266	50.24
1980	5.072	3.468	68.39	2.077	0.997	48.02	2.817	1,339	47,53	3.255	1.639	50.36
1981	6.245	4.353	69.70	2.288	1,500	65.54	2.899	0.979	33.75	7.989	3.033	37.97
1982	4.059	2.636	64,93	1.639	1.119	68.28	1.435	0.927	64.59	0.575	0.162	28.23
1983	3.558	3.111	87.43	2.992	2.094	70.00	2.703	1.065	39.41	0.559	0.194	34.79
1984	4.726	4,227	89.43	4.051	3.121	77.05	1.835	0.989	53.88	0.417	0.093	22.40
1985	4,719	4.026	85.31	3.262	2.761	84.62	2.071	0.909	43.90	0.389	0.103	26.40
1986	3.783	3.075	81,27	3.869	2.925	75.59	2,168	1.387	63.98	1.505	0.999	66.35
1987	3.342	2.519	75.60	1.953	1,426	73.01	1.002	0.539	53.78	2.196	0.506	23.05
1988	4.094	3.166	77.34	4.182	2.642	63.17	3.082	1,997	64.79	1.642	0.472	28.76
1989	7.619	5.223	68.55	4.241	2.079	49.03	0.455	0.201	44.06			
1990	13.426	7.092	52,82	30.293	14.945	49.33	8.201	3.341	40.74	3.825	1.017	26.59
1991	9.493	6.658	70.14	7.678	3.096	40.32						
1992	14.423	12.034	83.44	9.454	6.136	61.90						
1993	18.518	14.255	76.98	11.610	9.980	85.96	14,867	9,539	64.16	11.563	6.714	58.07
1994	12.790	10.653	83.29	8,427	6.778	80.42						
1995	5,610	4.964	88.46	5.245	4.081	77.87						
1996	7.004	5.995	85.59	5.861	4.971	84.81						
1997	5,037	3.547	70.41	4.109	2.411	58.67	2.648	1.452	54.83	2.995	1.252	41.81
1998	5.598	1.145	74.04	2.152	1.178	54,76	1.008	0.537	53.24	3.000	1.350	45.02
1999	5.662	4.089	72.22	1,983	1.007	50.78						
2000	3,063	2.084	68.05	1.203	0.833	69.25	0.391	0.330	84,24	3.782	0.426	11.28
2001	0.552	0.286	51.70	0.134	0,118	87.91	0.124	0.100	80,31	0.076	0.063	83.26
2002	2.830	2.229	78.78	1.573	1.190	75.68	0,735	0.588	79.98	0.653	0.428	65.62
2003	1,576	0.922	58.50	0.658	0.458	69.62	0.299	0.213	71.42			
Average	6.441	4.902	75.60	5.594	3.544	68.41	3.219	1.846	58.94	2.690	1.272	46.72

Figure 6.29 shows the time series of baseflow for the months from January to April, and the regression lines superimposed on the time series. Evidently, there has been a sharp declining trend in baseflow of the river. The decrease has been 50%, 70%, 90%, and 65% for January, February, March and April, respectively, from 1974 to 2003.

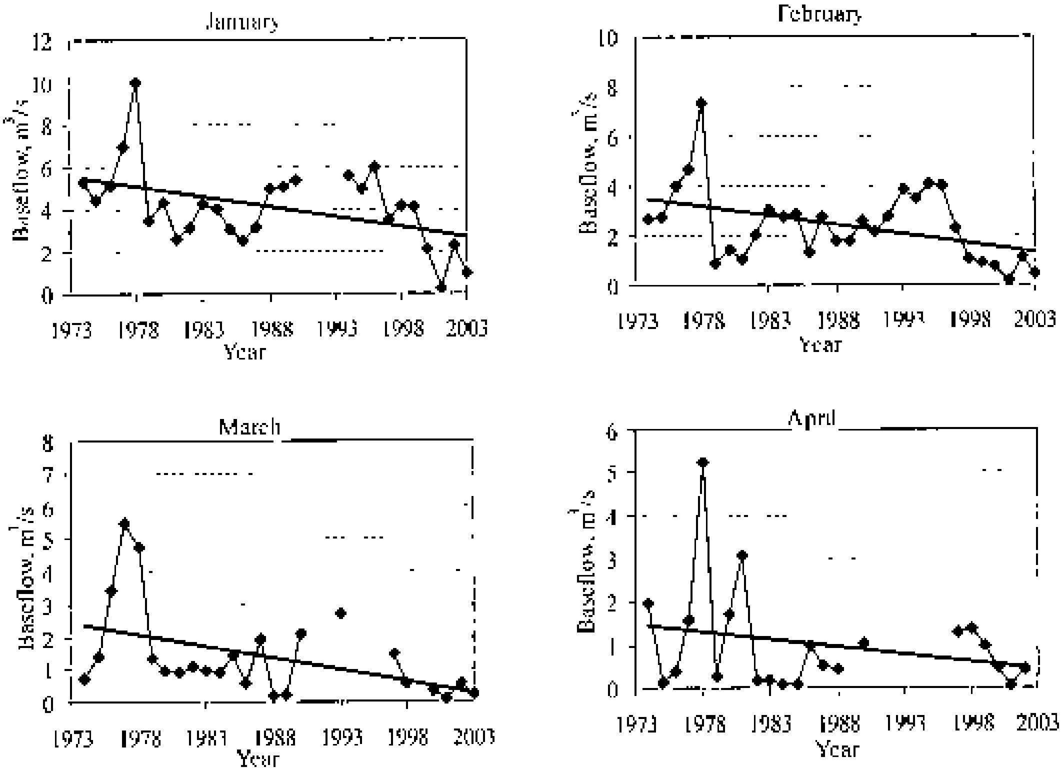


Figure 6.29 Time series plots of baseflow of Little Jamuna river for dry season months of January, February, March and April

6.9 Flow Duration Curve

Flow duration curves are plotted for the years in Figure 6.30. The relatively flat slope of the flow duration curves indicates that the river receives good amount of baseflow from the groundwater reservoir. The river has never been perennial: it is seen that some 25-30 years ago, the river had flow 90% of the time in a year. However, with time the duration of no flow period increased. However, the complete analysis of flow duration curve could not be achieved because of lack of a large number of data during the dry season in many years.

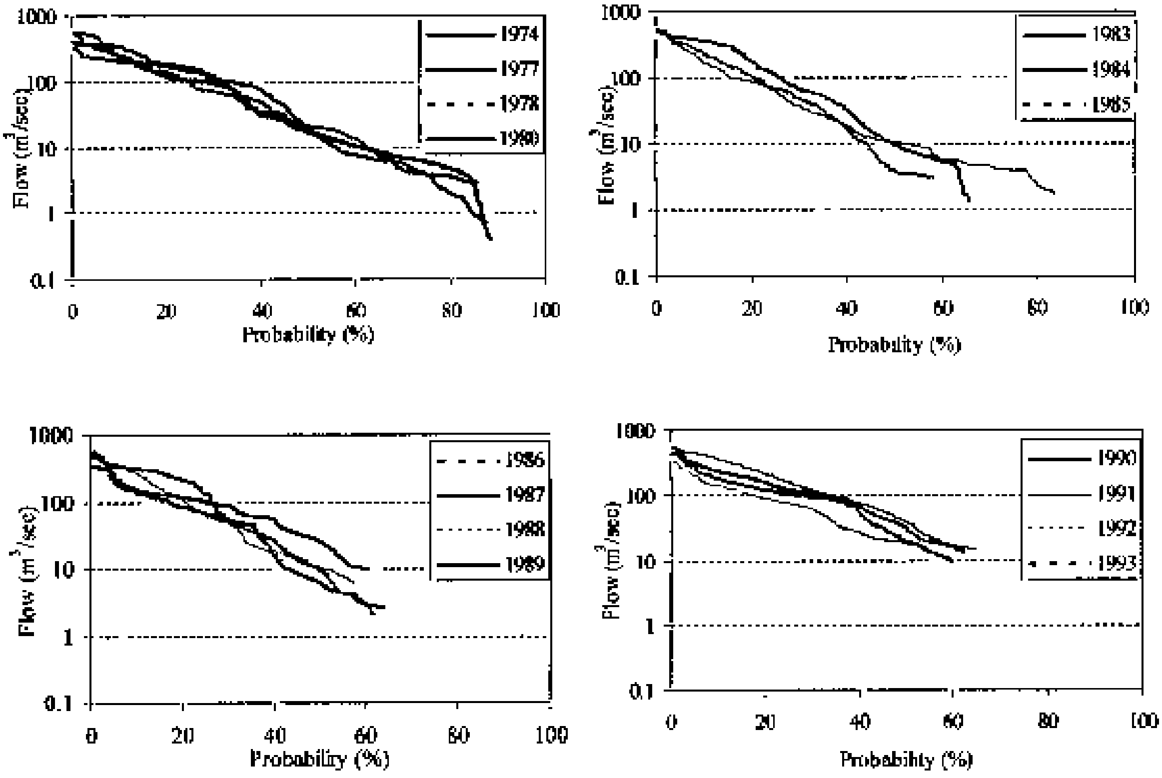


Figure 6.30 Flow duration curve for Little Jamuna river

6.10 Rainfall Distribution

Since the major contribution to stream flow comes from baseflow in the dry season, the loweing of stream flow (or baseflow) could be due to two possibilities: (i) declining groundwater recharge from antecedent wet season rainfall; and (ii) declining level of the groundwater reservoir due to increased drawdown resulting from irrigation pumping. In order to examine whether rainfall had any role in the reduction of flow, historical rainfall records are analyzed for trends at two important rain gage stations in the study area for the wet season (and also for dry season). The results are presented in Figures 6.31. It is clearly seen that there is no apparent decreasing trend in rainfall, and the effect of rainfall on the lowering of groundwater level and hence on the reduction of stream flow is minimal.

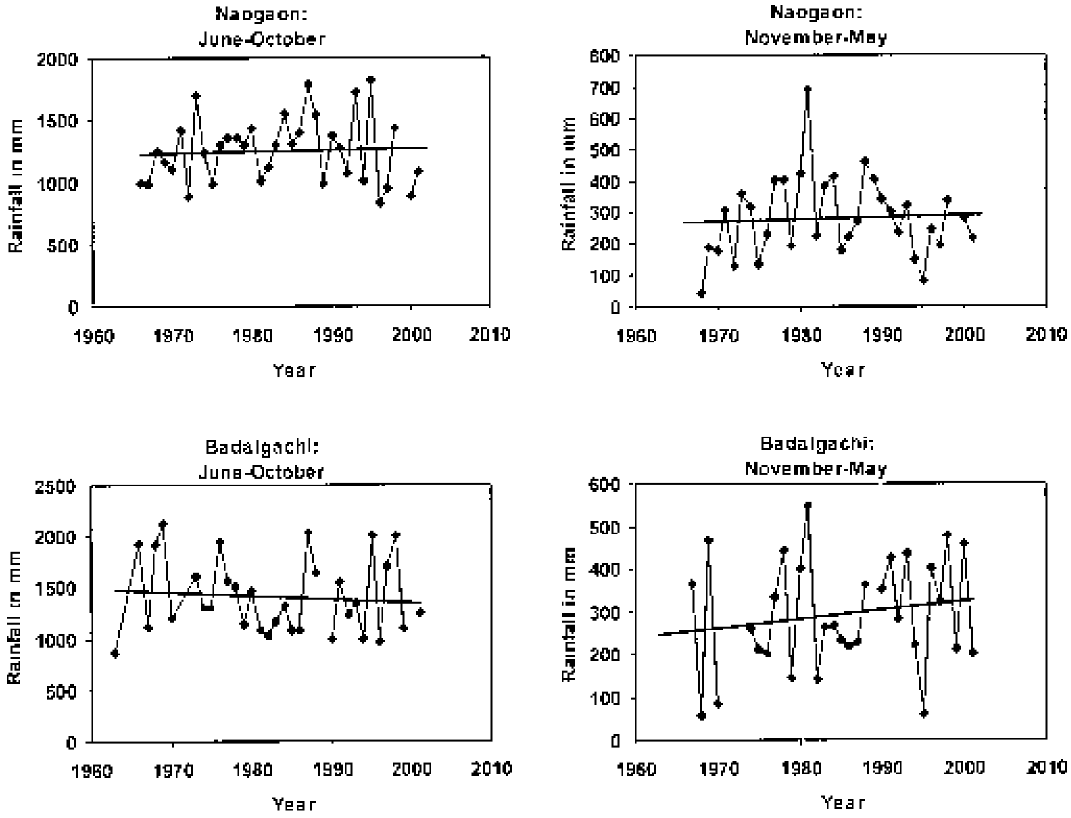


Figure 6.31 Time series plots of rainfall at stations Naogaon and Badalgachi.

6.11 Effect of Irrigation Pumping on Surface water-Groundwater Interaction

Irrigation development

Groundwater withdrawal or abstraction through tube wells principally for irrigation is estimated from the number of irrigation unit and pumping hours. Thana wise shallow tube well and deep tube well installed in different thanas of the study area. and total groundwater withdrawals for irrigation are presented in Figures 6.32 and 6.33 Figure 6.32 shows the numbers of shallow and deep tube wells installed over the years and Figure 6.33 shows the irrigation water volume withdrawn from the groundwater. From Figure 6.32. it is observed that expansion of irrigation coverage and more agricultural production have taken place in the study area. manifested by the increase in numbers of Deep tube wells over the years. Deep tube wells are installed more because of its high capacity of extraction of deep groundwater as groundwater level falls alarmingly in recent time. As seen in Figure 6.32, the number of deep tube wells increased in all six thanas of the study area. On the other hand, in two thanas (Badalgachhi and Raninagar), the numbers of shallow tube wells have also increased over the time, while in three thanas (Nagaon Sadar, Akkelpure and Adamdighi), the numbers of shallow tube wells had steadily increased up to 1997-1999. After that time, the numbers of shallow tube well have decreased. In Dhupchachia thana, the shallow tube well development have been less compared to the other thanas: irrigation has mostly been dominated by deep tubewells. Several factors are apparently responsible for the decline in shallow tube wells in some of the thanas (many of which were also substantiated in the field survey). Some shallow tube wells are being abandoned due to mechanical problems; some are being in-operative because of deep tube well's areal coverage and lowering of groundwater level by deep tube-well extraction; and some people use surface water from river at the beginning of irrigation period and after that time, they use groundwater from deep tube well. From the above discussion, it is possible that impact of lowering of water level by deep tube wells on the shallow tube wells was less Badalgachhi and Raninagar, while it was more in Nagaon Sadar, Akkelpur and Adamdighi As evident from Figure 6.33, major irrigation water volume is contributed by the STWs in almost all six thanas.

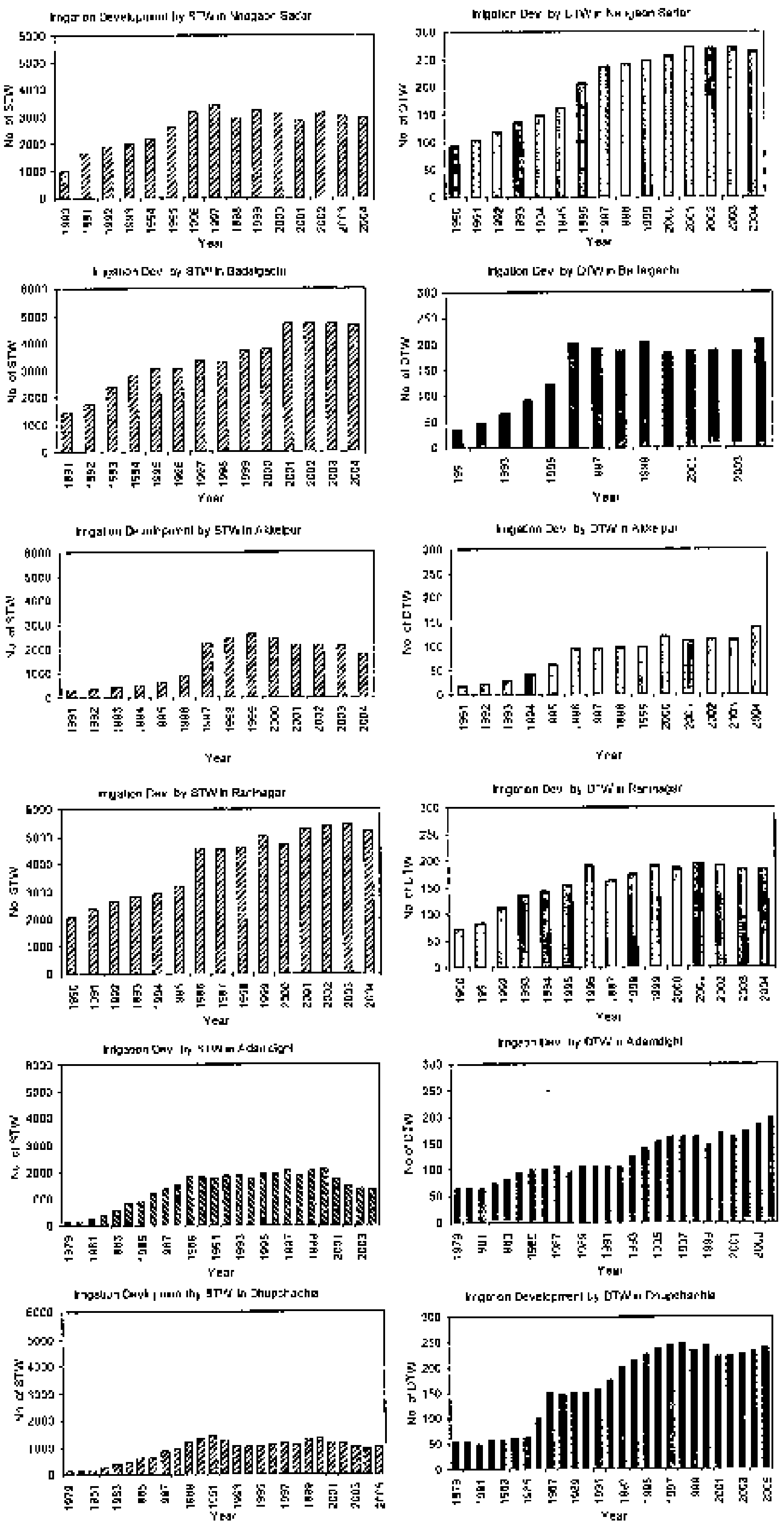


Figure 6.32 Irrigation development (number of STW and DTW) in the study area.

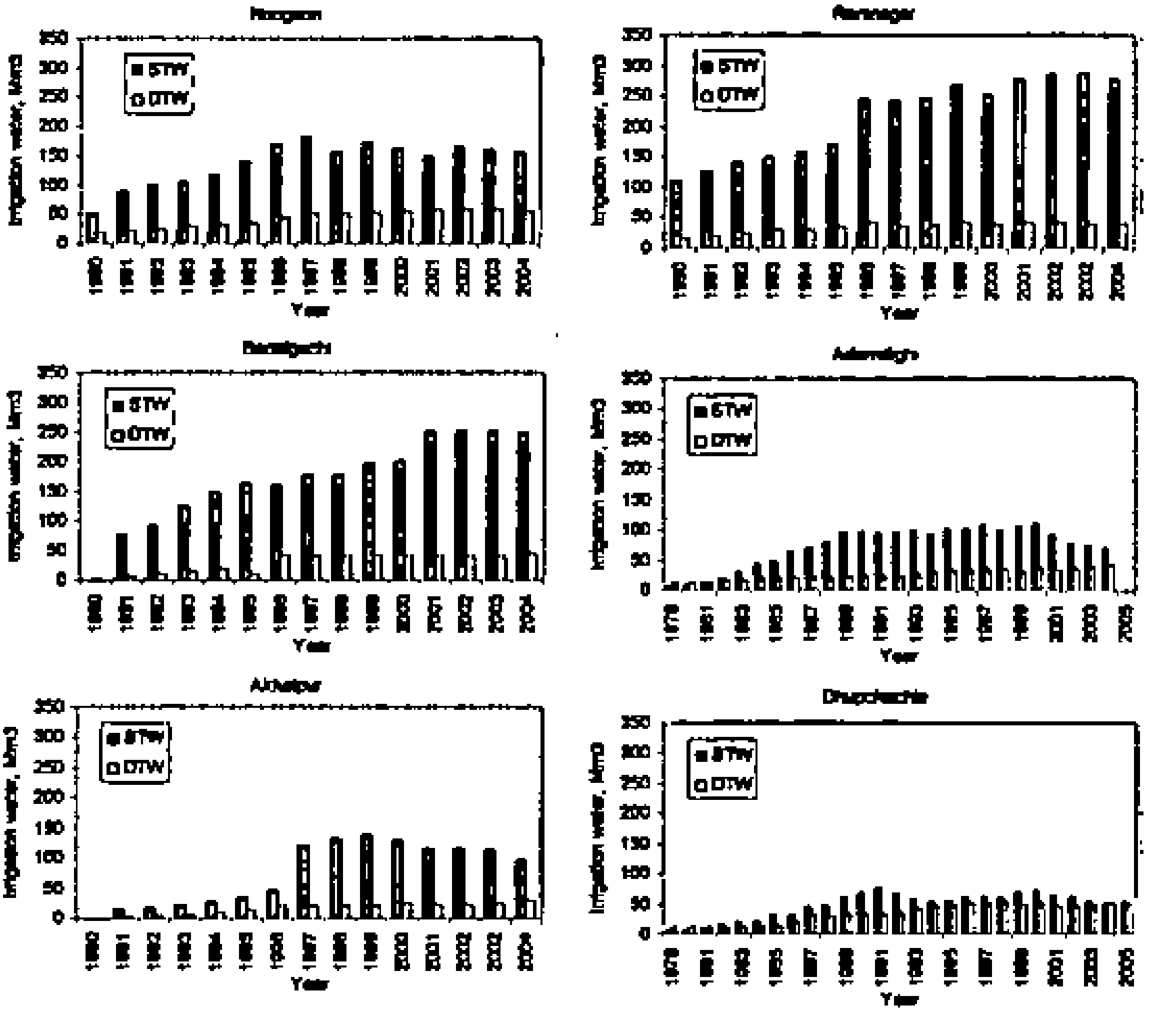


Figure 6.33 Year-wise irrigation water withdrawals in different thanas in the study area.

Comparison of irrigation development with groundwater level

Irrigation development and groundwater level fluctuations are plotted in Figure 6.34. It is observed that irrigation development and groundwater level are related with each other and they are inversely correlated. Irrigation development has had impacts on the groundwater levels in different parts of the study area.

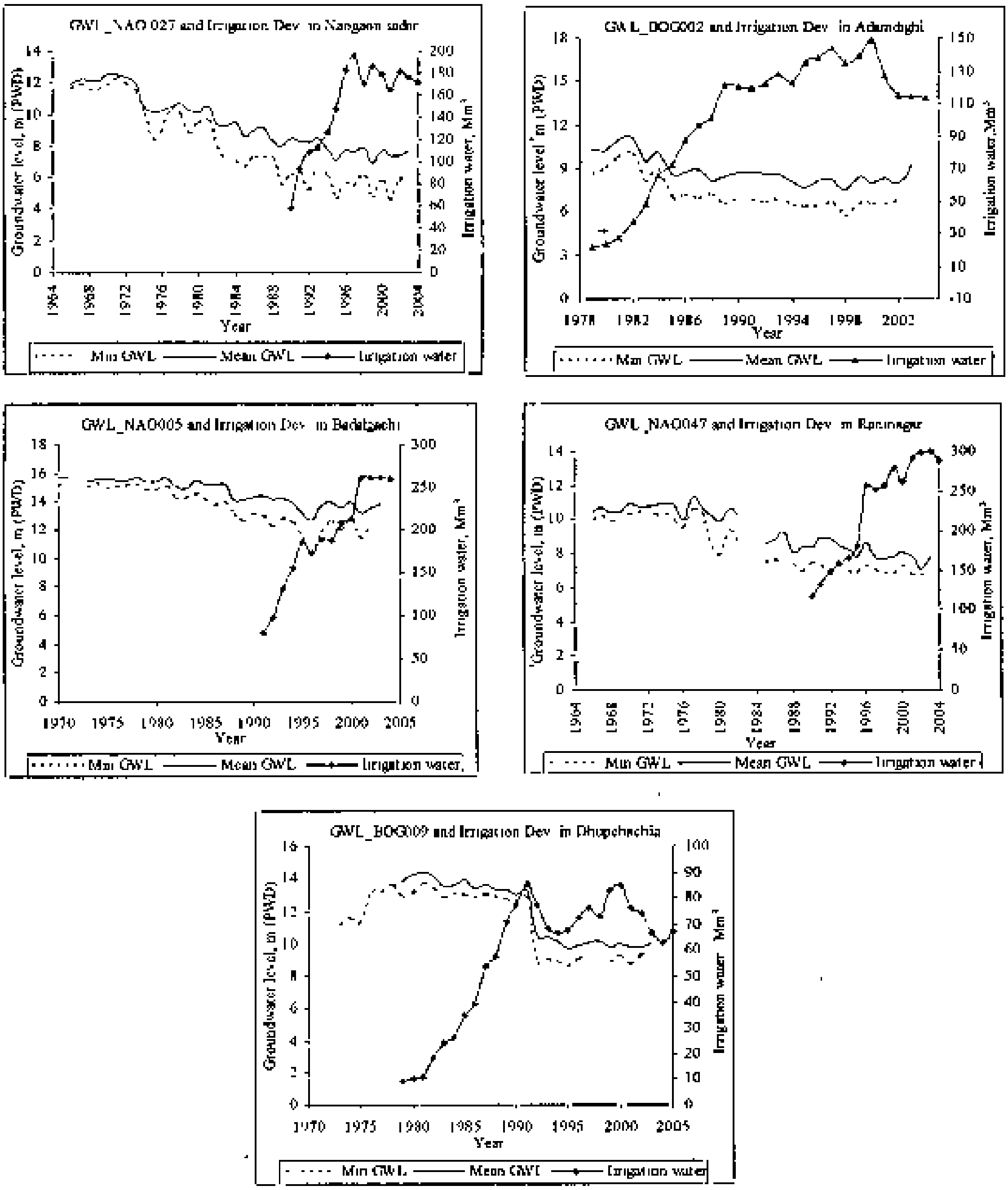


Figure 6.34 Comparison of Irrigation developments with groundwater level

Correlation analysis

Linear correlation regression analysis was performed with irrigation development and corresponding average groundwater level (surrogate for groundwater drawdown) in the study area. The resulting correlation plots are presented in Figure 6.35. Irrigation development shows strong correlation with groundwater level in all six thanas. The correlation improves when the irrigation volume extracted by deep tube wells are added to the volume abstracted by the shallow tube wells. This indicates a strong possibility of good hydraulic connection between the upper and lower aquifers.

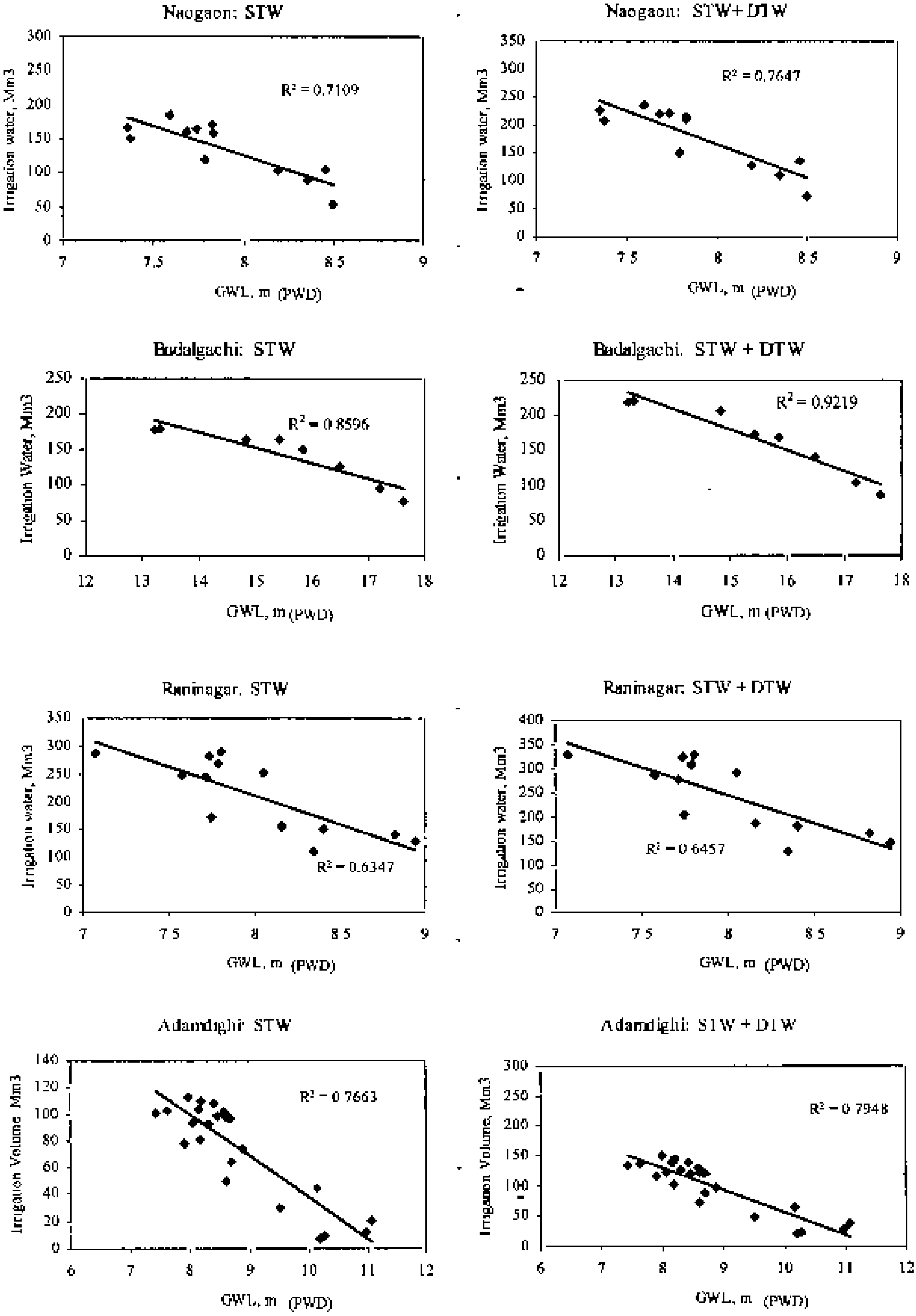


Figure 6.35 Best-fit linear correlations for irrigation development with average groundwater level (surrogate for drawdown).

From the above analysis, it is clear that irrigation pumping has had negative impacts on the groundwater levels, and since rainfall does not apparently have any role to play, it is very reasonable to infer that groundwater irrigation is one major reason for depletion of flow in the Little Jamuna river. This is further established from Figure 6.36, which shows a strong negative correlation between irrigation pumping and stream flow

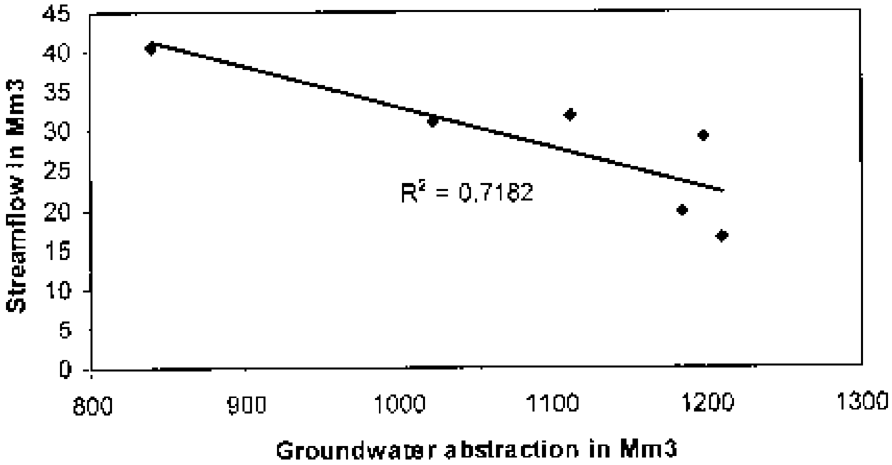


Figure 6.36 Correlation between groundwater abstraction for irrigation and stream flow in Little Jamuna river.

6.12 Field Survey

6.12.1 Questionnaire Survey and Purposive Interviews

The results from the questionnaire survey and purposive interviews (with the help of semi-structured questionnaire) conducted in four thanas (Nagaon Sadar, Badalgachhi, Raninagar, Adamdighi) near the Little Jamuna river are summarized below. All the respondents in questionnaire survey in the visited areas reported that the source of drinking water of people is hand tube-wells throughout the year except April and May. In Naogaon Sadar, people drink supply water from adjacent tank constructed near Deep Tube well (see Figure 6.37) or collect water from around DTW in April and May. The collection of water is mostly done by the women, and it is hard work for them.

Figure 6.37 Photograph showing over-head tank filled with DTW water as source of drinking water during April and May in Naogaon Sadar

River drying up?

All the respondents agreed that the river is drying up. About 85% of the respondents thought the river started drying up during the period from 1990-1995, while 15% of the respondents thought it started to occur during 1985-1990. The majority of the people, however, had the consensus that river has started gradually drying up since around 1990-91. All the respondents reported that there was enough water flow in this river before 20 to 25 years. The river has been almost fully drying up in the months of March and April since 1992. The problem is getting worse and at present drying up is happening from February to April. This is consistent with the finding of the hydrologic analysis (Section 6.3, Figure 6.6), which showed that flows have been declining over the years and the problem of very low flow or no flow have been in the months of March and April since around 1990, and the problem of very low flow or no flow has recently been extending to the month of February.

The respondents fear that parts of the river, which have already turned into stagnant water during the dry months of March and April, will dry up completely in a few years. Farmers now cultivate crops in the dry riverbeds during the dry season. They have installed shallow tubewells at river bed and with the help of these they cultivate Boro, Potato and various types of vegetables in the riverbed from 8 or 10 years ago. They also breed fish in the stagnating river areas. The respondents (100%) also added that ponds, khal, and bills are drying up from January to April every year, and the situation turns to an acute level towards the end of the dry season (February 15 to April 15). Examples of such beels are Munsur Beel, Digli Beel, Gutar Beel and Lal gola Beel in Naogaon Sadar thana, which have been converted from fish farm to irrigation fields since 12 years ago.

Reasons for river drying up

A majority of respondents (70%) cited lowering of groundwater level as a possible cause of drying up of the river. Extraction of water by deep tube-wells has had impacts on extraction of water from shallow depths. Local people, especially located in Naogaon sadar, Badalgachi and Raninagar area, pointed out that their hand tube wells fail to extract water; shallow tube well can not extract enough water, while deep tube well can extract enough water during the dry season, especially from February to April In the past the people used to pump drinking water from 25 to 30 feet below the land surface by using shallow hand tubewells. Now people in some areas do not get water even from 30 feet deep during the lean months of March, April and May since deepest pumps which have a suction capacity of lifting water from 80 feet deep, are becoming inoperative. Super Tara pumps which can lift water from 100 feet deep are now also becoming inoperative.

Interviews with BWDB and BMDA officials revealed that the numbers of shallow tube wells (STW) are decreasing. But the numbers of Deep tube wells (DTW) as well as the numbers of Deep Set tube wells (DSTW) are increasing because shallow tube wells can not cover expected area for irrigation. For expanding the irrigation area, more Deep tube wells are installed. This results groundwater being extracted more, leading to lowering of groundwater level. As a consequence, shallow tube wells surrounding these Deep tube wells can not extract water any more and they become inactive. Lowering of groundwater levels due to irrigation water withdrawals are causing decline in river water flow.

Rise of riverbed was also observed by most of the respondents as one of the important factors. The same observation was also found from interviews with BWDB and BMDA officials. River bed has been rising continually due to deposition of silt in the last 20 years, coupled with erosion of crop-field soil and massive encroachment. About 30 years ago, farmers used to cultivate only two crops. Aman and winter vegetables. But now they are growing Boro, which causes more soil erosion and the eroded soil is ultimately discharged into the canals and rivers leading to filling up of river beds. Depletion of river water has adversely affected navigation.

A conception that is commonly found among many people is that dams and barrages constructed upstream in India cause decline of water flows inside Bangladesh. However, interview with local BWDB officials revealed that the Little Jamuna river is not affected by any barrage (for example Farakka barrage) or dams in India. It is the lack of care and proper management that is the reason behind this. This makes sense since Little Jamuna has an independent catchment within Bangladesh. which does not receive flow from any of the upper catchments that fall within the Ganges dependent area.

Environmental impacts

All the respondents in the questionnaire revealed that the drying up of rivers (and of beels and khals) have had negative impact on the environmental ecosystem Among the species of fish that are disappearing include 'bheda', 'choto chanda', 'potka', 'boal' and 'koi' (all local names) Reduction of water bodies has also had impacts on the migratory birds

Mitigation measures – people's perception

People's perception is that mitigation measures can be in the form of dredging/ excavation of river bed. construction of a rubber dam across the river. and encouraging plantation of vegetation cover on the banks of the river to protect erosion of banks and inhibit silt deposition. All respondents expect that Government should take initiative and proper steps to manage Little Jamuna river flow for agricultural product and environmental wellbeing.

6.12.2 Hydro-geologic Characterization of Little Jamuna River Reach

As mentioned in Chapter five, information was gathered through interview of people at every ½-km over a distance of 17.5 km along the Little Jamuna river. The synthesis of all information is summarized in Figure 6.38 and Table 6.7. Depending on similarities in characteristics, the river reach is categorized into three types of sub-reaches: A (A1, A2, A3, A4, A5), B (B1, B2), and C (C1, C2).

In type A, the problem of river drying up is the greatest. This is also manifested by the drying up of hand tube wells for a considerable length of time because of lowering of groundwater table. The effect of drawdown by irrigation pumping extends to this part; shallow tube wells are frequently needed to be lowered into the ground by about 2 meters to extract water. The exfiltration of water into the aquifer from the river is easier because of the sandy characteristics of the bed materials. The dryness of the river in these sections, however, has led the farmers to cultivate on to the river bed.

In type B, the problem of drying up is moderate compared to that type A sections. The duration of river drying is less. The problems of hand tube wells becoming inoperative are there, but the duration is smaller compared to that in type A sections. The effect of irrigation pumping also reaches these sections; however, no shallow tube wells are needed to be lowered into the ground, neither the people grow any crops in river bed.

In type C, the river has water and so does the nearby water bodies. The effect of irrigation pumping has not been as much compared to other sections. Hand tube wells mostly work except for a period of a little over two weeks. The clayey nature of riverbed allows slow depletion of river flow.

The reasons behind the dissimilarities could be manifold, including the heterogeneity in aquifer materials, and the difference in hydraulic connection between rivers and aquifer (which affects the rate at which water will be exchanged between river and aquifer).

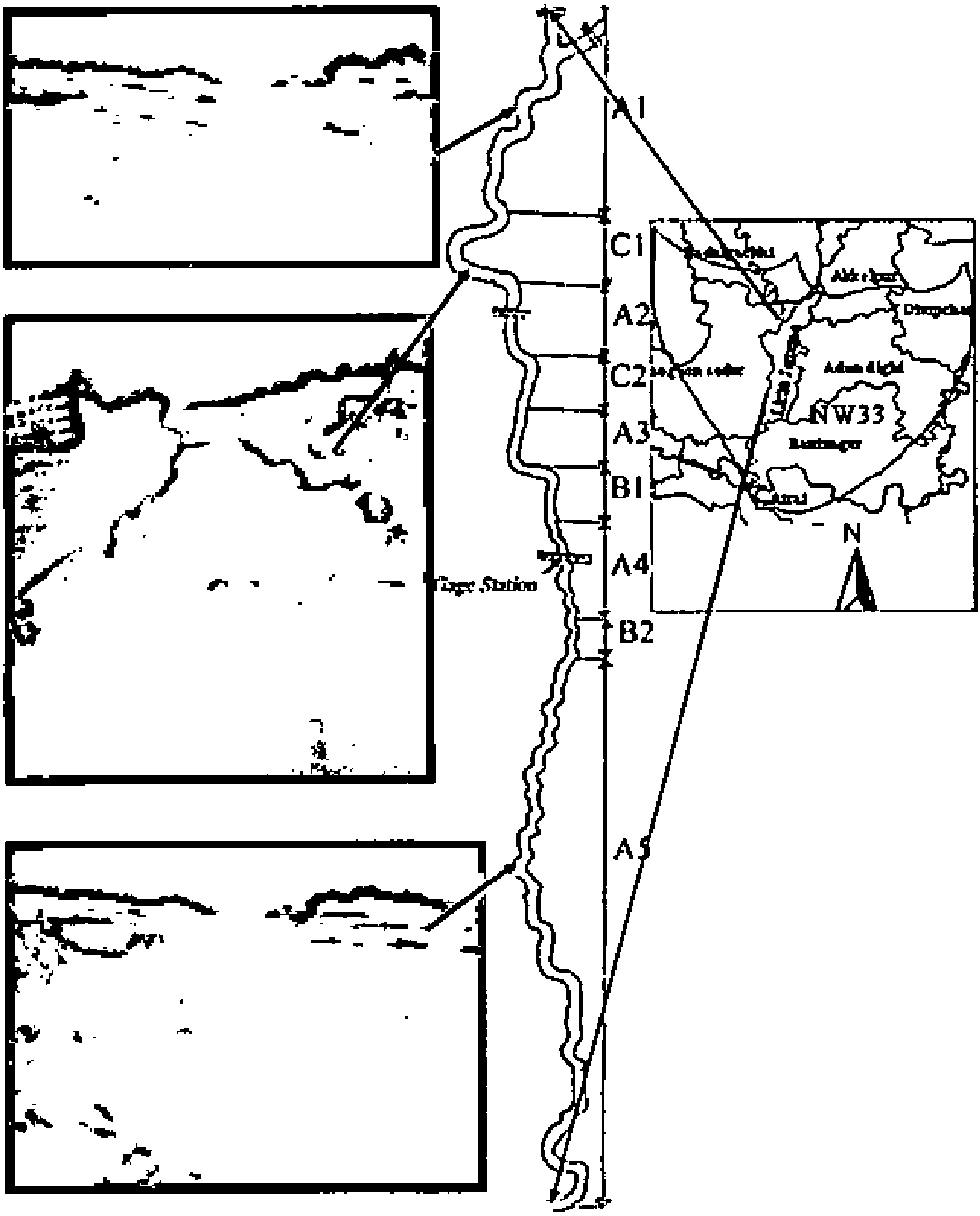


Figure 6.38 Stretch of Little Jamuna river surveyed every ½ a kilometer.

Table 6.7 Hydro-geologic characterization of Little Jamuna river

Segment	Overall condition in dry season	Characteristics
A (A1, A2, A3, A4, A5)	river is completely dried up	• River bottom is completely dried up from March 15 to May 15 each and every year and that condition started from 1985 – 1990 • River is partly dried up from February 01 to March 15 which started from 1980 – 1985. • Ponds, khals and beels are completely dried up with river also drying and seem to be related with each other. When river is full of water, other water bodies are full, and vice versa. • The soil characteristic is of sandy in nature. • Hand tubewells do not get water for 45 days in the dry season • Shallow tubewell installed on the land surface, can not extract enough water for irrigation in the month of March to May. • If shallow tube wells are installed below land surface from 5 to 7 ft, all the shallow tube wells can extract or get enough water for irrigation fulfill the required demand all over the year. • For boro cultivation, irrigation water is used firstly from river water using shallow tubewell. When river water is used up completely then groundwater through shallow or deep tube wells is used for irrigation • When there is no water in segment A and shallow tube wells installed on the land surface can not extract groundwater, deep tube wells or shallow tube wells are installed on the bottom of the river. • Boro and vegetables are grown on the river bed.
B (B1, B2)	river is partly dried up	• River bottom is partially dried up from February – May and this situation is continuous from 1985 – 1990 • Some ponds have water but no water is there in khals or beels. When river stage goes down, water level in khals or beels follow the same. • The soil characteristic is of sand, silt, clay mixed in nature • Hand tubewells do not get water for 30 days in the dry season • Shallow tubewell installed on the land surface, can not extract or get enough water for irrigation in the month of April to May. • If shallow tubewells are installed below land surface from 3 to 4 ft, all the shallow tubewells can extract or get enough water for irrigation fulfill the required demand all over the year. • For boro cultivation, irrigation water is used firstly from river using shallow tubewell. When river water is used up completely, then groundwater through shallow or deep tube wells is used for irrigation. But where small water level is available, both groundwater and river water are used. • No shallow or deep tube wells are installed on the river bed, they are installed on the land surface • No crops are grown on the river bed
C (C1, C2)	River has always water	• Water is available all the year round • Ponds have enough water • The soil characteristic is of clayey in nature. • Hand tubewells do not get water for 15–20 days in the dry season • Shallow tube well installed on the land surface, can not extract or get enough water for irrigation in the month of only May. • If shallow tube wells are installed below land surface from 2 to 3 ft, all the shallow tube wells can extract or get enough water for irrigation fulfill the required demand all over the year • For boro cultivation, irrigation water is used from river water and groundwater using shallow tube well in the study area • No shallow or deep tube wells are installed on the river bed, they are installed on the land surface. • No crops are grown on the river bed

Chapter Seven

CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

The conclusions of the study are listed below:

- There is direct connection between the river and the underlying aquifer in the floodplain alluvium of the Little Jamuna river. There is hydraulic connection between the floodplain aquifer and the upper aquifer in areas underlain by the clay aquitard.

- There are strong declining trends in the yearly minimum water level and river flow in dry season months. The flow in Little Jamuna river in January, February, March and April have decreased by approximately 40%, 50%, 70% and 70%, respectively from 1974 to 2003.

- Although the recovery is found to be more or less good in most of the wells, there is a marked decreasing trend in minimum groundwater level in many of the observation wells over the years.

- There is a time lag of 2 to 3 months between the effects of rainfall to be felt in groundwater levels. For example, correlation coefficient for a well improves from 0.075 at zero lag to 0.83 after a lag of 3 months.

- The river-aquifer interaction is strongest near the river with a correlation coefficient as high as 0.814 between river stage and groundwater level at 2 km from the river.

- However, there is a lag time in the response between the groundwater and surface water. Maximum correlation among 0 to 4 months lag does not show as sharp decrease with distance as correlation for only zero lag shows with distance. Strong correlation coefficients were obtained at greater distances after some lag time. A correlation coefficient of 0.760 was obtained with a 3 month lag time at a distance 8 km away from the river. This is even higher than correlation coefficients, obtained at some other observation wells nearer to the stream.

- It is thus important to recognize the delayed response between groundwater level and river in analyzing the interaction between surface water and groundwater. It is important to consider the effect of irrigation pumping on stream flow depletion even in areas relatively far from the river.

- Stream flow in Little Jamuna river is dominated by base flow in the dry months, especially in January and February, with baseflow contributing from 47% to 76% of total stream flow during the period. There has been a sharp declining trend in baseflow of the river, the decline being 50%, 70%, 90%, and 65% in the months of January, February, March and April, respectively, from 1974 to 2003.

- Rainfall distribution was not found to have played any major role in affecting groundwater levels and hence stream flow. It is the irrigation development that have affected gradual lowering of the groundwater level, which in turn caused reduction of base flow and hence stream flow in the dry season months.

- The river had started to dry up since 1990-91, and the dry season months of March and April have been mostly affected since then. However, the recent trend shows that the problem is extending to as early as February.

- The water bodies in the area followed a pattern similar to the Little Jamuna river; a good number of beels have dried up over the years.

- Apart from lowering of groundwater level by irrigation pumping, another important factor is siltation in river bed as a result of soil erosion, which contributes to drying up of rivers in several patches.

- The flow depletion of rivers and reduction in water bodies have had negative impacts on the environmental ecosystem, with many of the local fish species started to disappearing, and the migratory birds getting lower in number.

- The degree of impact on stream flow by groundwater lowering depends, among others, on the heterogeneity in aquifer materials, and the spatial difference in hydraulic connection between rivers and aquifer. Not all the places along the river experienced the same degree of the problem of river drying up. Lowering of groundwater have impacted the drinking water supply by hand tube wells over different durations of time in different places.

- In areas where the problem is acute to moderate, irrigation by STWs in floodplains near the river has been affected.

7.2 Recommendations

A number of recommendations are provided below:

- The groundwater abstraction volume responsible for a declining groundwater level is mainly contributed by shallow tube wells What is needed is the reduction of indiscriminate use of shallow tube wells, and enhancement of community based use of shallow tube wells. Reduction of shallow tubewells and enhancement of deep tube wells may be an answer.

- Dredging of rivers and construction of a rubber dam at the downstream location of the river may enhance the water availability in rivers. However, since these are costly methods, detailed data collection and analysis would be needed.

- The study used a variety of analytical techniques to study the interaction between the Little Jamuna river and the underlying aquifer. However, detailed analysis of resources (surface water and groundwater) and how surface water and groundwater can be used conjunctively can be investigated in future. Use of numerical model simulations will be a useful tool in this regard.

- The spatial variation of river-aquifer interaction mechanism could not be analyzed because of lack of adequate number of observation wells very close to the river and lack of water level and discharge measuring stations at various locations. A pilot study can be taken in consideration to this followed by the application of a combination of analytical and numerical modeling approaches.

REFERENCES

Adamowski, K. and Feluch, W. (1991). Application of nonparametric regression to groundwater level prediction, Can. J. Civil Eng., 18 (4). 600-606.

Ahmed, K.M., and Burgess, W.G. (1995). Bils and the Barind Tract Aquifer, Bangladesh. Chapter 8, In: Geomorphology and Groundwater. Edited by A.G. Brown, John Wiley & Sons Ltd.

Ahmed, K.M., and Burgess, W.G. (2003). Surface water groundwater interaction in Bangladesh hydrology. In Groundwater Resources and Development in Bangladesh, Edited by A. A. Rahman and P. Ravenscroft, The University Press Limited, Dhaka.

Ahmed, S. (1986). Study of groundwater system in the Mymensingh-Tangail area using numerical methods. M.Sc. Engg. (Weter Resources) thesis, BUET, Dhaka.

Ahmed, K. M. (1994). The Hydrologeology of Dupi Tila Sands Aquifer of the Barind Tract, NW Bangladesh. Ph.D Thesis, University of London, U.K.

Alam, M.K., Hasan, A.K.M.S., Khan, M.R., and Whitney, J.W. (1990). Geological map of Bangladesh. scale 1:1,000.000. Geological Survey of Bangladesh, Dhaka, Bangladesh. Figure 6: Delineated wellhead protection area around the well in Nachole for two user defined time periods. Journal of Spatial Hydrology.

Ali, G.M.M. (1993). Geophysical study of subsurface structure in Nachole Thana of Greater Rajshahi District, M.Sc. Thesis, No. 247, Department of Applied Physics & Electronics, Rajshahi University. Bangladesh. 71p (Unpublished).

Alpers, C.N., and Whittemore, D.O. (1990). Hydrogeochemistry and stable isotopes of ground and surface waters from two adjacent closed basins, Atacama Desert, Northern Chile, Appl. Geochem., 5(5/6), 719-734.

Anderson, D. (2003). Groundwater – Surface Water Investigation in the Warm Springs Canal Frenchglen Mercantile Site Frenchglen. Oregon: a Technical Memorandum, Oregon State Department of Environmental Quality.

Arnold, J.G., Allen, P.M., Muttiah, R., and Bernhardt, G. (1995). Automated base flow separation and recession analysis techniques. Ground Water 33(6). 1010-1018.

Arnold, J.G. and Allen, P.M. (1999). Automated methods for estimating baseflow and ground water recharge from streamflow records. Journal of the American Water Resources Association 35(2): 411-424.

Asaduzzaman, M. and Rushtom, K.R. (1998). Barind: Predicted a Failure, Proved a Success, Hydrology in a Challenging Environment, Brotish Hydrological Society.

Azad, M.A.S., and Bashar, K. (2000). Groundwater Zonation of Nawabganj Sadar Thana and its Relation to Groundwater Chemistry. Bangladesh Journal of Geology, 19, 57-71.

BADC (2004). Survey and Monitoring Project for Development of Minor Irrigation. Ministry of Agriculture, Bangladesh.

BADC (2005). Survey and Monitoring Project for Development of Minor Irrigation, Ministry of Agriculture, Bangladesh.

BWDB (2005). Bangladesher Nod-Nodi (in Bangla). Bangladesh Water Development Board.

BBS (2001). Bangladesh Bureau of Staristics Statistical yearbook of Bangladesh.

Begum. S.F. (1992). Evaluation of hydraulic properties of the aquifer from pumping test analysis of the Barind area, M.Sc. Thesis. Dhaka University. Dhaka, p. 148 (Unpublished).

Begum, S.F., Bashar, K., and Hossain. M.S. (1997). An evaluation of hydraulic parameters of the aquifer and wells of the western part of the Barind area, Bangladesh, Bangladesh Geoscience Journal, 3. 49-64.

Belanger. T.V., and Montgomery, M.E. (1992) Seepage meter errors. Limnology and Oceanography. 37 (8). 1787-1795.

Bent, Gardner C. (2000). Streamflow, Base Flow, and Ground-Water Recharge in the Housatonic River Basin, Western Massachusetts and Parts of Eastern New York and Northwestern Connecticut.

Bevans, H.E. (1986). Estimating stream-aquifer interactions in coal areas of eastern Kansas by using streamflow records. U.S. Geological. Survey. Water-Supply Paper. 2290, pp. 51-64.

BGS (2001). Groundwater studies for arsenic contamination in Bangladesh, In: British Geological Survey Report WC/00/19. edited by D.G. Kinniburg and R.L. Snedly. London.

BWDB (1990). Groundwater table data in the Barind Integrated Area Development Project of the District of Naogaon, Rajshahi and Chapai Nawabganj from October 1988 to December 1989. BWDB Water Supply Paoer 511, Groundwater Circle BWDB, Dhaka.

Carey, Barbara M. (2001). Groundwater/Surface Water Interactions in the Sammamish River: a Preliminary Analysis Quality Assurance Project Plan. Washington State Department of Ecology, Environmental Assessment Program Olympia.

Chapman. TG., Maxwell, A.I. (1996) Baseflow separation—comparison of numerical methods with tracer experiments. Hydrological and Water Resources Symposium, Institution of Engineers Australia, Hobart: 539–545.

Chapman. T.G (1991) Comment on evaluation of automated techniques for base flow and recession analyses, by RJ Nathan and TA McMahon. Water Resources Research, 27(7), 1783-1784.

Cooper, H.H., Jr., and Rorabaugh, M.I. (1963). Groundwater movements and bank storage due to flood stages in surface streams. U.S. Geological Survey, Water Supply paper. 1536, 343-366.

Dingman SL. (1994). Physical Hydrology. Macmillan, New York.

Donato, Mary M. (1998). Surface-Water & Ground-Water Relations in the Lemhi River Basin, East-Central Idaho. Water-Resources Investigations Report 98–4185, In cooperation with the Bureau of Reclamation Boise, Idaho.

Eckhardt. K. (2005). How to construct recursive digital filters for baseflow separation. Hydrological Processes 19. 507-515.

Faisal. M. Islam. (1988). Study of Rainfall and River Stage on Groundwater Table by Regressional Model. M.Sc Thesis, Dept. of WRE. BUET, Dhaka.

Ferris. J. G. (1951) "Cyclic Fluctuations of Water levels as a Basis for Determining Aquifer Transmissibility." Int. Assoc. Sci. Hydrol., Pub. 33, pp 148-155.

Fox, Garey A (2004). Evaluation of a Stream Aquifer Analysis Test Using Analytical Solutions and Field Data. Journal of the American Water Resources Association. USA.

Glover, R.E. (1994). Transient groundwater hydraulics. Department of Civil Engineering. Colorado State University, Fort Collins. Reprinted in 1985 by Water Resources Publications, High Land Ranch.

Hall, F. R., and Moench, A. G (1972). "Application of the Convolution Equation to Stream Aquifer Relationships," Water Resources Research 8(2), pp 487-493.

Hall, F.R. (1968). Base-flow recessions--a review, Water Resources Research, 4(5). 973-983.

Hantush, M.S. (1965). Wells nears with semi-pervious beds. Journal of Geophysical Research, 70(12), 2829-2838.

Haque, M.N., Keramat, M., and Rahman. A.M.A. (2000). Delineation of groundwater potential zones in the western Barind Tract of Bangladesh, Journal of the Bangladesh National Geographical Association, 21-26(1-2), 13-20.

Herczeg, A.L., Barnes, C.J., Macumber. P.G., and Olley, J.M (1992). A stable isotope investigation of groundwater-surface water interactions at lake Tyrrell, Victoria, Australia, Chem. Geol., 96(1-2), 19-32.

Herrmann, A. (1997). Global review of isotope hydrological investigations. In. Oberlin, G., Desbos, E. (Eds.). FRIEND third Report, UNESCO, Paris.

Hoque, M.M. (1986) Conjunctive use of groundwater and surface water in Gangeg-Kobadak Project, 1st interim report, IFCDR. BUET.

IBRD (1971). Bangladesh Land and water Resources Sector study on the Groundwater Potential.

IH (1978). Low Flow Studies. Institute of Hydrology, Wallingford. UK.

Ivkovic, K M . Letcher, RA., and Croke, BFW. (2004). 'Groundwater-river interactions in the Namoi Catchment and their implications for water allocation'. 9th Murray-Darling Basin Groundwater Workshop 2004, Bendigo.

Ivkovic. K.M , Letcher. R A., Croke. B.F.W.. Evans. W.R., and Stauffacher. M. (2005). A framework for characterizing groundwater and river water interactions: A case study for the Namoi Catchment, NSW. Proceeding of the 29th Hydrology and water Resources Symposium, 21-23 February, Canberra.

IWM (2005). Groundwater Management and Zoning Study for repair and rehabilitation of deep tubewell project in greater Dinajpur district under post drought agricultural rehabilitation programme. Draft final report. BWDB. Ministry of Water Resources.

Jenkins, C.T. (1968). Computation of rate and volume of stream depletion by well. in techniques of water-Resources Investigations ot the U S. Geological Survey. Chapter D1. U.S. Government Printing Office. Washington. D.C.

Johnson. G.S., Bishop, C.W., Hubbell. J.M., and Lucas, J.G. (1993). Simulation of the Impacts of Aquifer Water Use on Flow in the Snake River. Idaho Water Resources Research Institute, University of Idaho, 56 p.

Karim. M. (1984). Upazilla-wise Groundwater Recharge Condition of Bangladesh. Groundwater Circle, BWDB, Dhaka

Khan, L.R . and Mawdsley, J.A. (1984). Assessment of aquifer yield using linear programming technique, J. of IEB. 2(3):9-16.

Khan, L.R.. and Mawdsley. J.A. (1986). Groundwater yield assessment of a stream-aquifer system using a lumped model, Proceedings of groundwater workshop, Roorkee. India.

Khan. L.R., (1982). Modeling of Groundwater recharge and yield. Ph.D thesis, University of Newcastle upon Tyne, U.K.

Khan, F.H. (1991). Geology of Bangladesh, New Delhi. Wiley Eastern Limited.

Krabbenhoft. D.P., Bowser, C.J., Kendall. C., and Gat, J R. (1994). Use of oxygen-18 and deuterium to assess the hydrology of groundwater-lake systems, in Env. Chem. of Lakes and Reservoirs. edited by L.A. Baker, Amer. Chem. Soc. Adv. in Chem Ser. No. 237. pp. 67-90.

Larkin, R.G., Sharp. J.M. Jr. (1992). On the relationship between river basin geomorphology. aquifer hydraulics, and groundwater flow direction in alluvial aquifers. Geol Soc Am Bull 104:1608–1620.

Lee, T.M. and Swancar, A. (1994). The influence of evaporation, groundwater, and uncertainty in the hydrologic budget of Lake Lucerne, a seepage lake in Polk County, Florida. U.S. Geol. Surv. Open-File Rept. 93-26.

Lyne, V., and Hollick, M. (1979). Stochastic time-variable rainfall-runoff modelling. Institute of Engineers Australia National Conference. Publ. 79/10, 89-93.

Majumder, M. K. (1998). Ground Water Level in Barind Tract Falls Alarmingly.

McDonald, M.G., and Harbaugh, A.W. (1984). A modular three-dimensional finite-difference groundwater flow model. U.S.G.S. Open File Report 83.

Meigs, L. C. and Bahr, J.M. (1995) Three-dimensional groundwater flow near narrow surface water bodies, water Resources Research, Vol. 31, No. 12, pp 3299-3307

MMI/HTS (1992). Deep Tubewell II Project. Final Report. Vol. 2.1 National Resources. Mott MacDolnald Ltd. And Hunting Technical Services Ltd. Bangladesh Agricultural Development Corporation.

Mosner, Melinda S. (2002). Stream-Aquifer Relations and the Potentiometric Surface of the Upper Floridan Aquifer in the Lower Apalachicola–Chattahoochee–Flint River Basin in parts of Georgia, Florida, and Alabama, 1999 – 2000. U.S. Geological Survey. Water-Resources Investigations Report 02-4244 Prepared in cooperation with the Georgia Department of Natural Resources Environmental Protection Division, Georgia Geologic Survey, Atlanta, Georgia.

MPO (1985). Geology of Bangladesh, Technical Report No. 4.

MPO (1985). The Groundwater Resources and its Availability for Development, Technical Report No. 5.

MPO (1986). National Water Plan: Phase I. Master Plan Organisation, Ministry of Irrigation, Water Development and flood Control, Government of Bangladesh. Harza Eng. Co and Sir M. MacDonald and Partners.

MPO (1987). Planning Area analysis, Technical Report No. 15.

Nathan, R.J., and McMahon, T.A. (1990) Evaluation of automated techniques for base flow and recession analysis. Water Resources Research, AGU, 26(7):1465-1473.

Niestle, A. and Reusing, G. (1990). An approach for drought risk assessment based on hydrologic records of the River Nile in connection with a groundwater flow model, Berliner Geowiss. Abh., Reihe A, 120(2), 1041-1072.

Nish, R.D. Mac., Peters, C.J., Schulte, M.A., Goodrich, D.C., Pool, D.R., Maddock III, T., Unkrich, C.L., Whitaker, M.P.L., and Goff, B.F. (1998). Quantification of Groundwater-Surface Water Interaction in a Southwestern Riparian System. Arizona, USA.

NMIC (2003). National Minor Irrigation Census, Department of Agriculture Extension, Ministry of agriculture. Dhaka.

NWMP (2000). National Water Management Plan Project. Irrigation and Rural FCD. Draft Development Strategy, Annex M Appendix 2. Dhaka

NWMP (2004). National Water Management Plan Project, Irrigation and Rural FCD. Draft Development Strategy. Annex M Appendix 2. Dhaka.

Ojima, M. (2003), Investigation and Analyses on Interaction of Groundwater and River Water in an Alluvial Plain of Eastern Area of Tokushima, Japan.

Pinder, G.F., Bredehoeft, J.D.. and Cooper. H.H. (1969). "Determination of Aquifer Diffusivity from Aquifer Response to Fluctuations in River Stage," Water Resources Research 5(4). pp 850-855.

Martin. H. Otz. Heinz, K. Otz., Ines, Otz., Siegel, Donald I. (2003). Surface water /groundwater interaction in the Piora Aquifer, Switzerland: evidence from dye tracing tests. Hydrogeology Journal (2003) 11:228-239.

Oxtobee. Jaime P.A.. and Novakowski, Kent. (2001). A Numerical Modeling Study of Groundwater /Surface Water Interaction in a Fractured Bedrock Environment. Department of Civil Engineering. Queen's University, Kingston, Ontario, Canada, K7L 3N6.

Pettyjohn. W.A and Hemming, R. (1979). Preliminary estimate of groundwater recharge rates. related stream flow and water quality in Ohio. Ohio State University Water Resources Center Project Completion Report No. 552. 323pp

Priest. sherlyn and Clarke, john S. (2003). Ground-Water Contribution to Streamflow: Stream-Aquifer Relations in The Coastal Area of Georgia and Adjacent Parts of Florida and South Carolina.

Prudic, D.E. (1989). Documentation of a computer program to simulate stream-aquifer relations using a modular. infinite-difference. groundwater flow model, U.S. Geological Survey. Open-File Report. 88-729.

Rahman, M.R., and Chowdhury, J.U. (2003). Interaction between surface water and groundwater. Need for integrated management. In Groundwater Resources and Development in Bangladesh, Edited by A.A. Rahman and P. Ravenscroft, the University Press Limited, Dhaka.

Rahman. A A., and Peter, R. (2003). Groundwater Resources and Development in Bangladesh, The University Press Ltd Dhaka, Bangladesh 2003.

Rao, Z.. and Jamieson, D.G.. (1997). The use of neural networks and genetic algorithms for design of groundwater remediation schemes. Hydrology and Earth System Sciences, 1, pp 345 – 356.

Rao, Z., and O'Connell, P.E. (1999). Integrating ANNs and process-based models for water quality modelling. In Proceedings of the Second Inter-Regional Conference on Environment-Water, Lausanne, Switzerland, 1st – 4th September 1999.

Rastogi, A.K (1991). Computation of average seasonal groundwater flows in phreatic aquifer-river systems, J. Hydrol., 123(3-4), 355-365.

REM (2002). 'Watermark: sustainable groundwater use within irrigated regions. Project 2: Conjunctive resource management, milestone 2 final report. A review of stream-aquifer interaction assessment methods', Resource & Environmental Management, Prepared for the Murray-Darling Basin Commission.

Ravenscroft, P. (2003). Overview of the hydrogeology of Bangladesh, In Groundwater Resources and Development in Bangladesh, Edited by A.A. Rahman and P. Ravenscroft, the University Press Limited, Dhaka.

Rorabaugh, M.I. (1960). Groundwater in northeast Louisville and Kentucky with reference to induced infiltration, U.S. Geol. Surv Water Supply paper 1360-B.

Rorabaugh, M.I. (1964). Estimating changes in bank storage and groundwater contribution to streamflow. Int. Assoc. Sci. Hydrol. Publ. 63, pp. 432-441.

Rushton, K.R., and Tomlinson, L.M. (1979). Possible mechanisms for leakage between aquifers and rivers. Journal of Hydrology, 40:49-65.

Saleh, A.F.M. (1985). Hydrological evaluation of irrigation from groundwater: a case study in Bangladesh, Ph.D Thesis, Dept. of Agricultural Engg., Cornell Univ., Ithaca.

Salehin, M. (2005). Interaction between Surface Water and Groundwater. Institute of Water and Flood Management, Bangladesh University of Engineering and Technology Dhaka, Bangladesh

Scott, R.W., Wehrmann, H.A., and Hollinger, S.E. (2002). Operation of Rain Gauge and Groundwater Monitoring Networks for the Imperial Valley Water Authority Year Nine: September 2000 - August 2001. Illinois State Water Survey Contract Report 2001-15.

Searcy, J.K. (1959). Flow-duration curves, manual of hydrology-part 2, low flow techniques: U.S. Geological Survey Water-Supply Paper 1542-A.

Shams, S. (2002). Prototype GIS and Expert System for Arsenic Evaluation and Mitigation: A Case Study of Chapai Nawabganj District in Bangladesh, TRITA-LWR Master Thesis: 02-36, Royal Institute of Technology, ISSN 1651-064X.

Sloto, R.A . and Crouse, M.Y. (1996). HYSEP: A computer program for stream flow hydrograph separation and analysis. US Geological Survey Water Resources Investigation Report 96-4040 46pp.

Smakhtin, V.Y. (2001). Estimating continuous monthly baseflow time series and their possible applications in the context of the ecological reserve. CSIR: Environmentek, PO Box 395. Pretoria 0001. South Africa.

Smakhtin, V.Y. (2001). Low flow hydrology: a review Journal of Hydrology, 240. 147-186.

Smits, F. J. C., and Hemker. C. J. (2004). Modelling the interaction of surface-water and groundwater flow by linking Duflow to MicroFem. Hydrology and Geo-Environmental sciences, Vrije Universiteit Amsterdam, De Boelelaan 1085, 1081 HV, Amsterdam, The Netherlands.

Sophocleous, M A. (2000). The origin and evolution of safe yield policies in the Kansas Groundwater Management Districts.Nat Resour Res 9(2):99–110.

Sophocleous. M. (2002). Interactions between Groundwater and Surface water: The State of Science. Hydrogeology Journal, 10:52-67

Spalding, C.P. and Khaleel, R. (1991). An evaluation of analytical solutions to estimate drawdowns and stream depletions by wells. Water Resources Research, 27(4). 597-609.

Stauffer, R E. (1985). Use of solute tracers released by weathering to estimate groundwater inflow to lakes. Env. Sci. Techn. 19(5), 405-411

Swain, E.D. and Wexler. E.J. (1996). A Coupled Surface-Water and groundwater Flow Model (MODBRANCH) for Simulation of Stream-Aquifer interaction. Chapter 6: Techniques of Water-Resources Investigations of the United States Geological Sunrey. United States Goverment Printing Office, Washington, pp.125.

SWMC (1996). Further Study on the Hydrological Processes in the Jamuneswari Basin.

SWMC (2000). Surface Water Groundwater Interaction Model study, Technical Report No. 6, National Water Management Plan.

Theis, C.V. (1941). The effect of a well on the flow of a nearby stream, Eos Trans. AGU, 22, 734-738.

Umitsu, M. (1993). Late Quaternary Sedimentary Environments and Landforms in the Ganges Delta. Sedimentary Geology, 83 (1993) 177-186. Elsevier Science Publishers B. Vulnerability. Amsterdam.

UNESCO (1980). Surface Water and Groundwater Interaction: A Contribution to the International Hydrological Programme. Report prepared by the International Commission on Groundwater, Edited by C E Wright, UNESCO.

Wallace, R B., Darama, Y., and Annable, M.D. (1990). Stream depletion by cyclic pumping of wells, Water Resour. Res., 26(6), 1263-1270.

Ward, RC. (1975). Principles of hydrology 2nd edition., McGraw Hill Book Company (UK) Limited.

Winter, T.C., Harvey, J.W., Franke, O.L., Alley, W.M. (1998). Groundwater and Surface water – A Single Resource. U.S. Geological Survey Circular 1139.

Winter, TC. (1995). Recent advances in understanding the interaction of groundwater and surface water. Rev Geophys (Suppl): 985–994.

Winter, TC. (1998). Relation of streams, lakes, and wetlands to groundwater flow systems. Hydrogeology Journals. 7:28–45.

Wondzell. S.M., and Swanson, F.I. (1998). Seasonal and storm dynamics of the hyporheic zone of a 4th order mountain stream, Hydrologic processes, Journal of North American Benthological Society 15(1): 3-19.

Xu. Y., Titus, R., Holness, SD., Zhang, J., and Tonder, G.J. (2002). A hydrogeomorphological approach to quantification of groundwater discharge to streams in South Africa ISSN 0378-4738 = Water SA Vol. 28 No. 4 October 2002. Available on website http://www.wrc.org.za.

Younger, P.L., Mackay, R. and Connorton, B.J. (1993). Streambed sediment as a barrier to groundwater pollution: Insights from fieldwork and modelling in the River Thames basin. Journal of the Institute of Water and Environmental Management 7 pp. 577-585.

Zaman, M. Asad uz., and Rushton, K.R. (1995). Barind: Predicted a Failure, Proved a Success. Chapter 17. In Groundwater Resources and Development in Bangladesh by A Atiq Rahamn & Peter Revenscroft, The University Press Ltd Dhaka. Bangladesh 2003.

BMDA (2005). Data Bank. Edited by M. Asad uz Zaman. Barind tract Multipurpose Development Authority, Rajshahi

Zarriello, P.J. and Ries, K.G. III (2000). A precipitation-runoff model for the analysis of the effects of withdrawals on streamflow. Ipswich River Basin. Mass., U.S. Geological Survey Water-Resources Investigation Report 00-4029, 99 p.

Zarriello. Phillip J., Barlow, Paul M., and Duda, Paul B. (2001). Simulating the Effects of Ground-Water Withdrawals on Streamflow in a Precipitation-Runoff Model. U.S. Geological Survey, Northborough, May and Aqua Terra Consultants, Dacatur, GA.

Zhang, W.Z. (1992). Transient groundwater flow in an aquifer-aquitard system in response to water level changes in rivers or canals, J. Hydrol., 133(3-4), 233-257.

APPENDIX - A

Data Status of the study area

Data Type	Station Name	Source	Data Length	Missing Data	Data used for analysis
Rainfall	Naogaon (191)	BWDD	01/04/1961-01/04/2003	01/04/1964-01/04/1965, 01/04/2002-01/05/2002, 01/09/2002-31/10/2002	1983 - 2003
	Badalgachhi (152)	BWDB	01/09/1961-31/03/2003	01/04/1963-30/04/1963. 01/08/1963-31/08/1963, 01/04/1964-31/03/1965, 21/03/1971-31/07/1971 01/12/1971-31/03/1972, 01/04/2002-30/04/2002, 01/09/2002-31/10/2002	1983 - 2003
	Adamdighi (151)	BWDB	01/04/1962-31/12/1998	01/04/1964-01/03/1965, 01/04/1968-31/03/1969, 01/04/1996-03/05/1997, 01/12/1997-30/09/1998	1983 - 1998
	Dhupchanchia (169)	BWDB	01/04/1983-31/03/2003	01/04/2002-30/04/2002, 01/09/2002-31/10/2002	1983 - 2003
	Atrai (003)	BWDB	01/04/1962-31/03/1998	01/04/2002-30/04/2002, 01/09/2002-31/10/2002	1983 - 1998
Water level	Naogaon (133)	BWDB	01/04/1964-31/03/2003	21/04/1971-11/05/1971, 06/07/1973, 16/09/1977, 01/04/1989-26/05/1989, 06/03/1991-15/05/1991 08/03/1992-13/06/1992, 25/03/1994-17/05/1994, 28/03/1995-05/06/1995	
Discharge	Naogaon (133)	BWDB	01/05/1973-31/12/1993	13/04/1974, 19/04/1974-04/05/1974, 25/02/1975-22/05/1975, 15/02/1976-30/04/1976, 20/11/1976-31/03/1977, 31/07/1977, 19/02/1978-18/05/1978, 16/01/1979-21/06/1979, 16/02/1980-15/05/1980, 16/02/1982-10.06/1982, 04/02/1983-17/05/1983 18/03/1984-15/05/1984, 11/01/1985-24/06/1985, 24/01/1986-20/05/1986, 09/01/1987-23/06/1987 04/02/1988-25.06/1988, 20/01/1989-29/05/1989, 05/01/1990-05/06/1990, 09/01/1991-24/05/1991, 17/01/1992-03/07/1992, 15/01/1993-18/05/1993	
Observed Discharge	Naogaon (133)	BWDB		01/04/1994-30/06/1994, 01/12/1995-31/05/1995, 01/01/1996-31/05/1996, 01/01/1997-30/06/1997, 01/01/1998-30/06/1998, 01/01/1999-30/06/1999, 01/03/2000-30/06/2000, 01/02/2001-31/05/2001, 01/01/2002-30/06/2002, 01/01/2003-30/06/2003	
	GT1006001 (BOG001) Installed Date Dug: 08/02/1973 Piezometer: 01/01/1986	BWDB	12/02/1973 to 12/12/2003	26/02/1973-05/03/1973, 21/01/1974, 25/08/1975-01/09/1975, 12/07/1976, 07/01/1980, 24/03/1980-05/05/1980, 08/02/1982-08/03/1982, 05/04/1982-21/06/1982, 31/01/1983-08/08/1983, 12/03/1984-28/05/1984, 19/11/1984-13/01/1986 16/03/1987-23/03/1987, 25/05/1987 24/10/1988-31/10/1988, 18/12/1989-25/12/1989, 18/06/1990, 25/11/1991-23/12/1991, 25/10/1993-01/11/1993, 24/01/1994, 29/08/1994-12/09/1994, 14/02/2000-21/02/2000, 15/07/2002	

Data Type	Station Name	Source	Data Length	Missing Data	
Groundwater Water	GT1006002 (BOG002) Installed Date Dug: 20/10/1977 Piezometer: 01/05/1984	BWDB	01/01/1979 to 28/03/2005	10/03/1980-12/05/1980, 02/11/1981-16/11/1981, 01/03/1982, 14/06/1982 13/09/1982-18/10/1982, 21/02/1983-20/06/1983, 26/03/1984-07/05/1984, 10/12/1984, 11/02/1985, 07/12/1987, 14/12/1987, 29/02/1988-19/09/1988, 14/11/1988, 19/12/1988, 26/12/1988, 20/11/1989-01/12/1989 25/12/1989, 08/10/1990-26/11/1990, 08/04/1991, 15/04/1991, 31/05/1999, 24/02/2003-31/03/2003, 26/05/2003, 01/08/2003	
	GT1033009 (BOG009) Installed Date Dug: 08/02/1973 Piezometer: 14/01/1986	BWDB	12/02/1973 to 24/11/2003	26/02/1973-05/03/1973, 04/06/1973-11/06/1973, 02/07/1973-17/09/1973, 17/12/1973-31/12/1973, 14/10/1974-20/01/1975, 01/09/1975 03/12/1979, 10/12/1979, 22/12/1980, 29/12/1980, 16/03/1981-30/03/1981, 13/02/1989, 20/02/1989, 25/06/1990, 24/08/1990-15/10/1990, 24/06/1991-06/01/1992, 10/02/1992 07/03/1994, 11/04/1994, 27/06/1994 04/07/1994, 19/09/1994	
	GT6406004 (NAO004) Installed Date Dug: 01/05/1965 Piezometer: 02/03/1992	BWDB	10/05/1965 to 15/12/2003	27/03/1967-02/12/1968, 22/12/1969-29/12/1969, 01/03/1971-18/09/1972, 21/05/1973-01/10/1973, 07/01/1974, 05/01/1976-26/01/1976, 05/04/1976, 26/04/1976, 09/11/1981, 02/04/1984-07/01/1985, 07/08/1989-21/08/1989, 25/12/1989, 08/10/1990, 24/05/1993	
	GT6406005 (NAO005) (NAO025)Installed Date Dug: 01/02/1966 Piezometer: 15/04/1986	BWDB	10/05/1965-28/03/2005	14/03/1966, 6/06/1966, 05/09/1966, 19/09/1966, 05/12/1966, 08/05/1967-05/06/1967, 26/06/1967, 29/12/1969, 19/01/1970-29/01/1970, 22/03/1971-27/11/1972, 26/02/1973, 11/06/1973, 18/06/1973, 20/08/1973-22/10/1973, 18/02/1974-11/03/1974, 06/03/1978, 19/06/1978-26/06/1978, 04/09/1978, 09/11/1981-23/11/1981, 30/07/1984, 16/03/1987-23/03/1987, 01/02/1988-08/02/1988 11/09/1989-18/09/1989, 18/12/1989-25/12/1989, 14/05/1990, 30/07/1990-06/08/1990, 31/12/1990, 28/12/1992, 11/11/1996-18/11/1996, 10/11/2003-17/11/2003	
	GT6406006 (NAO006) Installed Date Dug: 17/03/1980 Piezometer: 01/01/1992	BWDB	17/03/1980-15/06/1998	15/05/1980, 06/04/1981, 31/03/1986, 05/01/1987, 16/11/1987, 18/12/1989, 28/12/1989, 11/02/1991-11/03/1991, 24/06/1991, 19/08/1991, 18/11/1993, 15/03/1993, 22/03/1993, 01/11/1993-15/11/1993, 20/12/1993-10/01/1994, 04/07/1994, 11/07//1994, 24/11/1997-29/12/1997	
	GT6485048 (NAO048) Installed Date Dug: Piezometer: 25/05/1979	BWDB	21/05/1979-12/06/2000	07/12/1981, 19/01/1987, 26/01/1987, 18/09/1989, 18/12/1989, 25/12/1989, 22/07/1991, 14/12/1992, 04/01/1993, 11/01/1993, 07/06/1993, 14/06/1993	

Data Type	Station Name	Source	Data Length	Missing Data
Groundwater Water	GT6460025 (NAO025) Installed Date Dug: 01/05/1965 Piezometer: 05/03/1988	BWDB	10/05/1965-28/03/2005	05/06/1967. 22/12/1969, 29/12/1969. 12/10/1970. 19/10/1970. 29/03/1971-26/07/1971. 30/08/1971-18/09/1972, 18/12/1972, 25/12/1972. 04/06/1973-27/08/1973, 17/09/1973-29/10/1973 21/07/1975. 27/10/1975, 27/06/1977. 25/07/1977, 01/08/1977. 19/12/1977, 26/12/1977. 19/12/1983-26/12/1983, 18/12/1989, 25/12/1989 12/10/1992, 10/10/1994. 17/10/1994. 01/09/1997. 09/12/1990-30/12/1990. 15/09/2003-29/12/2003
	GT6460026 (NAO026) Installed Date Dug: 01/02/1966 Piezometer: 18/04/1986	BWDB	14/02/1966-28/03/2005	19/03/1970, 29/03/1971-05/04/1971. 07/06/1971-20/11/1972, 25/12/1972-01/01/1973. 18/06/1973. 25/06/1973. 13/08/1973-08/10/1973, 10/12/1973-24/12/1973. 11/02/1974, 15/04/1974. 07/10/1974, 25/11/1974, 02/12/1974. 12/12/1977. 05/12/1983, 26/12/1983. 26/11/1984. 03/12/1984, 10/06/1985. 02/12/1985-30/12/1985 03/02/1986, 11/05/1987. 18/05/1987 23/11/1987. 30/11/1987. 21/12/1987 28/12/1987. 20/06/1988, 27/06/1988. 21/11/1988 28/11/1988, 04/12/1989-25/12/1989 20/05/1991. 07/12/1992, 14/12/1992. 26/04/1993-03/05/1993. 13/12/1993-27/12/1993. 07/02/1994. 16/10/1995. 14/01/2002, 21/01/2002 29/12/2003
	GT6460027 (NAO027) Installed Date Dug: 01/02/1966 Piezometer: 23/02/1985	BWDB	14/02/1966-28/03/2005	12/10/1970. 19/10/1970, 15/03/1971-11/01/1972. 03/01/1977. 18/04/1977, 25/04/1977. 19/09/1983. 24/10/1983. 31/10/1983. 16/06/1986. 23/06/1986, 23/05/1988. 25/07/1988. 01/08/1988. 28/11/1988, 05/12/1988, 25/12/1989. 03/01/1991-24/01/1994. 19/12/1994, 23/09/2002, 14/10/2002-28/10/2002, 22/12/2003, 29/12/2003. 19/07/2004. 26/07/2004
	GT6485047 (NAO047) Installed Date Dug: 01/05/1965 Piezometer: 20/11/1984	BWDB	10/05/1965-28/03/2005	19/01/1970, 26/01/1970 16/02/1970, 09/03/1970, 16/03/1970 04/05/1970 15/06/1970 06/07/1970, 14/09/1970. 05/10/1970 12/10/1970 05/04/1971-06/03/1972, 27/03/1972-01/09/1972, 23/10/1972-20/11/1972, 01/01/1973, 29/01/1973-12/02/1973 05/09/1973, 10/09/1973, 10/12/1973-31/12/1973 01/04/1974-27/05/1974, 16/12/1974-30/12/1974, 26/01/1976 23/02/1976, 26/12/1977-16/01/1978, 22/03/1982-31/12/1984, 28/02/1985, 01/05/1989, 13/11/1989, 20/11/1989 25/12/1989, 11/03/1991, 30/09/1991 21/12/1992, 28/12/1992

APPENDIX – B

Location together with specification of observation wells in the study area

Well_ID	New_Id	Thana	Village	Well type	Ins_Date	Lat.	Long.	RL	PH	Depth
GT1006001	BOG001	Adamdighi	Talshoes	Dug	8/2/1973	244925	890245	14.75	0.8	6.59
GT1006001	BOG001	Adamdighi	Talshoes	Piezometer	1/1/1986	244925	890245	14.21	0.38	32.94
GT1006002	BOG002	Adamdighi	Sontehar	Dug	20/10/1977	244900	885940	15.81	0.73	7.35
GT1006002	BOG002	Adamdighi	Sontehar	Piezometer	1/5/1984	244900	885940	15.59	0.45	32.94
GT1006002	BOG002	Adamdighi	Sontehar	Piezometer	24/9/1988	244900	885940	15.65	0.45	27.44
GT1006009	BOG009	Dhupchanchia	Barogram	Dug	8/2/1973	245446	890748	19.16	0.74	6.91
GT1006009	BOG009	Dhupchanchia	Barogram	Piezometer	14/1/1986	245446	890748	19.06	0.74	26.21
GT6406004	NAO004	Badalgachhi	Badalgachhi	Dug	1/5/1965	243736	885450	19.99	0.78	7.85
GT6406004	NAO004	Badalgachhi	Badalgachhi	Piezometer	2/3/1992	243736	885450	19.99	0.37	32.93
GT6406005	NAO005	Badalgachhi	Gopalpur	Dug	1/2/1966	250012	885710	19.3	0.66	5.64
GT6406005	NAO005	Badalgachhi	Gopalpur	Piezometer	15/4/1986	250012	885710	18.98	0.45	32.43
GT6406006	NAO006	Badalgachhi	Jagadishpur	Dug	17/3/1980	250035	890015	21.39	0.99	7.34
GT6406006	NAO006	Badalgachhi	Jagadishpur	Piezometer	1/1/1992	250035	890015	20.89	0.45	23.78
GT6460025	NAO025	Naogaon sadar	Dubulhati	Dug	1/5/1965	244700	885303	17.41	1.2	10.85
GT6460025	NAO025	Naogaon sadar	Dubulhati	Piezometer	5/3/1988	244700	885303	16.72	0.45	32.93
GT6460026	NAO026	Naogaon sadar	Kirtipur	Dug	1/2/1966	250012	885110	17.77	0.81	8
GT6460026	NAO026	Naogaon sadar	Kirtipur	Piezometer	18/4/1986	250012	885110	16.84	0.58	26.99
GT6460027	NAO027	Naogaon sadar	Par naogaon	Dug	1/2/1966	244848	885040	16.35	0.7	8.05
GT6460027	NAO027	Naogaon sadar	Par naogaon	Piezometer	23/2/1985	244848	885040	15.96	0.2	32.94
GT6485047	NAO047	Raninagar	Abedpur	Dug	1/5/1965	244254	890524	15.76	0.74	5.64
GT6485047	NAO047	Raninagar	Abedpur	Piezometer	26/11/1984	244254	890524	15.26	0.45	32.93
GT6485048	NAO048	Raninagar	Raninagar	Piezometer	25/5/1979	244415	885840	14.18	0.45	56.69

Where:

Depth. Depth from Measuring Point to Ground Water Level in Meters; Ins_Date: Date of Installation; Lat.. Latitude in BTM (Bangladesh Transverse Mercado) Coordinate in Meters; Long. . Longitude in BTM (Bangladesh Transverse Mercado) Coordinate in Meters, New_Id: Given By BWDB, Incorporating The Abbreviated New District Name (Where The Well Is Situated) With ID i.e BOG For Bogra, PH: Parapet Height in Meters; RL Reduced Level (RL) of the Measuring Point Well in Meters; Thana: Thana Name; Village: Village Name; Well_ID. Well identification Number (Last three digit is for well number, Middle two is district code and the rest is division code), Well Type: Piezometer well or dug well.

APPENDIX-C

Borelog Data Status in and around the Study Area

Geocode	Borehole_ID	MOUZA	Village	Jl_No	Plot_No	Drill_Purp	Start_Date	End_Date	X_Coord	Y_Coord	Long	Lat
640684000	GL6406005	Paiora		94	419	Irrigation	5/16/1988	5/16/1988	397082.938	762677.688	88.980	24.978
640621000	GL6406006	Poynari	Poynari	549	392	Irrigation	3/17/1988	3/18/1988	385208.500	763265.750	88.862	24.983
640684000	GL6406007	Ujalpur	Ujalpur	141	145	Irrigation	4/17/1992	4/17/1992	398799.063	763531.000	88.997	24.986
640652000	GL6406008	Nunuz	Nunuz	85	596	Irrigation	5/15/1992	5/15/1992	399633.031	767355.063	89.005	25.020
640631000	GL6406009	Dhekra	Dhekra	570	1296	Irrigation	5/1/1988	5/2/1988	392748.063	754448.813	88.938	24.903
640684000	GL6406010	Pirijpur	Pirijpur	46	92	Irrigation	5/10/1992	5/11/1992	397694.063	765853.250	88.986	25.007
640673000	GL6406011	Chakabir	Chakabir	245	149	Irrigation	6/30/1992	6/30/1992	390022.094	767968.313	88.910	25.025
640663000	GL6406012	Purbabangram		149	229	Irrigation	4/24/1992	4/25/1992	398987.688	759777.563	88.999	24.952
646065000	GL6460034	Hasigari	Hasigari	35	771	Irrigation	5/12/1996	5/12/1996	383951.125	737827.625	88.852	24.753
646021000	GL6460035	Marma	Marma	92	256	Irrigation	6/16/1995	6/17/1995	386097.781	755169.625	88.872	24.909
646000000	GL6460036	Chalkproshad	Chalkproshad	178	781	Irrigation	4/2/1997	4/2/1997	392261.188	743958.500	88.934	24.809
646000000	GL6460001		Naogaon T			Test Drilling	4/24/1965	5/2/1965	391195.094	742475.438	88.923	24.795
646000000	GL6460002		Naogaon T			Test Drilling	4/27/1965	5/3/1965	391800.125	742473.375	88.929	24.795
646000000	GL6460003		Naogaon T			Test Drilling	4/15/1965	5/6/1965	392584.375	742483.125	88.937	24.795
646000000	GL6460004		Naogaon T			Test Drilling	4/10/1965	4/14/1965	391219.563	741748.250	88.924	24.789
646000000	GL6460005		Naogaon T			Test Drilling	4/5/1965	4/7/1965	391912.813	741805.563	88.931	24.789
646000000	GL6460006			294	871	Irrigation	12/20/1974	12/20/1974	392552.750	741810.125	88.937	24.789
646000000	GL6460007			286	309	Irrigation	12/19/1974	12/19/1974	395724.281	743585.500	88.968	24.806
646000000	GL6460008			287	225	Irrigation	12/21/1974	12/21/1974	391244.406	740922.875	88.924	24.781
646000000	GL6460009			288	963	Irrigation	12/20/1974	12/21/1974	391882.688	740928.188	88.930	24.781
646000000	GL6460010			290	802	Irrigation	12/8/1974	12/8/1974	392626.031	740934.000	88.938	24.781
646000000	GL6460011			275	648	Irrigation	12/3/1974	12/3/1974	391204.500	739936.875	88.924	24.772
646000000	GL6460012			292	2040	Irrigation	12/14/1974	12/14/1974	391893.906	739943.125	88.931	24.772
646000000	GL6460013			290	154	Irrigation	12/10/1974	12/10/1974	392529.969	740213.438	88.937	24.775
646000000	GL6460014			293	687	Irrigation	12/2/1974	12/2/1974	390737.313	740325.750	88.919	24.776
646094000	GL6460030			280	838	Irrigation	12/3/1974	12/4/1974	398024.719	751186.563	88.990	24.874
646000000	GL6460031			263	460	Irrigation	12/17/1974	12/17/1974	391018.000	745272.375	88.921	24.820
646000000	GL6460032			283	378	Irrigation	12/7/1974	12/7/1974	391717.125	745323.500	88.928	24.821
646029000	GL6460033	Ekarkuri	Ekarkuri	284	702	Irrigation	12/10/1974	12/10/1974	396268.656	744688.813	88.973	24.816
644761000	GL6447001	Lalitpur	Lalitpur	562	474	GW Investig	3/15/1989	3/19/1989	378232.125	746861.750	88.795	24.834

Geocode	Borehole_ID	MOUZA	Village	Jl_No	Plot_No	Drill_Purp	Start_Date	End_Date	X_Coord	Y_Coord	Long	Lat
646000000	GL6460015		Balihari	415		G.Water Sur	1/20/1978	1/28/1978	391760.531	743129.938	88.929	24.801
646051000	GL6460016	Fatehpur		278	113	Irrigation	12/14/1975	12/14/1975	388081.219	743499.125	88.893	24.804
646029000	GL6460017	Khairabad	Khairabad	282	271	Irrigation	12/18/1975	12/20/1975	397589.750	745709.688	88.986	24.825
646043000	GL6460018	Chandipur		292	734	Irrigation	12/18/1975	12/18/1975	393998.344	737974.438	88.951	24.755
646043000	GL6460019	Chak Bolaki		291	317	Irrigation	12/15/1975	12/15/1975	395472.875	737320.750	88.966	24.749
646036000	GL6460020	Sherpur		203	1294	Irrigation	2/1/1975	2/1/1975	392504.563	739573.813	88.937	24.769
646094000	GL6460021	Dakahar	Dakahar	272	348	Irrigation	11/20/1974	11/20/1974	398133.406	751430.688	88.991	24.877
646094000	GL6460022	Mangalpur	Mongolpur	280	25	Irrigation	11/19/1974	11/19/1974	396313.875	747561.000	88.974	24.842
646043000	GL6460023	Simulia	Shimulia	289	3295	Irrigation	12/18/1974	12/18/1974	395692.688	741027.125	88.968	24.782
646029000	GL6460024	Rajkpur		286	396	Irrigation	12/21/1974	12/22/1974	396185.406	743750.000	88.973	24.807
646029000	GL6460025	Boalia		298	1022	Irrigation	12/12/1974	12/12/1974	395259.406	746843.750	88.963	24.835
646094000	GL6460026	Malancha		261	320	Irrigation	7/12/1974	8/12/1974	399592.313	753408.188	89.006	24.895
646094000	GL6460027	Purba Mirzapur		273	346	Irrigation	11/25/1974	11/25/1974	398203.438	749990.000	88.992	24.864
646029000	GL6460028	Khagarkuri		281	302	Irrigation	12/17/1974	12/18/1974	396984.750	746641.063	88.980	24.833
646094000	GL6460029	Nagar Kusumbi		274	412	Irrigation	11/23/1974	11/23/1974	397822.531	750063.063	88.988	24.864
648584000	GL6485001	Lohachura	Lohachura	47	789	Irrigation	3/23/1975	3/23/1975	398275.813	733639.875	88.994	24.716
648584000	GL6485002	Chhaibaria	Chhaibaria	58	399	Irrigation	3/27/1975	3/29/1975	400135.656	734289.000	89.012	24.722
648510000	GL6485003	Bhadalia	Bhadalia	217	442	Irrigation	5/4/1975	5/4/1975	400340.156	730492.188	89.015	24.688
648510000	GL6485004	Umarpur	Omarpur	175	144	Irrigation	7/4/1975	7/4/1975	402025.719	731598.188	89.031	24.698
648542000	GL6485005	Ratoal	Ratoal	221	734	Irrigation	1/4/1975	1/4/1975	404826.188	730333.188	89.059	24.686
648510000	GL6485006	Kundasail	Kundasail	267	35	Irrigation	4/4/1975	4/4/1975	406475.313	729262.813	89.075	24.677
648573000	GL6485007	Arazi Bishnupur	Bishnupur	154	246	Irrigation	2/4/1975	2/4/1975	407811.344	736498.188	89.088	24.742
648552000	GL6485008	Chak Adin	Chak Adin	05	1128	Irrigation	3/20/1975	3/20/1975	393815.656	734813.500	88.950	24.726
648542000	GL6485009	Rakhalgachhi	Rakhalgachhi	167	326	Irrigation	1/16/1975	1/16/1975	403755.344	730840.813	89.048	24.691
648521000	GL6485010	Tekundir	Tekundir	260	176	Irrigation	7/1/1975	8/1/1975	409860.969	727823.563	89.109	24.664
640684000	GL6406001	Mithapur	Mithapur			Irrigation	6/27/1984	6/27/1984	397880.594	764239.313	88.988	24.992
640621000	GL6406002	Charrail	Chakrail			Irrigation	6/26/1984	6/27/1984	386025.063	762262.125	88.871	24.974
640610000	GL6406003	Paricha	Paricha			Irrigation	6/24/1984	6/25/1984	394146.875	760788.000	88.951	24.961
640663000	GL6406004	Kesal	Keshail			Irrigation	6/21/1984	6/22/1984	397109.938	761231.063	88.981	24.965
648584000	GL8134017	Santoshpur	Santoshpur			Irrigation	10/23/1984	10/24/1984	394632.500	734866.250	88.958	24.727

Geocode	Borehole_ID	Village	Site	Depth_m	Dia_cm	Drill_Purp	Source	X_Coord	Y_Coord	Longt	Lat
640684000	GL6406001	Mithapur	Union-Mithapur	61	36	Irrigation	BADC	397880.594	764239.313	88.988	24.992
640621000	GL6406002	Chakrail	Union-Badalgachhi	67	36	Irrigation	BADC	386025.063	762262.125	88.871	24.974
640610000	GL6406003	Paricha	Union-Adhaipur	61	36	Irrigation	BADC	394146.875	760788.000	88.951	24.961
640663000	GL6406004	Keshail	Union-Kola	61	36	Irrigation	BADC	397109.938	761231.063	88.981	24.965
640684000	GL6406005		Union-Mithapur	58	36	Irrigation	BIADP	397082.938	762677.688	88.980	24.978
640621000	GL6406006	Poynari	Union-Badalgachi	64	36	Irrigation	BMDA	385208.500	763265.750	88.862	24.983
640684000	GL6406007	Ujalpur	Union-Mithapur	56	36	Irrigation	BMDA	398799.063	763531.000	88.997	24.986
640652000	GL6406008	Nunuz	Union-Jagodispur	56	36	Irrigation	BMDA	399633.031	767355.063	89.005	25.020
640631000	GL6406009	Dhekra	Union-Balubhara	56	36	Irrigation	BMDA	392748.063	754448.813	88.938	24.903
640684000	GL6406010	Purjpur	Union-Mothurapur	56	36	Irrigation	BMDA	397694.063	765853.250	88.986	25.007
640673000	GL6406011	Chakabir	Union-Bilashbari	55	36	Irrigation	BMDA	390022.094	767968.313	88.910	25.025
640663000	GL6406012		Union-Kola	54	36	Irrigation	BMDA	398987.688	759777.563	88.999	24.952
644761000	GL6447001	Lalitpur	Union-Mainam	92	0	GW Invest	BWDB	378232.125	746861.750	88.795	24.834
646000000	GL6460001	Naogaon Town	Well N0-1	64	10	Test Drilling	DPHE	391195.094	742475.438	88.923	24.795
646000000	GL6460002	Naogaon Town	Well No-4	64	10	Test Drilling	DPHE	391800.125	742473.375	88.929	24.795
646000000	GL6460003	Naogaon Town	Well No-2	64	10	Test Drilling	DPHE	392584.375	742483.125	88.937	24.795
646000000	GL6460004	Naogaon Town	Well No-3	64	10	Test Drilling	DPHE	391219.563	741748.250	88.924	24.789
646000000	GL6460005	Naogaon Town	Well No-4	64	10	Test Drilling	DPHE	391912.813	741805.563	88.931	24.789
646000000	GL6460006			40	36	Irrigation	BADC	392552.750	741810.125	88.937	24.789
646000000	GL6460007			40	36	Irrigation	BADC	395724.281	743585.500	88.968	24.806
646000000	GL6460008			47	36	Irrigation	BADC	391244.406	740922.875	88.924	24.781
646000000	GL6460009			41	36	Irrigation	BADC	391882.688	740928.188	88.930	24.781
646000000	GL6460010			43	36	Irrigation	BADC	392626.031	740934.000	88.938	24.781
646000000	GL6460011			41	36	Irrigation	BADC	391204.500	739936.875	88.924	24.772
646000000	GL6460012			41	36	Irrigation	BADC	391893.906	739943.125	88.931	24.772
646000000	GL6460013			47	36	Irrigation	BADC	392529.969	740213.438	88.937	24.775
646000000	GL6460014			52	36	Irrigation	BADC	390737.313	740325.750	88.919	24.776
646000000	GL6460015	Balihari	Balihari	107	15	GW Surv	BWDB	391760.531	743129.938	88.929	24.801
646051000	GL6460016		Union- Tilakpur	57	36	Irrigation	BADC	388081.219	743499.125	88.893	24.804
646029000	GL6460017	Khairabad	Union-Boalia	56	36	Irrigation	BADC	397589.750	745709.688	88.986	24.825

Geocode	Borehole_ID	Village	Site	Depth_M	Dia_cm	Drill_Purp	Source	X_Coord	Y_Coord	Longt	Lat
646043000	GL6460018		Union- Chandipur	41	36	Irrigation	BADC	393998.344	737974.438	88.951	24.755
646043000	GL6460019		Union- Chandipur	41	36	Irrigation	BADC	395472.875	737320.750	88.966	24.749
646036000	GL6460020		Union- Kirtipur	58	36	Irrigation	BADC	392504.563	739573.813	88.937	24.769
646094000	GL6460021	Dakahar	Union-Tilakpur	46	36	Irrigation	BADC	398133.406	751430.688	88.991	24.877
646094000	GL6460022	Mongolpur	Union-Tilakpur	49	36	Irrigation	BADC	396313.875	747561.000	88.974	24.842
646043000	GL6460023	Shimulia	Union-Chandipur	52	36	Irrigation	BADC	395692.688	741027.125	88.968	24.782
646029000	GL6460024		Paurashava	53	36	Irrigation	BADC	396185.406	743750.000	88.973	24.807
646029000	GL6460025		Union- Boalia	38	36	Irrigation	BADC	395259.406	746843.750	88.963	24.835
646094000	GL6460026		Union- Tilakpur	58	36	Irrigation	BADC	399592.313	753408.188	89.006	24.895
646094000	GL6460027		Union- Tilakpur	49	36	Irrigation	BADC	398203.438	749990.000	88.992	24.864
646029000	GL6460028		Union- Boalia	41	36	Irrigation	BADC	396984.750	746641.063	88.980	24.833
646094000	GL6460029		Union- Tilakpur	41	36	Irrigation	BADC	397822.531	750063.063	88.988	24.864
646094000	GL6460030			45	36	Irrigation	BADC	398024.719	751186.563	88.990	24.874
646000000	GL6460031			53	36	Irrigation	BADC	391018.000	745272.375	88.921	24.820
646000000	GL6460032			46	36	Irrigation	BADC	391717.125	745323.500	88.928	24.821
646029000	GL6460033	Ekarkuri	Union-Boalia	50	36	Irrigation	BADC	396268.656	744688.813	88.973	24.816
646065000	GL6460034	Hasigari	Union-Hasigari	58	36	Irrigation	BMDA	383951.125	737827.625	88.852	24.753
646021000	GL6460035	Mayma	Union-Barshail	61	36	Irrigation	BMDA	386097.781	755169.625	88.872	24.909
646000000	GL6460036	Chalkproshad	Union-Paurashava	61	36	Irrigation	BMDA	392261.188	743958.500	88.934	24.809
648584000	GL6485001	Lohachura	Union-Raninagar	44	36	Irrigation	BADC	398275.813	733639.875	88.994	24.716
648584000	GL6485002	Chhaibaria	Union-Raninagar	52	36	Irrigation	BADC	400135.656	734289.000	89.012	24.722
648510000	GL6485003	Bhadalia	Union-Bargachha	61	36	Irrigation	BADC	400340.156	730492.188	89.015	24.688
648510000	GL6485004	Omarpur	Union-Bargachha	59	36	Irrigation	BADC	402025.719	731598.188	89.031	24.698
648542000	GL6485005	Ratnal	Union-Kaligraml	55	36	Irrigation	BADC	404826.188	730333.188	89.059	24.686
648510000	GL6485006	Kundasail	Union-Bargachha	59	36	Irrigation	BADC	406475.313	729262.813	89.075	24.677
648573000	GL6485007	Bishnupur	Union-Parail	58	36	Irrigation	BADC	407811.344	736498.188	89.088	24.742
648552000	GL6485008	Chak Adin	Union-Kashimpur	52	36	Irrigation	BADC	393815.656	734813.500	88.950	24.726
648542000	GL6485009	Rakhalgachhi	Union-Kaligram	54	36	Irrigation	BADC	403755.344	730840.813	89.048	24.691
648521000	GL6485010	Tekundir	Union-Ekdala	41	36	Irrigation	BADC	409860.969	727823.563	89.109	24.664
648584000	GL8134017	Santoshpur	Union-Godagari	55	36	Irrigation	BADC	394632.500	734866.250	88.958	24.727

APPENDIX- D

Thanawise Irrigation data

Thana: Raninagar

Year	No. of STW	No. of DTW	Irrigation water, Mm^3/Year
1990	2084	73	115.453
1991	2386	83	132.153
1992	2651	113	147.943
1993	2824	138	158.540
1994	2933	143	164.642
1995	3203	157	179.843
1996	4594	191	256.116
1997	4546	162	251.995
1998	4622	176	256.812
1999	5034	191	279.667
2000	4717	188	262.539
2001	5255	194	291.657
2002	5382	192	298.347
2003	5425	185	300.274
2004	5201	185	288.285

Thana: Akkelpur

Year	No. of STW	No. of DTW	Irrigation water, Mm^3/Year
1991	317	19	17.984
1992	362	22	20.554
1993	431	29	24.621
1994	513	43	29.760
1995	652	62	38.217
1996	869	95	51.598
1997	2262	94	126.104
1998	2467	97	137.238
1999	2614	99	145.213
2000	2444	120	137.238
2001	2186	110	122.893
2002	2167	113	122.037
2003	2143	116	120.913
2004	1817	138	104.641

Thana: Badalgachhi

Year	No. of STW	No. of DTW	Irrigation water, Mm^3/Year
1991	1452	34	79.538
1992	1757	47	96.559
1993	2367	67	130.279
1994	2789	92	154.205
1995	3062	42	166.141
1996	3036	201	173.260
1997	3341	190	188.996
1998	3322	186	187.765
1999	3697	204	208.800
2000	3785	184	212.440
2001	4696	189	261.469
2002	4701	188	261.683
2003	4709	187	262.057
2004	4649	211	260.131

Thana: Naogaon Sadar

Year	No. of STW	No. of DTW	Irrigation water, Mm^3/Year
1990	987	93	57.807
1991	1652	103	93.936
1992	1908	117	108.388
1993	1967	135	112.509
1994	2209	147	126.104
1995	2596	163	147.675
1996	3191	207	181.877
1997	3441	237	196.864
1998	2946	241	170.584
1999	3242	247	186.748
2000	3086	258	178.987
2001	2805	271	164.642
2002	3109	270	180.860
2003	3012	272	175.775
2004	2945	263	171.708

Thana: Adamdighi

Year	No. of STW	No. of DTW	Irrigation water, Mm^3/Year
1979	141	65	21.463
1980	179	65	23.497
1981	242	68	27.512
1982	384	75	36.611
1983	568	81	47 744
1984	840	97	65 728
1985	929	102	71.563
1986	1206	103	86.603
1987	1369	106	95.970
1988	1509	96	101.322
1989	1833	106	120 805
1990	1816	106	119.896
1991	1796	107	119.039
1992	1845	108	121.876
1993	1896	125	128.245
1994	1741	140	123.161
1995	1926	153	135.846
1996	1931	161	137.826
1997	2054	161	144.410
1998	1876	161	134.882
1999	2012	147	139.164
2000	2111	169	149.174
2001	1724	164	127.389
2002	1457	173	115.025
2003	1385	187	114.168
2004	1329	198	113.526

Thana : Dhupahanchia

Year	No. of STW	No. of DTW	Irrigation water, Mm^3/Year
1979	112	55	8.939
1980	132	54	9.956
1981	154	51	10.973
1982	287	58	18.466
1983	394	59	24.247
1984	436	61	26.602
1985	594	63	35.166
1986	631	99	39.073
1987	855	150	53.792
1988	923	147	57.272
1989	1179	150	71.134
1990	1293	151	77.290
1991	1445	157	85.747
1992	1274	177	77.664
1993	1071	200	68.030
1994	1034	215	66.852
1995	1034	227	67.495
1996	1118	240	72.687
1997	1185	245	76.540
1998	1116	249	73.061
1999	1309	234	82.589
2000	1343	244	84.944
2001	1202	221	76.166
2002	1163	223	74.185
2003	1013	229	66.478
2004	945	235	63.159

Sources : DAE, BADC, NMIC, WARPO

N.B : No of STW = (No of STW+No of DSSTW+No of VDSSTW)

Pumping Hour:

10 hr/day
105 day/ season or 105 day/ year

Pumping Rate : Pumping rate 2 cusec for DTW
Pumping rate 0.5 cusec for STW

APPENDIX -E

QUESTIONNAIRE SURVEY FOR LOCAL RESPONDENTS

(Naogaon sadar, Badalgachi, Raninagar and Adamdighi)

Title of the Thesis Work: River-Aquifer Interaction in Little Jamuna Catchment in the Northwest of Bangladesh

Serial No. . . . . . .

Date: . . . . /. . ./200 ...

1. Location:

Village: . . . .

Union: . . . .

Upazila: . . . .

District . . . .

2. Distance from the river: . . . . .

3. Identification of the respondent:

Name of the respondent . . . .

Father's name . . . .

Age: . . . .

4. Education:

- Don't know how to read and write
- Passed ------ class
- Passed S.S.C./H.S.C /Bachelor degree/Master degree/More
- Madrasha

5. Occupation:

☐ Agriculture, ☐ Service, ☐ General Labour, ☐ Business/Trader,

☐ Artesian, ☐ Transport operator, ☐ Unemployed, ☐ Old/Handicapped,

☐ Other ....

6. Period of living in the village/locality:

☐ Less than10 years,☐ 10 to 15 years, ☐15 to 20 years, ☐ 20 to 25 years,

☐ More than 25 years

7. Source of drinking water:

☐ Hand tube well, ☐ Well, ☐ Pond ☐ River, ☐ Rainwater harvesting

If hand tube well is used: ☐ With arsenic, ☐ Arsenic free, ☐ Don't know

8. Do you think that river is drying up? ☐ Yes, ☐ No, ☐ Don't know

9. Does the river dry up completely? ☐ Yes, ☐ No, ☐ Don't know

If yes, since when it has been the case?

10. How many years ago do you think there was enough water flow in this river?

☐ 5 years, ☐ 10 years, ☐ 15 years, ☐ 20 years, ☐ 25 years, ☐ 30 years

☐ More than 30 years

11. Since which year this river is being dried up?

☐ 2000, ☐ 1995 to 2000, ☐ 1990 to 1995, ☐ 1985 to 1990, ☐ 1980 to 1985,

☐ 1975 to 1980, ☐ 1970 to 1975, ☐ <1970

12. Is the problem of river drying up getting worse?: ☐ Yes, ☐ No, ☐ Don't know

13 Rate of drying up of river:

	High	Medium	Low	Don't know
1975				
1985				
1995				
2005				

14. Duration over which river remains dry:

Year				
Month				
Duration				

15. When is the river at the lowest level or dries up?

☐ December, ☐ January, ☐ February, ☐ March, ☐ April

16. Causes of decrease of the river flow or water level/Causes of drying up of the river:

☐ Lowering of groundwater level, ☐ Insufficient of rainfall,

☐ Upstream embankment, ☐ Upstream withdrawl of water, ☐ Rise of river bed,

☐ Don't Know ☐ Others ....

17. What are the other water bodies drying up?,

☐ Ponds ☐ Khal, Bils are dried up ☐ Don't know

18. Is dryiung up of other water bodies related to the river being dried up?

☐ Yes ☐ No ☐ Don't know

19. What kind of irrigation system you are practicing?

☐ Groundwater, ☐ Surface water, ☐ Rainwater, ☐ No Irrigation

20. Is your dug well water level getting lowered? If yes, since when?

21. How many shallow tube wells did you have in the past and you have at present in your locality?

22. How many deep tube wells did you have in the past and you have at present in your locality?

23. Do your shallow tube wells dry up? ☐ Yes, ☐ No, ☐ Don't know

If yes, since when?

24. Do you think that ☐ Hand Tubewell can not extract enough water in dry season?

☐ Depth of Hand Tubewell . . . . .

☐ Shallow Tubewell can not extract enough water in dry season

☐ Depth of Shallow Tubewell . . . . .

☐ Deep Tubewell can not extract enough water in dry season

☐ Depth of Deep Tubewell . . . . .

25. The number of Shallow Tube well (STW): ☐ Increasing, ☐ Decreasing

26. The number of Deep Set Tube well (DSTW): ☐ Increasing, ☐ Decreasing

27. Do you think, the demand of irrigated water will gradually increase?

☐ Yes, ☐ No, ☐ Don't know

28. Do you think that due to river flow or water level reduction, navigation is hampering?

☐ Yes, ☐ No, ☐ Don't know

29. Condition of irrigation development (Area of Irrigation) in this area in the recent:

☐ Increasing, ☐ Decreasing

30 Condition of crop yield in this area in the recent: ☐ Increasing, ☐ Decreasing

If decreasing, why?

31. What can be the mitigation measure for dry up of river, do you think?

☐ Dredging / Excavation of river bed, ☐ Prohibit upstream embankment,

☐ Construction of rubber dam, ☐ No mitigation measure, ☐ Don't know

32. Availability of birds at present: ☐ Increasing, ☐ Decreasing

33. The source of fish: Before: ☐ River, ☐ Pond, ☐ Haor-baor, ☐ Khal-Bill, ☐ Bazar/Market

At present: ☐ River, ☐ Pond, ☐ Haor-baor, ☐ Khal-Bill, ☐ Bazar/Market

34. Availability of fish at present: ☐ Increasing, ☐ Decreasing

35. Any change in fish diversity: ☐ Increasing, ☐ Decreasing

APPENDIX - F

PURPOSIVE INTERVIEWS FOR LOCAL RESPONDENTS ALONG 18 KM REACH OF LITTLE JAMUNA

Title of the Thesis Work: River-Aquifer Interaction in Little Jamuna Catchment in the Northwest of Bangladesh

ক্রমিক নং ঃ - তারিখ ঃ - / /২০০ ইং

১. উত্তরদাতার নাম ঃ

উত্তরদাতার পিতার নাম ঃ

উত্তরদাতার বয়স (৫০ বছরের বেশী হতে হবে) ঃ

২. উত্তরদাতার ঠিকানা ঃ গ্রাম ঃ ইউনিয়ন ঃ

উপজেলা/থানা ঃ জেলা ঃ

৩. নওগাঁ শহরের ব্রিজ থেকে উক্ত গ্রামের দূরত্ব ঃ . . . . . কি.মি./ . . . . মাইল।

৪. উত্তরদাতার লেখাপড়া ঃ টিক (√) দাও।

☐ কোন লেখাপড়া জানে না, ☐ ক্লাশ . . . . পর্যন্ত জানে ; ☐ এস.এস.সি

☐ এইচ.এস.সি ☐ ডিগ্রী ☐ অনার্স ☐ মাস্টার্স পাশ ☐ মাদ্রাসা . . . . .

৫. উত্তরদাতার পেশা ঃ টিক (√) দাও।

☐ কৃষি কাজ ☐ সাধারণ শ্রমিক ☐ চাকরিজীবি ☐ . . . . . . ব্যবসায়ী ☐ মিস্ত্রী

☐ বেকার ☐ চালক (ভ্যান/রিক্সা/মোটর) ☐ বৃদ্ধ/ অকর্মন্য ☐ অন্যান্য . . . . . .

৬. কত বছর যাবত এই গ্রাম / এলাকায় বাস করছে ?

☐ ১০ বছরের কম ☐ ১০ থেকে ১৫ বছর ☐ ১৫ থেকে ২০ বছর ☐ ২০ থেকে ২৫ বছর

☐ ২৫ বছরের বেশি

৭. খাবার পানির উৎস ঃ ☐ নলকূপ (Hand Tubewell) ☐ অগভীর নলকূপ (Shallow Tubewell)

☐ গভীর নলকূপ (Dip Tubewell) ☐ কূপ/ কুয়া ☐ পুকুর

☐ নদী ☐ বৃষ্টির পানি

যদি খাবার পানির উৎস হিসাবে নলকূপের পানি (Hand Tubewell) ব্যবহৃত হয় তবে ঃ

☐ পানিতে আর্সেনিক আছে ☐ পানিতে আর্সেনিক নেই ☐ জানি না

৮. নদীর তলদেশ সম্পূর্ণ শুকিয়ে যায় কি ? ☐ হ্যাঁ ☐ না ☐ জানি না

(ক) যদি হ্যাঁ হয়, তবে সাধারণত কোন্ মাস থেকে কোন্ মাস পর্যন্ত সম্পূর্ণ শুকিয়ে যায় ?

. . . . . . মাস থেকে . . . . . . মাস পর্যন্ত।

(খ) যদি না হয়, তবে সাধারণত কোন্ মাস থেকে কোন্ মাস আংশিক শুকিয়ে যায় ?

. . . . . . মাস থেকে . . . . . . মাস পর্যন্ত।

৯. সাধারণত কোন্ মাস থেকে নদীর স্রোত বন্ধ হয়ে যায় ?

. . . . . . মাস থেকে . . . . . মাস পর্যন্ত।

১০. সাধারণত কোন্ মাস থেকে নদীর স্রোত শুরু হয় ?

. . . . . . মাস থেকে . . . . . . মাস পর্যন্ত।

১১. কত সাল থেকে নদীর তলদেশ সম্পূর্ণ শুকিয়ে যায় ?

☐ ২০০০ ☐ ১৯৯৫ - ২০০০ ☐ ১৯৯০ - ১৯৯৫ ☐ ১৯৮৫ - ১৯৯০

☐ ১৯৮০ - ১৯৮৫ ☐ ১৯৭৫ - ১৯৮০ ☐ ১৯৭০ - ১৯৭৫

☐ ১৯৭০ সালের আগের থেকে।

১২. কত সাল থেকে নদীর তলদেশ আংশিক শুকিয়ে যায় ?

☐ ২০০০ ☐ ১৯৯৫ - ২০০০ ☐ ১৯৯০ - ১৯৯৫ ☐ ১৯৮৫ - ১৯৯০

☐ ১৯৮০ - ১৯৮৫ ☐ ১৯৭৫ - ১৯৮০ ☐ ১৯৭০ - ১৯৭৫

☐ ১৯৭০ সালের আগের থেকে।

১৩. কত সাল থেকে নদীর স্রোত বন্ধ হওয়া শুরু হয় ?

☐ ২০০০ ☐ ১৯৯৫ - ২০০০ ☐ ১৯৯০ - ১৯৯৫ ☐ ১৯৮৫ - ১৯৯০

☐ ১৯৮০ - ১৯৮৫ ☐ ১৯৭৫ - ১৯৮০ ☐ ১৯৭০ - ১৯৭৫

☐ ১৯৭০ সালের আগের থেকে।

১৪. কত বছর আগে নদীতে যথেষ্ট পরিমাণ পানি ছিল বলে আপনি মনে করেন ?

☐ ৫ বছর ☐ ১০ বছর ☐ ১৫ বছর ☐ ২০ বছর

☐ ২৫ বছর ☐ ৩০ বছর ☐ ৩০ বছরের বেশি

১৫. কত বছর আগে নদীতে স্রোত পানি ছিল বলে আপনি মনে করেন ?

☐ ৫ বছর ☐ ১০ বছর ☐ ১৫ বছর ☐ ২০ বছর

☐ ২৫ বছর ☐ ৩০ বছর ☐ ৩০ বছরের বেশি

১৬. নদী শুকানো সমস্যা ক্রমাগত খারাপ হচ্ছে কিনা ? ☐ হ্যাঁ ☐ না ☐ জানি না।

১৭. নদীতে পানির স্রোত না থাকা / নদী শুকিয়ে যাওয়ার কারণ কি বলে আপনি মনে করেন ?

☐ বৃষ্টির পরিমাণ কম হওয়া ☐ নদীর উপরিভাগে বাঁধ দেওয়া ☐ নদী থেকে পানি সেচ কাজে ব্যবহার করা ☐ নদীর উপরিভাগ থেকে পানি সেচ কাজে ব্যবহার করা

☐ নদীর তলদেশ ভরাট হয়ে যাওয়া ☐ ভূগর্ভস্থ পানির লেভেল নিচে নেমে যাওয়া ☐ জানি না

☐ অন্য কোন কারণ . . . .

১৮. অন্য শুকানো জলাশয় কি কি ? ☐ পুকুর ☐ খাল ☐ বিল ☐ জানি না

১৯. নদীর পানি শুকানোর সাথে সাথে পুকুর এবং বিলের পানি শুকায়ে যায় কিনা ?

☐ হ্যাঁ ☐ না ☐ জানি না

২০. বোরো ধান চাষে (জানুয়ারী থেকে মে মাস) জমিতে সেচের কাজে কোন্ পানি ব্যবহার করে থাকেন ?

☐ শুধু নদীর পানি ☐ শুধু ভূগর্ভস্থ পানি ☐ প্রথমে নদীর পানি পরে ভূগর্ভস্থ পানি

☐ শুধু বৃষ্টির পানি ☐ জমিতে সেচ দেওয়ার দরকার হয় না

২১. নলকূপ / টিউব ওয়েল পানি পায় না বা পানির লেভেল নিচে নেমে যায় কি ?

☐ হ্যাঁ ☐ না ☐ জানি না

যদি পানির লেভেল নিচে নেমে যায় বা পানি না পায়, তবে তবে সাধারণত কোন্ মাস থেকে কোন্ মাস ? . . . . . . মাস থেকে . . . . . . মাস পর্যন্ত।

২২. অগভীর নলকূপ / স্যালো টিউব ওয়েল ভূতলে স্থাপন করলে সব সময় পানি পায় কিনা ?

☐ হ্যাঁ ☐ না ☐ জানি না

(ক) অগভীর নলকূপ / স্যালো টিউব ওয়েল ভূমিতলে স্থাপন করলে সব সময় পানি পায় না, সাধারণত কোন্ মাস থেকে কোন্ মাস ?

. . . . . . মাস থেকে . . . . . . মাস পর্যন্ত।

(খ) অগভীর নলকূপ / স্যালো টিউব ওয়েল ভূ-অভ্যন্তরে বা মাটির নিচে বা সাধারণ ভূমিতল থেকে কত নিচে স্থাপন করলে সব সময় পানি পাওয়া যায় ? সাধারণত . . . ফুট।

২৩. (ক) নলকূপ / হ্যান্ড টিউব ওয়েলের পাইপ মাটির কত ফুট গভীরে দেওয়া আছে ?

সাধারণত . . . . . . ফুট।

(খ) অগভীর নলকূপ / স্যালো টিউব ওয়েলের পাইপ মাটির কত ফুট গভীরে দেওয়া আছে ?

সাধারণত . . . . . . ফুট।

(গ) গভীর নলকূপ / ডীপ টিউব ওয়েলের পাইপ মাটির কত ফুট গভীরে দেওয়া আছে ?

সাধারণত . . . . . . ফুট।

২৪. (ক) অগভীর নলকূপ / স্যালো টিউব ওয়েলের সংখ্যা ঃ ☐ কমে যাচ্ছে ☐ বৃদ্ধি পাচ্ছে।

যদি অগভীর নলকূপ / স্যালো টিউব ওয়েলের সংখ্যা কমে যায়, তবে কারণ কি হতে পারে ?

কারণ ঃ

(খ) গভীর নলকূপ / ডীপ টিউব ওয়েলের সংখ্যা ঃ ☐ কমে যাচ্ছে ☐ বৃদ্ধি পাচ্ছে।

যদি গভীর নলকূপ / ডীপ টিউব ওয়েলের সংখ্যা বেড়ে যায়, তবে কারণ কি হতে পারে ?

কারণ ঃ

২৫. প্রতি বছর সেচের জমিতে পানির চাহিদা ক্রমাগত বেড়ে যাচ্ছে কিনা ?

☐ হ্যাঁ ☐ না ☐ জানি না

২৬. সেচের আওতায় বর্তমানে চাষের জমি আগের থেকে ☐ বেড়েছে ☐ কমেছে।

২৭. সেচের আওতায় বর্তমানে চাষের জমিতে ধানের ফলন আগের থেকে

☐ বেড়েছে ☐ কমেছে।

যদি ধানের ফলন আগের থেকে কমে থাকে, তবে কারণ কি ?

কারণ ঃ

২৮. নদীর পানি যাতে না শুকায় সেজন্য কি ব্যবস্থা গ্রহন করা যেতে পারে বলে আপনি মনে করেন ?

☐ নদীর তলদেশ খনন করা ☐ নদীর উপরিভাগে বাঁধ না দেওয়া

☐ নদীতে রাবার ড্যাম নির্মান করা ☐ নদীর নিচের ভাগে বাঁধ নির্মান করা

☐ নদীর পানি সেচ কাজে ব্যবহার না করা ☐ নদীর পানি শুকানোর প্রতিরোধে কোনো ব্যবস্থা গ্রহন না করা ☐ নদীর পানি শুকানোর প্রতিরোধের কোনো ব্যবস্থা নেই ☐ জানি না

☐ অন্য কোনো উপায় (যদি থাকে) . . . . .

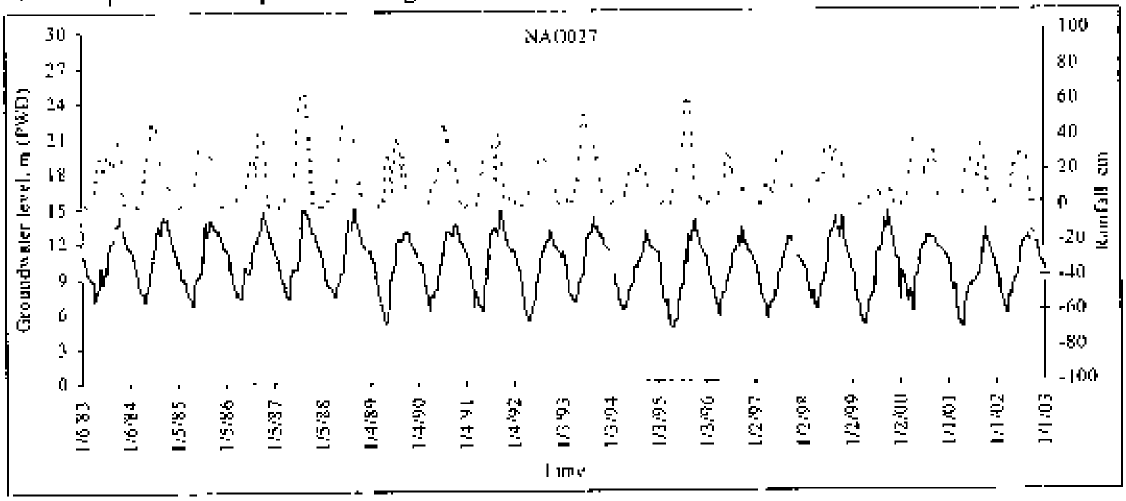
APPENDIX-G

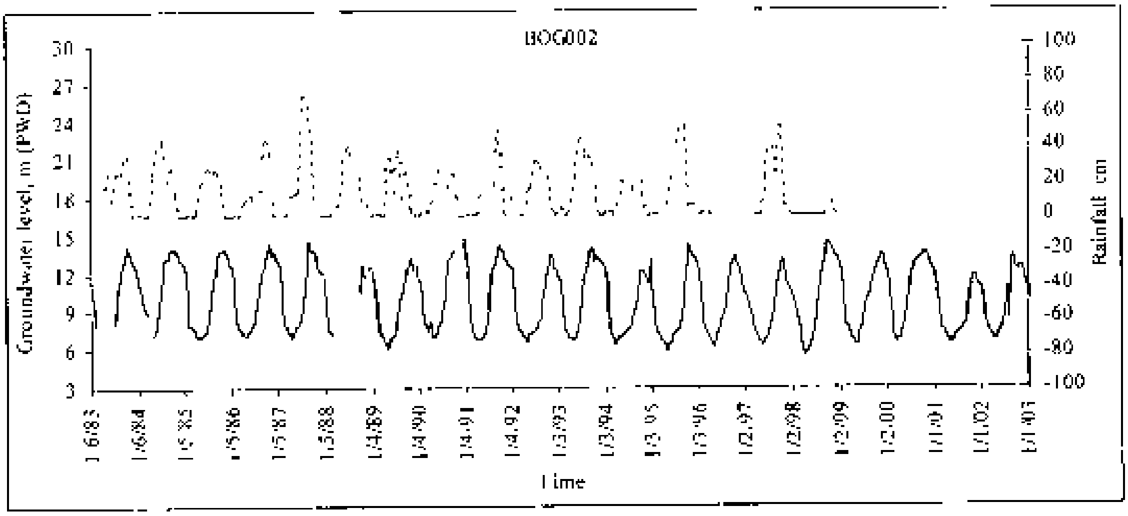
Lithological layer formation (Major eight layers) using borelog data information

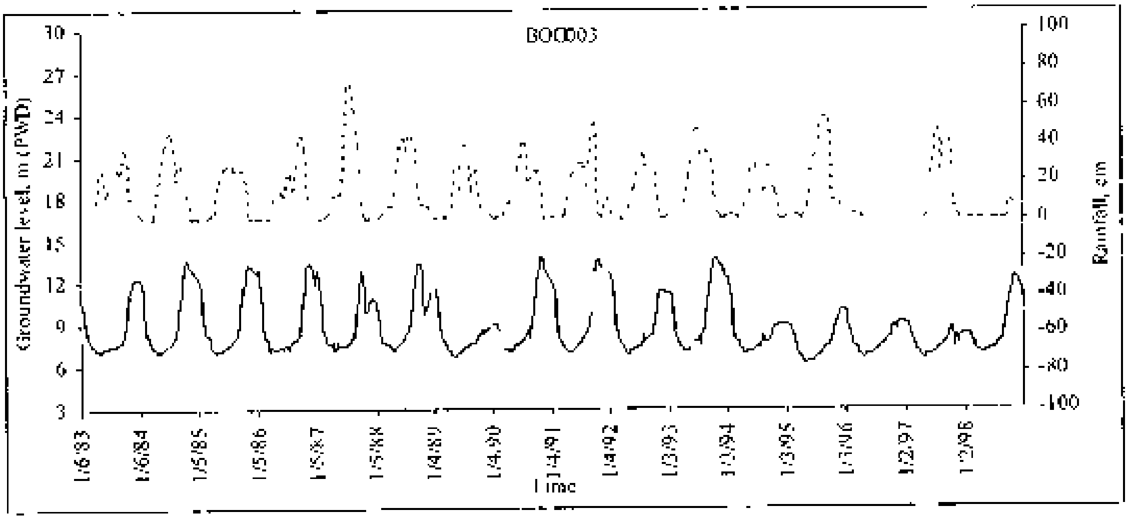
	Major Layer	Lithological status
1	Pure Sand	i) Only Sand
2	Graveliferous Sand	i) Sand+Gravel
		ii) Sand+Mica
		iv)Sand+Mica+Gravel
		v) Sand+Plastic Gravel
3	Silty Sand	i) Silt+Sand
		ii)Silt+Mica
		iii) Silt+Gravel
		iv) Silt+Sand+Mica
		v)Silt+Sand+Mica+Gravel
		vi)Silt+Sand+Gravel
		vii)Silt+Mica+Gravel
4	Pure Silt	i) Only Silt
5	Sandy Clay	i) Clay+Sand
		ii) Clay+Sand+Gravel
		iii)Clay+Sand+Mica
6	Sand Clay Silt Mixed	i) Sand+Silt+Clay
7	Silty Clay	i) Clay+Silt;
		ii) Clay+Silt+Concret
		iii) Clay+Silt+Gravel
8	Pure Clay	i) Clay
		ii) Plastic Clay

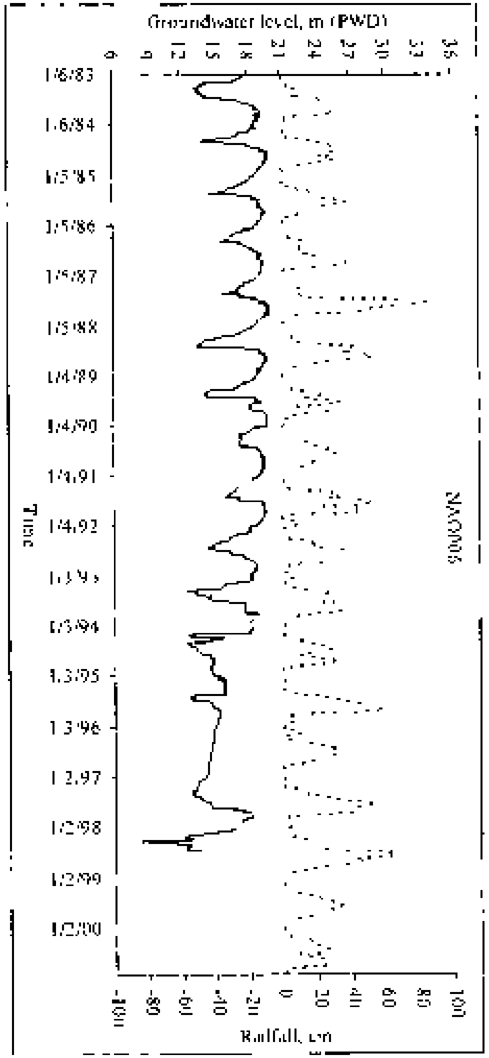
APPENDIX – H

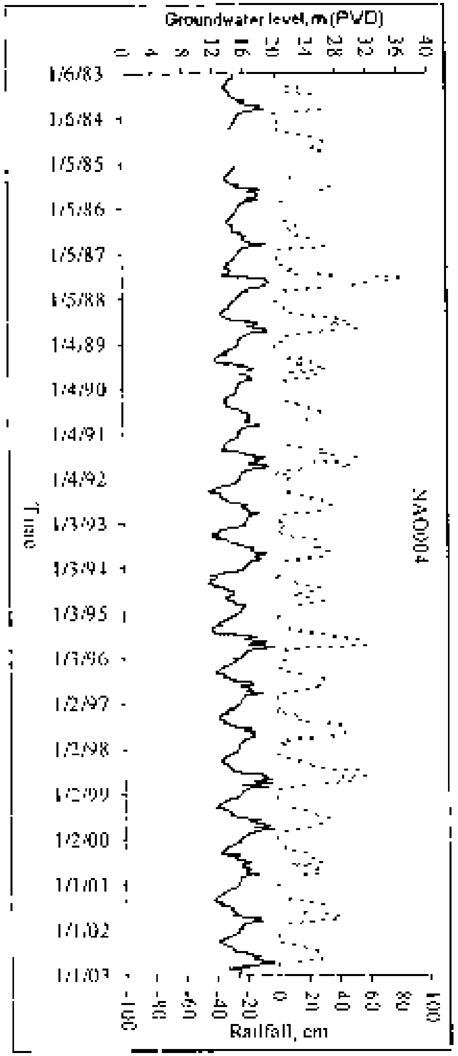
Rainfall pattern compared with groundwater level in the study area

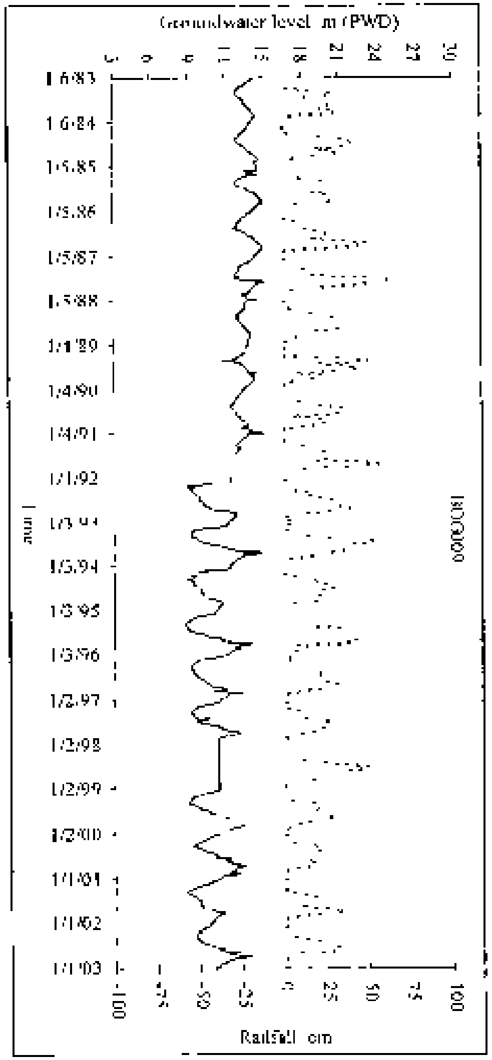







Groundwater level, m (PWD)
6 9 12 15 18 21 24 27 30 33 36
Time
1/6/83
1/6/84
1/5/85
1/5/86
1/5/87
1/5/88
1/4/89
1/4/90
1/4/91
1/4/92
1/3/93
1/3/94
1/3/95
1/3/96
1/2/97
1/2/98
1/2/99
1/2/00
-100 -80 -60 -40 -20 0 20 40 60 80 100
Rainfall, cm
NAO005

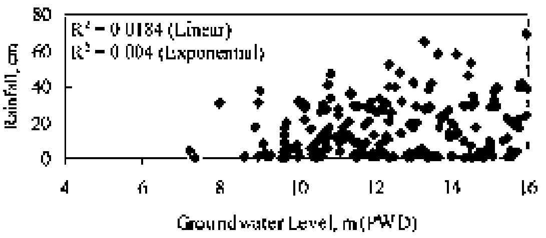

Groundwater level, m(PWD)
0 4 8 12 16 20 24 28 32 36 40
Time
1/6/83
1/6/84
1/5/85
1/5/86
1/5/87
1/5/88
1/4/89
1/4/90
1/4/91
1/4/92
1/3/93
1/3/94
1/3/95
1/3/96
1/2/97
1/2/98
1/2/99
1/2/00
1/1/01
1/1/02
1/1/03
-100 -80 -60 -40 -20 0 20 40 60 80 100
Rainfall, cm
NAO004


Groundwater level, m (PWD)
3 6 9 12 15 18 21 24 27 30
Time
1/6/83
1/6/84
1/5/85
1/5/86
1/5/87
1/5/88
1/4/89
1/4/90
1/4/91
1/1/92
1/1/93
1/3/94
1/3/95
1/3/96
1/2/97
1/2/98
1/2/99
1/2/00
1/1/01
1/1/02
1/1/03
-100 -75 -50 -25 0 25 50 75 100
Rainfall, cm

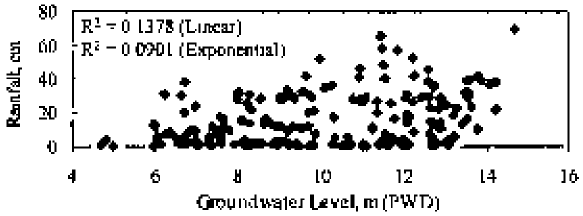
APPENDIX – 1

Rainfall and Groundwater correlation in the study area

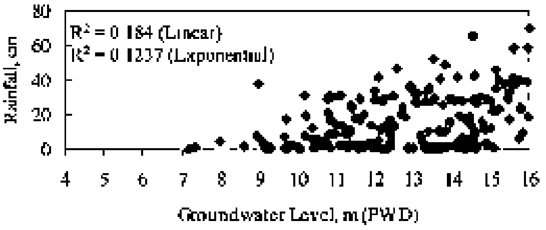
Correlation with Rainfall and 0 Month Lagged GWL_Piezmeter (NAO026) at Naogaon Sadar



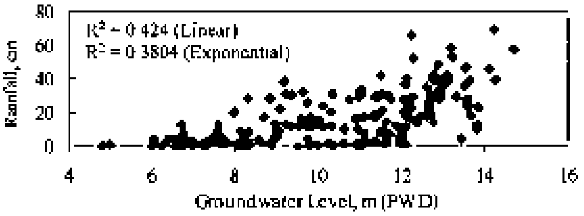
Correlation with Rainfall and 0 Month Lagged GWL_Piezmeter (NAO027) at Naogaon Sadar



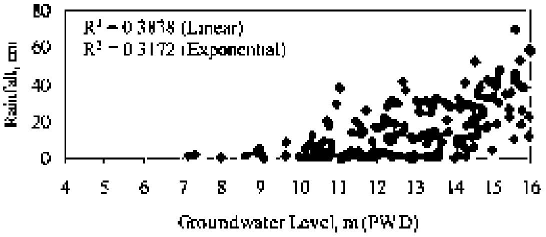
Correlation with Rainfall and 1 Month Lagged GWL_Piezmeter (NAO026) at Naogaon Sadar



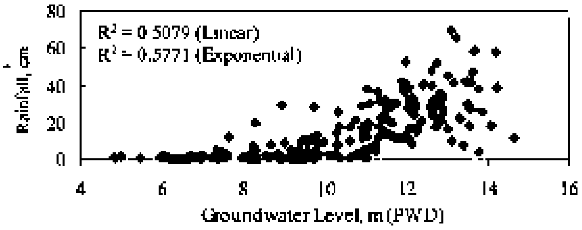
Correlation with Rainfall and 1 Month Lagged GWL_Piezmeter (NAO027) at Naogaon Sadar



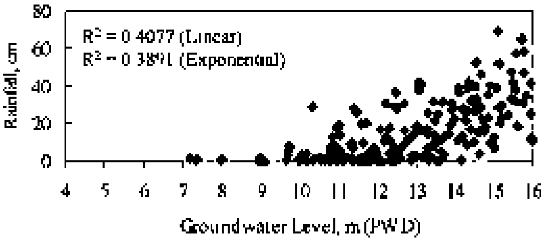
Correlation with Rainfall and 2 Month Lagged GWL_Piezmeter (NAO026) at Naogaon Sadar



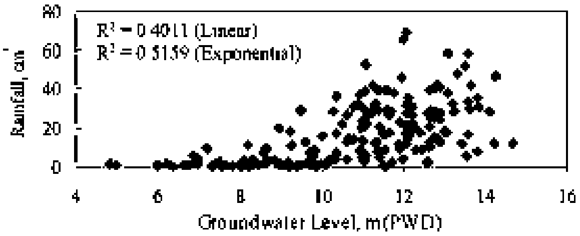
Correlation with Rainfall and 2 Month Lagged GWL_Piezmeter (NAO027) at Naogaon Sadar



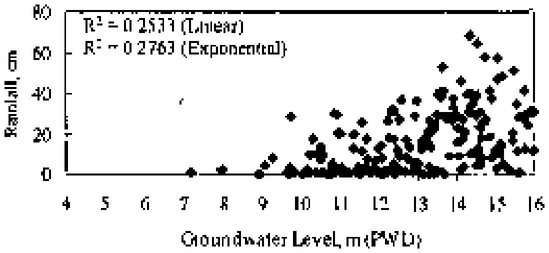
Correlation with Rainfall and 3 Month Lagged GWL_Piezmeter (NAO026) at Naogaon Sadar



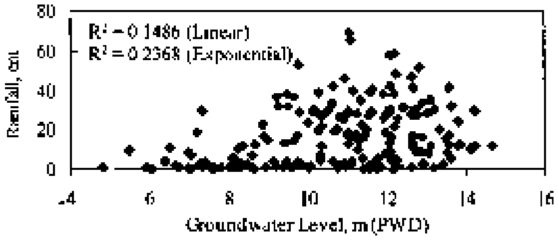
Correlation with Rainfall and 3 Month Lagged GWL_Piezmeter (NAO027) at Naogaon Sadar

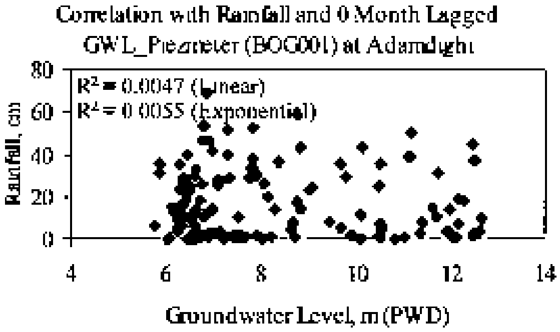


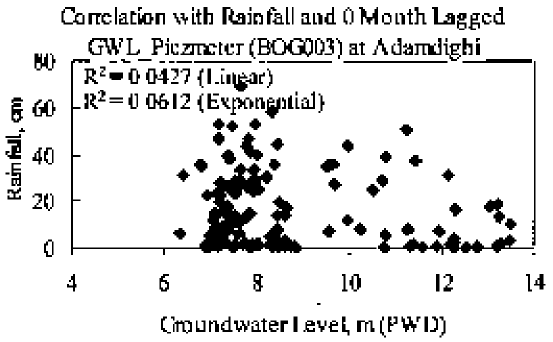
Correlation with Rainfall and 4 Month Lagged GWL_Piezmeter (NAO026) at Naogaon Sadar

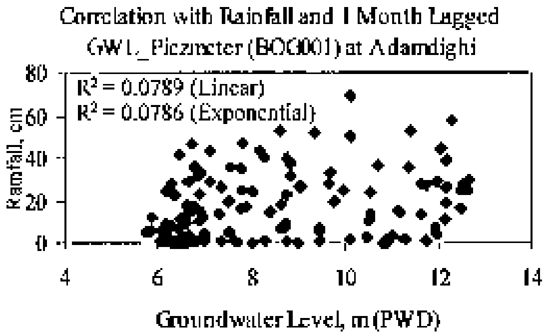


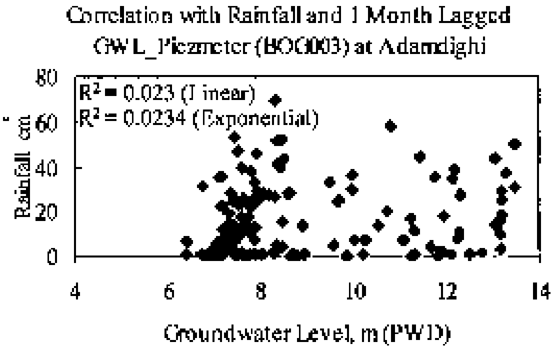
Correlation with Rainfall and 4 Month Lagged GWL_Piezmeter (NAO027) at Naogaon Sadar

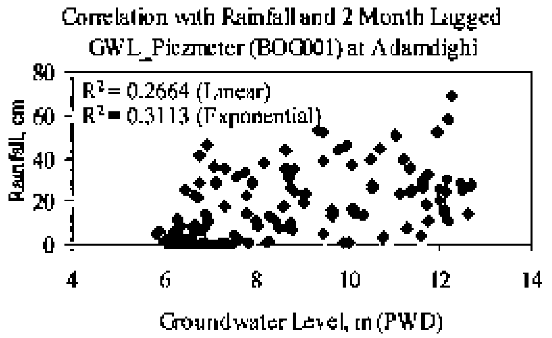


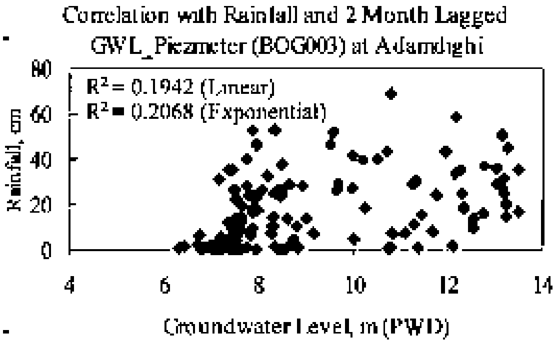

Correlation with Rainfall and 0 Month Lagged GWL_Piezmeter (BOG001) at Adamdighi

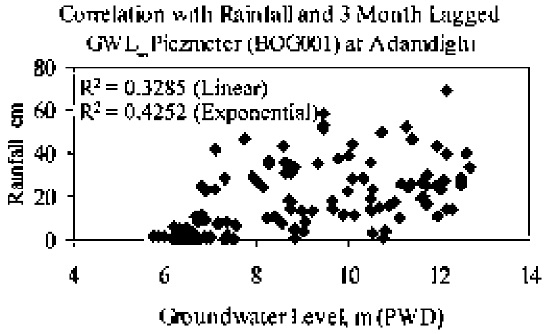

Correlation with Rainfall and 0 Month Lagged GWL_Piezmeter (BOG003) at Adamdighi

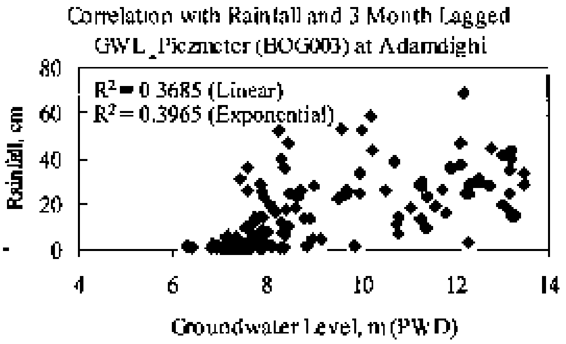

Correlation with Rainfall and 1 Month Lagged GWL_Piezmeter (BOG001) at Adamdighi

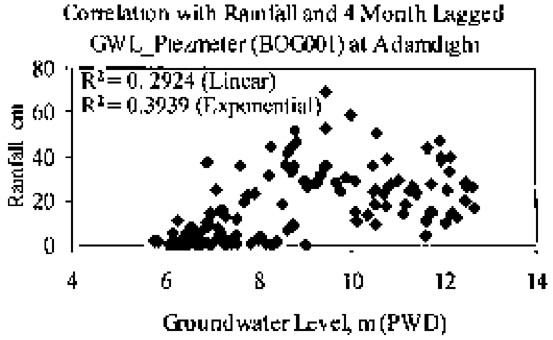

Correlation with Rainfall and 1 Month Lagged GWL_Piezmeter (BOG003) at Adamdighi

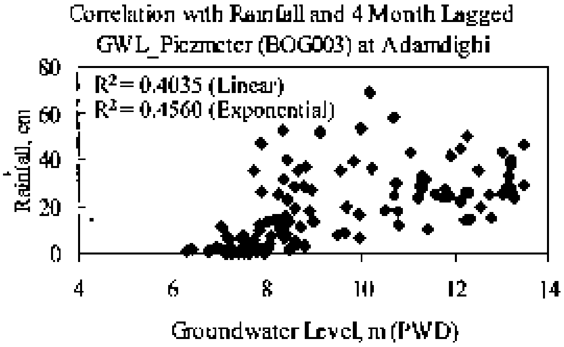

Correlation with Rainfall and 2 Month Lagged GWL_Piezmeter (BOG001) at Adamdighi


Correlation with Rainfall and 2 Month Lagged GWL_Piezmeter (BOG003) at Adamdighi

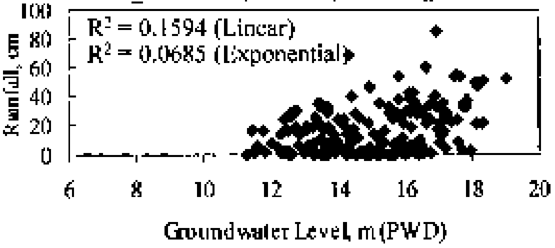

Correlation with Rainfall and 3 Month Lagged GWL_Piezmeter (BOG001) at Adamdighi


Correlation with Rainfall and 3 Month Lagged GWL_Piezmeter (BOG003) at Adamdighi

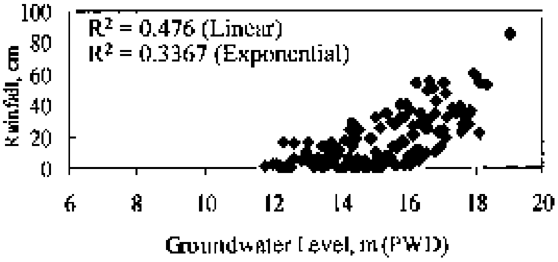

Correlation with Rainfall and 4 Month Lagged GWL_Piezmeter (BOG001) at Adamdighi


Correlation with Rainfall and 4 Month Lagged GWL_Piezmeter (BOG003) at Adamdighi

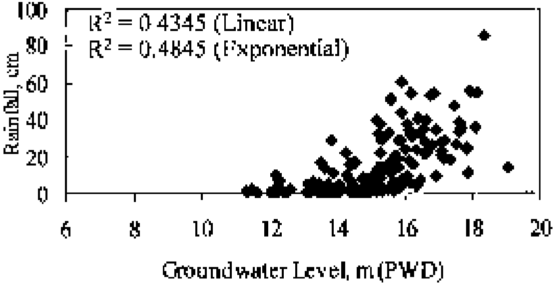
Correlation with Rainfall and 0 Month Lagged GWL_Piezmeter (NAO004) at Badalgachi



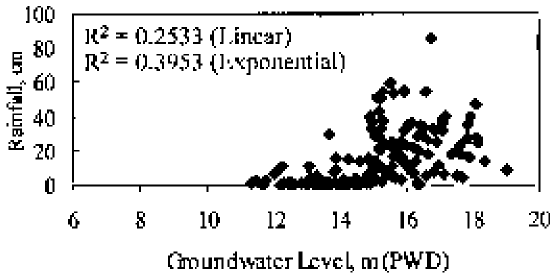
Correlation with Rainfall and 1 Month Lagged GWL_Piezmeter (NAO004) at Badalgachi



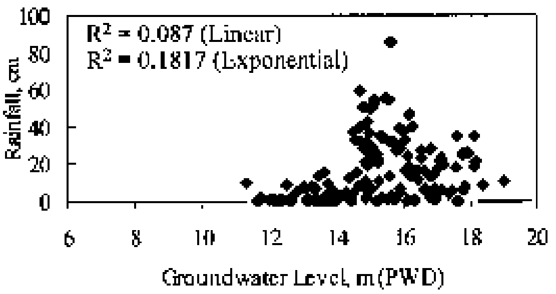
Correlation with Rainfall and 2 Month Lagged GWL_Piezmeter (NAO004) at Badalgachi



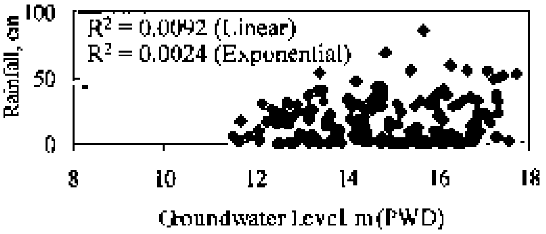
Correlation with Rainfall and 3 Month Lagged GWL_Piezmeter (NAO004) at Badalgachi



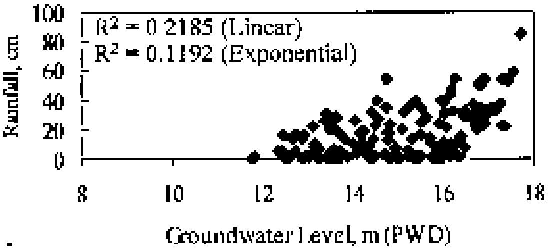
Correlation with Rainfall and 4 Month Lagged GWL_Piezmeter (NAO004) at Badalgachi



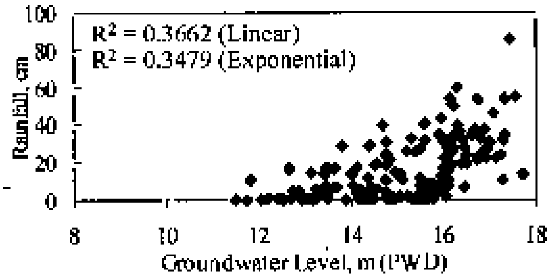
Correlation with Rainfall and 0 Month Lagged GWL_Piezmeter (NAO005) at Badalgachi



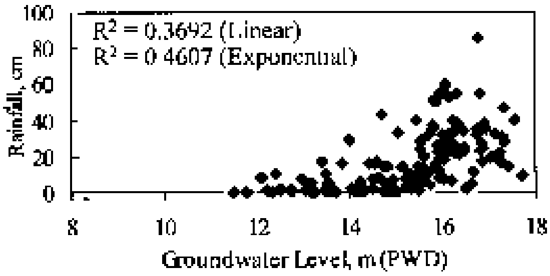
Correlation with Rainfall and 1 Month Lagged GWL_Piezmeter (NAO005) at Badalgachi



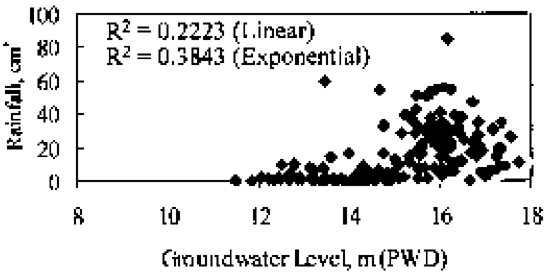
Correlation with Rainfall and 2 Month Lagged GWL_Piezmeter (NAO005) at Badalgachi

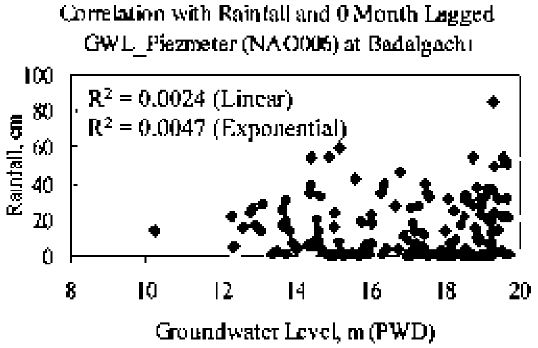


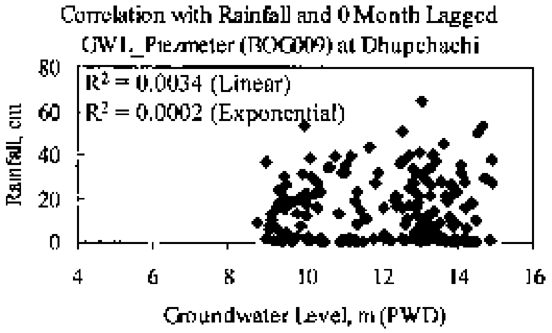
Correlation with Rainfall and 3 Month Lagged GWL_Piezmeter (NAO005) at Badalgachi

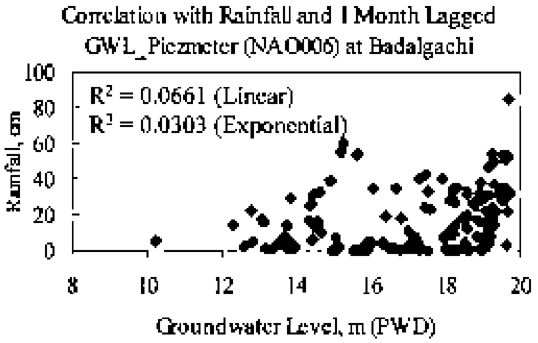


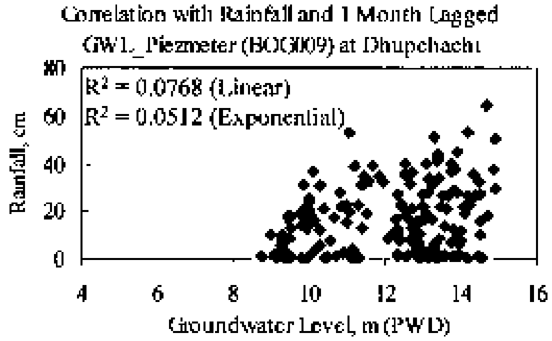
Correlation with Rainfall and 4 Month Lagged GWL_Piezmeter (NAO005) at Badalgachi

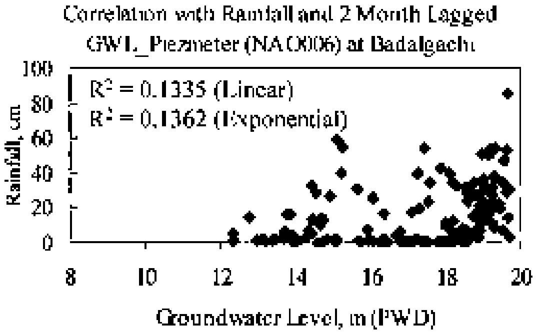


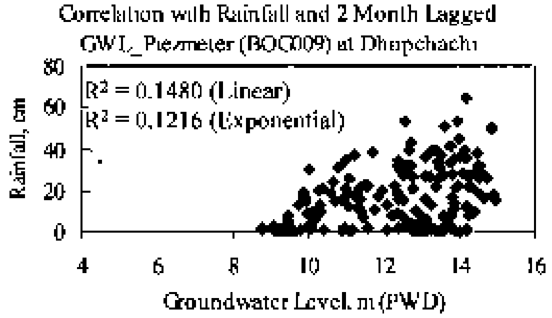

Correlation with Rainfall and 0 Month Lagged GWL_Piezmeter (NAO006) at Badalgachi
R² = 0.0024 (Linear)
R² = 0.0047 (Exponential)
Rainfall, cm
0
20
40
60
80
100
8
10
12
14
16
18
20
Groundwater Level, m (PWD)

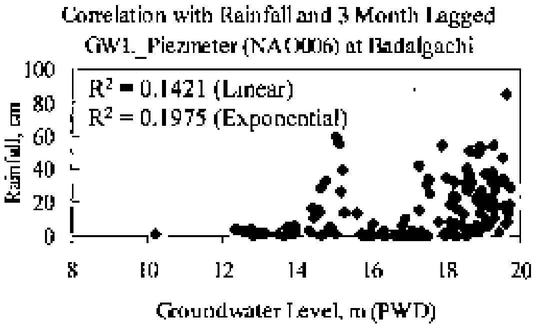

Correlation with Rainfall and 0 Month Lagged GWL_Piezmeter (BOG009) at Dhupchachi
R² = 0.0034 (Linear)
R² = 0.0002 (Exponential)
Rainfall, cm
0
20
40
60
80
4
6
8
10
12
14
16
Groundwater Level, m (PWD)

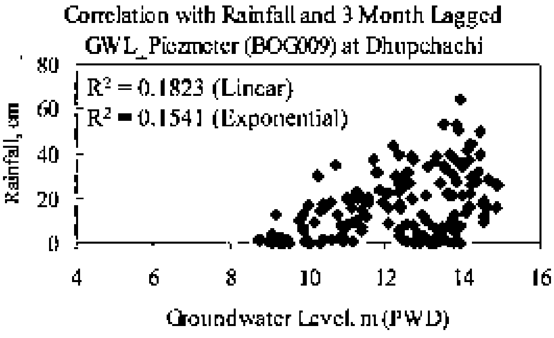

Correlation with Rainfall and 1 Month Lagged GWL_Piezmeter (NAO006) at Badalgachi
R² = 0.0661 (Linear)
R² = 0.0303 (Exponential)
Rainfall, cm
0
20
40
60
80
100
8
10
12
14
16
18
20
Groundwater Level, m (PWD)

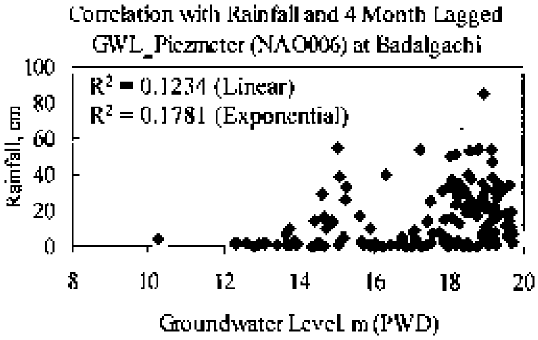

Correlation with Rainfall and 1 Month Lagged GWL_Piezmeter (BOG009) at Dhupchachi
R² = 0.0768 (Linear)
R² = 0.0512 (Exponential)
Rainfall, cm
0
20
40
60
80
4
6
8
10
12
14
16
Groundwater Level, m (PWD)

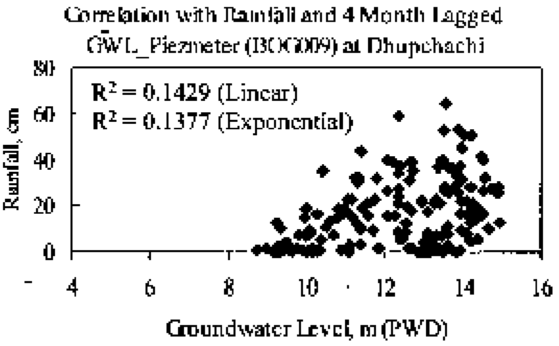

Correlation with Rainfall and 2 Month Lagged GWL_Piezmeter (NAO006) at Badalgachi
R² = 0.1335 (Linear)
R² = 0.1362 (Exponential)
Rainfall, cm
0
20
40
60
80
100
8
10
12
14
16
18
20
Groundwater Level, m (PWD)


Correlation with Rainfall and 2 Month Lagged GWL_Piezmeter (BOG009) at Dhupchachi
R² = 0.1480 (Linear)
R² = 0.1216 (Exponential)
Rainfall, cm
0
20
40
60
80
4
6
8
10
12
14
16
Groundwater Level, m (PWD)


Correlation with Rainfall and 3 Month Lagged GWL_Piezmeter (NAO006) at Badalgachi
R² = 0.1421 (Linear)
R² = 0.1975 (Exponential)
Rainfall, cm
0
20
40
60
80
100
8
10
12
14
16
18
20
Groundwater Level, m (PWD)


Correlation with Rainfall and 3 Month Lagged GWL_Piezmeter (BOG009) at Dhupchachi
R² = 0.1823 (Linear)
R² = 0.1541 (Exponential)
Rainfall, cm
0
20
40
60
80
4
6
8
10
12
14
16
Groundwater Level, m (PWD)

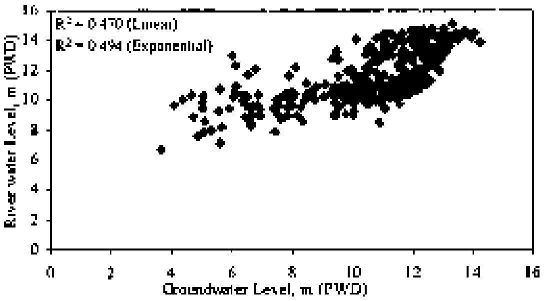

Correlation with Rainfall and 4 Month Lagged GWL_Piezmeter (NAO006) at Badalgachi
R² = 0.1234 (Linear)
R² = 0.1781 (Exponential)
Rainfall, cm
0
20
40
60
80
100
8
10
12
14
16
18
20
Groundwater Level, m (PWD)


Correlation with Rainfall and 4 Month Lagged GWL_Piezmeter (BOG009) at Dhupchachi
R² = 0.1429 (Linear)
R² = 0.1377 (Exponential)
Rainfall, cm
0
20
40
60
80
4
6
8
10
12
14
16
Groundwater Level, m (PWD)

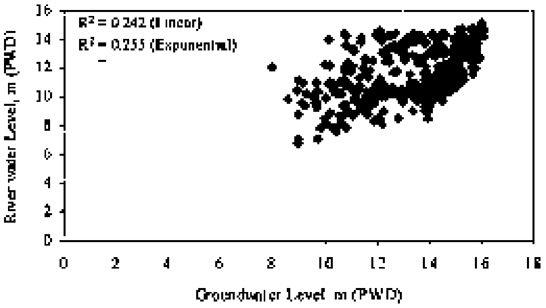
APPENDIX –J

Patterns of groundwater level and Surface water level at Little Jamuna river

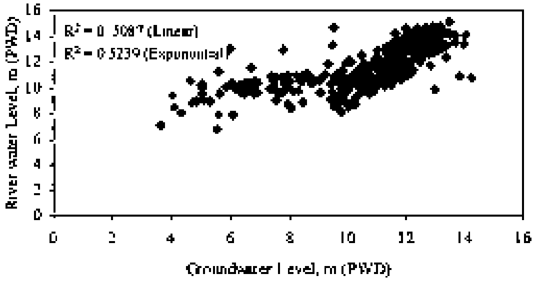
Correlation with 0 month lagged GWL_NAO025 and River water level



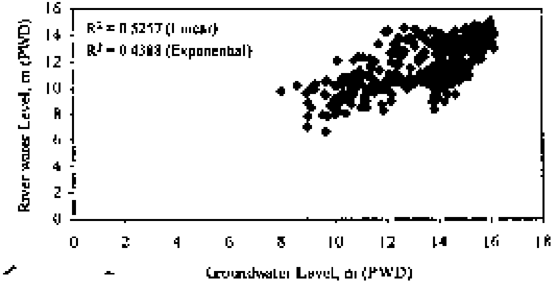
Correlation with 0 month lagged GWL_NAO026 and River water level



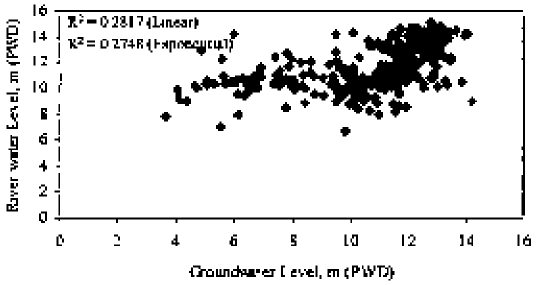
Correlation with 1 month lagged GWL_NAO025 and River water level



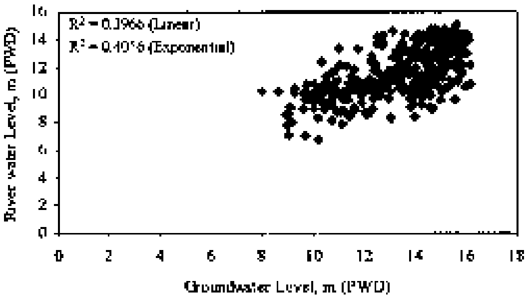
Correlation with 1 month lagged GWL_NAO026 and River water level



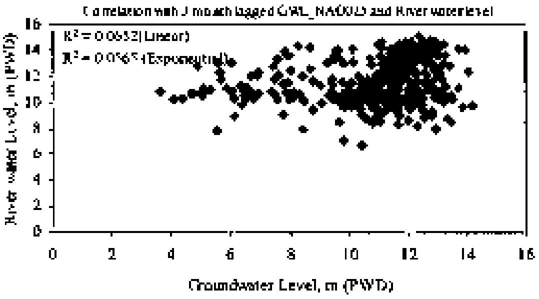
Correlation with 2 month lagged GWL_NAO025 and River water level



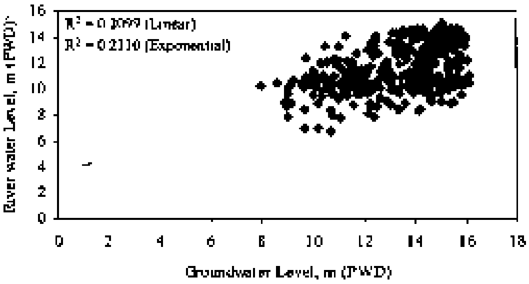
Correlation with 2 month lagged GWL_NAO026 and River water level



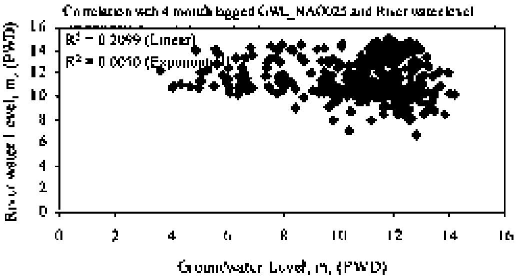
Correlation with 3 month lagged GWL_NAO025 and River water level



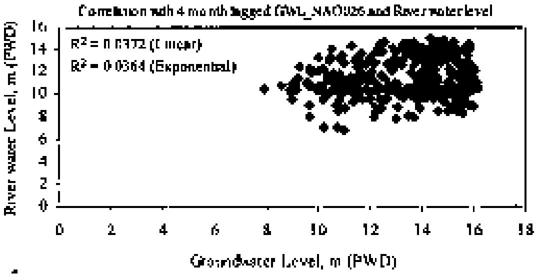
Correlation with 3 month lagged GWL_NAO026 and River water level

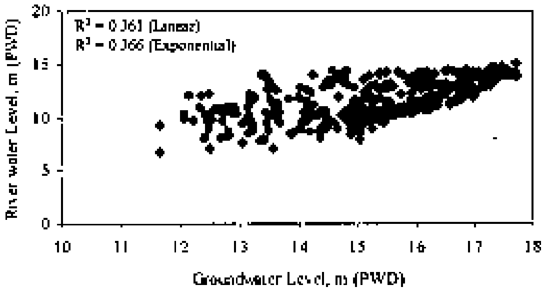


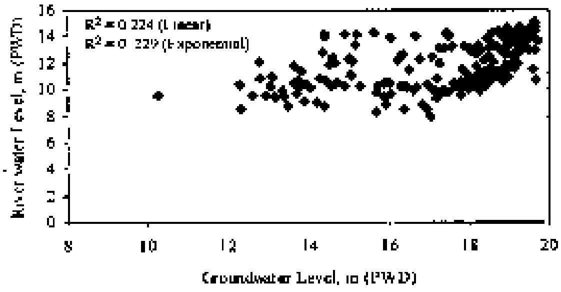
Correlation with 4 month lagged GWL_NAO025 and River water level

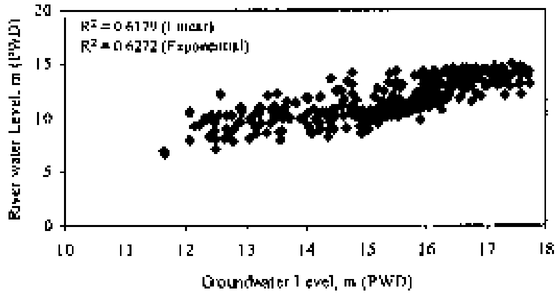


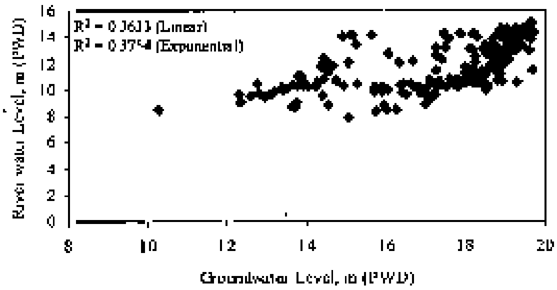
Correlation with 4 month lagged GWL_NAO026 and River water level

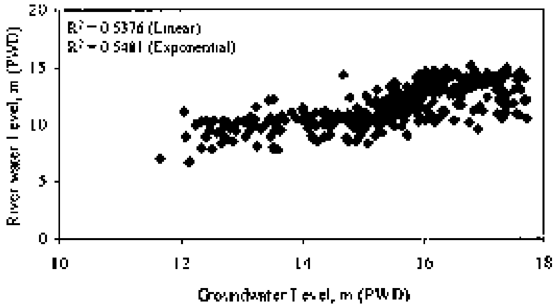


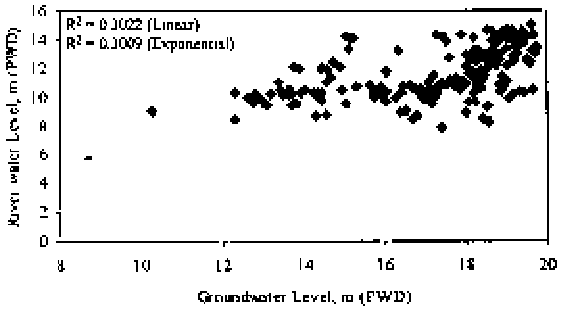

Correlation with 0 month lagged GWL_NAO005 and River water level

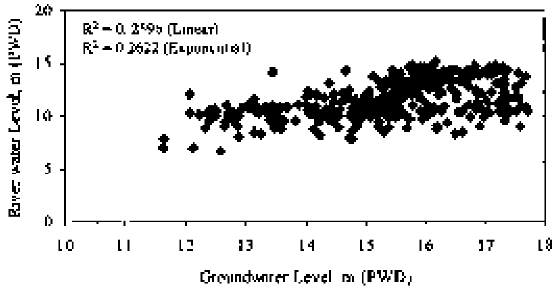

Correlation with 0 month lagged GWL_NAO006 and River water level

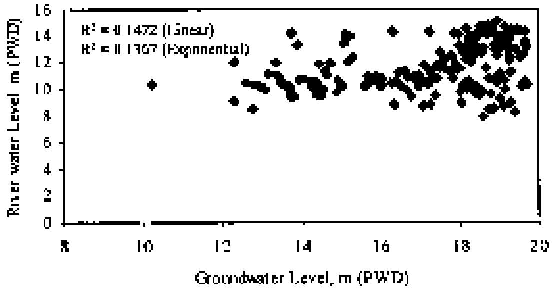

Correlation with 1month lagged GWL_NAO005 and River water level

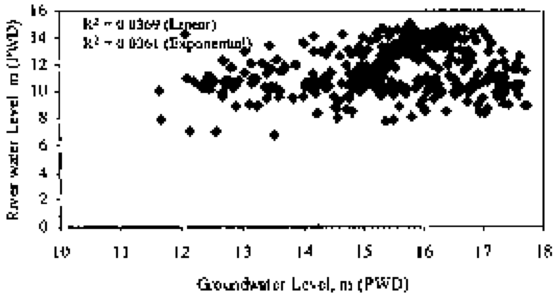

Correlation with 1month lagged GWL_NAO006 and River water level

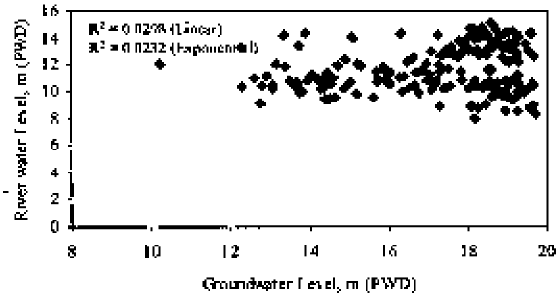

Correlation with 2 month lagged GWL_NAO005 and River water level

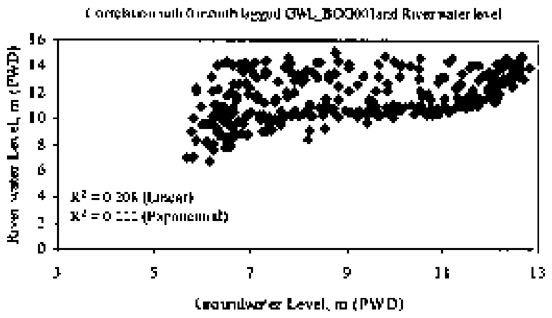

Correlation with 2 month lagged GWL_NAO006 and River water level

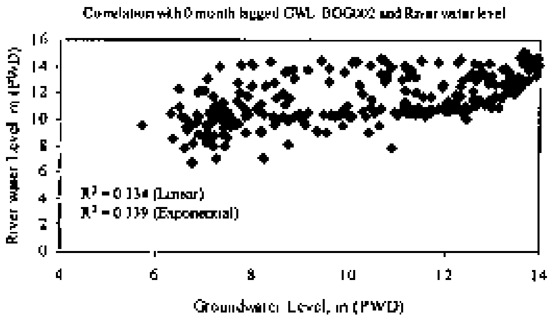

Correlation with 3 month lagged GWL_NAO005 and River water level

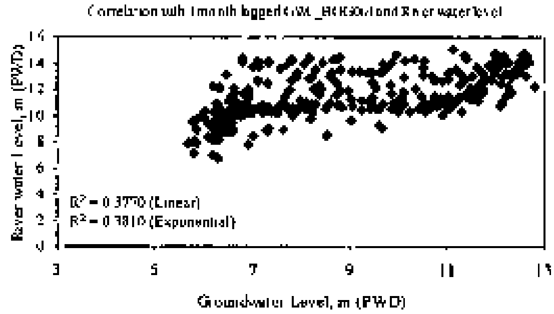

Correlation with 3 month lagged GWL_NAO006 and River water level

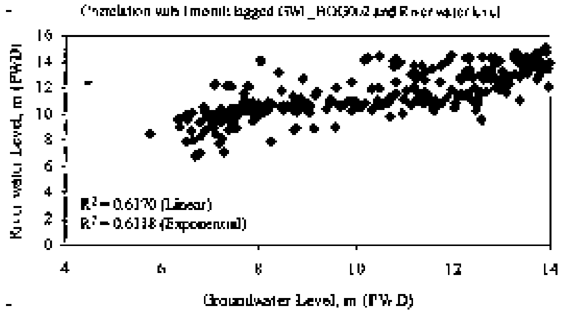

Correlation with 4 month lagged GWL_NAO005 and River water level

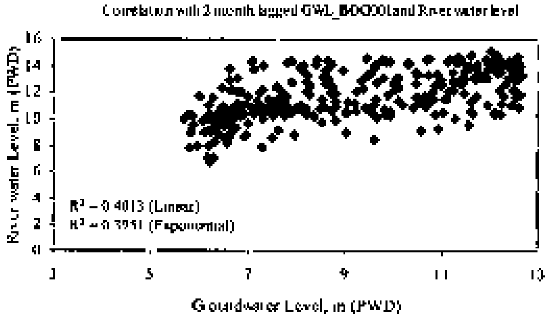

Correlation with 4 month lagged GWL_NAO006 and River water level

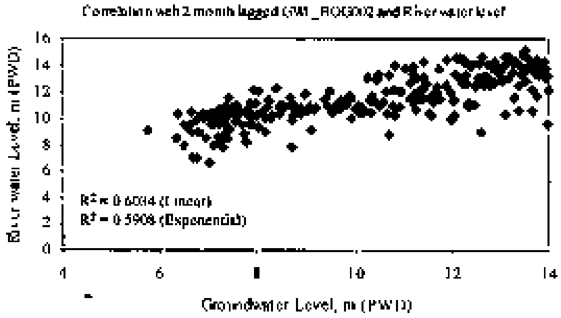

Correlation with 0 month lagged GWL_BOG001 and River water level

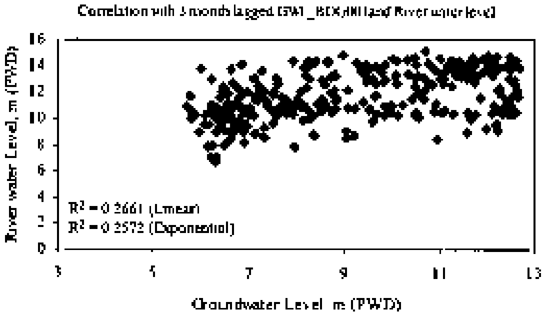

Correlation with 0 month lagged GWL_BOG002 and River water level

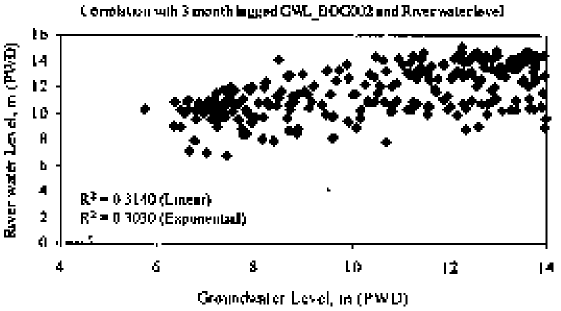

Correlation with 1 month lagged GWL_BOG001 and River water level

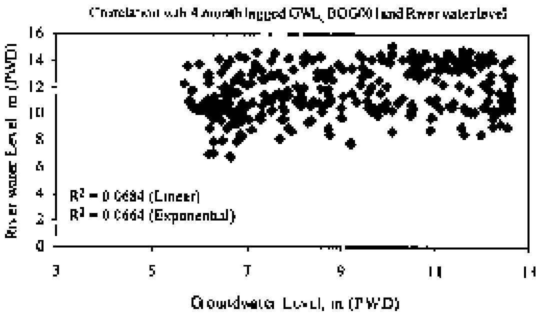

Correlation with 1 month lagged GWL_BOG002 and River water level

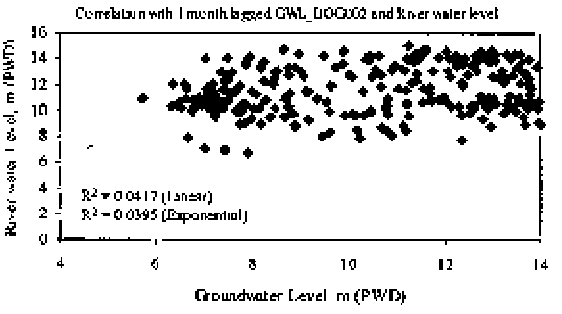

Correlation with 2 month lagged GWL_BOG001 and River water level


Correlation with 2 month lagged GWL_BOG002 and River water level

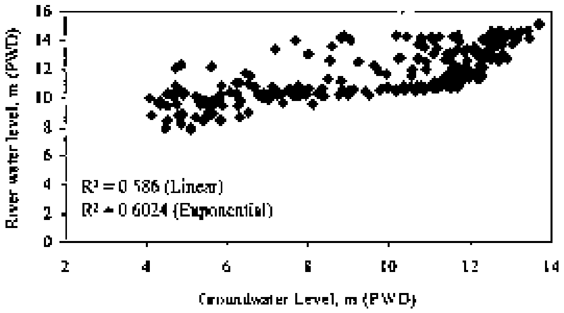

Correlation with 3 month lagged GWL_BOG001 and River water level


Correlation with 3 month lagged GWL_BOG002 and River water level

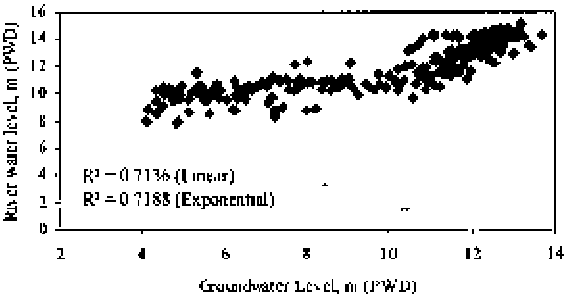

Correlation with 4 month lagged GWL_BOG001 and River water level


Correlation with 1 month lagged GWL_BOG002 and River water level

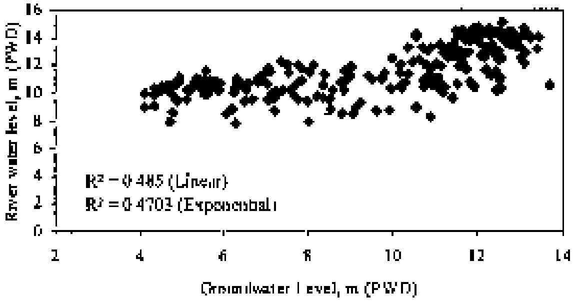
Correlation with 0 month lagged GWL_NAO048 and River water level



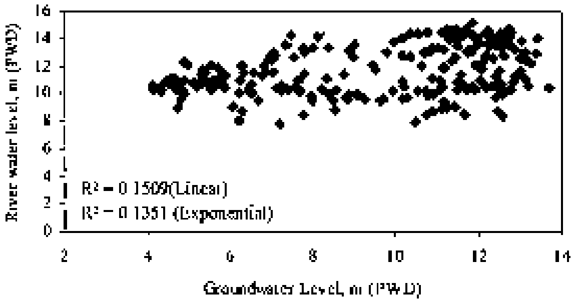
Correlation with 1 month lagged GWL_NAO048 and River water level



Correlation with 2 month lagged GWL_NAO048 and River water level



Correlation with 3 month lagged GWL_NAO048 and River water level



Correlation with 4 month lagged GWL_NAO048 and River water level