GROUNDWATER DEVELOPMENT AND MANAGEMENT AT FORDWAH EASTERN SADIQIA (SOUTH) PROJECT, BAHAWALNAGER, PUNJAB, PAKISTAN

by

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ABSTRACT

The semi arid climate at the Fordwah Eastern Sadiqia (South) Project, Pakistan, comprised of 105,000 ha of culturable command area, is characterized by large seasonal temperature fluctuations and a monsoon season. The canal system behaves as a recharge source to the regional groundwater and has caused waterlogging and salinity problems. The aquifer of the project area is unconfined and underlain by sediments deposited by the Sutleg-Hakra river system.

To quantify the rate of groundwater recharge in the project area, a numerical groundwater model was developed. A network of 125 observation wells was installed and watertable depth data were collected for the period of June 1994 to June 1997. Within this network, a distinction was made between internal and external nodes representing nodal areas and boundary conditions, respectively. Other data used in the model were aquifer characteristics obtained from seven historical and five newly performed pumped well tests. The aquifer analysis showed a regional decrease in aquifer transmissivity from the eastern region to the western. The hydraulic conductivity values obtained from these analyses were assigned to each side of each nodal area.

The aim of the present study was to develop a more reliable and time consuming methodology to determine the yearly, seasonal and monthly net-recharge occurring in the study area. The SGMP model was run for the period of July 94 to June 97 in inverse mode in order to estimate net-recharge values. More than 60 % of the area showed consistently positive net-recharge values over the three year period The calculated net-recharge had a maximum seasonal positive value of 0.17 mm day^{-1} and was of similar magnitude for both the monsoon 1994 and the non-monsoon 1995-96. This indicated that the recharge in the area is not solely due to monsoon rains: other factors such as canal seepage must be major sources of recharge.

The yearly net-recharge averaged of 0.12 mm day^{-1} in the 1994-95 and 1995-96 seasons. However, a 50 % decrease in the net-recharge was observed in 1996-97.

For a worst case scenario analysis, the net-recharge values of 1995-96 (July-June) were used for prediction modelling. Those are the net-recharge values expected if no water management remedial action is taken. In July 1994, an area of 696 km^2 had a watertable depth less than 1.5 m. These areas increased to 872, 1212 and 1522 km^2 in years 1994, 1996 and 1997 respectively. The predicted values for the year 2002 showed that 459 km^2 will have a watertable of less than 0.5 m, and 1830 km^2 less than 1.5 m; this represents 20 and 80 % of the total area.

The model developed offers an efficient approximate way to assess net-recharge values and will help to refine the drainage coefficient used for the design of the sub-surface drainage systems as well as to monitor the performance of Phase-II (post drainage) of the project.

RÉSUMÉ

Le climat semi-aride du Projet Sud de l'Est du Fordwah Sadiqia, Pakistan, comprend 105,000 ha de région cultivable. Il est caractérisé par de grandes variations des températures saisonnières et une saison de mousson. Le système de canaux de cette région permet le réapprovisionnement de l'eau souterraine. Cependant, cela cause des problèmes de salinité et entraîne la saturation du sol. La nappe aquifère de la région du projet n'est pas confinée et des sédiments provenant du système de rivières du Sutleg-Hakra s'y sont déposés.

Pour quantifier le taux de réapprovisionnement de la nappe aquifère dans la région du projet, un modèle numérique a été développé. Un réseau de 125 puits d'observation a été installé et la profondeur de l'eau souterraine a été mesurée de juin 1994 à juin 1997. Dans ce réseau, une distinction a été faite entre noeuds internes et externes qui représentent respectivement des régions nodales ou des conditions de limite. Parmi d'autres données utilisées dans le modèle font parties les caractéristiques de la nappe d'eau obtenues des sept puits existants et des cinq nouveaux puits. L'analyse de la nappe a montré une baisse régionale dans la transmissivité de la région Est à Ouest. Les valeurs de la conductivité hydraulique obtenues par ces analyses ont été assignées à chacun des côtés des régions nodales.

Le but de cette étude était de développer une méthode plus fiable et plus rapide pour déterminer l'approvisionnement annuel, saisonnier et mensuel de la nappe aquifère de la région. Le modèle SGMP a été testé pour la période de juillet 94 à juin 97 en mode inverse afin d'estimer les valeurs d'approvisionnement. Plus de 60% de la région a montré une recharge positive pendant cette période de trois ans. La valeur maximale de la recharge saisonnière calculée pendant cette période était de 0.17 mm/jour. Cette valeur fût la même pendant la mousson 1994 et la non-mousson 1995-96. Cela indique que la recharge dans la région n'est pas uniquement due aux pluies de la mousson; d'autres facteurs comme l'infiltration du canal doivent être une des sources majeures de réapprovisionnement.

L'approvisionnement annuel était de 0.12 mm/jour en moyenne pendant les saisons 1994-95 et 1995-96. Cependant, une réduction de 50% a été observée en 1996-97.

Pour une analyse du pire scénario, les valeurs de recharge de 1995-96 (juillet-juin) ont été utilisées pour les modèles de prédiction. Cela correspond à des valeurs de recharge lorsqu'aucune méthode de gestion de l'eau n'est adoptée. En juillet 1994, une région de 696 km^2 avait un niveau d'eau de moins de 1.5 m qui a augmenté à 872, 1212 et 1522 pour les années 1994, 1996 et 1997. Les valeurs prédites pour l'année 2002 ont montré que 459 km^2 auront un niveau d'eau de moins de 0.5 m, et 1830 km^2 auront moins que 1.5 m; cela représente 20 et 80% de la région totale.

Le modèle développé dans cette étude offre une approche effective pour déterminer les valeurs de réapprovisionnement. Il aidera à optimiser le coefficient d'écoulement utilisé lors de la conception des systèmes de drainage souterrain et permettra d'évaluer la performance de la Phase-II (après drainage) du projet.

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NOMENCLATURE

A	the water balance area (m^2)
A_b	area associated with node b (L^2)
AGWP	actual groundwater withdrawal via pumpage
CCA	culturable command area
D	saturated thickness
D(x,y,t)	saturated thickness of the aquifer at time t (L)
$D_{i,b}$	saturated thickness of the aquifer along $W_{i,b}$ (m)
DP	deep percolation from the upper system (unsaturated)
D′	saturated thickness of the covering strata (L)
E	the rate of evapotranspiration from the unsaturated zone (mm/d)
E_O	evaporation from the land surface (mm/d)
EP	the evaporation from this sub-system
ET	evaporation losses directly from the groundwater table
Etg	is the groundwater evapotranspiration
FDP	The Fourth Drainage Project
FESS	Fordwah Eastern Sadiqia (South) Project
G	the rate of capillary rise from the saturated zone (mm/d)
GFD	groundwater flow toward the surface and sub surface drain
ΔGWS	the change in groundwater storage
ha	hectare
h (x,y,t)	hydraulic head in the aquifer at time t (L)
h_i ,h_b	absolute water table elevation at node b and nodes i (m)
h′	hydraulic head in the covering strata (L)
Δh	the rise or fall of the watertable during the computation interval (mm)
IDA	International Development Agencies
I	the rate of infiltration into the unsaturated zone (mm/d)

ILRI	International Institute for Land Reclamation and Improvement
IWASRI	International Waterlogging and Salinity Research Institute
$K_{i,b}$	horizontal hydraulic conductivity of aquifer across $W_{i,b}$
km	kilometer
K (x,y)	hydraulic conductivity of the aquifer for horizontal flow (LT^{-1})
K′	the covering strata's vertical hydraulic conductivity (LT^{-1})
LAWOO	The Netherlands Land and Water Research Group
$L_{i,b}$	distance between node i and b (L)
m	meter
md^{-1}	meter per day
m/day	meter per day
m/yr	meter per year
mm/yr	millimeter per year
m^2/d	meter square per day
m^3/sec	cubic meter per second
MP	measuring point i.e well top
N (x,y,t)	source or sink term at time t (LT^{-1})
NESPAK	National Engineering Services Pakistan
NRAP	The Netherlands Research Assistance Project
NSL	natural surface level i.e soil surface
O	outflow consists of the groundwater runoff Q_g
P	precipitation for the time interval (mm/d)
P(x,y,t)	the net rate of abstraction (LT^{-1})
$Q_{gi} = (Q_{gih} + Q_{giv})$	the total rate of groundwater inflow into the shallow unconfined aquifer (m^3/d)
$Q_{go} = (Q_{goh} + Q_{gov})$	the total rate of groundwater outflow from the shallow unconfined aquifer (m^3/d)
Q_{gih}	the rate of horizontal groundwater inflow into the shallow unconfined aquifer (m^3/d)

Q_{goh}	the rate of horizontal groundwater outflow from the shallow unconfined aquifer (m^3/d)
Q_{giv}	the rate of vertical groundwater inflow from the deep confined aquifer into the shallow unconfined aquifer (m^3/d)
Q_{gov}	the rate of vertical groundwater outflow from the shallow unconfined aquifer into the deep confined aquifer (m^3/d)
Q_{nb}	net recharge to aquifer at node b
Q_{si}	lateral inflow of surface water into the water balance area (A) (m^3/d)
Q_{so}	lateral outflow of surface water from the water balance area (A) (m^3/d)
Q_{sub}	is the subsurface underflow
q_n	the net recharge to the aquifer (mm day $^{-1}$)
R	the rate of percolation to the saturated zone (mm/d)
R(x,y,t)	the net rate of recharge (LT^{-1})
RR	recharge from rivers
RLC	recharge from link canals
S	Storage coefficient of the aquifer (dimensionless)
SATEM	Selected Aquifer Test Evaluation Methods
SCARP	Salinity Control and Reclamation Project
SGMP	The Standard Groundwater Model Package
SMO	SCARP Monitoring Organization
sq.km	square kilometer
ΔSMS	the change in soil moisture storage
S_{y_b}	specific yield of the node b (dimensionless)
ΔS_g	is the change in groundwater storage
T	the transpiration through plants
t	time (T)
t/ha	tons per hectare

Δt	the computation interval of time (d)
μ	the specific yield or effective drainable porosity, as a fraction of the volume of soil (unitless)
$\mu(x,y)$	specific yield of the aquifer (dimensionless)
μ'	specific yield of the covering strata (dimensionless)
WAPDA	Water and Power Development Authority
$W_{i,b}$	length of the side between nodes i and b (L)
WINSURF	Surfer, 1994. Surfer Version 5.0. Golden Software inc, Colorado USA.
ΔW_s	the change in surface water storage (mm)
ΔW_U	the change in soil water storage in the unsaturated zone (mm)
%	percent
θdz	soil moisture content as a function of depth

CHAPTER I

INTRODUCTION

1.1 Pakistan

The Islamic Republic of Pakistan covers an area of 805,000 sq. km.(80.5 million ha) of which about 90,000 sq.km is covered with flat alluvial plains and sandy deserts. About 32.1 million ha is arable, of which 23.5 million ha is currently cultivated. The territory of Pakistan is bounded to the west, north-west and north by Iran and Afghanistan, to the east and south-east by India and Jammu and Kashmir, and to the south by the Arabian sea. Much of Pakistan is mountainous or highland. It's northern most territories consist of the Himalayas, the Karakorum and Pamir ranges. The south-east is mainly flat country that is part of the Indo-Gangetic plain. This plain consists of materials brought down by the Indus and its tributaries; the Jhelum, Ravi, Beas and Sutlej Rivers located in the Punjab.

The irrigation system in Pakistan is, with 14.6 million ha of command area, the largest contiguous irrigation system in the world supplied by a single river system. It comprises the Indus river and its major tributaries, three major storage reservoirs, 19 barrages/headworks, 43 canal commands and some 89,000 tertiary units.

The total length of canals is about 56,000 km, with watercourses, farm channels and ditches running another 1.6 million km in length (Rizvi, 1993). With foreign aid Pakistan builds large dams and link canals to transport water to areas affected by the water treaty with India. Waterlogging and salinity problems are inherent to most irrigated agriculture. These problems are no where so serious as in Pakistan where the economy is mainly based on irrigated agriculture. Waterlogging and salinity is widely spread throughout the Indus Basin. By the late 1930's and early 1940's the water table had risen over most of the irrigated areas to very close to the ground surface creating a waterlogged condition.

After independence of the country in 1947, efforts to eradicate waterlogging and salinity were intensified with the assistance of the United Nations and its subordinate organizations. In 1949-50, the Government of Pakistan requested FAO to help solve the problem. This was followed by visits of experts of the U.S. Salinity Laboratory and the United States Bureau of Reclamation which suggested the need for an action program.

In 1954, the Government of Pakistan, in cooperation with the United States International Administration (ICA) and its successor USAID, started a comprehensive study of geology and hydrology of the Indus Plains. Water and Power Development Authority (WAPDA) initiated the Salinity Control and Reclamation Projects (SCARP) in 1960 to provide solutions to the problem of waterlogging and salinity in selected areas.

Subsurface horizontal pipe drainage for areas with shallow aquifers and saline ground water was initiated in 1977. In 1983 WAPDA implemented the Fourth Drainage Project with the financial assistance of the World Bank, International Development Agencies (IDA) and The Netherlands Government. Due to growing concern about the problem of waterlogging and salinity, the Government of Pakistan requested IDA assistance for financing another subsurface saline drainage project in the Punjab Province. WAPDA planned to construct the Fordwah Eastern Sadiqia (South) Phase-1 Project and awarded the contract for consultancy of the Project to M/s Euroconsult-Lahmeyer-NDC Joint Venture Consultants. The Project envisages to construct 150 km of surface drains, 180 km interceptor drains, to carry out trials for subsurface and interceptor drains and prepare proposals for Phase-II of the Project (NESPAK,1992). The main objectives of the project are to: (1) increase agriculture productivity and income; (2) reduce the need for expensive subsurface drainage and avert related environmentally harmful effects; and (3) improve the equity of water distribution.

The International Waterlogging and Salinity Research Institute (IWASRI) was established in 1986. The basic objective of this Institute is to unify and coordinate national research on waterlogging and salinity and to develop and disseminate economically and technically sound solutions to end users and researchers. The Institute forms the nucleus for research in the field of waterlogging and salinity in Pakistan and has international linkages. In October 1988, The Netherlands Research Assistance Project (NRAP) initiated cooperation with IWASRI in Lahore, Pakistan as part of a bilateral agreement between the Netherlands and Pakistani governments. The bilateral support to IWASRI is furnished by The Netherlands Land and Water Research Group (LAWOO) with the International Institute for Land Reclamation and Improvement (ILRI) as the lead Institute. A regional groundwater study for the Fordwah Eastern Sadiqia (South) Project, Bahawalnager was initiated in 1994 and will be used to evaluate the performance of the drainage system proposed for Phase II. With the use of a groundwater model, a drainage coefficient will possibly be refined, and areas most in need of drainage will be identified.

1.2 The Project Area

The Fordwah Eastern Sadiqia (South) Project (FESS), Bahawalnager is located 300 km south of Lahore in the south-eastern corner of the Punjab Province of Pakistan (Figure 1.1). The project comprises parts of the Tehsils Bahawalnager, Haroonabad and Chistian canals of the Bahawalnager District.

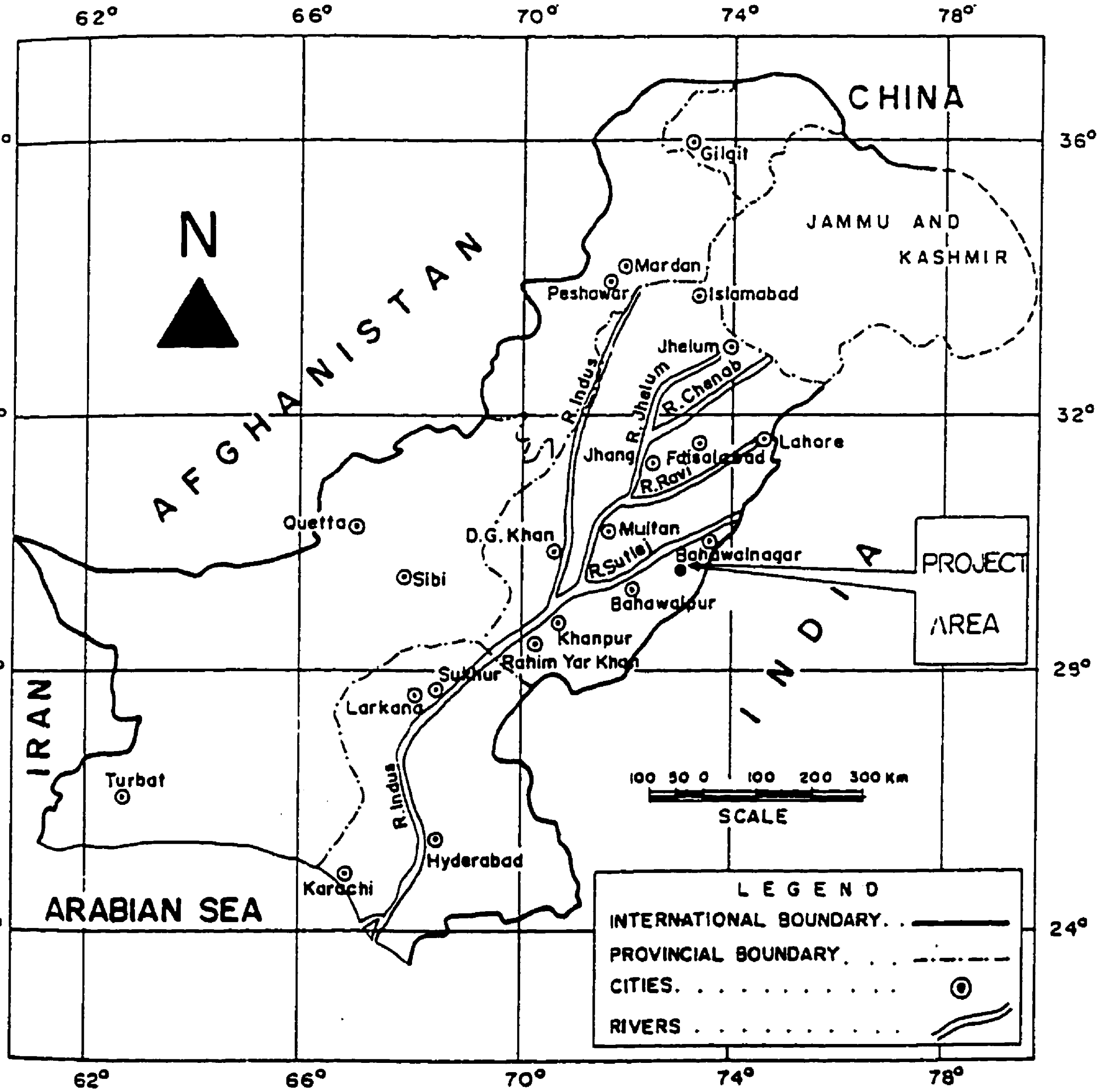


Figure 1.1 Location of Fordwah Eastern Sadiqia (South) Project Bhawalnager

The study area is between two canals: Hakra and Malik. The Malik branch canal is on the north west, the Hakra is on the south east, some distributories of the Hakra are on the south and the Pakistan/India border is to the east (Figure 1.2). The gross area of the project is 299,000 acres (121, 000 ha) with a culturable command area (CCA) of 259,455 acres (105,000 ha) (SMO, 1993). The population of the area (242,000) is located in numerous small villages. Haroonabad is the major town in the project area, while two other smaller towns are Dunga Bunga and Dahranwala.

The climate of the area is typical of the low lying interior of the Indo-Pak Sub-Continent and is characterized by large seasonal fluctuations in temperature and rainfall. The area has hot summers and mild winters. The hottest month is June when the average maximum temperature over a period of fifteen years has been recorded as 45.9 °C. The temperature frequently exceeds 48.9 °C. January is the coldest month; the mean maximum and minimum temperatures being 24.2 °C. and 0.°C., respectively. The area experiences an arid climate in the dry season (59 mm/yr) except during the June-September monsoon season (134 mm/yr). The weighted average depth of precipitation over the area on an annual basis amounts to 193 mm (Hassan et al., 1995).

Water is applied to the project area via the Hakra and Malik branch canals, which are supplied by the Eastern Sadiqia canal which has its source at the Suleimanki head works (completed in 1893) located on the Sutleg River. The Fordwah and Eastern Sadiqia canal system acted as new recharge source to the groundwater and disrupted the natural equilibrium. The groundwater moves westward from the Eastern Sadiqia canal towards the Sutluj River. The Malik branch acts as a groundwater divide, where groundwater movement is towards both the evaporation ponds in the south and to the north-west. Before the introduction of the Fordwah Eastern Sadiqia canal system in 1926-1932 the watertable was at depths greater than 18m. Waterlogging first appeared in the area at the upstream part of the Hakra branch canal and has since progressively invaded the project area. Currently, the watertable is rising at a rate of 0.15 m/yr. In 1992 the depth to water table in the project area ranged from less than

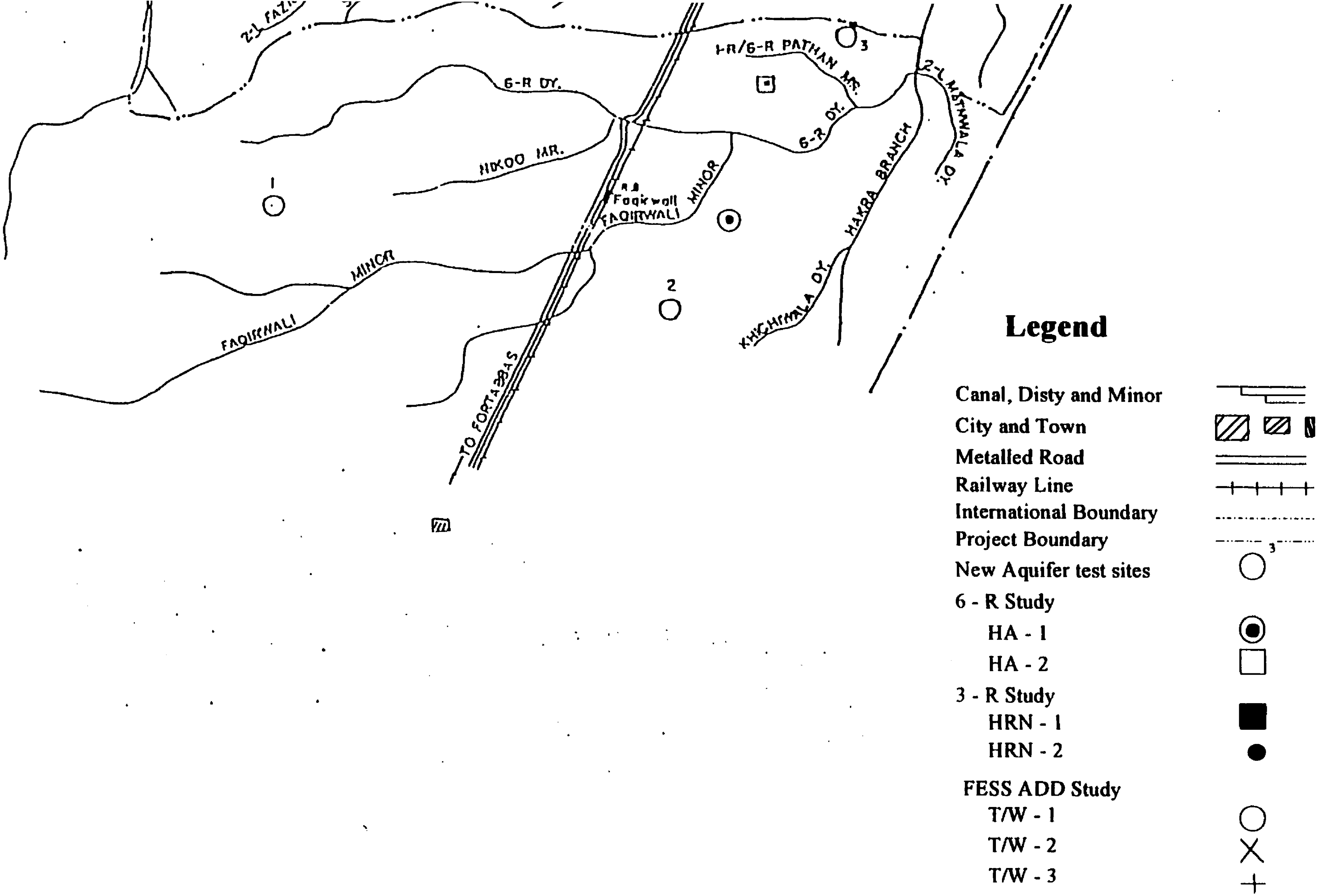
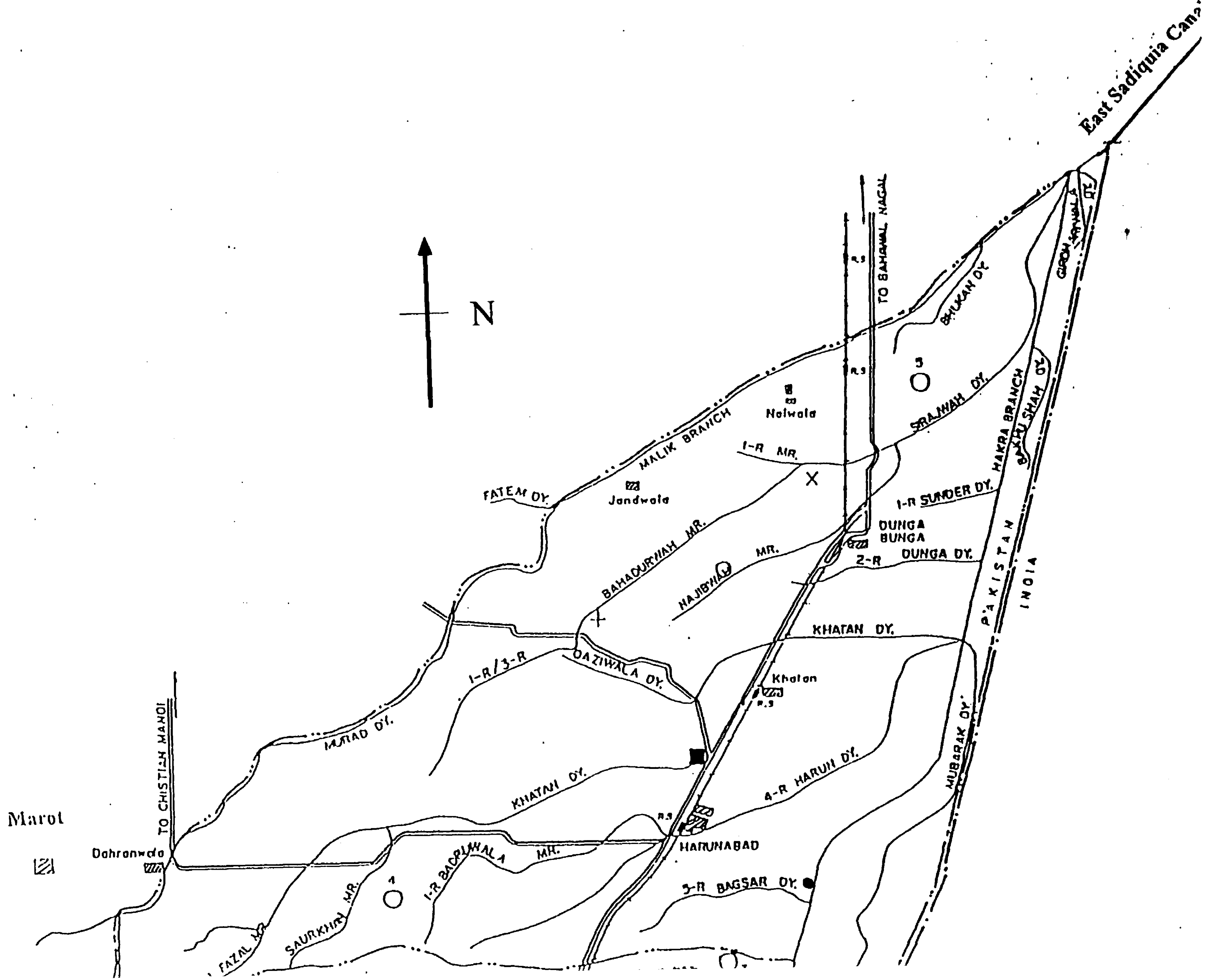


Figure 1.2 Fordwah Eastern Sadiqia (South) Project Bahawalnager



East Sadiquia Canal
N
TO BAHAWAL NAGAR
TO CHISTIAN MANDI
Marot
Dahranwala
MALIK BRANCH
FATEM DY.
Jandwala
Nalwala
1-R MR.
BHUKAN DY.
SRAJWAH DY.
HAKRA BRANCH
BAKRU SHAH DY.
1-R SUNDER DY.
DUNGA BUNGA
2-R DUNGA DY.
BAHADURWAH MR.
HAJIBWAH MR.
KHATAN DY.
QAZIWALA DY.
1-R/3-R
MURAD DY.
KHATNI DY.
Khalan
4-R HARUN DY.
MUBARAK DY.
HARUNABAD
3-R BAGSAR DY.
1-R BAGRIWALA MR.
SAURKHAN MR.
FAZAL
PAKISTAN
INDIA
R.S

1.5 m to about 18 m. At that time, water table depth ranged from 0-1.5 m over 35 percent of the area, 1.5-3 m over 24 percent, 3- 4.5 m over 10 percent and is in excess of 4.5 m in the remaining part of the area. About 50 % of the Project cultureable command area (CCA) is considered waterlogged (NESPAK, 1992).

The Project area is underlain by sediments deposited by the Sutlej-Hakra river system. The unconsolidated sediments are mainly composed of fine to medium sands and discontinuous lenses of silty-clay deposits. Gravel deposits are rare and the alluvial deposits existing in the south -western part of the Project area are covered with fine aeoian sands derived from adjacent arid lands. Some aeoian sands are also found scattered throughout the project area. The Quaternary alluvial sand deposits are the principal conveyors of groundwater (Feasibility Report, 1978).

About 12 percent of the project area has a salinity value high enough to prevent crop cultivation. It is estimated that by the year 2000 about 50 % of the CCA will have a water table depth of less than 1.2 m and an EC of more than 8 dS/m . By the year 2010 this area is expected to increase to 65 % (Feasibility Report, 1978).

The major crops of the area are wheat, cotton, sugarcane, fodder and rice. Crop yields however, are low; yields in the area are: rice 1.6, cotton 1.3, wheat 1.9 and sugarcane 30 t/ha. Inadequate water supply in the project area is a continuing problem (SMO, 1993).

1.3 Modeling

There are many groundwater flow problems for which analytical solutions are difficult. The reason is that these problems are complex, possessing non-linear features that cannot be included in analytical solutions. Owing to the difficulties of obtaining analytical solutions to complex groundwater flow problems, there is a need for simpler techniques that enable meaningful solutions.

Such techniques exist in the form of mathematical or numerical modeling. Numerical modeling and simulation of groundwater flow is an essential analytical tool for water resource planning and management. Recent developments in numerical methods for groundwater hydrology, when coupled with the results of field observations and investigation, provide powerful as well as reliable information for prediction and management of groundwater behavior. The finite difference method of approximating the solution of differential equations is fairly simple. It replaces the partial differential equations for two-dimensional flow in an aquifer by an equivalent system of finite difference equations which are solved in short time steps by a computer (Boonstra and de Ridder, 1990).

The Standard Groundwater Model Package "SGMP" (Boonstra and de Ridder, 1990) was developed for a study conducted during the Schedule 1-B period of the Fourth Drainage Project (FDP) Faisalabad, in which eleven sump units were installed. The Fourth Drainage Project lies in the southwestern part of the Rechna Doab, located in the Faisalabad district of the Punjab Province, Pakistan. A horizontal subsurface PVC pipe drainage system for an area of 30,350 hectares was installed. The objective of that study was to establish a better drainage design procedure as well as methodology for the assessment for drainage surplus for an irrigated area (Boonstra and Bhutta, 1996). Research at that project has revealed that accurate assessment of the drainage surplus is a major problem because natural conditions are diverse and different water sources are involved in contributing to the drainage surplus. Experience at the FDP has indicated that much more effort should be undertaken to estimate, refine, and verify the drainage coefficient used for proper design and operation of a drainage system.

The regional groundwater study at Fordwah Eastern Sadiqia (South) is different in nature from the FDP. New elements have to be incorporated i.e. i) simulation of seepage from branch canals, ii) influence of canal interceptor drains , iii) influence of canal lining, iv) influence of improved surface drainage and v) influence of evaporation ponds.

Experience gained from the FDP will be useful. The SGMP will be altered as necessary and used in the Fordwah Eastern Sadiqia (South) Project (FESS), Bahawalnager.

1.4 Objectives

1. Assessment of historical net recharge values for the period of June 1994 to June 1997 by running the numerical groundwater simulation model (SGMP) in inverse mode.
2. To identify areas in greatest need of drainage.
3. To forecast watertable levels as a function of time.

1.5 Need of the study

Briefly the information obtained by this study can be useful in the following ways:

i) By identifying the areas most in need of drainage. This will reduce the need for expensive sub-surface drainage projects and minimize environmentally harmful effects.

ii) The results of this study will be helpful in comparing, evaluating and assessing the contribution of different recharge & discharge components.

iii) This study will help in the traditional decomposition approach for calculation of groundwater recharge, where the results of the planned canal seepage studies can be integrated for their effect on the drainage needs of the area.

iv) This study will help to refine and verify the drainage coefficient to be used for design of the sub-surface drainage systems.

v) The model developed can be used to forecast and then to monitor the performance of the Phase-II of the Fordwah Eastern Sadiqia (South) Project, Bahawalnager.

vi) The model can be used to predict the occurrence of future waterlogging and salinity in the canal command area.

CHAPTER II

LITERATURE REVIEW

2.1 Water balance

The hydrological or water balance equation derived from the law of conservation of mass, as applied to the hydrological cycle, states that in a specific period of time all water entering a specific area must either be stored within its boundaries, for consumption therein as well as export therefrom, or flow out over and under the ground (Brown et al., 1972). Water balance analyses are among the various prerequisites to calculate drainable surplus of a particular area (i.e. drainage requirement). The general representation of a water balance according to the hydrological equation is as follows:

Change in storage = Inflow - Outflow

Each of these three components, namely inflow, outflow, and change in storage are inherently diverse. For example, inflow is comprised of surface water inflow, groundwater inflow, and imported water, whereas outflow includes surface water outflow, groundwater outflow, evapotranspiration, and exported water. A change in storage could result from an alteration in surface water storage, groundwater storage, or soil water storage. These parameters (surface water inflow & outflow and evapotranspiration) except changes in groundwater inflow, outflow, and storage can readily be measured with a fair degree of accuracy. Accurate estimation of changes in groundwater inflow, outflow, and storage is limited by the need for frequent qualitative and quantitative measurements of watertable. An appropriate knowledge of spatial variation in effective porosity of the soil experiencing watertable fluctuations has also to be considered. This conservation of mass approach can only be used if an accurate determination of all the components is possible (De Ridder and Boonstra, 1994). In the case of missing component/data, a valid method must be used to input a value. Water balance studies are usually required for those irrigated areas that partially include a river catchment or a physical groundwater reservoir. The surface and sub-surface inflow across the vertical planes of these boundaries must also be taken into account (De Ridder and Boonstra, 1994). Once the precise data has been obtained for each of the hydrological components, an overall water balance can be made (De Ridder and Boonstra, 1994).

Any waterbalance method has four characteristic features. They are:

a to assess the water balance for any subsystem of the hydrological cycle,

b to check whether all flow and storage components involved have been considered quantitatively,

c to calculate any unknown component of the balance equation, provided that the other variables are known with sufficient accuracy,

d to develop a model for predicting subsequent effects caused by changes in one or more components of the system or subsystem.

An overall water balance calculation can be broken into three sub-systems 1) an unsaturated zone (soil water sub-system) where the voids include a mixture of water, vapor & air 2) at the land surface (surface water sub-system) and 3) the saturated zone (groundwater sub-system) where each void space is filled with water (Sen, 1995).

2.1.1 Water balance of the unsaturated zone

The water balance for the unsaturated zone (i.e. the voids filled with a mixture of water, vapor, and the air) can be expressed by employing the following equation (McWhorter and Sunada, 1988).

$$(I - E - T - W)\ \Delta t = \Delta \left(\int_0^D \theta \, dz \right) \tag{1}$$

Where **I**, **E**, **T**, and **W** denote the rate of infiltration, evaporation, transpiration, and flow across the lower boundary of an unsaturated zone, respectively. The right hand side of the equation represents the change in storage in the soil-water subsystem.

Where

D = depth of the soil-water zone

θdz = soil moisture content as a function of depth

Δt = The computation interval of time (d)

Recently, de Ridder and Boonstra (1994) reported the following equation for the unsaturated zone;

$$\mathbf{I - E + G - R = \Delta W_U / \Delta t} \qquad (2)$$

Where

I = the rate of infiltration into the unsaturated zone (mm/d)

E = the rate of evapotranspiration from the unsaturated zone (mm/d)

G = the rate of capillary rise from the saturated zone (mm/d)

R = the rate of percolation to the saturated zone (mm/d)

ΔW_U = the change in soil water storage in the unsaturated zone (mm)

Δt = The computation interval of time (d)

The common assumption is that the flow direction in the zone is mainly vertical and thus lateral flow can be neglected for the water balance. Recently, Hassan et al. (1996) reported a mass balance equation for the unsaturated zone used to estimate groundwater recharge in Rechna Doab, Pakistan:

$$\mathbf{I - EP - T - DP = \Delta SMS} \qquad (3)$$

Where

I = the infiltration from upper sub -system.

EP = the evaporation from this sub-system.

T = the transpiration through plants.

DP = the deep percolation which enters the groundwater system.

ΔSMS = the change in soil moisture storage.

All the parameters are the same except that de Ridder and Boonstra (1994) have included the capillary rise from the saturated zone.

2.1.2 Water balance at the land surface

Because the rate of infiltration (I) in equation 2 is a recharge into the unsaturated zone, its values are related to the inflow and outflow components of the surface water balance. These components are:

- water reaching the land surface via precipitation;
- water entering and leaving the water balance area by lateral surface flow;
- water evaporating from the land surface.

The difference between these components results in changes to surface water storage. Infiltration in the unsaturated zone can be expressed by the following equation; de Ridder and Boonstra (1994).

$$I = P - E_O + 1000 \{ (Q_{si} - Q_{so}) / A \} - \Delta W_s / \Delta t \qquad (4)$$

Where

P	= precipitation for the time interval (mm/d)
E_O	= evaporation from the land surface (mm/d)
Q_{si}	= lateral inflow of surface water into the water balance area (A) (m^3/d)
Q_{so}	= lateral outflow of surface water from the water balance area (A) (m^3/d)
A	= the water balance area (m^2)
ΔW_s	= the change in surface water storage (mm)
Δt	= The computation interval of time (d)

In irrigated areas, the major input and output of a water balance are usually determined by two artificial components, namely the application of water required for irrigation and leaching as well as the removal of excess irrigation water (surface drainage) and excess groundwater (subsurface drainage).

2.1.3 Groundwater balance

The water balance for the saturated zone (groundwater sub system) is called the groundwater balance. Bear (1979) has reported the following equation for a regional groundwater balance.

{ Groundwater inflow } - { Groundwater outflow } + { Natural replenishment from precipitation } - { Return flow } + { Artificial recharge } + { inflow from streams and lakes} - { Spring discharge } - { Evapo-transpiration } - { Pumpage and drainage } = { Increase in volume of water stored in aquifer } (5)

De Ridder and Boonstra (1994) have reported a more elaborate form for the water balance of the saturated zone.

$$R - G + 1000\,\{(Q_{gi} - Q_{go})/A\} = \mu\, \Delta h/\Delta t \qquad (6)$$

Where

R = the rate of percolation into the saturated zone (mm/d)

G = the rate of capillary rise from the saturated zone (mm/d)

Q_{gi} = $(Q_{gih} + Q_{giv})$; the total rate of groundwater inflow into the shallow unconfined aquifer (m^3/d).

Q_{go} = $(Q_{goh} + Q_{gov})$; the total rate of groundwater outflow from the shallow unconfined aquifer (m^3/d).

Q_{gih} = the rate of horizontal groundwater inflow into the shallow unconfined aquifer (m^3/d).

Q_{goh} = the rate of horizontal groundwater outflow from the shallow unconfined aquifer (m^3/d).

Q_{giv} = the rate of vertical groundwater inflow from the deep confined aquifer into the shallow unconfined aquifer (m^3/d).

Q_{gov} = the rate of vertical groundwater outflow from the shallow unconfined aquifer into the deep confined aquifer (m^3/d).

μ = the specific yield or effective porosity, as a fraction of the volume of soil (unitless).

Δh = the rise or fall of the watertable during the computation interval (mm)

Δt = the computation time interval (day).

A = the water balance area (m^2).

Boonstra and Bhutta (1996) and Boonstra et al., 1996 have reported the following equation of groundwater balance for an unconfined aquifer (Figure 2.1). Note this is the general equation used in the thesis for making the waterbalance. Details of each component are derived / used in equation 18.

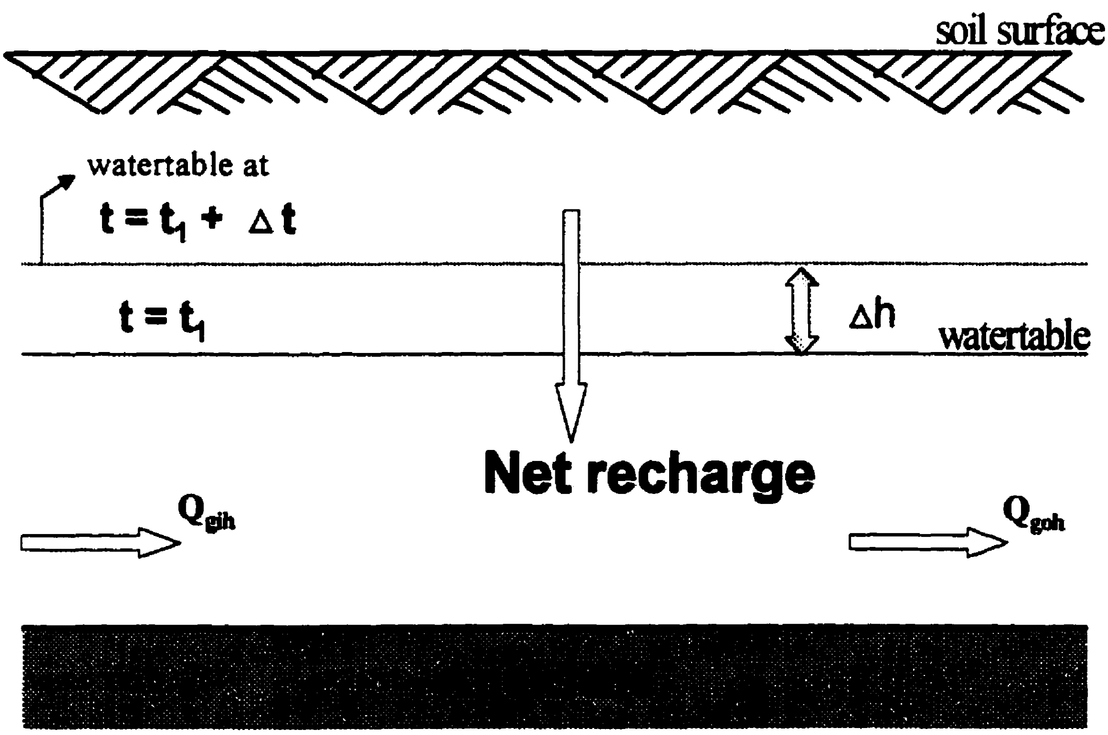


Figure 2.1 Groundwater-balance components of an unconfined aquifer

$$q_n + (Q_{gih} - Q_{goh})/A - \mu\,(\Delta h/\Delta t) = 0 \qquad (7)$$

Where

q_n = the net recharge to the aquifer (day $^{-1}$)

Q_{gih} = the lateral subsurface inflow (m^3 day $^{-1}$)

Q_{goh} = the lateral subsurface outflow (m^3 day $^{-1}$)

μ = the specific yield or effective porosity, as a fraction of the volume of soil (unitless)

Δh = the rise or fall of the watertable (m)

A = the water balance area (m^2)

Δt = the computation time interval (day)

In irrigated areas, the watertable in the unconfined aquifer can be higher than the piezometric surface of an undelaying confined aquifer. Therefore, downward seepage from the shallow to the deep aquifer should be included in the water balance. In many studies the total groundwater outflow is equivalent to the sum of horizontal and vertical outflows. In contrast, Hassan et al. (1996) considered net lateral flows, to and from the system, as non-significant in the following equation.

$$\mathbf{RR + RLC + DP - AGWP - GFD - ET = \Delta GWS} \tag{8}$$

Where

RR = recharge from rivers

RLC = recharge from link canals

DP = deep percolation from the upper system (unsaturated)

AGWP = actual groundwater withdrawal via pumpage

GFD = groundwater flow toward the surface and sub surface drain

ET = evaporation losses directly from the groundwater table

ΔGWS= the change in groundwater storage.

Finally, in Kashef (1986) the following groundwater budget equation is reported along with references to Schicht and Walton (1961):

$$\mathbf{I - O = R_g - \{ Q_g + (ET)_g + Q_{sub}\} = \pm \Delta S_g} \tag{9}$$

Where

I = inflow is the groundwater recharge R_g

O = outflow consists of the groundwater runoff Q_g

ET_g = groundwater evapotranspiration

Q_{sub} = subsurface underflow

ΔS_g = change in groundwater storage

De Ridder and Boonstra (1994) suggest that the horizontal groundwater inflow and outflow can be determined through the boundaries of the irrigated areas. This could be accomplished by using watertable contour maps, which suggest the direction of groundwater flow and hydraulic gradient and by considering aquifer transmissivity at the boundary. Upward and downward seepage can be determined through an underlying semi-confined layer, change in storage by using hydrographs, and the specific yield or drainable pore space of the shallow aquifer. A water balance for larger areas can be obtained by subdividing the basin into smaller hydrogeological zones. De Ridder and Boonstra (1994) showed that the yearly water balance for an entire basin can be obtained by adding monthly water balances from these sub-areas. Appropriate basin discretization requires knowledge of sufficient and accurate data on watertable fluctuations throughout the basin, the specific yield of the unsaturated zone, and thickness and hydraulic conductivity of the saturated zone. Normally to discretize a groundwater basin into sub-areas or nodal areas, a network polygon is created.

2.2 Design of a nodal network

Boonstra and de Ridder (1990) virtually rule out the possibility of occurrence of any hard and fast rules to design and apply a nodal network. But generally, a nodal network can be designed in two phases. The first being the choice of the nodal size and location of external boundaries of the area and the approximate number and distribution of the nodes. The second phase is composed of actual construction of the nodal network. In general, the area studied should include all major recharge areas and all areas of major pumping or outflow. The number and distribution of nodes depends upon the study area, size of the computer, the model to be used and above all, the finances available. Because of the spatial and temporal variability of geological and hydrogeological conditions, nodal network designs are usually basin as well as problem specific.

Tyagi et al. (1993) incorporated the guidelines presented by Boonstra and de Ridder (1990) to design a nodal network for the development of a groundwater simulation model for predicting watertable levels in the Lower Ghaggar Basin in Bukar, India. Moghal et al. (1992) used the Thiesan polygon method for designing a nodal network to simulate seasonal net recharge to an aquifer underlying the schedule I-B of Fourth Drainage Project Faisalabad, Pakistan. Boonstra and de-Ridder (1990) and Moghal et al. (1992) stress the significance of the following factors when designing a nodal network.

i) type of problems to be solved;
ii) boundaries of the model area;
iii) homogenity or heterogenity of the aquifer;
iv) availability of data;
v) number of nodes.

2.2.1 Type of problems to solve

Hydrologic challenges to be faced can be regional or local, simple or complex and reconnaissance or detailed in nature. A reconnaissance study of a large groundwater basin will require a network with a large mesh; a detailed local problem will require a network with a small mesh. Moghal et al. (1992) describe the specific requirements for the design of a nodal network to incorporate the influence of different sump units in the FDP study area of Pakistan. However, Boonstra (1993) reported that the development of a more dense network for the Fordwah Eastern Sadiqia (South) Project Bahawalnager, Pakistan will result in a dramatic increase in manpower requirements.

2.2.2 Boundaries of the model area

One of the most important and difficult problems is the delineation of boundaries for the external nodes. The internal boundaries along with the hydrogeological conditions pose no specific requirement on the nodal network. Conversely, different types of external boundaries exist, and these may or may not be a function of time. These can be zero flow boundaries, head controlled boundaries and flow controlled boundaries. Boundaries at the external nodes of the groundwater simulation model in question have been identified as flow controlled (Tyagi et al., 1993). Nevertheless, the groundwater basin is not an isolated one and its boundaries in reality extend well beyond the study area. Moghal et al.(1992) confined their model area between the two main canals (Lower Gugera Branch canal & Burala Branch canal) FDP, Pakistan in order to include seepage losses. Their influence was indirectly incorporated via the historical data of observed watertable elevations, which were presented to the model as so called head controlled boundaries. Boonstra (1993) indicated two approaches to simulate canals seepage for the nodal network of the Fordwah Eastern Sadiqia (South) Project, Bahawalnager. In the first approach, nodal network can be extended beyond the Malik and Hakra branch canals and the external nodes can act as head controlled boundaries. In the second approach, the Malik and Hakra branch canals can act as boundary mirror images thereby simulating their influence on the watertable behavior as flow controlled boundaries.

2.2.3 Homogeneity or heterogeneity of the aquifer

According to water-transmitting properties, subterranean strata have been classified as aquifers, aquitards or aquicludes. Generally, vertical flow in aquifers, horizontal flow in the aquitards, and both vertical and horizontal flow in aquicludes are small enough to be neglected. The four main types of aquifers are: the confined aquifer, the unconfined aquifer, the leaky aquifer, and the multi-layered aquifer. Few aquifers are homogenous over their lateral extent. In aquifers that show a clear transition from unconfined to partly confined, an adjustment in the network pattern should be adopted.

The proposed study area is a part of the vast Indo-Gangetic Plain formed by sediment deposition in the geosyncline created during the Himalayan Mountains orogeny of Tertiary times. The present stratigraphy is the result of wind and water action that operated during the Pleistocene period. These Pleistocene deposits were placed in a subsiding basin by the Indus

River and its tributaries, giving rise to a thick accumulation of stratified sedimentary deposits (Feasibility Report, 1978). The south-western part of the area is covered by aeolian deposits commonly occurring as dunes and are composed of well-sorted and well-rounded sand and silt. These aeolian deposits generally occur above the watertable. The sediments underlying the project area are principally composed of loose sand, silt and clay (Feasibility Report, 1978). Generally, the silty clay and fine sand formations contain a calcareous layer, locally known as Kankar. The alluvium is highly heterogeneous consisting of poorly stratified beds and lenses. The thickness of the unconsolidated alluvium in the project area is not known precisely. The Quaternary alluvial sands are the principal source of groundwater. These aquifers are composed mainly of fine to medium alluvial sands. In spite of the local heterogeneities, on the large scale, these aquifers behave as homogeneous aquifers under watertable or semi-confined conditions. Bundesansalt fur Geowissenschaflen und Rohstoffe (1992) conducted a number of aquifer tests in the groundwater zone near Fort Abas that lies outside the project area along the southern boundary. The following table presents an overview of the resulting aquifer parameters of the relevant sites.

Table 2.1 Results of aquifer parameters for the Fort Abbas groundwater zone

Location	Transmissivity (m^2/d)	Storativity (-)
T/W-14	340	6.6×10^{-3}
T/W-1	240	9.2×10^{-4}
T/W-2	210	3.6×10^{-4}
T/W-3	380	6.3×10^{-4}
T/W-4	310	4.9×10^{-4}
T/W-12	490	1.3×10^{-3}
T/W-5	1220	8.6×10^{-4}

Site T/W-1 is near to FortAbbas and T/W-5 is near Marot. The results of the aquifer test data revealed a semi-confined aquifer system with transmissivity and storativity values of 210 to 1220 m^2/d, 3.6 (10^{-4}) to 9.2 (10^{-4}), respectively.

Khalid and Riaz (1992) conducted two aquifer tests located within the project area and results of these tests also suggest a semi-confined aquifer system with a transmissivity value of 450 m^2/d and storativity of 10^{-4}. On the other hand, NESPAK-NDC (1988) conducted two aquifer tests within the project area and observations indicated the occurrence of an unconfined aquifer system with transmissivity ranging from 1200 to 1500 m^2/d.

NESPAK (1991) conducted another two aquifer tests within the project area and results also indicated an unconfined aquifer system but the transmissivity ranged from 700 to 950 m^2/d. Kamal and Shamsi (1965) conducted 21 aquifer tests located just west of the project area. No data for transmissivity or storativity were reported except that the aquifer system was characterized as unconfined with unknown thickness (more than 300m).

The reported values of the aquifer properties indicate both spatial variability in the aquifer parameters as well as different aquifer types. More pumping tests are required. An integrated research plan (UTG, 1994) reported that three additional tests are required, whereas Boonstra (1996) suggests that at least five more are required.

Dettingger and Wilson (1981) discuss information uncertainty which results from a lack in quantity and quality of information concerning an aquifer system. Estimates of various properties or descriptive parameters of a system will generally contain inaccuracies, both small and large. Another source of uncertainty is due to the appropriateness of a model and the completeness of the governing equations. Delhomme (1979) reported that if transmissivity data are too scattered or inaccurate, further investigation is required.

Three methods (Theis, Jacob, and Hantush) for evaluating aquifer and single-well tests in confined, leaky, and unconfined aquifers have been incorporated in the program package SATEM (Boonstra, 1989) used for many studies in Pakistan & India. This is the package chosen for use in this thesis.

2.2.4 The availability of data

The availability of data posed no specific requirement for the design of the nodal network, because the type of the problem dictated the data requirements. In larger groundwater basin studies, data may not be available with the same consistency in all parts of the basin. In remote sectors of it, data are likely to be scarce. If so it makes little sense to use small nodal sizes in these locations. Small nodal sizes require more data, but since these are not available, averages or estimates would have to be substituted.

Moghal et al. (1992) and Boonstra et al. (1994) used existing data for use in the model for a groundwater study at FDP Faisalabad, Pakistan. This data watertable elevation was collected by the SCARP Monitoring Organization (SMO) and WAPDA for five year semi-annually. A major consequence of that study was that only seasonal water balances could be assessed. This experience led to the recommendation that watertable elevation should be collected on a monthly bases with an accuracy within a 4-6 cm..

2.2.5 The number of nodes

There is much discussion in the literature on the number of nodes required to model an aquifer. Rushton and Redshaw (1979) reported the possibility of using 500 to 2000 nodes. However, Boonstra and de Ridder (1990) suggested following the advice of Thomas (1973) of restricting the number of nodes to 10 or 15 in the case of a first estimate. Available funds may also restrict the number of nodes. Anderson and William (1992) emphasized the need to minimize the number of nodes that fall outside the boundaries (inactive nodes) of the modeled area in a finite difference model. Finite element models do not have any inactive nodes, because the elements are fitted exactly to the boundaries and it is critical to approximate the boundaries as closely as possible. Moghal et al.(1992), Boonstra et al. (1994,1997), Boonstra and Bhutta (1996), and Rizvi et al. (1996) used a network of 56 nodes for the groundwater study at FDP Pakistan, out of which 24 external nodes acted as boundary conditions and the remaining 32 nodes represented the internal nodal areas, which varied in size from 0.3 to 3.0 km^2 with an average size of 1.6 km^2. These internal nodal areas represented the study area and comprised some 66 km^2. On the other hand, Tyagi et al. (1993) used 24 nodes for the nodal network of groundwater simulation for planning salinity control in the Lower Ghaggar basin, Karnal, Haryana India. Out of these, only 9 were internal nodes; the 15 external nodes acted under a flow control state. The area of each polygon ranged between 412.5 to 622.5 km^2 and the total nodal network area comprised some 5000 km^2.

2.3 Development of a groundwater balance Model

There are many types of groundwater models, both steady state and unsteady state. In the case of a steady state model, the groundwater flow is assumed to be unchanging, i.e the hydraulic heads do not change with time, and the change in storage is equal to zero. Steady state models are often used in situations with simple or consistent hydrologic conditions. Whereas in the case of unsteady state models, the hydraulic heads are assumed to change with time. This approach is usually better for the simulation of actual groundwater systems. They require far more input data than do steady state models. For both types of models, the inputs are: geometry of the aquifer system, type of aquifer, hydraulic characteristics and hydrologic inflows and outflows.

De Ridder and Boonstra (1994) reported on a saturated zone model which simulated two dimensional horizontal flow. They discretized the aquifer system into a network of nodal areas. To each nodal area, values for the thickness of the aquifer, the saturated hydraulic conductivity, and the specific yield or storage coefficient were attributed. In addition, they assigned values for the initial pressure heads in each nodal area and for the boundary conditions at the top and lateral sides (boundary conditions).

Based on the theory of potential for transient recharge, Singh et al. (1996) developed a finite element model with which to study watertable fluctuations and recharge in infinite aquifers. The model has been validated by comparing simulation results with data reported in the literature. The study indicated that a finite element model can be used as an effective numerical tool to study the response of a watertable when subjected to a variable recharge rate. Many other authors such as Freeze and Witherspoon (1966) Pinder and Frind (1972), Gray and Pinder (1976), Gorelick (1983), McWhorter and Sunada (1988) report that finite difference models are easily understandable. Their reports provide viable procedures for evaluating the behavior of groundwater from the mathematician's view point.

The numerical solution procedure of finite differences is fairly simple and straight forward. However, the application of a model to a given physical system can be complex and requires considerable judgement and skill in setting up the problem and in interpretation of results. Gray and Pinder (1976) compared the finite difference and finite element methods for the solution of a partial differential equation. The truncation error of the finite element equation at a node was assessed by considering the interaction between all the equations which applied to the domain spanned by the basis function of that node. In contrast to finite difference procedures, in which the accuracy of the solution is the same at all nodes, the accuracy of the finite element solution is dependent upon the type of node under consideration.

2.4 Finite difference models

Moghal et al. (1992) reported that the development of a groundwater simulation model requires that both time and space should be discretized and that their numerical model could be used to determine the seasonal net recharge to an aquifer. Boonstra and Bhutta (1996) indicate that the process of setting up water balances for an area can be complicated and time consuming. Spatial variation in the magnitude of the contributing components can make it necessary to split the study area into various sub areas. Each of the sub areas require a separate water balance and these problems can be solved with the use of a numerical simulation model. Sophocleous and McAllister (1987) point out that the direct measurement of groundwater recharge provides only point information. Subsequently, more means must be used to regionalize this point data. Furthermore, observations on groundwater recharge, measured by standard techniques are rarely available on a network basis. Therefore the basin should be divided into unit areas. In the study of Sophocleous and McAllister (1987) the basin was divided into climatic subregions using a Thiessen type polygon technique. An integrated methodology was used to obtain a daily water balance within the 1982-1983 period. The daily values were then used to calculate the water balance components.

A standard Groundwater Model Package (SGMP) was developed for groundwater studies at the Schedule 1-B area of the Fourth Drainage Project, Faisalabad Pakistan and run in inverse mode. In inverse mode, depth to water-table data of 56 observation wells read twice per year for the period of 1985-1990 (Monsoon and non-monsoon) alongwith aquifer characteristics were used to determine the seasonal net recharge (Moghal et al., 1992; Boonstra and Bhutta, 1996 ; Boonstra et al., 1994, 1997). Afterwards, Rizvi et al.(1996) applied the same numerical groundwater model in the same area to determine the monthly net recharge with monthly depth to watertable data of observation wells. Boonstra et al. (1994,1997) Boonstra and Bhutta (1996), and Rizvi et al. (1996) have calibrated the same model (SGMP) with the following three criteria:

i) minimum difference between seasonal nodal net recharge values resulting from inverse modeling and those calculated with the traditional waterbalance approach (water balance with magnitude of recharge & discharge for each component),

ii) minimum difference between watertable elevations as simulated by SGMP in the normal mode, and those observed in the field using the nodal net recharge values from the traditional waterbalance approach, (Note: this approach used in section 4.5 for checking of model results where nodal net recharge values obtained from inverse mode),

iii) minimum differences between seasonal average recharge values obtained from inverse modeling and those calculated with the traditional waterbalance approach from normal mode..

Anderson and William (1992) emphasized making comparisons between contour maps of measured and simulated heads which can provide a visual, qualitative measure of the similarity between patterns and also gives some idea of the spatial distribution of error in the calibration. But this should not be used as the only proof of calibration. A listing of measured and simulated heads together with their differences and some from of average of the differences is a common way of reporting calibration results. The average of the difference is then used to quantify the average error in calibration. Three ways of expressing the average difference between simulated and measured heads are commonly used; the mean error, mean absolute error and the root mean squared error or the standard deviation. The calibrated results can be used in the model for predictions but a number of possible scenarios should be simulated to reflect uncertainty in future events. Results the modeling efforts may be presented graphically or in the form of contour maps.

An integrated water management model was developed (Boonstra et al., 1996) and linked with an unsaturated flow model and a groundwater simulation model for the groundwater study for Sirsa district, Haryana (India). The model was applied to an area of 4200 km^2 and was calibrated on the basis of observed historical watertable levels for the period ranging of 1977 to 1981 by making adjustments in a number of spatially distributed input parameters. The integrated model was subsequently tested for the observation period of 1982 to 1991. In 1984, Alley has examined several (two- to- six) parameter regional water balance models by using 50-year record at 10 sites in New Jersey. Some problems in parameter identification are noted. For example, difficulties in identifying an appropriate time lag factor for basins with little groundwater storage. One of these model 'abcd' (Alley, 1984) resulted in a simulated seasonal cycle of groundwater levels similar to the fluctuations observed in wells. The results suggest that extreme caution should be used while attaching physical significance to model parameters.

Tyagi et al. (1993) applied an exiting groundwater simulation model (developed by Tyson and Webber, 1964) to predict watertable behavior and calibrated the model with historical data. The verified model has been used to predict watertable levels up to 2000 A.D.

Gates and Kisiel (1974) pointed out certain errors associated with mathematical assumptions in basic data of groundwater modeling. Errors due to interpolation, and due to nonrepresentative data are significant problems. Also, the coefficient of storage and the specific yield are difficult to know precisely. Reduced specific yield could be because of slow drainage of water from sediments. Moreover, the occurrence of errors in initial water levels results in errors in final water levels and the use of more than one historical period of time used in calibrating the model can lead to modeling errors.

2.5 Review of model SGMP used

Groundwater models are based on two well known equations, Darcy's equation and the equation of conservation of mass. The combination of these two equations results in a partial differential equation that can be solved approximately by a numerical approach. The two best known approximate methods are the finite difference method with or without an asymmetric grid and the finite element method (Zaradny, 1993). These methods require that the space should be divided into small but finite intervals. The sub areas thus formed are called nodal areas. In 1989, Goodwill modified the Tyson and Weber model (1964) and termed it a multiple cell approach which incorporated the best features of finite difference and finite element approaches.

Taylor (1974) reported that in the finite difference method the initial condition must be known for every point in the mesh. The accuracy of a finite difference model largely depends upon the sizes of the mesh and time increments. A finite difference model converges if the solution approximates more and more closely the true solution as the mesh and the time increments become smaller. This approach permits use of polygons of regular and irregular shape, each being treated as a reservoir capable of receiving, yielding and storing water. The polygon can give water and receive water from adjacent polygons by subsurface flow of externally by pumping and recharge. These flows must satisfy the equation of continuity and Darcy's law (Goodwill, 1989). Moreover, Boonstra and de Ridder (1990) reported that each nodal area must have a node which is used to connect mathematically with its neighbors and it can be assumed that all recharge and abstraction in a nodal area occur at that node ; in other words, each node is considered to be representative of its nodal area. To each node a certain storage coefficient or specific yield is assigned, which can be constant and representative for the nodal area. Also, a certain hydraulic conductivity can be assigned to the boundaries between nodal areas, thus allowing directional anisotropic conditions.

Many authors, including Boonstra and de Ridder (1990), Moghal et at.(1992), Boonstra et al.(1994, 1996, 1997), Boonstra and Bhutta (1996), and Rizvi et al. (1996) have applied a numerical groundwater model which is an updated version of the standard Groundwater Model Package, SGMP (Boonstra and de Ridder 1990). The SGMP is based on Darcy's law and the equation of conservation of mass. The combination of these equations results in a partial differential equation for unsteady flow (Boonstra and de Ridder, 1990):

$$\partial/\partial \mathbf{x}\ \{\mathbf{KD}\ (\partial \mathbf{h}/\partial \mathbf{x})\}+\partial/\partial \mathbf{y}\ \{\mathbf{KD}\ (\partial \mathbf{h}/\partial \mathbf{y})\}= -\ \mathbf{N} \qquad (10)$$

Where

K (x,y) = hydraulic conductivity of the aquifer for horizontal flow (LT^{-1})

D (x,y,t) = saturated thickness of the aquifer at time t (L)

h (x,y,t) = hydraulic head in the aquifer at time t (L)

N (x,y,t) = source or sink term at time t (LT^{-1})

The first term of Equation 10 represents the horizontal flow in the aquifer and the second term is the vertical flow. Vertical flow (N) consists of different flow components, depending on the type of aquifer (unconfined , confined and semi-confined). This parameter is discussed in more detail below.

(i) N for unconfined Aquifers

$$\mathbf{N = R - P - \mu\ (\partial h/\partial t)} \qquad (11)$$

Where

R(x,y,t) = the net rate of recharge (LT^{-1})

P(x,y,t) = the net rate of abstraction (LT^{-1})

$\mu(x,y)$ = specific yield of the aquifer (dimensionless)

$h(x,y,t)$ = hydraulic head in the aquifer (L)

t = time (T)

During unsteady flow the term μ **(∂h/∂t)** is related to the movement of the free watertable. Watertable movement is an indication of a change in storage. The specific yield μ is defined as the volume of water released or stored per unit surface area of the aquifer per unit change in the component of head normal to that surface. The value of μ for upward and downward movement of the watertable is usually assumed to be equal and gravity yield is assumed to be instantaneous. In unconfined aquifers the saturated thickness **D** is not a constant, but is a function of the position of the free watertable.

(ii) N for confined Aquifers

$$\mathbf{N = - P - S\ (\partial h/\partial t)} \tag{12}$$

Where

S = Storage coefficient of the aquifer (dimensionless)

For confined aquifers **S** is termed the storage coefficient and is defined in the same way as the specific yield for unconfined aquifers. The saturated thickness **D**, at any one location of a confined aquifer, is constant.

(iii) N for semi-confined Aquifers

In this case there are two differential equations , one for the aquifer itself and another for the covering strata. Also, **N** is the sum of three terms.

$$\mathbf{N = - P - S\ (\partial h/\partial t) + (K'/\ D')\ (\ h' - h)} \tag{13}$$

Where

K' = the covering strata's vertical hydraulic conductivity (LT^{-1})

D' = saturated thickness of the covering strata (L)

h' = hydraulic head in the covering strata (L) and the other symbols are already defined

Vertical flow through the covering strata is caused by the head difference between the water in the covering strata and that in the underlying aquifer. At any one location the saturated thickness **D** of the aquifer is constant. For the covering strata flow there is a one-dimensional differential equation.

$$\mathbf{R} - \mu'(\partial \mathbf{h}/\partial \mathbf{t}) = (\mathbf{K}' / \mathbf{D}')(\mathbf{h}' - \mathbf{h}) \tag{14}$$

Where

μ' = specific yield of the covering strata (dimensionless)

The covering strata layer has a free watertable, thus its saturated thickness **D′** is not constant with respect to time.

2.5.1 Numerical approach used in SGMP

Boonstra and de Ridder (1990), Moghal et at. (1992), Boonstra et al. (1994, 1996,1997), Boonstra and Bhutta (1996) and Rizvi et al. (1996) reported that in SGMP the discretization in space is done with a nodal network. A distinction is made between internal and external nodes. Each internal node represents a particular nodal area, whereas the external nodes act as boundary conditions. The aquifers underlying the study areas are part of a larger physical groundwater reservoir, so that the location of external boundaries can be considered as arbitrary and artificial. In all the studies listed above the model area was confined to a region between two canals except for the groundwater study located at Sirsa District, Haryana (India). Seepage losses were incorporated by historicaly observed watertable elevations along with aquifer characteristics. For the study at Sirsa, two models SIWARE and SGMP were combined . The net recharge towards the aquifer was assessed in the SIWARE model.

In SGMP, instead of using transmissivity, separate values for the hydraulic conductivity and thickness of the aquifer must be supplied. Moghal et al.(1992), Boonstra et al. (1994,1997), Boonstra and Bhutta (1996) and Rizvi et al. (1996) have applied a uniform hydraulic conductivity value to all the nodal areas. This is because there was no indication of a clear spatial variability of this parameter. The aquifer test results did not yield a consistent value for the hydraulic conductivity, three different values 20 , 30 and 40 md^{-1} were used in the groundwater model in the above mentioned studies. Available data on aquifer parameters were too limited to choose a uniform specific yield so three values 5, 10 and 15 percent were adopted in the model. All the authors mentioned above report that the solution of the partial differential equation can be obtained by using a finite difference method. An approximate solution to equation 10 can be obtained by replacing it with an equivalent system of finite difference equations, the solution gives the results of '**h**' at a finite number of nodes. To illustrate this, the finite difference equation for an unconfined aquifer shall be elaborated.

2.5.2 Nodal Geometry

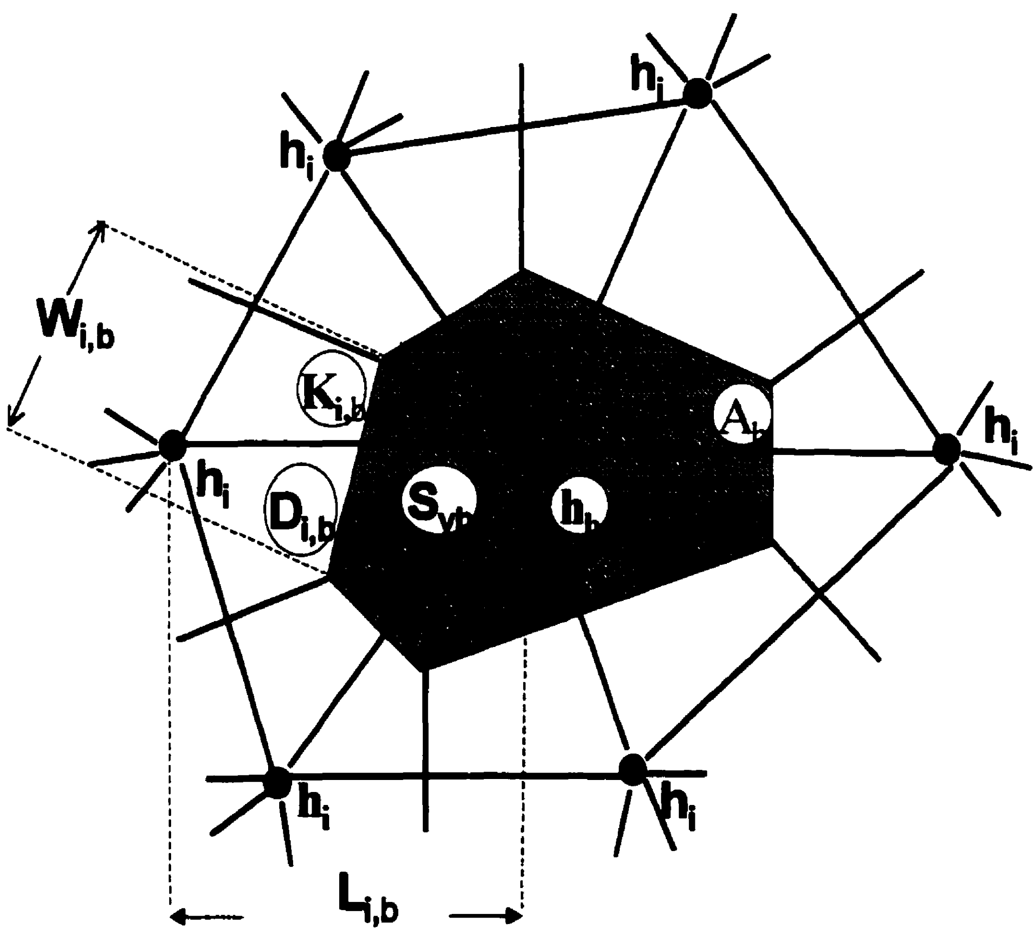


Figure 2.2 Nodal geometry of (node "**b**" at the center) a groundwater model (plain view)

For an arbitrary node **b** of a nodal network (Figure 2.2) the equation for an unconfined aquifer is obtained by combing equations 10 and 11 . This yields:

$$\sum_i (h_i - h_b)[(W_{i,b}K_{i,b}D_{i,b}) / L_{i,b}] = -A_bR_b + A_bP_b + [A_bS_{yb}(dh_b/d_t)] \quad (15)$$

Where

$K_{i,b}$	= horizontal hydraulic conductivity of aquifer across $W_{i,b}$
$D_{i,b}$	= saturated thickness of the aquifer along $W_{i,b}$ (m)
h_i, h_b	= absolute water table elevation at node b and nodes i (m)
$W_{i,b}$	= length of the side between nodes i and b (L)
$L_{i,b}$	= distance between node i and b (L)
A_b	= area associated with node b (L^2)
S_{yb}	= specific yield of the node b (dimensionless)
	other symbols as defined above.

Since the watertable at the node changes with time, owing to changes in recharge and abstraction, the model also requires a descretization of time. A number of successive time intervals have to be chosen and for each time interval the watertable is computed then the calculation is repeated at successive times. Discretizing the time requires that Equation 15 be replaced by:

$$\sum_i \{[h_i\ (t+\Delta t) - h_b(t+\Delta t)]\ [(W_{i,b}K_{i,b}D_{i,b}) / L_{i,b}]\} = \{ -A_bR_b\ (t+\Delta t)$$

$$+ [\ A_bP_b\ (t+\Delta t) + (A_bS_{yb}) / \Delta t\ ]\ [h_b\ (t+\Delta t) - h_b(t)]\} \quad (16)$$

Equation 16 has been solved by an implicit numerical integration technique (Richtmeyer and Morton, 1967).This method of integration has the advantage that the magnitude of the time step, Δt, does not depend on a stability criterion. Some of the principles of Thomas (1973) are used in solving Equation 16.

Initial watertable elevations are assigned to all nodes. At the end of the first time step, Δt, the components of the water balance (Equation 16) are calculated for each nodal area according to the given set of input variables $W_{i,b}$, $K_{i,b}$, $H_{i,b}$, S_{yb}, $L_{i,b}$. This results in a change in the water content for each nodal area. All flows are balanced at each node by setting their sum equal to a residual term. The new watertable elevations at each node are then adjusted by the magnitude of these residuals, as follows:

$$h_b\,(t+\Delta t) = h_b\,(t) + \frac{\textit{residual for nodal area b}}{\sum_{i}^{0} \frac{W_{i,b}\,K_{i,b}\,D_{i,b}}{L_{i,b}} + \frac{A_b S_{yb}}{\Delta t}} \qquad 17$$

These changes in watertable elevations influence the lateral direction & magnitude of groundwater flow from one nodal area to another. If the aquifer is semi-confined, the changes also influence vertical flow through the confining layer.

In the 'inverse mode' SGMP calculates net recharge values for the nodal areas using observed water table elevations at each node as initial & final values. The net-recharge values are based on the following groundwater balance equation which is a more elaborate form of Equation (7) (Boonstra and Bhutta, 1996).

$$Q_{nb} + \sum_{i} [(h_i - h_b)(W_{i,b}K_{i,b}D_{i,b}) / (L_{i,b}\,A_b)] - [\,\mu_b\,(\Delta h_b / \Delta t)] = 0 \quad (18)$$

Where

Q_{nb} = net recharge to aquifer at node b

h_b & h_i = are absolute water table elevation at node b and node i (m)

$W_{i,b}$ = length of nodal area side between nodes i and b (m)

$K_{i,b}$ = vertical hydraulic conductivity of aquifer along $W_{i,b}$ (m day^{-1})

$D_{i,b}$ = saturated thickness of aquifer along $W_{i,b}$ (m)

$L_{i,b}$ = distance between nodes i and b (m) and the other symbols as defined earlier.

μ = specific yield or effective porosity of node b (unitless)

Freeze (1969) has used the term recharge as entry of water into a saturated zone made available at the watertable surface, together with the associated flow away from the watertable within the saturated zone. Whereas, discharge is the removal of water from the saturated zone across the watertable surface, together with the associated flow towards the watertable within the saturated zone. Watertable levels fluctuate when the of groundwater recharge or discharge does not match with the unsaturated flow rate created by infiltration or evapotranspiration.

In SGMP, the convention is that recharge to the aquifer (i.e. downward flow towards the water table and lateral subsurface flow entering a nodal area) is taken as positive, while discharge from the aquifer (i.e. upward flow from the watertable and lateral subsurface flow leaving a nodal area) is taken as negative. So, a $\Delta \mathbf{h} > 0$ indicates a rise in watertable owing to recharge from rainfall and /or irrigation, whereas a $\Delta \mathbf{h} < 0$ indicates a drop in watertable owing to discharge from capillary rise and /or tubewell pumping(assuming no deep seepage losses).

CHAPTER III

METHODOLOGY AND MATERIALS

The Fordwah Eastern Sadiqia (South) Project (FESS) in Bahawalnager, Pakistan, was selected as a study area for the calculation of a groundwater balance for an unconfined aquifer and the refinement of a groundwater model. The groundwater model used is an updated version of the Standard Groundwater Model Pakage 'SGMP' (Boonstra and de Ridder 1990). Numerical groundwater modeling requires a discretization in space. In the finite difference based Standard Groundwater Model Package (SGMP) , this has been achieved with a nodal network. Within this nodal network, a distinction was made between internal and external nodes. Internal nodes represent nodal areas, whereas the external nodes represent boundary conditions. For this approach a nodal network and nodal co-ordinates were designed as described below.

3.1 Wells and Nodal Network

For the groundwater management study at the Fordwah Eastern Sadiqia (South) Project a network of 138 observation wells was designed with the wells placed in a triangular pattern. A standard pipe length of 4 meter was used except for those situated in the evaporation pond (desert area). Typical well construction is shown in Figure 3.1.

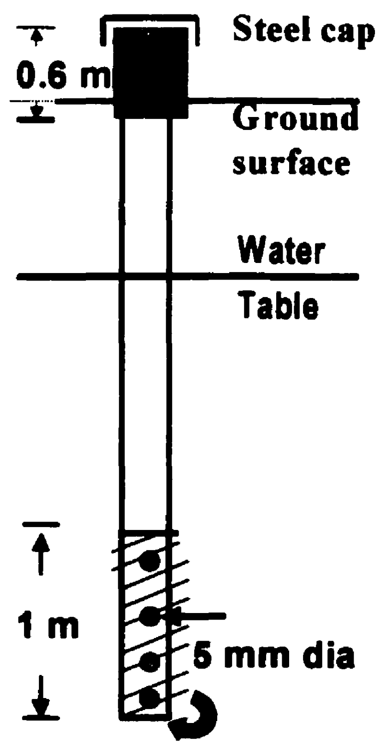


Figure: 3.1 Observation well design

The network was designed in such a way that the observation wells were situated along parallel lines, some 4 to 5 km apart. These lines were oriented perpendicular to the general direction of regional groundwater flow.

Wells were situated in the irrigated part of the project area totaled 125 and the remaining 13 well were located in the Cholistan area (desert area), where the evaporation ponds are expected to be located. Those in the evaporation pond area are not included in this study. All observation wells have been monitored for watertable depth since June, 1994. Of the 125 wells, 23 were located on outer embankments of the Malik and Hakra branch canals. These are to be used to obtain direct data on canal seepage. These 23 and another 57 wells constituted the internal nodes. In addition, 45 external boundary nodes define the outer limits of the study. All observation wells were monitored monthly in a fixed sequence for depth to water table (by two parties from SMO) using electrical sounders.

To discretize the groundwater basin into nodal areas, a network of polygons was superimposed on the area as shown in Figure 3.2. There were no hard and fast rules followed to design the network because varying geological and hydrological conditions demanded some flexibility. The Aquifer underlying the FESS area is part of a larger, physical groundwater reservoir, and the external boundaries of the model area are both arbitrary and artificial. There were two options, either to take north-west and south-east observation wells as head-control boundaries or the Malik & Hakra branch canals as flow-controlled boundaries. The north-west and south-east observation wells were used as external nodes of the nodal network as head-controlled boundaries. For the internal nodes, the hydrogeological conditions posed no specific requirement on the network. To include seepage from canals and its influence on watertable behavior, both canals were considered as internal nodes of the network consisting of nodes coinciding with the locations of the observation wells.

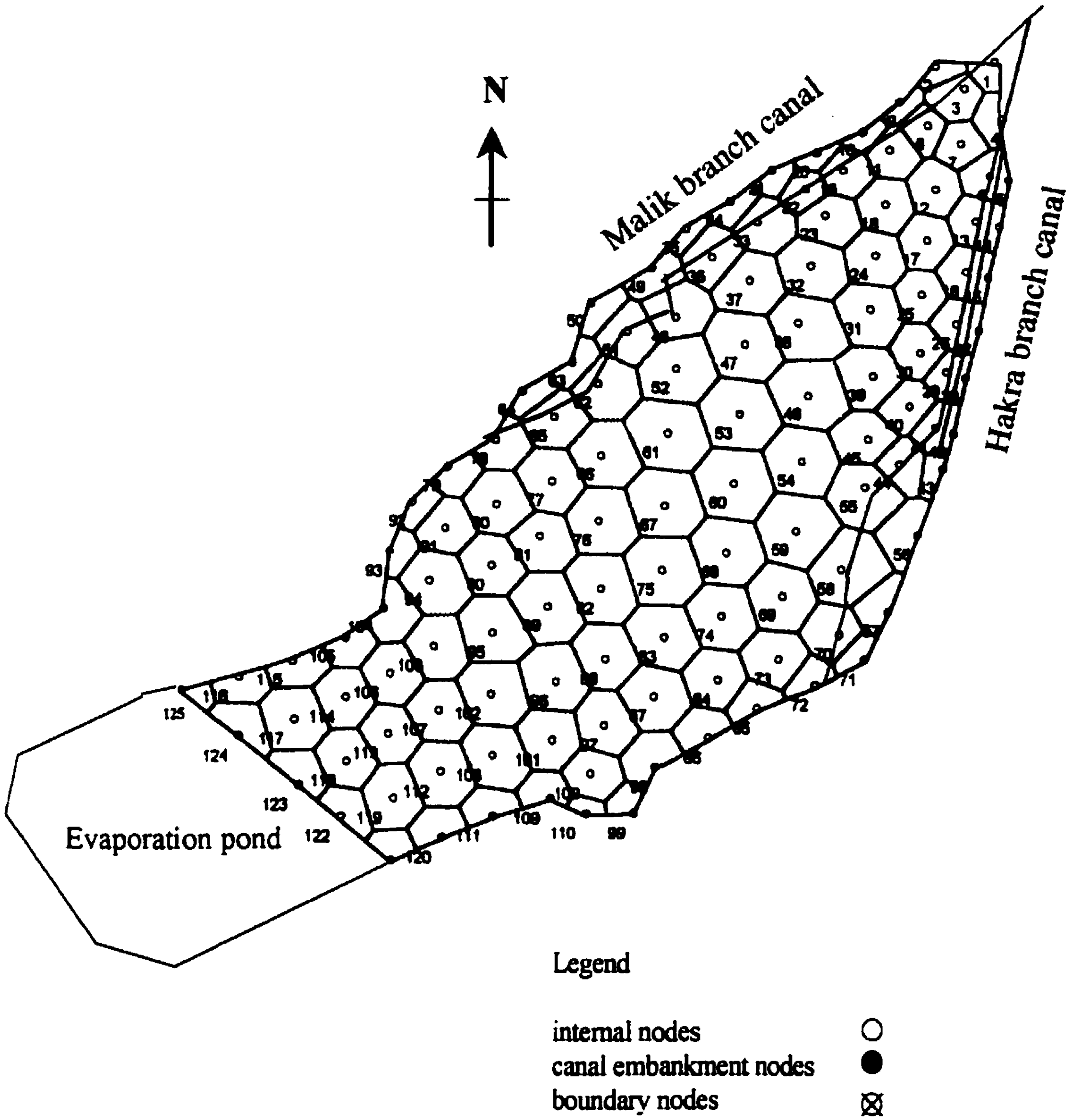


Figure 3.2 Nodal network of groundwater study at FESS, total 125 well sites used as nodes

3.2 Nodal coordinates

To enable the program package to calculate the different flow rates across the boundaries of the nodal areas and the change in storage inside these areas, data are required on: 1) the flow path length between adjacent nodes, 2) the width of cross-sectional area of flow and 3) the surface area of each nodal area. For this purpose a Cartesian coordinate system was introduced on the nodal network map and values prescribed to each node and nodal boundary line.

3.3 Historical watertable elevations

Water level depth in all the observation wells, except those situated in the Cholistan (desert) area were collected over the period of June 1994 to June 1997. These depths were recorded onto a spreadsheet package. Using the known elevations of the well heads, the depth to watertable values were converted to absolute elevations above sea level. The observation network was divided into 21 sections shown in Figure 3.3, each consisting of 4-6 wells. Based on absolute watertable elevations, groundwater hydrographs (watertable elevation with respect to time) were prepared using LOTUS . Monthly watertable elevation contour maps based on absolute watertable elevations were prepared using WINSURF. Examination of the hydrographs enabled identification of erroneous field data and all data was screened for such irregularities. The monthly contour maps were used for rough identification of the areas in greatest need of drainage. The screened data was fed into the SGMP data base as input files.

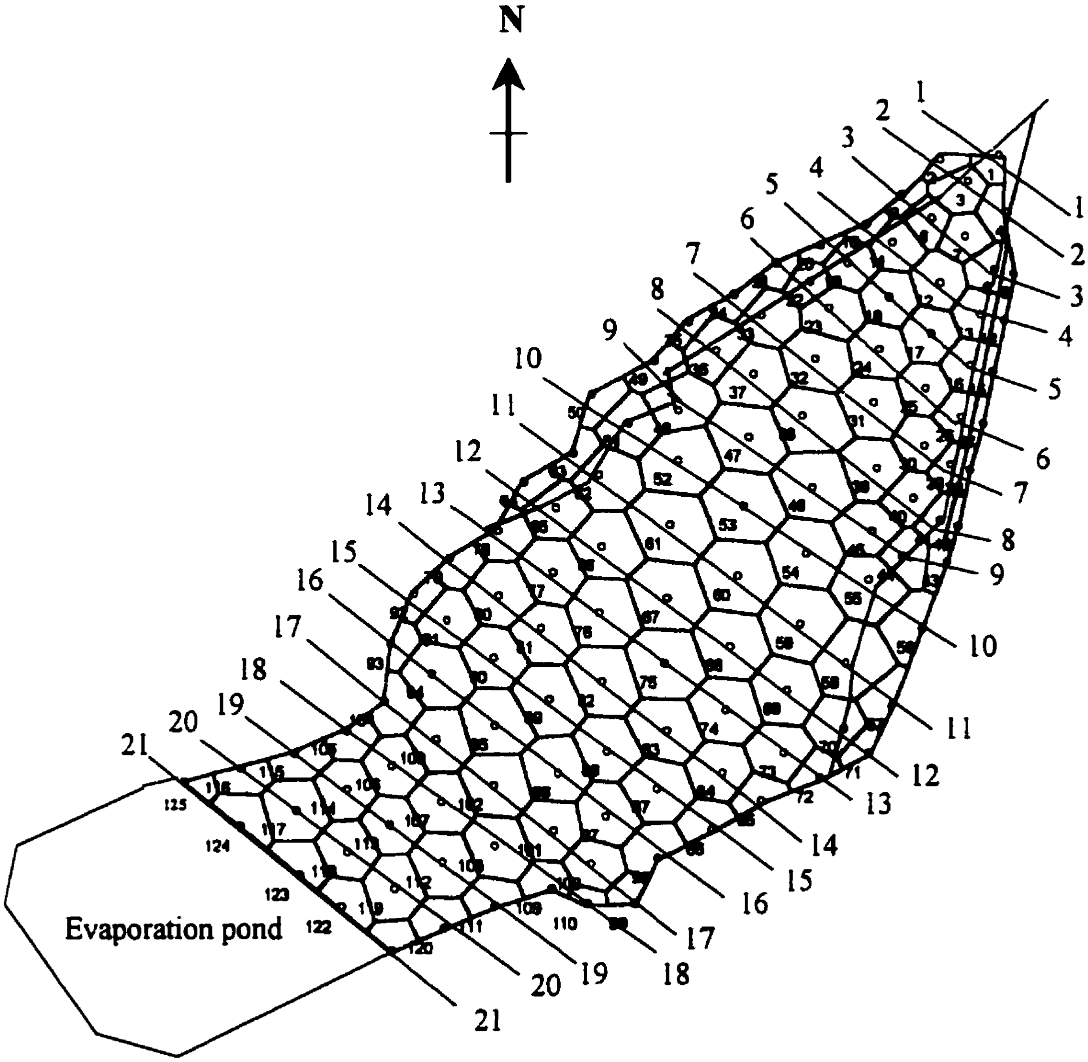


Figure 3.3 Cross sections of observation network

3.4 Aquifer test data

The magnitude and spatial distribution of the aquifer characteristics are needed. Separate values of hydraulic conductivity and thickness of the aquifer are required by the model. Detailed information on aquifer tests performed in the past, located within as well as outside the study area (Figure 1.2), along with five new Aquifer tests within the project area were collected. The software package Selected Aquifer Test Evaluation Methods (SATEM) (Boonstra, 1989) was used for analyzing the collected data. A transimissivity and hydraulic conductivity map were prepared using the software WINSURF. For the purpose of calculating the groundwater flow across the boundaries of the nodal areas, the weighted mean hydraulic conductivity values midway between all the nodes is required. This was calculated by superimposing the network map on the hydraulic conductivity contour map. The hydraulic conductivity of each side of each nodal area was found by interpolation or, in the case of two or more conductivity isoperms crossing a side, the weighted mean hydraulic conductivity was used.

3.5 Use of the model

Historical net recharge was assessed by using a groundwater balance approach based on the results obtained from the numerical groundwater simulation model. For this purpose the groundwater model was run in the 'inverse mode'. In the so called 'inverse mode', input consisted of aquifer characteristics, nodal location and changes in watertable elevations over the three years of known data (1994-97). Output consisted of changes in storage, inflow and outflow on a nodal basis, as lumped net-recharge values. The resulting net recharge which is a lumped parameter: all the relevant components of recharge and discharge (presented in Figure 3.4) are integrated in its value based on Eq.17.

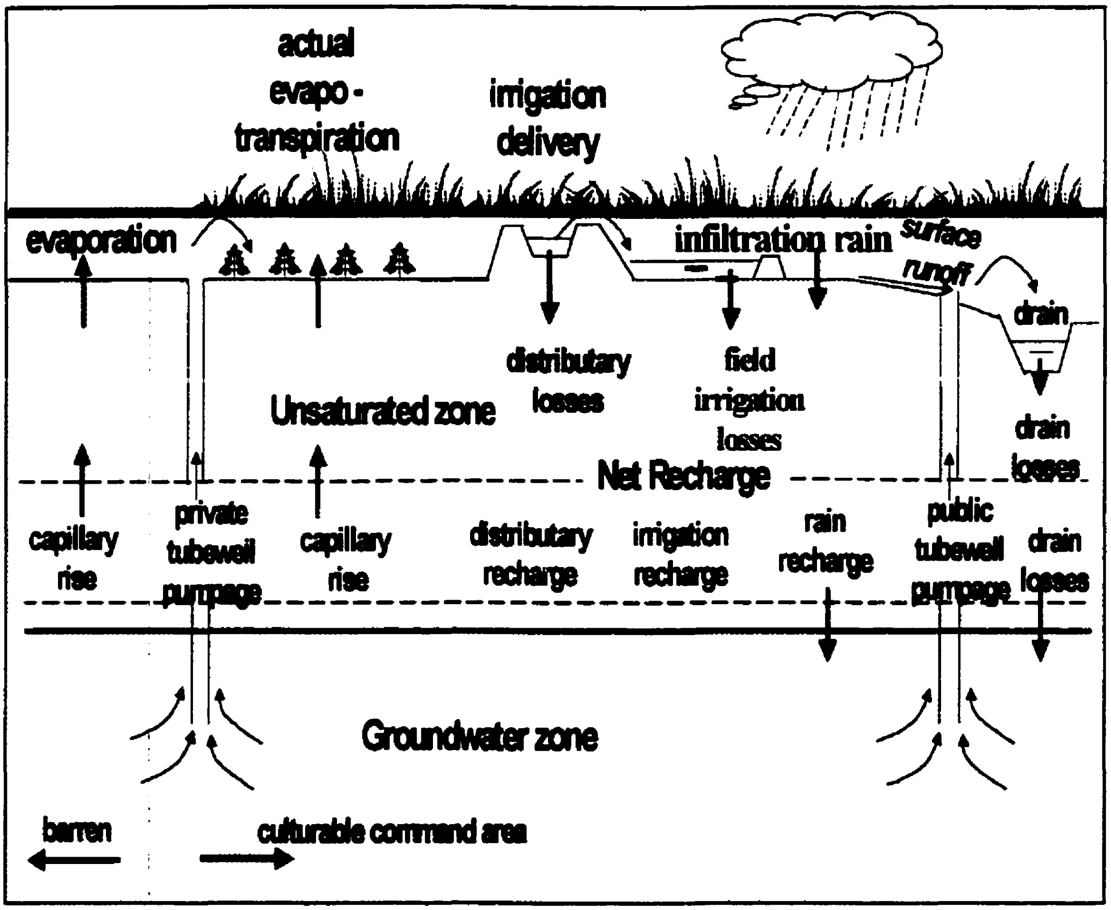


Figure 3.4 Relevant recharge and discharge components in FESS, contributing to the overall net recharge

Note: In groundwater balances the convention is that recharge to the aquifer, i.e. downward flow towards the watertable and horizontal groundwater flow entering a nodal area, are taken as positive, while discharge from the aquifer, i.e. upward flow from the watertable and horizontal groundwater flow leaving a nodal area, are taken as negative.

The model was then run in " normal mode ". In this mode input is the recharge output from the inverse mode. The output of normal mode is watertable elevations. These are compared with actual watertable elevations. An appropriate tolerance value was set and the EXCEL spreadsheet curve comparison function was used to compare model watertable elevation to actual watertable elevation. The output files were converted into a format usable as input files for the next step. That is, the model was used for prediction of watertable elevations. For initial conditions, watertable elevations and aquifer characteristics are used. The nodal net-recharge from 1995-96 (July-June) is assumed to be the pattern of recharge for the future. The year 1995-96 was used because it had the best comparison under normal mode analysis of the model.

3.6 Processing, Screening of data

3.6.1 Watertable data

The depth to watertable data collected in the field were processed using spreadsheet files. An appropriate format is required for processing the data to eliminate the occurrence of any possible field measurement or reading errors. The following three points constitute the bases used for designing the spreadsheet format.

a. The layout of each monthly spreadsheet was designed in such a way that errors of the field data could easily be observed. To identify field errors, groundwater hydrographs for all 21 sections in the nodal network were made automatically in an attached spreadsheet file as the data were entered. These were used to visually isolate obvious data errors (Figure 3.5) as well as missing watertable elevation data for different time steps (months).

b. The spreadsheet also contained commands to generate files usable by WINSURF.

c. Other command files were used to arrange the data in a format usable by SGMP Model.

The data on observation wells were tabulated row-wise and for each observation well, date of measurement, elevation of the well top, soil surface elevation, depth to watertable were placed column-wise and used to calculate the absolute watertable elevations above the sea level.

The groundwater hydrographs for all 125 observation wells were also prepared via the groundwater model and hence used to identify any irregularities. Irregularities were these instances where the watertable of a certain observation well during a certain period exhibited an opposite trend or behavior with respect to all neighbouring observation wells in that period. The groundwater hydrographs (Figure 3.5) clearly reveal the measurement errors that

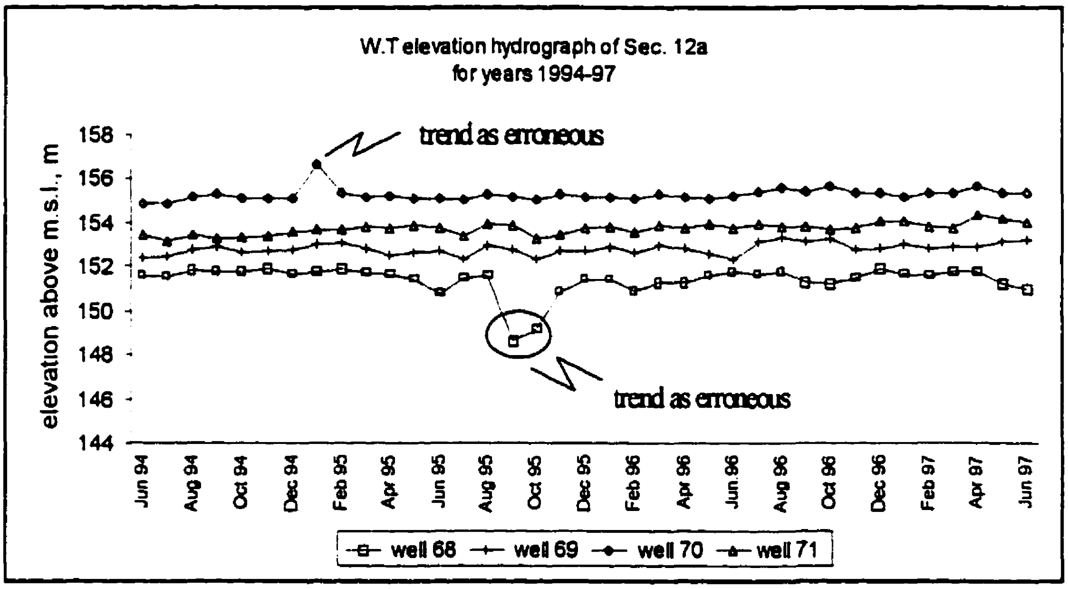


Figure 3.5 Groundwater elevation hydrograph showing irregularities of observation wells 68 & 70

occasionally occurred due to field or reading error. Data identified as erroneous were adjusted such that the hydrographs were smooth. The Table 3.1 shows the adjusted values and it should be noted that time step-1 and 33 refer to June 1994 and March 1997 respectively.

Table 3.1 Estimates for missing & irregular watertable data

Observation well	Time Step	Old Depth to Watertable (cm)	New Depth to Watertable (cm)	Watertable Elevation (m)	Remarks
2	1	192.94	140.0	157.60	Irregularities
5	14	39.0	89.0	162.22	//
5	26	43.0	81.5	162.3	//
8	32	153.0	123.0	160.54	//
11	3	53.0	109.6	159.3	//
13	6	256.0	52.0	161.50	//
18	5	47.0	136.6	159.19	//
25	1	265.18	130.7	158.90	//
26	0	99.0	31.7	161.00	//
26	3		31.7	161.00	Missing
26	4		31.7	161.00	//
26	5		31.7	161.00	//
26	6		31.7	161.00	//
30	9		183.2	159.60	//
31	28		160.5	158.45	//
31	29		182.5	158.23	//
31	30		190.5	158.15	//
31	31		200.5	158.05	//
31	32		210.5	157.95	//
32	9		140.0	157.50	//
35	3		196.1	155.00	//
38	9		123.2	156.00	//
52	33		205.9	153.50	//

54	4	106.0	126.0	154.83	Irregularities
54	26		123.6	154.85	Missing
54	27		128.6	154.80	//
54	28		151.6	154.57	//
54	29		137.6	154.71	//
54	30		128.6	154.80	//
54	31		138.6	154.70	//
54	32		148.6	154.60	//
60	26		99.6	152.80	//
60	27		105.4	152.74	//
60	28		120.4	152.59	//
60	29		123.4	152.56	//
60	30		119.4	152.6	//
68	15	433.0	183.0	151.13	Irregularities
68	16	379.0	190.0	151.06	//
68	17	211.0	175.0	151.21	//
68	21		166.0	151.30	Missing
68	22		166.0	151.30	//
68	23		136.0	151.60	//
70	7		212.4	155.26	//
72	7		189.3	155.35	//
78	8		213.9	150.40	//
84	15		206.3	151.50	//
86	33		126.2	149.25	//
86	34		121.2	149.30	//
91	30		295.0	146.30	//
91	31		295.0	146.30	//

91	32		308.0	146.17	//
91	33		317.0	146.08	//
93	11		363.8	145.10	//
99	18	70.0	95.7	147.80	Irregularities
100	14	291.0	336.1	146.20	//
102	12		490.4	141.25	Missing
109	1	408.13	468.1	142.13	Irregularities
109	20		401.2	142.80	Missing
109	21		401.2	142.80	//
109	22		401.2	142.80	//
109	23		401.2	142.80	//
122	14		1326.0	129.10	//
122	15		1316.0	129.20	//

3.6.2 Absolute elevation data (reduced level)

Kriging interpolation module with 0.25 m interval of the software package WINSURF was used in preparation of the watertable elevation contour maps. These monthly contour maps were used for the purpose of establishing any irregularities in the certain areas of the Fordwah Eastern Sadiqia (South) project. Irregularities are defined as any pattern of contour lines that was inconsistent in that area as compared to other watertable contour maps. The watertable contour maps showed consistent anomalies in certain parts of the study area, thereby, indicating possible errors in the benchmark levels of some of the observation wells. Initially, the elevation above sea level of the well tops were established using benchmarks from various government agencies. The result was somewhat erratic. Therefore one agency's benchmarks (Irrigation Dept.) were used to re-level and establish well top elevations. Also, any wells found to be damaged or chocked were re-dug and well top elevations re-established (Table 3.2).

Table 3.2 Adjustments made of well elevations

Well no.	Time Step	Old NSL Level (m)	New NSL Level (m)	Diff. (m)	Old MP Level(m)	New MP Level (m)	Diff. (m)
1		162.399	162.358	-0.041	162.737	162.696	-0.041
1A	7	162.376	162.334	-0.042	163.153	163.111	-0.042
3		162.667	162.543	-0.124	162.938	162.813	-0.125
3A	7	162.400	162.293	-0.107	163.446	163.383	-0.063
4A	8		162.435			162.825	
6A	7		162.211			163.735	
7		161.131	160.968	-0.163	161.709	161.547	-0.162
8		161.450	160.462	-0.012	161.759	161.771	0.012
10		160.247	160.260	0.013	160.597	160.610	0.013
11		160.094	159.999	-0.095	160.491	160.396	-0.095
11A	7	160.047	159.957	-0.090	160.626	160.536	-0.090
13A	7		161.673			163.327	
16A	7		161.777			163.129	
18		160.458	160.297	-0.161	160.722	160.561	-0.161
19		159.512	159.529	0.017	160.042	160.059	0.017
19A	7	159.727	159.745	0.018	160.456	160.474	0.018
20		159.494	159.500	0.006	160.085	160.090	0.005
22		159.253	159.069	-0.184	159.802	159.618	-0.184
22A	7	159.300	159.106	-0.194	160.992	160.798	-0.194
23		159.543	159.294	-0.249	159.912	159.663	-0.249
24		160.436	159.611	-0.825	160.771	159.946	-0.825
26A	7	160.929	160.227	-0.702	163.199	162.497	-0.702
27		161.710	161.585	-0.125	162.432	162.307	-0.125
29		160.899	160.602	-0.287	161.222	160.977	-0.245

29A	7	161.648	160.967	-0.681	163.389	163.122	-0.267
31*	33	159.756	159.791	0.035	160.055	160.090	0.035
33		158.619	158.445	-0.174	159.107	159.040	-0.067
33A	7	158.514	158.615	0.101	159.413	159.340	-0.073
35		156.592	156.404	-0.188	156.961	156.773	-0.188
36		157.019	157.076	0.057	157.501	157.558	0.057
36A	7	157.019	157.075	0.056	158.347	158.403	0.056
37		157.205	156.572	-0.633	157.626	156.993	-0.633
38		156.970	156.865	-0.105	157.232	157.080	-0.152
41A	7		158.213			159.246	
44A	7		157.915			159.331	
48A	7		154.913			156.665	
51A	7		155.006			156.134	
52*	33	154.928	155.029	0.101	155.370	155.559	0.189
54*	33	155.794	155.802	0.008	156.086	156.226	0.140
55A	7		157.766			159.334	
58A	7		155.279			157.667	
60*	32	153.392	153.392	0.000	153.794	153.746	-0.048
61		152.072	152.085	-0.013	152.703	152.520	-0.183
62A	7		153.366			154.622	
65A	7		151.964			153.31	
68*	24	152.661	152.652	-0.009	152.960	152.902	-0.058
70		154.989	155.452	0.463	155.459	155.922	0.463
70A	7	152.989	155.442	0.453	156.929	157.382	0.453
71		154.919	155.041	0.122	155.410	155.532	0.122
72		154.962	155.003	0.041	155.456	155.497	0.041
72A	7	154.964	155.001	0.039	157.243	157.282	0.039

73		153.932	153.839	-0.093	154.325	154.232	-0.093
77		151.557	151.356	-0.210	152.203	152.056	-0.147
80		147.757	149.140	1.383	148.263	149.646	1.383
81		149.433	149.391	-0.042	149.808	149.791	-0.017
82		149.579	149.710	0.131	150.064	150.115	0.517
83		151.262	151.206	-0.056	151.695	151.581	-0.114
84*	16	153.161	153.174	0.013	153.563	153.889	0.326
88		149.820	149.705	-0.115	150.350	150.355	0.005
93*	12	148.238	148.185	-0.053	148.738	148.681	-0.057
94		147.242	147.368	0.126	147.598	147.724	0.126
96		148.022	148.435	0.413	148.445	148.858	0.413
99		149.808	148.407	-1.401	150.213	148.757	-1.456
102		145.684	147.050	1.386	146.154	147.540	1.386
103		145.468	145.228	-0.240	145.885	145.646	-0.239
106		144.986	144.455	-0.531	145.294	144.955	-0.339
109*	24	146.501	146.635	0.134	146.812	147.062	0.248
113		145.029	143.924	-1.105	145.419	144.539	-0.88
118		144.294	144.084	-0.21	144.648	144.424	-0.224
122*	16	141.829	141.876	0.047	142.36	142.586	0.226
123		141.118	141.004	-0.114	141.420	141.319	-0.101

Note: A: replacement wells; example well # 1 located away from canal embankment (data used from June 94 to January 95) then replaced by # 1A placed on the canal embankment (data used from February 95 to June 97).

Time step: time step 1 is July 94, and progresses to time step 36 of June 97.

NSL: natural surface level i.e soil surface.

MP: measuring point i.e well top.

* : level corrected on damaged or clogged wells.

CHAPTER IV

RESULTS, INTERPRETATION AND DISCUSSION

This section of the thesis is organized in the following manner:
First, watertable elevations are presented & discussed. Secondly the aquifer pumping results are discussed. Finally the model is applied to the data.

4.1 Watertable behavior

New groundwater hydrographs for all sections were prepared using the adjusted data. The hydrograps in Figures from 4.1 to 4.21 show a consistent pattern of water table elevations. From these figures the following inferences were derived:

i) The groundwater hydrographs show that the amplitude of the water level fluctuation in the various wells are not exactly the same, but show a great similarity and watertable reaction to recharge and discharge everywhere in a similar manner.

ii) On an annual basis, the watertable elevation steadily rose in almost all the observation wells; except wells 5, 16, 17, 26, 36, 54, 68, 93. The rate of rise ranged from 3 (# 25) to 142 cm (# 19). The average rise was 131 cm; standard deviation of 11.5.

iii) The watertable rose between 40 and 142 cm for observation wells no 1, 2, 3, 6, 7, 10, 11, 15, 19, 20, 22, 29, 31, 32, 38, 41, 43, 44, 47, 48, 50, 51, 52, 55, 56, 57, 58, 60, 61, 62, 63, 64, 65, 66, 69, 75, 76, 77, 78, 80, 81, 82, 83, 88, 89, 90, 92, 94, 95, 96, 97, 98, 99, 101, 102, 103, 104, 105, 106, 107,108, 109, 110, 111, 133, 118, 120, 122 and 123. Observation wells 10, 11, 19, 31, 48 and 97 show a rise in watertable elevation of more than 1 meter.

iv) The largest rise occurred during the monsoon period (July to October) of 1994. In general, levels rose during the monsoon period and fell in the subsequent non-monsoon period (November to June). For most wells the amount of watertable rise in anyone year decreased over the 3 year period. The rate of capillary loses can be expected to rise as the watertable approaches the soil surface. This can explain the ever decreasing rate of the watertable over the years. During this period the average groundwater depths of observation wells 1-100 were less than 142, 132 and 118 cm for the hydrological years (July to June) 1994-95 , 1995-96 and 1996-97, respectively.

v) Within each section (for sections 11-21) the rise and fall of the watertable tends to occur at the same time of year. A rise in one well along a section is accompanied by a similar rise of the other wells along that section. In sections 1-10 the watertable rise & fall is more erratic.

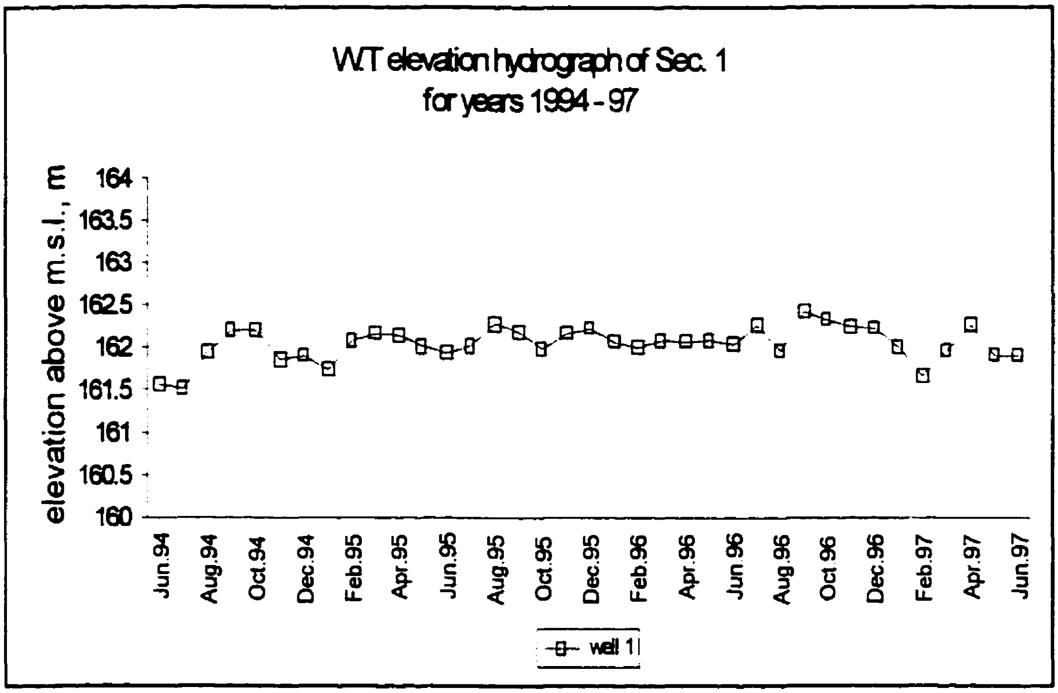


Figure 4.1 Watertable elevation hydrographs along cross-section 1

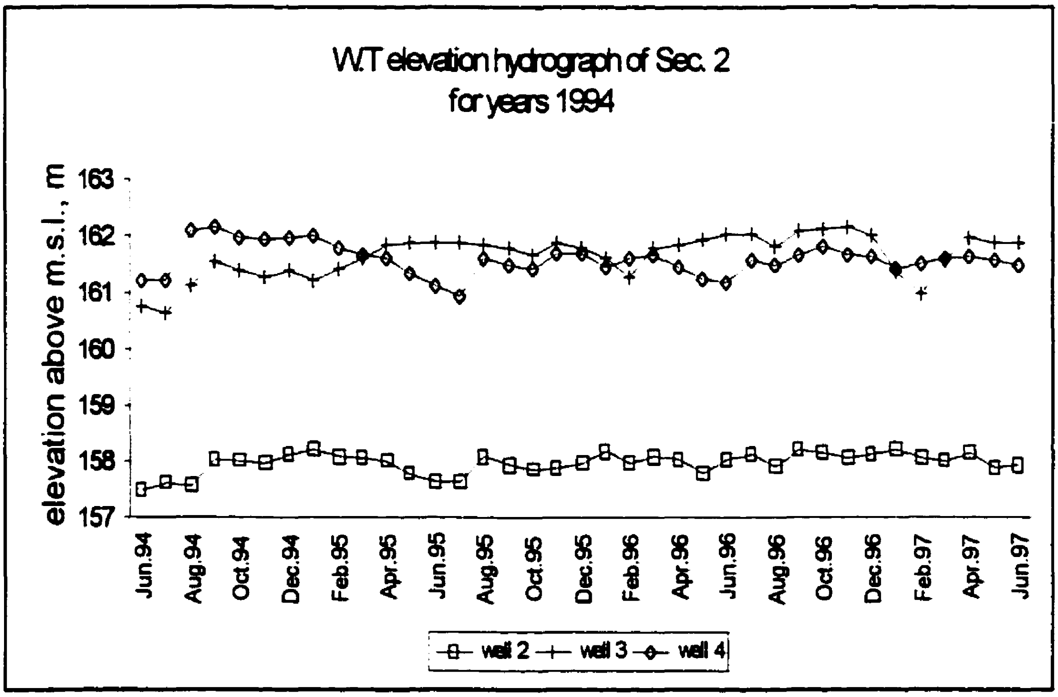


Figure 4.2 Watertable elevation hydrographs along cross-section 2

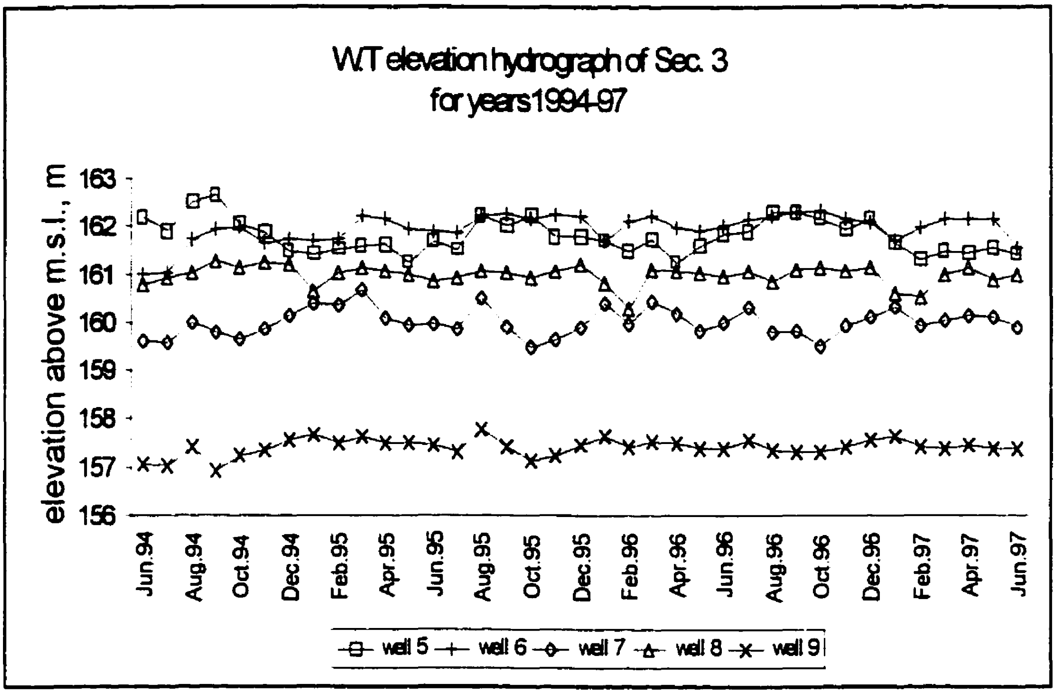


Figure 4.3 Watertable elevation hydrographs along cross-section 3

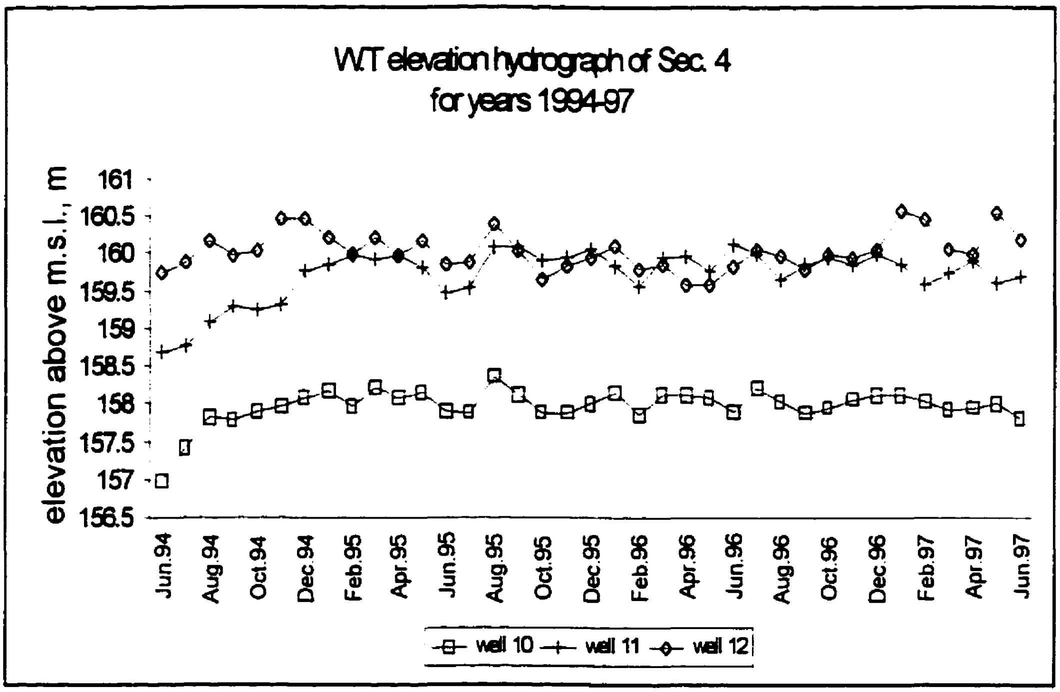


Figure 4.4 Watertable elevation hydrographs along cross-section 4

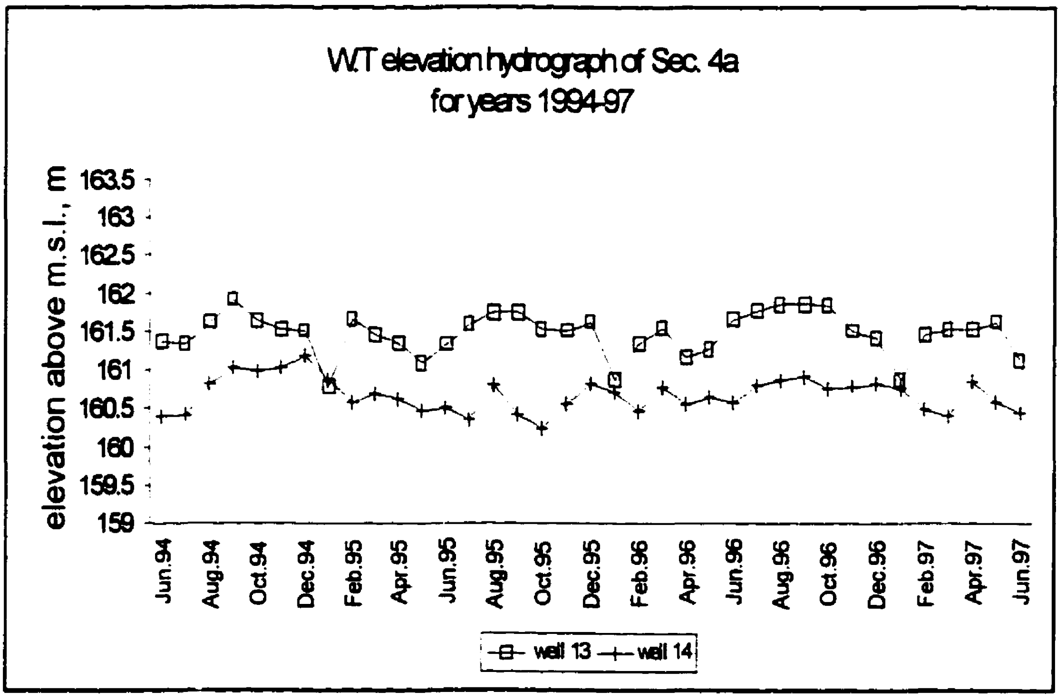


Figure 4.4a Watertable elevation hydrographs along cross-section 4

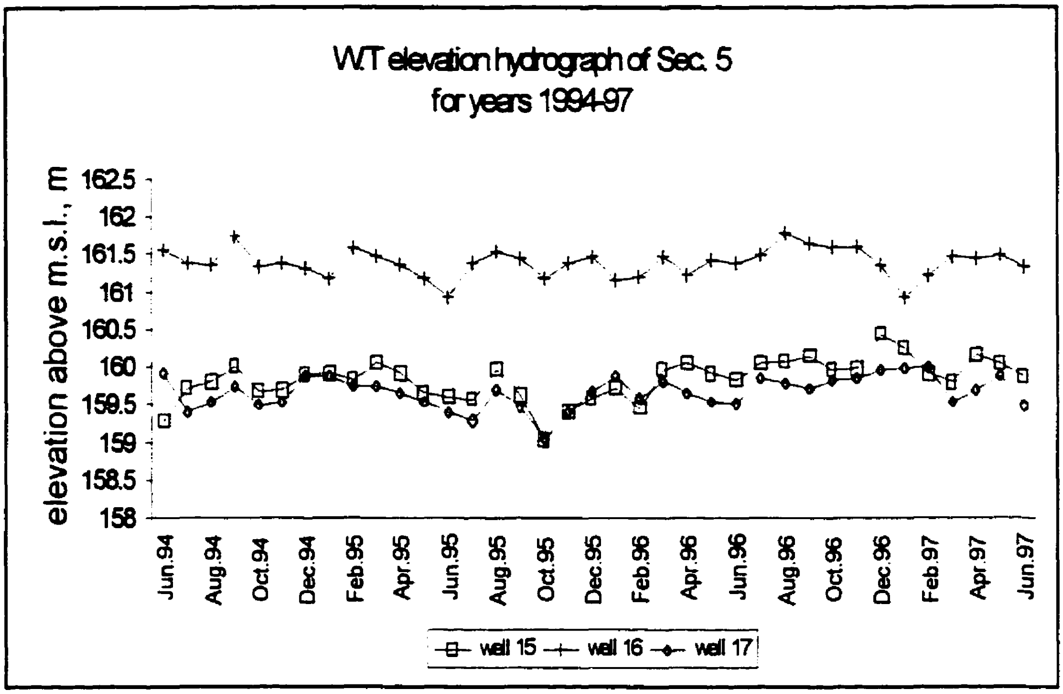


Figure 4.5 Watertable elevation hydrographs along cross-section 5

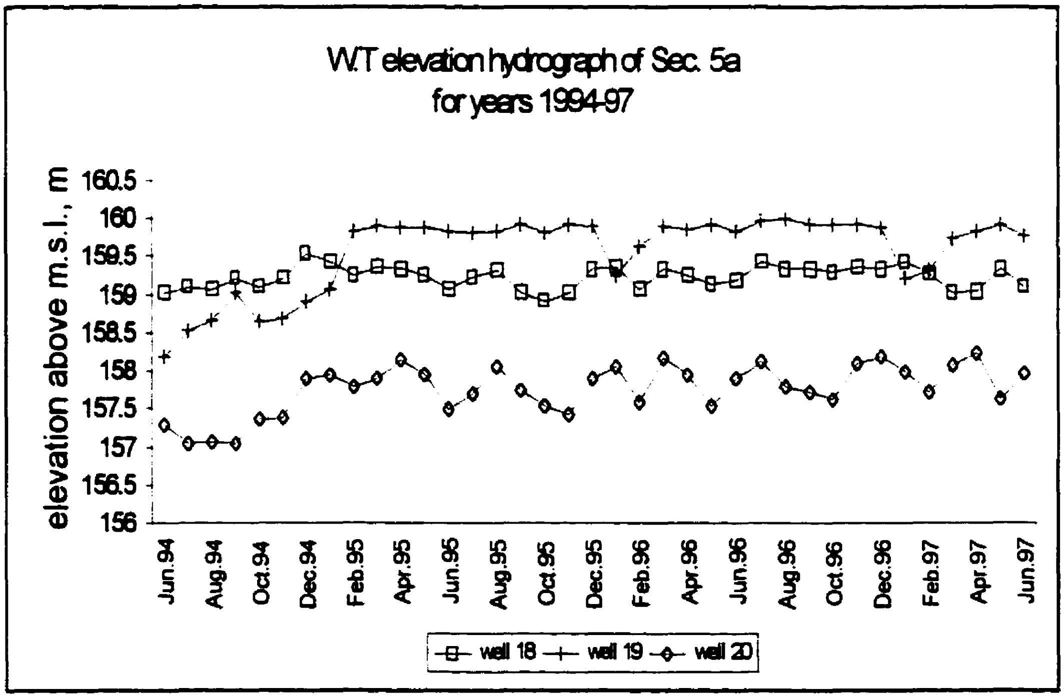


Figure 4.5a Watertable elevation hydrographs along cross-section 5

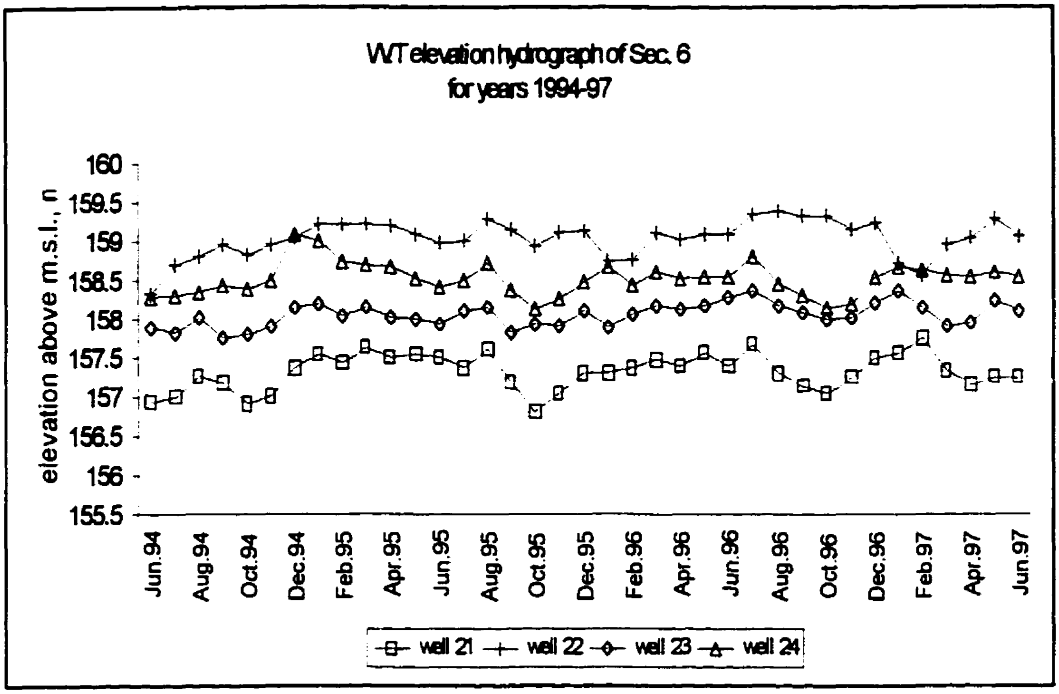


Figure 4.6 Watertable elevation hydrographs along cross-section 6

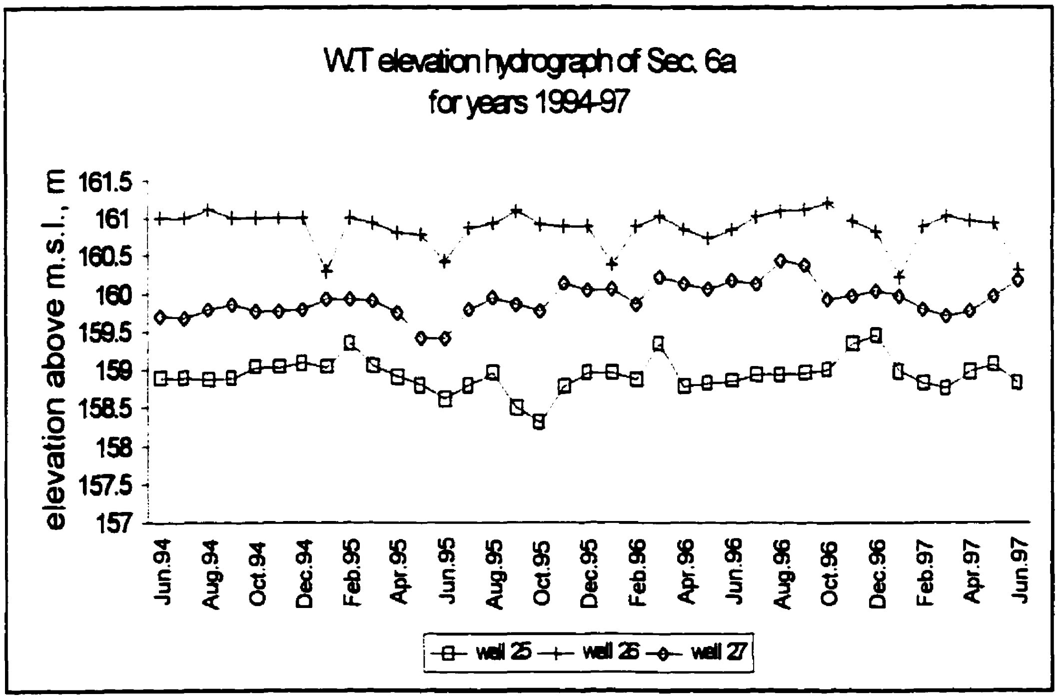


Figure 4.6a Watertable elevation hydrographs along cross-section 6

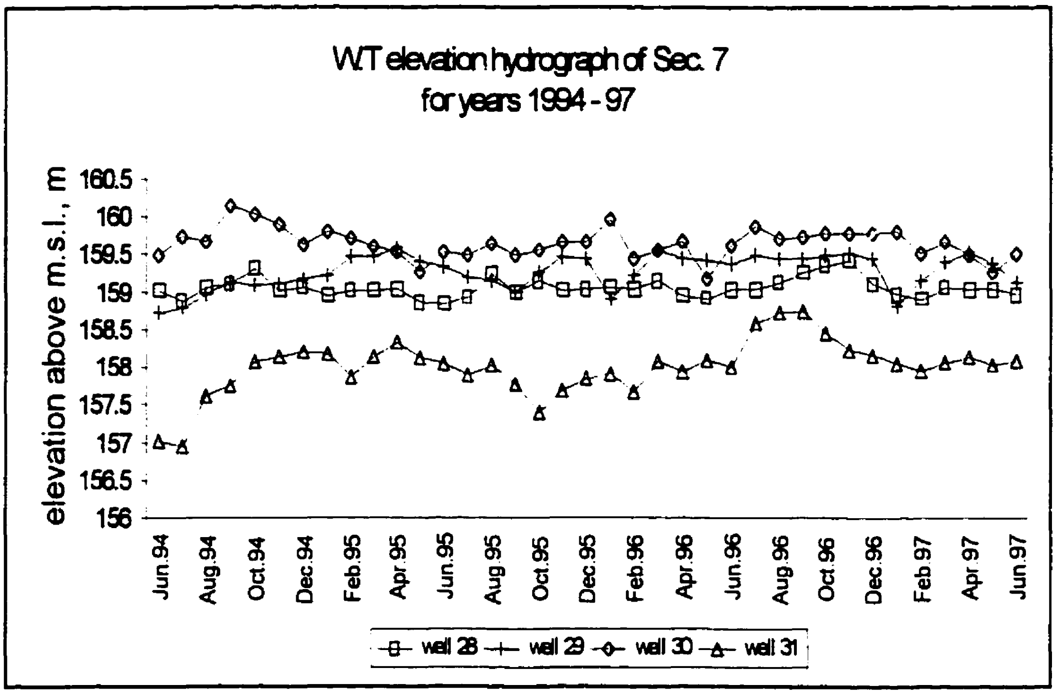


Figure 4.7 Watertable elevation hydrographs along cross-section 7

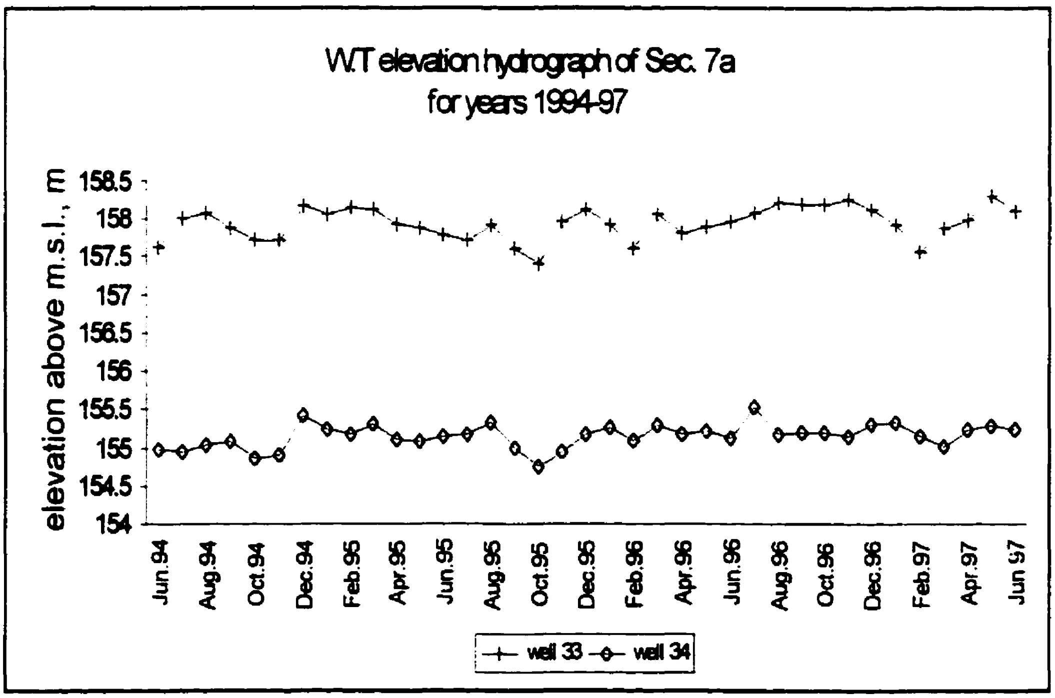


Figure 4.7a Watertable elevation hydrographs along cross-section 7

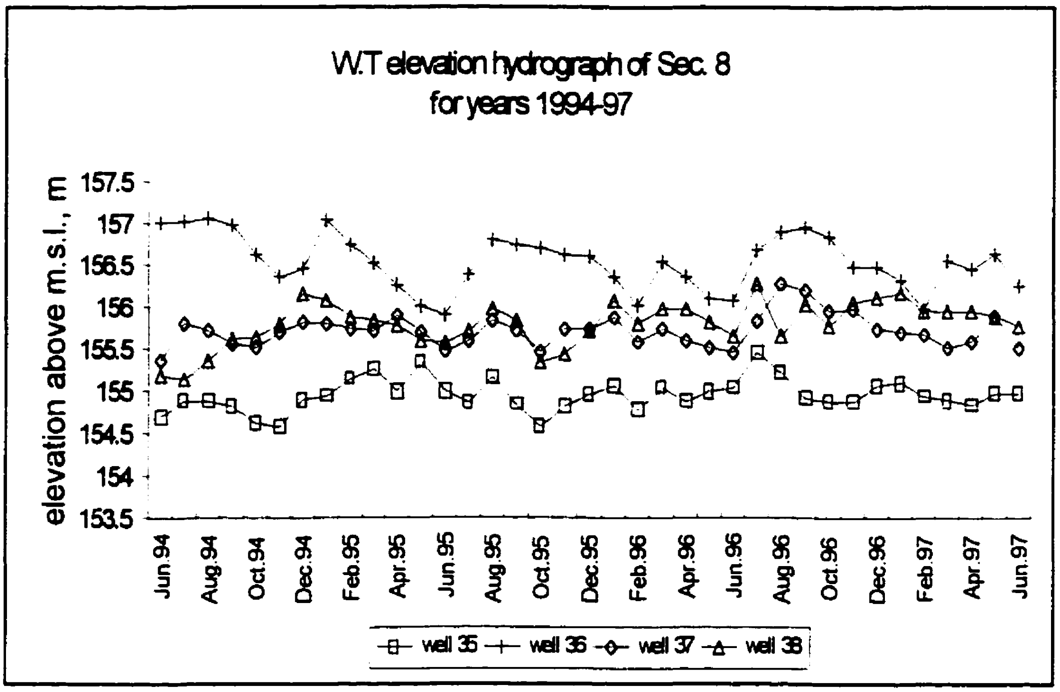


Figure 4.8 Watertable elevation hydrographs along cross-section 8

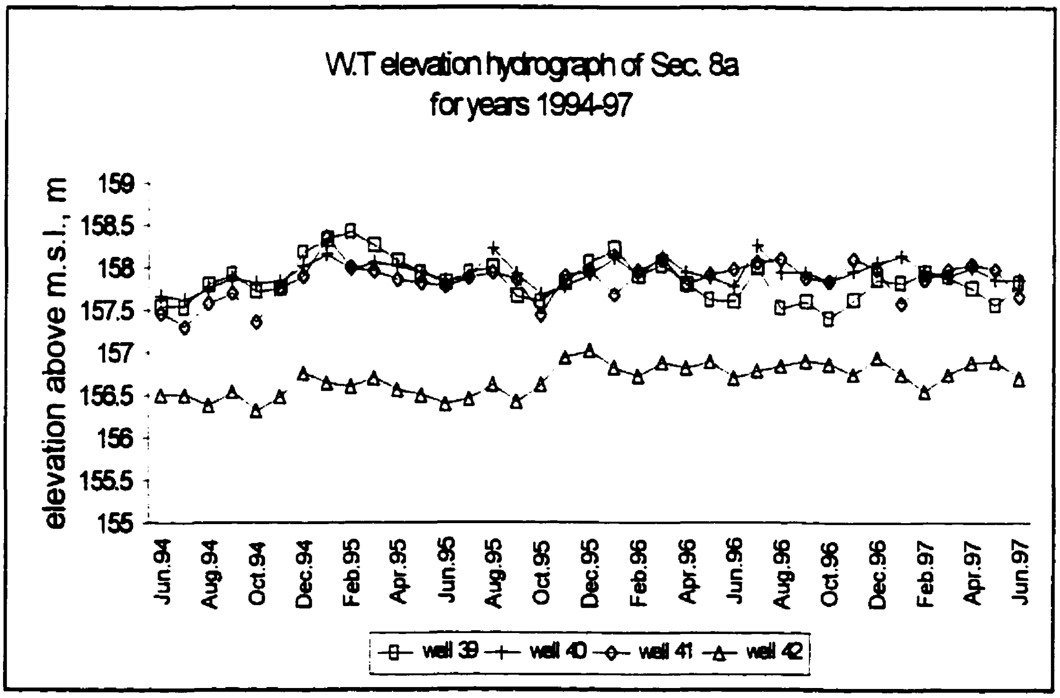


Figure 4.8a Watertable elevation hydrographs along cross-section 8

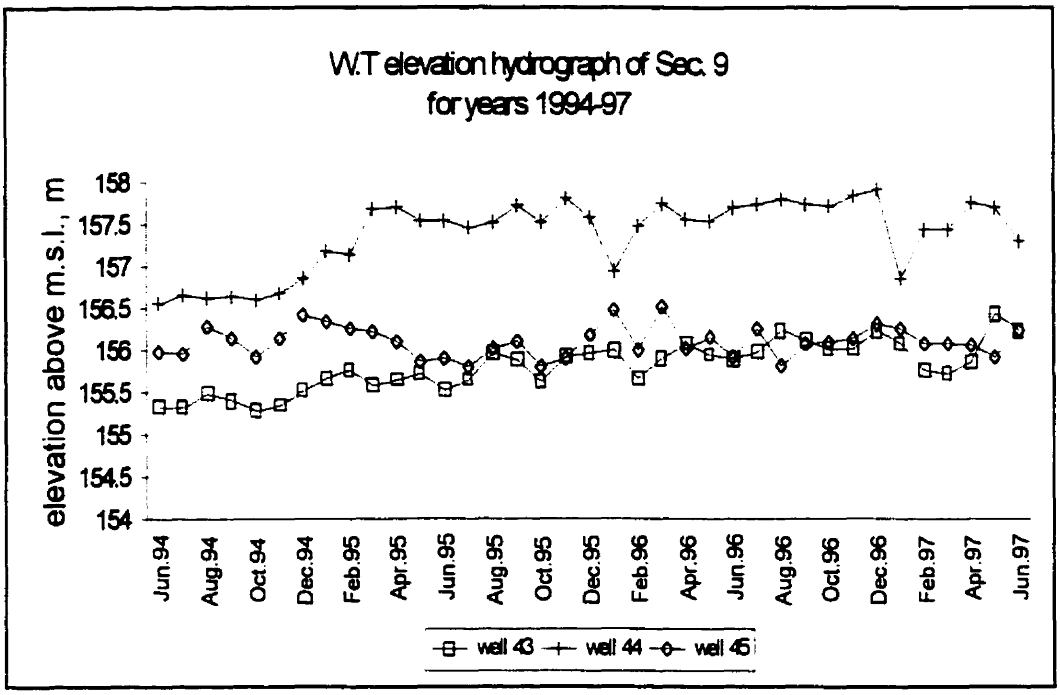


Figure 4.9 Watertable elevation hydrographs along cross-section 9

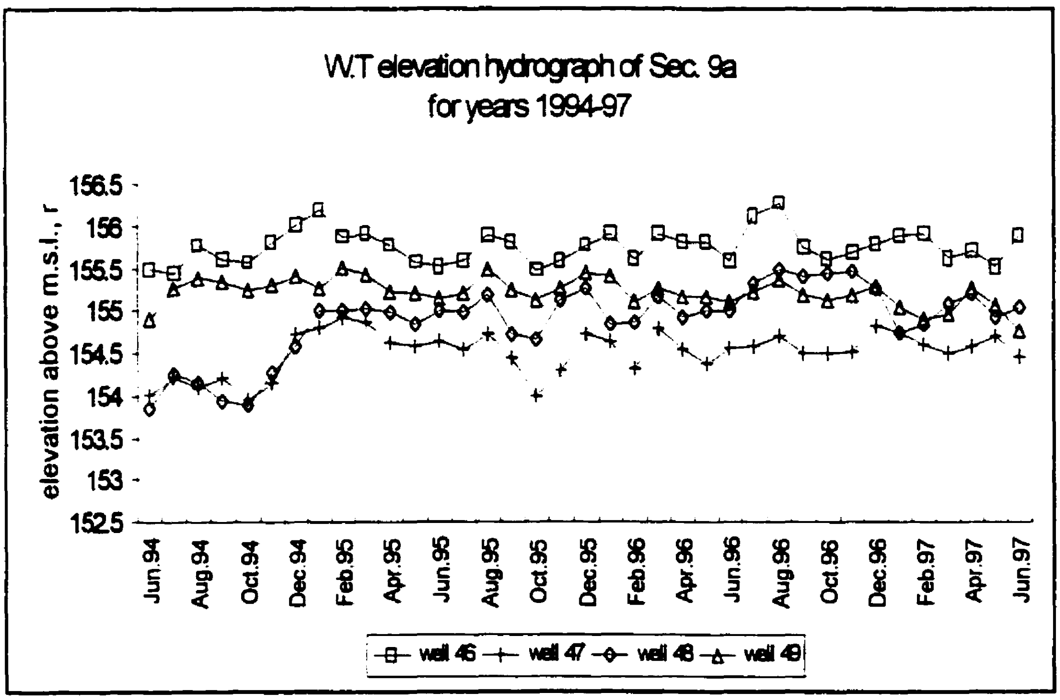


Figure 4.9a Watertable elevation hydrographs along cross-section 9

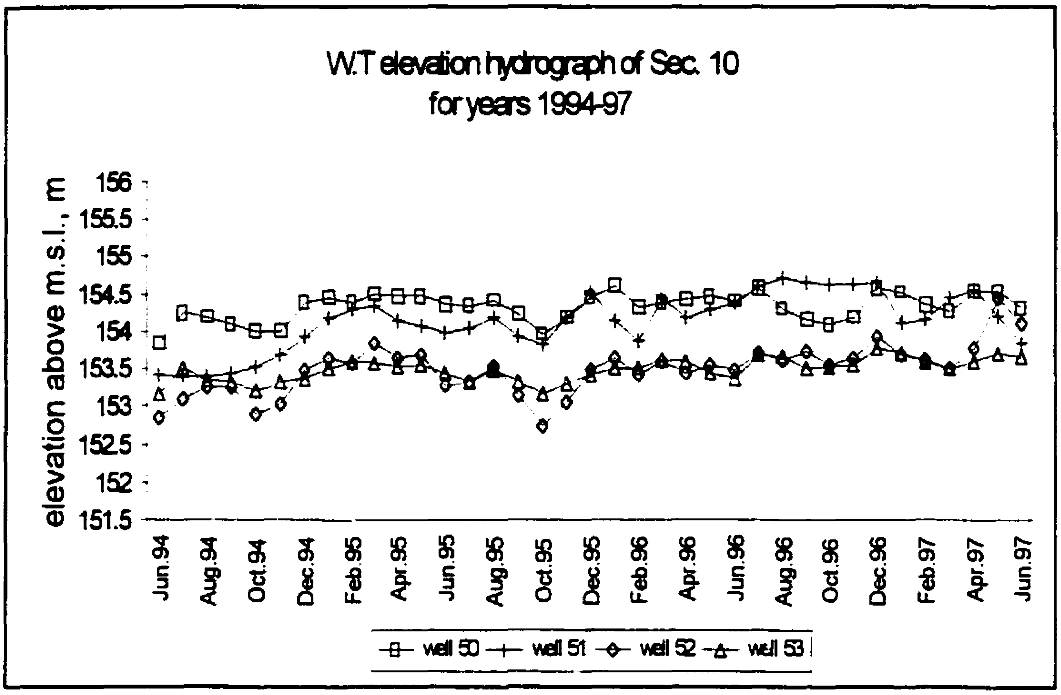


Figure 4.10 Watertable elevation hydrographs along cross-section 10

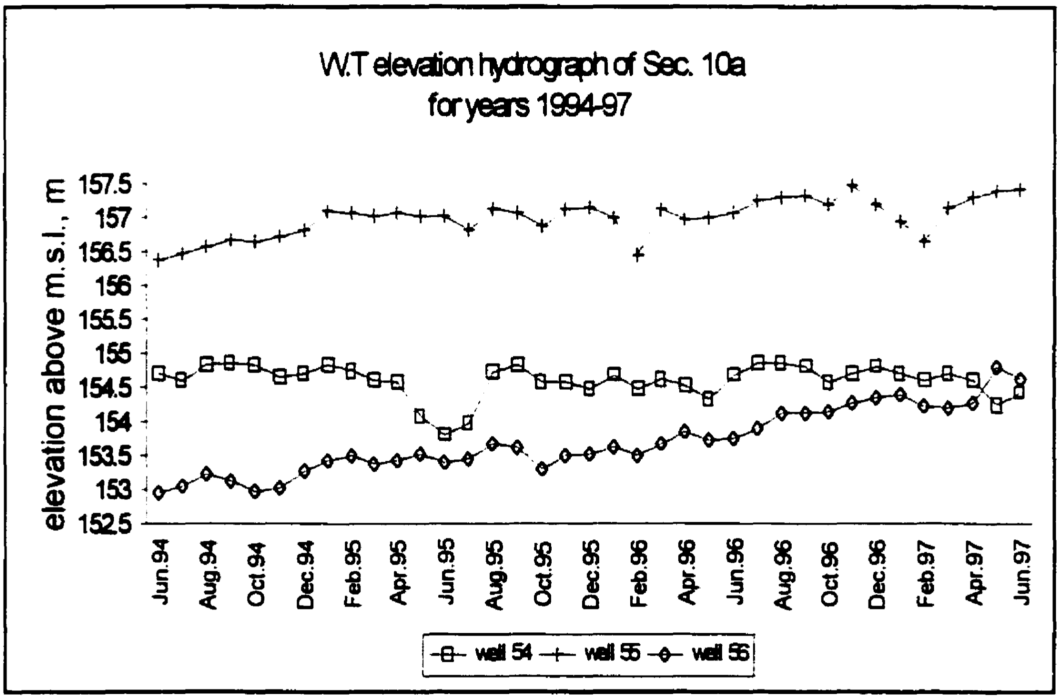


Figure 4.10a Watertable elevation hydrographs along cross-section 10

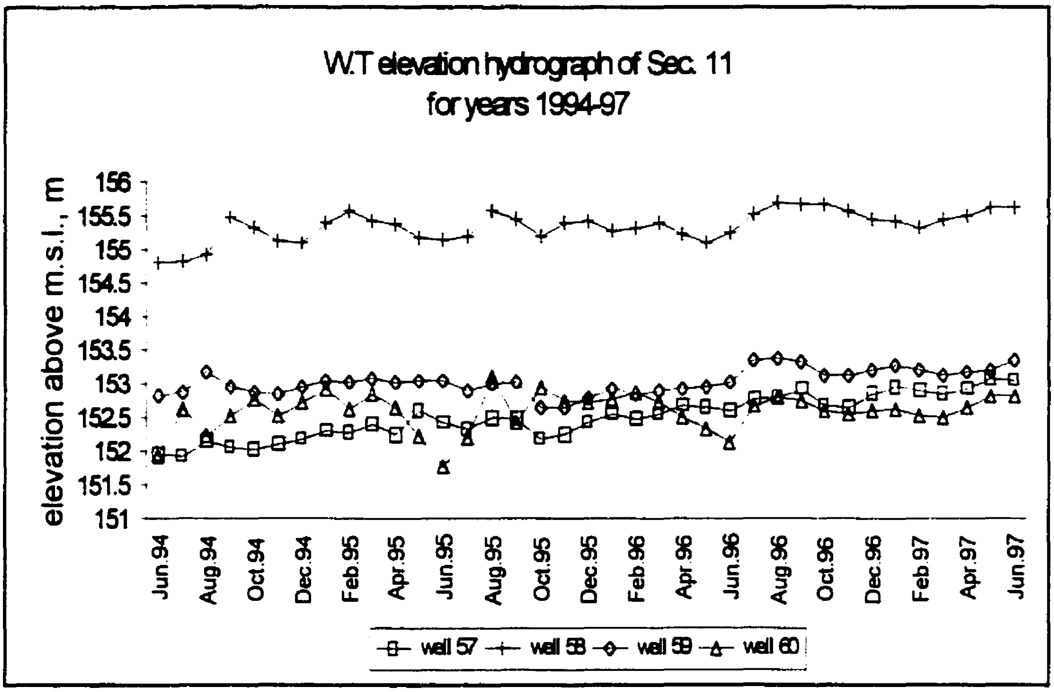


Figure 4.11 Watertable elevation hydrographs along cross-section 11

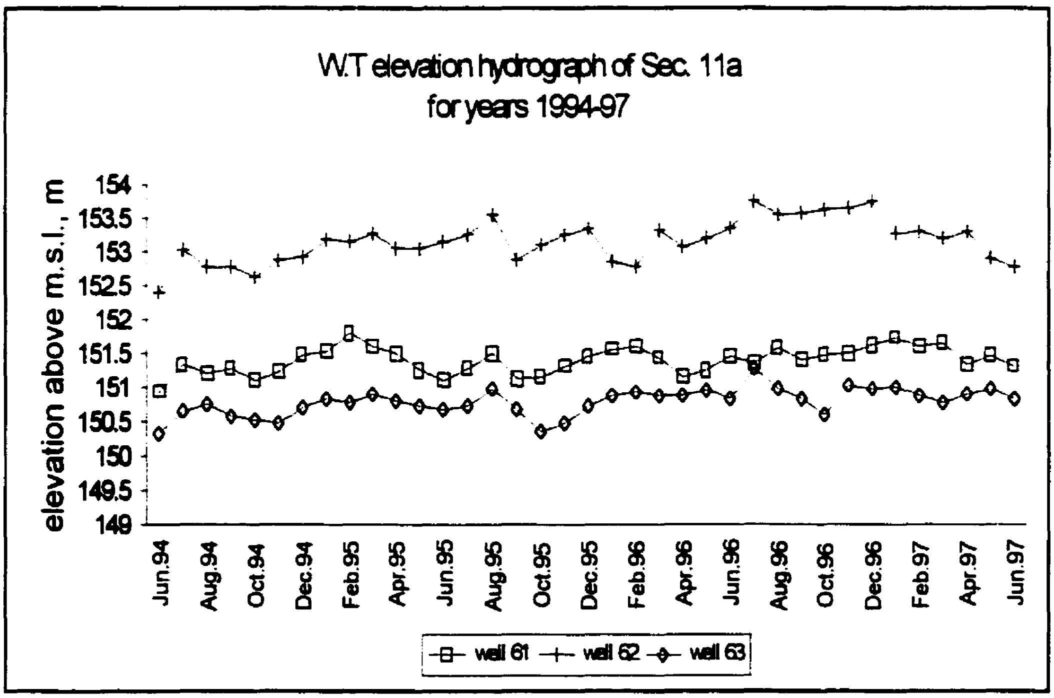


Figure 4.11a Watertable elevation hydrographs along cross-section 11

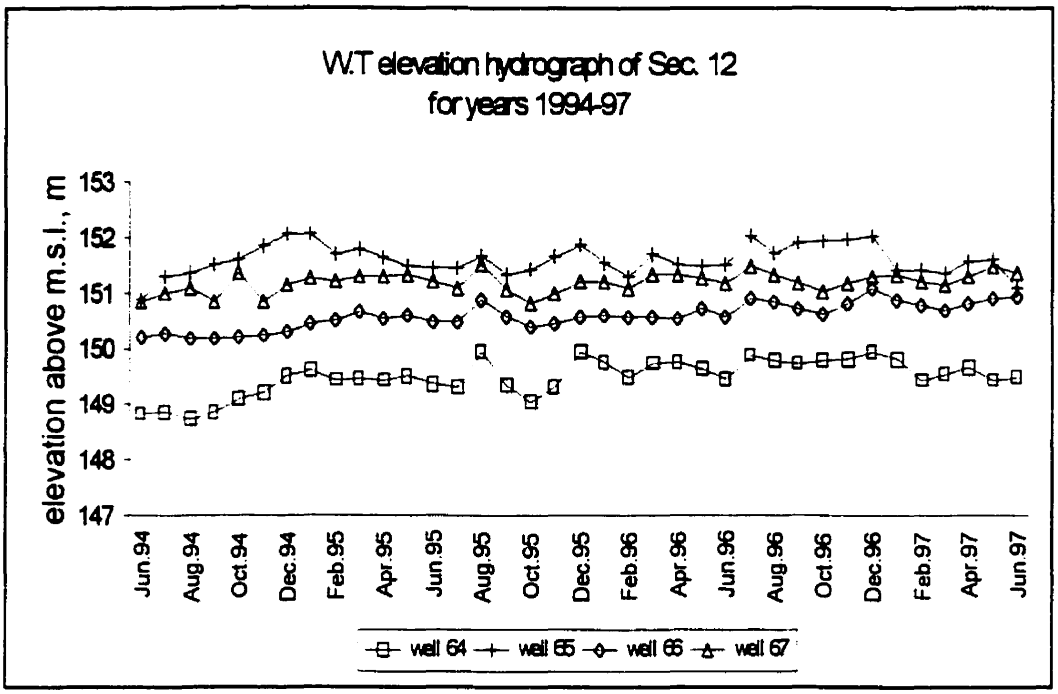


Figure 4.12 Watertable elevation hydrographs along cross-section 12

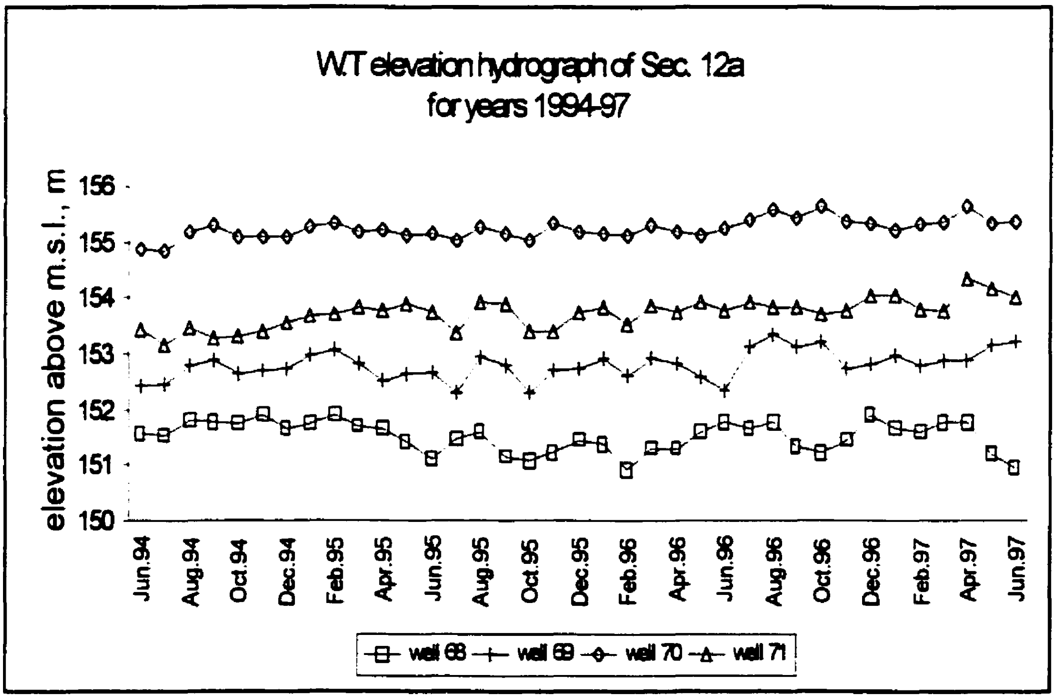


Figure 4.12a Watertable elevation hydrographs along cross-section 12

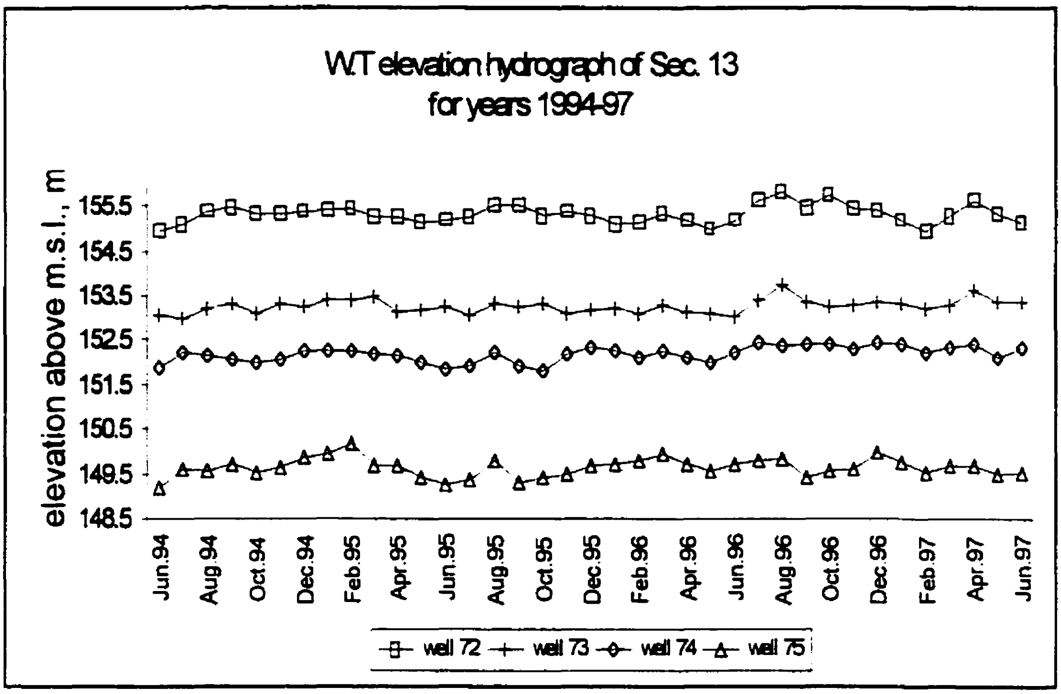


Figure 4.13 Watertable elevation hydrographs along cross-section 13

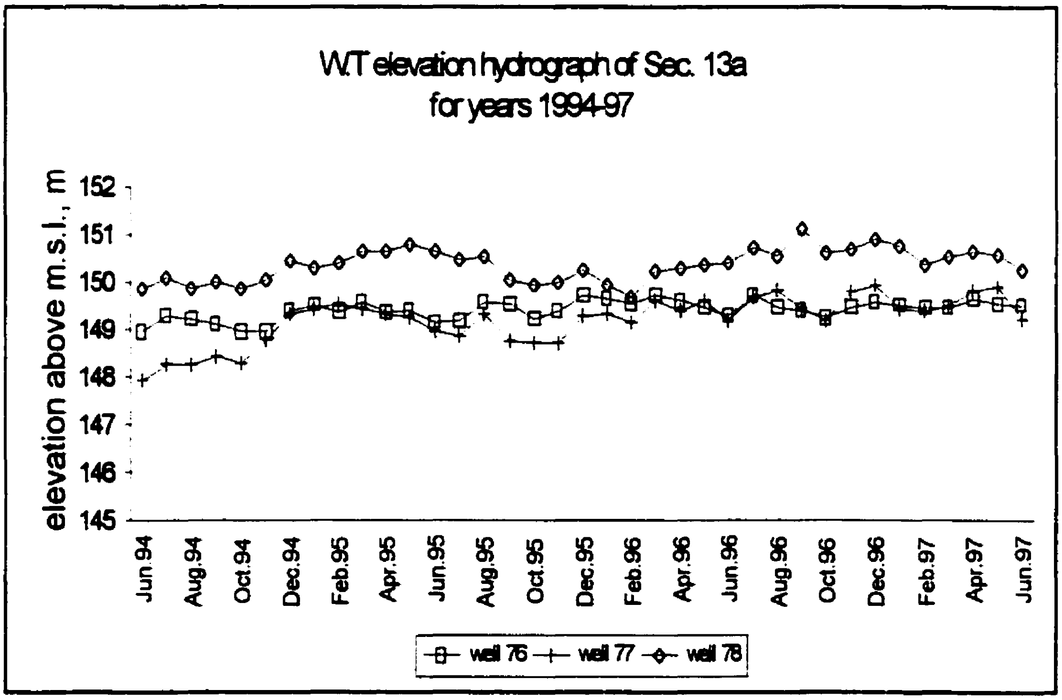


Figure 4.13a Watertable elevation hydrographs along cross-section 13

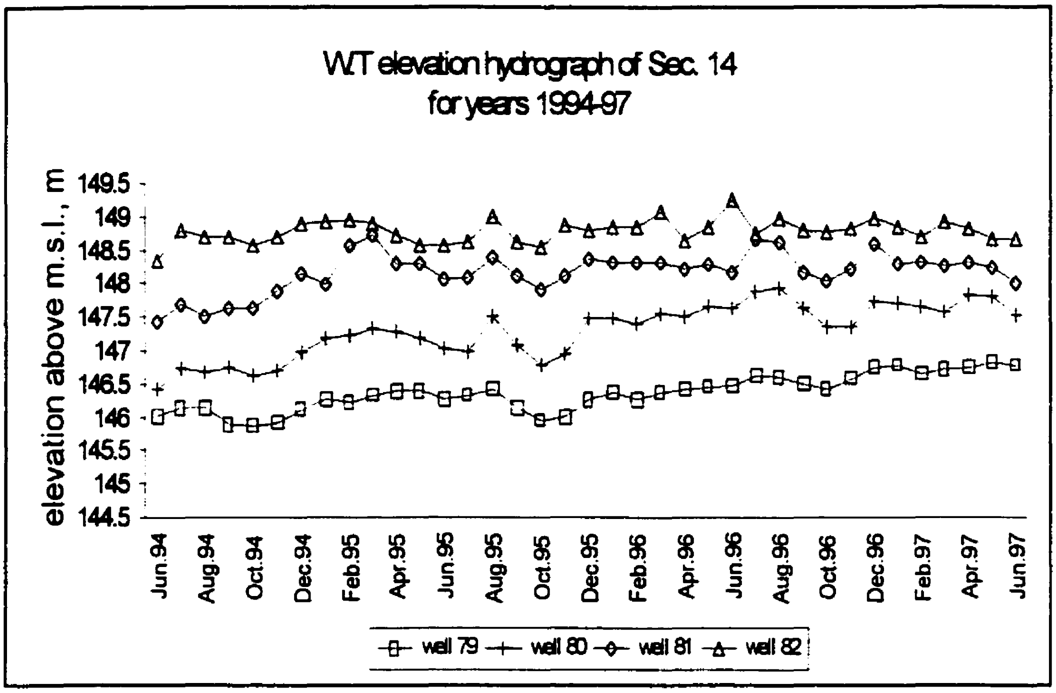


Figure 4.14 Watertable elevation hydrographs along cross-section 14

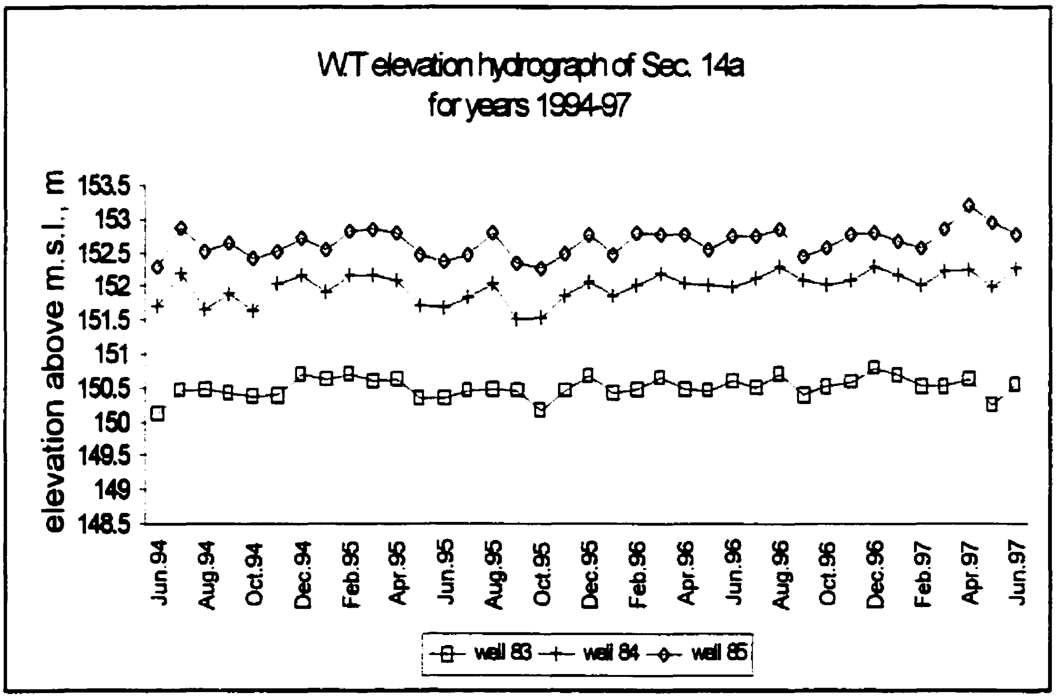


Figure 4.14a Watertable elevation hydrographs along cross-section 14

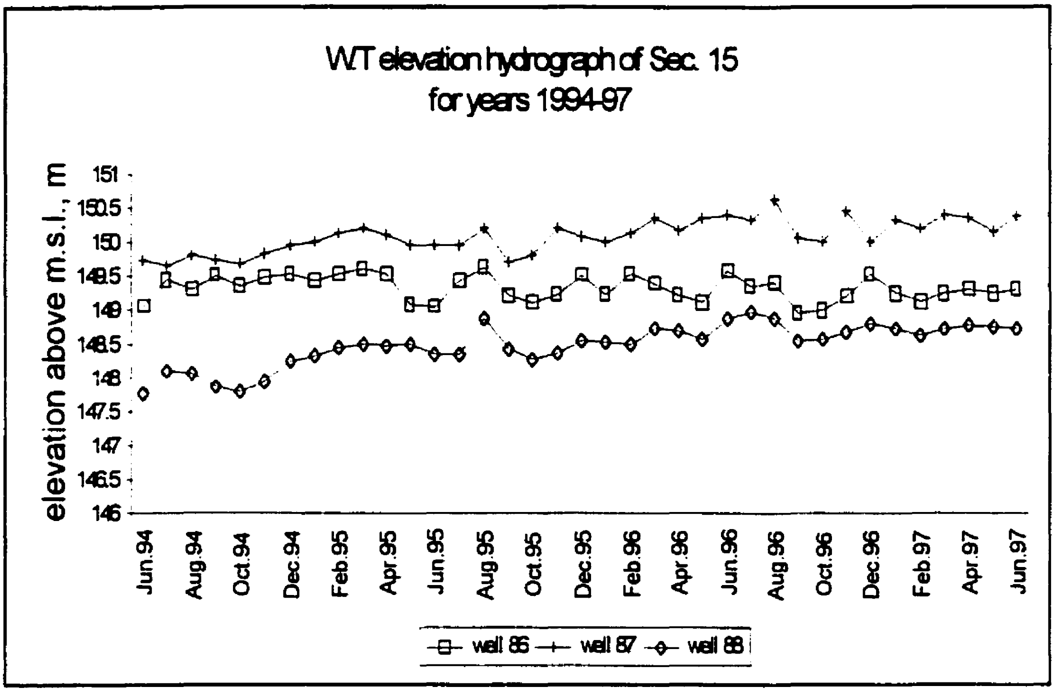


Figure 4.15 Watertable elevation hydrographs along cross-section 15

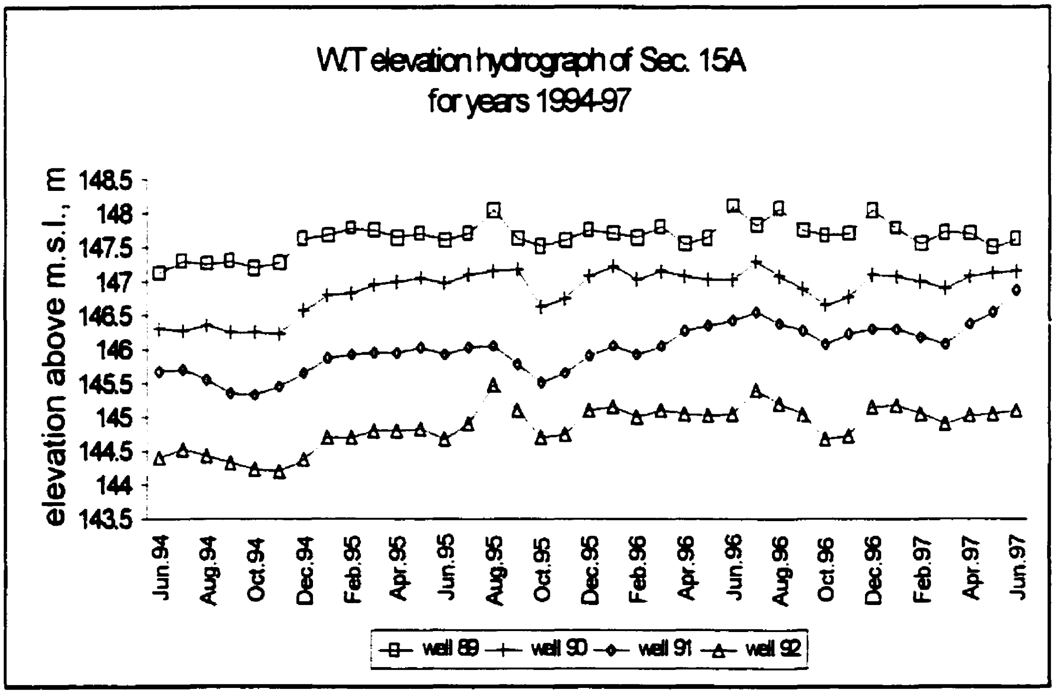


Figure 4.15a Watertable elevation hydrographs along cross-section 15

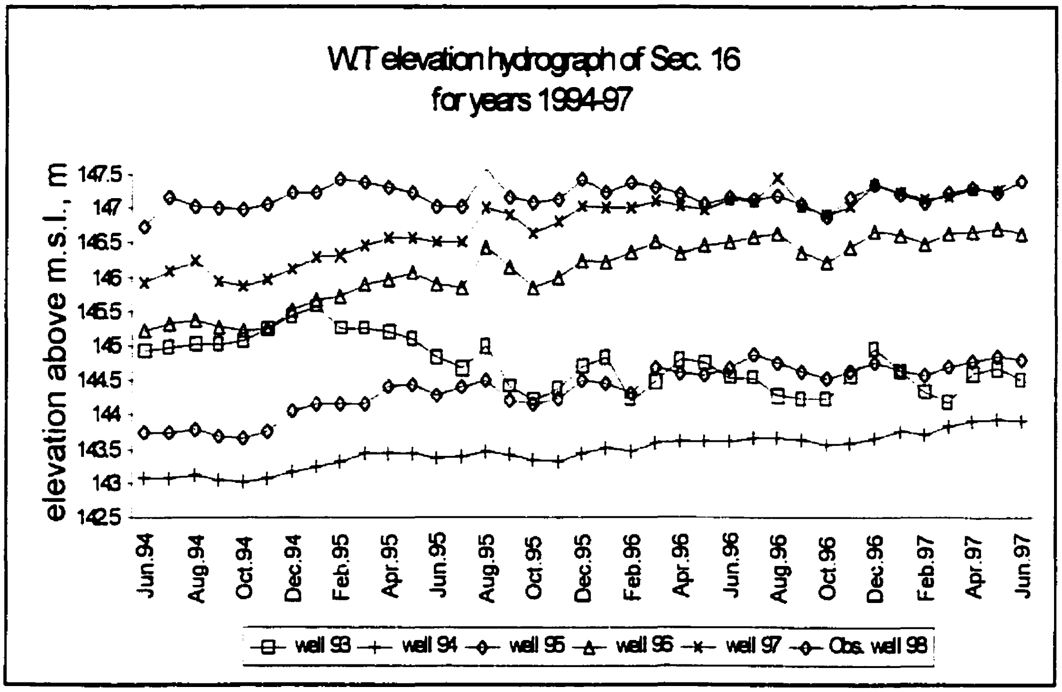


Figure 4.16 Watertable elevation hydrographs along cross-section 16

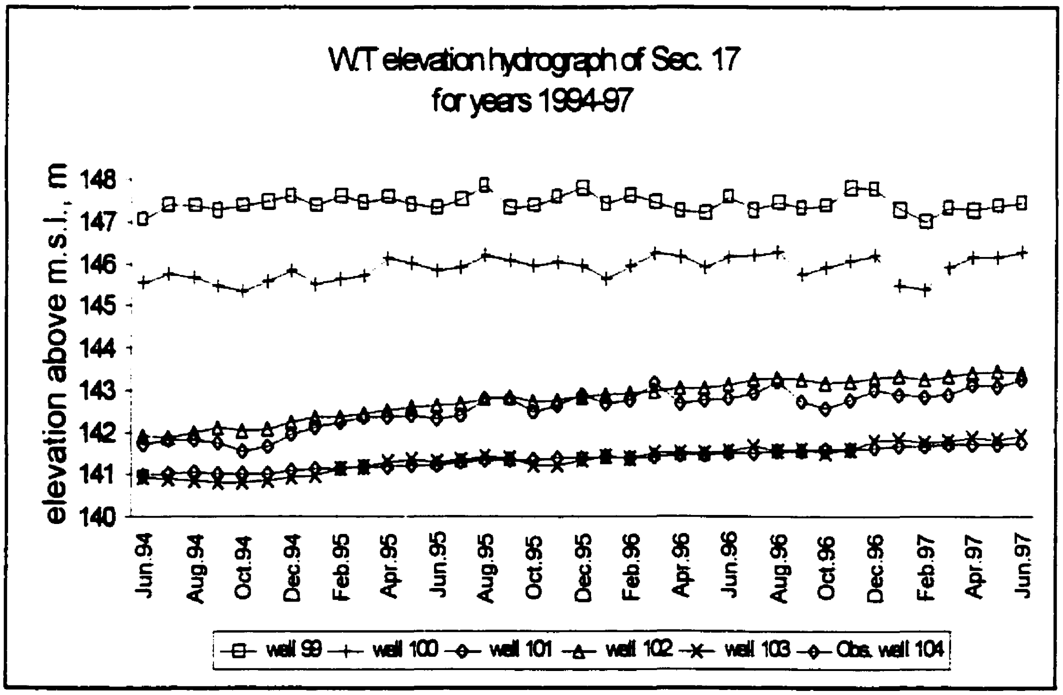


Figure 4.17 Watertable elevation hydrographs along cross-section 17

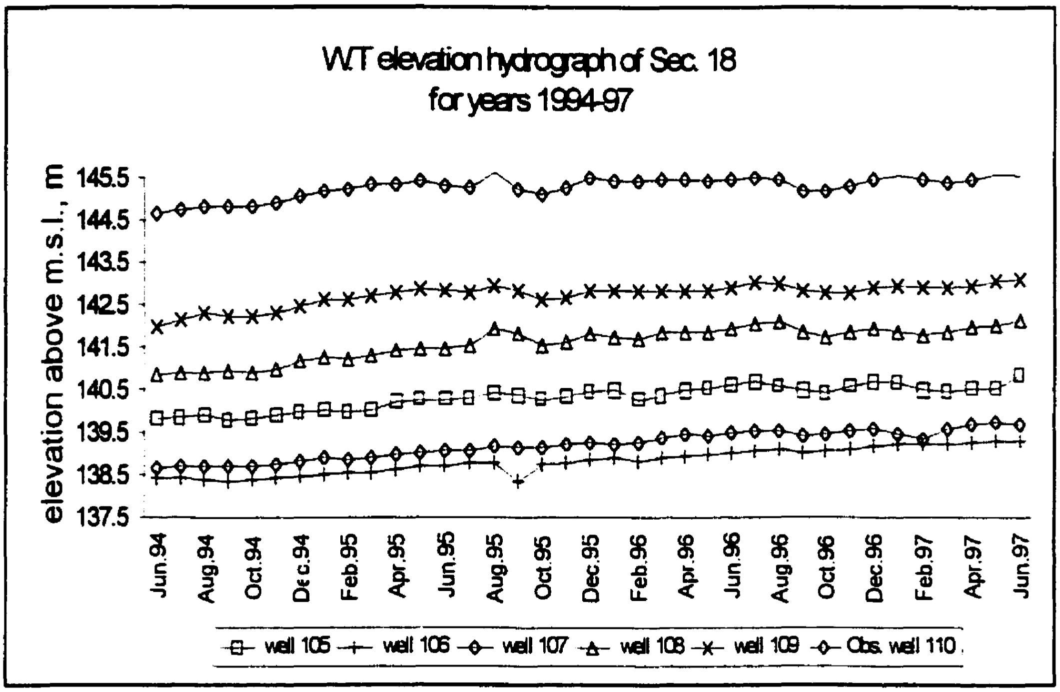


Figure 4.18 Watertable elevation hydrographs along cross-section 18

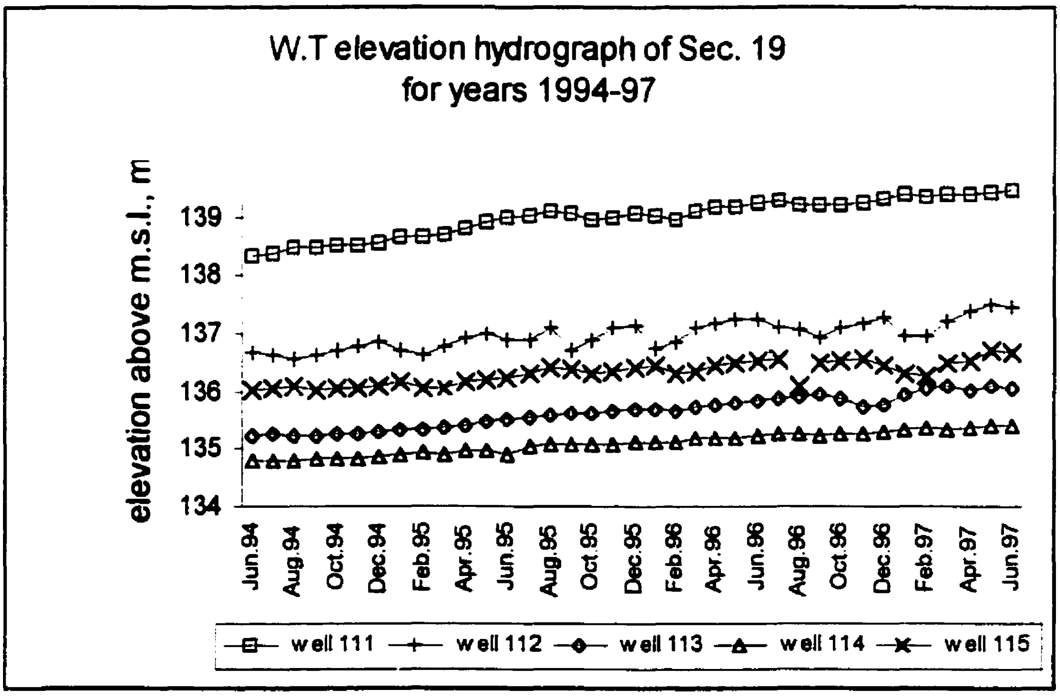


Figure 4.19 Watertable elevation hydrographs along cross-section 19

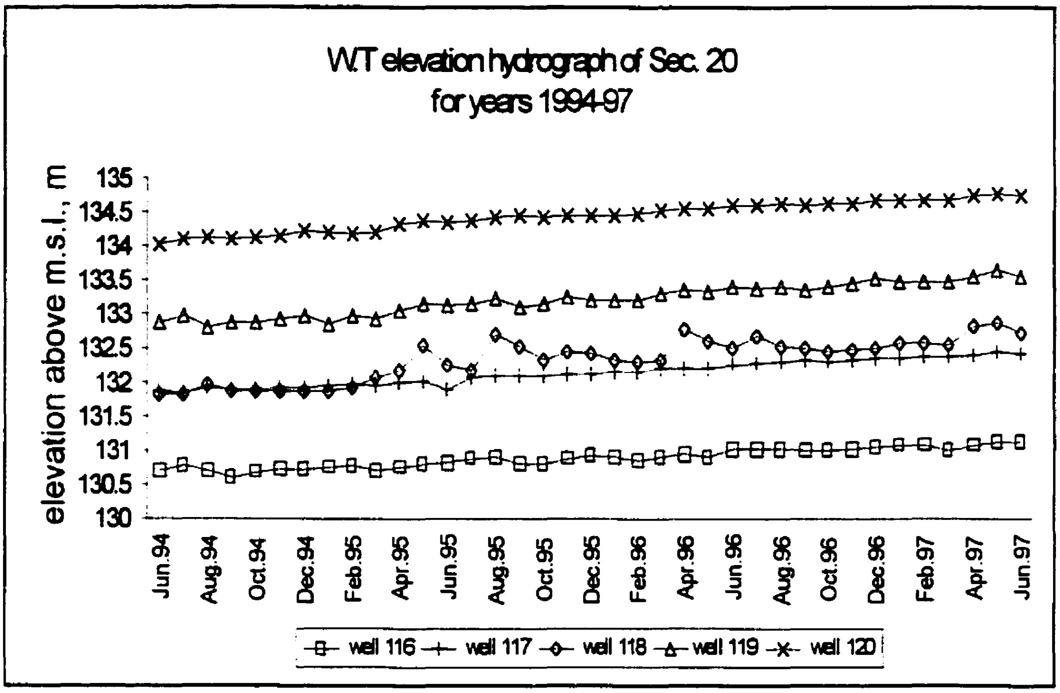


Figure 4.20 Watertable elevation hydrographs along cross-section 20

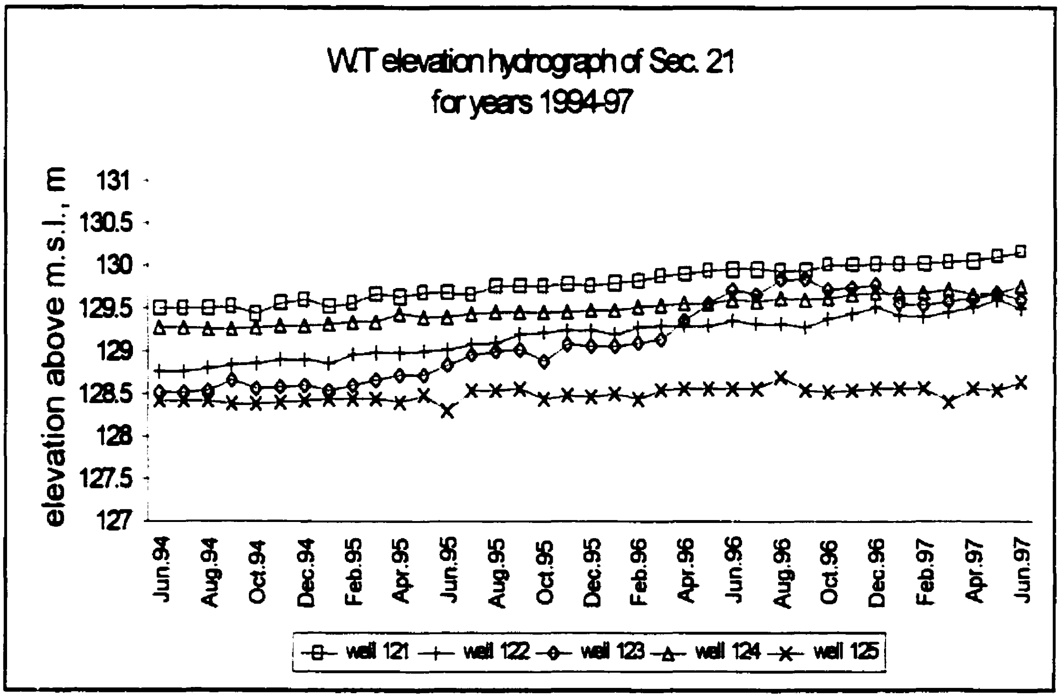


Figure 4.21 Watertable elevation hydrographs along cross-section

4.2 Watertable elevation contours

Monthly water table elevation contour maps were prepared (Figures 4.22 to 4.28). These maps show a consistent pattern of water table contour elevation over the 3 years. Over three year, very little change in the overall pattern of these contours occurred. These contour maps of the watertable elevation have been used as a basis for the determination of the direction of the groundwater flow and identification of recharge & discharge areas. If the soil is assumed to be homogeneous and isotropic the direction of groundwater flow can be illustrated by drawing flow lines perpendicular to the contour lines (equipotential lines) (Boonstra & de Ridder, 1994). The following observations can be made from Figures 4.22 to 4.28

i) From these figures, it can be seen that both the Malik & Hakra branch canals contribute recharge to the study area and also recharge the zones outside the study area. Note also that the largest gradient is in the north west corner where the Malik branch canal is recharging the zone outside the study area. In summary, both canals contribute to the study area groundwater; the Hakra to a somewhat larger degree. This may be because the Hakra carries 84 m^3/sec water with a greater depth than the Malik at 54 m^3/sec.

ii) These maps show a mound shape of the water table along the Hakra & Malik branch canals. This means the canals continuously loose water along their lengths.

iii) The Hakra branch canal and its distributaries cause various local mounds in the water table due to local recharge and also the groundwater moves in different directions from these mounds.

iv) In general, the contour lines at the east boundary along the Hakra branch canal are close to perpendicular to the area boundaries. This means that little flow across this boundary occurs. In contrast, the contour lines near the north-west boundary at the Malik branch canal trend to be parallel to the area boundary. This suggests large flows across this boundary.

v) A cluster of observation wells exhibits an opposite trend or behavior with respect to all adjacent wells. This occurred over the three year period of study. Observation wells 89, 82, 75 and 68 exhibited a downward tendency of the watertable elevations while adjacent wells exhibited an upward tendency. No specific reason can be given for this peculiar behavior. A possible explanation could be that the 6-R distributary (Hakra system) had no water for an unknown extended period of time.

vi) Away from the canals, the groundwater has a fairly steady smooth slope from north to south west: entering the region of the evaporation ponds This follows the same general trend of soil surface contours. (Figure 4.29).

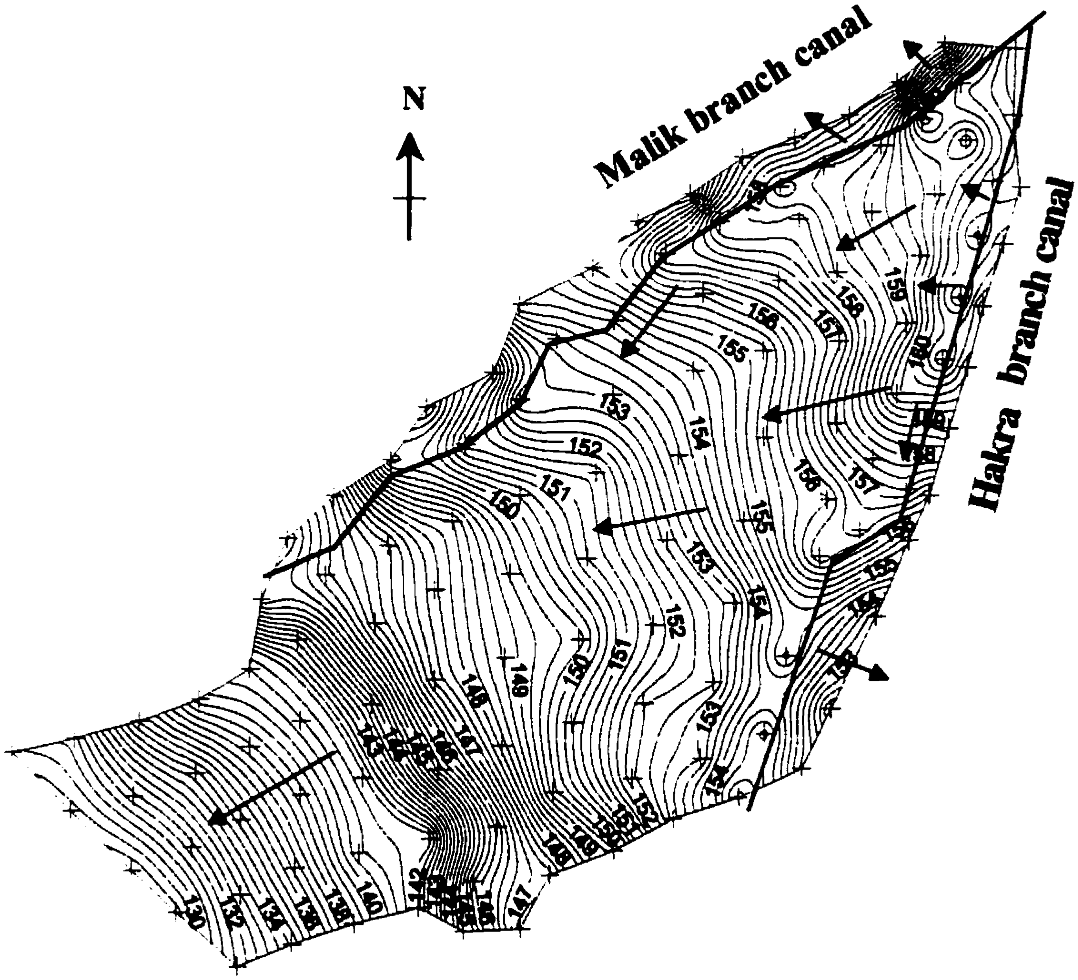


Figure 4.22 Watertable elevation contour map June 1994

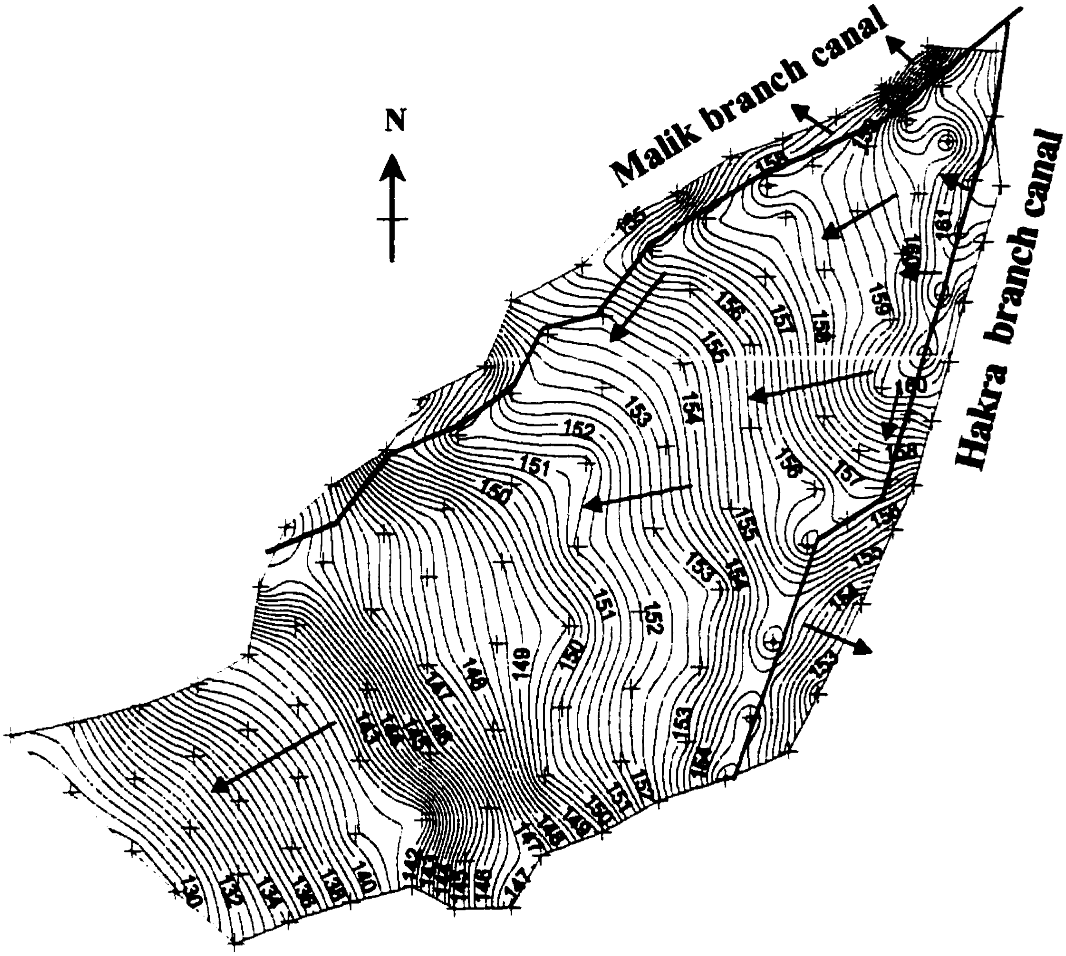


Figure 4.23 Watertable elevation contour map October 1994

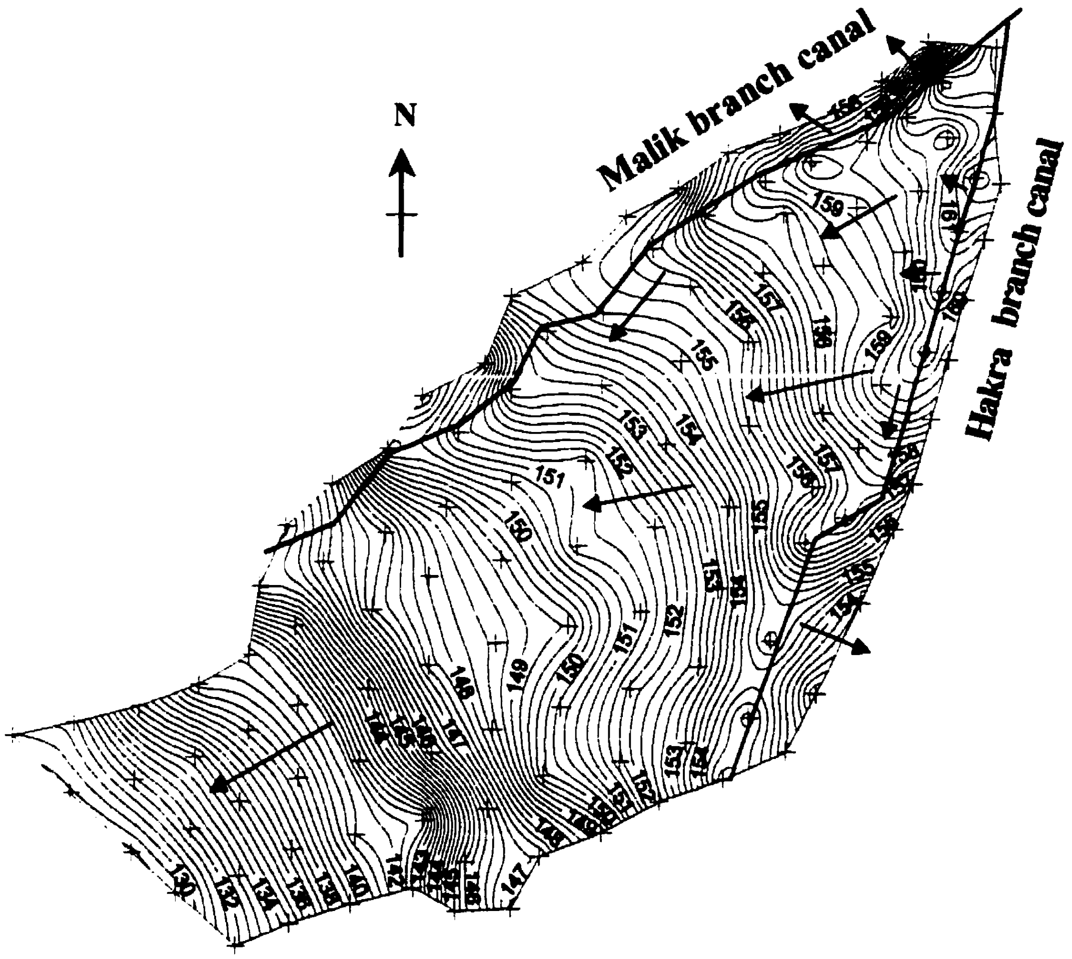


Figure 4.24 Watertable elevation contour map June 1995

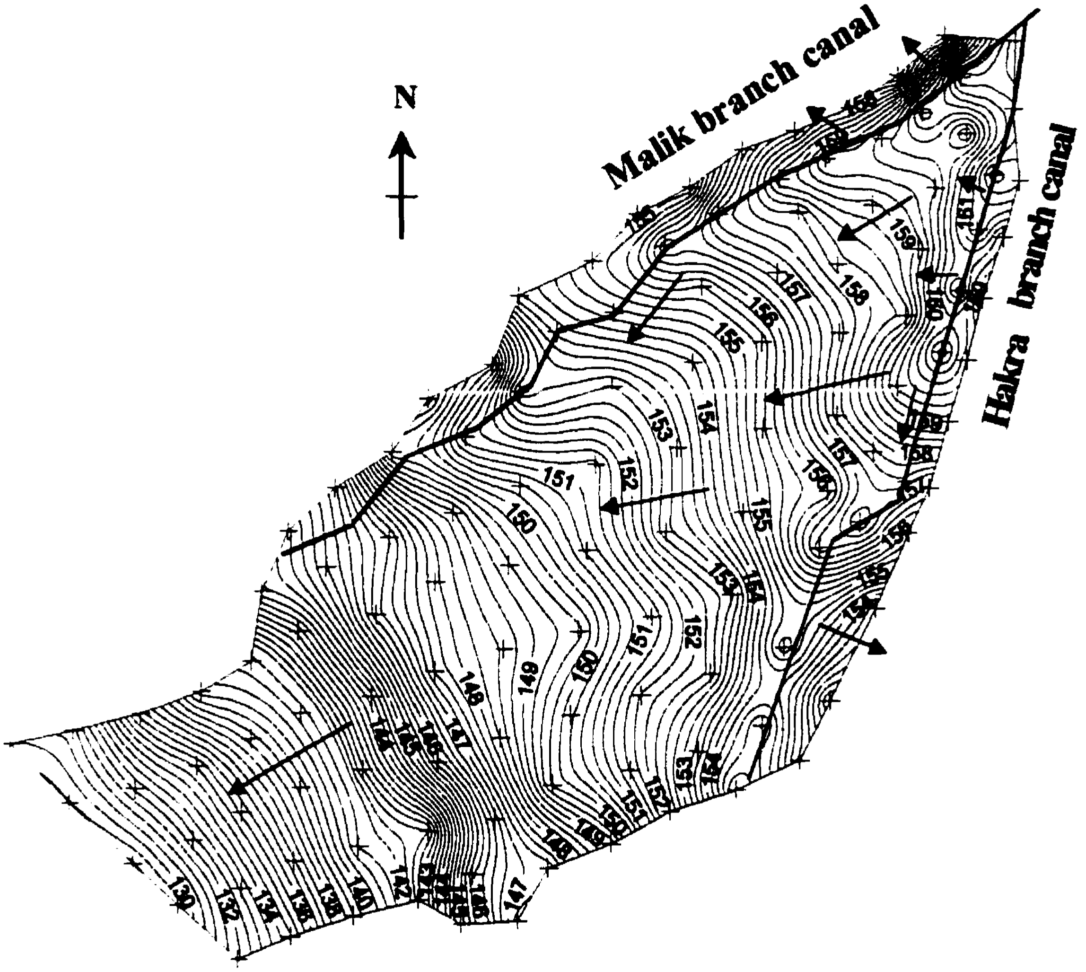


Figure 4.25 Watertable elevation contour map October 1995

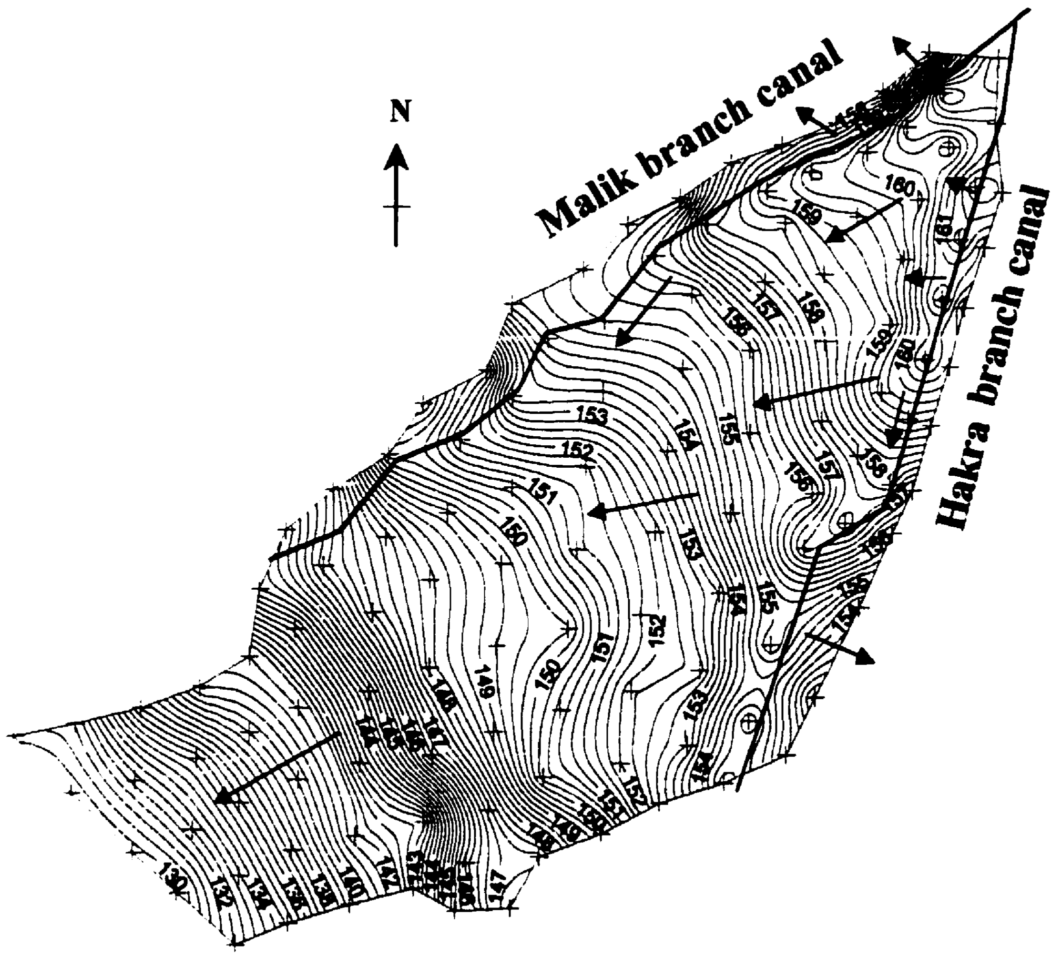


Figure 4.26 Watertable elevation contour map June 1996

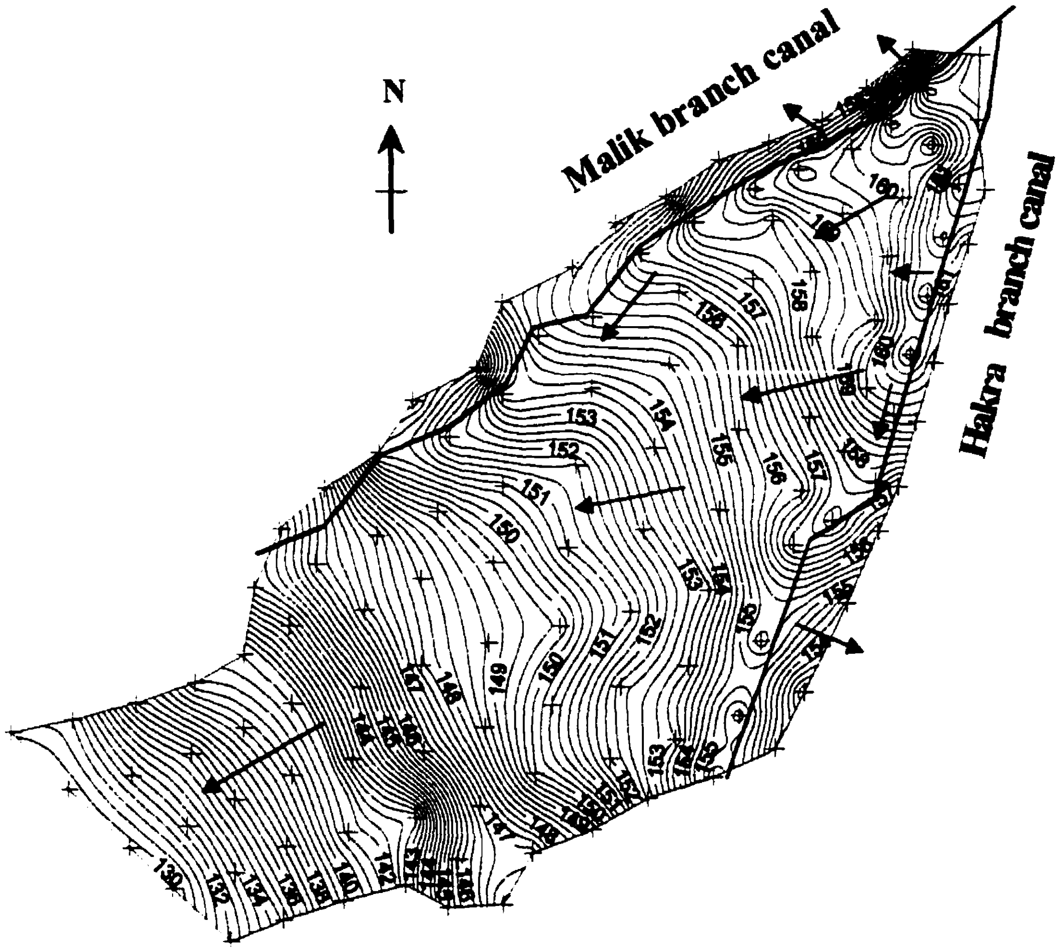


Figure 4.27 Watertable elevation contour map October 1996

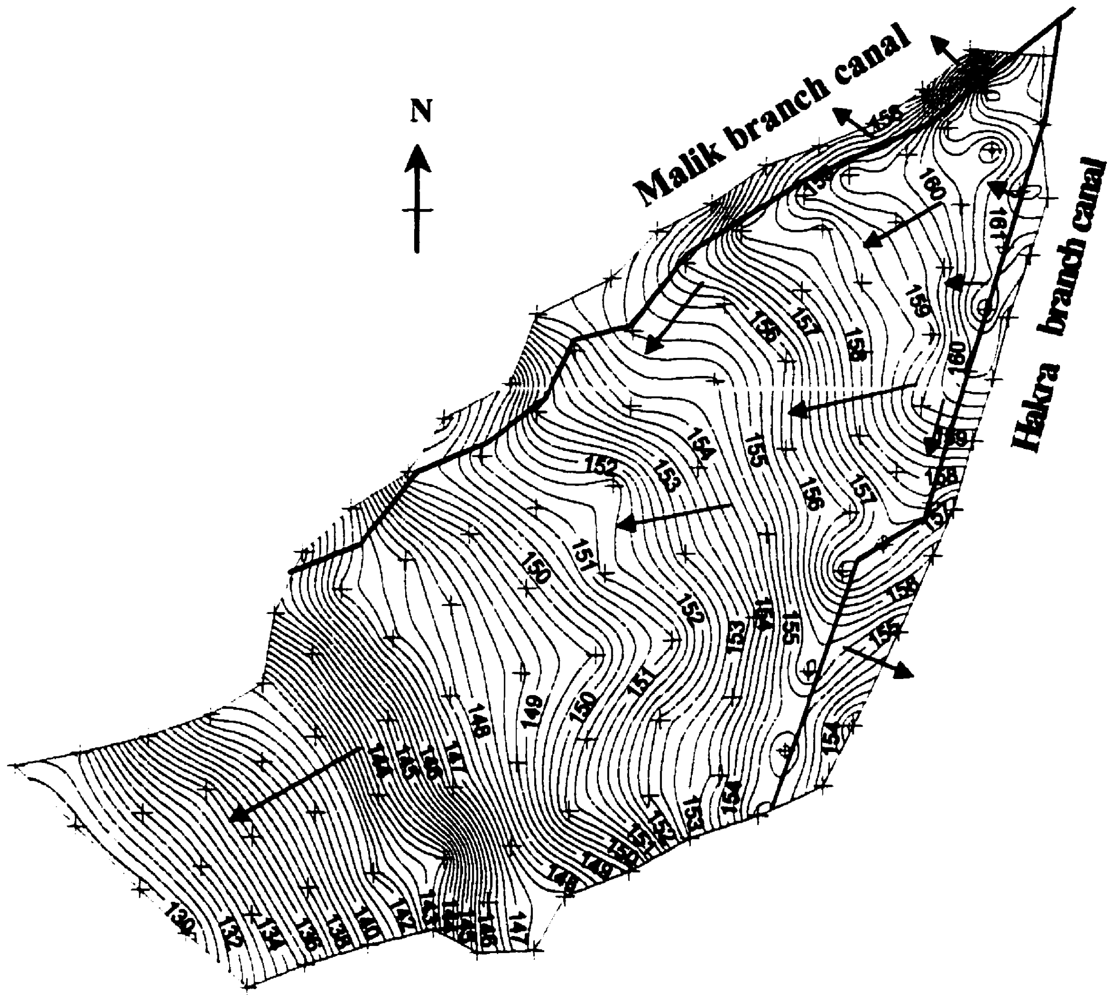


Figure 4.28 Watertable elevation contour map June 1997

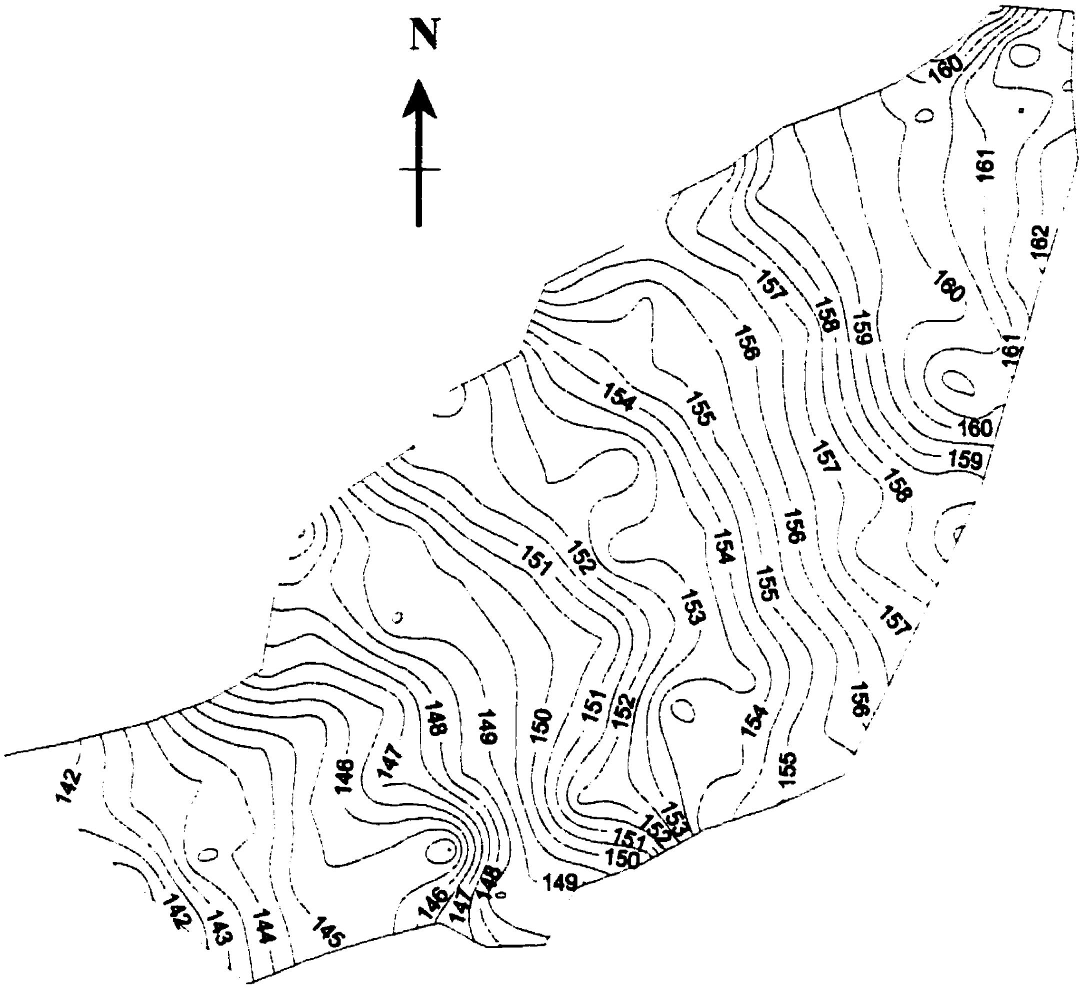


Figure 4.29 Natural soil surface contour map of FESS, contours in 0.5 m intervals show elevations above sea level.

4.3 Aquifer test analyses

The study area is located in the vast Indo-Gangetic Plain formed by the deposition of sediments in the geosyncline that was created during Himalayan Mountains orogeny of Territory times. The sediments underlying the project area are principally composed of loose sand, silt and clay (Feasibility Report, 1978). Considering the spatial variability in the aquifer parameters and differences in aquifer types as reported in the past, this study was planned to collect detailed information from seven different aquifer tests which were preformed in the past , as well as five new aquifer tests. Subsequently, this information was analyzed by using the software "Selected Test Evaluation Method" SATEM (Boonstra, 1989). The specific information regarding these aquifer tests is presented in Appendix A (Table A .1) and the locations of the different pumping test sites are shown in Figure 1.2.

4.3.1 Five new tests

4.3.1.1 Aquifer test site 1

Test site #1 is located south of Dahranwala town between the 6-R Distributary and the Faqirwali Minor. In this aquifer test the watertable was monitored in three observation wells located 3, 15 and 30 m from the pumped well were monitored. Time drawdown analysis indicated transmissivity values from 647-734 m^2/day. Similarly, time-recovery analysis transmissivity values from 618-763 m^2/day. The average obtained was 684 m^2/day (Appendix A). Figure 4.30 a and b present the data of three tests; using SATEM. The crosses represent new data and the solid lines are derived such that the line matches the maximum number of data points, plus the matching behavior of neighboring wells (see Boonstra, (1989) for details). The data from the well located 3 m away from the pumped well was analyzed using the partial penetration method (Boonstra, 1989). This method yields transmissivity values from 650 to 700 m^2/day . From this test method, aquifer thickness was found to be 105 m, therefore the hydraulic conductivity was 6- 6.5 m/day (Figures 4.30c & 4.30d).

Time-Drawdown

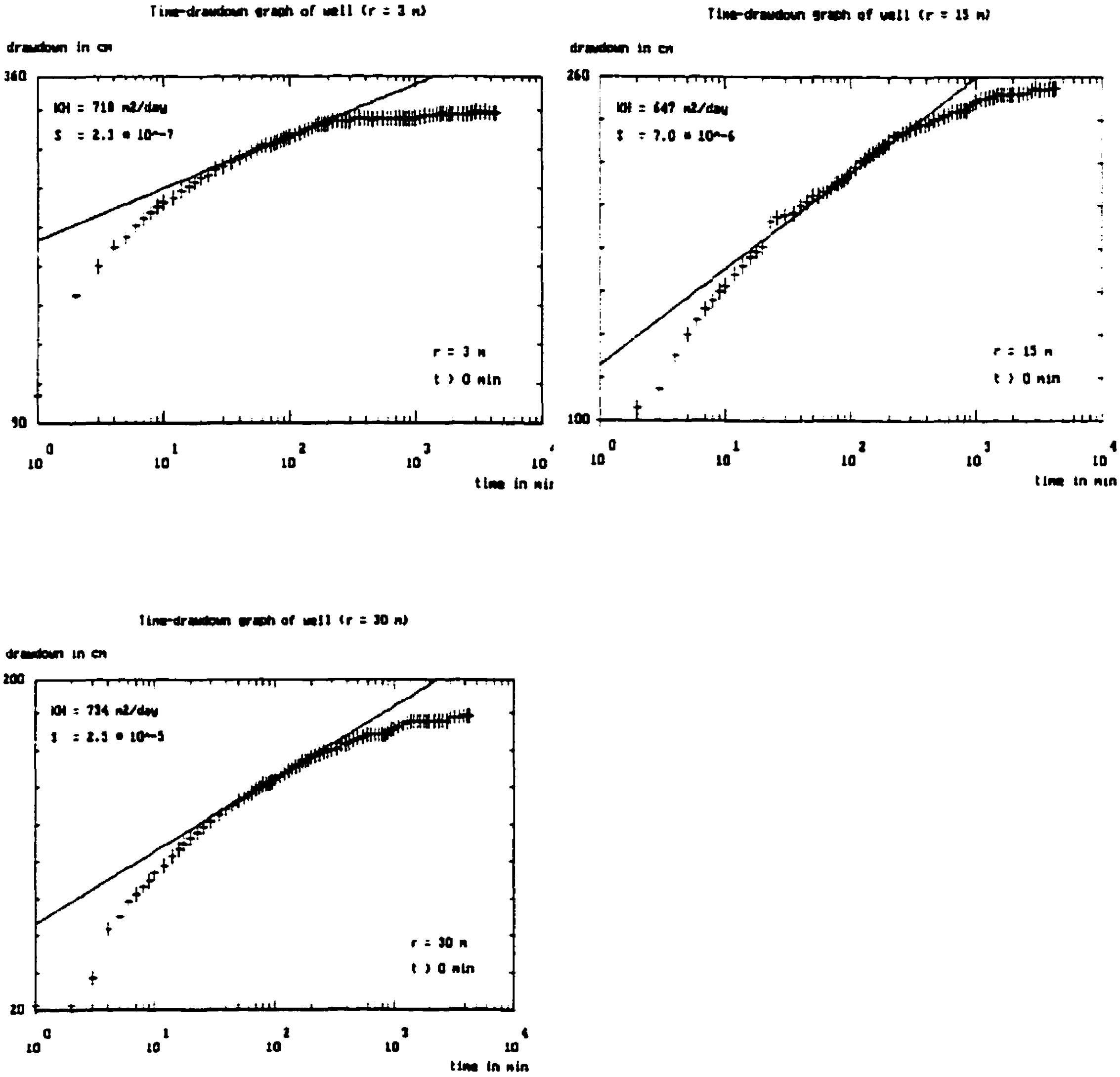


Figure 4.30a Time-drawdown analysis of aquifer test # 1

Time-Recovery

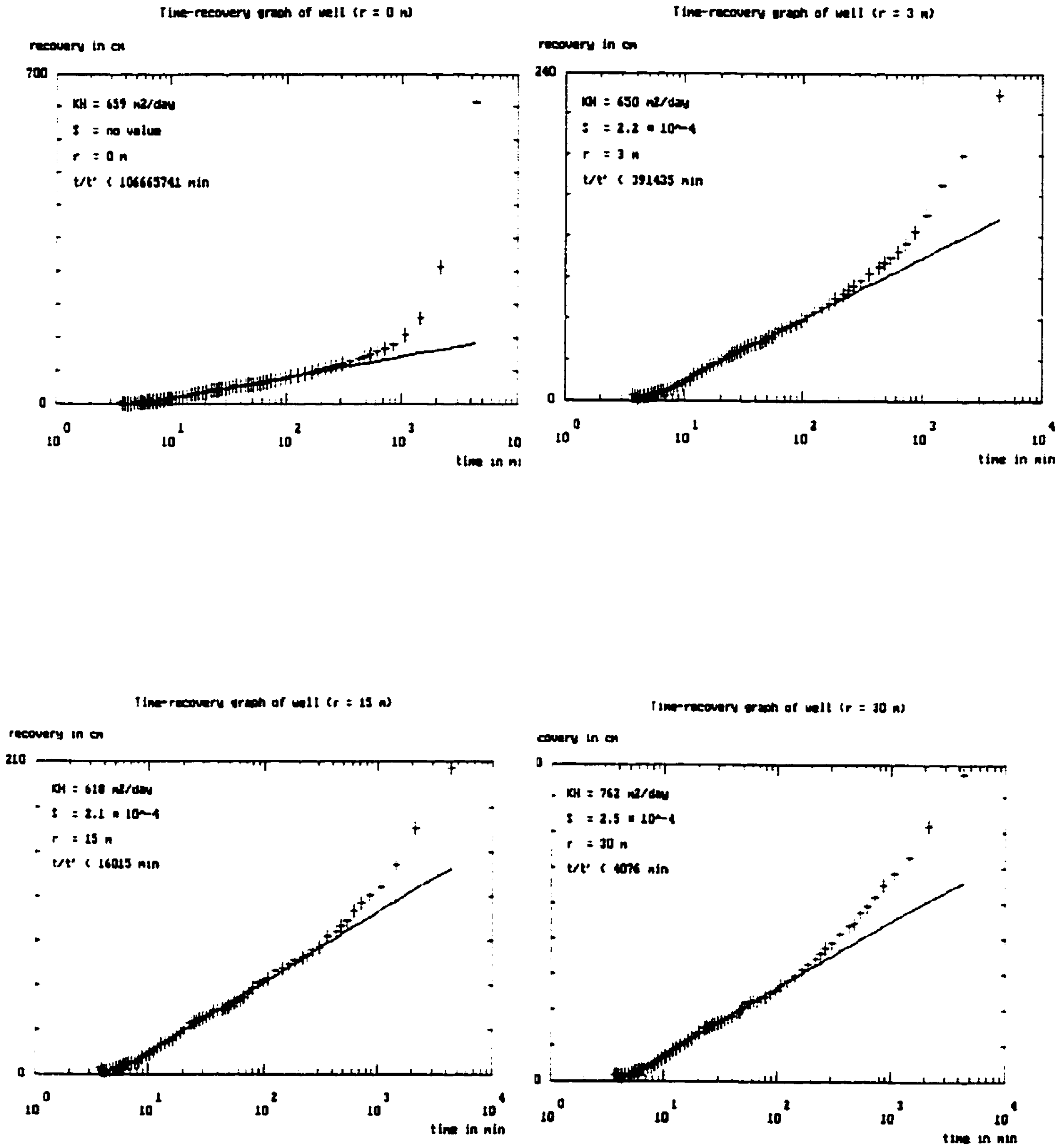


Figure 4.30b Time-recovery analysis of aquifer test # 1

Time-drawdown

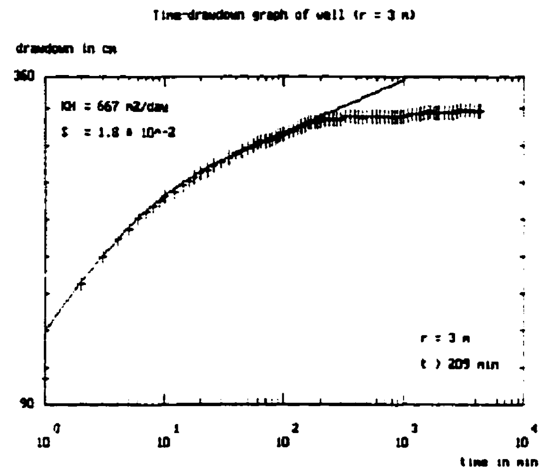


Figure 4.30c Time-drawdown analysis(partial penetration) of aquifer test # 1

Time-Recovery

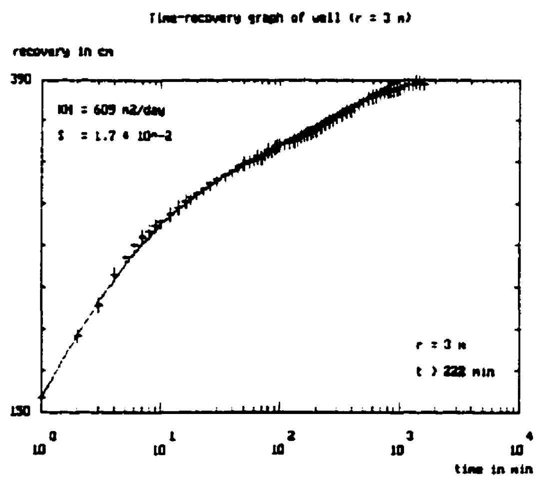


Figure 4.30d Time-recovery analysis(partial penetration) of aquifer test # 1

4.3.1.2 Aquifer test site 2

Aquifer test site-2 is located south of Harunabad, between the Faqirwali Minor and the Khichiwala Distributary. In this test, the watertable of pumped well and three observation wells located 6, 19 and 60 m from the pumped well were monitored. Analysis of these wells yield a transmissivity value ranging from 1336 m^2/day to 1379 m^2/day for time-drawdown and from 2650 m^2/day to 2907 m^2/day for time-recovery (Appendix A).

The large variation in transmissivity between the two methods causes concern with respect to data reliability. Also, a value in the order of 2907 m^2/day is much higher than any other tests in the area. For these reasons this test site data were discarded.

4.3.1.3 Aquifer test site 3

Aquifer test site # 3 is located south-south-east of Harunabad between the 5-R Bagsar Distributary and the 1R/6R Pathan Minor. In this test, the watertable of pumped well and three observation wells located 6, 19 and 60 m from the pumped well were monitored. The analysis of these wells resulted in a transmissivity value ranging from 1716 m^2/day to 1919 m^2/day for time-drawdown and from 1787 m^2/day to 1847 m^2/day for time-recovery (Figures 4.31a & b and Appendix A).The average obtained was 1806 m^2/day.

4.3.1.4 Aquifer test site 4

The Aquifer test site # 4 is located in the west-south-west of Harunabad between the Saurkhan Minor and the 1-R Badruwala Minor. In this test, the watertable of pumped well and three observation wells located 3, 15 and 30 m from the pumped well were monitored. The analysis of these wells resulted in a transmissivity value ranging from 820 m^2/day to 882 m^2/day for time-drawdown and from 821 m^2/day to 836 m^2/day for time-recovery (Figures 4.32a & b and Appendix A).The average obtained was 840 m^2/day.

Time-Drawdown

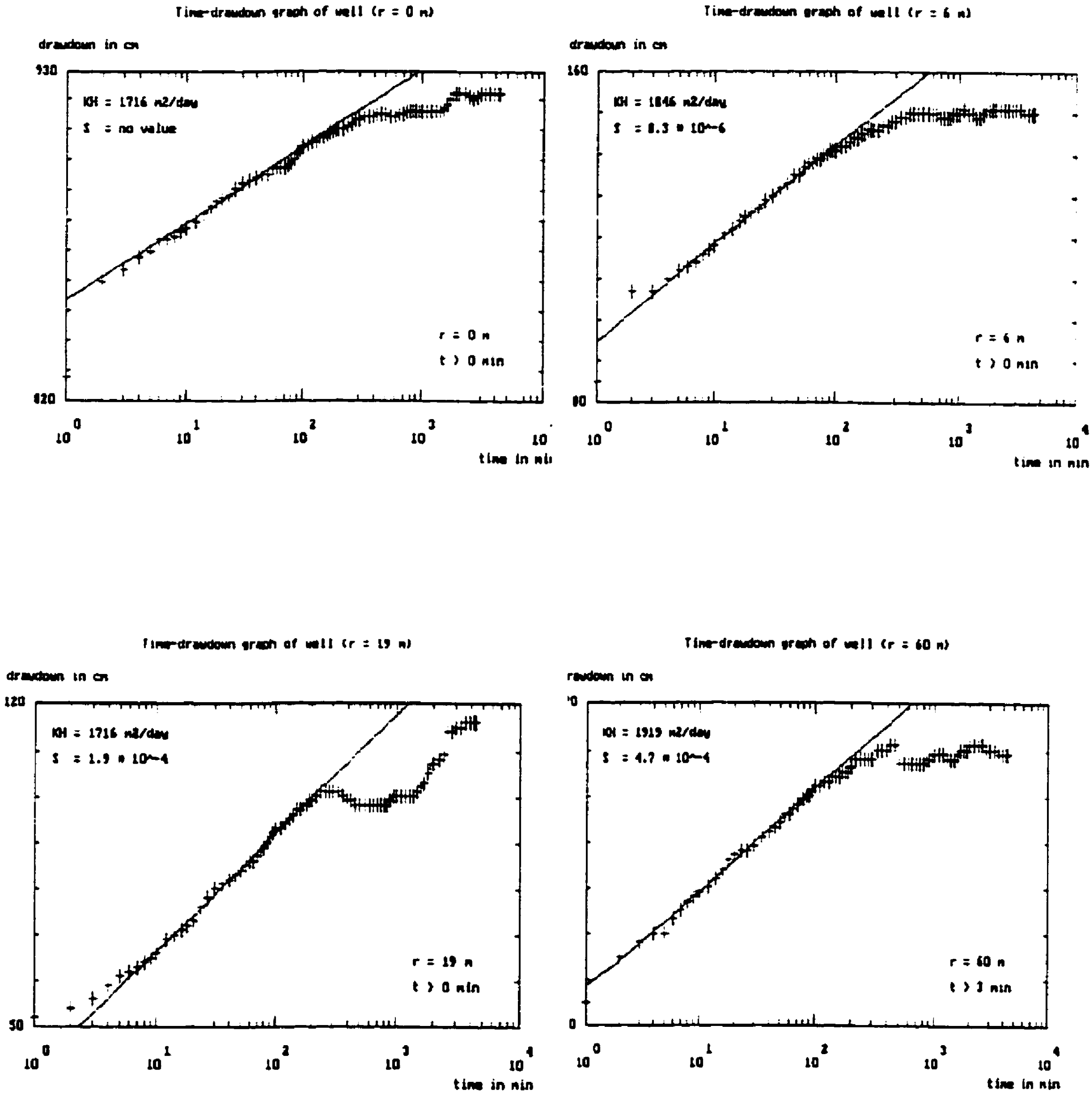


Figure 4.31a Time-drawdown analysis of aquifer test # 3

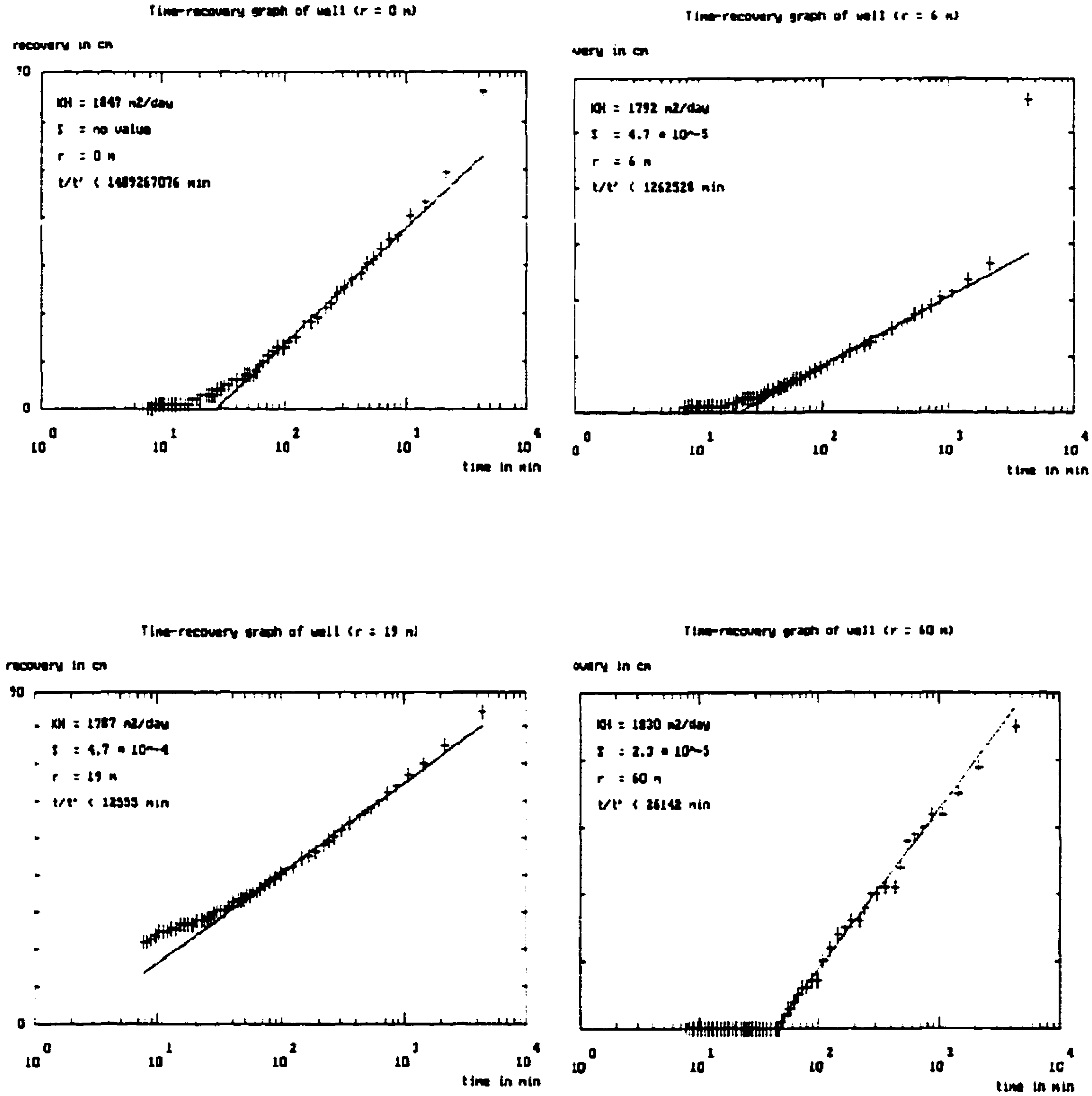


Figure 4.31b Time-recovery analysis of aquifer test # 3

Time-Drawdown

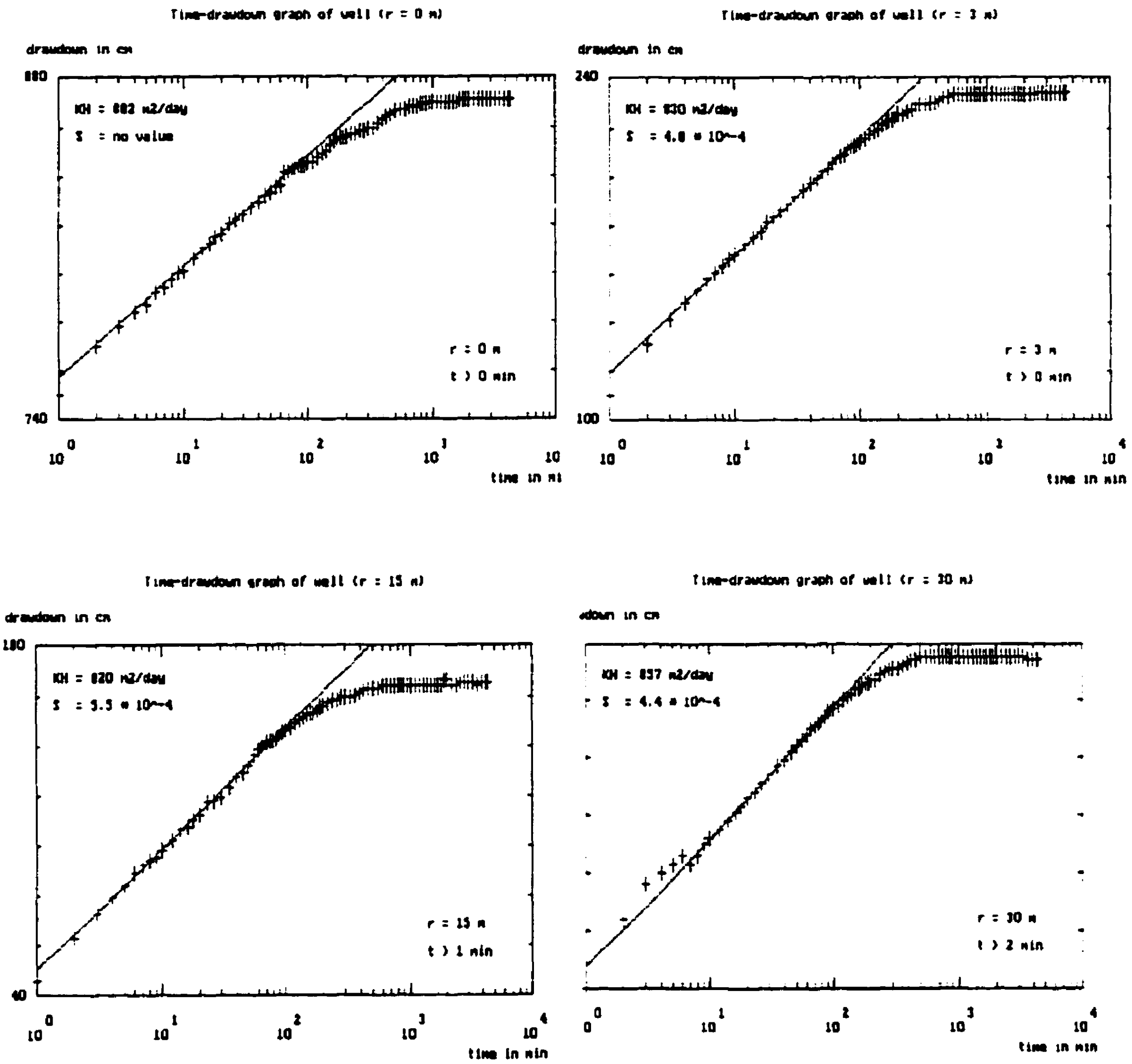


Figure 4.32a Time-drawdown analysis of aquifer test # 4

Time-Recovery

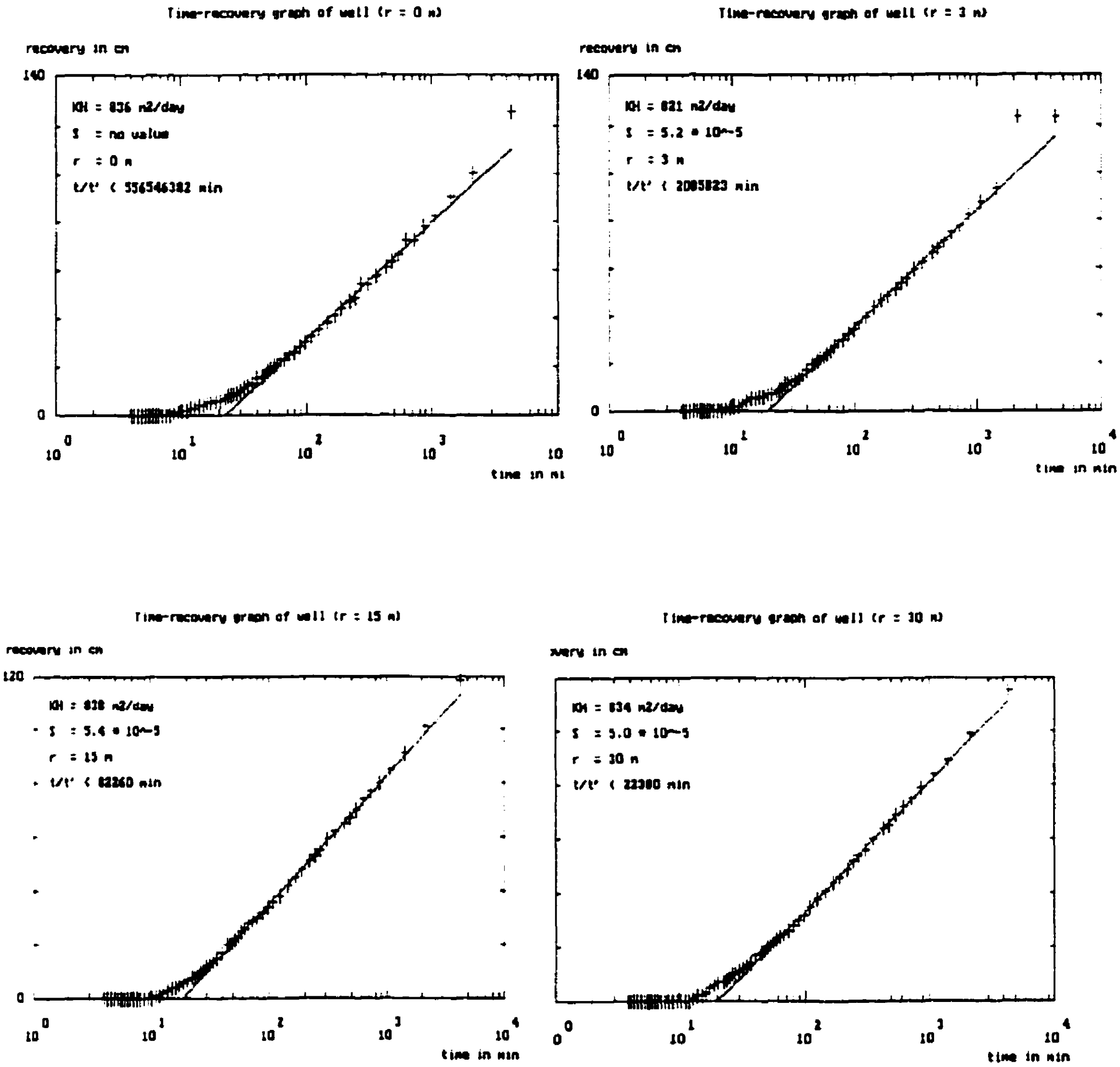


Figure 4.32b Time-recovery analysis of aquifer test # 4

4.3.1.5 Aquifer test site 5

Aquifer test site # 5 is located north-north-west of Dunga Bunga between the Bukhan and the Sirajwala Distributaries. In this test, the watertable of pumped well and two observation wells located 3 and 15 m from the pumped well were monitored. The analysis of these wells resulted in a transmissivity value ranging from 856 m^2/day to 934 m^2/day for time-drawdown and from 997 m^2/day to 1081 m^2/day for time-recovery (Figures 4.33a & b and Appendix A).The average obtained was 972 m^2/day.

4.3.2 Seven historical tests

4.3.2.1 Aquifer test 6-R Hakra: HA-1

This test was conducted by NESPAK-NDC in 1988 during drainage investigation study of 6 - R Hakra. The test site is located south of Harunabad between the Faqirwali Minor and the Hakra branch canal. In this test, the watertable of pumped well and two observation wells located 30 m (deep & shallow) from the pumped well were monitored. The analysis of these wells indicated a transmissivity value ranging from 1249 m^2/day to 1281 m^2/day for time-drawdown, from 1379 m^2/day to 1435 m^2/day for time-recovery and from 1131 m^2/day to 1364 m^2/day for residual-drawdown (Figures 4.34a & b and Appendix A).The average obtained from the time-drawdown and residual-drawdown data was 1270 m^2/day.

4.3.2.2 Aquifer test 6-R Hakra: HA-2

The aquifer test was conducted by NESPAK-NDC in 1988 during a drainage investigation study of 6-R Hakra. The test site is located south of Harunabad between the Faqirwali Minor and the Hakra branch canal. In this test, the watertable of pumped well and one observation wells located 30 m from the pumped well were monitored. The analysis of these wells resulted in a transmissivity value ranging from 1401 m^2/day to 2068 m^2/day for time-drawdown, from

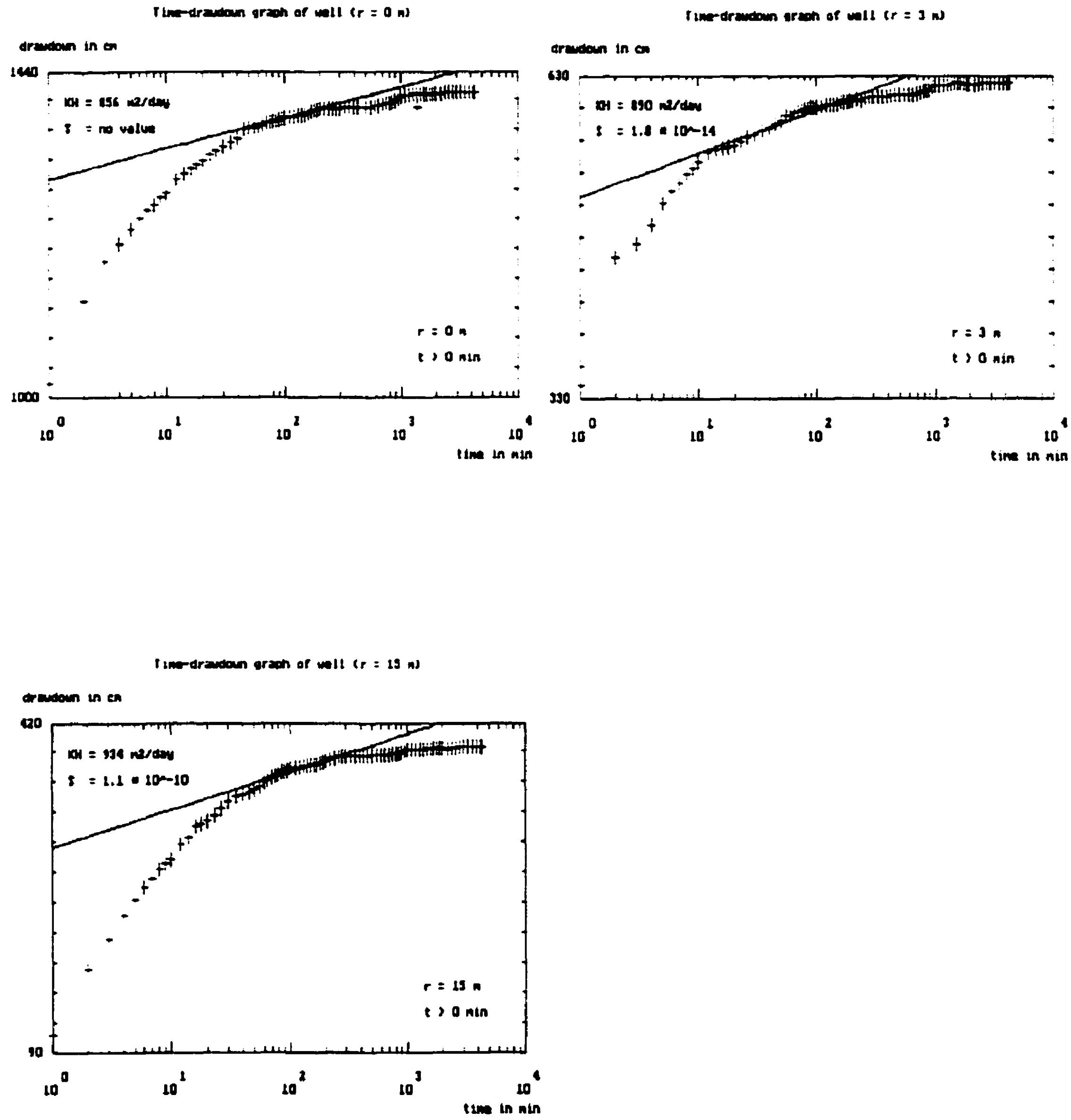


Figure 4.33a Time-drawdown analysis of aquifer test # 5

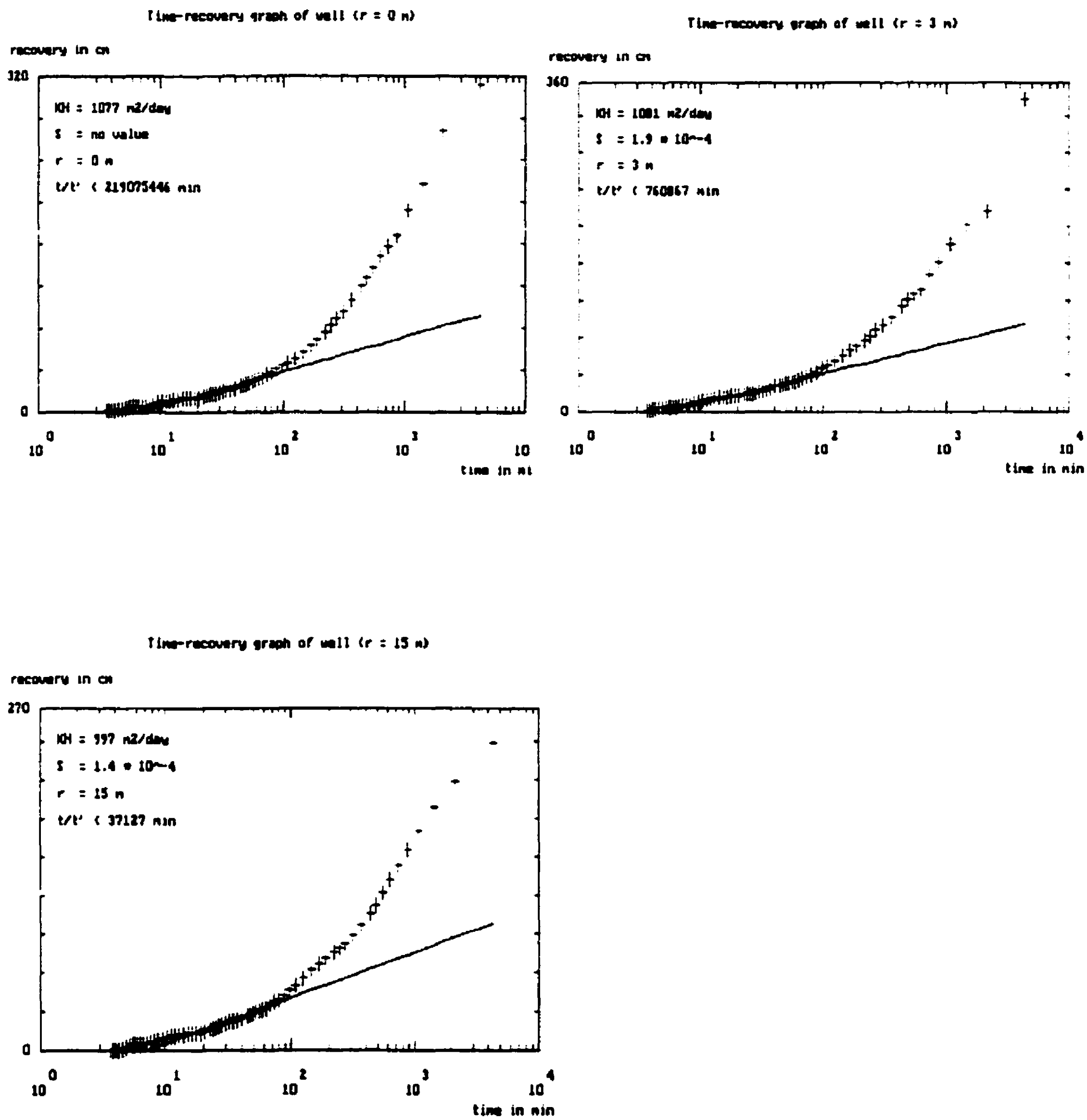


Figure 4.33b Time-recovery analysis of aquifer test # 5

Time-drawdown **Time-recovery**

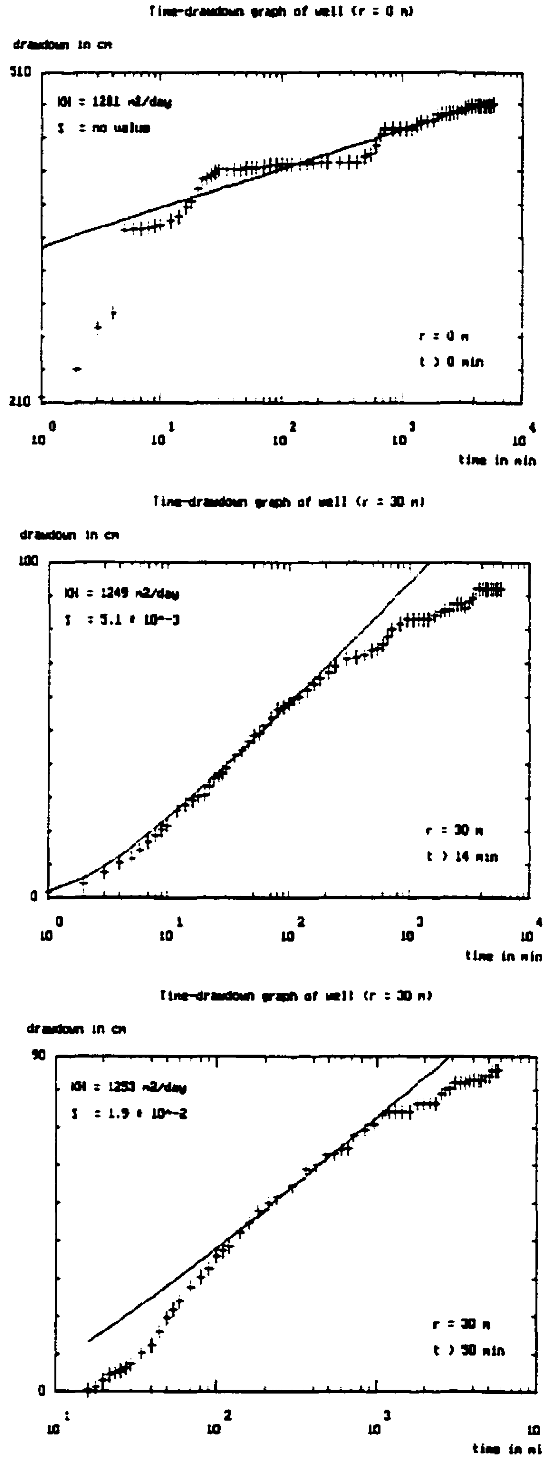


Figure 4.34a Time-drawdown analysis of test site # HA-1

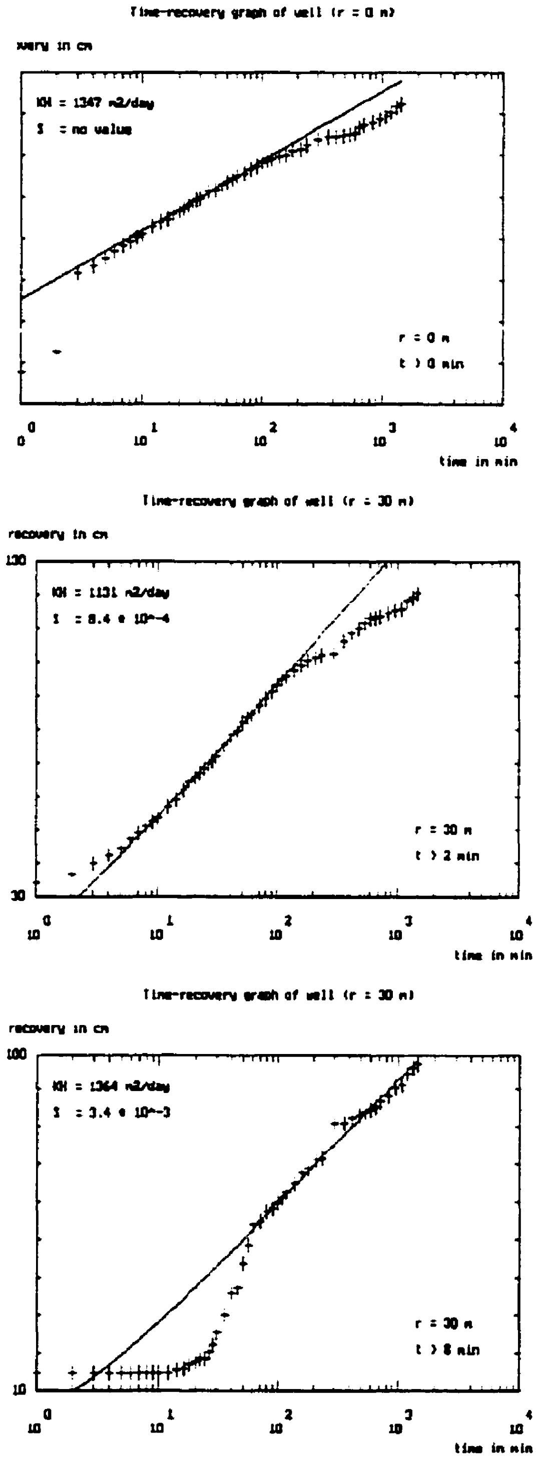


Figure 4.34b Time-recovery analysis of test site # HA-1

1558 m^2/day to 2397 m^2/day for time-recovery and from 1198 m^2/day to 2933 m^2/day for residual-drawdown (Appendix A).

The large variation in transmissivity between the three methods causes concern with respect to data reliability. Also, a value in the order of 2933 m^2/day is much higher than most other tests in the area. For these reasons this test site data was discarded from further analysis.

4.3.2.3 Aquifer test groundwater study: HRN-1

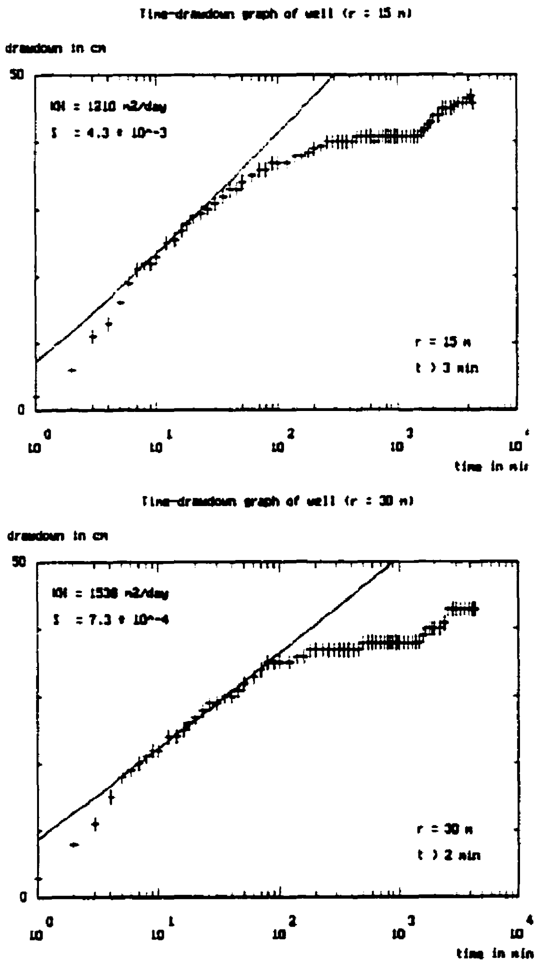
This aquifer test was conducted by Khalid and Riaz (1992) during a groundwater study at along the Hakra canal and the 3-R Distributary. The test site is located north of Harunabad near the railway track on Khatan Distributary. In this test, the watertable of pumped well and two observation wells located 15 and 30 m from the pumped well were monitored.
The analysis of these wells indicated a transmissivity value ranging from 1210 m^2/day to 1538 m^2/day for time-drawdown and from 1209 m^2/day to 1471 m^2/day for time-recovery (Figures 4.35a & b and Appendix A). The average obtained was 1350 m^2/day.

4.3.2.4 Aquifer test groundwater study: HRN-2

This aquifer test was conducted by Khalid and Riaz (1992) during a groundwater study at along the Hakra canal and the 3-R Distributary. The test site is located east of Harunabad on the Hakra branch near the 5-R Bagsar Distributary. In this test, the watertable of pumped well and four observation wells located 15, 30, 45 and 60 m from the pumped well were monitored. The analysis of these wells yield a transmissivity value ranging from 1044 m^2/day to 2724 m^2/day for time-drawdown (Appendix A).

Non availability of time-recovery data and the large variation in transmissivity value results in concern about accuracy. Thus this test site data was not used for further analysis

Time-drawdown **Time-Recovery**



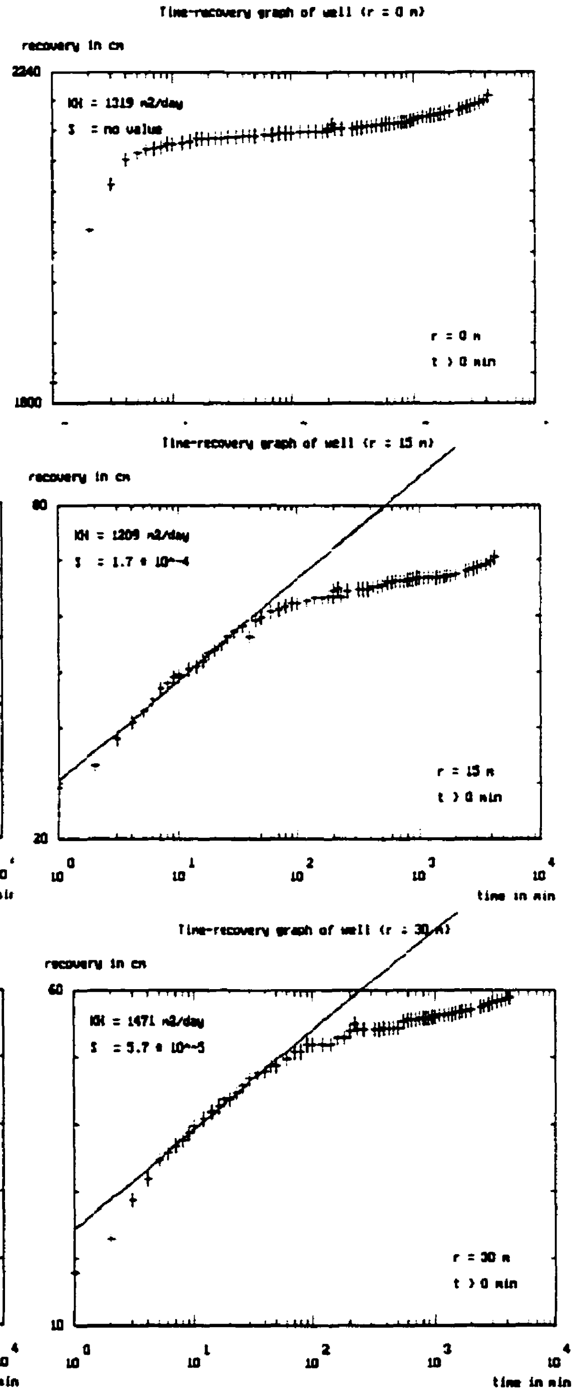


Figure 4.35a Time-drawdown analysis of test site # HRN-1

Figure 4.35b Time-recovery analysis of test site # HRN-1

4.3.2.5 Aquifer test FESS additional studies: T/W-1

This aquifer test was conducted by NESPAK 1991, for additional FESS studies. The test site is located south-west of Dunga Bunga between the Najibwal and the Bahadurwah Minors. In this test, the watertable of three observation wells located 8 and 46 m (deep & shallow) from the pumped well were monitored. Analysis of these wells resulted in a transmissivity value ranging from 1003 m^2/day to 1146 m^2/day for time-drawdown, from 500 m^2/day to 1028 m^2/day for time-recovery and from 618 m^2/day to 914 m^2/day for residual-drawdown (Figures 4.36a & b and Appendix A).The average obtained from the time-drawdown and residual-drawdown data was 948 m^2/day.

4.3.2.6 Aquifer test FESS additional studies: T/W-2

This aquifer test was conducted by NESPAK 1991, for additional FESS studies. The test site is located north-west of Dunga Bunga between the Najibwal and the 1-R Minors. In this test, the watertable of four observation wells located 8 (deep & shallow) and 46 m (deep & shallow) from the pumped well were monitored. The analysis of these wells resulted in a transmissivity value ranging from 883 m^2/day to 1334 m^2/day for time-drawdown, from 457 m^2/day to 942 m^2/day for time-recovery and from 768 m^2/day to 957 m^2/day for residual-drawdown (Figures 4.37a & b and Appendix A).The average obtained from the time-drawdown and residual-drawdown data was 980 m^2/day.

4.3.2.7 Aquifer test FESS additional studies: T/W-3

This aquifer test was conducted by NESPAK 1991, for additional FESS studies. The test site is located south-west of Dunga Bunga between the Najibwal Minor and the Qaziwala Distributary. In this test, the watertable of three observation wells located 8 and 46 m (deep & shallow) from the pumped well were monitored. The analysis of these wells resulted in a transmissivity value ranging from 935 m^2/day to 1286 m^2/day for time-drawdown, from 912 m^2/day to 1229 m^2/day for time-recovery and from 1094 m^2/day to 1155 m^2/day for residual-drawdown (Figures 4.38 a & b and Appendix A).The average obtained from the time-drawdown and residual-drawdown data was 1088 m^2/day.

Time-drawdown

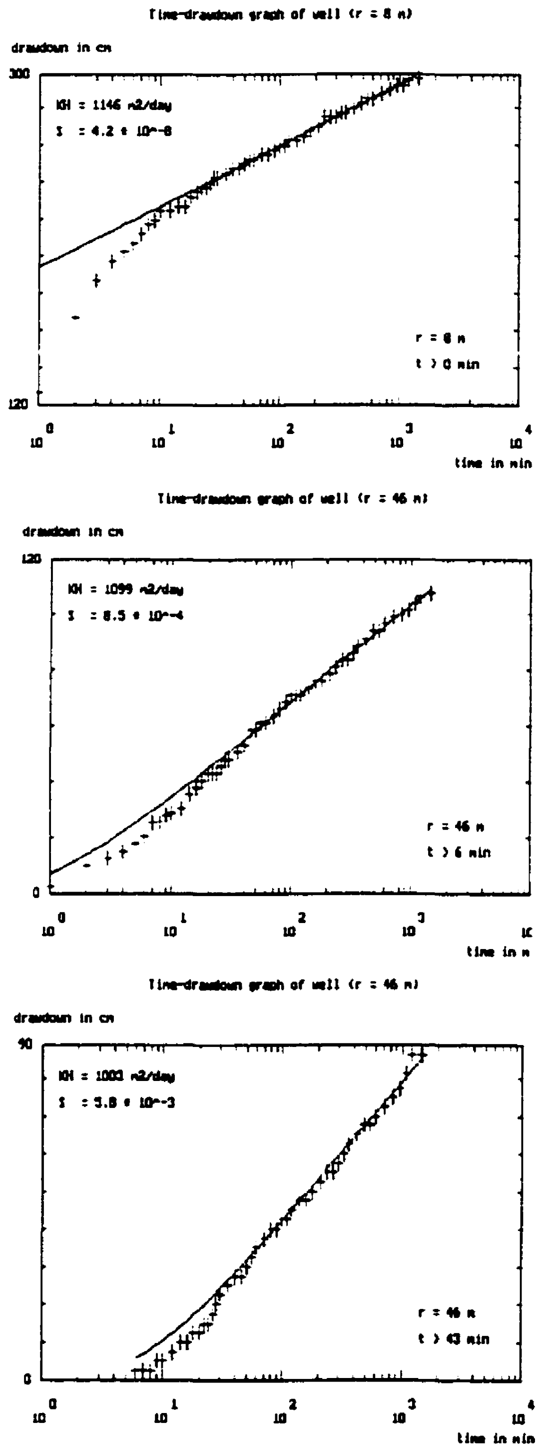


Figure 4.36a Time-drawdown analysis of test site # T/W-1

Time-recovery

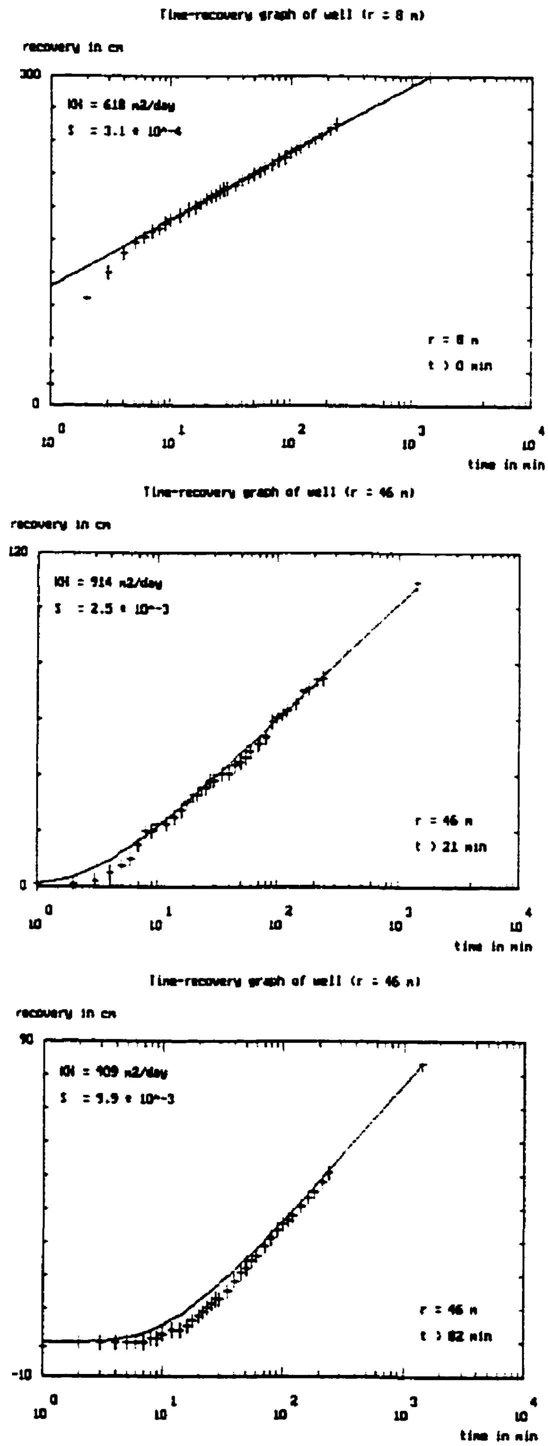


Figure 4.36b Time-recovery analysis of test site # T/W-1

Time-drawdown | **Time-recovery**

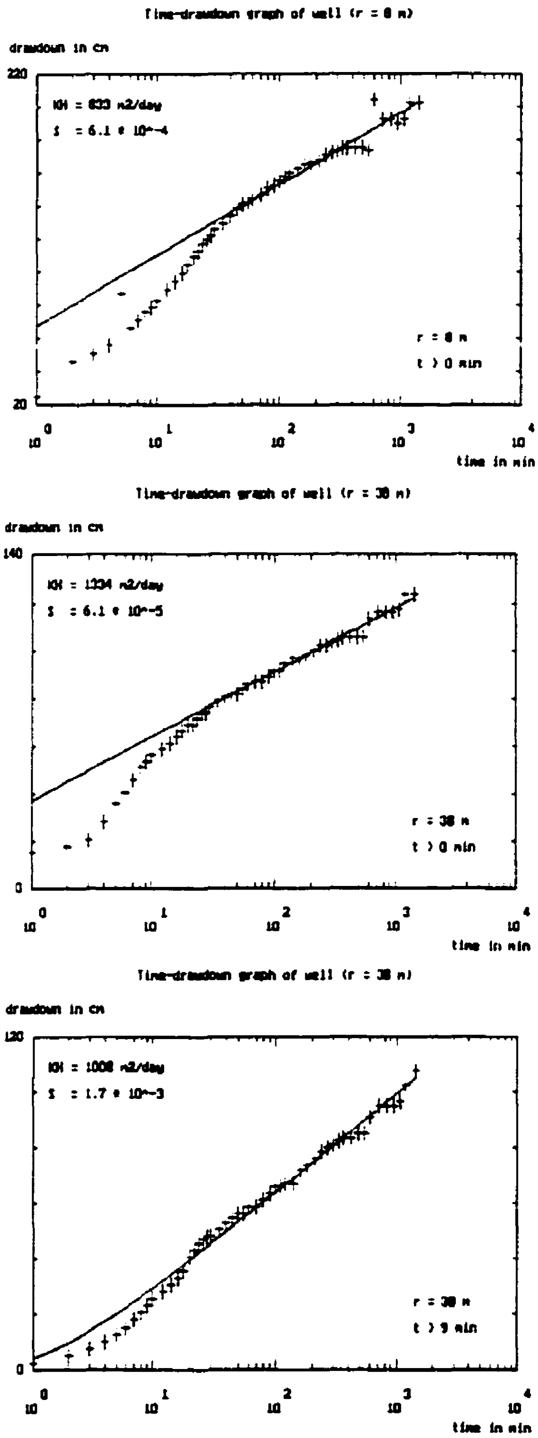


Figure 4.37a Time-drawdown analysis of test site # T/W-2

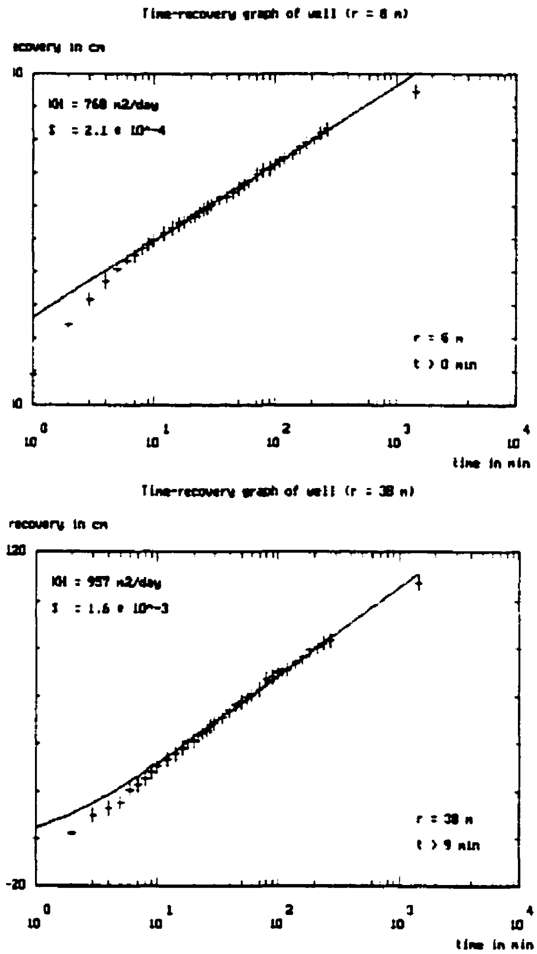
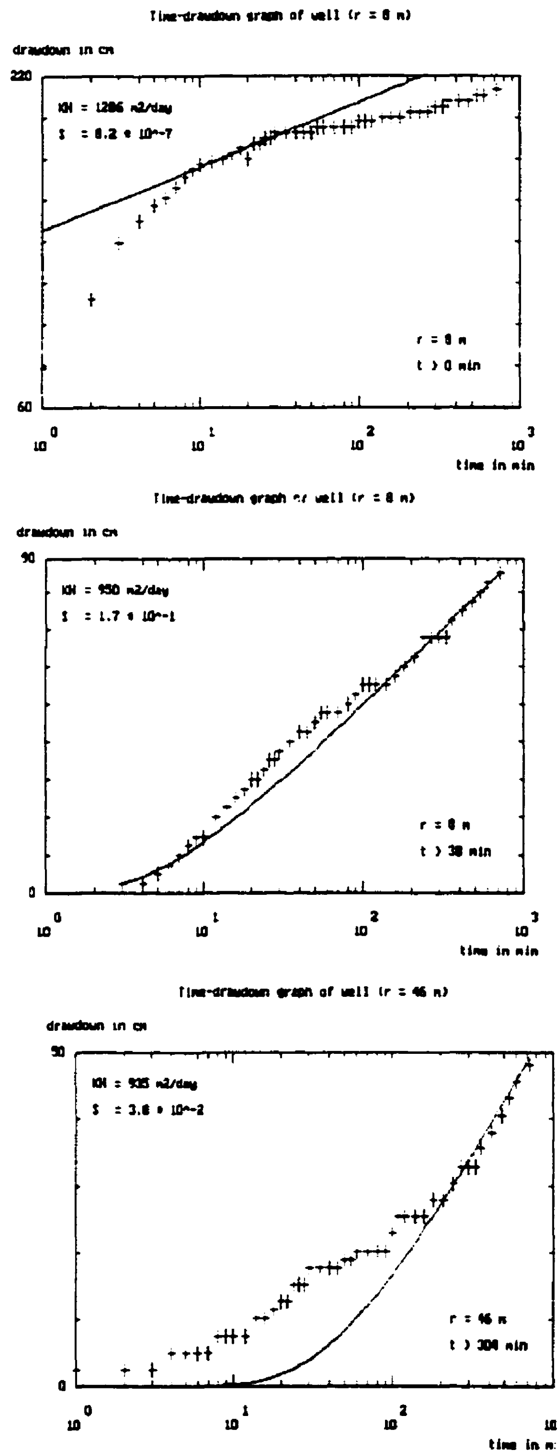


Figure 4.37b Time-recovery analysis of test site # T/W-2

Time-drawdown



Time-recovery

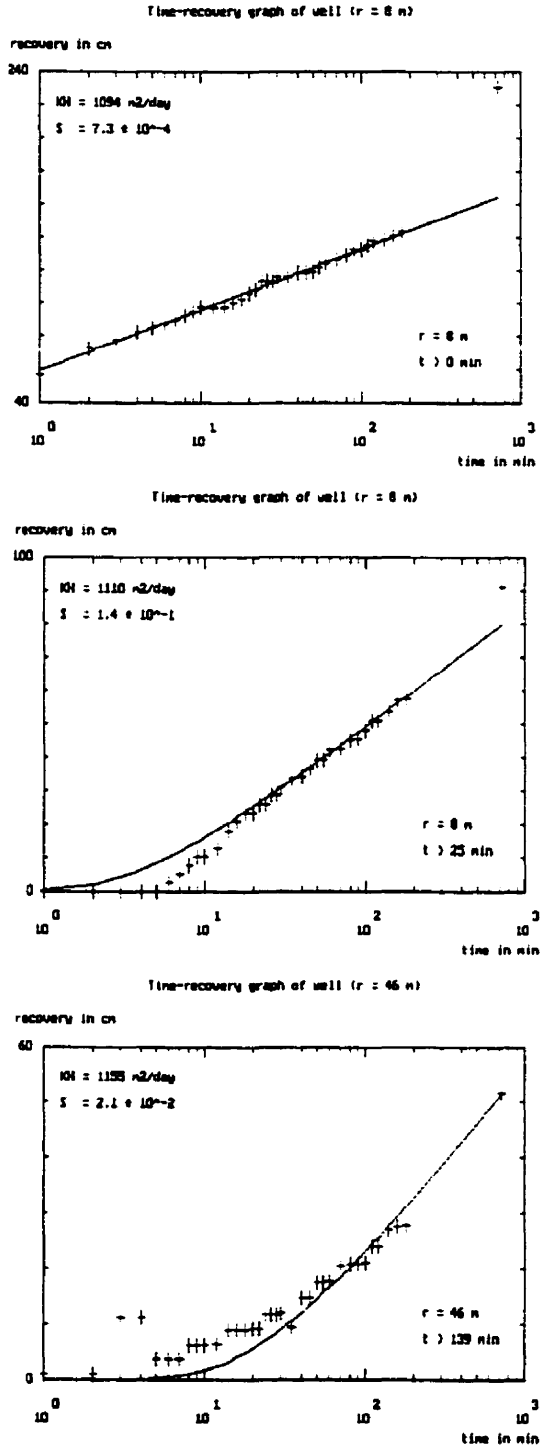


Figure 4.38a Time-drawdown analysis of test site # T/W-3

Figure 4.38b Time-recovery analysis of test site # T/W-3

4.3.3 Transmissivity contour map

Transmissivity contour maps were prepared from four new sites and five of the historical sites using the software WINSURF (Figures 4.39 to 4.41). This map shows that transmissivity is highest (1806 m^2/day) in the south-east and decreases from this point in all directions.

Table 4.1 reveals the summary of results of transmissivity values obtained using with the program package SATEM (Boonstra, 1989).

Table 4.1. Summary of aquifer tests analysis

Test site	Transmissivity (m^2/day)	Test site	Transmissivity (m^2/day)
Aquifer test - 1	684	HA - 1	1270
Aquifer test - 3	1806	HRN - 1	1350
Aquifer test - 4	840	T/W - 1	948
Aquifer test - 5	972	T/W - 2	980
		T/W - 3	1088

It can be concluded the transmissivity of the aquifer ranges from 684 to 1806 m^2/day (see Table 4.1). The range is slightly larger than reported in the past (see section 2.2.3). Also, data analysis indicates that the aquifer is un-confined. If, as assumed, the aquifer has a constant specific yield then analysis of Figure 4.41 suggests that the aquifer was thickest in the south-east corner.

The SGMP requires separate values for the hydraulic conductivity and thickness of the aquifer, because transmissivity of an unconfined aquifer is not constant, but varies with the saturated thickness and the specific yield. A uniform aquifer thickness of 105 m was taken for the entire area. This value was obtained from using partial penetration analysis of test site #

(i). This thickness was used to determined hydraulic conductivity from the transmissivity map Figure 4.41. The hydraulic conductivity for each node was then obtained by superimposing the nodal network map on Figure 4.41. Hydraulic conductivity values were not assigned to the nodes but to each side of every node. The actual values of hydraulic conductivity for the sides of each nodal area were found by interpolation. That is, if one isoperm of Figure 4.41 crossed the nodal side; then this value was assigned to that side. If more then one isoperm crossed the nodal side; an weighted average was assigned. These values were then used as input to the SGMP.

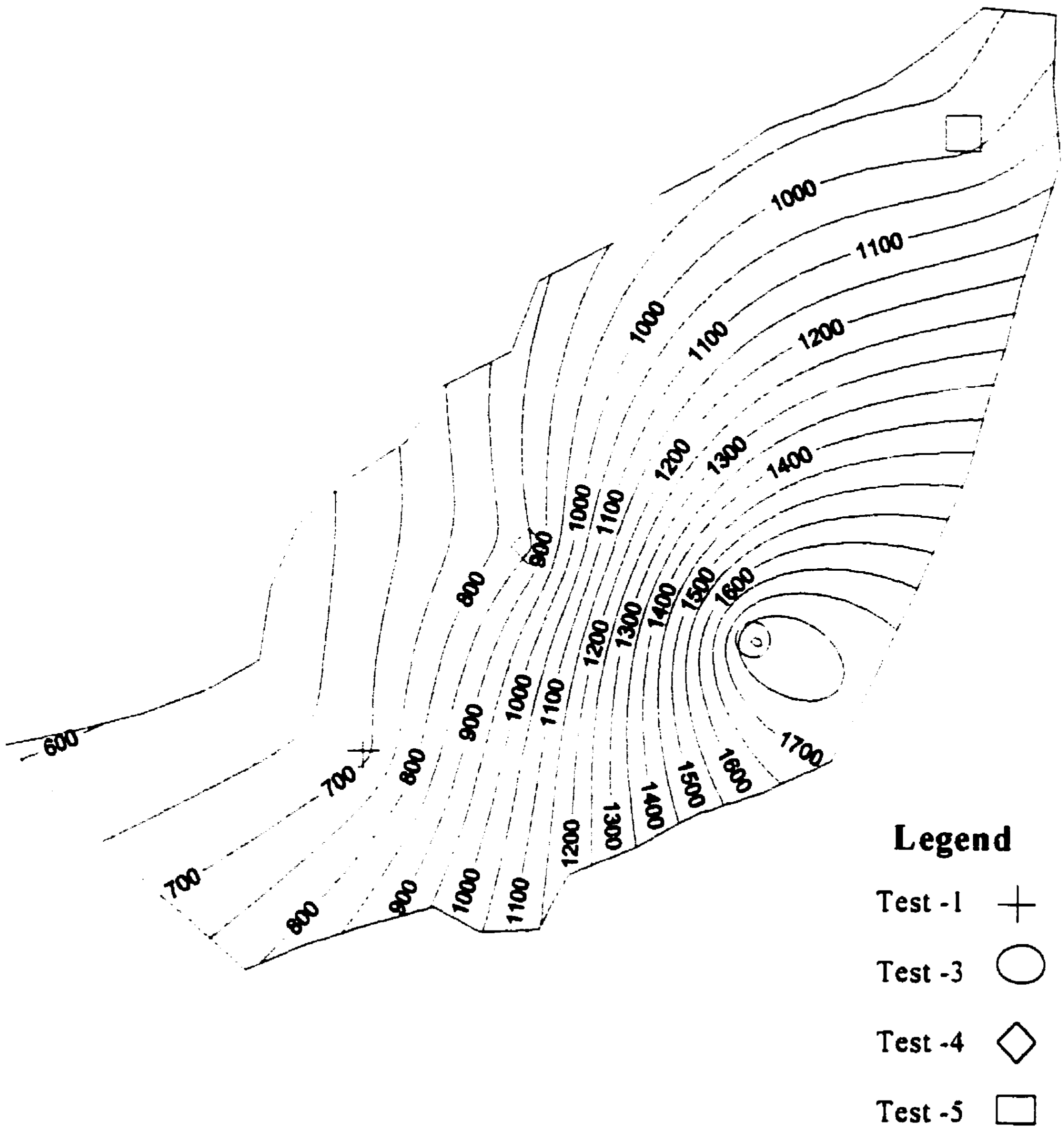


Figure 4.39 Tansmissivity map at FESS using average value from 4 new test sites (Appendix A, Table A.2-A.6)

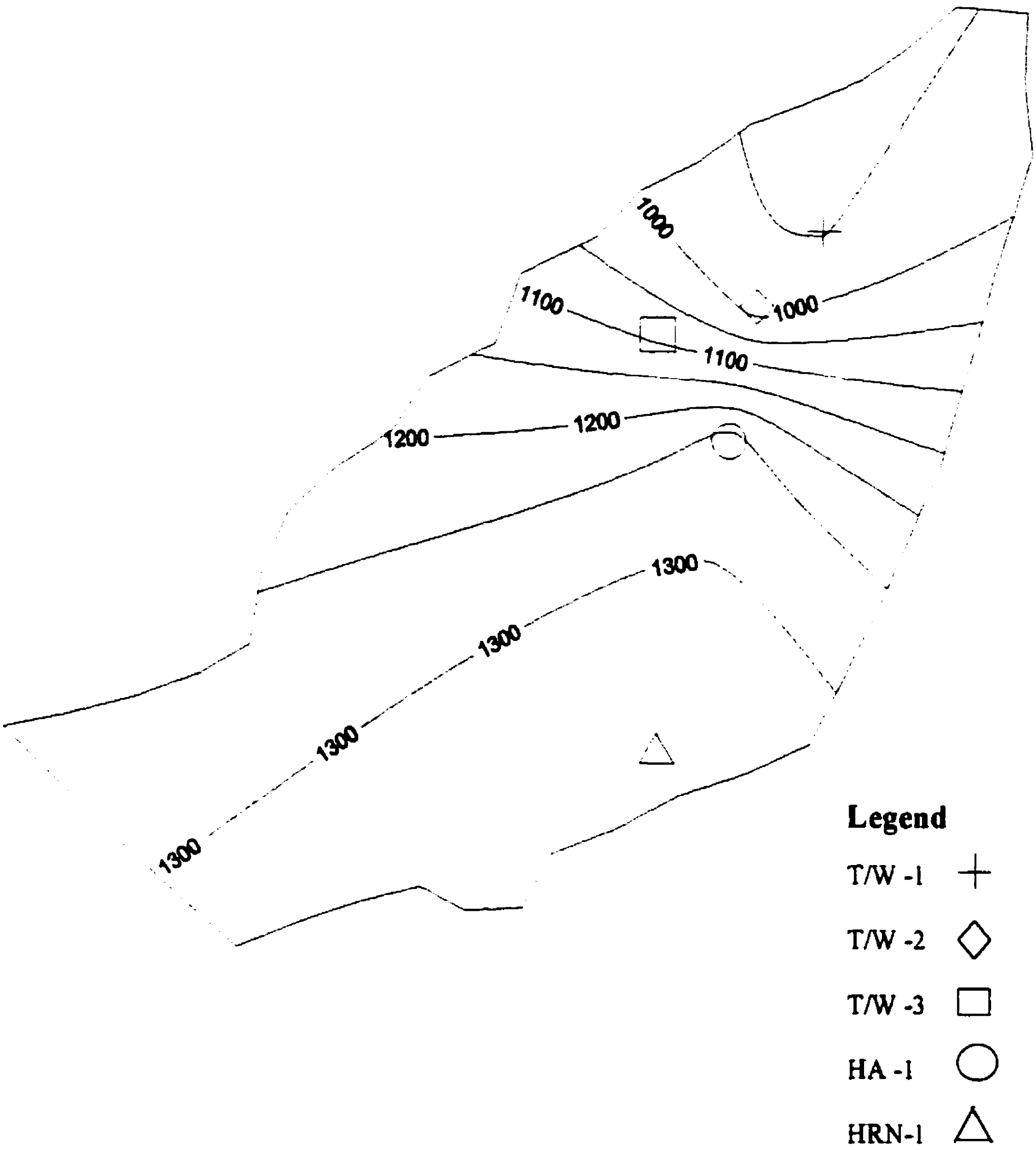


Figure 4.40 Tansmissivity map at FESS using average value from 5 historical test sites (Appendix A, Table A.7-A.13)

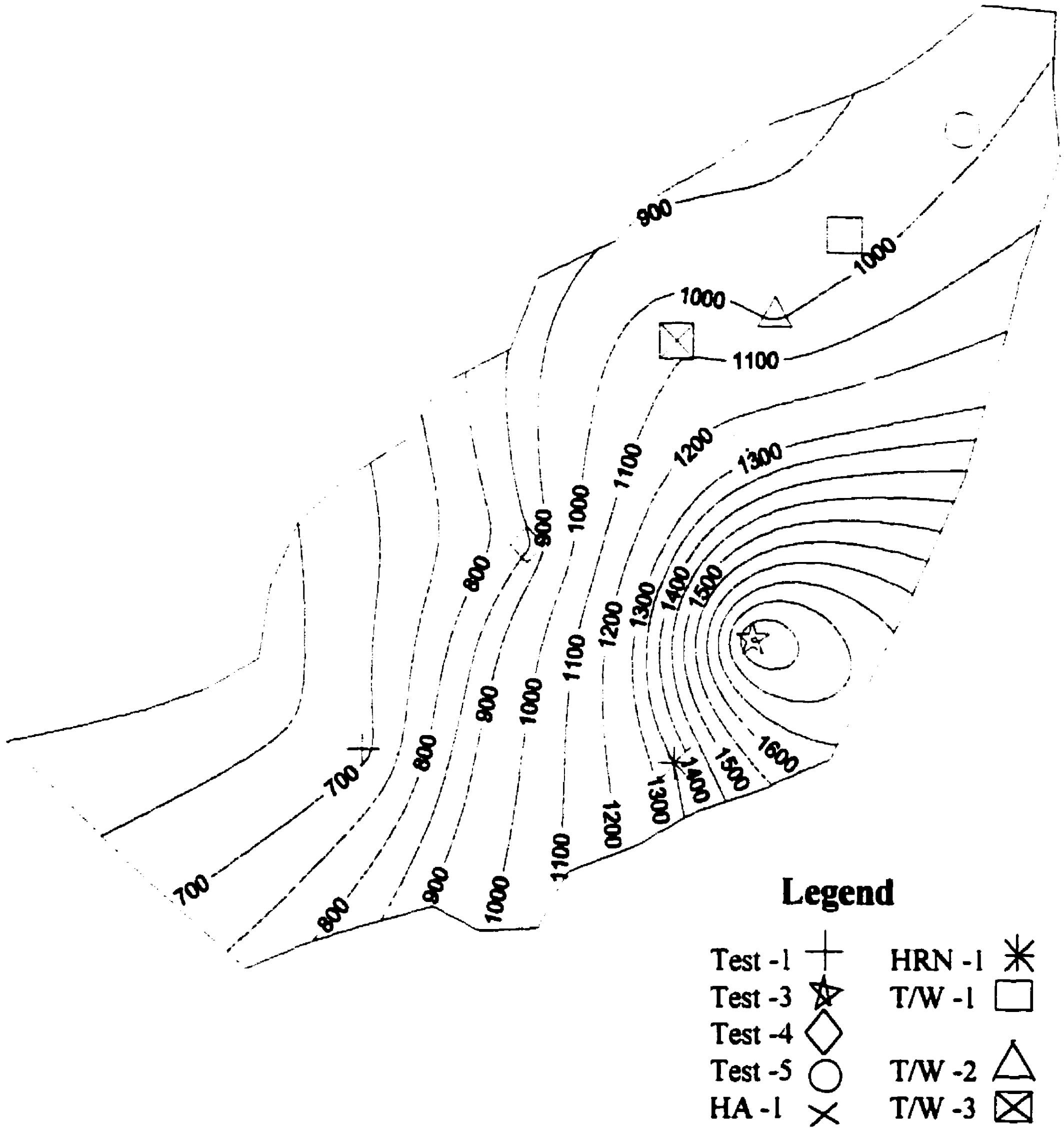


Figure 4.41 Tansmissivity map at FESS using average value from 10 new & historical test sites (Appendix A, Table A.2-A.13)

4.4 Inverse Modeling

In numerical groundwater modeling, the geometry and hydraulic characteristics of the aquifer system must always be prescribed. Although they might show considerable variations from one nodal area to another they are assumed to be constant within a nodal area. In addition to aquifer parameters, initial and boundary conditions must also be prescribed. The initial conditions of the model include the absolute watertable elevations of nodes taken from a chosen set of observed values. Boundary conditions describe certain characteristics at the edge of a study. The model which was run for the period of July 1994-June 1997 (36 months) at a time step of 4, and 12 months yielded 9 and 3 sets of water balance data, respectively.

4.4.1 Analysis of the 4 month time step data

A four month time step is useful because it isolates the 4-month monsoon season as a single entity. Table 4.2 clearly shows the seasonal net recharge, subsurface inflow, subsurface outflow and change-in-storage in monsoon and non-monsoon seasons for the total model area, as calculated by this Inverse Modeling method. That is, input files consisted of monthly absolute watertable elevations & aquifer characteristics and output files are net-recharge, subsurface inflow, subsurface outflow & change in storage. Details regarding the output values of net recharge for each node and lumped recharge (weighted average) for the entire model area are given in Appendix B.

Table 4.2 4 month time-step data set (mm/d)

Season	Net [(1)] recharge	Subsurface [(1)] inflow	Subsurface [(1)] outflow	Change in[(1)] storage
Monsoon 1994	+0.16 (0.34)	+0.01	-0.05	-0.12
Non-Monsoon 1994-95	+0.105 (0.40)	+0.01	-0.05	-0.06
Monsoon 1995	-0.01 (0.39)	+0.01	-0.05	+0.05
Non-Monsoon 1995-96	+0.17 (0.29)	+0.01	-0.05	-0.12
Monsoon 1996	+0.06 (0.37)	+0.01	-0.05	-0.05
Non-Monsoon 1996-97	+0.06 (0.31)	+0.01	-0.05	-0.02

[(1)] Lumped sum values: i.e. average of all nodes combined, standard deviation in brackets

Note: Monsoon is one time-step of 4 months (July-Oct.)
Non-monsoon is two time-steps of 4 months each (Nov.-June)

From the Table 4.2 the following observations can be made:

i) A positive sign "net recharge" indicates a downward flow towards the watertable. This could be the result of seepage, excess rainfall and/or excess irrigation.

ii) The calculated net recharge has a positive value except in monsoon 1995. This negative could be attributed to an unusually low rainfall for this monsoon. Appendix C shows the average rainfall of the Jahanawala weather station situated near Donga Bonga town and the Bahawalnager weather station (located 40 km outside study area).

iii) Subsurface inflow & outflow values are constant so the net lateral subsurface flow is small compared to other two groundwater-balance components. Because of this phenomenon, the net recharge is primarily a factor of change-in-storage; the latter being directly related to the historical watertable behavior.

iv) The calculated net recharge has high positive values of 0.16 and 0.17 during monsoon 1994 and non-monsoon 1995-96, respectively. This indicates that recharge in this study area is not primarily a result of the monsoon season. Other factors such canal seepage must be a major source of recharge. Non-monsoon season '94-'95 and '95-

'96 show much higher recharge than non-monsoon season '96-'97. During '96-'97 about 3735 km of canal interceptor drains were installed along the Malik & Hakra branch canals and 2750 km along Khatan distibutary. Also, trial subsurface drainage systems were installed near the canals on 800 ha of land. Finally, general water management features such as surface drains and lining of distributaries were installed. This may be the reason why net-recharge for the monsoon & non-monsoon '96-'97 is low.

4.4.2 Analysis of the 12 month time step data

The following table exhibits groundwater balance components for the three hydrological years.

Table 4.3 12 month time-step data set (mm/d)

Years	Net (1) recharge	Subsurface (1) inflow	Subsurface (1) outflow	Change-in- (1) storage
1994-95	+0.12 (0.38)	+0.01	-0.05	-0.08
1995-96	+0.11 (0.34)	+0.01	-0.05	-0.07
1996-97	+0.06 (0.33)	+0.01	-0.05	-0.02

(1) Lumped sum values: i.e. average of all nodes combined, standard deviation in brackets

Note: Hydrological year is one time-step of 12 months (July-June)

From the Table 4.3, the net recharge for 1994-95 and 1995-96 is of the same magnitude, however, a 50% reduction occurs during year 1996-97. Again, this is likely due to the water management features implemented during this year.

4.4.3 Analysis of the 12 month time step data for internal nodes

To have more insight into the spatial distribution of the calculated net-recharge, Table 4.4 details the net recharge of each internal nodal area for the three years. Only internal nodes are used because in the case of boundary nodal areas, these nodes act as head-control boundaries.

Table 4.4 12 month time-step data set (mm/d) for internal nodes

Nodal no.	Nodal area (m^2)	Nodal net recharge mm/day			Nodal no.	Nodal area (m^2)	Nodal net recharge mm/day		
		1994-95	1995-96	1996-97			1994-95	1995-96	1996-97
3	14.46	+0.81	+0.69	+0.59	61	34.34	-0.05	-0.02	-0.16
6	11.54	+0.59	+0.53	+0.36	62	24.60	+0.42	+0.28	+0.08
7	13.70	-0.37	-0.47	-0.53	65	22.79	+0.35	+0.18	+0.01
8	12.73	+0.61	+0.54	+0.52	66	30.03	+0.03	-0.01	+0.07
11	15.52	+0.25	+0.30	-0.02	67	32.67	+0.14	+0.04	+0.09
12	18.61	-0.02	-0.14	+0.02	68	30.92	-0.16	+0.10	-0.31
13	12.47	+0.33	+0.51	+0.23	69	27.15	-0.09	-0.25	+0.10
16	12.23	+0.65	+1.01	+0.76	70	21.12	+0.52	+0.47	+0.48
17	19.87	-0.25	-0.07	-0.08	73	21.45	-0.05	-0.17	-0.02
18	20.75	+0.01	-0.01	-0.06	74	27.30	+0.06	+0.18	+0.12
19	14.02	+0.68	+0.37	+0.33	75	30.78	-0.11	-0.01	-0.20
22	12.17	+0.58	+0.40	+0.36	76	30.11	+0.02	+0.01	+0.03
23	17.26	-0.16	-0.08	-0.22	77	25.54	+0.24	+0.02	0.00
24	22.67	+0.08	+0.07	0.00	80	23.49	+0.09	+0.12	-0.08
25	20.16	-0.29	-0.18	-0.24	81	25.99	+0.18	+0.03	-0.04
26	11.61	+0.56	+0.78	+0.48	82	31.68	+0.05	+0.17	-0.18
29	10.63	+0.25	+0.15	+0.07	83	28.12	+.10	+0.10	0.00
30	17.39	+0.24	+0.22	+0.16	84	23.92	+0.07	+0.15	+0.17
31	26.67	+0.27	-0.04	+0.07	87	25.37	+0.22	+0.28	+0.16
32	23.89	+0.15	+0.07	+0.02	88	27.43	+0.16	+0.15	-0.03

33	19.42	+0.37	+0.35	+0.36	89	29.53	+0.21	+0.21	-0.07
36	17.60	-0.05	+0.26	+0.26	90	26.01	+0.26	+0.09	+0.10
37	25.68	-0.05	-0.09	-0.06	91	20.51	+0.11	+0.18	+0.19
38	29.33	0.00	-0.07	-0.06	94	22.44	0.00	+0.01	+0.04
39	24.43	+0.20	+0.05	+0.11	95	27.77	+0.10	+0.06	-0.01
40	15.29	+0.09	+0.03	+0.08	96	27.23	+0.24	+0.24	+0.12
41	10.59	+0.71	+0.59	+0.44	97	22.45	+0.09	+0.15	+0.14
44	14.93	+0.66	+0.60	+0.39	100	17.17	+0.22	+0.22	+0.12
45	21.11	-0.24	-0.27	-0.20	101	22.56	-0.13	-0.14	-0.15
46	33.56	+0.03	+0.04	+0.10	102	25.84	+0.21	+0.14	+0.11
47	32.07	+0.13	-0.06	-0.09	103	23.78	+0.08	+0.05	+0.09
48	24.76	+0.30	+0.05	+0.07	106	20.06	+0.08	+0.07	+0.08
51	20.77	+0.16	+0.15	-0.09	107	22.59	+0.07	+0.09	+0.02
52	31.41	+0.12	+0.04	+0.19	108	24.35	+0.30	+0.27	+0.19
53	34.65	+0.04	-0.05	+0.06	112	22.43	+0.04	+0.07	+0.02
54	33.06	-0.23	+0.24	-0.08	113	20.23	+0.06	+0.08	+0.05
55	27.53	+0.57	+0.40	+0.48	114	21.40	-0.06	+0.00	-0.05
58	31.46	+0.48	+0.42	+0.46	117	24.29	0.00	+0.08	+0.03
59	32.63	-0.14	-0.22	-0.09	118	20.48	+0.09	+0.05	+0.03
60	33.73	-0.06	+0.10	+0.17	119	21.10	+0.07	+0.07	+0.05

Table 4.4 reveals that the nodal net recharge values were not consistently positive during these three years, this means that some areas had negative net recharge over this period (an upward flow from the saturated to unsaturated zone occurs). These areas occur at nodes: 7, 17, 23 25, 37, 38, 45, 59, 61, 73, 75, and 101,whereas nodal areas 11, 12, 18, 31, 36, 47, 51, 53, 53, 60, 66, 69, 80, 81, 82, 88, 89, 95, and 114 had negative values during one and/or two years. The standard deviation of net recharge values for Table 4.4 are given in Appendix E.

The comparison of Figures 4.22 to 4.28 pointed towards the fact that nodal areas experiencing negative net recharge are generally located in shallow zones of the watertable contour lines. Also, see Figure 4.42 for comparison. In general, the more shallow the watertable, the more capillary rise that is likely to occur. Discharge components dominated over the recharge components in these areas.

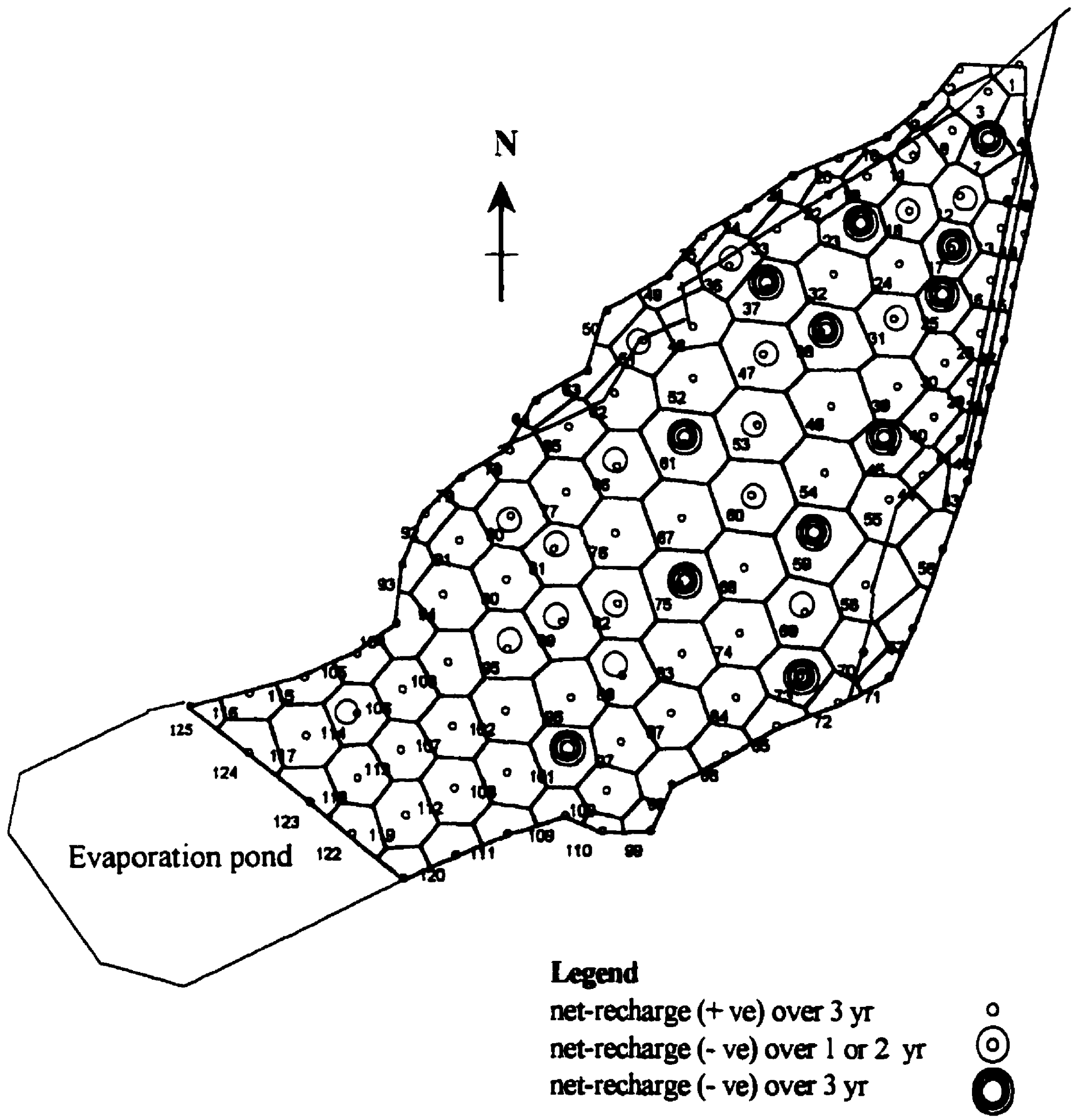


Figure 4.42 Areas with positive and negative nodal net-recharge over 3 year

According to Table 4.4, all other nodal areas show positive net recharge. In other words, groundwater flows from the unsaturated to the saturated zone. The watertable in these areas is generally relatively deep and hence experience in relatively low rates of capillary rise. Thus, it can be concluded that the recharge on account of canal seepage and/or irrigation losses clearly dominate over discharge via capillary rise and subsequent evaporation.

Table 4.4 also shows that in general the net recharge was maximum in the first hydrological year i.e. 1994-95 and decreases in subsequent years. The Figure 4.22 to 4.28 exhibit a slow rise in watertable elevation over the 3 years.

4.4.4 Spatial Aspects of Net Recharge

There is a large variation in the nodal net recharge values calculated within each of the 36 months. The following table exhibits the variation in net recharge value for the month of June 1996. June 1996 was chosen because it exhibits a period of high recharge.

Table 4.5 Nodal groundwater-balance components in mm/day for June 1996

Nodal no.	Nodal area (m^2)	Nodal net recharge	Net * Sub-surf. flow	Change in storage	Nodal no.	Nodal area (m^2)	Nodal net recharge	Net * Sub-surf. flow	Change in storage
3	14.46	+1.09	-0.73	-0.35	61	34.34	+0.56	+0.10	-0.65
6	11.54	+0.73	-0.44	-0.28	62	24.60	+0.70	-0.25	-0.46
7	13.70	+0.06	+0.46	-0.52	65	22.79	+0.23	-0.14	-0.09
8	12.73	+0.29	-0.48	+0.19	66	30.03	-0.52	+0.03	+0.48
11	15.52	+1.35	-0.20	-1.15	67	32.67	-0.25	-0.05	+0.30
12	18.61	+0.65	+0.15	-0.80	68	30.92	+0.63	0.00	-0.63
13	12.47	+1.81	-0.52	-1.29	69	27.15	-1.06	+0.25	+0.81

16	12.23	+0.75	-0.85	+0.10	70	21.12	+0.87	-0.48	-0.39
17	19.87	-0.16	+0.12	+0.04	73	21.45	-0.38	+0.15	+0.23
18	20.75	+0.11	+0.05	-0.16	74	27.30	+0.84	-0.09	-0.74
19	14.02	+0.07	-0.36	+0.28	75	30.78	+0.32	+0.15	-0.46
22	12.17	+0.37	-0.34	-0.03	76	30.11	-0.72	+0.06	+0.67
23	17.26	+0.17	+0.13	-0.29	77	25.54	-1.43	+0.04	+1.39
24	22.67	0.00	-0.03	-0.03	80	23.49	-0.06	+0.03	+0.03
25	20.16	-0.20	+0.25	-0.05	81	25.99	-0.46	+0.02	+0.45
26	11.61	+1.02	-0.59	-0.43	82	31.68	+1.27	-0.02	-1.26
29	10.63	+0.12	-0.21	+0.08	83	28.12	+0.54	-0.01	-0.53
30	17.39	+1.73	-0.21	-1.52	84	23.92	-0.01	-0.06	+0.08
31	26.67	-0.26	-0.01	+0.27	87	25.37	+0.36	-0.18	-0.18
32	23.89	+0.01	-0.04	+0.05	88	27.43	+0.95	-0.02	-0.93
33	19.42	+0.58	-0.34	-0.24	89	29.53	+1.55	-0.09	-1.46
36	17.60	+0.01	-0.13	+0.11	90	26.01	+0.05	-0.06	+0.01
37	25.68	-0.30	+0.11	+0.19	91	20.51	+0.33	-0.09	-0.24
38	29.33	-0.64	+0.11	+0.53	94	22.44	-0.05	+0.06	-0.01
39	24.43	-0.02	-0.06	+0.08	95	27.77	+0.30	+0.05	-0.35
40	15.29	-0.33	0.00	+0.33	96	27.23	+0.26	-0.08	-0.18
41	10.59	+0.82	-0.65	-0.17	97	22.45	+0.41	+0.01	-0.42
44	14.93	+1.18	-0.63	-0.55	100	17.17	+0.93	-0.13	-0.80
45	21.11	-1.08	+0.32	+0.76	101	22.56	-0.03	+0.29	-0.26
46	33.56	-0.70	-0.01	+0.71	102	25.84	+0.25	-0.01	-0.24
47	32.07	+0.56	+0.02	-0.59	103	23.78	+0.06	+0.02	-0.08
48	24.76	+0.04	-0.05	+0.01	106	20.06	+0.10	+0.01	-0.11
51	20.77	+0.37	-0.07	-0.30	107	22.59	+0.19	+0.03	-0.22

52	31.41	-0.23	+0.01	+0.21	108	24.35	+0.33	-0.15	-0.19
53	34.65	-0.31	+0.03	+0.28	112	22.43	+0.05	+0.02	-0.07
54	33.06	+1.20	-0.04	-1.15	113	20.23	+0.09	+0.02	-0.11
55	27.53	+0.65	-0.39	-0.26	114	21.40	+0.09	+0.10	-0.18
58	31.46	+0.88	-0.36	-0.52	117	24.29	+0.10	+0.02	-0.12
59	32.63	+0.03	+0.18	-0.21	118	20.48	-0.35	+0.03	+0.31
60	33.73	-0.66	-0.09	+0.57	119	21.10	+0.19	0.00	-0.19

* difference between subsurface inflow and outflow

Note: -ve value for change in storage means loss of storage volume, therefore a site of recharge

A map was made (Figure 4.43) for the month of June 1996 using the kriging interpolation module of the software package SURFER to show spatial variability of change in storage. From Figure 4.43, it can be seen that the largest positive value (+1.39 mm/d) of change in storage (representing a zone of discharge) occurred at observation well 77 located in the western part, whereas observation well 30 in the eastern part shows the largest negative change in storage of -1.52 mm/d. Table 4.5 shows that the highest and lowest net recharge values of +1.73 and -1.43 mm/day occur at nodal areas 30 and 77, respectively.

The Figure 4.44 shows a relationship between the net-recharge and change in groundwater storage for three typical nodes: 19, 33, and 62 over the three year period. These graphs reveal that in general net-recharge has a value similar in size but opposite in sign to the change in storage. If there was no horizontal flow (inflow or outflow) than recharge & change in storage would have equal magnitudes but opposite signs. This supports the information of Table 4.5 which shows small values for inflow-outflow.

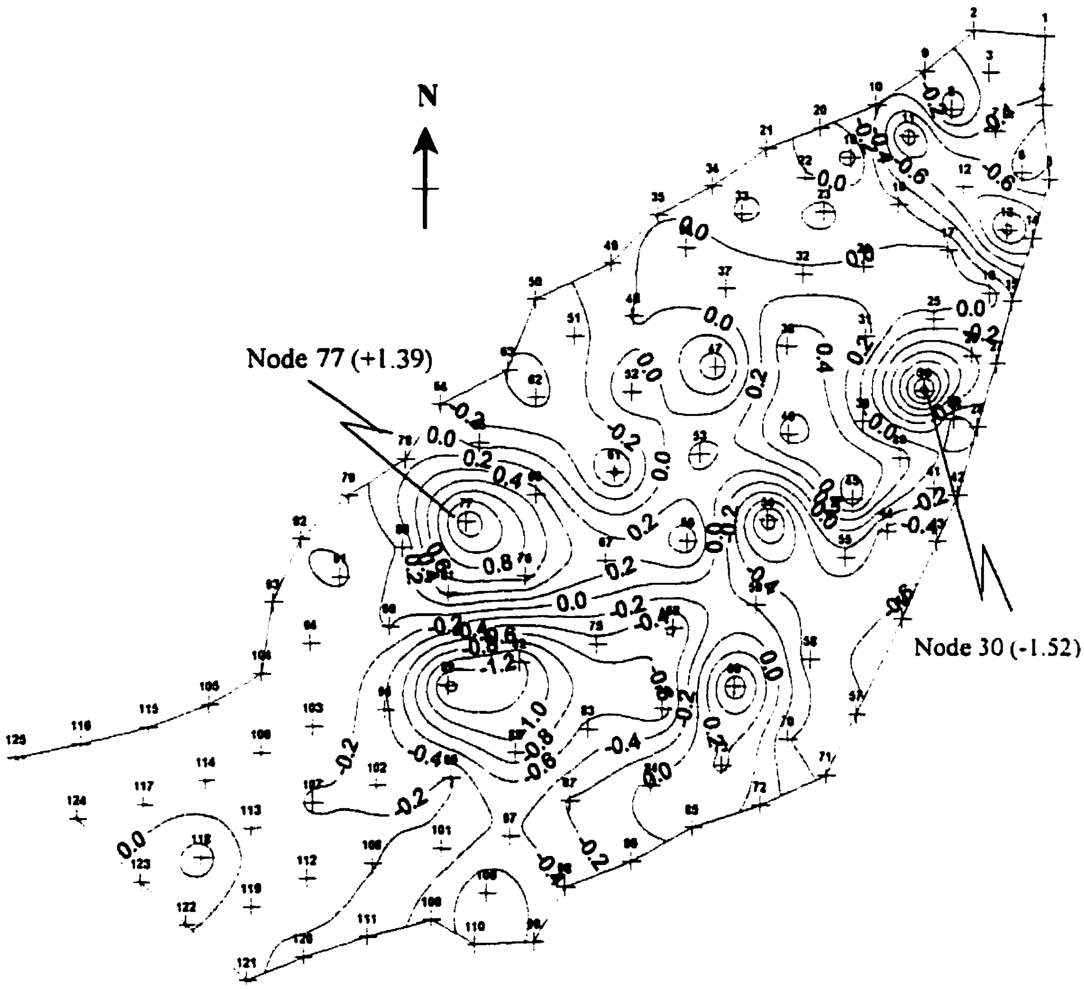


Figure 4.43 Change in storage contour map in mm/day for the month of June 1996. A negative value means loss of storage volume, therefore a recharge site.

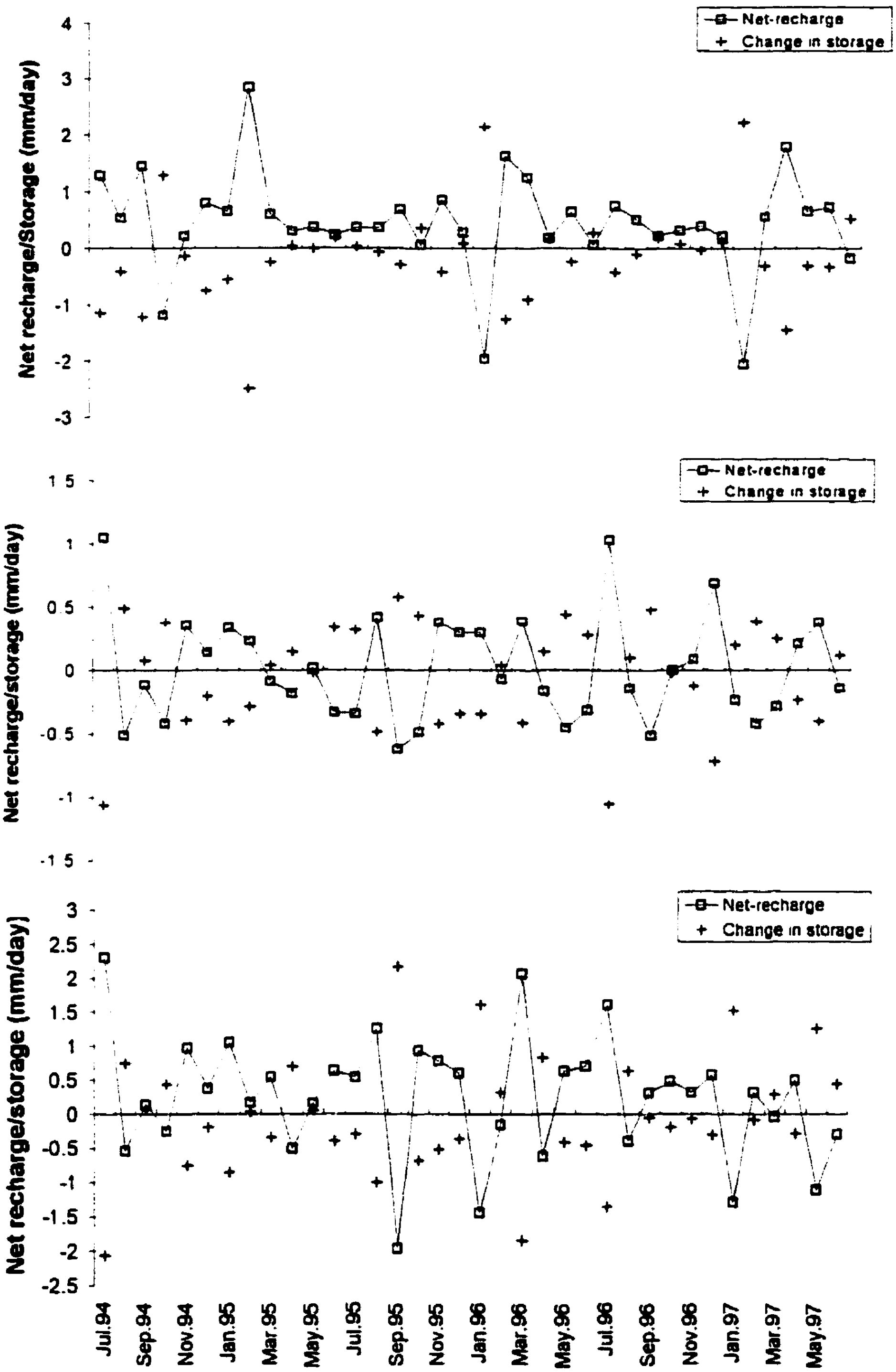


Figure 4.44 Graphs showing relationship between net recharge and change in groundwater storage of node numbers 19, 33, and 62 for the year 1994-997

4.5 Normal Modeling

In normal mode, the model can be checked by matching predicted watertable elevations in the various time steps, with the historical observed ones. To this end, a range DL (deviation level) should be prescribed to the model. When the watertable elevations calculated by the model are within this DL range, the model continues with calculation of the next time step. Whenever, during a certain time step, the calculated watertable elevation exceeds the DL, an additional flow rate called the DELQ is required. This rate enters the water balance as a new component with a plus or minus sign, depending on whether the calculated watertable elevation lies below or above this range. The calculation is then restarted for the same time step and the newly calculated watertable elevation is tested. If the watertable still exceeds the range, the additional flow rate is increased by its own value i.e. 2 * DELQ. This procedure is repeated as many times as required until the calculated watertable elevations matches the observed value; within the DL range.

When a relatively large DL value is chosen, the difference between calculated and observed watertable elevations can also be large. To reduce the difference, a small value of DL should be selected. In this study, a value of DL of 0.01 was required to ensure that the water balance components were calculated with sufficient accuracy. A DL value of 0.001 was tried, but the model would not converge.

Determining the value of a good DELQ is a matter of trial and error. If the value is too large the calculated watertable elevations will never be within the prescribed range. If the value is too low, then too many iterations will be required. In this study, a value of DELQ of 0.001 million cubic meters per month produced satisfactory results.

Figures 4.45 to 4.46 show the comparison between calculated and observed watertables for a sample of nodes using a DL of 0.01 and a DELQ of 0.001. Theoretically, ideal DL and DELQ value gives a perfect fit between observed and calculated data. The graphs show a very good match, giving a correlation > ±0.99.

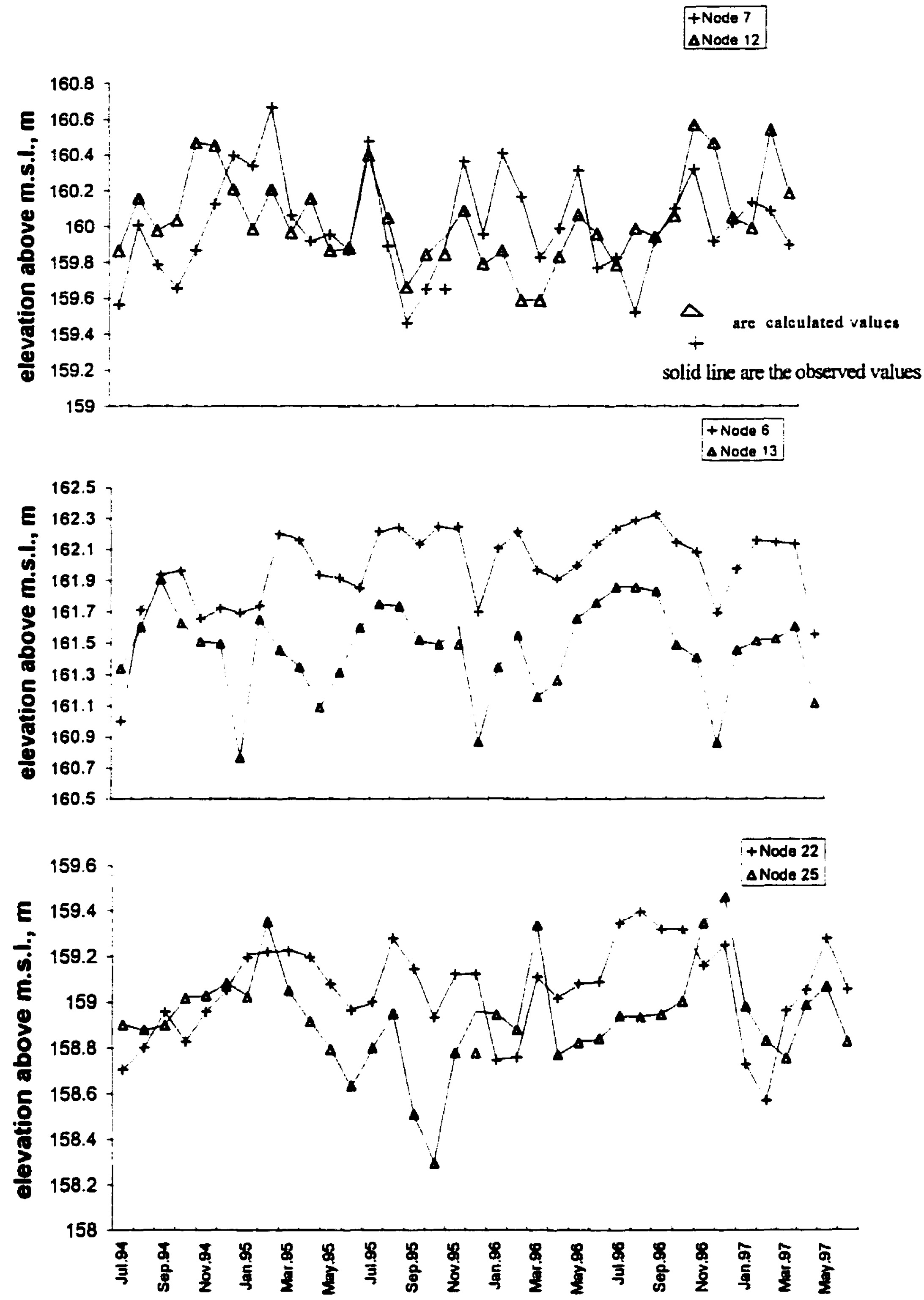


Figure 4.45 Comparison between calculated and observed watertable for different nodes situated in different sectors of FESS

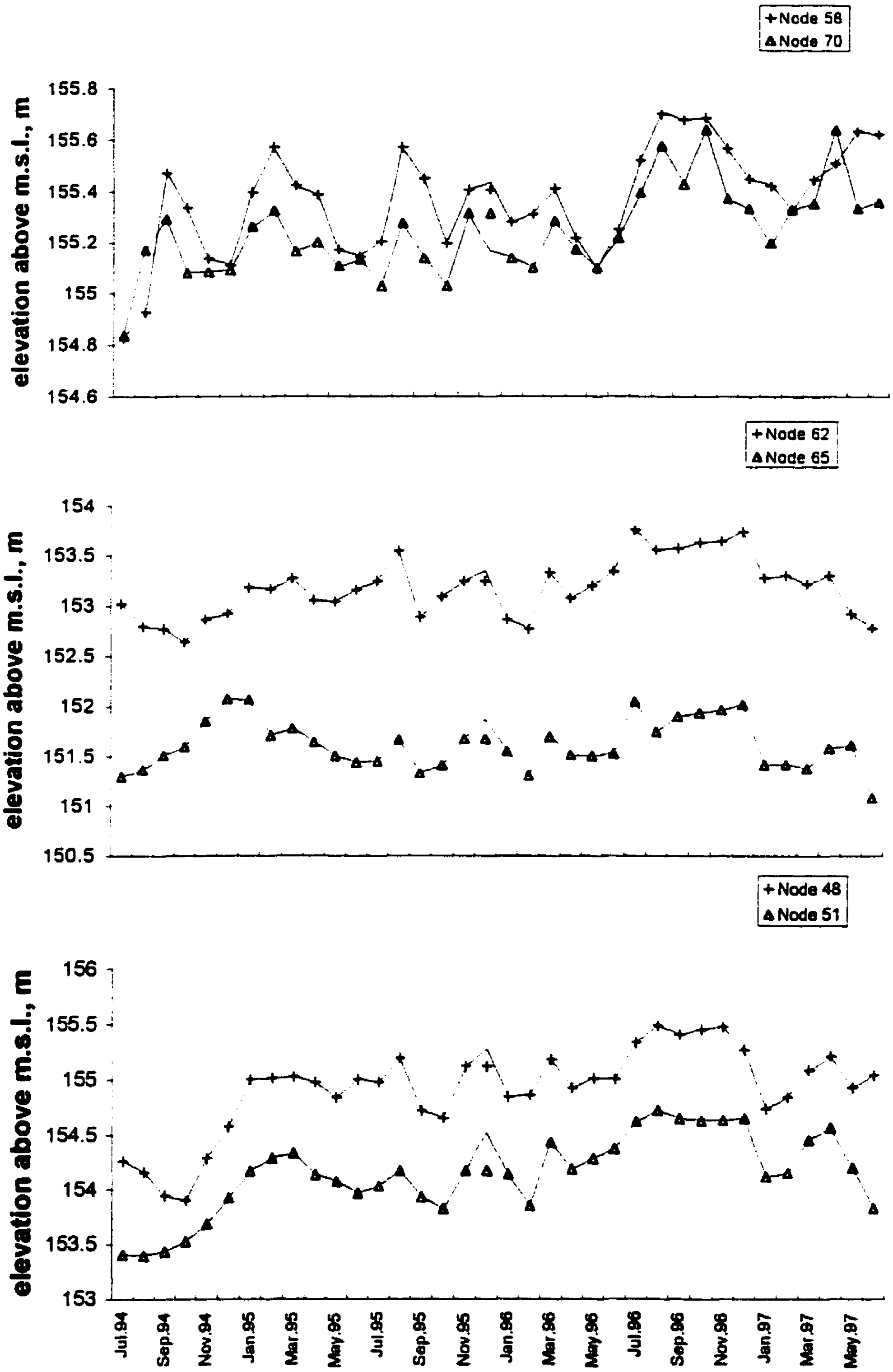


Figure 4.46 Comparison between calculated and observed watertable for different nodes situated in different sectors of FESS

4.6 Areas in need of Drainage; Now and in the Future

The calculated depth- to-watertable data obtained from the normal modeling process used above can be used to identify the areas in need of drainage. For this, watertable depth contour maps for the years 1994, 1995, 1996 and 1997 were prepared using the software WINSURF (Figures 4.47-4.50). The watertable depth of 1.5 m is considered to be the permissible limit and is used in design for different drainage projects in Pakistan. For all these maps, a contour interval of 0.25 m is used for watertable depths less than 1.5 m and the rest of the map uses an interval of one meter.

From Figure 4.47-4.50 the following observations can be made.

i) In July 1994, an area of 11.75 km^2, 0.5 % of the total nodal area (2235 km^2) near node numbers 26 & 36 had a watertable depth of less than 0.5 m. This area increases to 23, 43.75 and 174.75 km^2 (1, 2, 7.8 %) in the years 1995, 1996 and 1997, respectively. In 1997 node numbers 3, 6, 7, 8, 11, 13, 19, 22, 26, 48, 58, and 70 had watertable depths of less than 0.5 m (see Appendix D).

ii) In July 1994, node numbers 3, 6, 7, 8, 11, 12, 13, 16, 17, 18, 19, 22, 23, 24, 25, 26, 30, 33, 36, 37, 38, 39, 40, 41, 45, 46, 47, 48, 53, 54, 58, 60, 61, 62, 65, 68, 69, 70, 73, 74, 75, 82, 83, and 84 had a watertable depth less than 1.5 m and covered an area of 646.25 km^2, which is 30 % of the project area. This area (< 1.5 m) shows a consistent increase in the years 1995, 1996 and 1997 to 872.5, 1212.75 and 1522.75 km^2 (39, 54, 68 %), respectively. In 1997, in addition to the above mentioned nodes, node numbers 29, 31, 32, 44, 51, 55, 67, 76, 77, 80, 81, 87, 89 and 97 (Appendix D) were also registered watertable depths of less than 1.5 m.

Year 1994-95 and 1995-96 had experienced similar amount of recharge. Year 1996-97 was unusually dry plus some remedial measures (interceptor drain and canal lining) were put into place. The recharge value of 1995-96 was chosen as the base data input for prediction purposes. It was assumed that these recharge values remained constant during future years and that current water management practices will not change (canal lining, installed interceptor drains and/or subsurface drainage systems etc). This is the worst case scenario. The model was run in prediction mode to make forecasts of future values of watertable depths. The resulting watertable depth contour maps for years 2002 and 2007 are shown in Figures 4.51-4.52.

From Figure 4.51-4.52 the following observations can be made.

iii) the predicied values for the year 2002 show that a 459.25 km^2 area will have a watertable depth of less than 0.5 m. In addition to the nodes mentioned in 1997, node numbers 16, 23, 33, 41, 44, 51, 62, 65, 68, 75, 80, 81, 82, 83, 84, 87, 88, 89, 96, 97 and 101 (Appendix D) would also experience be watertable depths of less than 0.5 m. This area represents 20 % of the study area. This percent will increase to 35 % in the year 2007.

iv) the predicted values for the year 2002 also show that a 1830 km^2 area will have a watertable depths of less than 1.5 m. This represents 81 % of the total area, this percentage will increase to 87 % in the year 2007.

v) the numbers show the importance of continuing with remediations started in 1997. If these measures can maintain future recharge value to 1997 levels then in year 2002 only 53 % experiences watertable less than 1.5 m.

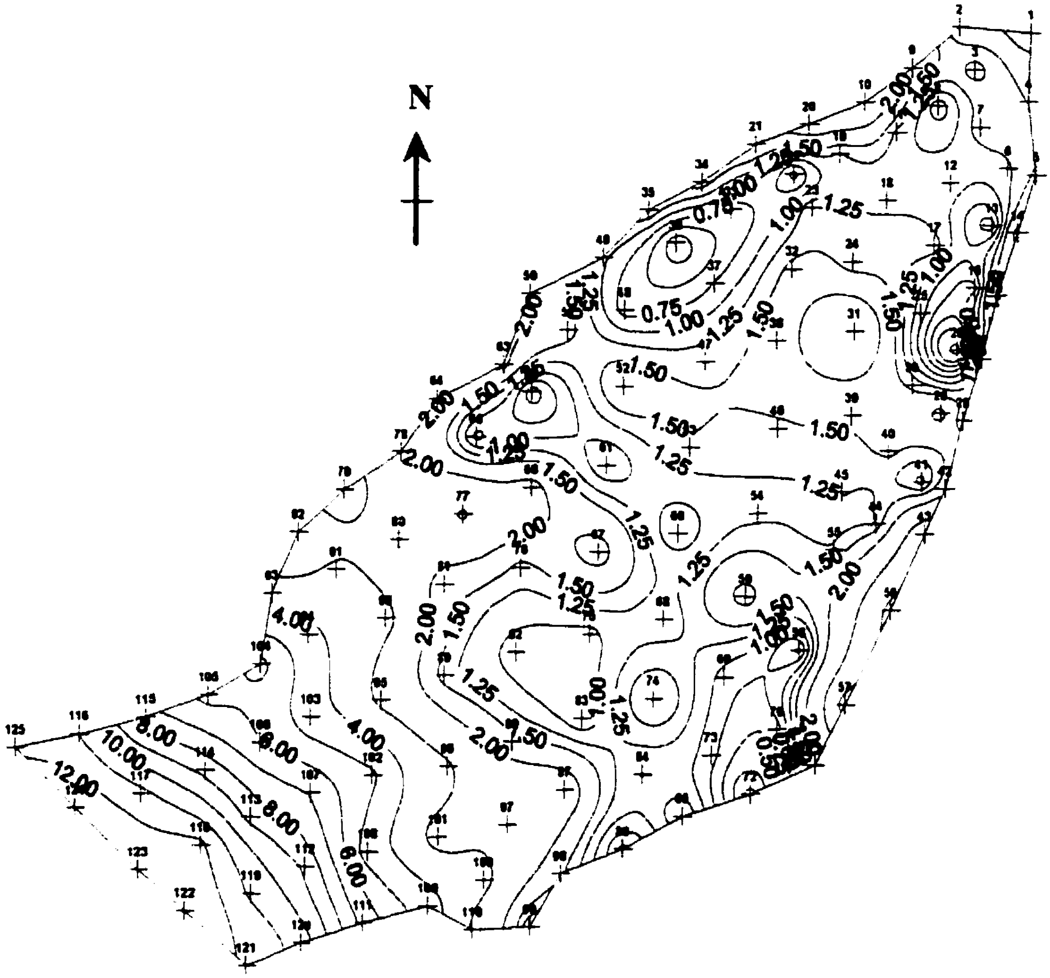


Figure 4.47 Watertable depth contour map in m for the month of July 1994

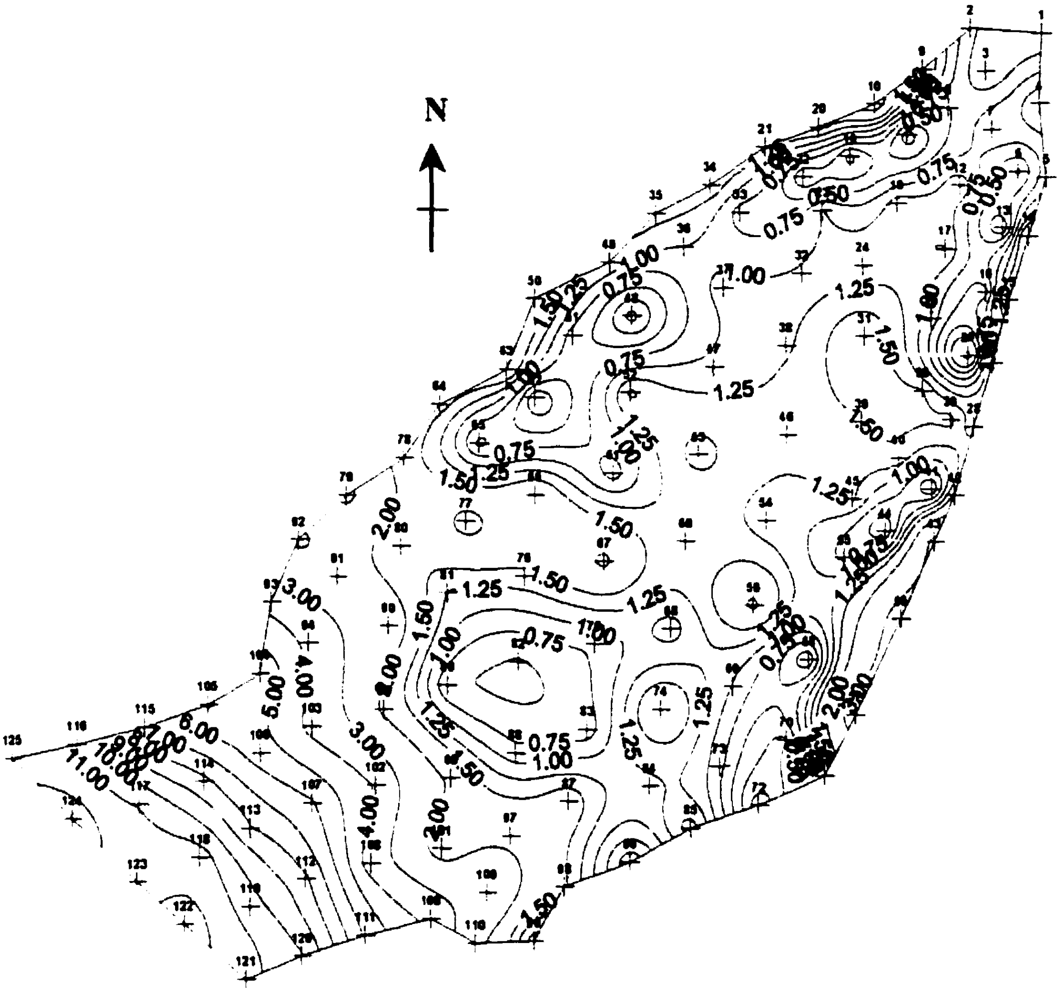


Figure 4.48 Watertable depth contour map in m for the month of June 1995

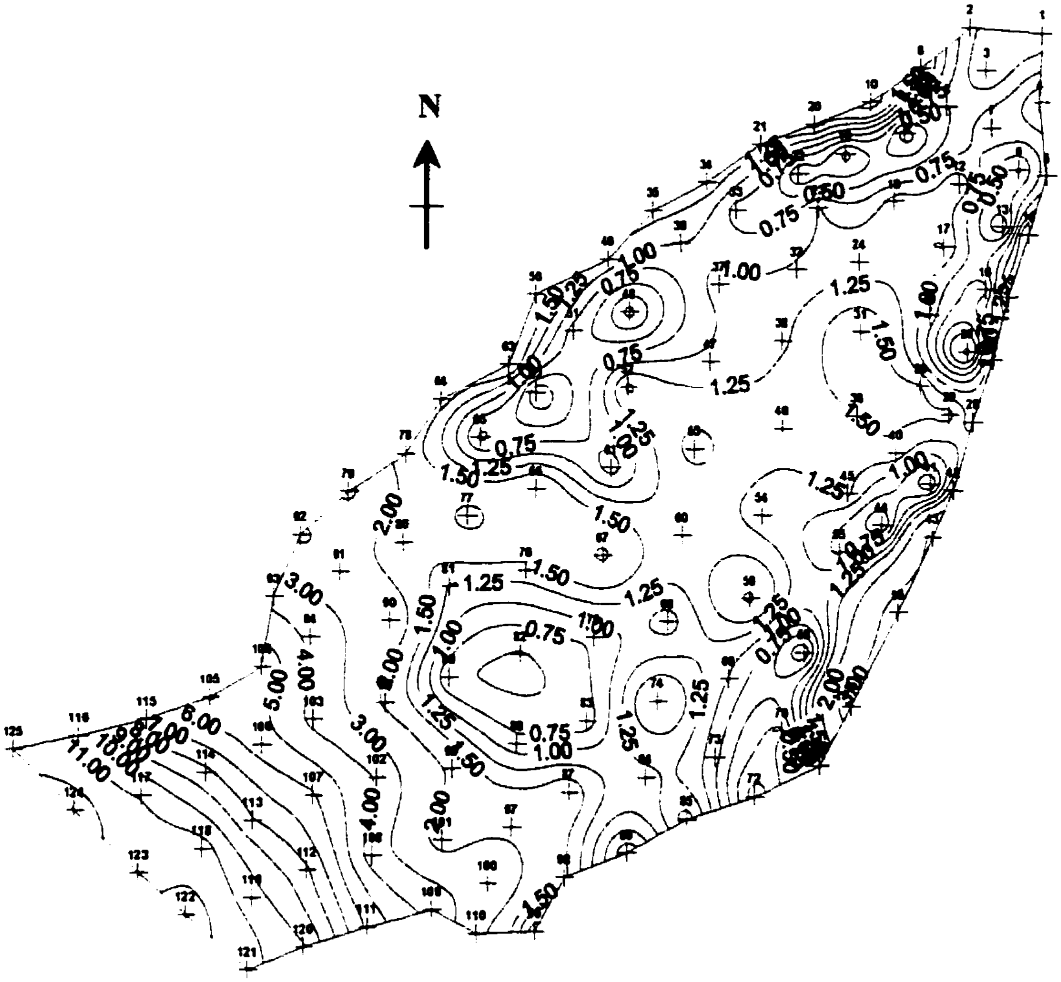


Figure 4.49 Watertable depth contour map in m for the month of June 1996

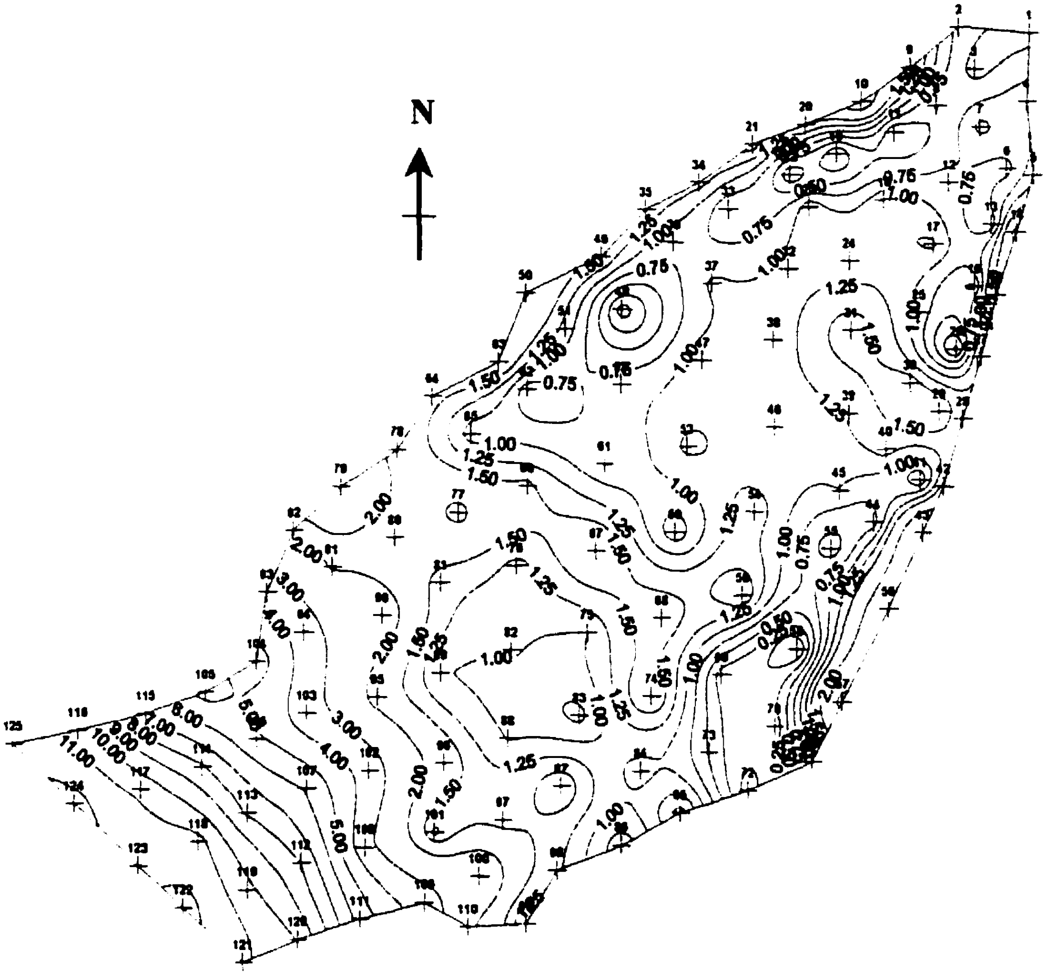


Figure 4.50 Watertable depth contour map in m for the month of June 1997

Figure 4.51 Watertable depth contour map in m for the month of June 2002

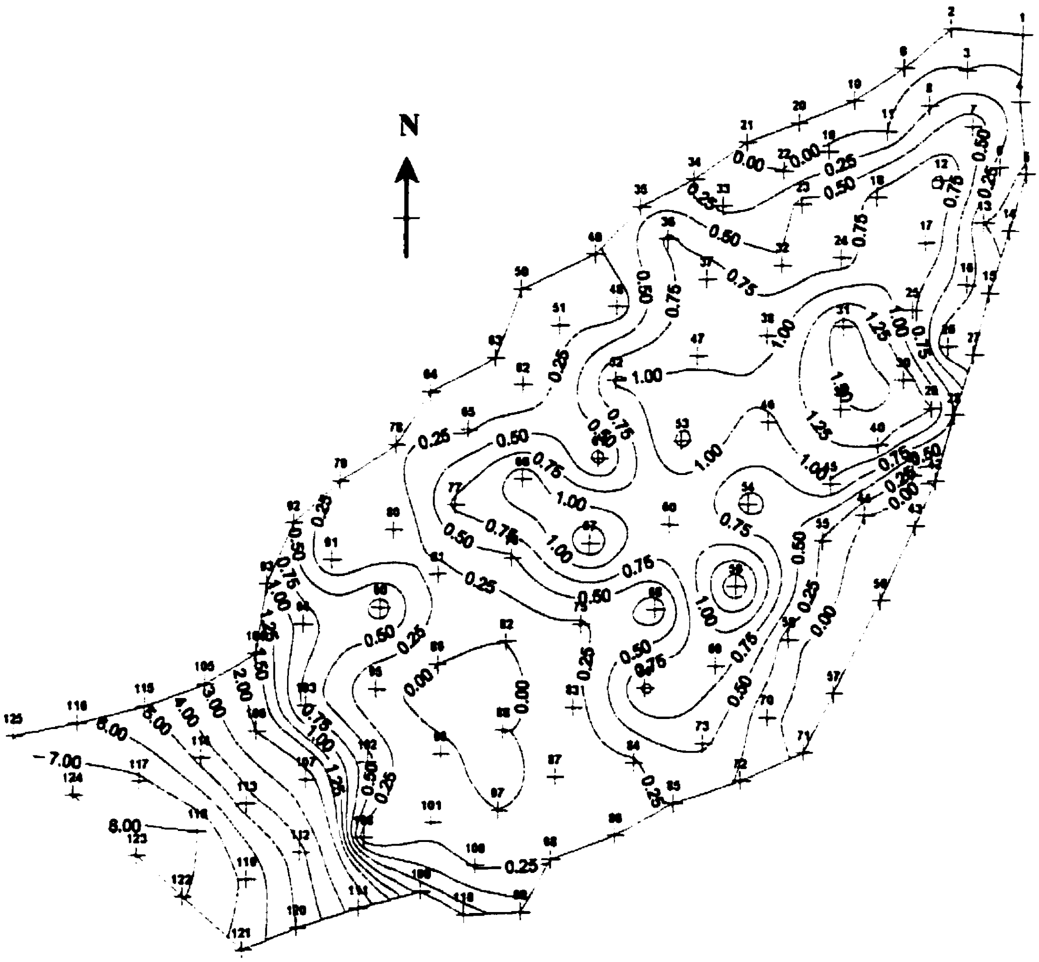


Figure 4.52 Watertable depth contour map in m for the month of June 2007

CHAPTER V

5 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary

Quantification of natural groundwater recharge is a prerequisite for designing a drainage system in waterlogged areas. Numerical modeling and simulation of flow in groundwater basins are essential elements of planning and management of water resources. Recent developments in numerical methods for groundwater hydrology, when coupled with results of field observations and investigations, provide a powerful as well as reliable tool for the management and prediction of groundwater behavior.

The Fordwah Eastern Sadiqia (South) Project Bahawalnager, Punjab, Pakistan, is comprised of 105,000 ha of culturable command area. Waterlogging and salinity is widely spread throughout the project. A numerical groundwater model (SGMP) was developed for the calculation of a groundwater balance. A nodal network comprised of 80 internal and 45 external nodes, nodal area varies from 3.45-34.65 km^2, was prepared from network of 125 observation wells. Internal nodes represent nodal areas, whereas the external nodes represent boundary conditions. Watertable depths were collected for the period of June, 1994 to June, 1997, other data used in the model included aquifer characteristics obtained from seven historical and five newly performed pumped well tests. The data were analyzed by the model in:

i) inverse mode to determine yearly, seasonal and monthly net-recharge values using a groundwater balance approach,

ii) normal mode to compare model results with the actual historical watertable elevations, and

iii) prediction mode to forecast values of watertable depths and areas in need of drainage.

5.2 Conclusions

1) The calculated net-recharge had positive values of 0.16 and 0.17 mm day^{-1} during monsoon 1994 and non-monsoon 1995-96, respectively. This indicates that the recharge in this area is not solely a result of the monsoon rains; other factors such as canal seepage must be a major source of recharge.

2) The calculated net-recharge of 80 internal nodes for the years '94-95, '95- 96' and '96-97' shows that the values were not consistently positive during three years. This means that in some areas upward flow from the saturated to the unsaturated zone did occur. The nodes numbered 3, 6, 8, 13, 16, 19, 22, 24, 26, 29,30, 32, 33, 40, 41, 44, 46, 48, 52, 55, 58, 62, 65, 67, 70, 74, 76, 77, 83, 84, 87, 90, 91, 94, 96, 97,100,102,103,106,107,108,112,113,117,118 and 119 show consistently positive net-recharge values over the three period.

3) The calculated net-recharge for '94-95' and '95-96' show a higher recharge of 0.12 mm day^{-1} than the year '96-97'. During '96-97 ', canal trial interceptor drain systems were installed near the canals. This may be the reason why net-recharge for this year was only 0.06 mm day^{-1}.

4) The calculated seasonal net-recharge had a positive value except during monsoon 1995. This negative value could be attributed to an unusually low rainfall that occurred in this period.

5) The aquifer analysis showed transmissivity ranging from 684 to 1806 m^2/day, the highest value occurred in the south-east of the project area and decreases from this point in all direction. Also, data analysis indicated the un-confined nature of the aquifer.

6) The watertable level steadily rose in almost all observation wells and the average rise was 131 cm over the three year period. In 1994, an area of 646.25 km^2 had a watertable depth less than 1.5 m which is 30 % of the project area. The same conditions (<1.5 m) showed a consistent increase in area in the years 1995, 1996 and 1997 to 872.5,1212.75and 1522.75 km^2 (39, 54, 68 %), respectively.

7) The SGMP model was run in the prediction mode to forecast future values of watertable depths. The recharge values of '95-96' were chosen as the base data input for prediction purposes. It was assumed that the recharge values were constant during future years and that current water-management practices did not change. The predicted values for the year 2002 showed that a 459 km^2 area will have a watertable of less than 0.5 m; representing 20 % of the study area. This percentage will increase to 35 % in the year 2007.

8) The predicted values for the year 2002 also showed that a 1830 km^2 area would have a watertable depth of less than 1.5 m. This represents 81 % of the total area.

The resultant net-recharge was a lumped parameter; all relevant contributing recharge and discharge components were integrated in its value. The advantage of assessing the net-recharge with the inverse modeling approach is the need for less input data as compared to the traditional waterbalance approach. For instance, to assess the same net-recharge by integrating the water balance for the unsaturated zone and at the land surface would require considerably more data (e.g. data on rainfall, irrigation, seepage from open water bodies, crops, soil, and tubewells). The collection and subsequent processing of these data is time consuming, and their reliability is sometimes questionable. Hence, using a groundwater-balance approach with inverse modeling to assess the net-recharge to an aquifer system deserves more attention.

5.3 Recommendations

1) To simulate the effects of the proposed anti-canal seepage measures on the regional groundwater table, data must be provided on the reduction in loss rates per unit length of canal (branch canals, distributaries, minors, water courses etc.) and type of measures taken (lining or interceptor drainage). These values should be subtracted from the overall nodal net-recharge values obtained from the inverse modeling results of this study. Then the groundwater simulation model can be run in normal mode to evaluate these effects on the regional watertable.

2) To refine design drainage coefficients, the contribution of different recharge and discharge components can be assessed without making a traditional water balance study. The rainfall recharge methodology (Maasland procedure) (Maasland et al., 1963) developed for the Fourth Drainage Project Faisalabad groundwater study can be applied to transform the historical net-recharge values of this study to design net-recharge values. These design values can than be used for future work. Though the rainfall data obtained from the meteorological stations in Bahawalnager and Jahanawala, Fordwah Eastern Sadiqia (South) Project is less than that observed in Fourth Drainage Project Faisalabad. These areas have similar geographic features (canals, drains, irrigation systems etc. Thus it is proposed that the Maasland procedure be used at the FESS project in order to develop design net-recharge based on rainfall which then needs to be added to inverse modeling results.

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APPENDICES

APPENDIX A

Table A.1. Information on different aquifer test sites

Aquifer test site	r-value * (m)	Discharge (m^3/d)	Depth of well (m)	Length of[1] Screen (m)
1	0.0 3.0 30.0	2040	72.0 54.8 55.0	24.4 3.0 3.0
2	0.0 6.0 19.0 60.0	2400	214.0 170.0 170.0 170.0	80.0 10.0 10.0 10.0
3	0.0 6.0 19.0 60.0	2400	214.0 170.0 170.0 170.0	80.0 10.0 10.0 10.0
4	0.0 3.0 15.0 30.0	2184	58.0 46.0 46.0 46.0	20.0 3.0 3.0 3.0
5	0.0 3.0 15.0	1944	58.0 46.0 46.0	24.0 3.0 3.0
HA-1	0.0 30.5 30.5	2457	– – –	– – –
HA-2	0.2 30.5	3685	– –	– –
HRN-1	0.0 15.2 30.5	1200	– – –	– – –

HRN-2	0.0 15.0 30.0 45.0 60.0	3133	– – – – –	– – – – –
T/W-1	7.6 45.7 45.7	2080	19.8 19.8 13.7	1.5 1.5 1.5
T/W-2	7.6 7.6 38.1 38.1	1957	19.8 7.6 19.8 19.8	1.5 1.5 1.5 1.5
T/W-3	7.6 7.6 45.7	2202	19.8 7.6 7.6	1.5 1.5 1.5

* distance from central pumped well. A zero designates the pumped well
[1] screen length always at bottom of the well
– data not available

APPENDIX A

Aquifer Site # test -1

Table A.2 shows the results of the analysis with the program package SATEM (Boonstra 1989). The time-drawdown & time-recovery data were analyzed using the Theis/Jacob method.

Table A.2. Transmissivity values determined with SATEM Site # test -1

Distance to pumped well (m)	Time range (min)	KH value (m^2/d)	Remarks
0.0 0.0	40-400 10-100	395* 659	drawdown recovery
3 3	30-200 10-100	718 650	drawdown recovery
15 15	10-500 10-100	647 618	drawdown recovery
30 30	40-200 10-100	734 762	drawdown recovery
Average		684	

* values thought to be erroneous not included in average
KH Transmissivity values m^2/d

The above data were also analyzed using the partial penetration module of SATEM. This yielded information on the hydraulic conductivity (6 - 6.5 m/d), the thickness of the aquifer (105 m) and storativity (2.3×10^{-2}).

General remarks:

- the transmissivity values were consistent and considered to be representative for the aquifer system;
- the storativity determined using the partial penetration method was 2.3×10^{-2}.
- The lithological log of this pumped well shows the soil classification from top to bottom as clay silt & sand (7 m), silty clay (3 m), sand silt (10 m), sand & silt (9 m), fine sand (8 m), silty clay (5 m), fine sand (15 m), silty clay (7 m) and sand/silt (18 m).

APPENDIX A

Aquifer Site # test-2

Table A.3 shows the results of the analysis with the program package SATEM (Boonstra 1989). The time-drawdown & time-recovery data were analyzed using the Theis/Jacob method.

Table A.3. Transmissivity values determined with SATEM Site # test -2

Distance to pumped well (m)	Time range (min)	KH value (m^2/d)	Remarks
0.0	10-1000	1379	drawdown
0.0	10-300	2650	recovery
3	10-40	1336	drawdown
3	10-100	2907	recovery
30	20-60	1338	drawdown
30	10-200	2752	recovery
Average		2060	

KH Transmissivity values m^2/d

All the time-drawdown graphs either showed recharge effects or indicated delayed yield effects or showed partial penetration effects.

General remarks:

- the transmissivity values were consistent in time-drawdown but different in time-recovery; recovery values average 2770 m^2/d. This is the only test giving such high values. Therefore all values from this test were excluded from further analysis.
- The lithological log of this pumped well shows the soil classification from top to bottom as silty clay (21 m), fine sand (4 m), silty clay (3 m), fine sand (6 m), fine-medium sand (18 m) sand & clay (3 m), fine - medium sand (25 m).

APPENDIX A

Aquifer Site # test-3

Table A.4 shows the results of the analysis with the program package SATEM (Boonstra 1989). The time-drawdown & time-recovery data were analyzed using the Theis/Jacob method.

Table A.4. Transmissivity values determined with SATEM Site # test-3

Distance to pumped well (m)	Time range (min)	KH value (m^2/d)	Remarks
0.0	2-100	1716	drawdown
0.0	50-1000	1847	recovery
6	6-100	1846	drawdown
6	50-1000	1792	recovery
19	10-100	1716	drawdown
19	50-1000	1787	recovery
60	5-100	1919	drawdown
60	50-1000	1830	recovery
Average		1806	

KH Transmissivity values m^2/d

During the pumping period all time-drawdown graphs (Fig 4.31a) indicated obvious delayed yield effects. During pumping period of around t = 200 minutes a shift in the straight line was visible in the drawdown graphs. The reason for this shift is not known. This phenomenon was not included in the analysis. The transmissivity values were calculated using the straight lines as shown as shown on the graphs.

General remarks:

- the transmissivity values were consistent and considered to be representative for the aquifer system;
- The lithological log of this pumped well shows the soil classification from top to bottom as silty clay (42 m), fine-medium sand (46 m) fine sand with silty clay (46 m), medium-coarse sand (25 m).

APPENDIX A

Aquifer Site # test -4

Table A.5 shows the results of the analysis with the program package SATEM (Boonstra 1989). The time-drawdown & time-recovery data were analyzed using the Theis/Jacob method.

Table A.5. Transmissivity values determined with SATEM Site # test-4

Distance to pumped well (m)	Time range (min)	KH value (m^2/d)	Remarks
0.0 0.0	2-100 50-1000	882 836	drawdown recovery
3 3	2-100 50-1000	830 821	drawdown recovery
15 15	2-100 50-1000	820 838	drawdown recovery
30 30	7-100 50-1000	857 834	drawdown recovery
Average		840	

KH Transmissivity values m^2/d

During the pumping period all time-drawdown graphs (Fig 4.32 a)indicated obvious delayed yield effects. This phenomenon is quite common in unconfined aquifers.

General remarks:

- the transmissivity values were consistent and considered to be representative for the aquifer system;
- The lithological log of this pumped well shows the soil classification from top to bottom as silty clay (14 m), fine - medium sand (11 m) hard clay (11 m), medium-coarse sand (22 m) and hard clay (13 m).

APPENDIX A

Aquifer Site # test-5

Table A.6 shows the results of the analysis with the program package SATEM (Boonstra 1989). The time-drawdown & time-recovery data were analyzed using the Theis/Jacob method.

Table A.6. Transmissivity values determined with SATEM Site # test-5

Distance to pumped well (m)	Time range (min)	KH value (m^2/d)	Remarks
0.0 0.0	50-200 10-100	856 1077	drawdown recovery
3 3	10-300 10-100	890 1081	drawdown recovery
15 15	50-300 10-100	934 997	drawdown recovery
Average		972	

KH Transmissivity values m^2/d

During the pumping period all time-drawdown graphs indicated obvious delayed yield effects. This phenomenon is quite common in unconfined aquifers.

General remarks:

- the transmissivity values were consistent and considered to be representative for the aquifer system;
- The lithological log of this pumped well shows the soil classification from top to bottom as silty clay (15 m), fine-medium sand (8 m) silty clay (15 m), sand (4 m), silty clay (32 m).

APPENDIX A

6-R Hakra: Site # HA-1

Table A.7 shows the results of the analysis with the program package SATEM (Boonstra 1989). The time-drawdown & time-recovery data were analyzed using the Theis/Jacob method and the residual-drawdown data were analyzed with Theis-recovery method.

Table A.7. Transmissivity values determined with SATEM, Site # HA-1

Distance to pumped well (m)	Time range (min)	KH value (m^2/d)	Remarks
0.0	5-5760	1281	drawdown
0.0	15-100	1347	residual
0.0	5-5761	1379	recovery
31	15-200	1249	drawdown
31	10-100	1131	residual
31	1-1440	1435	recovery
31	100-1000	1253	drawdown
31	50-1440	1364	residual
Average		1270*	

* average is taken between drawdown and residual (recovery values not used)
KH Transmissivity values m^2/d

Initially the drawdown in the shallow observation well (Fig 4.34 a) showed firstly a time lag behind that of the deep observation well. Then, recovery accelerated and was of the same order of magnitude at the end of the pumping period.

General remarks:

- the time-drawdown in the pumped well showed irregular behavior indicating that the discharge of the pump may have been irregular;
- the transmissivity values were consistent and considered to be representative for the aquifer system;

APPENDIX A

6-R Hakra: Site # HA-2

Table A.8 shows the results of the analysis with the program package SATEM (Boonstra 1989). The time-drawdown & time-recovery data were analyzed using the Theis/Jacob method and the residual-drawdown data were analyzed with Theis-recovery method.

Table A.8. Transmissivity values determined with SATEM Site # HA-2

Distance to pumped well (m)	Time range (min)	KH value (m^2/d)	Remarks
0.0	5-5760	2068	drawdown
0.0	3-10	2397	residual
0.0	5-5760	2933	recovery
31	15-100	1401	drawdown
31	10-100	1558	residual
31	5-5760	1198	recovery
Average		1856*	

* average is calculated using only drawdown and residual. not recovery values
KH Transmissivity values m^2/d

General remarks:

- the transmissivity values were not consistent and showed large variation. Therefore all values from this test were excluded from further analysis.

APPENDIX A

Groundwater study: Site # HRN-1

Table A.9 shows the results of the analysis with the program package SATEM (Boonstra 1989). The time-drawdown & time-recovery data were analyzed using the Theis/Jacob method.

Table A.9. Transmissivity values determined with SATEM Site # HRN-1

Distance to pumped well (m)	Time range (min)	KH value (m^2/d)	Remarks
0.0	10-4300	178 *	drawdown
0.0	10-1000	1319	recovery
15	6-20	1210	drawdown
15	2-40	1209	recovery
31	4-80	1538	drawdown
31	4-60	1471	recovery
Average		1350	

* value not included in average
KH Transmissivity values m^2/d

All time-drawdown graphs indicated clear delayed yield effects except that of the pumped well. This phenomenon indicates that the tested aquifer can be considered unconfined.

General remarks:

- the time-drawdown in the pumped well was excessively high indicating that the well was in a poor condition; this may be the explanation of the low transmissivity value of this well during the pumping period;
- other transmissivity values were consistent and considered to be representative for the aquifer system;

APPENDIX A

Groundwater study: Site # HRN-2

Table A.10 shows the results of the analysis with the program package SATEM (Boonstra 1989). The time-drawdown data were analyzed using the Theis/Jacob method

Table A.10. Transmissivity values determined with SATEM Site # HRN-2

Distance to pumped well (m)	Time range (min)	KH value (m^2/d)	Remarks
0.0	1-3800	2445	drawdown
15	0.2-3800	1044	drawdown
30	0.2-3800	2724	drawdown
45	0.3-3800	1674	drawdown
60	0.8-2800	2177	drawdown
Average		2013	

KH Transmissivity values m^2/d

General remarks:

- no recovery data were available for this test site; the transmissivity values were not consistent and showed large variation in drawdown. Therefore all values from this test were excluded from further analysis.

APPENDIX A

FESS Additional Studies: Site # T/W-1

Table A.11 shows the results of the analysis with the program package SATEM (Boonstra 1989). The time-drawdown & time-recovery data were analyzed using the Theis/Jacob method and the residual-drawdown data were analyzed with Theis-recovery method.

Table A.11. Transmissivity values determined with SATEM Site # T/W-1

Distance to pumped well (m)	Time range (min)	KH value (m^2/d)	Remarks
8	30-1440	1146	drawdown
8	10-1470	618	residual
8	2-1441	500	recovery
46	30-1470	1099	drawdown
46	15-1410	914	residual
46	2-1441	1028	recovery
46	50-1470	1003	drawdown
46	30-1410	909	residual
Average		948 *	

* average is taken between drawdown and residual, not recovery values
KH Transmissivity values m^2/d

No drawdown data were available for the pumped well itself. The results test exhibit (Fig 4.36 a & b) a smaller recharge effect likely because the test were made during canal closure.

General remarks:

- no information on the position and length of the well screens was available.
- transmissivity values used were consistent and considered to be representative for the aquifer system;

APPENDIX A

FESS Additional Studies: Site # T/W-2

Table A.12 shows the results of the analysis with the program package SATEM (Boonstra 1989). The time-drawdown & time-recovery data were analyzed using the Theis/Jacob method and the residual-drawdown data were analyzed with Theis-recovery method.

Table A.12. Transmissivity values determined with SATEM Site # T/W-2

Distance to pumped well (m)	Time range (min)	KH value (m^2/d)	Remarks
8	30-1440	1754[1]	drawdown
8	10-200	768	residual
8	2-1441	671	recovery
8	30-1440	833	drawdown
8	4-300	432[1]	residual
8	2-1441	457	recovery
38	30-1440	1334	drawdown
38	1-1440	957	residual
38	2-1441	942	recovery
38	1-1440	1008	drawdown
Average		980 *	

* average is taken between drawdown and residual, not recovery values
[1] values not included in average
KH Transmissivity values m^2/d

No drawdown data were available for the pumped well itself. The results test exhibit (Fig 4.37 a & b) a smaller recharge effect likely because the test were made during canal closure. The data of the shallow observation well at a distance of 38 m could not be analyzed for recovery behavior because recovery data was missing.

General remarks:

- no information on the position and length of the well screens was available.
- transmissivity values used were consistent and considered to be representative for the aquifer system;

APPENDIX A

FESS Additional Studies: Site # T/W-3

Table A.13 shows the results of the analysis with the program package SATEM (Boonstra 1989). The time-drawdown & time-recovery data were analyzed using the Theis/Jacob method and the residual-drawdown data were analyzed with Theis-recovery method.

Table A.13. Transmissivity values determined with SATEM Site # T/W-3

Distance to pumped well (m)	Time range (min)	KH value (m^2/d)	Remarks
8	10-30	1286	drawdown
8	2-200	1094	residual
8	2-721	912	recovery
8	150-720	950	drawdown
8	10-200	1110	residual
8	2-721	1229	recovery
46	300-720	935	drawdown
46	100-720	1155	residual
Average		1088 *	

* average is taken between drawdown and residual, not recovery values
KH Transmissivity values m^2/d

No data were available for the pumped well itself. The results test exhibit (Fig 4.39 a & b) a smaller recharge effect likely because the test were made during canal closure. The data of the deep observation well at a distance of 46 m could not be analyzed because of its very irregular drawdown behavior.

General remarks:

- the transmissivity values used were consistent and considered to be representative for the aquifer system;

Appendix B

Table B.1. Groundwater balance components as average values over the July-October 1994 (monsoon) period.

Node number	Change in storage mm/day	Subsurface[1] flow rate mm/day	Net recharge mm/day	Node number	Change in storage	Subsurface[1] flow rate mm/day	Net recharge mm/day
3	-0.52	-0.45	0.97	66	-0.01	0.04	-0.03
6	-0.79	-0.14	0.93	67	-0.43	-0.04	0.47
7	-0.04	0.54	-0.50	68	-0.15	0.02	0.13
8	-0.29	-0.73	1.03	69	-0.19	0.16	0.02
11	-0.46	0.05	0.41	70	-0.17	-0.48	0.65
12	-0.25	0.05	0.19	73	-0.05	0.12	-0.06
13	-0.21	-0.45	0.66	74	-0.08	-0.07	0.16
16	0.19	-0.88	0.69	75	-0.28	0.14	0.14
17	0.36	0.12	-0.48	76	0.00	0.02	-0.02
18	-0.05	-0.02	0.07	77	-0.31	0.09	0.22
19	-0.37	-0.16	0.53	80	-0.16	0.06	0.10
22	-0.41	-0.42	0.83	81	-0.16	0.00	0.16
23	0.07	0.15	-0.22	82	-0.20	-0.01	0.20
24	-0.08	-0.05	0.13	83	-0.20	-0.05	0.25
25	-0.10	0.22	-0.13	84	0.04	-0.07	0.03
26	0.00	-0.81	0.80	87	0.03	-0.15	0.12
29	-0.29	0.15	0.14	88	-0.01	0.00	0.00
30	-0.44	-0.34	0.79	89	-0.06	-0.08	0.14
31	-0.86	0.06	0.81	90	0.04	-0.06	0.03
32	-0.22	-0.01	0.23	91	0.29	-0.04	-0.25
33	-0.08	-0.33	0.41	94	0.04	0.08	-0.11
36	0.31	-0.36	0.05	95	0.06	0.06	-0.11
37	-0.13	0.08	0.06	96	0.00	-0.05	0.05
38	-0.37	0.11	0.26	97	0.03	0.07	-0.11
39	-0.14	-0.10	0.24	100	0.16	-0.16	0.00
40	-0.13	-0.06	0.19	101	0.11	0.31	-0.42
41	0.08	-0.50	0.42	102	-0.12	0.00	0.12
44	-0.01	-0.27	0.29	103	0.10	0.02	-0.12
45	0.06	0.16	-0.22	106	0.01	0.01	-0.02
46	-0.06	-0.01	0.07	107	-0.02	0.03	-0.01
47	0.04	0.06	-0.10	108	-0.04	-0.13	0.17
48	-0.04	0.07	-0.03	112	0.00	0.01	-0.01
51	-0.09	0.02	0.07	113	-0.03	0.02	0.01
52	-0.05	-0.01	0.05	114	-0.03	0.08	-0.06

Node number	Change in storage mm/day	Subsurface[1] flow rate mm/day	Net recharge mm/day	Node number	Change in storage	Subsurface[1] flow rate mm/day	Net recharge mm/day
53	-0.03	0.03	0.00	117	-0.01	0.01	0.00
54	-0.11	-0.06	0.17	118	-0.05	0.03	0.02
55	-0.24	-0.37	0.60	119	0.00	-0.01	0.00
58	-0.44	-0.39	0.83				
59	-0.02	0.20	-0.17				
60	-0.69	0.02	0.67				
61	-0.14	0.10	0.04				
62	-0.20	-0.21	0.42				
65	-0.59	-0.21	0.80				
				Average	-0.12	-0.04	0.16

1 difference of inflow and outflow

Appendix B

Table B.2.1. Groundwater balance components as average values over the November-February 1994-95 (non-monsoon) period.

Node number	Change in storage mm/day	Subsurface flow rate mm/day	Net recharge mm/day	Node number	Change in storage	Subsurface flow rate mm/day	Net recharge mm/day
3	-0.01	-0.44	0.45	66	-0.24	0.07	0.17
6	0.18	-0.31	0.13	67	0.13	-0.02	-0.11
7	-0.56	0.41	0.15	68	-0.11	0.03	0.08
8	0.11	-0.55	0.44	69	-0.34	0.15	0.19
11	-0.59	-0.07	0.66	70	-0.20	-0.45	0.65
12	0.04	0.03	-0.07	73	-0.25	0.10	0.15
13	-0.02	-0.26	0.28	74	-0.22	-0.06	0.28
16	-0.20	-0.81	1.01	75	-0.52	0.11	0.41
17	-0.21	0.10	0.11	76	-0.32	0.04	0.28
18	-0.13	0.01	0.12	77	-1.01	0.02	0.99
19	-0.97	-0.16	1.13	80	-0.49	0.08	0.42
22	-0.32	-0.42	0.74	81	-0.75	-0.02	0.77
23	-0.19	0.18	0.02	82	-0.29	0.01	0.29
24	-0.30	-0.08	0.37	83	-0.28	-0.04	0.32
25	-0.27	0.20	0.08	84	-0.42	-0.09	0.51
26	0.00	-0.63	0.63	87	-0.37	-0.16	0.53
29	-0.32	-0.07	0.39	88	-0.53	0.00	0.54
30	0.27	-0.22	-0.05	89	-0.47	-0.09	0.56
31	0.15	0.02	-0.17	90	-0.48	-0.06	0.54
32	-0.26	-0.02	0.28	91	-0.48	-0.04	0.52
33	-0.35	-0.32	0.67	94	-0.23	0.09	0.15
36	-0.10	-0.26	0.36	95	-0.40	0.05	0.35
37	-0.19	0.09	0.09	96	-0.40	-0.05	0.45
38	-0.20	0.09	0.11	97	-0.36	0.09	0.28
39	-0.58	-0.14	0.72	100	-0.24	-0.13	0.37
40	-0.13	0.00	0.14	101	-0.57	0.30	0.26
41	-0.53	-0.75	1.28	102	-0.26	0.00	0.26
44	-0.45	-0.30	0.74	103	-0.25	0.02	0.23
45	-0.28	0.18	0.09	106	-0.12	0.01	0.11
46	-0.25	-0.03	0.28	107	-0.15	0.03	0.11
47	-0.79	0.03	0.76	108	-0.25	-0.14	0.39
48	-0.91	0.01	0.91	112	0.06	0.02	-0.08
51	-0.62	-0.03	0.65	113	-0.09	0.02	0.07
52	-0.54	0.01	0.53	114	-0.08	0.08	0.00
53	-0.32	0.05	0.27	117	-0.07	0.01	0.06
54	0.06	-0.02	-0.05	118	-0.02	0.04	-0.02

Node number	Change in storage mm/day	Subsurface flow rate mm/day	Net recharge mm/day	Node number	Change in storage	Subsurface flow rate mm/day	Net recharge mm/day
55	-0.35	-0.41	0.76	119	-0.08	0.00	0.08
58	-0.19	-0.40	0.59				
59	-0.13	0.22	-0.09				
60	0.11	0.01	-0.11				
61	-0.58	0.09	0.49				
62	-0.43	-0.21	0.64				
65	-0.09	-0.22	0.31	Average	-0.29	-0.04	0.33

Table B.2.2. Groundwater balance components as average values over the March-June 1995(non-monsoon) period.

Node number	Change in storage mm/day	Subsurface flow rate mm/day	Net recharge mm/day	Node number	Change in storage	Subsurface flow rate mm/day	Net recharge mm/day
3	-0.38	-0.65	1.03	66	0.02	0.04	-0.05
6	-0.15	-0.55	0.69	67	0.01	-0.06	0.06
7	0.31	0.43	-0.75	68	0.65	0.06	-0.71
8	0.14	-0.51	0.37	69	0.32	0.17	-0.50
11	0.40	-0.08	-0.33	70	0.16	-0.43	0.27
12	0.10	0.08	-0.18	73	0.14	0.09	-0.23
13	0.28	-0.33	0.06	74	0.33	-0.06	-0.26
16	0.53	-0.79	0.26	75	0.73	0.15	-0.88
17	0.28	0.10	-0.38	76	0.16	0.04	-0.19
18	0.13	0.03	-0.16	77	0.47	0.03	-0.50
19	0.00	-0.38	0.38	80	0.18	0.08	-0.26
22	0.21	-0.37	0.16	81	0.41	-0.03	-0.39
23	0.08	0.20	-0.28	82	0.31	0.02	-0.33
24	0.28	-0.04	-0.25	83	0.30	-0.04	-0.26
25	0.59	0.24	-0.83	84	0.39	-0.07	-0.31
26	0.47	-0.71	0.24	87	0.15	-0.17	0.02
29	0.11	-0.33	0.22	88	0.07	-0.02	-0.05
30	0.14	-0.13	-0.01	89	0.15	-0.08	-0.07
31	-0.14	-0.03	0.17	90	-0.13	-0.08	0.21
32	0.10	-0.04	-0.06	91	0.00	-0.04	0.04
33	0.30	-0.31	0.02	94	-0.03	0.08	-0.04
36	0.69	-0.12	-0.57	95	-0.11	0.05	0.06
37	0.21	0.07	-0.29	96	-0.16	-0.07	0.23
38	0.26	0.13	-0.38	97	-0.16	0.06	0.10
39	0.49	-0.14	-0.35	100	-0.14	-0.14	0.28
40	0.10	-0.04	-0.06	101	-0.05	0.30	-0.24
41	0.18	-0.61	0.43	102	-0.23	0.00	0.24
44	-0.33	-0.63	0.96	103	-0.15	0.01	0.14
45	0.29	0.29	-0.58	106	-0.15	0.01	0.13
46	0.27	-0.01	-0.26	107	-0.15	0.04	0.10
47	0.24	0.03	-0.27	108	-0.21	-0.14	0.35
48	0.01	-0.04	0.03	112	-0.22	0.02	0.20
51	0.26	-0.02	-0.24	113	-0.13	0.02	0.10
52	0.24	-0.01	-0.23	114	0.03	0.09	-0.13
53	0.13	0.02	-0.14	117	0.06	0.01	-0.07

Node number	Change in storage mm/day	Subsurface flow rate mm/day	Net recharge mm/day	Node number	Change in storage	Subsurface flow rate mm/day	Net recharge mm/day
54	0.78	0.04	-0.82	118	-0.27	0.01	0.27
55	0.05	-0.41	0.36	119	-0.13	0.00	0.13
58	0.35	-0.38	0.03				
59	-0.02	0.17	-0.15				
60	0.71	0.04	-0.74				
61	0.57	0.12	-0.69				
62	0.01	-0.22	0.21				
65	0.22	-0.15	-0.06	Average	0.17	-0.04	-0.12

Table B.3. Groundwater balance components as average values over the July-October 1995(monsoon) period.

Node number	Change in storage mm/day	Subsurface flow rate mm/day	Net recharge mm/day	Node number	Change in storage	Subsurface flow rate mm/day	Net recharge mm/day
3	0.18	-0.66	0.48	66	0.07	0.02	-0.10
6	-0.18	-0.46	0.64	67	0.31	-0.04	-0.27
7	0.40	0.51	-0.91	68	0.03	0.08	-0.11
8	-0.06	-0.53	0.58	69	0.29	0.18	-0.47
11	-0.35	-0.12	0.47	70	0.08	-0.43	0.35
12	0.17	0.10	-0.26	73	-0.08	0.08	0.00
13	-0.17	-0.54	0.70	74	0.04	-0.06	0.03
16	-0.21	-0.96	1.17	75	-0.11	0.15	-0.04
17	0.28	0.15	-0.43	76	-0.04	0.02	0.02
18	0.14	0.04	-0.18	77	0.22	0.06	-0.27
19	0.01	-0.39	0.37	80	0.20	0.07	-0.27
22	0.03	-0.41	0.38	81	0.11	-0.01	-0.10
23	0.00	0.18	-0.18	82	0.02	0.02	-0.04
24	0.22	-0.04	-0.18	83	0.13	-0.06	-0.07
25	0.28	0.28	-0.56	84	0.13	-0.05	-0.08
26	-0.40	-0.79	1.20	87	0.12	-0.14	0.03
29	0.07	-0.02	-0.05	88	0.06	-0.02	-0.05
30	-0.01	-0.21	0.22	89	0.06	-0.09	0.02
31	0.55	0.02	-0.57	90	0.29	-0.10	-0.19
32	0.36	-0.04	-0.32	91	0.35	-0.03	-0.32
33	0.31	-0.26	-0.05	94	0.02	0.06	-0.08
36	-0.66	-0.28	0.94	95	0.11	0.06	-0.17
37	0.02	0.09	-0.10	96	0.04	-0.07	0.02
38	0.18	0.10	-0.27	97	-0.11	0.03	0.08
39	0.18	-0.11	-0.07	100	-0.12	-0.14	0.26
40	0.14	-0.08	-0.06	101	-0.15	0.28	-0.13
41	0.29	-0.56	0.27	102	-0.05	-0.01	0.06
44	0.01	-0.60	0.59	103	0.06	0.01	-0.07
45	0.08	0.31	-0.39	106	-0.01	0.03	-0.02
46	0.05	-0.02	-0.03	107	-0.07	0.04	0.03
47	0.52	0.04	-0.56	108	-0.06	-0.15	0.21
48	0.29	-0.04	-0.25	112	0.00	0.04	-0.04
51	0.12	-0.03	-0.09	113	-0.10	0.02	0.08
52	0.44	0.03	-0.47	114	-0.15	0.09	0.06

Node number	Change in storage mm/day	Subsurface flow rate mm/day	Net recharge mm/day	Node number	Change in storage	Subsurface flow rate mm/day	Net recharge mm/day
53	0.21	0.04	-0.25	117	-0.17	0.01	0.15
54	-0.65	-0.01	0.65	118	-0.07	0.01	0.06
55	0.12	-0.39	0.27	119	-0.02	0.00	0.02
58	-0.04	-0.41	0.45				
59	0.32	0.21	-0.53				
60	-0.95	-0.02	0.97				
61	-0.04	0.11	-0.07				
62	0.06	-0.25	0.19				
65	0.02	-0.15	0.13	Average	0.05	-0.04	-0.01

Appendix B

Table B.4.1 Groundwater balance components as average values over the November-February 1995-96 (non-monsoon) period.

Node number	Change in storage mm/day	Subsurface flow rate mm/day	Net recharge mm/day	Node number	Change in storage	Subsurface flow rate mm/day	Net recharge mm/day
3	0.05	-0.61	0.56	66	-0.14	0.04	0.10
6	0.02	-0.53	0.51	67	-0.23	-0.03	0.25
7	-0.40	0.49	-0.08	68	0.11	0.11	-0.22
8	0.52	-0.47	-0.05	69	-0.25	0.15	0.10
11	0.29	-0.13	-0.16	70	-0.06	-0.45	0.51
12	-0.11	0.11	0.00	73	0.19	0.12	-0.31
13	0.14	-0.33	0.18	74	-0.25	-0.10	0.35
16	-0.01	-0.90	0.91	75	-0.33	0.13	0.20
17	-0.44	0.08	0.36	76	-0.26	0.01	0.25
18	-0.14	0.03	0.11	77	-0.38	0.04	0.34
19	0.15	-0.35	0.20	80	-0.51	0.05	0.47
22	0.14	-0.35	0.21	81	-0.32	-0.01	0.33
23	-0.11	0.17	-0.06	82	-0.27	0.02	0.25
24	-0.25	-0.04	0.29	83	-0.25	-0.03	0.27
25	-0.48	0.22	0.26	84	-0.39	-0.07	0.46
26	0.01	-0.58	0.56	87	-0.26	-0.16	0.42
29	0.03	-0.09	0.06	88	-0.19	0.00	0.19
30	0.10	-0.23	0.13	89	-0.11	-0.07	0.18
31	-0.22	0.04	0.18	90	-0.33	-0.09	0.41
32	-0.34	-0.03	0.37	91	-0.36	-0.03	0.39
33	-0.18	-0.32	0.50	94	-0.12	0.06	0.06
36	0.56	-0.19	-0.37	95	-0.14	0.05	0.08
37	-0.10	0.07	0.03	96	-0.41	-0.07	0.49
38	-0.37	0.10	0.28	97	-0.30	0.00	0.30
39	-0.25	-0.14	0.39	100	0.00	-0.09	0.09
40	-0.19	-0.02	0.21	101	-0.22	0.27	-0.05
41	-0.44	-0.50	0.94	102	-0.16	-0.01	0.17
44	0.04	-0.51	0.47	103	-0.14	0.02	0.12
45	-0.17	0.25	-0.08	106	-0.09	0.01	0.08
46	-0.12	-0.01	0.13	107	-0.09	0.04	0.06
47	-0.26	0.05	0.21	108	-0.12	-0.15	0.27
48	-0.17	-0.05	0.22	112	0.03	0.04	-0.06
51	-0.03	-0.04	0.07	113	-0.05	0.01	0.04
52	-0.56	0.02	0.54	114	-0.05	0.09	-0.05
53	-0.27	0.04	0.23	117	-0.05	0.01	0.03
54	0.09	0.00	-0.09	118	0.03	0.02	-0.05

Node number	Change in storage mm/day	Subsurface flow rate mm/day	Net recharge mm/day	Node number	Change in storage	Subsurface flow rate mm/day	Net recharge mm/day
55	0.35	-0.38	0.03	119	-0.03	0.00	0.03
58	-0.10	-0.40	0.50				
59	-0.16	0.23	-0.07				
60	0.06	-0.03	-0.03				
61	-0.37	0.10	0.27				
62	0.26	-0.21	-0.05				
65	0.09	-0.17	0.08	Average	-0.14	-0.04	-0.19

Table B.4.2 Groundwater balance components as average values over the March-June 1996 (non-monsoon) period.

Node number	Change in storage mm/day	Subsurface flow rate mm/day	Net recharge mm/day	Node number	Change in storage	Subsurface flow rate mm/day	Net recharge mm/day
3	-0.37	-0.67	1.04	66	-0.01	0.04	-0.03
6	0.09	-0.53	0.44	67	-0.07	-0.05	0.12
7	-0.02	0.44	-0.41	68	-0.70	0.06	0.64
8	-0.57	-0.52	1.09	69	0.23	0.17	-0.40
11	-0.45	-0.13	0.59	70	-0.10	-0.44	0.54
12	-0.03	0.17	-0.14	73	0.07	0.13	-0.20
13	-0.26	-0.38	0.64	74	-0.08	-0.07	0.15
16	-0.16	-0.80	0.97	75	0.07	0.13	-0.20
17	0.06	0.09	-0.15	76	0.22	0.03	-0.25
18	-0.09	0.03	0.05	77	-0.01	0.01	-0.01
19	-0.17	-0.37	0.54	80	-0.20	0.04	0.16
22	-0.27	-0.34	0.61	81	0.13	0.01	-0.13
23	-0.17	0.15	0.02	82	-0.31	0.01	0.30
24	-0.08	-0.03	0.11	83	-0.10	-0.02	0.12
25	0.03	0.22	-0.25	84	0.01	-0.09	0.08
26	0.03	-0.60	0.58	87	-0.22	-0.18	0.40
29	-0.14	-0.29	0.43	88	-0.30	-0.01	0.31
30	-0.16	-0.14	0.30	89	-0.37	-0.07	0.44
31	-0.28	0.00	0.28	90	0.01	-0.07	0.06
32	-0.14	-0.04	0.17	91	-0.41	-0.07	0.47
33	-0.29	-0.31	0.61	94	-0.11	0.06	0.05
36	-0.04	-0.17	0.21	95	-0.30	0.04	0.26
37	0.11	0.10	-0.21	96	-0.13	-0.09	0.21
38	0.12	0.09	-0.21	97	-0.09	0.01	0.07
39	0.25	-0.08	-0.17	100	-0.16	-0.13	0.30
40	0.10	-0.03	-0.07	101	-0.04	0.28	-0.24
41	-0.01	-0.55	0.56	102	-0.18	-0.01	0.19
44	-0.19	-0.56	0.75	103	-0.11	0.02	0.09
45	0.07	0.26	-0.33	106	-0.15	0.01	0.14
46	0.02	-0.02	0.00	107	-0.20	0.03	0.17
47	-0.20	0.04	0.16	108	-0.19	-0.15	0.34
48	-0.12	-0.05	0.17	112	-0.34	0.03	0.32
51	-0.43	-0.06	0.48	113	-0.14	0.02	0.12
52	-0.04	0.01	0.03	114	-0.09	0.10	-0.01
53	0.11	0.02	-0.13	117	-0.07	0.02	0.05
54	-0.17	0.00	0.17	118	-0.17	0.02	0.15

Node number	Change in storage mm/day	Subsurface flow rate mm/day	Net recharge mm/day	Node number	Change in storage	Subsurface flow rate mm/day	Net recharge mm/day
55	-0.51	-0.38	0.89	119	-0.16	0.00	0.16
58	0.05	-0.35	0.30				
59	-0.14	0.20	-0.06				
60	0.60	0.04	-0.64				
61	0.13	0.12	-0.26				
62	-0.47	-0.23	0.70				
65	-0.18	-0.14	0.32	Average	-0.10	-0.04	0.15

Table B.5. Groundwater balance components as average values over the July-October 1996(monsoon) period.

Node number	Change in storage mm/day	Subsurface flow rate mm/day	Net recharge mm/day	Node number	Change in storage	Subsurface flow rate mm/day	Net recharge mm/day
3	-0.06	-0.69	0.75	66	-0.04	0.03	0.01
6	-0.27	-0.47	0.74	67	0.13	-0.04	-0.08
7	0.38	0.58	-0.96	68	0.47	0.10	-0.57
8	-0.13	-0.55	0.68	69	-0.72	0.11	0.61
11	0.13	-0.09	-0.04	70	-0.35	-0.46	0.80
12	-0.13	0.14	-0.01	73	-0.19	0.13	0.07
13	-0.14	-0.48	0.63	74	-0.15	-0.09	0.24
16	-0.17	-0.86	1.03	75	0.14	0.14	-0.29
17	-0.25	0.09	0.17	76	0.00	0.04	-0.04
18	-0.09	0.02	0.08	77	0.01	0.03	-0.03
19	-0.06	-0.39	0.45	80	0.22	0.04	-0.27
22	-0.19	-0.45	0.64	81	0.10	-0.01	-0.09
23	0.23	0.19	-0.42	82	0.38	0.02	-0.41
24	0.32	0.03	-0.36	83	0.06	-0.01	-0.05
25	-0.13	0.29	-0.16	84	-0.02	-0.09	0.11
26	-0.27	-0.69	0.96	87	0.33	-0.17	-0.16
29	-0.09	-0.16	0.25	88	0.24	-0.02	-0.22
30	-0.11	-0.20	0.31	89	0.36	-0.07	-0.29
31	-0.37	-0.12	0.48	90	0.30	-0.06	-0.24
32	0.07	-0.03	-0.04	91	0.29	-0.07	-0.22
33	-0.17	-0.32	0.49	94	0.05	0.05	-0.10
36	-0.62	-0.24	0.87	95	0.12	0.04	-0.16
37	-0.42	0.06	0.35	96	0.25	-0.08	-0.17
38	-0.10	0.12	-0.02	97	0.18	-0.01	-0.17
39	0.16	0.00	-0.15	100	0.22	-0.12	-0.10
40	-0.04	-0.06	0.11	101	0.20	0.28	-0.48
41	0.11	-0.53	0.41	102	-0.03	-0.03	0.06
44	-0.02	-0.57	0.58	103	0.02	0.02	-0.04
45	-0.16	0.32	-0.16	106	-0.05	0.01	0.04
46	-0.01	-0.04	0.05	107	0.04	0.04	-0.07
47	0.06	0.07	-0.13	108	0.16	-0.15	-0.01
48	-0.36	-0.08	0.44	112	0.12	0.05	-0.17
51	-0.21	-0.09	0.30	113	-0.03	0.01	0.02
52	-0.07	0.02	0.05	114	-0.02	0.10	-0.07
53	-0.13	0.03	0.09	117	-0.05	0.02	0.04

Node number	Change in storage mm/day	Subsurface flow rate mm/day	Net recharge mm/day	Node number	Change in storage	Subsurface flow rate mm/day	Net recharge mm/day
54	0.09	-0.01	-0.08	118	0.04	0.03	-0.07
55	-0.11	-0.39	0.50	119	-0.01	0.00	0.01
58	-0.36	-0.37	0.73				
59	-0.10	0.19	-0.09				
60	-0.38	0.01	0.36				
61	-0.02	0.12	-0.11				
62	-0.24	-0.26	0.50				
65	-0.33	-0.16	0.49	Average	-0.02	-0.05	0.06

Appendix B

Table B.6.1. Groundwater balance components as average values over the November-February 1996-97 (non-monsoon) period.

Node number	Change in storage mm/day	Subsurface flow rate mm/day	Net recharge mm/day	Node number	Change in storage	Subsurface flow rate mm/day	Net recharge mm/day
3	0.95	-0.57	-0.39	66	-0.14	0.02	0.11
6	0.29	-0.44	0.15	67	-0.15	-0.04	0.19
7	-0.33	0.45	-0.12	68	-0.32	0.06	0.26
8	0.48	-0.46	-0.02	69	0.35	0.17	-0.52
11	0.30	-0.09	-0.20	70	0.25	-0.43	0.18
12	-0.39	0.05	0.35	73	0.05	0.11	-0.16
13	0.30	-0.26	-0.04	74	0.13	-0.09	-0.04
16	0.30	-0.65	0.35	75	0.02	0.14	-0.16
17	-0.16	0.03	0.13	76	-0.16	0.04	0.12
18	0.02	0.02	-0.04	77	-0.19	0.01	0.18
19	0.50	-0.28	-0.22	80	-0.24	0.05	0.18
22	0.61	-0.28	-0.33	81	-0.23	0.00	0.23
23	-0.13	0.13	0.00	82	0.06	0.02	-0.08
24	-0.40	0.00	0.40	83	0.01	-0.03	0.02
25	0.14	0.18	-0.32	84	0.00	-0.09	0.09
26	0.25	-0.55	0.29	87	-0.17	-0.16	0.33
29	0.28	-0.04	-0.24	88	-0.05	-0.01	0.06
30	0.21	-0.24	0.03	89	0.10	-0.06	-0.03
31	0.41	0.01	-0.42	90	-0.29	-0.06	0.36
32	0.01	-0.04	0.03	91	-0.08	-0.06	0.14
33	0.51	-0.31	-0.20	94	-0.12	0.06	0.07
36	0.70	-0.16	-0.53	95	-0.03	0.05	-0.02
37	0.24	0.08	-0.32	96	-0.23	-0.09	0.33
38	-0.14	0.07	0.07	97	-0.18	-0.02	0.20
39	-0.44	-0.06	0.50	100	0.42	-0.05	-0.37
40	-0.10	-0.08	0.18	101	-0.21	0.28	-0.07
41	-0.02	-0.52	0.54	102	-0.08	-0.03	0.11
44	0.23	-0.48	0.25	103	-0.20	0.01	0.19
45	0.02	0.25	-0.27	106	-0.11	0.00	0.11
46	-0.27	-0.01	0.28	107	0.09	0.04	-0.13
47	-0.10	0.05	0.05	108	-0.02	-0.14	0.16
48	0.50	-0.05	-0.45	112	0.12	0.05	-0.17
51	0.39	-0.05	-0.33	113	-0.14	0.02	0.12
52	-0.06	0.00	0.06	114	-0.08	0.09	-0.02
53	-0.06	0.02	0.03	117	-0.04	0.02	0.03
54	-0.02	-0.01	0.03	118	-0.09	0.04	0.05

Node number	Change in storage mm/day	Subsurface flow rate mm/day	Net recharge mm/day	Node number	Change in storage	Subsurface flow rate mm/day	Net recharge mm/day
55	0.46	-0.35	-0.11	119	-0.06	-0.01	0.07
58	0.29	-0.35	0.05				
59	-0.06	0.18	-0.12				
60	0.04	0.03	-0.08				
61	-0.12	0.11	0.02				
62	0.27	-0.25	-0.02				
65	0.42	-0.13	-0.30	Average	0.02	-0.04	0.01

Appendix B

Table B.6.2. Groundwater balance components as average values over the March-June 1997 (non-monsoon) period.

Node number	Change in storage mm/day	Subsurface flow rate mm/day	Net recharge mm/day	Node number	Change in storage	Subsurface flow rate mm/day	Net recharge mm/day
3	-0.75	-0.64	1.40	66	-0.11	0.01	0.10
6	0.35	-0.52	0.18	67	-0.12	-0.05	0.17
7	0.02	0.49	-0.50	68	0.53	0.10	-0.63
8	-0.35	-0.53	0.89	69	-0.34	0.14	0.20
11	-0.10	-0.08	0.17	70	-0.02	-0.42	0.45
12	0.23	0.05	-0.28	73	-0.14	0.11	0.03
13	0.28	-0.38	0.10	74	-0.09	-0.08	0.18
16	-0.07	-0.83	0.90	75	0.00	0.15	-0.14
17	0.44	0.10	-0.53	76	-0.04	0.03	0.01
18	0.14	0.06	-0.21	77	0.14	0.00	-0.14
19	-0.38	-0.37	0.75	80	0.10	0.05	-0.15
22	-0.40	-0.38	0.78	81	0.26	0.02	-0.28
23	0.04	0.19	-0.23	82	0.03	0.02	-0.05
24	0.07	-0.04	-0.03	83	-0.02	-0.01	0.03
25	0.00	0.23	-0.24	84	-0.21	-0.09	0.30
26	0.47	-0.65	0.18	87	-0.15	-0.17	0.32
29	0.02	-0.22	0.20	88	-0.07	-0.01	0.08
30	0.01	-0.15	0.14	89	-0.06	-0.05	0.11
31	-0.12	-0.02	0.14	90	-0.12	-0.06	0.18
32	-0.04	-0.03	0.08	91	-0.57	-0.08	0.65
33	-0.45	-0.34	0.79	94	-0.17	0.04	0.13
36	-0.22	-0.22	0.44	95	-0.19	0.04	0.15
37	0.12	0.10	-0.22	96	-0.11	-0.09	0.21
38	0.15	0.09	-0.24	97	-0.39	-0.02	0.41
39	0.10	-0.08	-0.01	100	-0.73	-0.11	0.84
40	0.09	-0.04	-0.05	101	-0.36	0.27	0.09
41	0.17	-0.54	0.37	102	-0.14	-0.03	0.17
44	0.12	-0.46	0.35	103	-0.13	0.01	0.12
45	-0.12	0.29	-0.17	106	-0.08	0.00	0.08
46	0.04	-0.01	-0.03	107	-0.30	0.04	0.27
47	0.12	0.06	-0.18	108	-0.29	-0.13	0.43
48	-0.16	-0.05	0.21	112	-0.42	0.03	0.40
51	0.26	-0.04	-0.22	113	-0.01	0.01	-0.01
52	-0.40	-0.05	0.45	114	-0.04	0.10	-0.06
53	-0.06	0.02	0.04	117	-0.05	0.02	0.04
54	0.15	0.03	-0.19	118	-0.13	0.02	0.11
55	-0.63	-0.41	1.04	119	-0.07	0.00	0.07

Node number	Change in storage mm/day	Subsurface flow rate mm/day	Net recharge mm/day	Node number	Change in storage	Subsurface flow rate mm/day	Net recharge mm/day
58	-0.24	-0.34	0.58				
59	-0.11	0.18	-0.07				
60	-0.23	0.00	0.23				
61	0.26	0.13	-0.39				
62	0.43	-0.19	-0.24	Average	-0.06	-0.04	0.11

Appendix C

Table C.1 Rainfall data in mm for Jahanawala and Bahawalnager Weather station

Month			Jahanawala	Bahawalnager
Jul. 94			6	5.6
			40	65.1
			8	11.9
			15	11.4
			50	43.5
			18	17.5
			1	2.8
Aug.				
Sept.				0.3
			2	2.2
			3	2.1
Oct.				
Monsoon 94		Sum	143	162.4
		Avg.	35.75	40.6
Nov.				
Dec.				
Jan. 95			1.56	2.7
			10.92	
Feb.			0.2	2
			0.4	
			7.2	
Mar.			3.4	4.8
			0.4	
Apr.			3.8	3
			1.8	1
			8.9	
May.				5
				9
Jun.			24.96	20
			17.55	26
non-monsoon 94-95		Sum	81.09	73.5
		Avg.	10.13	9.18

Jul.			6.24	55
			20.28	6
			26.36	38
			8.53	13
			0.2	2.6
			11.31	11.5
Aug.			0.3	
			9.67	8
			0.86	2
			0.86	2
			0.62	23
			3.59	6
			1.72	
Sept.				0.7
Oct.			13.26	16
Monsoon 95		Sum	103.8	183.8
		Avg.	25.95	45.95
Nov.				
Dec.			1	
Jan . 96			11	13
Feb.			4.9	7
			3.4	
Mar.			28	6
			2.8	23
				5
Apr.			1.4	5
			3.1	8
				17
May.			16.7	15
			20	
Jun.			12.8	23
			39.9	23
			3.8	50
			11.3	70
			11.2	
			2.4	
			32.4	
Non-monsoon 95-96		Sum	206.1	265
		Avg.	25.76	33.12

Jul.			1	
			1.7	
Aug.			5.2	23
			34.6	23
			64	50
			3.5	
Sept.				1
Oct.			8.5	12
			1.5	1
Monsoon 96		Sum	120	110
		Avg.	30	27.5
Nov.				
Dec.				
Jan. 97			4.2	7
			1.1	
Feb.			1	
Mar.			6.1	0.5
			1.4	0.3
			0.8	1.5
Apr.			2.4	3.7
			6.7	5.7
			7.8	4.9
			2.4	
May.			2	
			6	
			9.3	
			11	
Jun.				
Non-monsoon 96-97		Sum	62.2	23.6
		Avg	7.77	2.95

Appendix D

Table D.1. Nodes having watertable depth less than 0.5 m and 1.5 m

	OCT. 94	JUN. 95	JUN. 96	JUN. 97	JUN. 2002	JUN. 2007
< 0.5 m Node no.	26	3	3	3	3	3
	36	6	6	6	6	6
		8	8	7	7	7
		11	11	8	8	8
		13	13	11	11	11
		19	19	13	13	13
		22	22	19	16	16
		26	26	22	19	19
			48	26	22	22
				48	23	23
				58	26	26
				70	33	32
					41	33
					44	41
					48	44
					51	48
					55	51
					58	55
					62	58
					65	61
					68	62
					70	65
					75	68
					80	70
					81	75
					82	76
					83	80

	OCT. 94	JUN. 95	JUN. 96	JUN. 97	JUN. 2002	JUN. 2007
					84	81
					87	82
					88	83
					89	84
					96	87
					97	88
					101	89
						90
						95
						96
						97
						100
						101
						102
						108
Total area (km^2)	11.75	23.00	43.75	174.75	459.25	791.25

	OCT. 94	JUN. 95	JUN. 96	JUN. 97	JUN. 2002	JUN. 2007
< 1.5 m Node no.	3	3	3	3	3	3
	6	6	6	6	6	6
	7	7	7	7	7	7
	8	8	8	8	8	8
	11	11	11	11	11	11
	12	12	12	12	12	12
	13	13	13	13	13	13
	16	16	16	16	16	16
	17	17	17	17	17	17
	18	18	18	18	18	18
	19	19	19	19	19	19
	22	22	22	22	22	22
	23	23	23	23	23	23
	24	24	24	24	24	24
	25	25	25	25	25	25
	26	26	26	26	26	26
	30	29	29	29	29	29
	33	30	30	30	30	30
	36	31	31	31	31	31
	37	32	32	32	32	32
	38	33	33	33	33	33
	39	36	36	36	36	36
	40	37	37	37	37	37
	41	38	38	38	38	38
	45	39	39	39	39	39
	46	40	40	40	40	40
	47	41	41	41	41	41
	48	44	44	44	44	44
	53	45	45	45	45	45
	54	46	46	46	46	46

	OCT. 94	JUN. 95	JUN. 96	JUN. 97	JUN. 2002	JUN. 2007
	58	47	47	47	47	47
	60	48	48	48	48	48
	61	51	51	51	51	51
	62	52	52	52	52	52
	65	54	53	53	53	53
	68	55	54	54	54	54
	69	58	55	55	55	55
	70	60	58	58	58	58
	73	61	60	60	59	59
	74	62	61	61	60	60
	75	65	62	62	61	61
	82	68	65	65	62	62
	83	69	66	66	65	65
	84	70	67	67	66	66
		73	68	68	67	67
		74	69	69	68	68
		75	70	70	69	69
		81	73	73	70	70
		82	75	74	73	73
		83	76	75	74	74
		84	81	76	75	75
		88	82	77	76	76
		89	83	80	77	77
			84	81	80	80
			87	82	81	81
			88	83	82	82
			89	84	83	83
				87	84	84
				88	87	87
Total area (km^2)	646.25	872.50	1212.75	1522.75	1830.00	1944.00

Appendix E

Table E.1. Standard deviation of net recharge values for internal nodes (12 month time-step)

Nodal no.	Nodal area (m^2)	Standard deviation			Nodal no.	Nodal area (m^2)	Standard deviation		
		1994-95	1995-96	1996-97			1994-95	1995-96	1996-97
3	14.46	0.73	0.43	1.17	61	34.34	0.72	0.66	0.52
6	11.54	0.87	0.85	0.87	62	24.60	0.78	1.14	0.79
7	13.70	1.01	1.38	1.02	65	22.79	0.70	0.80	1.04
8	12.73	0.84	1.13	0.87	66	30.03	0.28	0.57	0.57
11	15.52	0.68	0.86	0.68	67	32.67	0.88	0.77	0.54
12	18.61	0.84	0.92	1.02	68	30.92	0.61	0.95	1.00
13	12.47	1.42	1.21	1.09	69	27.15	0.65	1.12	1.02
16	12.23	0.80	0.80	0.82	70	21.12	0.50	0.53	0.66
17	19.87	0.73	0.88	0.78	73	21.45	0.56	0.48	0.78
18	20.75	0.53	0.64	0.56	74	27.30	0.49	0.70	0.53
19	14.02	0.94	0.88	0.89	75	30.78	0.82	0.73	0.70
22	12.17	0.49	0.68	0.86	76	30.11	0.70	0.71	0.58
23	17.26	0.50	0.53	0.57	77	25.54	0.84	1.17	1.34
24	22.67	0.70	0.65	0.63	80	23.49	0.49	0.94	0.70
25	20.16	0.54	1.07	0.72	81	25.99	0.91	0.60	0.90
26	11.61	1.17	1.01	1.30	82	31.68	0.59	0.89	0.64
29	10.63	0.39	0.92	0.90	83	28.12	0.54	1.04	0.67
30	17.39	0.84	0.99	0.58	84	23.92	1.05	0.78	0.59
31	26.67	0.85	0.79	0.76	87	25.37	0.35	0.77	1.08
32	23.89	0.62	0.94	0.80	88	27.43	0.52	0.79	0.41
33	19.42	0.71	0.98	0.69	89	29.53	0.44	0.79	0.74

36	17.60	0.90	0.98	1.12	90	26.01	0.40	0.72	0.63
37	25.68	0.64	0.62	0.85	91	20.51	0.42	0.59	0.60
38	29.33	0.59	0.84	1.05	94	22.44	0.20	0.21	0.20
39	24.43	0.64	0.70	0.82	95	27.77	0.40	0.58	0.37
40	15.29	0.38	0.70	0.68	96	27.23	0.39	0.80	0.51
41	10.59	0.94	0.91	0.81	97	22.45	0.46	0.61	0.72
44	14.93	0.68	1.12	1.42	100	17.17	0.75	0.74	1.12
45	21.11	0.67	1.07	0.76	101	22.56	0.43	0.89	0.71
46	33.56	0.67	0.72	0.93	102	25.84	0.21	0.21	0.20
47	32.07	0.73	1.00	0.50	103	23.78	0.23	0.25	0.31
48	24.76	0.76	0.95	0.82	106	20.06	0.11	0.64	0.14
51	20.77	0.45	0.99	0.86	107	22.59	0.10	0.18	0.37
52	31.41	0.86	0.86	0.93	108	24.35	0.22	0.57	0.38
53	34.65	0.43	0.39	0.46	112	22.43	0.34	0.73	0.54
54	33.06	0.65	0.93	0.54	113	20.23	0.10	0.08	0.28
55	27.53	0.29	1.01	0.81	114	21.40	0.13	0.16	0.10
58	31.46	0.74	0.62	0.40	117	24.29	0.15	0.15	0.05
59	32.63	0.41	0.44	0.43	118	20.48	0.53	0.78	0.39
60	33.73	1.22	1.36	0.59	119	21.10	0.31	0.21	0.19