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# Develop a useful management tool for water resources allocation in the Saq aquifer in Al-Qassim Region, Saudi Arabia

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# Develop a useful management tool for water resources allocation in the Saq aquifer in Al-Qassim Region, Saudi Arabia

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## ABSTRACT

The main aquifer, which supplies most wells in the Al-Qassim region of Saudi Arabia, is the Saq aquifer. Due to the high quality and the abundant quantity of water that comes from the Saq aquifer, various hydrogeologic studies, including numerical groundwater flow modeling, have been conducted to understand and to manage the resource properly. The objectives of current study were: 1) to develop hydraulic properties of Saq aquifer by analyzing pumping test data, 2) to evaluate the impact of groundwater withdrawals from wells on future groundwater levels of Saq aquifer under different groundwater pumping scenarios using numerical techniques (MODFLOW), and 3) to evaluate the appropriate groundwater pumping scenario that can be adapted.

A quasi-three-dimensional simulation model was developed using the groundwater flow model MODFLOW (McDonald and Harbaugh, 1988). Four management plans were considered using different discharge rates for a planning period of 51 years (1999-2050) through the existing wells. The first management plan assumes that the present trend of increase in the water extraction rates continue until the end of year 2050. The second management plan was based on the assumption that the rate of increase in water extraction will be reduced by 50% of the first management plan. The third management plan allows that the rate of increase in water extraction will be increased by 50% of the first management plan. The fourth management plan is the combination of the second and third management plans.

The results of implementing the four different management plans show that the water level in the central area where the observation well # 10 is located, during the period of 1999 is 515 m, which will be reduced to 435 m at the end of the year of 2050 by implementing the

first management plan. The net drawdown during the planning period (1999-2050) will be 80 m. The water level conditions at the end of the year of 2050 will be improved by adapting the second management plan. The water level at the observation well in 2050 will be 475 m and the net drawdown will be reduced to 40 m by implementing the second management plan. On the other hand, by implementing the third management plan, the water level of the observation well # 10 will be reduced from 515 m in 1999 to as low as 395 m in 2050, which means that, the net drawdown during the planning period (1999-2050) will be increased to 120 m. However, by implementing the fourth management plan, which is the combination of the second and third management plans, the water level of the observation well will be improved at the end of the 2050. The water level will be 463 m at the end of 2050 and the resulting change in the hydraulic head (drawdown) will be 52 m.

From the above it seems that it is very important to implement the fourth management plan for the Al-Qassim area. Groundwater withdrawal from existing wells in future should be maintained at the present level, if not reduced. This can be achieved by implementation of different effective conservation plans to reduce the present and future water demands whether that demands from domestic or agricultural consumption. Serious efforts are needed by responsible government agencies, as well as private agencies associated with the distribution, treatment, and use of water, to adopt effective conservation programs.

# CHAPTER 1. INTRODUCTION

Dependable sources of water in Saudi Arabia come mainly from groundwater in the shallow alluvial and deep aquifers and from desalination. Agriculture, industry, and domestic requirements are supported by these three sources. Most of Saudi Arabia is located in an extremely arid zone where the average annual rainfall ranges from 25 to 150 mm in about 80% of the country (Abderrahman and Rasheeduddin, 1994).

Large volumes of groundwater are stored in the sedimentary basins that cover two thirds of the country. These groundwater resources, however, are being heavily utilized for agricultural activities. Recently estimates indicate 78% of the total water demand is used for agriculture. Correspondingly, excessive groundwater withdrawals have lead to large drops in the groundwater levels in many parts of the country. Moreover, at the present rate of withdrawal, some of the aquifers may be exhausted in only a few decades (MP, 1985). In Saudi Arabia, there are seven major deep aquifers, covering hundreds of square kilometers and extending from the Jordanian boundary in the north to the southern and eastern boundaries of Saudi Arabia. The thickness of the aquifers may reach 1000 m, and the total dissolved solids (TDS), an indicator of the water quality, is in range of 500 to more than 6000 ppm.

Due to the increase in the municipal demand, the kingdom of Saudi Arabia has constructed many desalination plants in the coastal areas within the last decade. As reported by (MP, 1985), there were 15 desalination plants located on the West Coast, and five on the East Coast. Desalinated water accounted for about 76% of the total domestic water use in Saudi Arabia. Most of the major cities currently depend on desalinated water. However, in the Al-Qassim area, which is located in the central part of Saudi Arabia, water supply is from groundwater only. In 1980, the amount of desalinated water needed to meet water demand was 63 MCM, and it increased to 605 MCM by 1985. In the year of 2000, the amount of desalinated water is expected to increase to 1200 MCM (MP, 1985). Because of the expense of desalination technology, as well as the long distance transport, desalinated water does not represent a future resource for central Saudi Arabia.

In arid and semiarid regions, and particularly in the Al-Qassim region in Saudi Arabia, where the rainfall is minimal and there are no available fresh water bodies other than groundwater, it must be kept in mind that there will always be a natural deficiency of water. Increased demand, whether domestic, agricultural, or industrial, is leading toward the depletion of the existing water resources. The main aquifer, which supplies most wells in the Al-Qassim region of Saudi Arabia, is the Saq aquifer. Due to the high quality and the abundant quantity of water that comes from the Saq aquifer, various hydrogeologic studies, including numerical groundwater flow modeling, have been conducted currently to understand and to manage the resource properly.

Due to the importance of the Saq aquifer in the Al-Qassim region of Saudi Arabia, for water supply for domestic, industrial and agricultural purposes, many investigators have studied its water quality of as a function of time (Faruq et al., 1996 and Abdel-Aal et al., 1997). All of these studies showed that the electrical conductivity (EC) as well as the Total Dissolved Solids (TDS) have increased with time due to an extensive water extraction of the groundwater in the Al-Qassim area.

Norconsult (1984) studied the quantity of the formations that are located above the Saq sandstone and their effects on the Saq aquifer. He showed that the water level in the Saq aquifer was higher than the water levels in Tabuk and the other formations during his study, so the groundwater in Saq aquifer would leak into Tabuk aquifer. On the other hand, he showed that when the water level in the Saq aquifer drops, as a result of increasing pumping, groundwater will leak from the other formations that have worse water quality into Saq aquifer, so the quality of groundwater in the Saq aquifer will be degraded.

The pumping of groundwater and the number of drilled wells in the Saq aquifer have increased over recent years. The number of wells in Al-Qassim area was 4500 wells in 1981 and has increased to 11441 wells in 1990 (MAW, 1994). The excessive groundwater withdrawal from a large number of wells has resulted in significant lowering of groundwater levels as well as on change in water quality of the Saq aquifer. Management alternatives, to include direction for future water development activities should be developed.

## Objectives

The objectives of this research were:

1) To develop hydraulic properties of Saq aquifer by conducting and analyzing pumping test data,

2) To evaluate the impact of groundwater withdrawals from wells on future groundwater levels of Saq aquifer under different groundwater pumping scenarios using a numerical model (MODFLOW), and

3) To evaluate the appropriate groundwater pumping scenario that can be adapted.

# CHAPTER 2. GENERAL DESCRIPTION OF THE AL-QASSIM REGION

## Geographic Setting

The study area is located in the Al-Qassim area of Saudi Arabia, which is the most important agricultural region of the nation due to its availability of groundwater for irrigation. The main crops in the Al-Qassim area are wheat and barley and these two crops are grown during the winter season. These two crops are irrigated by sprinkler irrigation method. The Al-Qassim region is located between latitudes (25° 00′ and 27° 00′ N.) and longitudes (42° 30′ and 45° 00′ E.) as shown in Figure 2.1. The Al-Qassim area is a rectangular shaped area on Figure 2.1 having a north/south of about 400 km and on east to west distance of about 200 km. This gives an estimated area of 80,000 $km^2$. The altitude of Al-Qassim area ranges between 600 – 850 m above sea level.

The weather in Al-Qassim region is generally dry. The air temperature is very hot during the summer season, ranging from 43 to 48 °C during the daytime and 32-36 °C during the nighttime. Air temperatures during the winter may fall below freezing.

The population of the Al-Qassim region, as surveyed in 1993, is 751,642 persons. About 33% of the Al-Qassim's population live in Buraydah city (latitude 26° 19′ 19″ N., longitude 43° 58′ 28″ E.), which is the biggest city in the region as well as the capital of the region, and 12% of the population live in Unayazh city (latitude 26° 05′ 40″ N. and longitude 43° 59′ 35″ E), which is the second most important city in the region. In 1974, the population of Buraydah city was estimated as 69,924 persons, while in 1993, the population was counted to be 248,636 persons. Correspondingly, the population in Unayzah city was about 26,990 persons in 1974, while in 1993, the population was determined to be 91,106

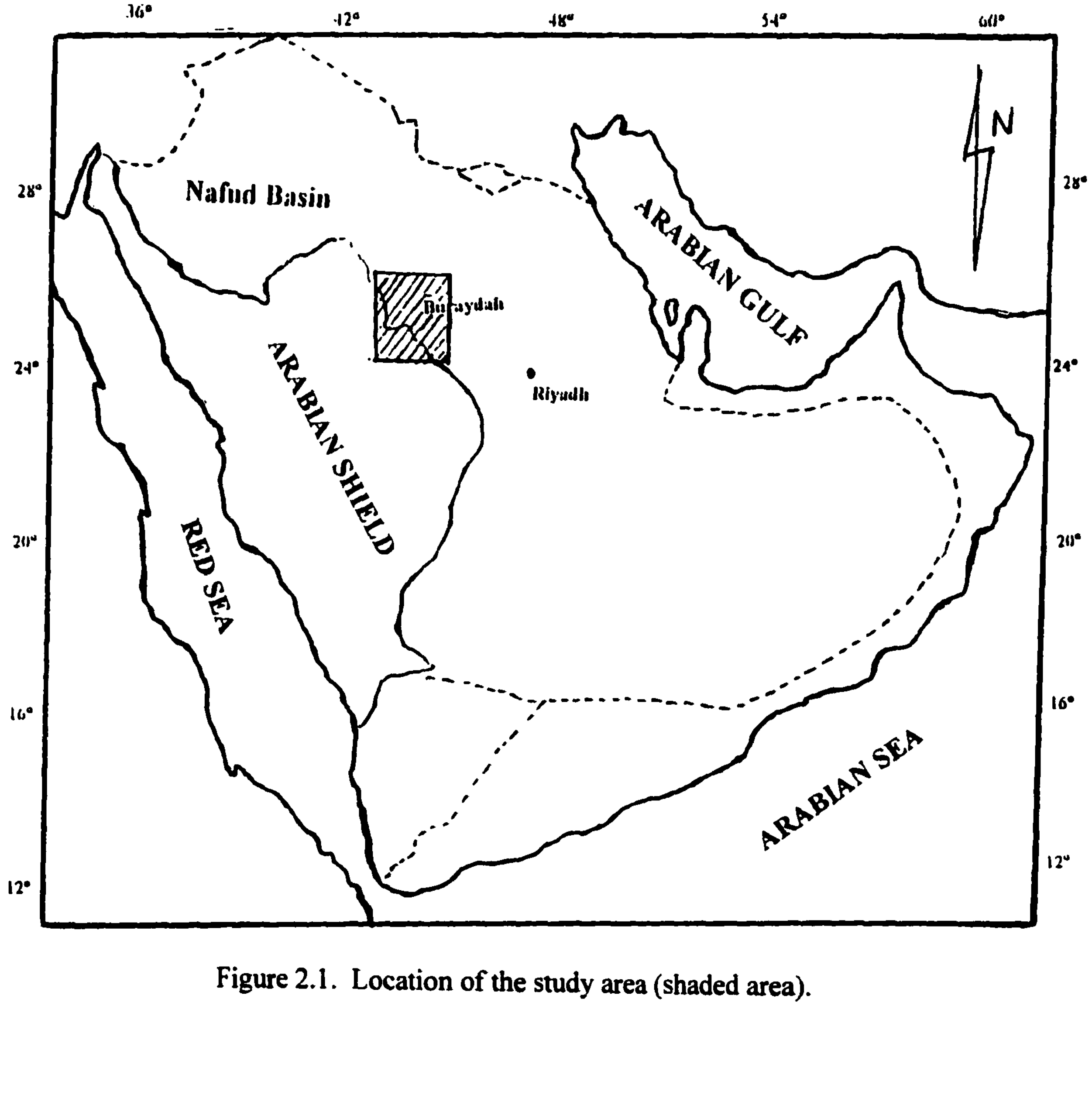


Figure 2.1. Location of the study area (shaded area).

persons (Al- Qhidan, 1998). If the present rates of increases in the population rates continues, then the population of Buraydah city is expected to be 784,800 persons (Figure 2.2) and the population of Unayzah city is expected to be 283,500 persons at the end of 2050 (Figure 2.3).

## Hydrogeological Setting

The results of hydrogeological studies by Powers et al. (1966) and MAW (1979) have indicated the existence of a multi-aquifer system in Al-Qassim region. The system consists of five main aquifers separated by semi-confining beds (Table 2.1). In descending order, they are:

Minjur Sandstone,

Jilh Formation,

Khuff Formation,

Tabuk Formation, and

Saq Sandstone.

The main productive aquifer in Al-Qassim area is the Saq aquifer, because of the poor water quality in the Khuff and Jilh formation, and the Minjur Sandstone. Moreover, the Tabuk formation has a good quality but water quantity is limited. Therefore, this study of the impact of water extraction on groundwater will be limited to only the Saq aquifer.

### *Saq Aquifer*

The Saq Formation is a medium to coarse sandstone, with local areas of fine sandstone. The rock type is poorly to well sorted quartz sandstone. The common color is buff to gray and white (Powers et al., 1966). The Saq aquifer is estimated to extend some 1200 km in a north/south direction starting just south of the Jordanian border in the north and

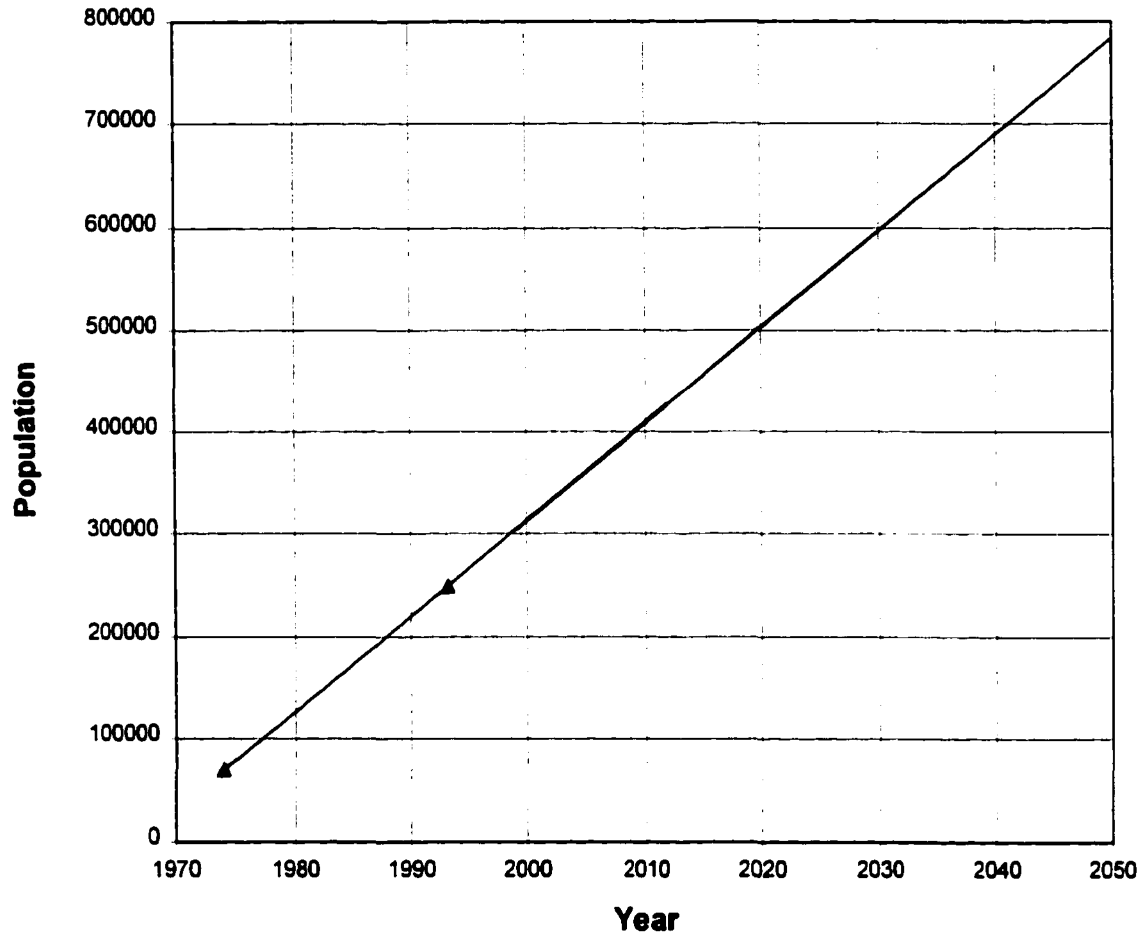


Figure 2.2. Population of Buraydah City as measured in 1974 and in 1993, and the predicted population of Buraydah City up to the year of 2050.

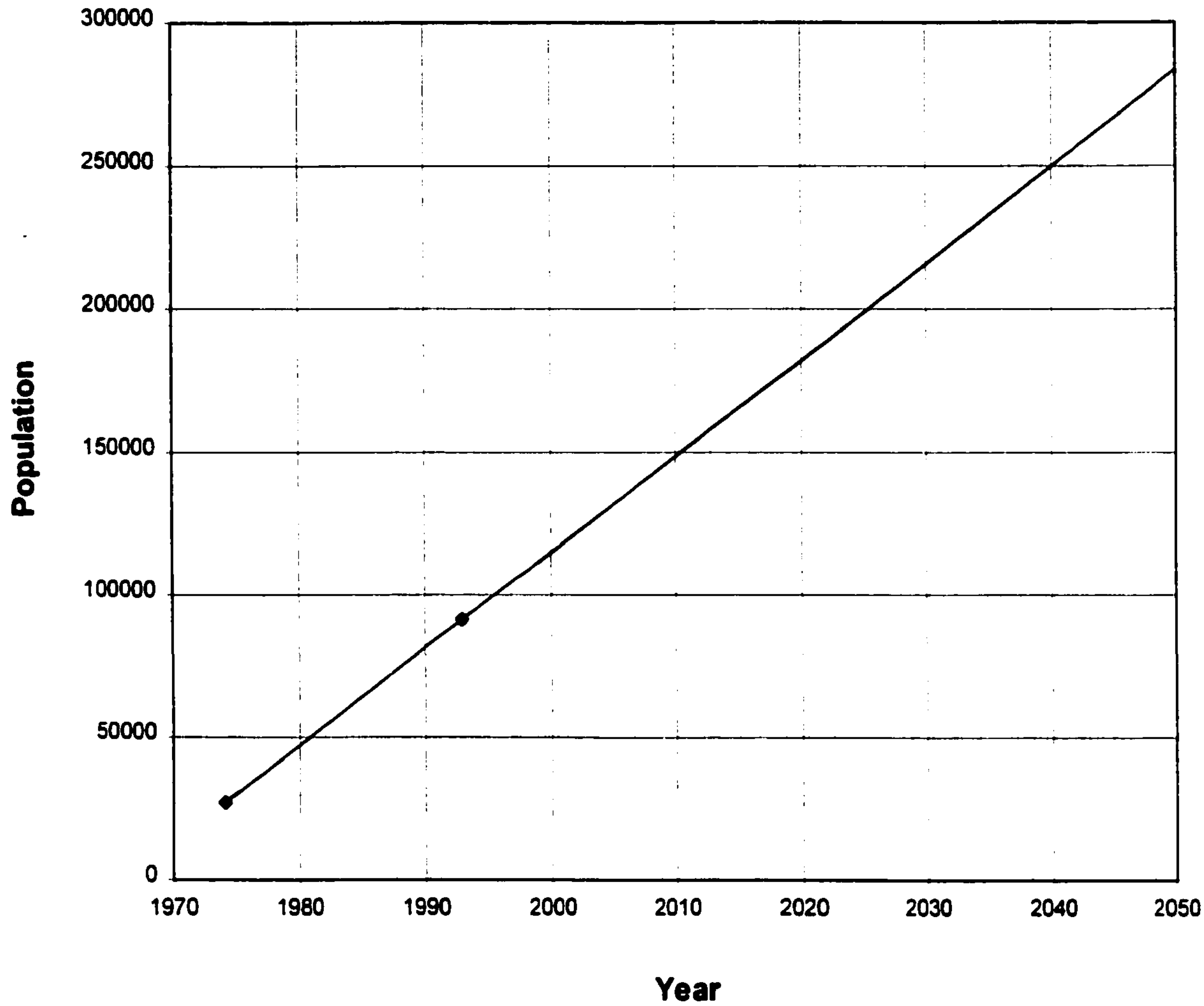


Figure 2.3. Population of Unayzah City as measured in 1974 and in 1993, and the predicted population of Unayzah City up to the year of 2050.

Table 2.1. Lithological Succession of the Al-Qassim Region (Norconsult, 1984).

| AGE | FORMATION | LITHOLOGICAL DESCRIPTION |
|---|---|---|
| Ouatrenary | Surficial dep. | Silt, Sand and Gravel |
| Cretaceous | Wasia | Sandstone, some shale and limestone |
| Jurassic | Tuwaiq | Limestone, subordinate shale |
| | Dhruma | Shale, horizons of limestone and sandstone |
| | Marrat | Limestone and silty sandstone |
| Triassic | Minjur | Massive sandstone, shale horizons |
| | Jilh | Silty sandstone, shale, limestone and dolomite, evaporites |
| | Sudair | Gypsiferous shale, sandstone, dolomite |
| Permian | Khuff | Dolomite, limestone and shale interbedded evaporite horizons |
| Devonian<br>Silurian<br>Ordovician | Tabuk | Medium and fine grained sandstone, partly cross-bedded, three beds of silty shale |
| Cambrian | Saq | Coarse and medium grained partly cross-bedded sandstone with thin shale horizons |
| Precambrian | Basement | Gneissic granites and metasediments intersected by intrusions and dykes of different age and composition |

extending to the central part of Saudi Arabia (Figure 2.4). The Saq aquifer outcrops only the southwestern border of the formation. The outcrop area is about 65,000 square kilometers. While the subsurface area is about 160,000 square kilometers. The thickness of the Saq aquifer ranges from 400 meters in the south to about 700 meters in the north (MAW, 1979).

The hydraulic properties of the Saq aquifer are not constant. In the Al-Qassim area, the transmissivity values have been reported as ranging from 0.024 to 1.62 $m^2$/min and the storage coefficient values have been reported as ranging from $2.5 \times 10^{-3}$ to $6.3 \times 10^{-5}$. The pumping rates of the wells in the Al-Qassim area ranged from 10 to 100 liters per second. The transmissivity values in the Tabuk area (north-east of the Al-Qassim region) are in the range of 0.54 to 2.28 $m^2$/min (MAW, 1979).

The total recharge to the Saq aquifer is considered to be very small considering the huge area that is covered by the Saq aquifer. The amount of recharge from rainfall in the Al-Qassim outcrop area east of the Arabian Shield was estimated to be 80 million cubic meters per year. While the amount of recharge in Tabuk area was estimated to be 150 million cubic meters per year. The amount of recharge from runoff was considered to be insignificant; an estimated 20 million cubic meters per year in an area east of hail, which is north of the Al-Qassim area (Parsons and Basil, 1968).

Due to intensive pumping, the cone of depression in the Buraydah area has expanded significantly since the mid-1960's. From 1966 to 1976, water levels dropped by 15 meters east of Buraydah in the confined area and 5 meters in the outcrop area. From 1980 to 1982, water levels dropped 5 meters near the center of the Buraydah city (MAW, 1979). It is expected that as aquifer withdrawals grow in this area, the rate of decline in the water levels will increase.

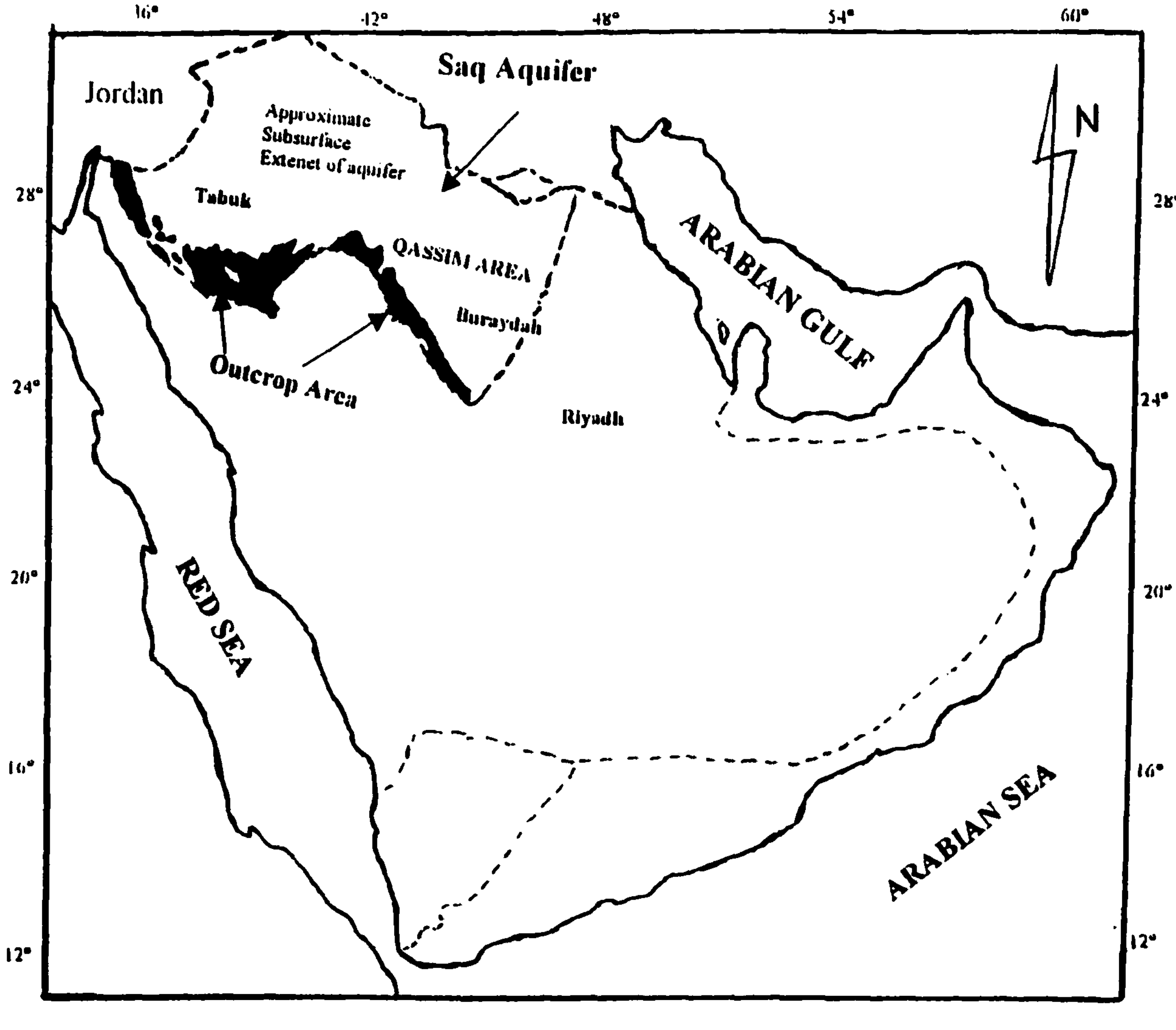


Figure 2.4. Location of the Saq Sandstone (MAW, 1984).

Water quality of the Saq aquifer was investigated by many studies. Faruq et al. (1996) studied the quality of groundwater in Al-Qassim region during the period of 1978 throughout 1987. Their study covered 35 locations in Al-Qassim area. They found that the concentrations of some chemical species of the groundwater increased during that period (1978 – 1987). They showed that the electrical conductivity (EC) increased from 1.93 dS/m in 1983 to 2.76 dS/m in 1987. They also showed that the Total Dissolved Solids (TDS) increased from 1395 mg/L in 1983 to 1992 mg/L in 1987. Abdel-Aal et al. (1997) evaluated the quality of groundwater in Al-Qassim area during the period of 1986 throughout 1993. They found that the salinity of groundwater in Al-Qassim area was in the range of 210 to 8200 ppm with an average of 2375 ppm. They showed that the salinity of groundwater increased from the period of 1986 to the period of 1993. They concluded that groundwater quality has deteriorated in that area due to extensive water extraction of the groundwater in the Al-Qassim area. In general, water from the Saq Aquifer was reasonably mineralized. The total dissolved solid (TDS) concentrations ranged between 300 – 1000 milligrams per liter (Sharaf and Hussein, 1996). In Al-Qassim area, the common ion concentrations are sodium and chloride. In the Tabuk area, the TDS concentrations are less than 600 milligrams per liter and the water quality was typically of a calcium sodium chloride type (Parsons and Basil, 1968).

***Tabuk Aquifer***

Tabuk aquifer is the second most important aquifer in Al-Qassim area. The Tabuk formation consists of sandstone, shale, and complicated interfered sandstone and shale. The color of the rocks varies from off-white to light purple, buff, brown, and brick red. There are three sandstone sections present in the formation. The three sections are the Upper Tabuk, Middle Tabuk, and Lower Tabuk. The shale members, named the Qusaiba, Raan, and Hanadir in sequence from top to bottom, separate each of the sandstone section from the other. The upper sandstone exists only to the north portion of the Al-Qassim area, but the middle and lower sandstones are existing throughout the Al-Qassim area, becoming truncated in the south (Powers et al., 1966).

The Tabuk Formation lengthens south and east from the Jordanian boundary to south of the Wadi Rimah (latitude 26° 38′ N., longitude 44° 18′ E.), where it is truncated under the Great Nafud Desert at Buraydah (latitude 26° 19′ 19″ N., longitude 43° 58′ 28″ E.). The formation most likely underlies the entire Nafud Basin. The Great Nafud Desert separates the four outcrop areas, which cover about 100,000 square kilometers. The Tabuk Formation is exposed at Tabuk, Tawil, and Jauf areas west of the Great Nafud Desert, and from southeast of the Great Nafud Desert, all of the four outcrop areas extend southeastward to Buraydah in the Qassim area (MAW, 1984).

The thickness of the Tabuk aquifer in the Tabuk area is 1,070 m where the thickness of the middle sandstone is about 40 m, which is located under the Qusaiba Shale. The lower sandstone is 130 meters thick starting at a depth of 130 meters below the land surface. The thickness of the middle and lower sandstones at the south of Al-Qassim area are 150 and 200 m, respectively (Parsons and Basil, 1968). In Al-Qassim area, the lower sandstone is the most extensively developed of the Tabuk sandstone units, and the pumping rates of the wells range from 5.6 to 10.5 liters per second. The average pumping rate from wells in Tabuk area is about 15 liters per second and it decreases to about 7 liters per second as you move eastward (MAW, 1979).

Most of the wells in Tabuk area are drilled in the Tabuk aquifer. However, the aquifer is amenable to overwithdrawal in the Tabuk area due to its limited quantity. A cone of depression had grown in this area in which the flow moved from the east and northeast. Furthermore, it was expected that dropping of the water levels would increase where withdrawals are to be increased (Parsons and Basil, 1968).

Various studies have been conducted to investigate the water quality of Tabuk aquifer. The TDS concentration in the Tabuk area was less than 1000 milligrams per liter. The water type from the Middle and Lower Tabuk sandstone units in the western area was a calcium sodium chloride type. Water with low mineral concentration exists northward and eastward of the Tabuk area but it is altered in the direction of the south where the TDS concentrations ranged from 2,500 to 4,000 milligrams per liter. East of the Tabuk area, the quality of the water was changeable with TDS concentration ranging from 600 to 3,500 milligrams per liter. In general, the Middle Tabuk sandstone unit had better quality water than the lower sandstone (MAW, 1979).

***Khuff Aquifer***

The Khuff aquifer has been estimated to extended some 1200 km from Bani Khatmah (latitude 18° 00′ N.) to the Great Nafud Desert (latitude 28° 10′ N.). The thickness of the Khuff aquifer in its central and northern extent is in the range of 235 to 300 meters, while the thickness in the southern area ranges from 195 to 250 meters. The Khuff aquifer overlies the Tabuk and Saq aquifers in the northern part of Saudi Arabia. The Khuff formation is generally impervious in Al-Qassim and much of the northern area. The TDS concentrations in the northern area were between 3000 to 4000 milligrams per liter, and the TDS concentrations in the central area were between 2000 to 6000 milligrams per liter. The lowest TDS concentrations were found to be in the southern area where the TDS concentrations were between 850 to 1900 milligrams per liter (Italconsult, 1969 and Sogreah, 1968).

***Jilh Aquifer***

The Jilh aquifer has been estimated to extend some 770 km from Haddar (latitude 22° 00′ N.) to Shamat Akbad from the north (latitude 28° 10′ N.). The thickness of the Jilh aquifer varies from 240 meters and to around 326 meters thick southward. The Jilh formation overlies the Khuff, Tabuk, and Saq aquifers, respectively. (Powers et al., 1966). Because of the low permeability, the Jilh aquifer is not an important aquifer in the Al-Qassim area. The water quality in Jilh aquifer is in generally poor. The TDS concentration in water from the Jilh aquifer in the Al-Qassim area exceeds 6000 milligrams per liter. The water quality is typically of a calcium sulfate type (MAW, 1979).

***Minjur Aquifer***

The rock type of the Minjur Sandstone is coarse to very coarse quartz sandstone with thin layers of limestone, shale, aggregate, and gypsum. A zone of shale and mudstones separate the formation into an upper and lower sandstone horizon. At the outcrop near to the Al-Qassim area, the sand is white or light gray to dark and red, or yellow, because of oxidized iron.

The Minjur Sandstone has been estimated to extended some 820 km from Haddar (latitude 21° 30′ N.) north to latitude 28° 07′ N. The sandstone units of the formation stretch out toward the south up to the Rub al-Khali and toward the east until the Arabian Gulf. The thickness of the Minjur outcrop is 315 meters at the Khashm al Khalta at latitude 23° 31′ N., longitude 46° 07′ 15″ E. in central Saudi Arabia, while the thickness of the Minjur sandstone is 400 meters at Riyadh, the capital of Saudi Arabia. The depth of the Minjur sandstone is in the range of 1200 to 1500 m from the land surface near Riyadh city, which indicates the aquifer is confined. The Minjur Sandstone overlies the Jilh, Khuff, Tabuk, and Saq aquifers, respectively. (Powers et al., 1966)

The TDS concentrations of the Minjur aquifer were in the range of 1,200 to 1,500 milligrams per liter near Riyadh, and the type of water is calcium, sodium, sulfate-chloride, or chloride-sulfate types. The TDS concentrations in the Al-Qassim area where unconfined conditions existed ranged from 1,000 to 5,800 milligrams per liter which indicates a poor water quality (Italconsult, 1969).

## History of Water Extraction

The pumping of groundwater, as well as the number of drilled wells in the Al-Qassim area, has increased in response to increasing water demands. The excessive groundwater withdrawal from the large number of wells in the region has already resulted in negative impacts on the groundwater levels. The available data and information from Othman (1983) show that the annual groundwater extraction rate from Saq aquifer increased from 36 to 90 Million Cubic Meters per year (MCM/yr) between 1957 and 1967, respectively, and to 232 MCM/yr in 1980 (Figure 2.5). If the present trend of increase in the water extraction rates from the Saq aquifer continues, then it is expected to reach about 454, 535, 616, 697, and 777 MCM/yr in years 2010, 2020, 2030, 2040, and 2050, respectively (Figure 2.6).

A major increase in water extraction started after 1975, due to major social, agricultural, and constructional developments. The Kingdom of Saudi Arabia began new development of the Al-Qassim region in 1975. Loans were more available to the people without interest rates for use in building houses and to support expansion of irrigation. The Saudi Arabia government helps farmers by providing price supports for agricultural crops.

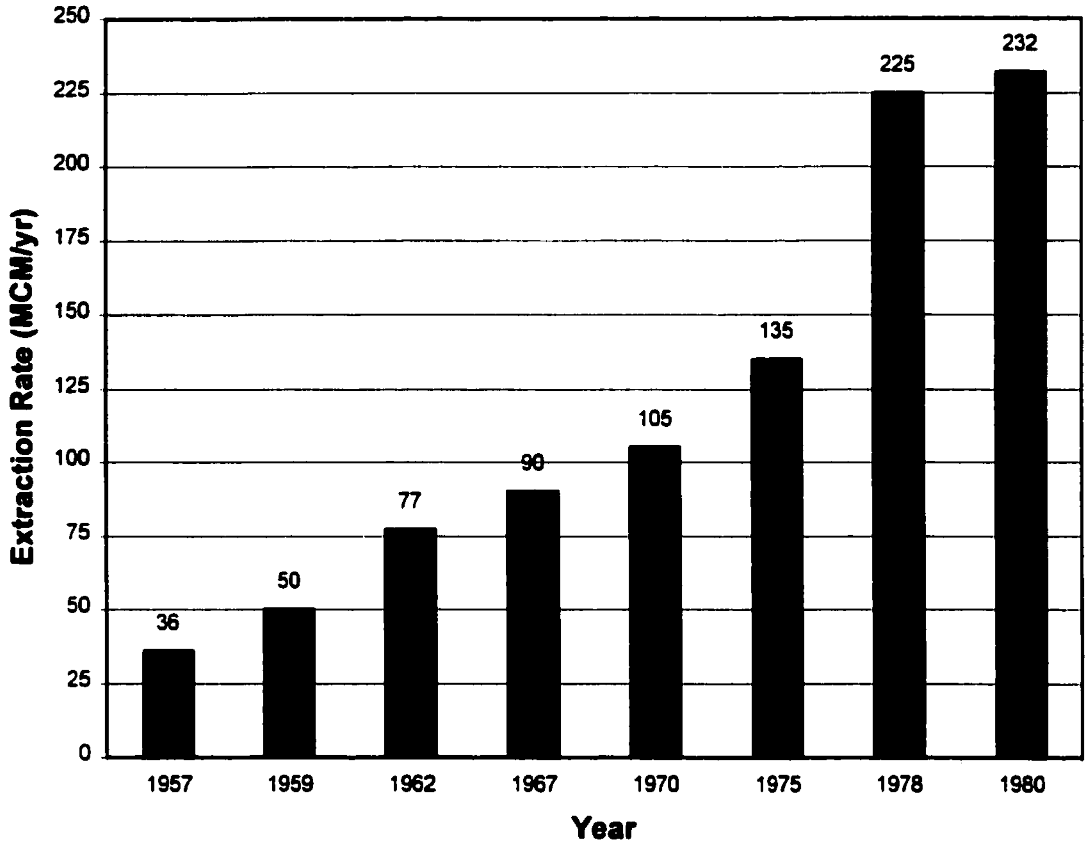


Figure 2.5. Extraction rates in Al-Qassim area from Saq aquifer.
Source: Othman (1983)

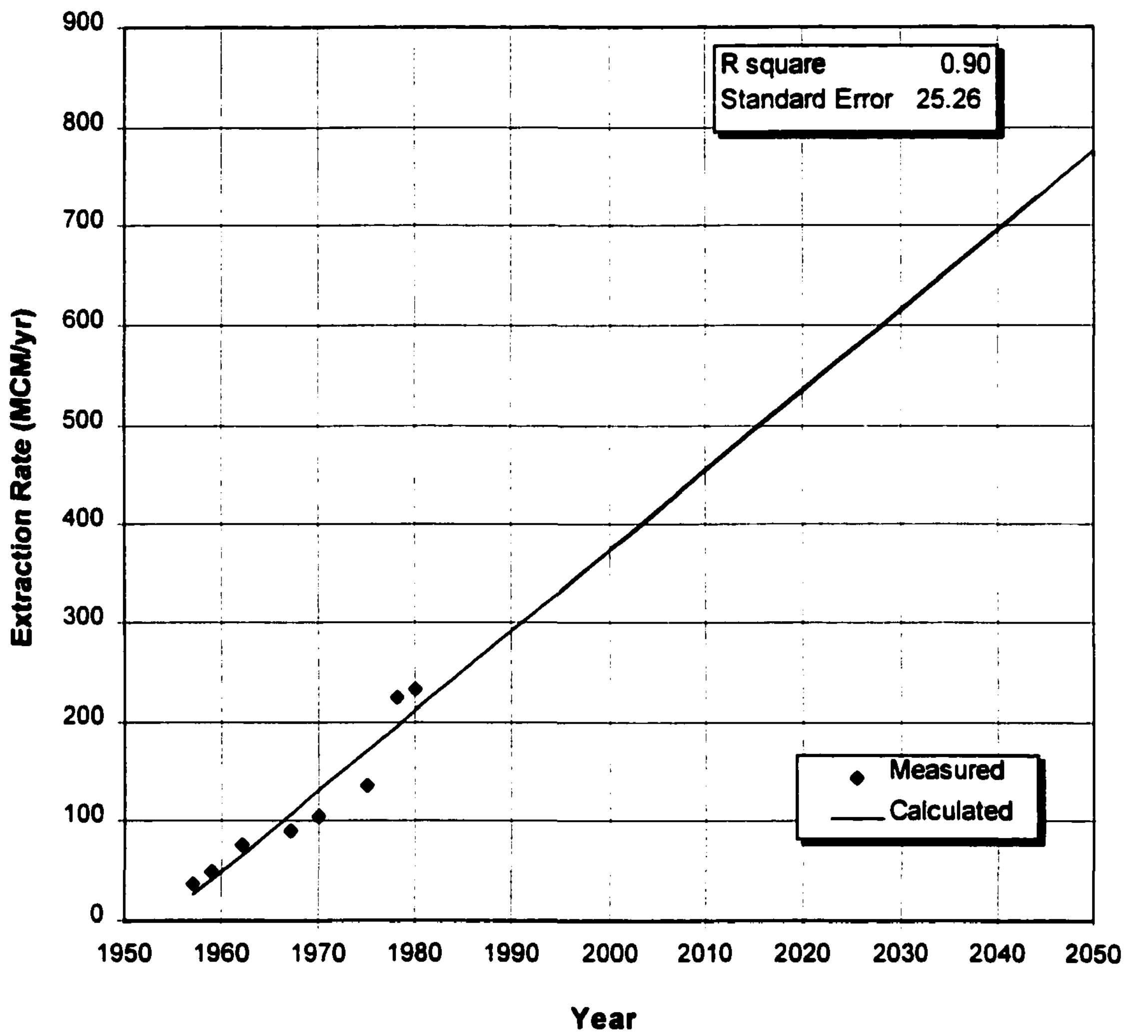


Figure 2.6. Extraction rates as measured by Othman (1983) and the calculated extraction rates in Al-Qassim area from Saq aquifer.

# CHAPTER 3. MODELING

The basic law in saturated flow is Darcy's Law. In groundwater work, the continuity equation is usually combined with Darcy's Law, which is an equation of motion, to yield a groundwater equation applicable to the region of interest. The groundwater equation is represented by mathematical expressions usually of complicated partial differential equations. The partial differential equations governing the non-steady-state, three-dimensional flow in a confined aquifer through a saturated anisotropic nonhomogeneous porous medium may be expressed as (Anderson and Woessner, 1992):

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)= S_s\frac{\partial h}{\partial t}-W \qquad (3.1)$$

where

$K_{xx}$ = is hydraulic conductivity of the aquifer in the X-direction, m/day,

$K_{yy}$ = is hydraulic conductivity of the aquifer in the Y-direction, m/day,

$K_{zz}$ = is hydraulic conductivity of the aquifer in the Z-direction, m/day,

$S_s$ = is the specific storage of the aquifer, $m^{-1}$,

t = is time, day, and

h = is hydraulic head of the aquifer, m, and

W = is a volumetric flux per unit volume and represents sources and/or sinks of water.

Analytical solutions of equation 3.1 are rarely possible, however, these kinds of equations are solved using numerical techniques by means of computer models. One of the most widely used for groundwater flow model is MODFLOW, which was developed and is maintained by U.S. Geological Survey (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996). MODFLOW is a three-dimensional finite-difference model. The partial differential equations in the MODFLOW are replaced by a set of finite difference equations from which one can obtain a numerical solution.

Equation (3.1) is derived by mathematically combining a water balance equation (continuity equation) with Darcy's law. Consider the flow into and out of an elemental cube whose sides are of length $\Delta x$, $\Delta y$, and $\Delta z$ (Figure 3.1). The volume of the cube is $\Delta V = \Delta x \, \Delta y \, \Delta z$.

The water balance equation (conservation of mass) states that:

$$\text{outflow - inflow = change in storage} \tag{3.2}$$

The mass balance is computed by summing the results from each component direction. For instant, the component $q_y$ represents the influx through the face $\Delta x \, \Delta z$, while the flux out through the face $\Delta x \, \Delta z$ is equal to

$$q_y + \frac{\partial q_y}{\partial y}\Delta y \tag{3.3}$$

The volumetric outflow rate minus volumetric inflow rate along the y-axis is

$$\left(q_y + \frac{\partial q_y}{\partial y}\Delta y - q_y\right)\Delta x \Delta z \tag{3.4}$$

The change in flow rate through the cube along the y-axis is

$$\frac{\partial q_y}{\partial y}(\Delta x \Delta y \Delta z) \tag{3.5}$$

The net change in the discharge rate in the x direction is

$$\frac{\partial q_x}{\partial x}(\Delta x \Delta y \Delta z) \tag{3.6}$$

Similar expressions can be written for the change in flow rate along the z direction as

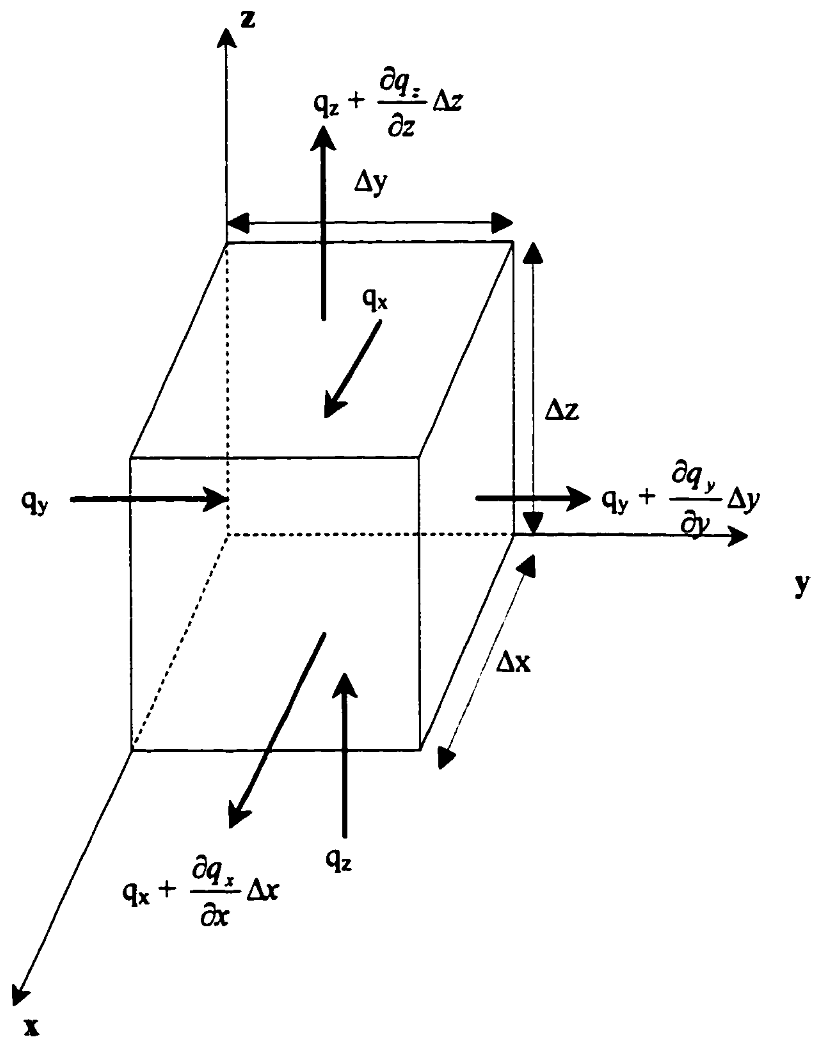


Figure 3.1. The representative elementary volume used in the derivation of the governing equation.

$$\frac{\partial q_z}{\partial z}(\Delta x \Delta y \Delta z) \tag{3.7}$$

The total change in flow rate is equal to the change in storage and is expressed as

$$\left(\frac{\partial q_x}{\partial x}+\frac{\partial q_y}{\partial y}+\frac{\partial q_z}{\partial z}\right)\Delta x \Delta y \Delta z = \text{change in storage} \tag{3.8}$$

The probability of a sink (e.g., a pumping well) or source of water (e.g., an injection well or some other source of recharge) within the cube must also be allowed. The volumetric inflow rate is represented by W Δx Δy Δz. When W is a source of water, W is defined to be as such positive; therefore, it is subtracted from the left-hand side of equation 3.8. Equation 3.8 can be written as

$$\left(\frac{\partial q_x}{\partial x}+\frac{\partial q_y}{\partial y}+\frac{\partial q_z}{\partial z}-W\right)\Delta x \Delta y \Delta z = \text{change in storage} \tag{3.9}$$

The change in storage in equation 3.2 is represented by specific storage ($S_s$), which is defined to be the volume of water released from storage per unit change in head (h) per unit volume of aquifer. The change in storage can be expressed as

$$S_s = -\frac{\Delta V}{\Delta h \Delta x \Delta y \Delta z} \tag{3.10}$$

The rate of change in storage in the cube is

$$\frac{\Delta V}{\Delta t} = -S_s \frac{\Delta h}{\Delta t}\Delta x \Delta y \Delta z \tag{3.11}$$

Equation 3.9 can be rearranged as

$$\left(\frac{\partial q_x}{\partial x}+\frac{\partial q_y}{\partial y}+\frac{\partial q_z}{\partial z}-W\right)\Delta x \Delta y \Delta z = -S_s \frac{\Delta h}{\Delta t}\Delta x \Delta y \Delta z \tag{3.12}$$

Dividing equation 3.12 by Δx Δy Δz, the result is

$$\left(\frac{\partial q_x}{\partial x}+\frac{\partial q_y}{\partial y}+\frac{\partial q_z}{\partial z}\right) = -S_s\frac{\partial h}{\partial t}+W \tag{3.13}$$

(q) in equation 3.13 cannot be determined directly, however, Darcy's law is used to define the relation between (q) and (h); head is a variable that can be determined directly. Darcy's law in three dimensions is written as

$$\left.\begin{aligned} q_x &= -K_{xx}\frac{\partial h}{\partial x} \\ q_y &= -K_{yy}\frac{\partial h}{\partial y} \\ q_z &= -K_{zz}\frac{\partial h}{\partial z} \end{aligned}\right\} \tag{3.14}$$

Substituted equations 3.14 into equation 3.13, the result is equation 3.1, which is the governing equation

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

The partial differential equations (equation 3.1) in the MODFLOW are replaced by a set of finite difference equations from which one can obtain a numerical solution. The finite difference equations in the MODFLOW are developed as follow:

Figure 3.2 represents a cell i,j,k and six nearby aquifer cells i+1,j,k; i-1,j,k; i,j+1,k; i,j-1,k; i,j,k+1; and i,j,k-1. Consider flows that come into cell i,j,k from the six nearby cells. According to Darcy's law, flow into cell i,j,k in the vertical direction from cell i,j,k+1 is approximated by:

$$q_{i,j,k+1/2} = KZ_{i,j,k+1/2}\,\Delta y_j \Delta x_i \frac{(h_{i,j,k+1}-h_{i,j,k})}{\Delta z_{k+1/2}} \tag{3.15}$$

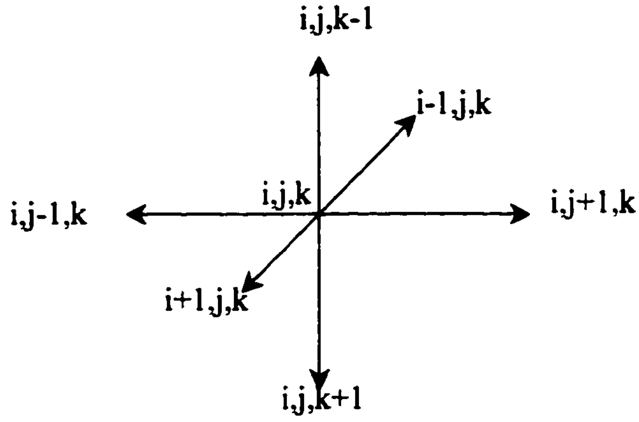


Figure 3.2. Cell i,j,k and six nearby aquifer cells.

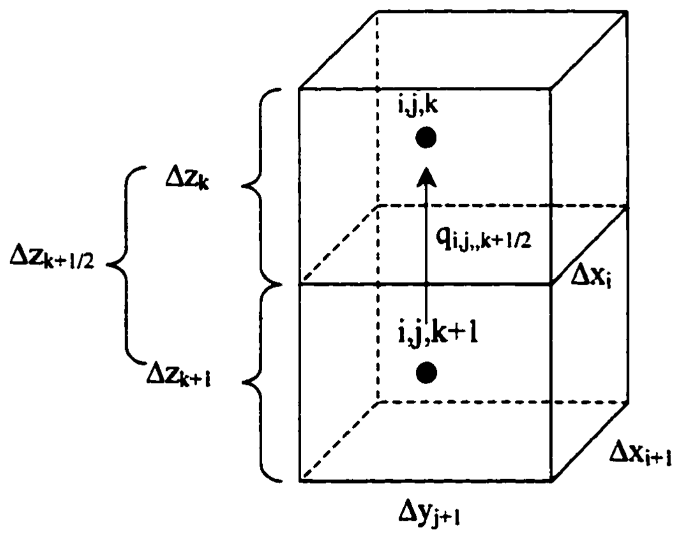


Figure 3.3. Flow into cell i,j,k from cell i,j,k+1.

where

$q_{i,j,k+1/2}$ is the volumetric flow rate through the face between cells i,j,k and i,j,k+1 ($m^3$/day),

$KZ_{i,j,k+1/2}$ is the hydraulic conductivity along the vertical between cells i,j,k and i,j,k+1 (m/day), and

$\Delta z_{k+1/2}$ is the distance between cells i,j,k and i,j,k+1 (m) (Figure 3.3).

while flow through the upper face given by

$$q_{i,j,k-1/2} = KZ_{i,j,k-1/2}\, \Delta y_j \Delta x_i \frac{(h_{i,j,k-1} - h_{i,j,k})}{\Delta z_{k-1/2}} \tag{3.16}$$

For the row direction, flow from cell i,j-1,k into cell i,j,k is given by

$$q_{i,j-1/2,k} = KY_{i,j-1/2,k}\, \Delta x_i \Delta z_k \frac{(h_{i,j-1,k} - h_{i,j,k})}{\Delta y_{j-1/2}} \tag{3.17}$$

while flow in the row direction through the face between cells i,j,k and i,j-1,k is given by

$$q_{i,j+1/2,k} = KY_{i,j+1/2,k}\, \Delta x_i \Delta z_k \frac{(h_{i,j+1,k} - h_{i,j,k})}{\Delta y_{j+1/2}} \tag{3.18}$$

For flow through the forward face of the block in the column direction is

$$q_{i+1/2,j,k} = KX_{i+1/2,j,k}\, \Delta y_j \Delta z_k \frac{(h_{i+1,j,k} - h_{i,j,k})}{\Delta x_{i+1/2}} \tag{3.19}$$

and flow through the rear face of the block is

$$q_{I-1/2,j,k} = KX_{i-1/2,j,k}\, \Delta y_j \Delta z_k \frac{(h_{i-1,j,k} - h_{i,j,k})}{\Delta x_{i-1/2}} \tag{3.20}$$

The finite-difference approximation for cell i,j,k is given by

$$KX_{i+1/2,j,k}\,\Delta y_j \Delta z_k \frac{(h_{i+1,j,k}-h_{i,j,k})}{\Delta x_{i+1/2}} + KX_{i-1/2,j,k}\,\Delta y_j \Delta z_k \frac{(h_{i-1,j,k}-h_{i,j,k})}{\Delta x_{i-1/2}} + KY_{i,j-1/2,k}$$

$$\Delta x_i \Delta z_k \frac{(h_{i,j-1,k}-h_{i,j,k})}{\Delta y_{j-1/2}} + KY_{i,j+1/2,k}\,\Delta x_i \Delta z_k \frac{(h_{i,j+1,k}-h_{i,j,k})}{\Delta y_{j+1/2}} + KZ_{i,j,k+1/2}\,\Delta y_j \Delta x_i \frac{(h_{i,j,k+1}-h_{i,j,k})}{\Delta z_{k+1/2}} +$$

$$KZ_{i,j,k-1/2}\,\Delta y_j \Delta x_i \frac{(h_{i,j,k-1}-h_{i,j,k})}{\Delta z_{k-1/2}} = Ss_{i,j,k} \frac{\Delta h_{i,j,k}}{\Delta t} \Delta x_i \Delta y_j \Delta z_k - W_{i,j,k} \tag{3.21}$$

where

| | |
|---|---|
| $\frac{\Delta h_{i,j,k}}{\Delta t}$ | is a finite-difference approximation for head change with respect to time, |
| $Ss_{i,j,k}$ | is the specific storage of cell i,j,k, |
| $\Delta x_i \Delta y_j \Delta z_k$ | is the volume of cell i,j,k, and |
| $W_{i,j,k}$ | is a volumetric flux per unit volume for cell i,j,k and represents sources and/or sinks of water. |

## Finite Difference Grid

In the finite-difference method, the region is divided into columns and rows. These rows and columns are spaced with constant space. However, a smaller space within rows and columns may be used in the interest area within the region. If there are N nodes, which resulted from multiplying the number of rows by the number of columns, there are N finite-difference equations need to be solved simultaneously to obtain the hydraulic head for each node.

# CHAPTER 4. FIELD MEASUREMENTS

## Pumping Test

A pumping test is the primary approach by which hydrogeologists obtain estimates of the hydraulic properties of an aquifer (i.e., transmissivity and storage coefficient). The transmissivity of the aquifer is a measure of the ability of a formation to allow water to move through. More specifically, transmissivity is the rate of flow through a unit strip of the aquifer, extending through the entire depth, under a unit gradient. The unit on transmissivity is length square per time, such as, $m^2$/day. The storage coefficient is a measure of the ability of a formation to store water. More specifically, storage coefficient is ratio of the volume of water released from storage with a unit change in the potentiometric level to the total aquifer volume. Storage coefficient is dimensionless.

Pumping tests are also useful for determining aquifer boundary conditions (i.e., recharge or barriers). There are four types of pumping tests as described by Bear (1979):

1) A drawdown test, in which the drawdown is measured in the pumping well itself,
2) A recovery test, in which the recovery of water level is measured in a pumping well after the pumping well is shut-off after pumping at a constant rate for a long period of time,
3) An interference test, in which the drawdown is measured with time at an observation well in the vicinity of the pumping well, and
4) A step drawdown test which has variable pumping rate i.e., pumping rate is increased in steps.

Drawdown is the difference in depth in feet or meters between the static water level (the initial water level in the well before pumping) and the pumping or dynamic level (the water level after pumping at any given rate). As a well is pumped at a constant rate, the drawdown is measured with time. If the well pumps long enough, the water level may reach a state of equilibrium (i.e., no increase in drawdown with time can be observed), but in many aquifers, the drawdown will continue to increase with time. These types of pumping tests are known as nonequilibrium tests.

The most popular methods for solving the nonequilibrium flow equation in a confined aquifer for determining aquifer properties are the Theis Method and the Jacob Straight-Line Time-Drawdown Method. Both methods are using data resulting from a pumping test. During the pumping test, a well is pumping at a constant rate and the drawdown with time is observed in an observation well.

A Pumping test was conducted at the Agricultural Research Center (latitude 26° 17′ 55″ N., longitude 43° 47′ 21.2″ E.) (Figure 2.1) in the Al-Qassim region, Saudi Arabia during summer, 1999 in order to determine the aquifer parameters. The region around the study area is in irrigated agricultural production, so there are many wells that supply the area. In order to do a pumping test, two wells located in the same area are needed. These two wells should be drilled in the same aquifer, which is being tested. One of these two is used as a pumping well while the other one is used as an observation well. In the Agricultural Research Center, there are three pumping wells and all of them are withdrawing from the Saq aquifer. These wells are all about 600 m below ground surface. The ground elevation of the area is about 650 m above the sea level.

One of the three wells in the Agricultural Research Center was used as a pumping well (latitude 26° 17′ 55″ N., longitude 43° 47′ 21.2″ E.), and another one was used as an observation well (latitude 26° 18′ 0.2″ N., longitude 43° 47′ 18.5″ E.). The one that was used as a pumping well was drilled in March, 1999, and the one that was used as an observation well was drilled in 1986 into the same formation.

The pumping test was conducted during the summer of 1999 at the Agricultural Research Center. Before the pumping started, the initial water level was measured in the observation well. The distance between the pumping well and the observation well was 180 m, measured using a portable GPS system. The pumping well was pumped at a constant rate (3.41 $m^3$/min), and the change in water level with time in the observation well was measured by a Water Level Indicator. The measurements of water levels with time were plotted on semi-log paper in the field. After a straight line trend was observed in the plotting data, the test was stopped.

Because the aquifer test did not reach an equilibrium, the data were analyzed by using the Theis Method and the Jacob Straight-Line Time-Drawdown Method for nonequilibrium radial flow in a confined aquifer.

The nonequilibrium formula introduced by Theis (1935) is widely used with pumping test data for determining the aquifer properties. The nonequilibrium formula is:

$$Z = \frac{Q}{4\pi T} \int_{u}^{\infty} \frac{e^{-u}}{u}\, du \tag{4.1}$$

The integral equation (4.1) can be approximated by an infinite series

$$Z = \frac{Q}{4\pi T} \left[ -0.5772 - \ln u + u - \frac{u^2}{2.2!} + \frac{u^3}{3.3!} - \ldots\ldots \right] \tag{4.2}$$

Where u is

$$u = \frac{r^2 S}{4Tt} \tag{4.3}$$

The infinite series term of equation 4.2 is called the well function, W(u), so equation (4.2) becomes as:

$$Z = \frac{Q}{4\pi T} W(u) \tag{4.4}$$

Equation 4.4 can be rearranged as:

$$T = \frac{Q}{4\pi Z} W(u) \tag{4.5}$$

Also, equation 4.3 can be rearranged as:

$$S = \frac{4Tt}{r^2 (1/u)} \tag{4.6}$$

where

Q is the constant pumping rate in $m^3$/day.

Z is the drawdown in meter.

T is the transmissivity of the aquifer in $m^2$/day.

S is the storage coefficient (dimensionless).

t is time since pumping started in days.

r is the radial distance between the pumping well and the observation well in m.

W(u) is the well function of u (dimensionless).

Theis developed a graphical solution method. In order to obtain a solution, a plot W(u) versus 1/u on full logarithmic paper is needed, and the resulting curve is called a Theis type curve (Figure 4.1). The data, which are used in the Theis type curve, are shown in Table 4.1.

The measurements of drawdown with time, which have been taken from the pumping test, were plotted on full logarithmic paper of the same scale as the Theis type curve. The resulting curve of drawdown versus time is called the data curve. The data curve was superimposed on the type curve, keeping the sets of axes parallel. The data curve's position

Table 4.1. Values of the function W(u) for various values of u*.

| U | W(u) | U | W(u) | u | W(u) | u | W(u) |
|---|---|---|---|---|---|---|---|
| $1 \times 10^{-10}$ | 22.45 | $1 \times 10^{-7}$ | 15.54 | $1 \times 10^{-4}$ | 8.63 | $1 \times 10^{-1}$ | 1.823 |
| 2 | 21.76 | 2 | 14.85 | 2 | 7.94 | 2 | 1.223 |
| 3 | 21.35 | 3 | 14.44 | 3 | 7.53 | 3 | 0.906 |
| 4 | 21.06 | 4 | 14.15 | 4 | 7.25 | 4 | 0.702 |
| 5 | 20.84 | 5 | 13.93 | 5 | 7.02 | 5 | 0.56 |
| 6 | 20.66 | 6 | 13.75 | 6 | 6.84 | 6 | 0.454 |
| 7 | 20.5 | 7 | 13.6 | 7 | 6.69 | 7 | 0.374 |
| 8 | 20.37 | 8 | 13.46 | 8 | 6.55 | 8 | 0.311 |
| 9 | 20.25 | 9 | 13.34 | 9 | 6.44 | 9 | 0.26 |
| $1 \times 10^{-9}$ | 20.15 | $1 \times 10^{-6}$ | 13.24 | $1 \times 10^{-3}$ | 6.33 | $1 \times 10^{-0}$ | 0.219 |
| 2 | 19.45 | 2 | 12.55 | 2 | 5.64 | 2 | 0.049 |
| 3 | 19.05 | 3 | 12.14 | 3 | 5.23 | 3 | 0.013 |
| 4 | 18.76 | 4 | 11.85 | 4 | 4.95 | 4 | 0.004 |
| 5 | 18.54 | 5 | 11.63 | 5 | 4.73 | 5 | 0.001 |
| 6 | 18.35 | 6 | 11.45 | 6 | 4.54 | | |
| 7 | 18.2 | 7 | 11.29 | 7 | 4.39 | | |
| 8 | 18.07 | 8 | 11.16 | 8 | 4.26 | | |
| 9 | 17.95 | 9 | 11.04 | 9 | 4.14 | | |
| $1 \times 10^{-8}$ | 17.84 | $1 \times 10^{-5}$ | 10.94 | $1 \times 10^{-2}$ | 4.04 | | |
| 2 | 17.15 | 2 | 10.24 | 2 | 3.35 | | |
| 3 | 16.74 | 3 | 9.84 | 3 | 2.96 | | |
| 4 | 16.46 | 4 | 9.55 | 4 | 2.68 | | |
| 5 | 16.23 | 5 | 9.33 | 5 | 2.47 | | |
| 6 | 16.05 | 6 | 9.14 | 6 | 2.3 | | |
| 7 | 15.9 | 7 | 8.99 | 7 | 2.15 | | |
| 8 | 15.76 | 8 | 8.86 | 8 | 2.03 | | |
| 9 | 15.65 | 9 | 8.74 | 9 | 1.92 | | |

*Source: Fetter, C. W. 1994. Applied Hydrogeology, third edition.

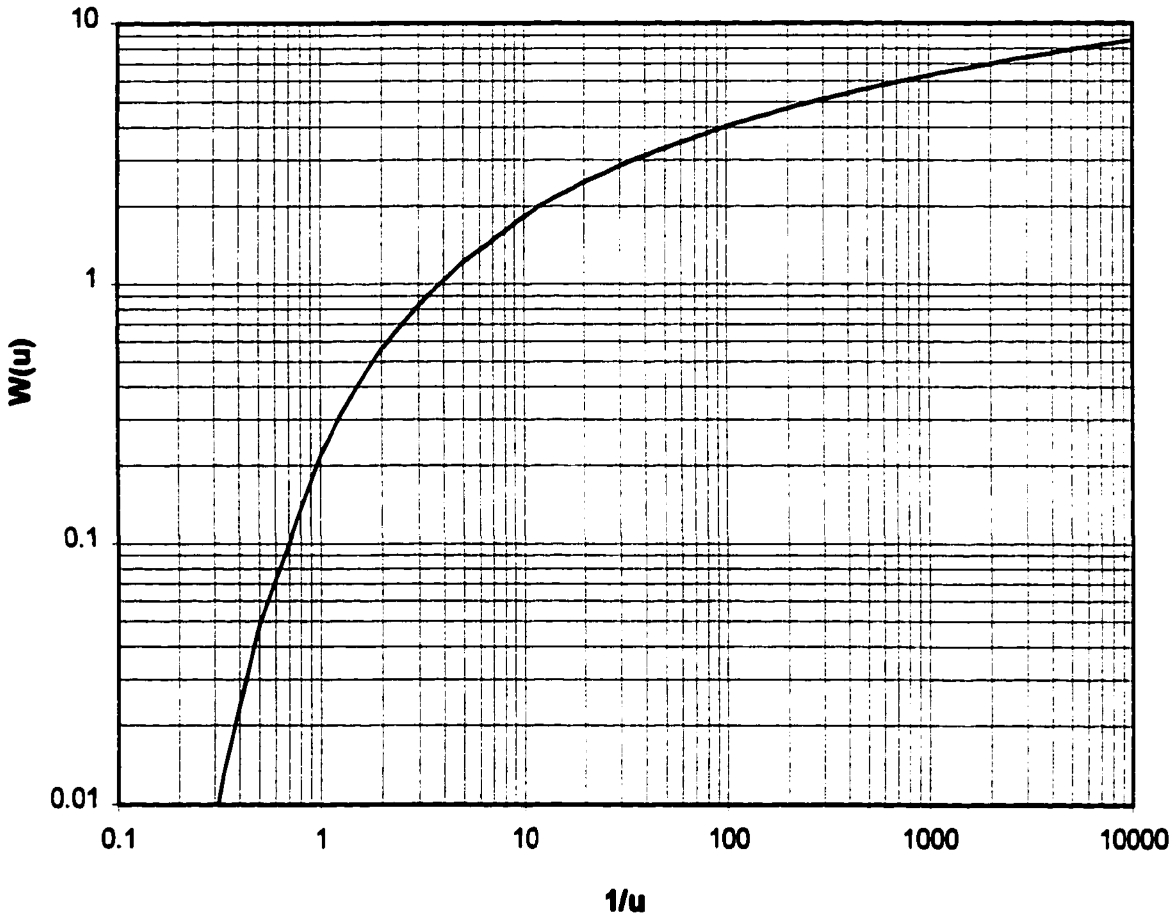


Figure 4.1. The nonequilibrium type curve (Theis curve) for a confined aquifer.

was adjusted until the data points superimposed the type curve, keeping the axes of both graphs parallel. A match point in the graphs where the intersection of the line W(u) = 1 and the line 1/u = 1 was selected. At that point, the value of drawdown and value of time were selected. From the match point, a set of values for W(u), 1/u, drawdown, and time were obtained. The values of pumping rate and drawdown, and W(u) from the match point were used in Equation 4.5 to determine the transmissivity. After determining the transmissivity, its value with the radial distance from the pumping well and the time and 1/u from the match point were substituted into Equation 4.6 to determine the storage coefficient.

The second method, which can be used to determine the aquifer properties, is Jacob Straight-Line Time-Drawdown Method. Jacob (1950) proposed a method based on the modified nonequilibrium formula 4.1. He showed that for values of $u < 0.01$, the well function can be closely approximated by the first two terms in the infinite series. Equation 4.1 can then be written as:

$$T = \frac{Q}{4\pi Z}\left[-0.5772 - \ln\left(\frac{r^2 S}{4Tt}\right)\right] \tag{4.7}$$

or

$$\mathrm{T} = \frac{Q}{4\pi Z}\left[-\ln(1.78) - \ln\left(\frac{r^2 S}{4Tt}\right)\right] \tag{4.8}$$

Combining natural log equation 4.8 becomes:

$$T = \frac{Q}{4\pi Z}\ln\left(\frac{4Tt}{1.78 r^2 S}\right) \tag{4.9}$$

Converting this to base 10 logs equation 4.9 becomes:

$$T = \frac{2.3Q}{4\pi Z}\log\left(\frac{2.25Tt}{r^2 S}\right) \tag{4.10}$$

The values of transmissivity and storage coefficient can be determined from the equations:

$$T = \frac{2.3Q}{4\pi\Delta Z} \tag{4.11}$$

and

$$S = \frac{2.25Tt_0}{r^2} \tag{4.12}$$

where

T is the transmissivity of the aquifer in $m^2$/day.

Q is the constant pumping rate in $m^3$/day.

$\Delta Z$ is the difference in drawdown in meter over 1 cycle of log scale.

S is the storage coefficient (dimensionless).

$t_0$ is the time at zero-drawdown in days.

r is the radial distance in meter between the pumping well and the observation well.

In the Jacob straight-line method, the measurements of drawdown with time, which have been taken from the pumping test, were plotted on semilogarithmic paper. A straight line is fitted between the later time data and extrapolated back to the zero- drawdown axis. The value of the drawdown per log cycle, $\Delta Z$, which was obtained from the slope of the straight line, was used to determine the transmissivity, and the time of zero drawdown was used to find the storage coefficient. The values of pumping rate and drawdown were substituted into Equation 4.11 to determine the transmissivity. After determining the transmissivity, its value with the radial distance from the pumping well and the time at zero-drawdown were substituted into Equation 4.12 to determine the storage coefficient.

**Results of the pumping test**

Table 4.2 shows the field pumping test data for the pumping test, which had been taken during the summer of 1999. As shown in the tables, the drawdown increased with time in the observation well as the result of the pumping in the pumping well which was about 180 m from the observation well. The pumping test data in Table 4.2 was analyzed using two different methods in order to develop the aquifer properties.

***Theis Method***

In Theis method, the measurements of drawdown with time which have been taken from the pumping test (Table 4.2) were plotted on full logarithmic paper of the same scale as the Theis type curve (Figure 4.1). The resulting curve of drawdown versus time is called the data curve. The data curve was superimposed on the type curve, keeping the sets of axes parallel (Figure 4.2). The data curve's position was adjusted until the data points superimposed the type curve, keeping the axes of both graphs parallel. From Figure 4.2, a match point in the graph where the intersection of the line $W(u) = 1$ and the line $1/u = 1$ was selected. At that point, the value of drawdown and the value of time were selected. From the match point, a set of values for $W(u)$, $1/u$, drawdown, and time were obtained. The values of pumping rate, drawdown, and $W(u)$ were substituted into Equation 4.5 to determine the transmissivity.

$Q \quad = 4906\ m^3/day$

$W(u) \quad = 1$

$Z \quad = 0.22\ m$

The transmissivity is determined as:

Table 4.2. Measurements of changes in water level with time during the pumping test.

| Time After Pumping Started (min) | Drawdown (cm) |
|---|---|
| 0 | 0 |
| 3 | 9 |
| 6 | 16 |
| 9 | 23 |
| 12 | 29 |
| 15 | 33 |
| 18 | 37 |
| 28 | 47 |
| 38 | 53 |
| 50 | 60 |
| 70 | 67 |
| 90 | 73 |
| 110 | 77 |
| 140 | 82 |
| 170 | 88 |

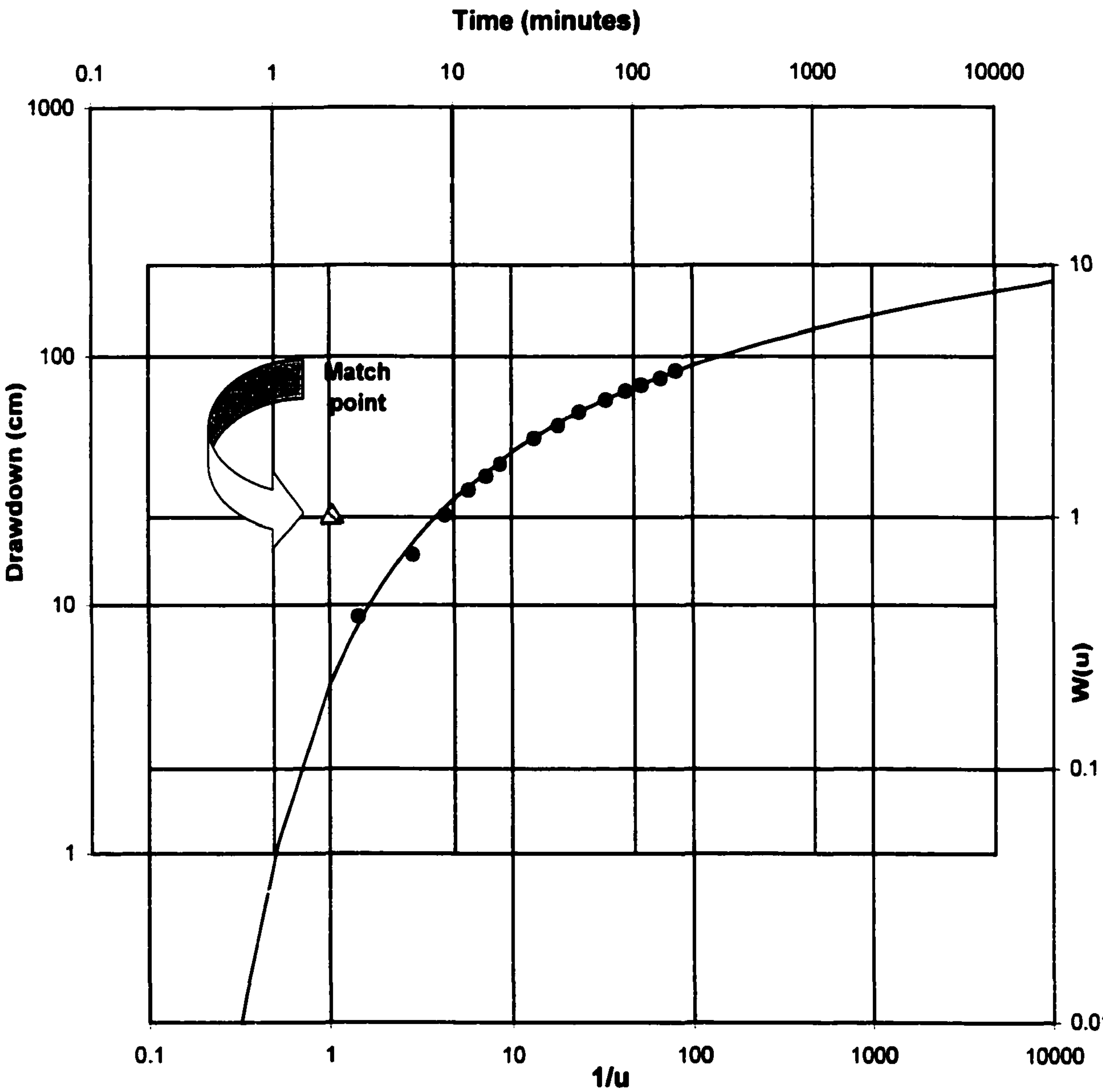


Figure 4.2. Match point on the measurements of drawdown versus time (field data) and Theis type curve for the pumping test.

$$T = \left(\frac{4906}{4\pi x 0.22}\right) * 1$$

$T = 1775\ m^2/day$

$T = 1.23\ m^2/min$

After determining the transmissivity, its value with the radial distance from the pumping well and time and 1/u from the match point were substituted into Equation 4.6 to determine the storage coefficient.

1/u = 1

t = 2 min = 2/1440 = 1.3888 x $10^{-3}$ day

r = 180 m

The storage coefficient is determined as:

$$S = \left(\frac{4 * 1774.55 * 1 * 1.3888 \times 10^{-3}}{180 * 180}\right)$$

S = 3.04 x $10^{-4}$

***Jacob Straight-Line Time-Drawdown Method***

In the Jacob straight-line method, the measurement of drawdowns with time, which have been taken from the pumping test (Table 4.2), were plotted on semilogarithmic paper (Figure 4.3). A straight line is fitted between the later time data and extrapolated back to the zero- drawdown axis (Figure 4.3). The value of the drawdown per log cycle, ΔZ, which was obtained from the slope of the straight line, was used to determine the transmissivity. The values of pumping rate and drawdown were substituted into Equation 4.11 to determine the transmissivity.

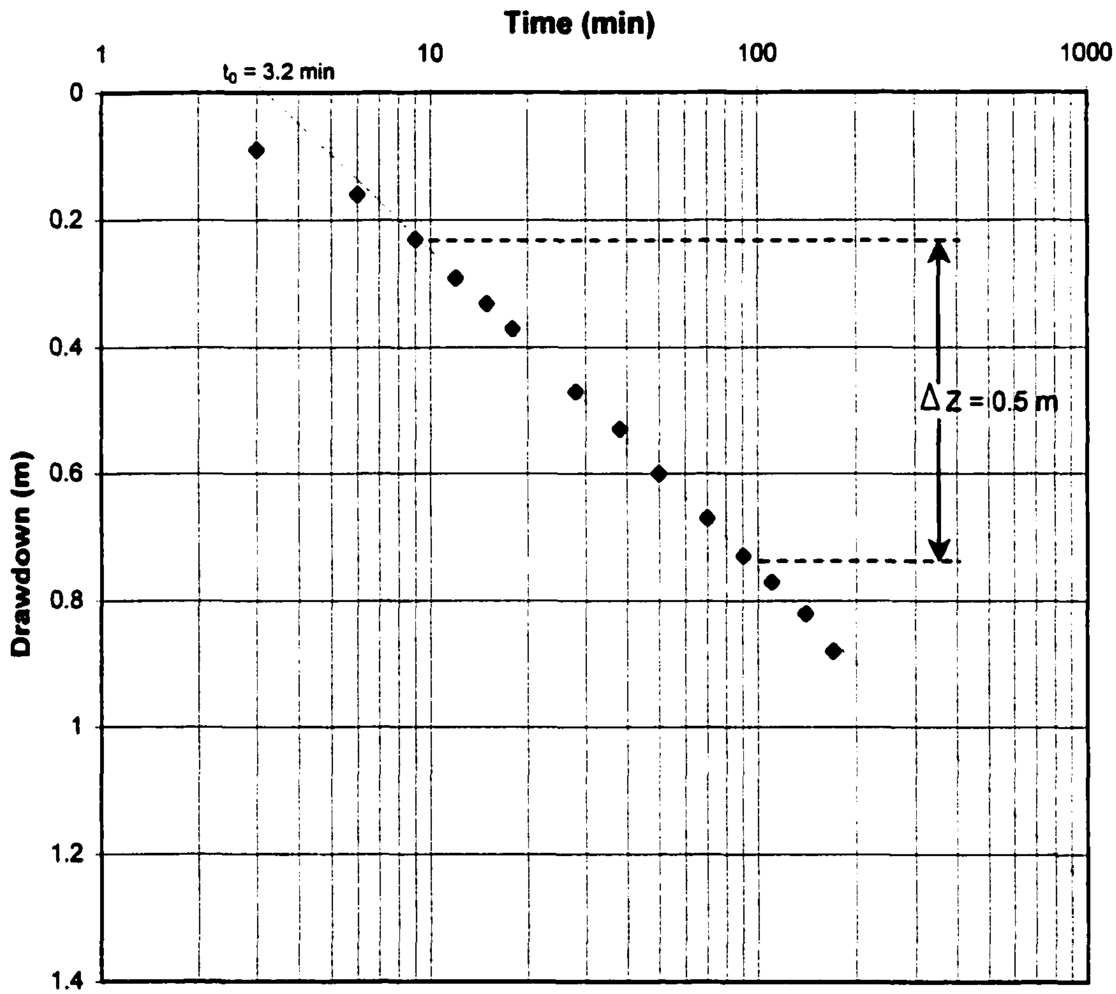


Figure 4.3. Jacob method of analyzing of pumping test, drawdown (m) versus time (min) on semilogarithmic paper using Jacob method.

Q = 4906 $m^3$/day

$\Delta Z$ = 0.50 m

The transmissivity is determined as:

$$T = \frac{2.3 * 4906}{4\pi * 0.50}$$

T = 1796 $m^2$/day

T = 1.25 $m^2$/min

After determining the transmissivity, its value with the radial distance from the pumping well and the time at zero-drawdown were substituted into Equation 4.12 to determine the storage coefficient.

$t_0$ = 3.2 min = 3.2/1440 = 2.22 x $10^{-3}$ day

r = 180 m

The storage coefficient is determined as:

$$S = \frac{2.25 * 1796 * 2.22 \times 10^{-3}}{180 * 180}$$

S = 2.77 x $10^{-4}$

The transsmisivity and storage coefficient which were obtained by Thies method were almost the same as hydraulic properties that were obtained by Jacob method but, there was a slight variation between the two answers because of the accuracy of the graph construction and personal judgments in matching field data to type curves in Thies method.

**Surveying The Major Wells in The Region**

A field trip was made to Saudi Arabia during the summer of 1999 (from May 23 to August 22). The purpose of the trip was to collect existing data on water withdrawals from the Saq aquifer. The study area is located in central Saudi Arabia between latitudes (25° 00′ and 27° 00′ N.) and longitudes (42° 30′ and 45° 00′ E.) (Figure 2.1). Due to the huge area of Al-Qassim, the field study area was focused in and around the two most important cities in the region.

In the Al-Qassim area, the groundwater is mainly used for domestic and agricultural purposes. Presently, more than 70 production wells are operational in the area (Figure 4.4). Most of these wells are located in Buraydah city, and around 16 wells are located in Unayzah city. From Figure 4.4, it seems that the wells, which are used for domestic purpose, are very close to each other.

Locations of the major wells in the Saq aquifer were determined by a portable GARMEN, GPS 48. Table 4.3 shows all the major wells, which were located in Buraydah and Unayzah cities. The pumping rate of each production well was determined by measuring the rate in the pumping gage. The pumping rates were in gallon per minute when they were measured, and they were converted to cubic meter per day (Table 4.3). It is very important for our study to know the static water level of each pumping well. For that purpose, static water levels of some of the pumping wells were determined by water level indicator (Table 4.3).

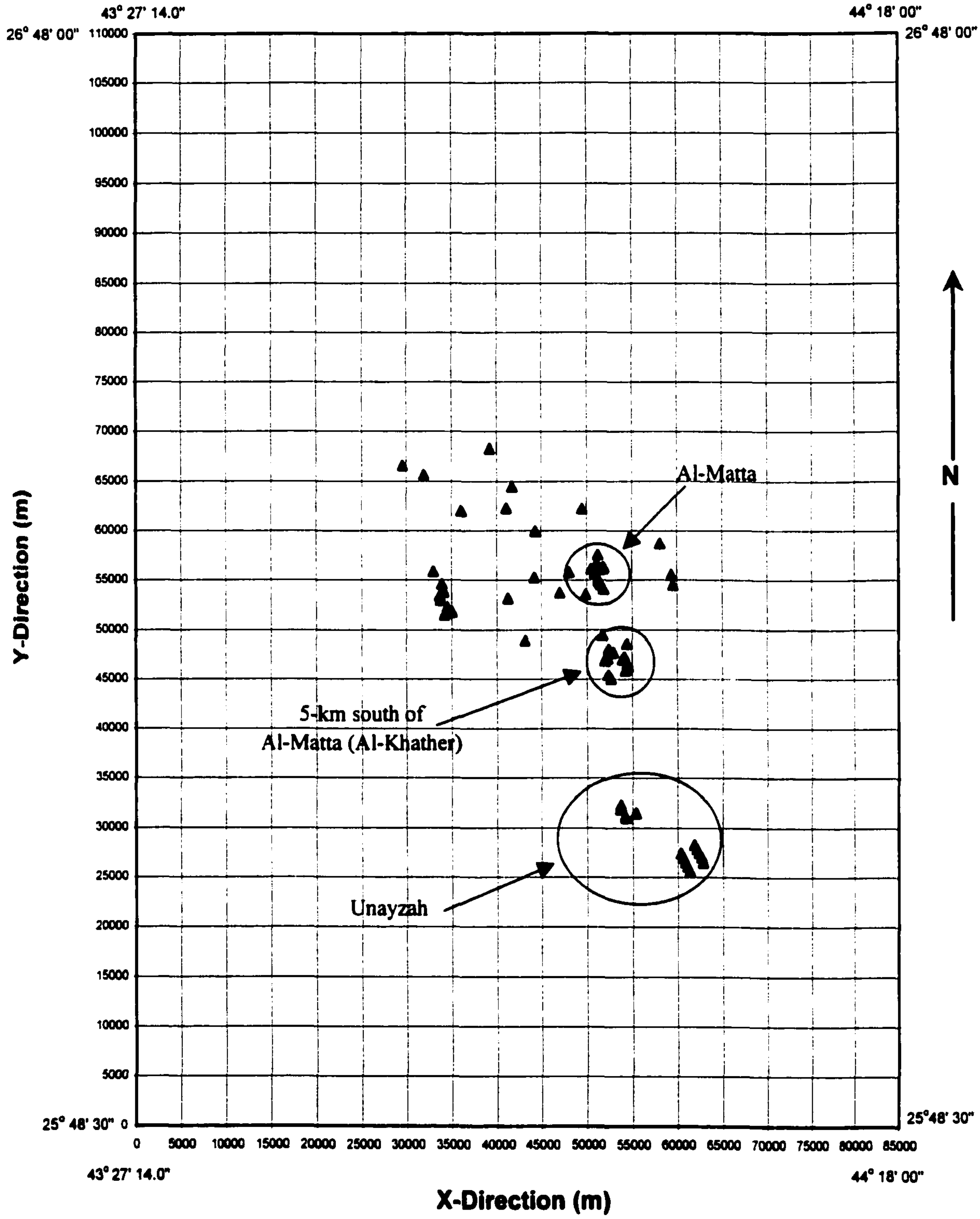


Figure 4.4. Location of pumping well system in the modeled area.

Table 4.3. Well field location, depth, and the pumping rate of each well.

| Well's name | Well location | Depth (m) | Static water level (m) | Pumping rate ($m^3$/day) |
|---|---|---|---|---|
| 1 | N 26° 19′ 18.4″<br>E 43° 57′ 57.1″ | 650 | 107 | 9267 |
| 2 | N 26° 18′ 40.5″<br>E 43° 57′ 40.1″ | 640 | 93 | 9267 |
| 3 | N 26° 19′ 2.5″<br>E 43° 57′ 25.4″ | 630 | 103 | 9267 |
| 4 | N 26° 20′ 3.8″<br>E 43° 57′ 37.6″ | 650 | 94 | 7631 |
| 5 | N 26° 19′ 29.5″<br>E 43° 57′ 31.1″ | 622 | | 3271 |
| 6 | N 26° 19′ 19.7″<br>E 43° 57′ 25.1″ | 614 | | 6814 |
| 7 | N 26° 19′ 22.7″<br>E 43° 58′ 0.2″ | 650 | 108 | 6541 |
| 8 | N 26° 19′ 15.9″<br>E 43° 57′ 45.4″ | 683 | | 2180 |
| 9 | N 26° 19′ 19.9″<br>E 43° 57′ 44.6″ | 653 | 102 | 9267 |
| 10 | N 26° 19′ 25.1″<br>E 43° 57′ 37.7″ | 650 | 93 | 5996 |
| 11 | N 26° 19′ 20.6″<br>E 43° 57′ 33.2″ | 650 | 97 | 6541 |
| 12 | N 26° 19′ 16.4″<br>E 43° 57′ 10.6″ | 650 | | 6541 |
| 14 | N 26° 18′ 36.3″<br>E 43° 57′ 42.5″ | 650 | 93 | 3271 |
| 15 | N 26° 18′ 29.2″<br>E 43° 57′ 47.4″ | 650 | | 9267 |
| 16 | N 26° 18′ 23.0″<br>E 43° 57′ 53.0″ | 650 | | 9812 |
| 17 | N 26° 18′ 10.8″<br>E 43° 58′ 0.1″ | 650 | | 8722 |
| 18 | N 26° 18′ 25.2″<br>E 44° 02′ 37.6″ | 650 | 106 | 6541 |
| 19 | N 26° 18′ 59.9″<br>E 44° 02′ 31.4″ | 600 | | 3543 |
| 20 | N 26° 20′ 42.7″<br>E 44° 01′ 45.1″ | 600 | | 2726 |

Table 4.3. Continued.

| Well's name | Well location | Depth (m) | Static water level (m) | Pumping rate ($m^3$/day) |
|---|---|---|---|---|
| 21 | N 26° 14′ 27.9″<br>E 43° 59′ 25.2″ | 655 | 109 | 3543 |
| 22 | N 26° 14′ 20.0″<br>E 43° 59′ 18.4″ | 600 | 107 | 9267 |
| 23 | N 26° 14′ 06.7″<br>E 43° 59′ 37.1″ | 650 | 100 | 9812 |
| 24 | N 26° 13′ 56.5″<br>E 43° 59′ 39.5″ | 650 | 103 | 8722 |
| 25 | N 26° 13′ 43.9″<br>E 43° 59′ 28.8″ | 650 | | 9267 |
| 26 | N 26° 13′ 16.0″<br>E 43° 58′ 31.9″ | 650 | 106 | 8722 |
| 27 | N 26° 13′ 28.1″<br>E 43° 58′ 21.3″ | 630 | | 8722 |
| 1-1 | N 26° 02′ 46.7″<br>E 44° 03′ 49.9″ | 602 | | 7631 |
| 1-2 | N 26° 03′ 02.4″<br>E 44° 03′ 41.8″ | 602 | | 7631 |
| 1-3 | N 26° 03′ 15.9″<br>E 44° 03′ 32.6″ | 602 | | 7631 |
| 1-4 | N 26° 03′ 31.2″<br>E 44° 03′ 24.5″ | 602 | | 7631 |
| 1-5 | N 26° 03′ 45.9″<br>E 44° 03′ 14.2″ | 602 | | 7631 |
| 2-1 | N 26° 03′ 15.7″<br>E 44° 04′ 42.6″ | 602 | 98 | 7631 |
| 2-2 | N 26° 03′ 33.3″<br>E 44° 04′ 36.7″ | 602 | | 7631 |
| 2-3 | N 26° 03′ 46.7″<br>E 44° 04′ 26.6″ | 602 | | 7631 |
| 2-4 | N 26° 04′ 0.0″<br>E 44° 04′ 18.1″ | 602 | | 7631 |
| 2-5 | N 26° 04′ 14.0″<br>E 44° 04′ 07.2″ | 602 | | 7631 |
| ALHDA | N 26° 05′ 39.9″<br>E 43° 59′ 34.4″ | 600 | 110 | 3271 |
| HARAT ANOZ | N 26° 22′ 33.7″<br>E 43° 51′ 30.8″ | 602 | | 3271 |

Table 4.3. Continued.

| Well's name | Well location | Depth (m) | Static water level (m) | Pumping rate ($m^3$/day) |
|---|---|---|---|---|
| AL-ARAMTHAE | N 26° 17′ 56.0″<br>E 43° 55′ 06.4″ | 600 | | 3271 |
| AL-ASKAN | N 26° 22′ 34.4″<br>E 43° 56′ 32.2″ | 650 | | 8177 |
| ATHRAS | N 26° 18′ 46.1″<br>E 43° 53′ 24.3″ | 600 | | 4470 |
| BOSSOR | N 26° 17′ 36.1″<br>E 43° 51′ 39.1″ | 600 | | 3271 |
| COLLEGE-1 | N 26° 17′ 55.0″<br>E 43° 47′ 21.2″ | 600 | | 4906 |
| COLLEGE-2 | N 26° 18′ 0.2″<br>E 43° 47′ 18.5″ | 600 | 115 | 4906 |
| COLLEGE-3 | N 26° 18′ 21.0″<br>E 43° 47′ 13.7″ | 600 | | 4906 |
| GRA'A | N 26° 24′ 20.9″<br>E 43° 45′ 58.1″ | 600 | | 3271 |
| AL-GRISH | N 26° 22′ 22.8″<br>E 43° 48′ 30.5″ | 600 | | 6541 |
| AL-GTHAI | N 26° 24′ 50.8″<br>E 43° 44′ 33.6″ | 600 | | 3271 |
| AL-HADIKA | N 26° 05′ 55.7″<br>E 44° 00′ 12.9″ | 600 | 105 | 3271 |
| AL-HNAIA-1 | N 26° 14′ 40.6″<br>E 43° 58′ 30.0″ | 650 | | 2180 |
| AL-HNAIA-2 | N 26° 14′ 53.1″<br>E 43° 58′ 23.5″ | 650 | | 2180 |
| HOILAN | N 26° 17′ 51.7″<br>E 43° 56′ 48.7″ | 600 | | 3271 |
| AL-HOMOR | N 26° 21′ 19.0″<br>E 43° 53′ 27.6″ | 600 | | 3271 |
| AL-KATHER | N 26° 15′ 11.7″<br>E 43° 59′ 34.5″ | 650 | | 3271 |
| KMAS | N 26° 15′ 18.6″<br>E 43° 52′ 48.1″ | 600 | | 3271 |
| AL-MOLIDA | N 26° 19′ 03.0″<br>E 43° 46′ 38.9″ | 600 | | 3271 |
| AL-MOSHIGH-1 | N 26° 16′ 48.7″<br>E 43° 47′ 55.2″ | 600 | | 3271 |

Table 4.3. Continued.

| Well's name | Well location | Depth (m) | Static water level (m) | Pumping rate ($m^3$/day) |
|---|---|---|---|---|
| AL-MOSHIGH-2 | N 26° 16′ 48.0″<br>E 43° 47′ 37.4″ | 600 | | 6541 |
| AL-MOSHIGH-3 | N 26° 16′ 39.6″<br>E 43° 47′ 23.6″ | 600 | | 3271 |
| AL-MOSHIGH-4 | N 26° 17′ 04.8″<br>E 43° 47′ 36.8″ | 600 | | 6541 |
| AL-MOTLQ-1 | N 26° 14′ 23.2″<br>E 43° 58′ 18.6″ | 650 | | 2180 |
| AL-MOTLQ-2 | N 26° 14′ 42.6″<br>E 43° 58′ 42.0″ | 650 | | 2180 |
| AL-MOREDSIHA | N 26° 19′ 04.6″<br>E 43° 55′ 42.5″ | 600 | | 3271 |
| AL-QUSAIHA | N 26° 15′ 39.3″<br>E 43° 57′ 56.9″ | 600 | | 3271 |
| AL-RAGHI-1 | N 26° 17′ 28.0″<br>E 43° 47′ 08.5″ | 600 | | 6541 |
| AL-RAGHI-2 | N 26° 17′ 41.6″<br>E 43° 47′ 05.2″ | 600 | | 6541 |
| AL-RAGHIA | N 26° 14′ 15.6″<br>E 43° 58′ 08.0″ | 650 | | 6541 |
| AL-ROKANI | N 26° 06′ 22.5″<br>E 43° 59′ 14.2″ | 600 | 102 | 3271 |
| AL-SALHIA | N 26° 05′ 46.7″<br>E 43° 59′ 30.9″ | 600 | 105 | 3271 |
| AL-SHAMALI-D | N 26° 06′ 08.6″<br>E 43° 59′ 12.1″ | 600 | 107 | 3271 |
| AL-SHAMALI-K | N 26° 06′ 08.8″<br>E 43° 59′ 13.3″ | 600 | 107 | 3271 |
| AL-SHOQA-A | N 26° 25′ 48.4″<br>E 43° 50′ 21.4″ | 600 | | 3271 |
| AL-SHOQA-S | N 26° 23′ 44.7″<br>E 43° 51′ 51.0″ | 600 | | 3271 |

# CHAPTER 5. MODEL DEVELOPMENT AND CALIBRATION

In the present study, a quasi-three-dimensional simulation model was developed using the groundwater flow model MODFLOW (McDonald and Harbaugh, 1988).

## Finite Difference Grid

The field study area was focused in and around the two most important cities in the Al-Qassim region (Buraydah and Unayzah). The study area is 85 x 110 km, with an approximated area of 9350 $km^2$. The study area was discretized into a finite difference mesh consisting of 50 columns and 60 rows, (a total of 3000 nodes) which means that there are 3000 equations like equation 3.21 need to be solved simultaneously. A smaller mesh spacing with cells of 1000 x 1000 m was used in areas of heavy pumping, while a larger mesh spacing of 5000 x 5000 m was used elsewhere in the region (Figure 5.1).

## Assumptions

The following are the main assumptions, which are made in the conceptual model of the Saq aquifer:

1) Based on the existing geologic and hydrogeologic informations:
    a) The Saq aquifer is assumed to be a single layer
    b) The Saq aquifer in the study area is assumed to be confined unit, and
    c) The aquifer system is assumed to be homogeneous and isotropic.
2) The recharge to the aquifer in the study area is assumed to be negligible since almost everywhere in the study area, the aquifer is a confined unit.
3) The withdrawal from the aquifer is only through wells.
4) Evapotranspiration from the water table of the Saq aquifer is assumed to be negligible since almost everywhere the hydraulic head of the Saq aquifer is below an effective depth

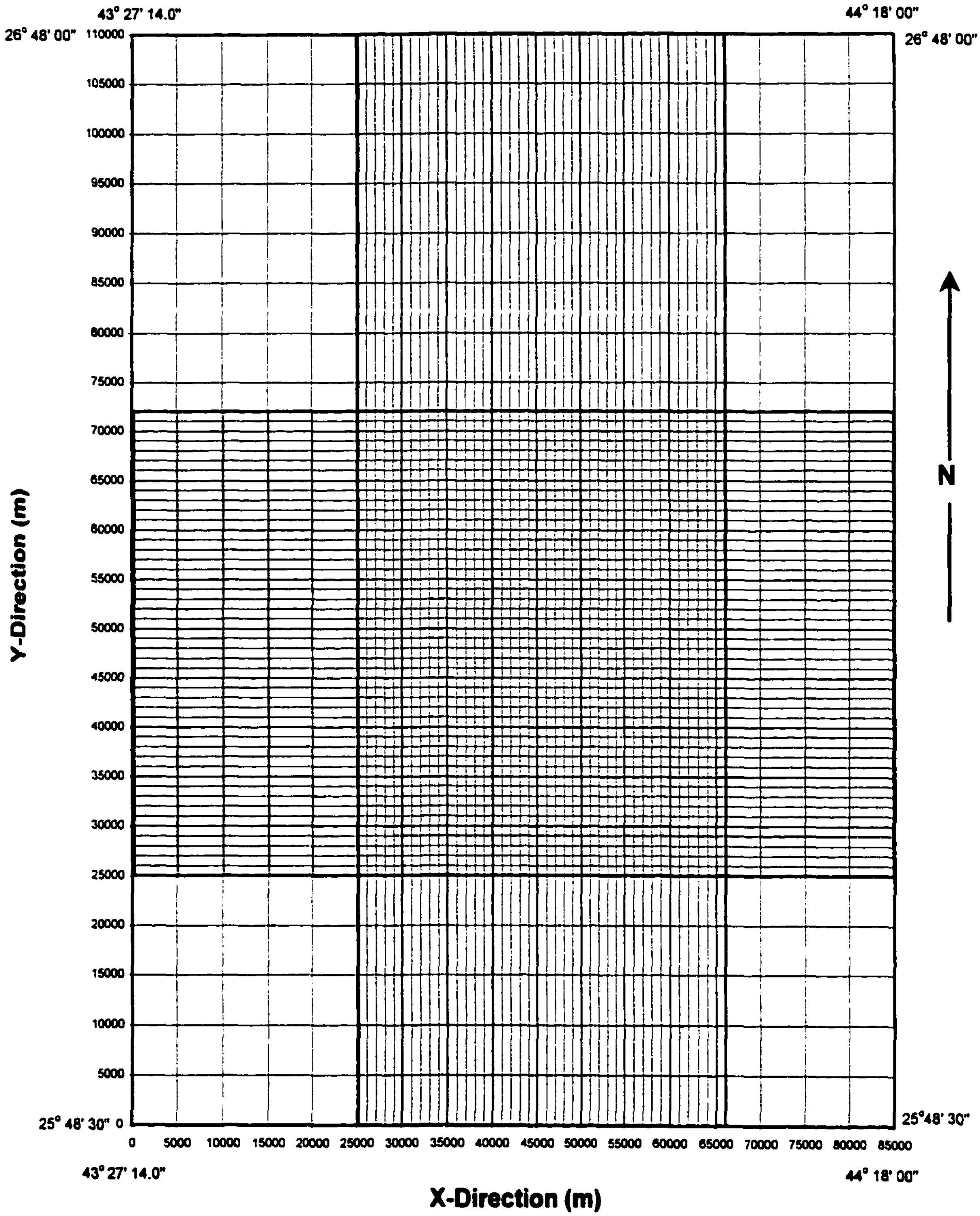


Figure 5.1. Finite-difference grid for the modeled area.

of which evapotranspiration could occur.

## Data Input

The input data that are needed for using of the MODFLOW is as following:

### *Aquifer parameters*

Aquifer parameters include hydraulic conductivity and specific storage. Both parameters were calculated through analysis of a pumping test, which was conducted in the area. From the pumping test analysis, both the transmissivity and storage coefficient were obtained, and from the transmissivity, the hydraulic conductivity of the aquifer was calculated by dividing the transmissivity over the saturated thickness of the aquifer. The hydraulic conductivity value that was used as a uniform value at all the nodes was 2.8 m/day. The specific storage was calculated by dividing the storage coefficient by the saturated thickness of the aquifer. A uniform value of $4.6 \times 10^{-7}$ $m^{-1}$ was assigned for the specific storage at all the nodes.

### *Definition of boundary conditions*

There are no source of recharges neither are there impervious boundaries located in the study area, boundaries may be arbitrarily located far from the center of the grid as long as the stresses to the system will not reach the boundaries during the simulation. That is, the assumption is that heads and flows in the vicinity of the boundaries will not change during the simulation. For that purpose, a value of 585 m for the hydraulic head, which was obtained from the Ministry of Agriculture and Water in 1982, was assigned as constant head boundaries.

***Initial hydraulic heads***

A value of 585 m for the hydraulic head was assigned for the initial hydraulic head, since that value of the hydraulic head was found in 1982 (MAW 1999) to be uniform for some of wells in the study area. In 1982, the Ministry of Agricultural and Water drilled two wells for domestic purpose, and the hydraulic head for both of the two wells was measured to be 585 m. One of the two wells is located in the central study area which named as 10-AlMatta AlShamali well, and the other one is located 5-km just south of the 10-AlMatta AlShamali well which named as 21-AlKhather well.

***Withdrawals through wells***

About 70 productive wells were surveyed in summer, 1999. However, this represents only a small sample of all wells in the region. The total amount of water withdrawn through the 70 wells in the study area is estimated to be 408,100 $m^3$/day (147 MCM/year), and this amount would be used in design of the development management plans.

## Development of Water Management Plans

The developed simulation model of Al-Qassim area was used to assess the effects of different pumping alternatives on future groundwater levels. Several management plans are considered using different discharge rates for a planning period of 51 years (1999-2050).

***First management plan***

The first management plan assumes that the present trend of increase in the water extraction rates continue to 2050. The estimated withdrawal in 1999 was 147 MCM/yr in the Buraydah and Unayzah cities. Assuming the present rate of increases in the water extraction continues, whithdrawals are expected to reach 313 MCM/yr by 2050, or a 113 % increase over the 1999 value. Table 5.1 shows the projected discharge rates used in the model.

***Second management plan***

The second management plan was based on the assumption that the rate of increase in water extraction will be reduced by 50% of the first management plan. This will be achieved by adopting different conservation alternatives to reduce the present and future water demands. With this assumption, the water extraction rate will increase by 57 % of the 1999 withdrawal by 2050. Therefore, the total water extraction is expected to be 230 MCM/yr in 2050. Table 5.2 shows the discharge rates for each well used in the model.

***Third management plan***

The third management plan projects the rate of increase in water extraction will be increased by 50 % over the first management plan. This plan allows new pumping for new areas to be developed. Based on this assumption, the total amount of water extraction is predicted to increase to 396 MCM/yr by 2050, or a 170 % increase over the 1999 value. Table 5.3 shows the water discharges expected in the third management plan.

***Fourth management plan***

The fourth management plan is the combination of the second and third management plans, i.e., the water extractions for the current wells of the second management plan stay as they are, but the total water extraction that is used for that plan is the same amount of that for the third management plan. This plan anticipates new development of irrigation in new areas of the region.

## Calibration

The validity of the model was tested by comparing the numerical solutions with observed data. The difference between the measured and calculated data should be minimized. In order to minimize the variations between observed and simulated values, hydraulic conductivity and storage coefficient were adjusted. The hydraulic conductivity value that was used as a uniform value at all the nodes was 2.8 m/day and a uniform value of $4.6 \times 10^{-7}\ m^{-1}$ was assigned for the specific storage at all the nodes. The calibration procedure for the present model was done under the steady-state condition, which means that the pumping rates were constant. The model was calibrated during the steady-state conditions of 1982 until 1999. Table 5.4 and Figure 5.2 show a comparison of simulated and observed heads during steady-state condition. The results of steady-state calibration closely match and perfectly simulate the measured piezometric heads.

Table 5.1. Discharge rates resulting from the first management plan.

| Well's Name | Discharge rate ($m^3$/day) | | | | | |
|---|---|---|---|---|---|---|
| | 1999 | 2010 | 2020 | 2030 | 2040 | 2050 |
| 1 | 9,267 | 11,522 | 13,573 | 15,623 | 17,674 | 19,724 |
| 2 | 9,267 | 11,522 | 13,573 | 15,623 | 17,674 | 19,724 |
| 3 | 9,267 | 11,522 | 13,573 | 15,623 | 17,674 | 19,724 |
| 4 | 7,631 | 9,489 | 11,178 | 12,866 | 14,555 | 16,244 |
| 5 | 3,271 | 4,067 | 4,790 | 5,514 | 6,238 | 6,962 |
| 6 | 6,814 | 8,472 | 9,980 | 11,488 | 12,996 | 14,503 |
| 7 | 6,541 | 8,133 | 9,581 | 11,028 | 12,476 | 13,923 |
| 8 | 2,180 | 2,711 | 3,194 | 3,676 | 4,159 | 4,641 |
| 9 | 9,267 | 11,522 | 13,573 | 15,623 | 17,674 | 19,724 |
| 10 | 5,996 | 7,456 | 8,782 | 10,109 | 11,436 | 12,763 |
| 11 | 6,541 | 8,133 | 9,581 | 11,028 | 12,476 | 13,923 |
| 12 | 6,541 | 8,133 | 9,581 | 11,028 | 12,476 | 13,923 |
| 14 | 3,271 | 4,067 | 4,790 | 5,514 | 6,238 | 6,962 |
| 15 | 9,267 | 11,522 | 13,573 | 15,623 | 17,674 | 19,724 |
| 16 | 9,812 | 12,200 | 14,371 | 16,542 | 18,714 | 20,885 |
| 17 | 8,722 | 10,845 | 12,774 | 14,704 | 16,634 | 18,564 |
| 18 | 6,541 | 8,133 | 9,581 | 11,028 | 12,476 | 13,923 |
| 19 | 3,543 | 4,406 | 5,190 | 5,974 | 6,758 | 7,542 |
| 20 | 2,726 | 3,389 | 3,992 | 4,595 | 5,198 | 5,801 |
| 21 | 3,543 | 4,406 | 5,190 | 5,974 | 6,758 | 7,542 |
| 22 | 9,267 | 11,522 | 13,573 | 15,623 | 17,674 | 19,724 |
| 23 | 9,812 | 12,200 | 14,371 | 16,542 | 18,714 | 20,885 |
| 24 | 8,722 | 10,845 | 12,774 | 14,704 | 16,634 | 18,564 |
| 25 | 9,267 | 11,522 | 13,573 | 15,623 | 17,674 | 19,724 |
| 26 | 8,722 | 10,845 | 12,774 | 14,704 | 16,634 | 18,564 |
| 27 | 8,722 | 10,845 | 12,774 | 14,704 | 16,634 | 18,564 |
| 1-1 | 7,631 | 9,489 | 11,178 | 12,866 | 14,555 | 16,244 |
| 1-2 | 7,631 | 9,489 | 11,178 | 12,866 | 14,555 | 16,244 |
| 1-3 | 7,631 | 9,489 | 11,178 | 12,866 | 14,555 | 16,244 |
| 1-4 | 7,631 | 9,489 | 11,178 | 12,866 | 14,555 | 16,244 |
| 1-5 | 7,631 | 9,489 | 11,178 | 12,866 | 14,555 | 16,244 |
| 2-1 | 7,631 | 9,489 | 11,178 | 12,866 | 14,555 | 16,244 |
| 2-2 | 7,631 | 9,489 | 11,178 | 12,866 | 14,555 | 16,244 |
| 2-3 | 7,631 | 9,489 | 11,178 | 12,866 | 14,555 | 16,244 |
| 2-4 | 7,631 | 9,489 | 11,178 | 12,866 | 14,555 | 16,244 |
| 2-5 | 7,631 | 9,489 | 11,178 | 12,866 | 14,555 | 16,244 |
| ALHDA | 3,271 | 4,067 | 4,790 | 5,514 | 6,238 | 6,962 |
| HARAT ANOZ | 3,271 | 4,067 | 4,790 | 5,514 | 6,238 | 6,962 |
| AL-ARAMTHAE | 3,271 | 4,067 | 4,790 | 5,514 | 6,238 | 6,962 |
| AL-ASKAN | 8,177 | 10,167 | 11,976 | 13,785 | 15,595 | 17,404 |

Table 5.1. Continued.

| Well's Name | Discharge rate ($m^3$/day) | | | | | |
|---|---|---|---|---|---|---|
| | 1999 | 2010 | 2020 | 2030 | 2040 | 2050 |
| ATHRAS | 4,470 | 5,558 | 6,547 | 7,536 | 8,525 | 9,514 |
| BOSSOR | 3,271 | 4,067 | 4,790 | 5,514 | 6,238 | 6,962 |
| COLLEGE-1 | 4,906 | 6,100 | 7,186 | 8,271 | 9,357 | 10,442 |
| COLLEGE-2 | 4,906 | 6,100 | 7,186 | 8,271 | 9,357 | 10,442 |
| COLLEGE-3 | 4,906 | 6,100 | 7,186 | 8,271 | 9,357 | 10,442 |
| GRA'A | 3,271 | 4,067 | 4,790 | 5,514 | 6,238 | 6,962 |
| AL-GRISH | 6,541 | 8,133 | 9,581 | 11,028 | 12,476 | 13,923 |
| AL-GTHAI | 3,271 | 4,067 | 4,790 | 5,514 | 6,238 | 6,962 |
| AL-HADIKA | 3,271 | 4,067 | 4,790 | 5,514 | 6,238 | 6,962 |
| AL-HNAIA-1 | 2,180 | 2,711 | 3,194 | 3,676 | 4,159 | 4,641 |
| AL-HNAIA-2 | 2,180 | 2,711 | 3,194 | 3,676 | 4,159 | 4,641 |
| HOILAN | 3,271 | 4,067 | 4,790 | 5,514 | 6,238 | 6,962 |
| AL-HOMOR | 3,271 | 4,067 | 4,790 | 5,514 | 6,238 | 6,962 |
| AL-KATHER | 3,271 | 4,067 | 4,790 | 5,514 | 6,238 | 6,962 |
| KMAS | 3,271 | 4,067 | 4,790 | 5,514 | 6,238 | 6,962 |
| AL-MOLIDA | 3,271 | 4,067 | 4,790 | 5,514 | 6,238 | 6,962 |
| AL-MOSHIGH-1 | 3,271 | 4,067 | 4,790 | 5,514 | 6,238 | 6,962 |
| AL-MOSHIGH-2 | 6,541 | 8,133 | 9,581 | 11,028 | 12,476 | 13,923 |
| AL-MOSHIGH-3 | 3,271 | 4,067 | 4,790 | 5,514 | 6,238 | 6,962 |
| AL-MOSHIGH-4 | 6,541 | 8,133 | 9,581 | 11,028 | 12,476 | 13,923 |
| AL-MOTLQ-1 | 2,180 | 2,711 | 3,194 | 3,676 | 4,159 | 4,641 |
| AL-MOTLQ-2 | 2,180 | 2,711 | 3,194 | 3,676 | 4,159 | 4,641 |
| AL-MOREDSIHA | 3,271 | 4,067 | 4,790 | 5,514 | 6,238 | 6,962 |
| AL-QUSAIHA | 3,271 | 4,067 | 4,790 | 5,514 | 6,238 | 6,962 |
| AL-RAGHI-1 | 6,541 | 8,133 | 9,581 | 11,028 | 12,476 | 13,923 |
| AL-RAGHI-2 | 6,541 | 8,133 | 9,581 | 11,028 | 12,476 | 13,923 |
| AL-RAGHIA | 6,541 | 8,133 | 9,581 | 11,028 | 12,476 | 13,923 |
| AL-ROKANI | 3,271 | 4,067 | 4,790 | 5,514 | 6,238 | 6,962 |
| AL-SALHIA | 3,271 | 4,067 | 4,790 | 5,514 | 6,238 | 6,962 |
| AL-SHAMALI-D | 3,271 | 4,067 | 4,790 | 5,514 | 6,238 | 6,962 |
| AL-SHAMALI-K | 3,271 | 4,067 | 4,790 | 5,514 | 6,238 | 6,962 |
| AL-SHOQA-A | 3,271 | 4,067 | 4,790 | 5,514 | 6,238 | 6,962 |
| AL-SHOQA-S | 3,271 | 4,067 | 4,790 | 5,514 | 6,238 | 6,962 |
| **Total** | **408,119** | **507,457** | **597,764** | **688,071** | **778,378** | **868,685** |

Table 5.2. Discharge rates resulting from the second management plan.

| Well's Name | Discharge rate ($m^3$/day) | | | | | |
|---|---|---|---|---|---|---|
| | 1999 | 2010 | 2020 | 2030 | 2040 | 2050 |
| 1 | 9,267 | 10,395 | 11,420 | 12,445 | 13,470 | 14,496 |
| 2 | 9,267 | 10,395 | 11,420 | 12,445 | 13,470 | 14,496 |
| 3 | 9,267 | 10,395 | 11,420 | 12,445 | 13,470 | 14,496 |
| 4 | 7,631 | 8,560 | 9,405 | 10,249 | 11,093 | 11,938 |
| 5 | 3,271 | 3,669 | 4,031 | 4,392 | 4,754 | 5,116 |
| 6 | 6,814 | 7,643 | 8,397 | 9,151 | 9,905 | 10,659 |
| 7 | 6,541 | 7,337 | 8,061 | 8,785 | 9,509 | 10,232 |
| 8 | 2,180 | 2,446 | 2,687 | 2,928 | 3,170 | 3,411 |
| 9 | 9,267 | 10,395 | 11,420 | 12,445 | 13,470 | 14,496 |
| 10 | 5,996 | 6,726 | 7,389 | 8,053 | 8,716 | 9,380 |
| 11 | 6,541 | 7,337 | 8,061 | 8,785 | 9,509 | 10,232 |
| 12 | 6,541 | 7,337 | 8,061 | 8,785 | 9,509 | 10,232 |
| 14 | 3,271 | 3,669 | 4,031 | 4,392 | 4,754 | 5,116 |
| 15 | 9,267 | 10,395 | 11,420 | 12,445 | 13,470 | 14,496 |
| 16 | 9,812 | 11,006 | 12,092 | 13,177 | 14,263 | 15,348 |
| 17 | 8,722 | 9,783 | 10,748 | 11,713 | 12,678 | 13,643 |
| 18 | 6,541 | 7,337 | 8,061 | 8,785 | 9,509 | 10,232 |
| 19 | 3,543 | 3,974 | 4,366 | 4,758 | 5,150 | 5,542 |
| 20 | 2,726 | 3,057 | 3,359 | 3,660 | 3,962 | 4,263 |
| 21 | 3,543 | 3,974 | 4,366 | 4,758 | 5,150 | 5,542 |
| 22 | 9,267 | 10,395 | 11,420 | 12,445 | 13,470 | 14,496 |
| 23 | 9,812 | 11,006 | 12,092 | 13,177 | 14,263 | 15,348 |
| 24 | 8,722 | 9,783 | 10,748 | 11,713 | 12,678 | 13,643 |
| 25 | 9,267 | 10,395 | 11,420 | 12,445 | 13,470 | 14,496 |
| 26 | 8,722 | 9,783 | 10,748 | 11,713 | 12,678 | 13,643 |
| 27 | 8,722 | 9,783 | 10,748 | 11,713 | 12,678 | 13,643 |
| 1-1 | 7,631 | 8,560 | 9,405 | 10,249 | 11,093 | 11,938 |
| 1-2 | 7,631 | 8,560 | 9,405 | 10,249 | 11,093 | 11,938 |
| 1-3 | 7,631 | 8,560 | 9,405 | 10,249 | 11,093 | 11,938 |
| 1-4 | 7,631 | 8,560 | 9,405 | 10,249 | 11,093 | 11,938 |
| 1-5 | 7,631 | 8,560 | 9,405 | 10,249 | 11,093 | 11,938 |
| 2-1 | 7,631 | 8,560 | 9,405 | 10,249 | 11,093 | 11,938 |
| 2-2 | 7,631 | 8,560 | 9,405 | 10,249 | 11,093 | 11,938 |
| 2-3 | 7,631 | 8,560 | 9,405 | 10,249 | 11,093 | 11,938 |
| 2-4 | 7,631 | 8,560 | 9,405 | 10,249 | 11,093 | 11,938 |
| 2-5 | 7,631 | 8,560 | 9,405 | 10,249 | 11,093 | 11,938 |
| ALHDA | 3,271 | 3,669 | 4,031 | 4,392 | 4,754 | 5,116 |
| HARAT ANOZ | 3,271 | 3,669 | 4,031 | 4,392 | 4,754 | 5,116 |
| AL-ARAMTHAE | 3,271 | 3,669 | 4,031 | 4,392 | 4,754 | 5,116 |
| AL-ASKAN | 8,177 | 9,172 | 10,076 | 10,981 | 11,886 | 12,790 |

Table 5.2. Continued.

| Well's Name | Discharge rate ($m^3$/day) | | | | | |
|---|---|---|---|---|---|---|
| | 1999 | 2010 | 2020 | 2030 | 2040 | 2050 |
| ATHRAS | 4,470 | 5,014 | 5,508 | 6,003 | 6,497 | 6,992 |
| BOSSOR | 3,271 | 3,669 | 4,031 | 4,392 | 4,754 | 5,116 |
| COLLEGE-1 | 4,906 | 5,503 | 6,046 | 6,589 | 7,131 | 7,674 |
| COLLEGE-2 | 4,906 | 5,503 | 6,046 | 6,589 | 7,131 | 7,674 |
| COLLEGE-3 | 4,906 | 5,503 | 6,046 | 6,589 | 7,131 | 7,674 |
| GRA'A | 3,271 | 3,669 | 4,031 | 4,392 | 4,754 | 5,116 |
| AL-GRISH | 6,541 | 7,337 | 8,061 | 8,785 | 9,509 | 10,232 |
| AL-GTHAI | 3,271 | 3,669 | 4,031 | 4,392 | 4,754 | 5,116 |
| AL-HADIKA | 3,271 | 3,669 | 4,031 | 4,392 | 4,754 | 5,116 |
| AL-HNAIA-1 | 2,180 | 2,446 | 2,687 | 2,928 | 3,170 | 3,411 |
| AL-HNAIA-2 | 2,180 | 2,446 | 2,687 | 2,928 | 3,170 | 3,411 |
| HOILAN | 3,271 | 3,669 | 4,031 | 4,392 | 4,754 | 5,116 |
| AL-HOMOR | 3,271 | 3,669 | 4,031 | 4,392 | 4,754 | 5,116 |
| AL-KATHER | 3,271 | 3,669 | 4,031 | 4,392 | 4,754 | 5,116 |
| KMAS | 3,271 | 3,669 | 4,031 | 4,392 | 4,754 | 5,116 |
| AL-MOLIDA | 3,271 | 3,669 | 4,031 | 4,392 | 4,754 | 5,116 |
| AL-MOSHIGH-1 | 3,271 | 3,669 | 4,031 | 4,392 | 4,754 | 5,116 |
| AL-MOSHIGH-2 | 6,541 | 7,337 | 8,061 | 8,785 | 9,509 | 10,232 |
| AL-MOSHIGH-3 | 3,271 | 3,669 | 4,031 | 4,392 | 4,754 | 5,116 |
| AL-MOSHIGH-4 | 6,541 | 7,337 | 8,061 | 8,785 | 9,509 | 10,232 |
| AL-MOTLQ-1 | 2,180 | 2,446 | 2,687 | 2,928 | 3,170 | 3,411 |
| AL-MOTLQ-2 | 2,180 | 2,446 | 2,687 | 2,928 | 3,170 | 3,411 |
| AL-MOREDSIHA | 3,271 | 3,669 | 4,031 | 4,392 | 4,754 | 5,116 |
| AL-QUSAIHA | 3,271 | 3,669 | 4,031 | 4,392 | 4,754 | 5,116 |
| AL-RAGHI-1 | 6,541 | 7,337 | 8,061 | 8,785 | 9,509 | 10,232 |
| AL-RAGHI-2 | 6,541 | 7,337 | 8,061 | 8,785 | 9,509 | 10,232 |
| AL-RAGHIA | 6,541 | 7,337 | 8,061 | 8,785 | 9,509 | 10,232 |
| AL-ROKANI | 3,271 | 3,669 | 4,031 | 4,392 | 4,754 | 5,116 |
| AL-SALHIA | 3,271 | 3,669 | 4,031 | 4,392 | 4,754 | 5,116 |
| AL-SHAMALI-D | 3,271 | 3,669 | 4,031 | 4,392 | 4,754 | 5,116 |
| AL-SHAMALI-K | 3,271 | 3,669 | 4,031 | 4,392 | 4,754 | 5,116 |
| AL-SHOQA-A | 3,271 | 3,669 | 4,031 | 4,392 | 4,754 | 5,116 |
| AL-SHOQA-S | 3,271 | 3,669 | 4,031 | 4,392 | 4,754 | 5,116 |
| **Total** | **408,119** | **457,788** | **502,941** | **548,095** | **593,248** | **638,402** |

Table 5.3. Discharge rates resulting from the third management plan.

| Well's Name | Discharge rate ($m^3$/day) | | | | | |
|---|---|---|---|---|---|---|
| | 1999 | 2010 | 2020 | 2030 | 2040 | 2050 |
| 1 | 9,267 | 12,650 | 15,726 | 18,802 | 21,877 | 24,953 |
| 2 | 9,267 | 12,650 | 15,726 | 18,802 | 21,877 | 24,953 |
| 3 | 9,267 | 12,650 | 15,726 | 18,802 | 21,877 | 24,953 |
| 4 | 7,631 | 10,418 | 12,951 | 15,484 | 18,017 | 20,550 |
| 5 | 3,271 | 4,465 | 5,550 | 6,636 | 7,721 | 8,807 |
| 6 | 6,814 | 9,302 | 11,563 | 13,825 | 16,086 | 18,348 |
| 7 | 6,541 | 8,930 | 11,101 | 13,272 | 15,443 | 17,614 |
| 8 | 2,180 | 2,977 | 3,700 | 4,424 | 5,148 | 5,871 |
| 9 | 9,267 | 12,650 | 15,726 | 18,802 | 21,877 | 24,953 |
| 10 | 5,996 | 8,185 | 10,176 | 12,166 | 14,156 | 16,146 |
| 11 | 6,541 | 8,930 | 11,101 | 13,272 | 15,443 | 17,614 |
| 12 | 6,541 | 8,930 | 11,101 | 13,272 | 15,443 | 17,614 |
| 14 | 3,271 | 4,465 | 5,550 | 6,636 | 7,721 | 8,807 |
| 15 | 9,267 | 12,650 | 15,726 | 18,802 | 21,877 | 24,953 |
| 16 | 9,812 | 13,394 | 16,651 | 19,908 | 23,164 | 26,421 |
| 17 | 8,722 | 11,906 | 14,801 | 17,696 | 20,591 | 23,485 |
| 18 | 6,541 | 8,930 | 11,101 | 13,272 | 15,443 | 17,614 |
| 19 | 3,543 | 4,837 | 6,013 | 7,189 | 8,365 | 9,541 |
| 20 | 2,726 | 3,721 | 4,625 | 5,530 | 6,435 | 7,339 |
| 21 | 3,543 | 4,837 | 6,013 | 7,189 | 8,365 | 9,541 |
| 22 | 9,267 | 12,650 | 15,726 | 18,802 | 21,877 | 24,953 |
| 23 | 9,812 | 13,394 | 16,651 | 19,908 | 23,164 | 26,421 |
| 24 | 8,722 | 11,906 | 14,801 | 17,696 | 20,591 | 23,485 |
| 25 | 9,267 | 12,650 | 15,726 | 18,802 | 21,877 | 24,953 |
| 26 | 8,722 | 11,906 | 14,801 | 17,696 | 20,591 | 23,485 |
| 27 | 8,722 | 11,906 | 14,801 | 17,696 | 20,591 | 23,485 |
| 1-1 | 7,631 | 10,418 | 12,951 | 15,484 | 18,017 | 20,550 |
| 1-2 | 7,631 | 10,418 | 12,951 | 15,484 | 18,017 | 20,550 |
| 1-3 | 7,631 | 10,418 | 12,951 | 15,484 | 18,017 | 20,550 |
| 1-4 | 7,631 | 10,418 | 12,951 | 15,484 | 18,017 | 20,550 |
| 1-5 | 7,631 | 10,418 | 12,951 | 15,484 | 18,017 | 20,550 |
| 2-1 | 7,631 | 10,418 | 12,951 | 15,484 | 18,017 | 20,550 |
| 2-2 | 7,631 | 10,418 | 12,951 | 15,484 | 18,017 | 20,550 |
| 2-3 | 7,631 | 10,418 | 12,951 | 15,484 | 18,017 | 20,550 |
| 2-4 | 7,631 | 10,418 | 12,951 | 15,484 | 18,017 | 20,550 |
| 2-5 | 7,631 | 10,418 | 12,951 | 15,484 | 18,017 | 20,550 |
| ALHDA | 3,271 | 4,465 | 5,550 | 6,636 | 7,721 | 8,807 |
| HARAT ANOZ | 3,271 | 4,465 | 5,550 | 6,636 | 7,721 | 8,807 |
| AL-ARAMTHAE | 3,271 | 4,465 | 5,550 | 6,636 | 7,721 | 8,807 |
| AL-ASKAN | 8,177 | 11,162 | 13,876 | 16,590 | 19,304 | 22,018 |

Table 5.3. Continued.

| Well's Name | Discharge rate ($m^3$/day) | | | | | |
|---|---|---|---|---|---|---|
| | 1999 | 2010 | 2020 | 2030 | 2040 | 2050 |
| ATHRAS | 4,470 | 6,102 | 7,585 | 9,069 | 10,553 | 12,036 |
| BOSSOR | 3,271 | 4,465 | 5,550 | 6,636 | 7,721 | 8,807 |
| COLLEGE-1 | 4,906 | 6,697 | 8,326 | 9,954 | 11,582 | 13,211 |
| COLLEGE-2 | 4,906 | 6,697 | 8,326 | 9,954 | 11,582 | 13,211 |
| COLLEGE-3 | 4,906 | 6,697 | 8,326 | 9,954 | 11,582 | 13,211 |
| GRA'A | 3,271 | 4,465 | 5,550 | 6,636 | 7,721 | 8,807 |
| AL-GRISH | 6,541 | 8,930 | 11,101 | 13,272 | 15,443 | 17,614 |
| AL-GTHAI | 3,271 | 4,465 | 5,550 | 6,636 | 7,721 | 8,807 |
| AL-HADIKA | 3,271 | 4,465 | 5,550 | 6,636 | 7,721 | 8,807 |
| AL-HNAIA-1 | 2,180 | 2,977 | 3,700 | 4,424 | 5,148 | 5,871 |
| AL-HNAIA-2 | 2,180 | 2,977 | 3,700 | 4,424 | 5,148 | 5,871 |
| HOILAN | 3,271 | 4,465 | 5,550 | 6,636 | 7,721 | 8,807 |
| AL-HOMOR | 3,271 | 4,465 | 5,550 | 6,636 | 7,721 | 8,807 |
| AL-KATHER | 3,271 | 4,465 | 5,550 | 6,636 | 7,721 | 8,807 |
| KMAS | 3,271 | 4,465 | 5,550 | 6,636 | 7,721 | 8,807 |
| AL-MOLIDA | 3,271 | 4,465 | 5,550 | 6,636 | 7,721 | 8,807 |
| AL-MOSHIGH-1 | 3,271 | 4,465 | 5,550 | 6,636 | 7,721 | 8,807 |
| AL-MOSHIGH-2 | 6,541 | 8,930 | 11,101 | 13,272 | 15,443 | 17,614 |
| AL-MOSHIGH-3 | 3,271 | 4,465 | 5,550 | 6,636 | 7,721 | 8,807 |
| AL-MOSHIGH-4 | 6,541 | 8,930 | 11,101 | 13,272 | 15,443 | 17,614 |
| AL-MOTLQ-1 | 2,180 | 2,977 | 3,700 | 4,424 | 5,148 | 5,871 |
| AL-MOTLQ-2 | 2,180 | 2,977 | 3,700 | 4,424 | 5,148 | 5,871 |
| AL-MOREDSIHA | 3,271 | 4,465 | 5,550 | 6,636 | 7,721 | 8,807 |
| AL-QUSAIHA | 3,271 | 4,465 | 5,550 | 6,636 | 7,721 | 8,807 |
| AL-RAGHI-1 | 6,541 | 8,930 | 11,101 | 13,272 | 15,443 | 17,614 |
| AL-RAGHI-2 | 6,541 | 8,930 | 11,101 | 13,272 | 15,443 | 17,614 |
| AL-RAGHIA | 6,541 | 8,930 | 11,101 | 13,272 | 15,443 | 17,614 |
| AL-ROKANI | 3,271 | 4,465 | 5,550 | 6,636 | 7,721 | 8,807 |
| AL-SALHIA | 3,271 | 4,465 | 5,550 | 6,636 | 7,721 | 8,807 |
| AL-SHAMALI-D | 3,271 | 4,465 | 5,550 | 6,636 | 7,721 | 8,807 |
| AL-SHAMALI-K | 3,271 | 4,465 | 5,550 | 6,636 | 7,721 | 8,807 |
| AL-SHOQA-A | 3,271 | 4,465 | 5,550 | 6,636 | 7,721 | 8,807 |
| AL-SHOQA-S | 3,271 | 4,465 | 5,550 | 6,636 | 7,721 | 8,807 |
| **Total** | **408,119** | **557,126** | **692,586** | **828,046** | **963,507** | **1,098,967** |

Table 5.4. A comparison of measured and calculated heads during steady-state condition.

| Observation well's name | Measured head (m) | Calculated head (m) |
|---|---|---|
| 2-AlMatta AlJanobi | 517 | 517.14 |
| 4-Salah Aldeen | 520 | 523.0 |
| 10-AlMatta AlShamali | 514 | 514.7 |
| 11- AlMatta AlShamali | 513 | 514.7 |
| 12- AlMatta AlShamali | 518 | 519.0 |
| 14- AlMatta AlJanobi | 517 | 517.2 |
| 20-AlThahai | 540 | 544.8 |
| 21-AlKhather | 529 | 529.3 |
| 22-AlKhather | 518 | 527.6 |
| 24-AlKhather | 525 | 528.0 |
| 2-1-Unayzah | 549 | 549.1 |

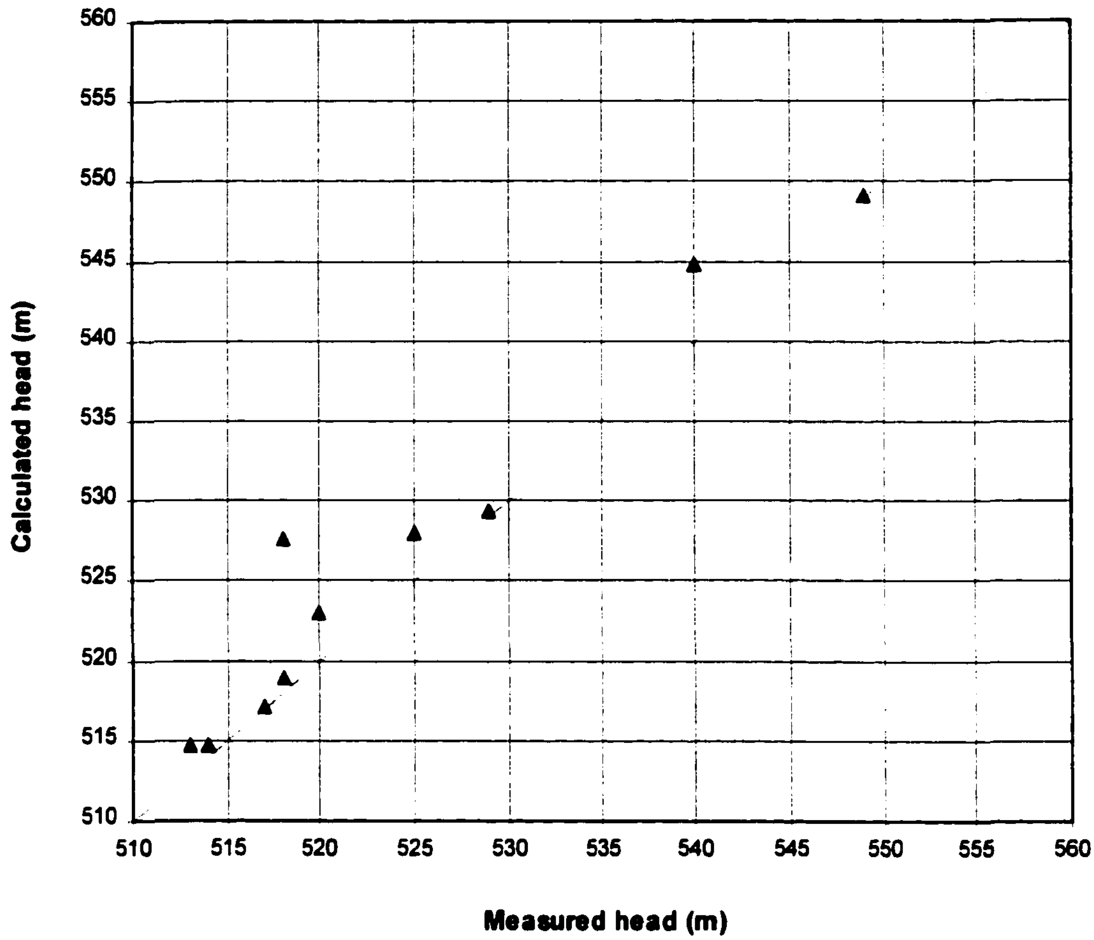


Figure 5.2. A comparison of measured and calculated heads during steady-state condition.

# CHAPTER 6. RESULTS AND DISCUSSION

## Effect of Different Pumping Alternatives on Groundwater Levels

The developed simulation model of Al-Qassim area was used to assess the effects of different pumping alternatives on future groundwater levels. Figure 6.1 shows the simulated distribution of the hydraulic head for the Saq aquifer at the end of 1999. The simulated distribution of the hydraulic head as predicted at the end of 1999 was used as the initial hydraulic head distribution for the future simulation.

Several management plans are considered using different discharge rates for a planning period of 51 years (1999-2050) and the results of these management plans are presented in the following paragraphs:

### *First management plan*

In this plan, it assumes that the present tend of increase in the water extraction rates continue until the end of year 2050. The predicted distribution of hydraulic head for the year of 2010 is shown in Figure 6.2. As shown in the figure, the lowest hydraulic head is in the center of the study area where there are many domestic wells for the city of Buraydah. The hydraulic head in the central area is 510 m and the resulting change of the hydraulic head (drawdown) from the current level (as calculated in 1999) is 15 m. The hydraulic head in south of the central area where there are some of the domestic wells as well as there are some irrigation wells in that area, is 522 m with drawdown about 13 m. The hydraulic head in Unayzah city, south of Buraydah city, is 547 m which is higher than the hydraulic head in Buraydah city and the resulting change of the hydraulic head from the current level is 8 m.

Figure 6.3 shows the predicted hydraulic head distribution for the year of 2020. The hydraulic head continues decreasing toward the center of the study area. The hydraulic head

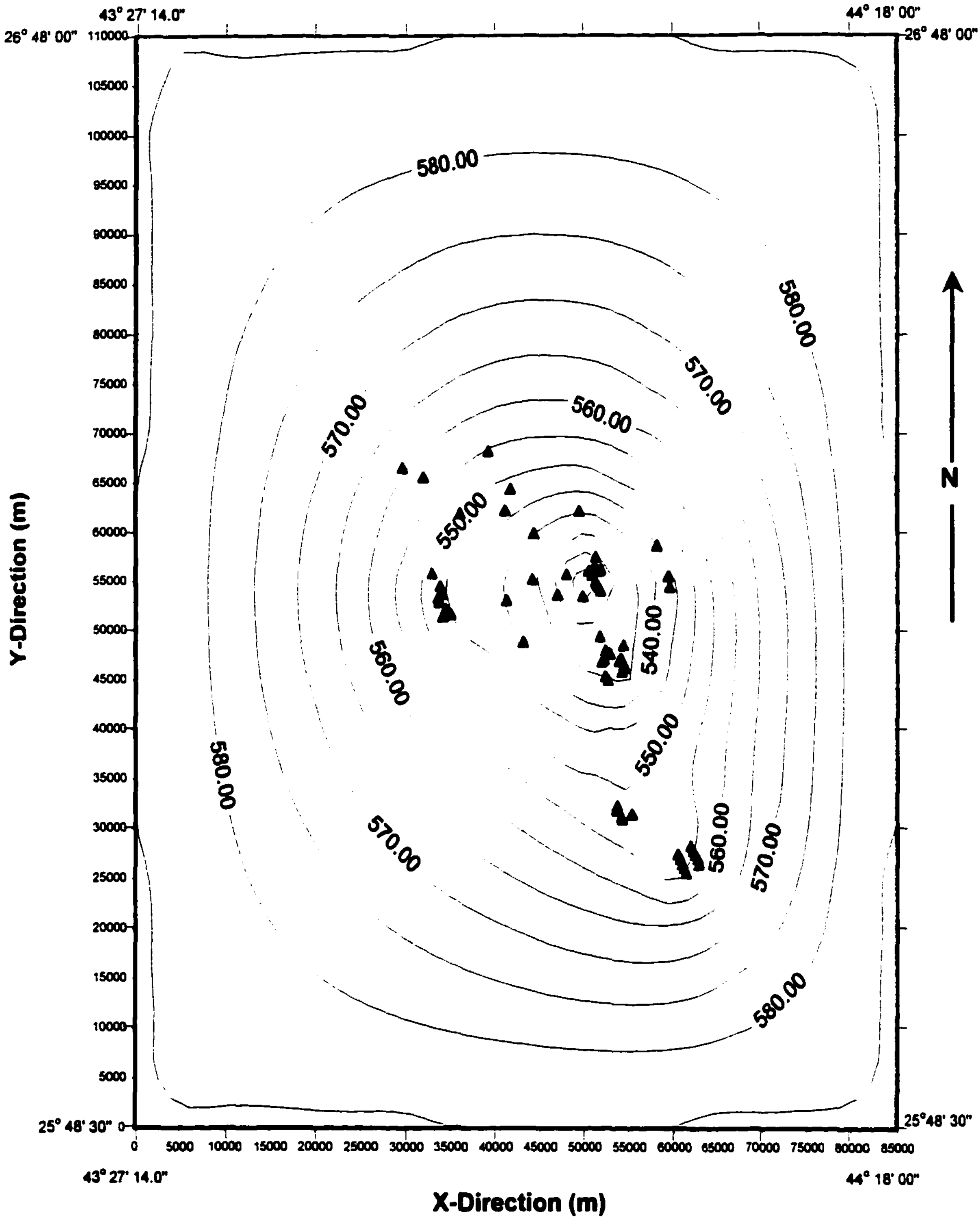


Figure 6.1. Predicted hydraulic head distribution for the year of 1999 which used as initial hydraulic heads

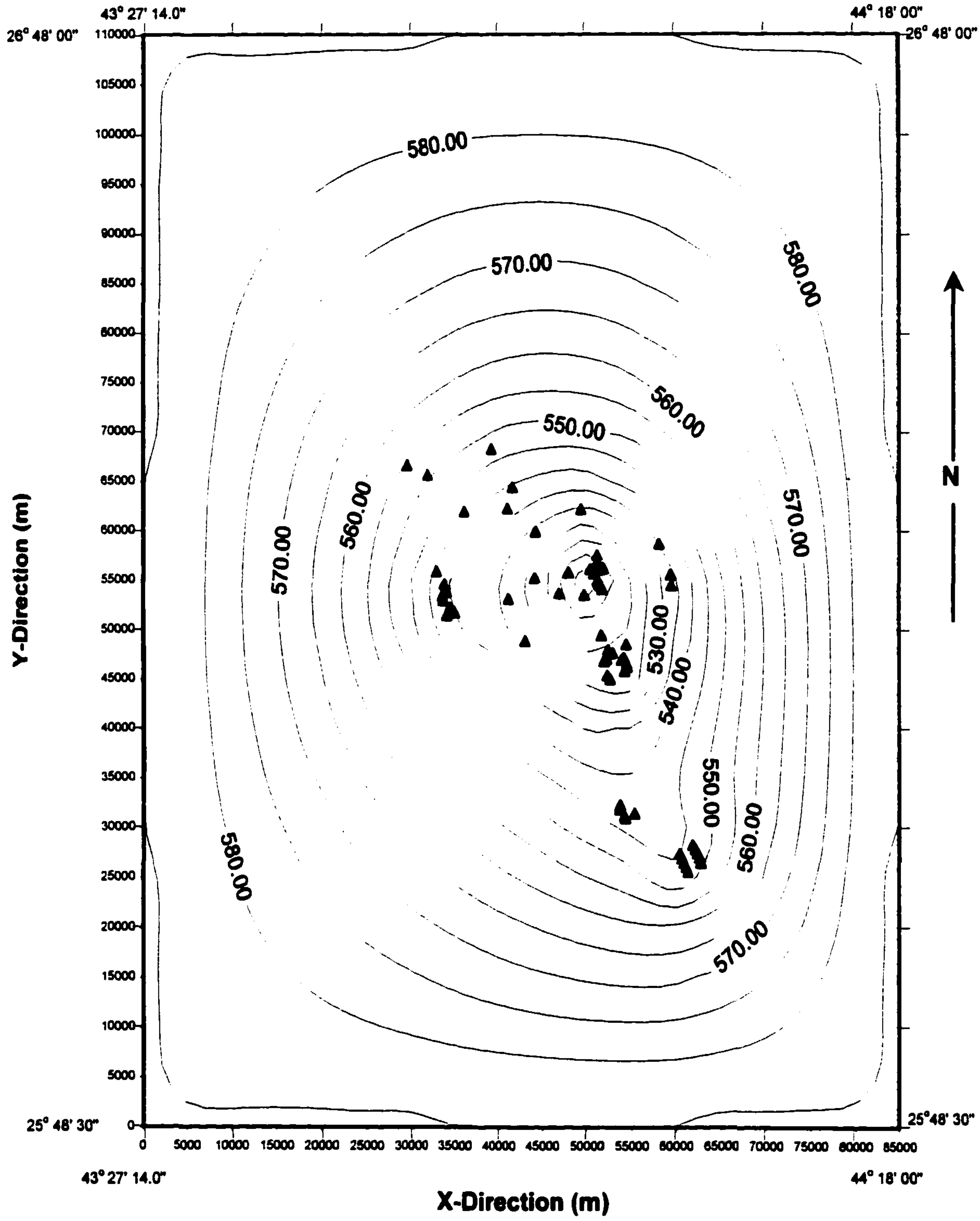


Figure 6.2. Predicted hydraulic head distribution for the first management plan during the period of 2010.

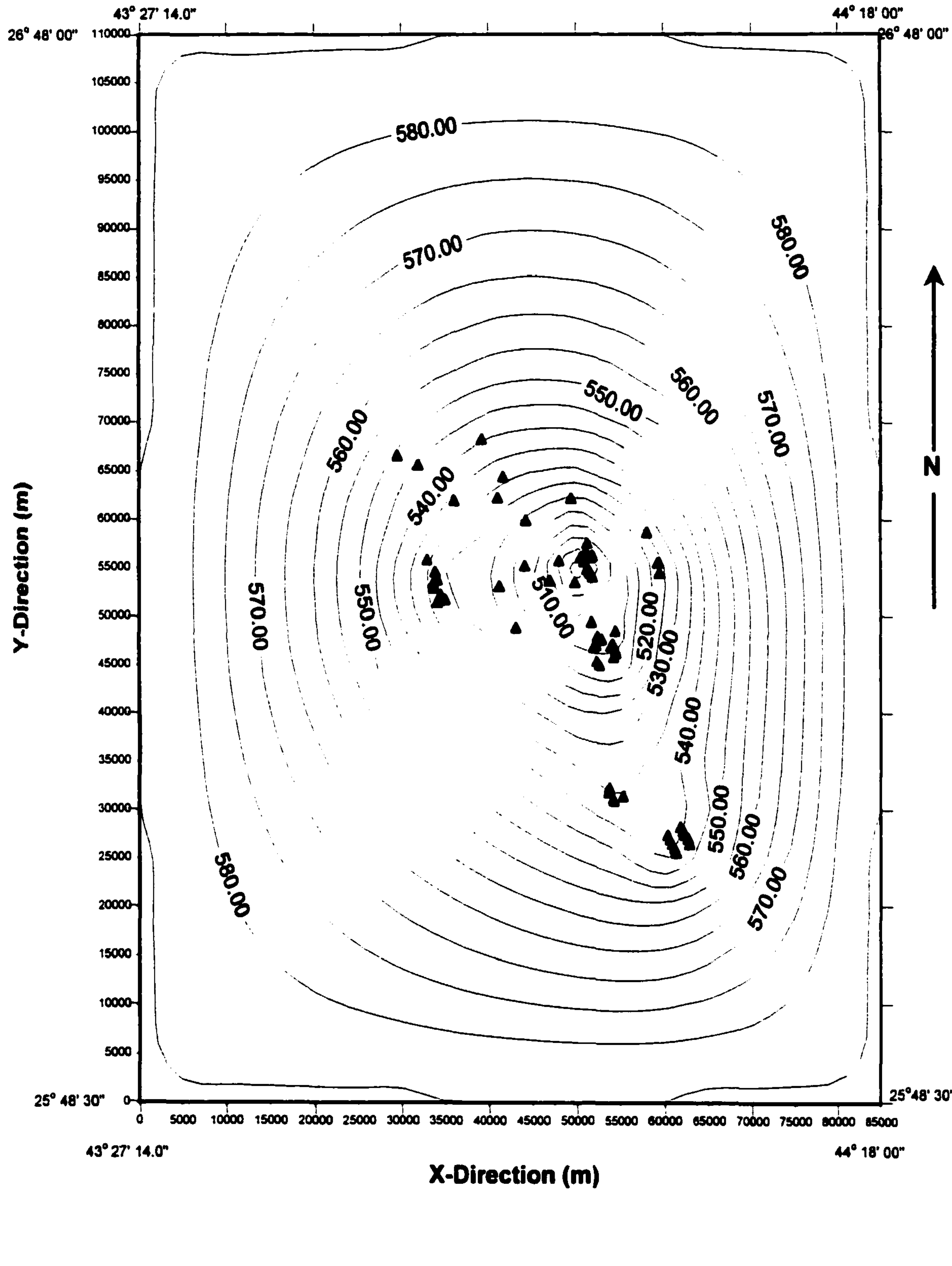


Figure 6.3. Predicted hydraulic head distribution for the first management plan during the period of 2020.

in Buraydah city is 500 m with maximum drawdown about 25 m and the hydraulic head in Unayzah city is predicted to be 540 m and the resulting changes of the hydraulic head (drawdown) from the current (1999 level) is 15 m. In the area which has some of the domestic wells (wells # 21, 22, 23, 24, 25, 26, and 27), the hydraulic head is 510 m, and the drawdown is 25 m.

The hydraulic head distribution for the year of 2030 is shown in Figure 6.4. As the result of the increase in pumping rates during that period, the lowest hydraulic head is found in the center of the study area, which has many domestic wells (wells # 1-17) and they are close to each other. The hydraulic head in that area, which called "Al-Matta", is 485 m with maximum drawdown about 40 m. In south of the center area (about 5 km south of the center area), the hydraulic head is 500 m, and the resulting change of the hydraulic head (drawdown) from the current level is 35 m. The hydraulic head in Unayzah city reaches a value of 535 m with drawdown about 20 m.

Figure 6.5 shows the predicted hydraulic head distribution for the period of 2040 for the period of 2040. As shown in the figure, the hydraulic head decreases toward the center of the study area, which has a lot of domestic wells. The hydraulic head in the center of the study (Al-Matta) is 470 m with the maximum drawdown about 55 m. About 5-km south from Al-Matta, the hydraulic head reaches about 485 m and the drawdown is 50 m. The hydraulic head in Unayzah city reaches a value of 528 m and the resulting change of the hydraulic head (drawdown) from the current level (as calculated in 1999) is 27 m.

The predicted distribution of the hydraulic head after 50 years (2050) is shown in Figure 6.6. The lowest hydraulic head is located in the center of the study area, which has heavy pumping rates. The hydraulic head in that area (Al-Matta) reaches about 460 m and

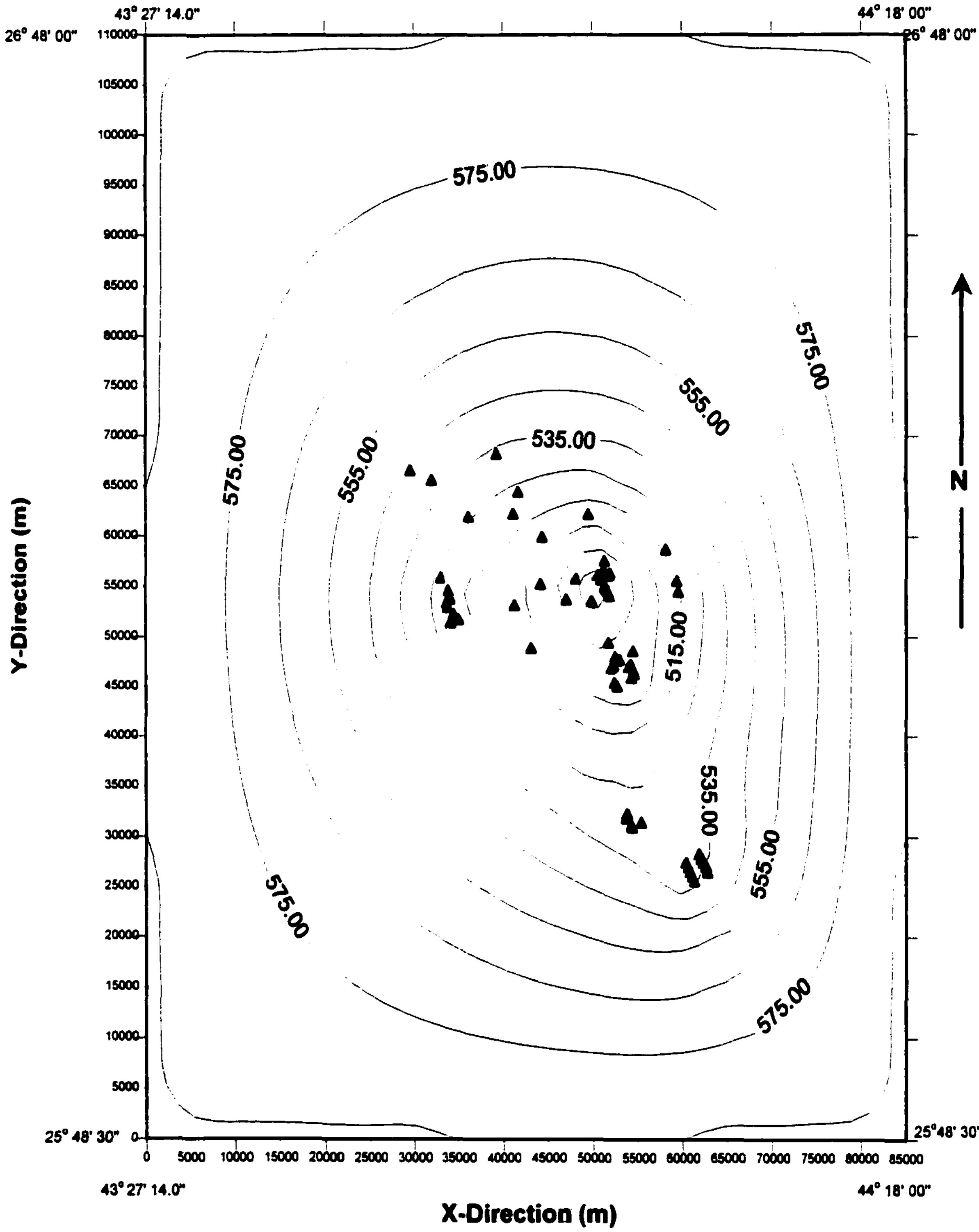


Figure 6.4. Predicted hydraulic head distribution for the first management plan during the period of 2030.

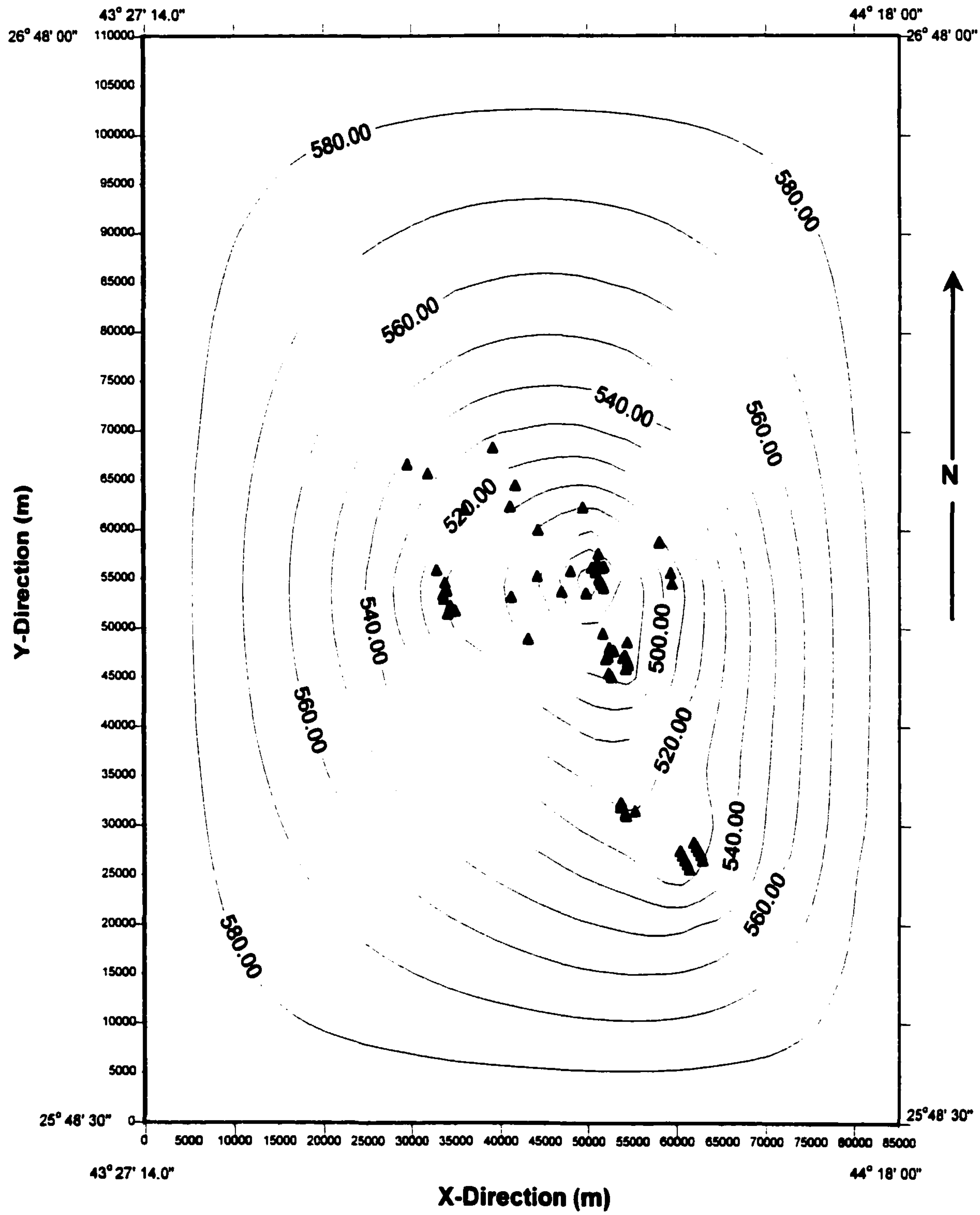


Figure 6.5. Predicted hydraulic head distribution for the first management plan during the period of 2040.

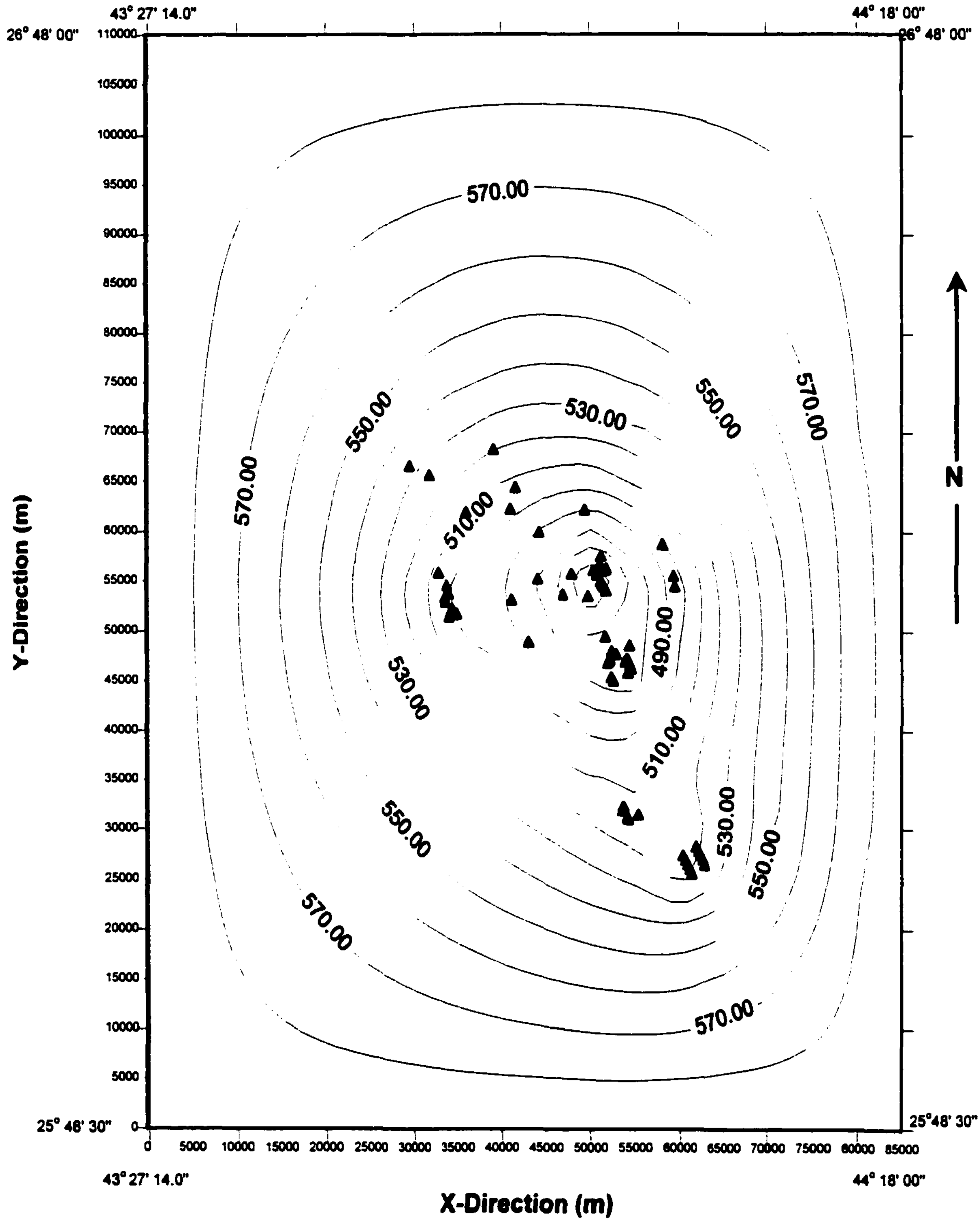


Figure 6.6. Predicted hydraulic head distribution for the first management plan during the period of 2050.

the maximum drawdown is about 65 m. The hydraulic head in south of that area, about 5 km south of Al-Matta, is 475 m and the resulting change in the hydraulic head (drawdown) is 60 m. In Unayzah city, the hydraulic head is about 520 m with drawdown about 35 m.

***Second management plan***

The second management plan was based on the assumption that the rate of increase in water extraction will be reduced by 50% of the first management plan. The hydraulic head distribution for the year of 2010 is shown in Figure 6.7. The lowest hydraulic head is found in the center of the study area, which has many domestic wells (wells # 1-17) and they are close to each other. The hydraulic head in that area, which called "Al-Matta", is 520 m with maximum drawdown about 5 m. In south of the center area (about 5 km south of the center area), the hydraulic head is 530 m, and the drawdown is 5 m. The hydraulic head in Unayzah city reaches a value of 552 m and the resulting change of the hydraulic head (drawdown) from the current level (as calculated in 1999) is about 3 m.

Figure 6.8 shows the predicted hydraulic head distribution for the year of 2020. The hydraulic head decreases toward the center of the study area. The hydraulic head in Buraydah city is 510 m with maximum drawdown about 15 m, while the hydraulic head in Unayzah city is 547 m and the drawdown is 8 m. In the area which has some of the domestic wells (wells # 21, 22, 23, 24, 25, 26, and 27), the hydraulic head is 523 m, and the resulting change of the hydraulic head (drawdown) from the current level (as calculated in 1999) drawdown is 12 m.

The predicted distribution of hydraulic head for the year of 2030 is shown in Figure 6.9. As shown in the figure, the lowest hydraulic head is in the center of the study area where there are many domestic wells for the city of Buraydah. The hydraulic head in the

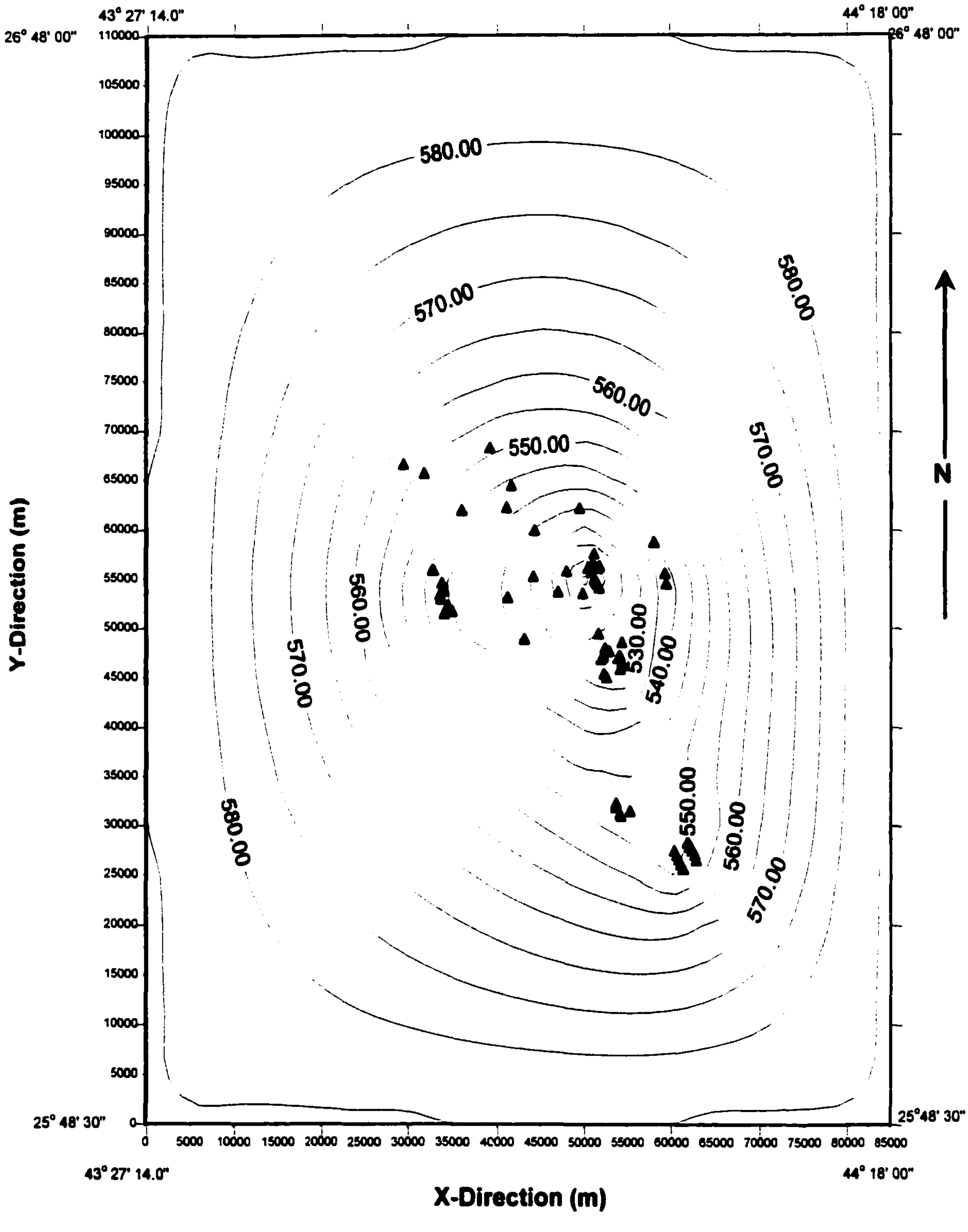


Figure 6.7. Predicted hydraulic head distribution for the second management plan during the period of 2010.

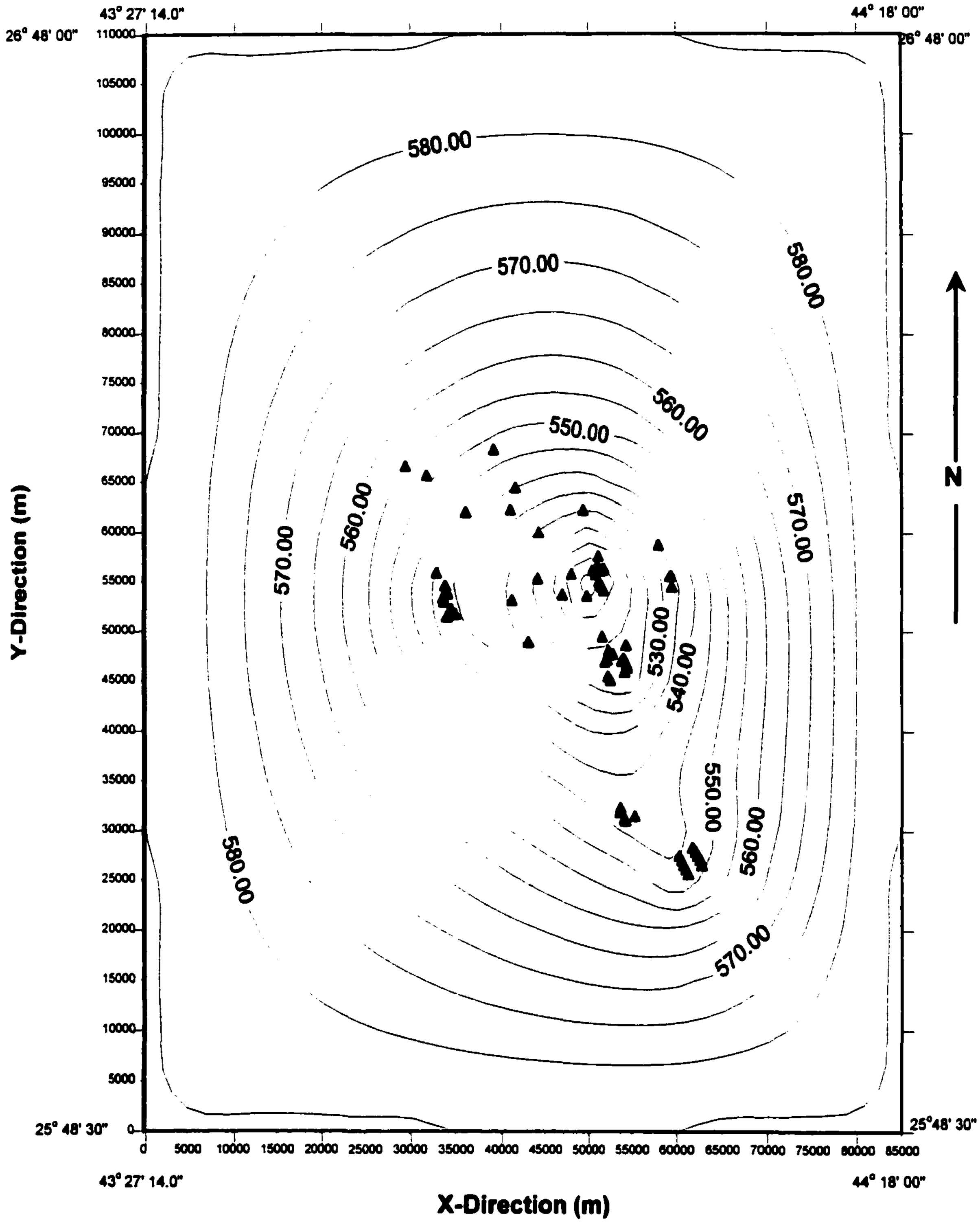


Figure 6.8. Predicted hydraulic head distribution for the second management plan during the period of 2020.

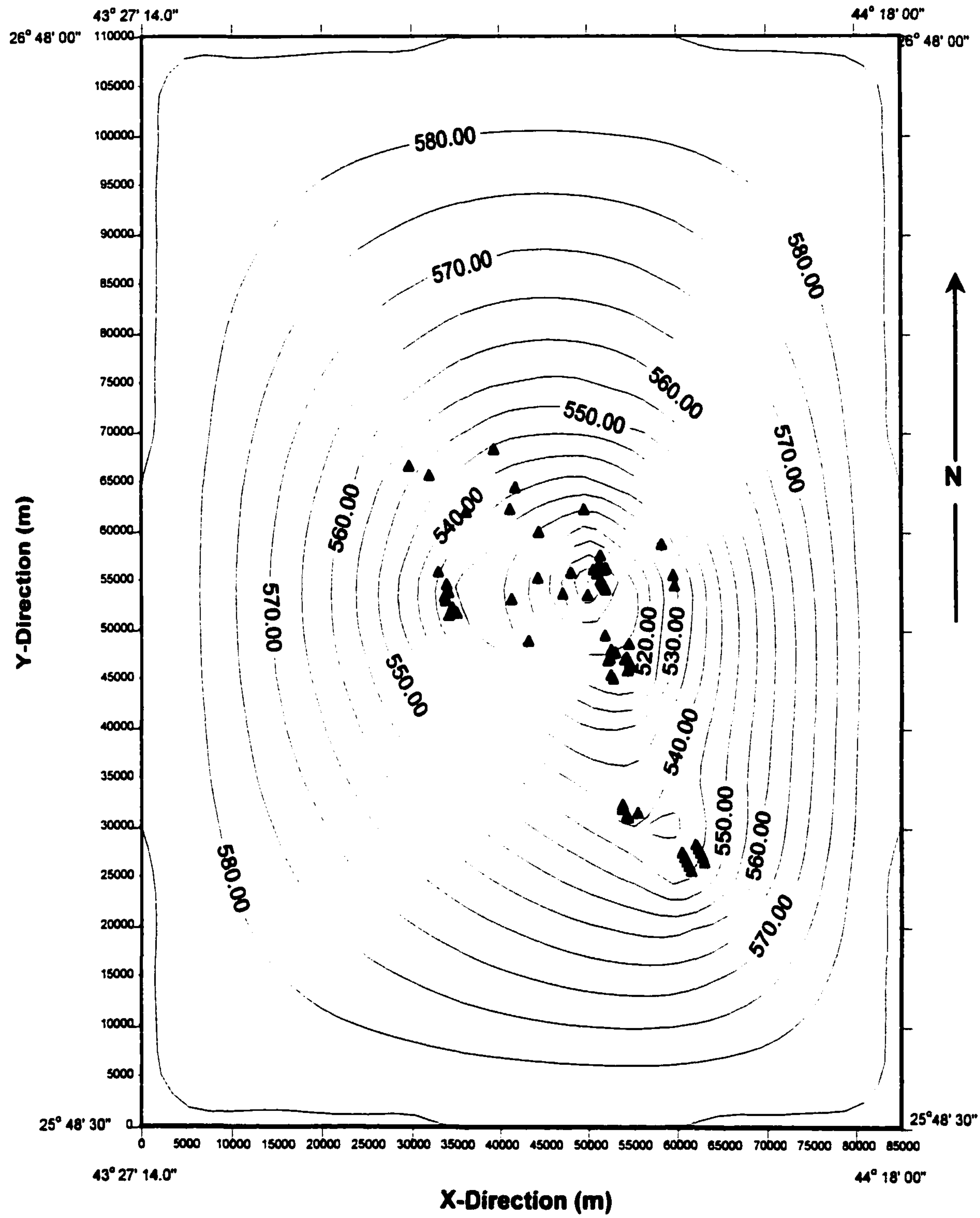


Figure 6.9. Predicted hydraulic head distribution for the second management plan during the period of 2030.

central area is 505 m and the resulting change of the hydraulic head (drawdown) from the current level (as calculated in 1999) is.20 m, while the hydraulic head in south of the central area where there are some of the domestic wells as well as there are irrigation wells in that area, is 517 m with drawdown about 18 m. The hydraulic head in Unayzah city, south of Buraydah city, is 545 m which is higher than the hydraulic head in Buraydah city and the maximum drawdown is about 10 m.

The predicted distribution of the hydraulic head after 40 years (2040) is shown in Figure 6.10. The lowest hydraulic head is located in the center of the study area, which has heavy pumping rates. The hydraulic head in that area (Al-Matta) reaches about 500 m with maximum drawdown about 25 m and the hydraulic head in south of that area, about 5 km south of Al-Matta, is 510 m with drawdown about 25 m. In Unayzah city, the hydraulic head is about 540 m and the resulting change of the hydraulic head (drawdown) from the current level (as calculated in 1999) is 15 m.

Figure 6.11 shows the predicted hydraulic head distribution for the period of 2050. As shown in the figure, the hydraulic head decreases toward the center of the study area, which has a lot of domestic wells. The hydraulic head in the center of the study (Al-Matta) is 493 m with the maximum drawdown about 32 m. About 5-km south from Al-Matta, the hydraulic head reaches about 505 m and the drawdown is 30 m. The hydraulic head in Unayzah city reaches a value of 537 m and the resulting change of the hydraulic head (drawdown) from the current level (as calculated in 1999) is about 18 m.

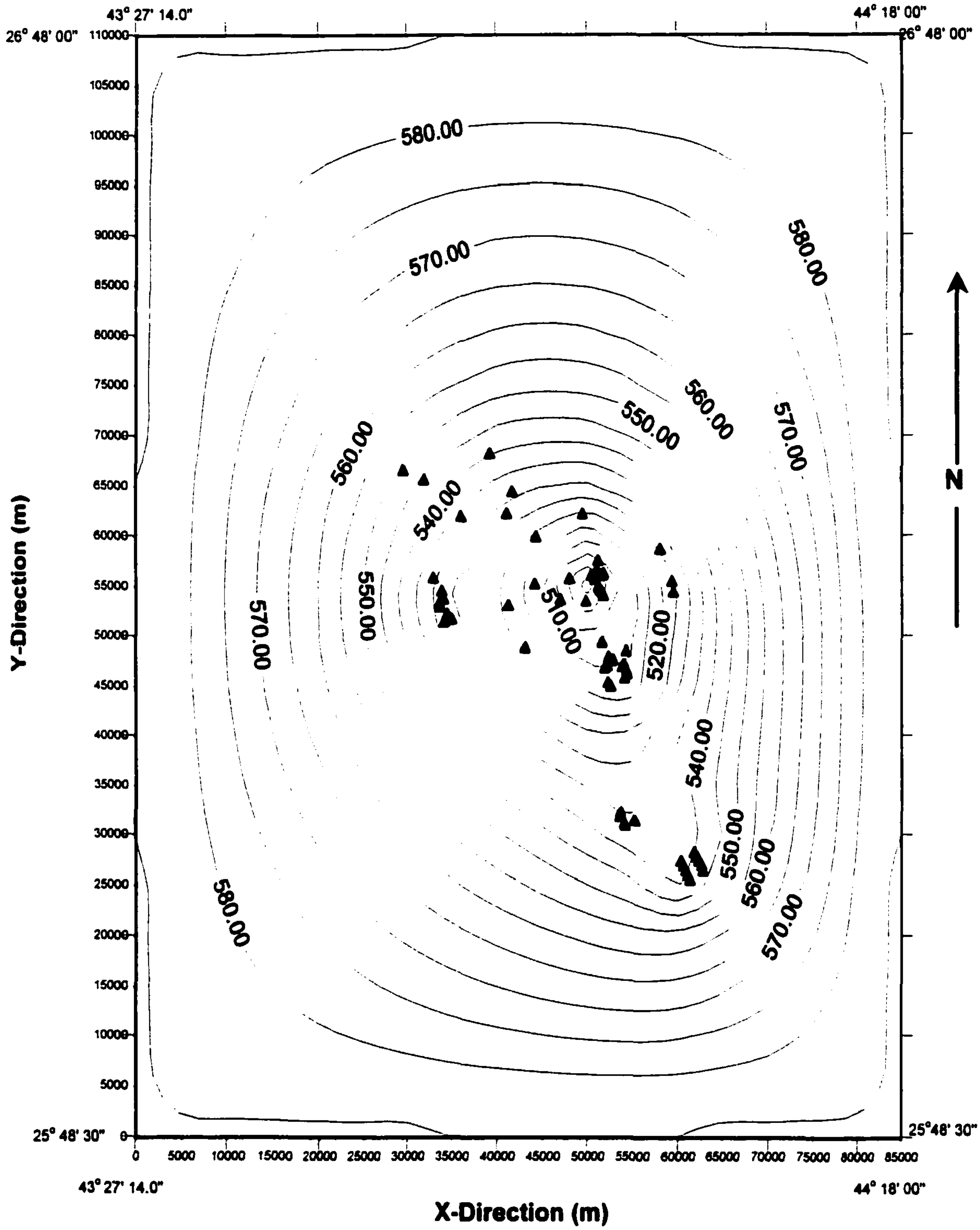


Figure 6.10. Predicted hydraulic head distribution for the second management plan during the period of 2040.

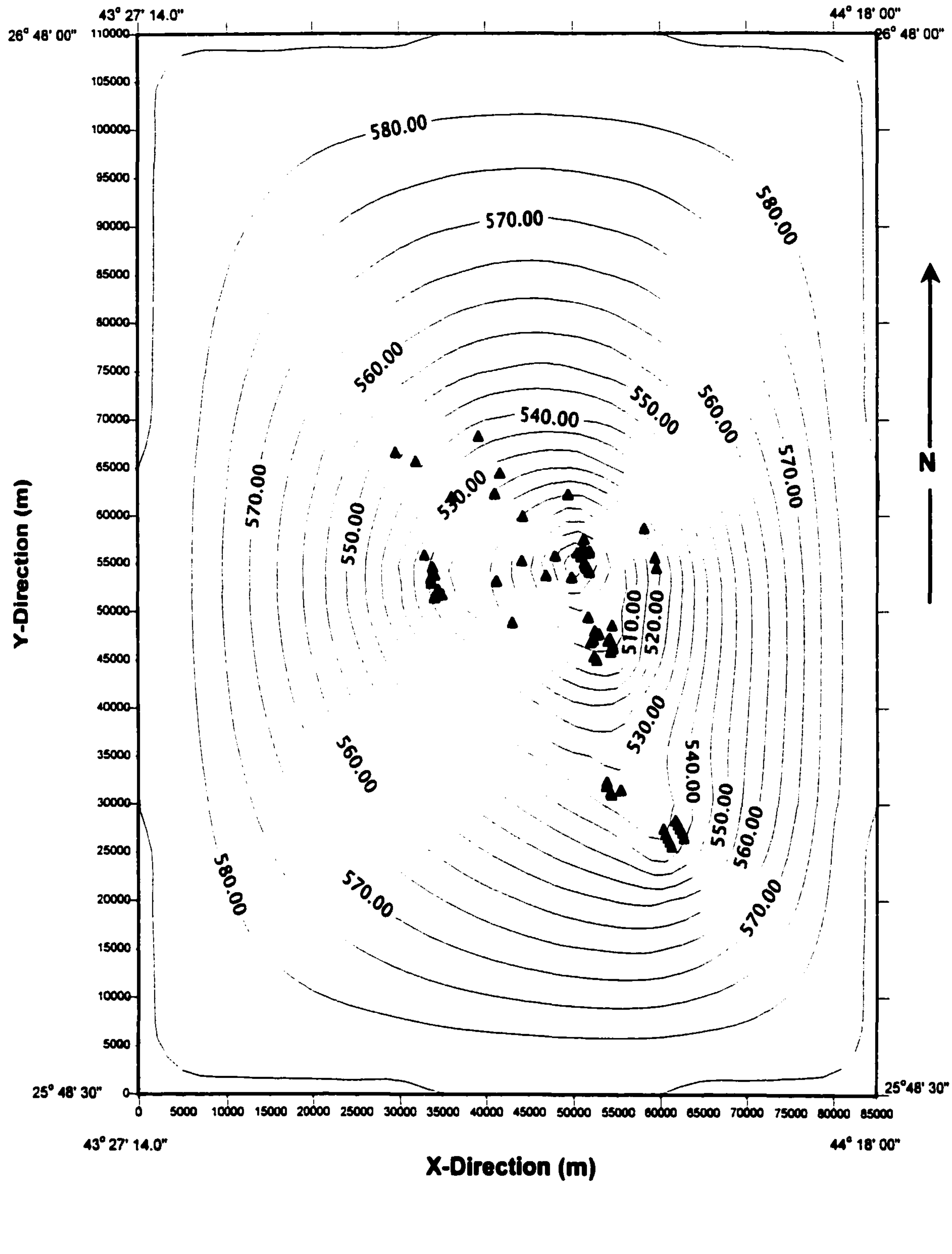


Figure 6.11. Predicted hydraulic head distribution for the second management plan during the period of 2050.

***Third management plan***

The third management plan allows that the rate of increase in water extraction will be increased by 50 % of the first management plan. The predicted distribution of hydraulic head for the year of 2010 is shown in Figure 6.12. As shown in the figure, the lowest hydraulic head is in the center of the study area where there are many domestic wells for the city of Buraydah. The hydraulic head in the central area is 505 m and the resulting change of the hydraulic head (drawdown) from the current level (as calculated in 1999) is 20. The hydraulic head in south of the central area where there are some of the domestic wells as well as there are some irrigation wells in that area, is 515 m with drawdown about 20 m. The hydraulic head in Unayzah city, south of Buraydah city, is 545 m which is higher than the hydraulic head in Buraydah city and the drawdown is about 10 m.

Figure 6.13 shows the predicted hydraulic head distribution for the year of 2020. The hydraulic head decreases toward the center of the study area. The hydraulic head in Buraydah city is 485 m with maximum drawdown about 40 m, while The hydraulic head in Unayzah city is 535 m and the drawdown is 20 m. In the area, which has some of the domestic wells (wells # 21, 22, 23, 24, 25, 26, and 27), the hydraulic head is 500 m and the resulting change of the hydraulic head (drawdown) from the current level (as calculated in 1999) is about 35 m.

Figure 6.14 shows the predicted hydraulic head distribution for the period of 2030. As shown in the figure, the hydraulic head decreases toward the center of the study area, which has a lot of domestic wells. The hydraulic head in the center of the study (Al-Matta) is 465 m with the maximum drawdown about 60 m. About 5-km south from Al-Matta, the hydraulic head reaches about 485 m and the drawdown is 50 m. The hydraulic head in

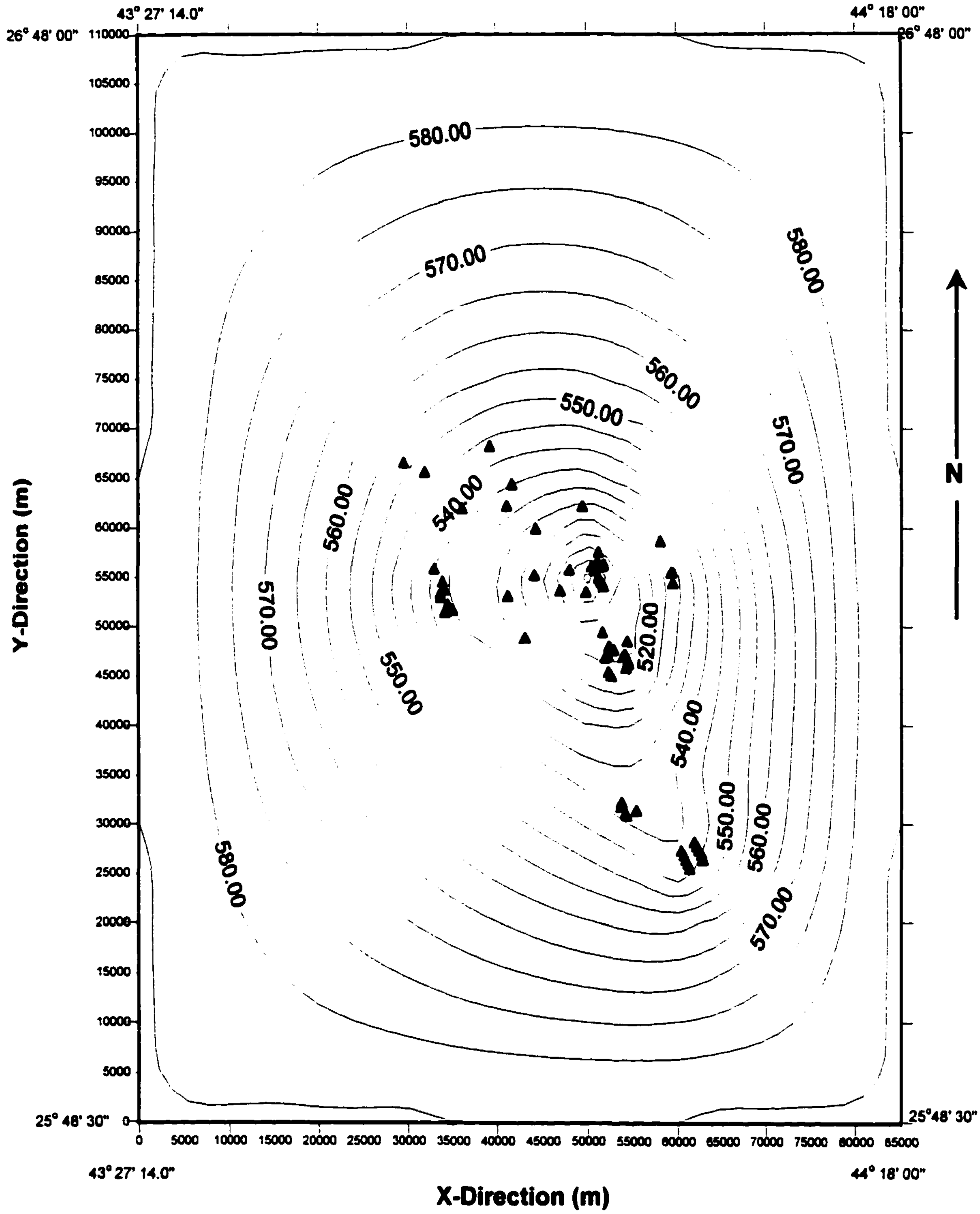


Figure 6.12. Predicted hydraulic head distribution for the third management plan during the period of 2010.

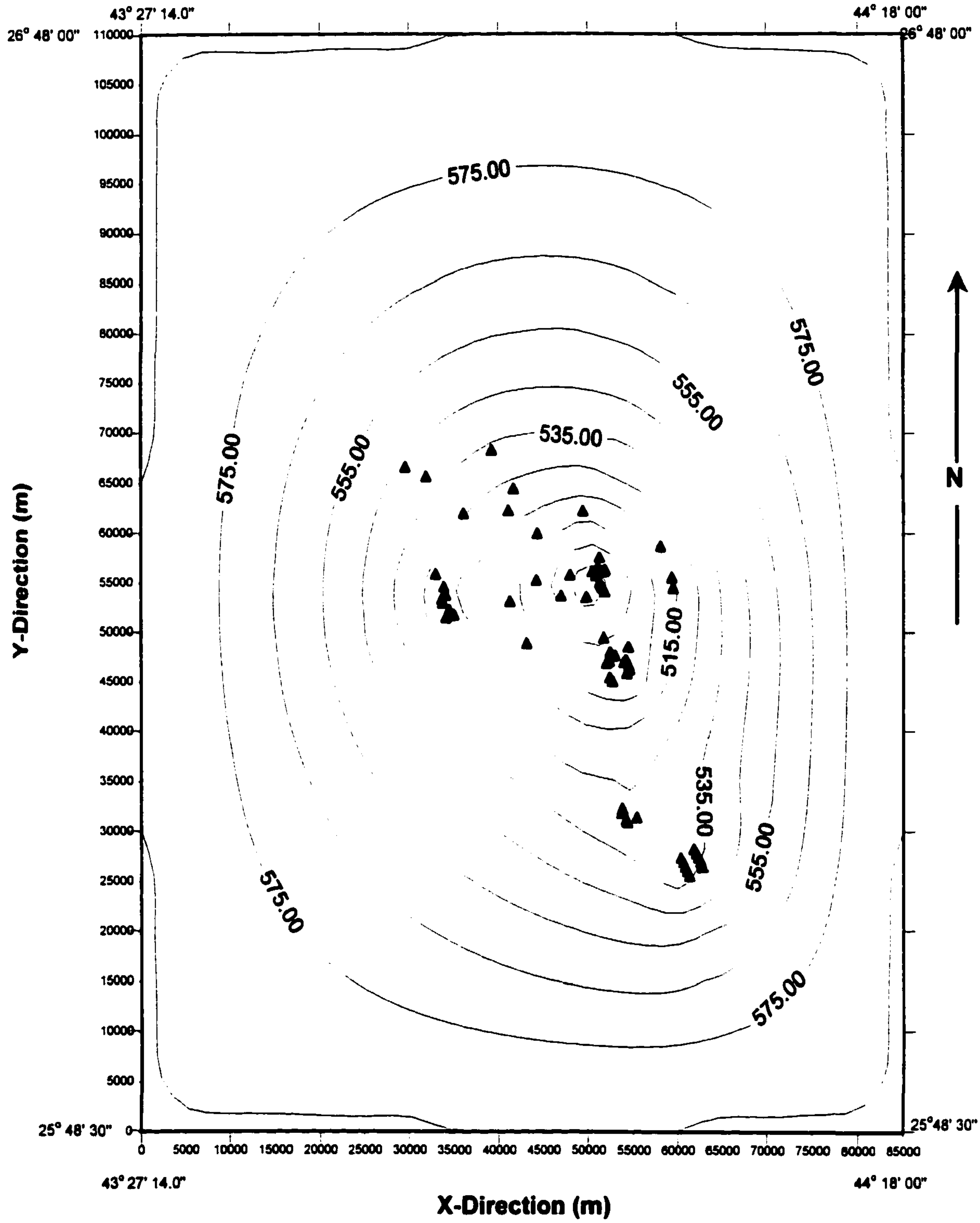


Figure 6.13. Predicted hydraulic head distribution for the third management plan during the period of 2020.

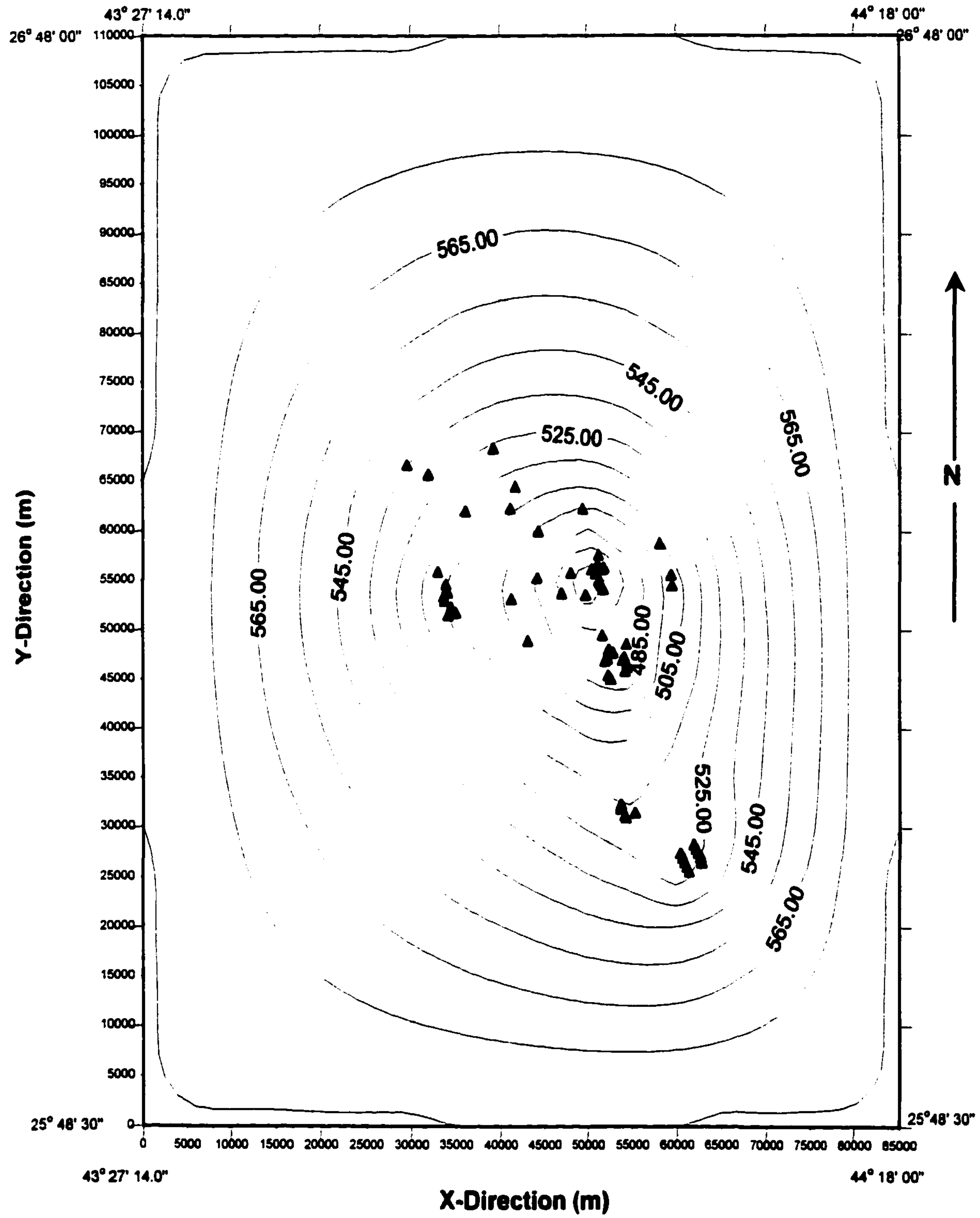


Figure 6.14. Predicted hydraulic head distribution for the third management plan during the period of 2030.

Unayzah city reaches a value of 525 m and the resulting change of the hydraulic head (drawdown) from the current level (as calculated in 1999) is 30 m.

The hydraulic head distribution for the year of 2040 is shown in Figure 6.15. As the result of the increase in pumping rates during that period, the lowest hydraulic head is found in the center of the study area, which has many domestic wells (wells # 1-17) and they are close to each other. The hydraulic head in that area, which called "Al-Matta", is 445 m and the resulting change of the hydraulic head (drawdown) from the current level (as calculated in 1999) is about 80 m. In south of the center area (about 5 km south of the center area), the hydraulic head is 465 m, and the drawdown is 70 m. The hydraulic head in Unayzah city reaches a value of 515 m with drawdown about 40 m.

The predicted distribution of the hydraulic head after 50 years (2050) is shown in Figure 6.16. The lowest hydraulic head is located in the center of the study area, where there are heavy pumping rates. The hydraulic head in that area (Al-Matta) reaches about 425 m with maximum drawdown about 100 m, while the hydraulic head in south of that area, about 5 km south of Al-Matta, is 445 m with drawdown about 90 m. In Unayzah city, the hydraulic head is about 505 m, which is higher than the hydraulic head in Buraydah city, and the drawdown is about 50 m.

***Fourth management plan***

The fourth management plan is the combination of the second and third management plans. The predicted distribution of hydraulic head for the year of 2010 is shown in Figure 6.17. As shown in the figure, the lowest hydraulic head is in the center of the study area where there are many domestic wells for the city of Buraydah. The hydraulic head in the central area is 515 m and the resulting change of the hydraulic head (drawdown) from the

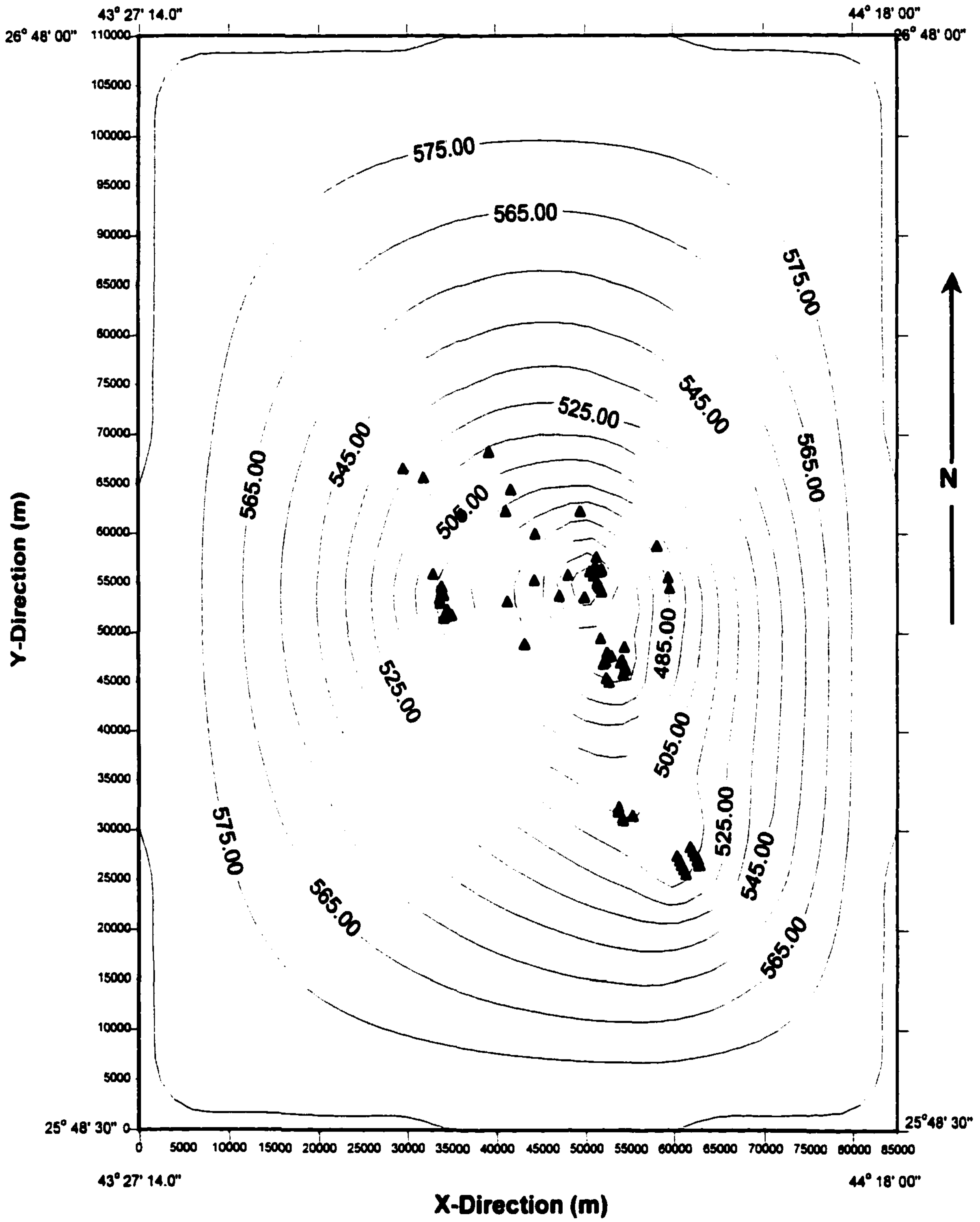


Figure 6.15. Predicted hydraulic head distribution for the third management plan during the period of 2040.

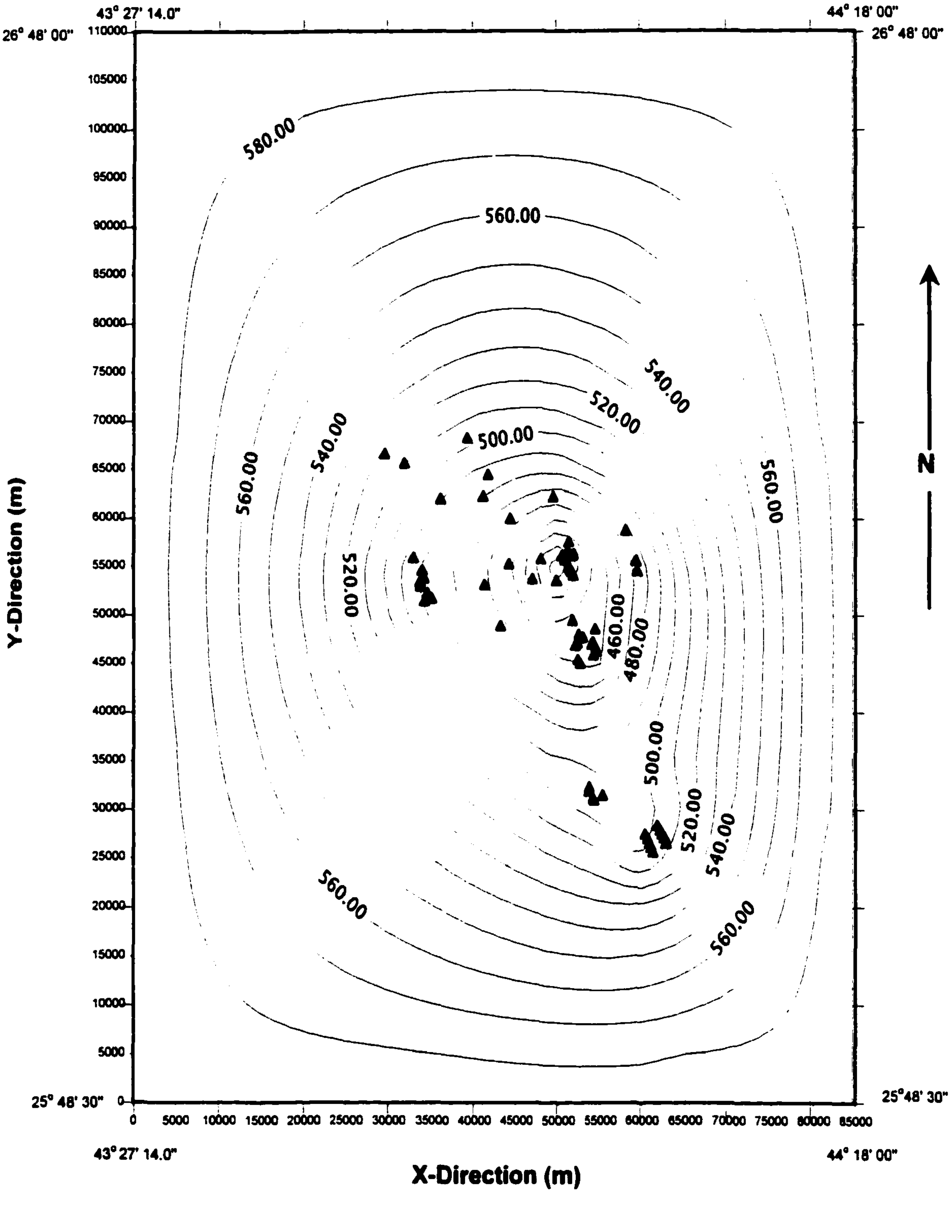


Figure 6.16. Predicted hydraulic head distribution for the third management plan during the period of 2050.

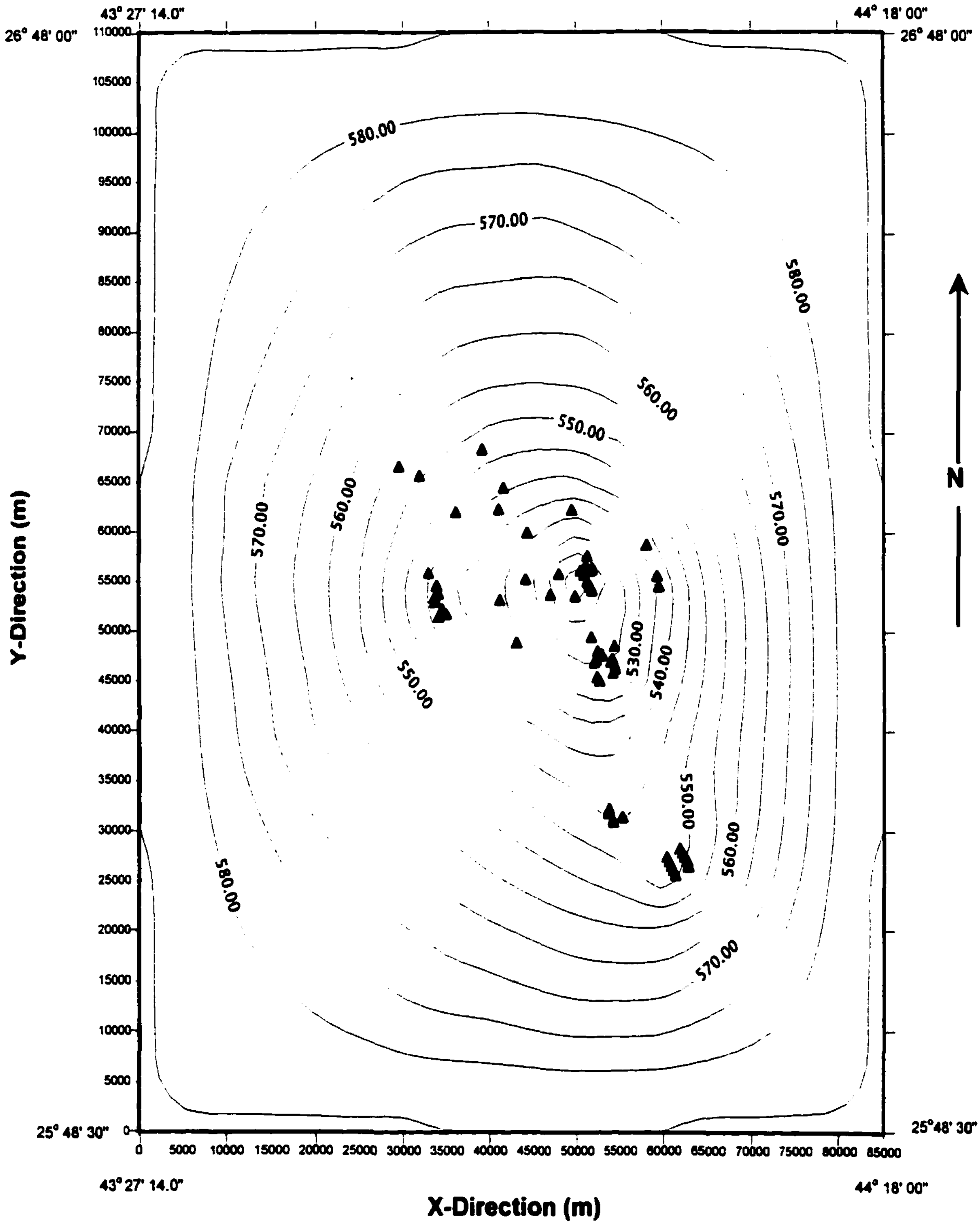


Figure 6.17. Predicted hydraulic head distribution for the fourth management plan during the period of 2010.

current level (as calculated in 1999) is 10 m. The hydraulic head in south of the central area where there are some of the domestic wells as well as there are some irrigation wells in that area, is 525 m with drawdown about 10 m. The hydraulic head in Unayzah city, south of Buraydah city, is 550 m which is higher than the hydraulic head in Buraydah city and the resulting change of the hydraulic head from the current level is 5 m.

Figure 6.18 shows the predicted hydraulic head distribution for the year of 2020. The hydraulic head continues decreasing toward the center of the study area. The hydraulic head in Buraydah city is 505 m with maximum drawdown about 20 m and the hydraulic head in Unayzah city is predicted to be 545 m and the resulting changes of the hydraulic head (drawdown) from the current (1999 level) is 10 m. In the area which has some of the domestic wells (wells # 21, 22, 23, 24, 25, 26, and 27), the hydraulic head is 517 m, and the drawdown is 18 m.

The hydraulic head distribution for the year of 2030 is shown in Figure 6.19. As the result of the increase in pumping rates during that period, the lowest hydraulic head is found in the center of the study area, which has many domestic wells (wells # 1-17) and they are close to each other. The hydraulic head in that area, which called "Al-Matta", is 495 m with maximum drawdown about 30 m. In south of the center area (about 5 km south of the center area), the hydraulic head is 510 m, and the resulting change of the hydraulic head (drawdown) from the current level is 25 m. The hydraulic head in Unayzah city reaches a value of 540 m with drawdown about 15 m.

Figure 6.20 shows the predicted hydraulic head distribution for the period of 2040 for the period of 2040. As shown in the figure, the hydraulic head decreases toward the center of the study area, which has a lot of domestic wells. The hydraulic head in the center of the

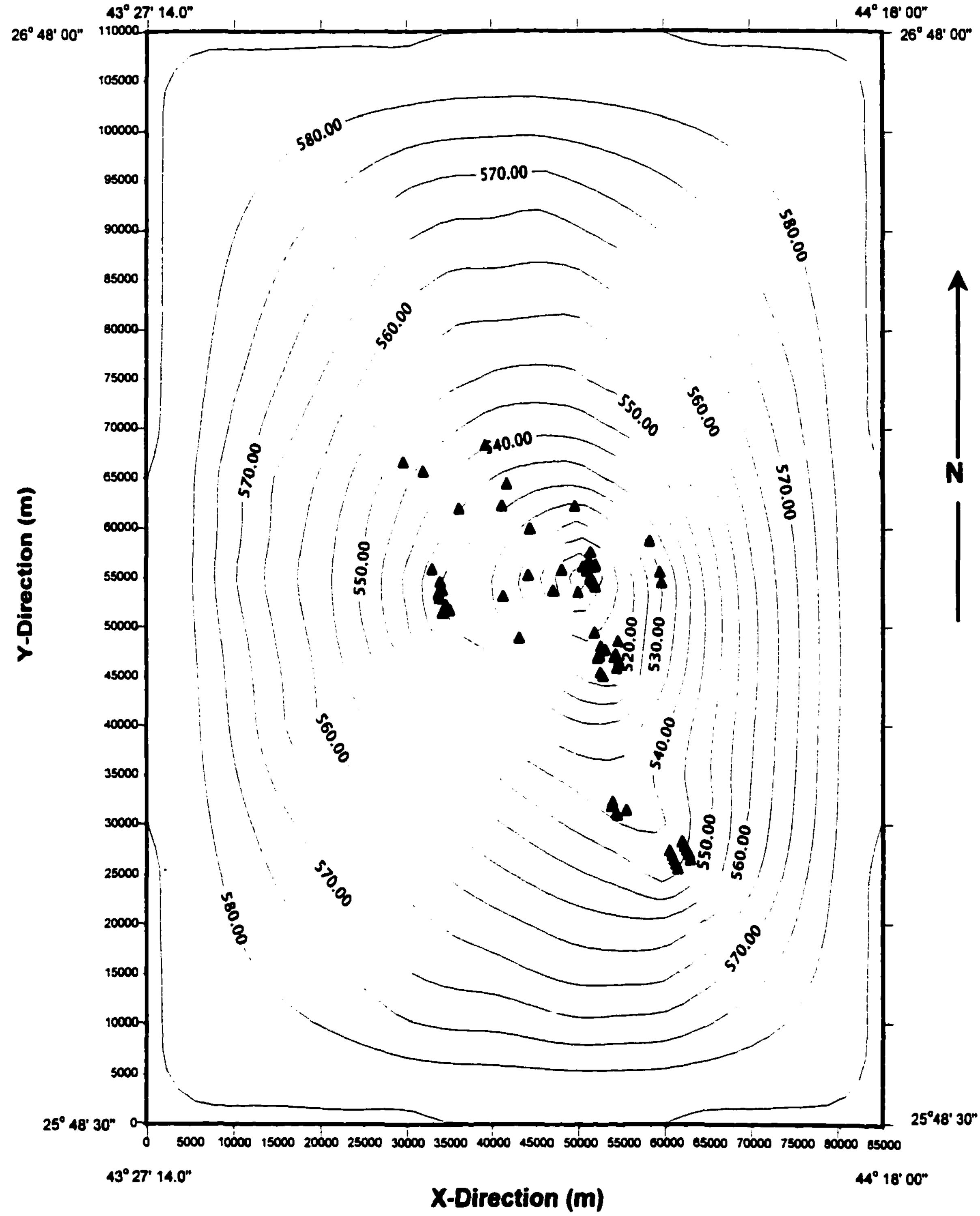


Figure 6.18. Predicted hydraulic head distribution for the fourth management plan during the period of 2020.

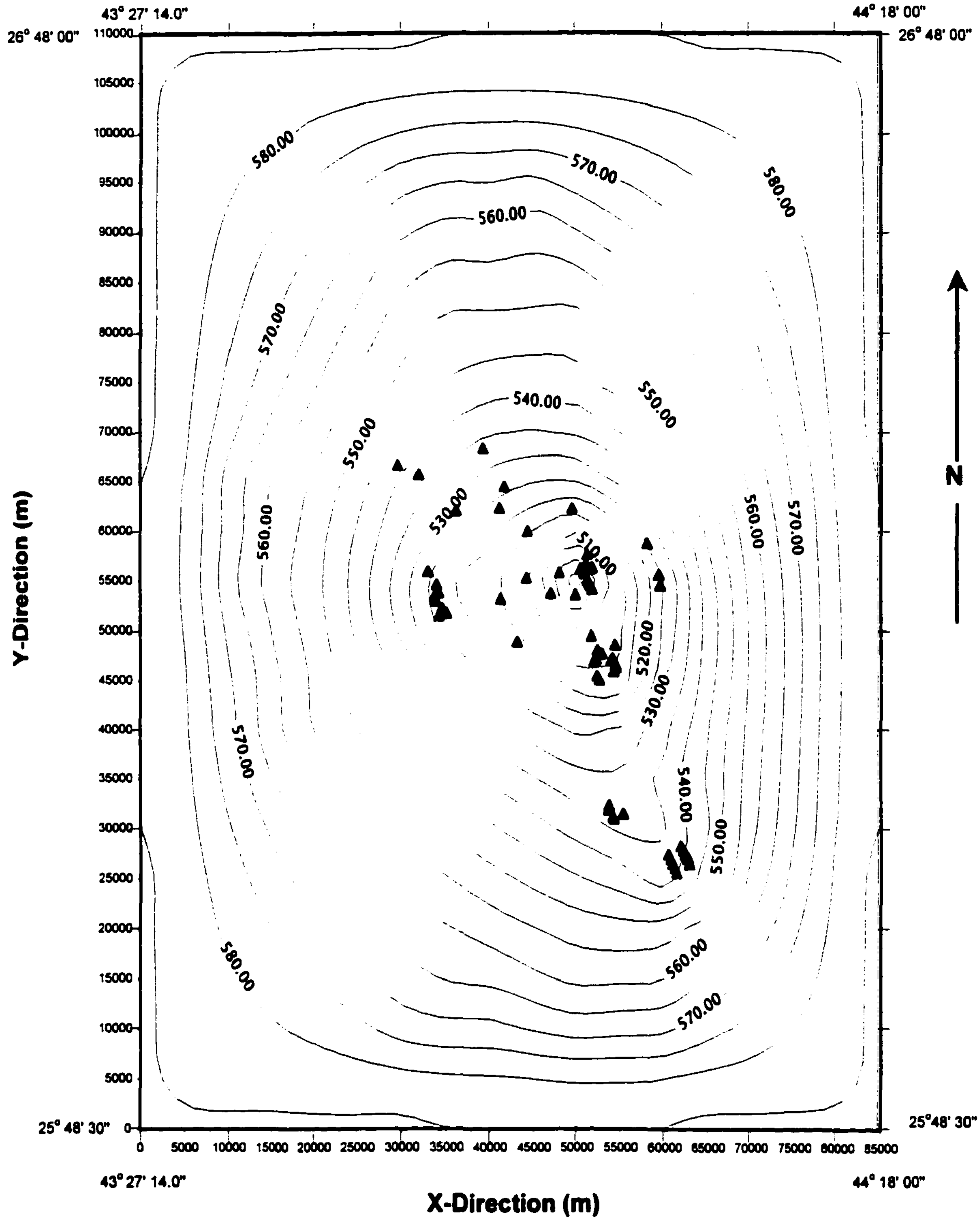


Figure 6.19. Predicted hydraulic head distribution for the fourth management plan during the period of 2030.

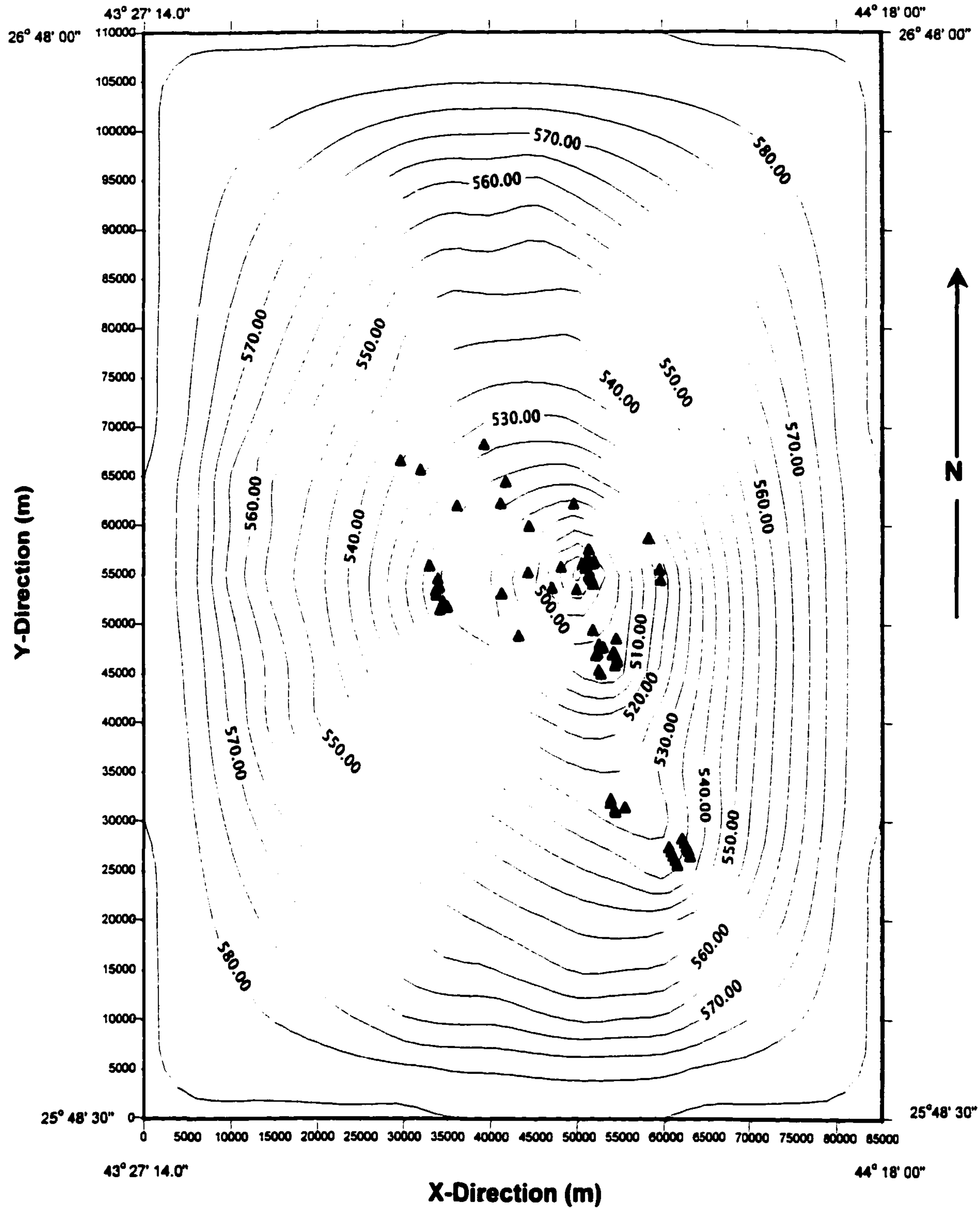


Figure 6.20. Predicted hydraulic head distribution for the fourth management plan during the period of 2040.

study (Al-Matta) is 485 m with the maximum drawdown about 40 m. About 5-km south from Al-Matta, the hydraulic head reaches about 502 m and the drawdown is 33 m. The hydraulic head in Unayzah city reaches a value of 535 m and the resulting change of the hydraulic head (drawdown) from the current level (as calculated in 1999) is 20 m.

The predicted distribution of the hydraulic head after 50 years (2050) is shown in Figure 6.21. The lowest hydraulic head is located in the center of the study area, which has heavy pumping rates. The hydraulic head in that area (Al-Matta) reaches about 475 m and the maximum drawdown is about 50 m. The hydraulic head in south of that area, about 5 km south of Al-Matta, is 495 m and the resulting change in the hydraulic head (drawdown) is 40 m. In Unayzah city, the hydraulic head is about 530 m with drawdown about 25 m.

## Additional Drawdown

MODFLOW calculates head decline or drawdown that resulted from pumped well node and that value represents the average drawdown or head decline over the whole finite difference grid. Therefore it is important to estimate the actual drawdown at any well.

The actual drawdown, $Z_w$, is the sum of the drawdown calculated by MODFLOW, $Z_a$, and the additional drawdown, $\Delta Z$, which can be calculated from the follwing equations:

The drawdown that resulted by MODFLOW is calculated by

$$Z_a = \frac{2.3Q}{4\pi T}\left(\log \frac{2.25Tt}{a^2 S}\right) \tag{6.1}$$

and the drawdown that resulted from the well is calculated by

$$Z_w = \frac{2.3Q}{4\pi T}\left(\log \frac{2.25Tt}{r_w^2 S}\right) \tag{6.2}$$

Subtract equation 6.1 from equation 6.2 and simplify:

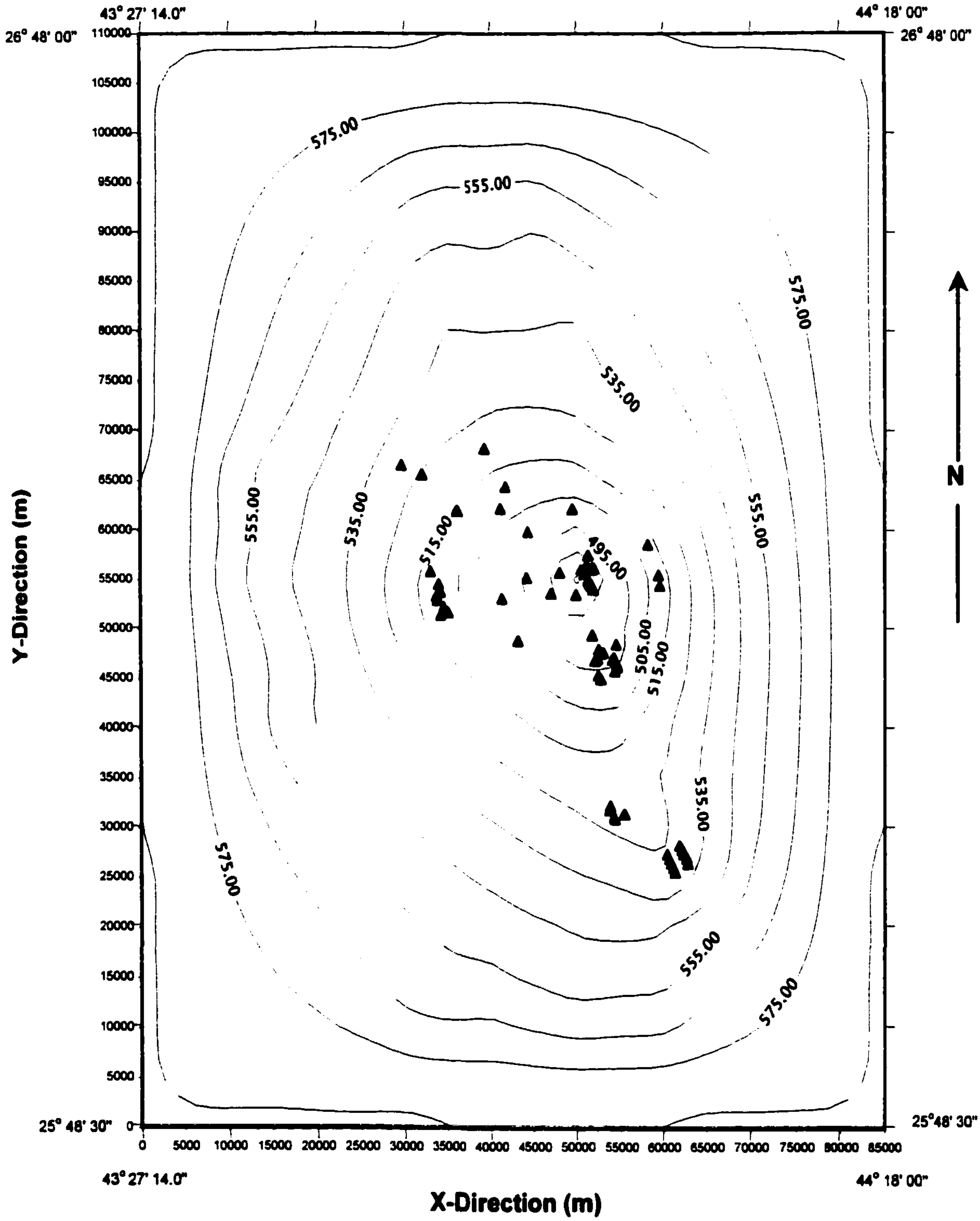


Figure 6.21. Predicted hydraulic head distribution for the fourth management plan during the period of 2050.

$$
\left.
\begin{aligned}
\Delta Z &= Z_w - Z_a \\
\Delta Z &= \left[\frac{2.3Q}{4\pi T}\left(\log\frac{2.25Tt}{r_w^2 S}\right)\right] - \left[\frac{2.3Q}{4\pi T}\left(\frac{2.25Tt}{a^2 S}\right)\right] \\
\Delta Z &= \frac{2.3Q}{4\pi T}\left[\left(\log\frac{2.25Tt}{S} - 2\log r_w\right)\right] - \left[\frac{2.3Q}{4\pi T}\left(\log\frac{2.25Tt}{S} - 2\log a\right)\right] \\
\Delta Z &= \frac{2.3Q}{4\pi T}\left[2\log a - 2\log r_w\right]
\end{aligned}
\right\} \quad (6.3)
$$

$$
\Delta Z = \frac{4.6Q}{4\pi T}\log\left(\frac{a}{r_w}\right) \qquad (6.4)
$$

where

$\Delta Z$ = Additional drawdown or head decline, m,

$Z_w$ = The drawdown in the well itself, m,

$Z_a$ = The drawdown that calculated by MODFLOW,m,

Q = Pumping rate of the well, $m^3$/day,

T = Aquifer transmissivity, $m^2$/day,

t = Time, days,

S = Storage coefficient of the aquifer, dimensionless,

a = Finite difference grid interval, m, and

$r_w$ = Effective radius of the simulated pumped well, m, which is calculated as (Prickett and Lonnquist, 1971):

$$
r_w = a/4.81 \qquad (5.5)
$$

Additional drawdown or head decline to be added to calculated value from pumped well node for each pumping well was calculated using equation 6.4. Table 6.1 shows the

Table 6.1. Additional drawdown resulting from the first management plan.

| Well's Name | Drawdown (m) 2010 | 2020 | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|
| 1 | 1.60 | 1.89 | 2.18 | 2.46 | 2.75 |
| 2 | 1.60 | 1.89 | 2.18 | 2.46 | 2.75 |
| 3 | 1.60 | 1.89 | 2.18 | 2.46 | 2.75 |
| 4 | 1.32 | 1.56 | 1.79 | 2.03 | 2.26 |
| 5 | 0.57 | 0.67 | 0.77 | 0.87 | 0.97 |
| 6 | 1.18 | 1.39 | 1.60 | 1.81 | 2.02 |
| 7 | 1.13 | 1.33 | 1.54 | 1.74 | 1.94 |
| 8 | 0.38 | 0.44 | 0.51 | 0.58 | 0.65 |
| 9 | 1.60 | 1.89 | 2.18 | 2.46 | 2.75 |
| 10 | 1.04 | 1.22 | 1.41 | 1.59 | 1.78 |
| 11 | 1.13 | 1.33 | 1.54 | 1.74 | 1.94 |
| 12 | 1.13 | 1.33 | 1.54 | 1.74 | 1.94 |
| 14 | 0.57 | 0.67 | 0.77 | 0.87 | 0.97 |
| 15 | 1.60 | 1.89 | 2.18 | 2.46 | .2.75 |
| 16 | 1.70 | 2.00 | 2.30 | 2.61 | 2.91 |
| 17 | 1.51 | 1.78 | 2.05 | 2.32 | 2.59 |
| 18 | 1.13 | 1.33 | 1.54 | 1.74 | 1.94 |
| 19 | 0.61 | 0.72 | 0.83 | 0.94 | 1.05 |
| 20 | 0.47 | 0.56 | 0.64 | 0.72 | 0.81 |
| 21 | 0.61 | 0.72 | 0.83 | 0.94 | 1.05 |
| 22 | 1.60 | 1.89 | 2.18 | 2.46 | 2.75 |
| 23 | 1.70 | 2.00 | 2.30 | 2.61 | 2.91 |
| 24 | 1.51 | 1.78 | 2.05 | 2.32 | 2.59 |
| 25 | 1.60 | 1.89 | 2.18 | 2.46 | 2.75 |
| 26 | 1.51 | 1.78 | 2.05 | 2.32 | 2.59 |
| 27 | 1.51 | 1.78 | 2.05 | 2.32 | 2.59 |
| 1-1 | 1.32 | 1.56 | 1.79 | 2.03 | 2.26 |
| 1-2 | 1.32 | 1.56 | 1.79 | 2.03 | 2.26 |
| 1-3 | 1.32 | 1.56 | 1.79 | 2.03 | 2.26 |
| 1-4 | 1.32 | 1.56 | 1.79 | 2.03 | 2.26 |
| 1-5 | 1.32 | 1.56 | 1.79 | 2.03 | 2.26 |
| 2-1 | 1.32 | 1.56 | 1.79 | 2.03 | 2.26 |
| 2-2 | 1.32 | 1.56 | 1.79 | 2.03 | 2.26 |
| 2-3 | 1.32 | 1.56 | 1.79 | 2.03 | 2.26 |
| 2-4 | 1.32 | 1.56 | 1.79 | 2.03 | 2.26 |
| 2-5 | 1.32 | 1.56 | 1.79 | 2.03 | 2.26 |
| ALHDA | 0.57 | 0.67 | 0.77 | 0.87 | 0.97 |
| HARAT ANOZ | 0.57 | 0.67 | 0.77 | 0.87 | 0.97 |
| AL-ARAMTHAE | 0.57 | 0.67 | 0.77 | 0.87 | 0.97 |

Table 6.1. Continued.

| Well's Name | Drawdown (m) | | | | |
|---|---|---|---|---|---|
| | 2010 | 2020 | 2030 | 2040 | 2050 |
| AL-ASKAN | 1.42 | 1.67 | 1.92 | 2.17 | 2.42 |
| ATHRAS | 0.77 | 0.91 | 1.05 | 1.19 | 1.32 |
| BOSSOR | 0.57 | 0.67 | 0.77 | 0.87 | 0.97 |
| COLLEGE-1 | 0.85 | 1.00 | 1.15 | 1.30 | 1.45 |
| COLLEGE-2 | 0.85 | 1.00 | 1.15 | 1.30 | 1.45 |
| COLLEGE-3 | 0.85 | 1.00 | 1.15 | 1.30 | 1.45 |
| GRA'A | 0.57 | 0.67 | 0.77 | 0.87 | 0.97 |
| AL-GRISH | 1.13 | 1.33 | 1.54 | 1.74 | 1.94 |
| AL-GTHAI | 0.57 | 0.67 | 0.77 | 0.87 | 0.97 |
| AL-HADIKA | 0.57 | 0.67 | 0.77 | 0.87 | 0.97 |
| AL-HNAIA-1 | 0.38 | 0.44 | 0.51 | 0.58 | 0.65 |
| AL-HNAIA-2 | 0.38 | 0.44 | 0.51 | 0.58 | 0.65 |
| HOILAN | 0.57 | 0.67 | 0.77 | 0.87 | 0.97 |
| AL-HOMOR | 0.57 | 0.67 | 0.77 | 0.87 | 0.97 |
| AL-KATHER | 0.57 | 0.67 | 0.77 | 0.87 | 0.97 |
| KMAS | 0.57 | 0.67 | 0.77 | 0.87 | 0.97 |
| AL-MOLIDA | 0.57 | 0.67 | 0.77 | 0.87 | 0.97 |
| AL-MOSHIGH-1 | 0.57 | 0.67 | 0.77 | 0.87 | 0.97 |
| AL-MOSHIGH-2 | 1.13 | 1.33 | 1.54 | 1.74 | 1.94 |
| AL-MOSHIGH-3 | 0.57 | 0.67 | 0.77 | 0.87 | 0.97 |
| AL-MOSHIGH-4 | 1.13 | 1.33 | 1.54 | 1.74 | 1.94 |
| AL-MOTLQ-1 | 0.38 | 0.44 | 0.51 | 0.58 | 0.65 |
| AL-MOTLQ-2 | 0.38 | 0.44 | 0.51 | 0.58 | 0.65 |
| AL-MOREDSIHA | 0.57 | 0.67 | 0.77 | 0.87 | 0.97 |
| AL-QUSAIHA | 0.57 | 0.67 | 0.77 | 0.87 | 0.97 |
| AL-RAGHI-1 | 1.13 | 1.33 | 1.54 | 1.74 | 1.94 |
| AL-RAGHI-2 | 1.13 | 1.33 | 1.54 | 1.74 | 1.94 |
| AL-RAGHIA | 1.13 | 1.33 | 1.54 | 1.74 | 1.94 |
| AL-ROKANI | 0.57 | 0.67 | 0.77 | 0.87 | 0.97 |
| AL-SALHIA | 0.57 | 0.67 | 0.77 | 0.87 | 0.97 |
| AL-SHAMALI-D | 0.57 | 0.67 | 0.77 | 0.87 | 0.97 |
| AL-SHAMALI-K | 0.57 | 0.67 | 0.77 | 0.87 | 0.97 |
| AL-SHOQA-A | 0.57 | 0.67 | 0.77 | 0.87 | 0.97 |
| AL-SHOQA-S | 0.57 | 0.67 | 0.77 | 0.87 | 0.97 |

additional drawdown for each pumping well in the modeled area that resulting from the first management plan, and Table 6.2 shows the calculated additional drawdown that resulting from the second management plan. Table 6.3 shows the additional drawdown for each pumping well that resulting from the third management plan. As shown in Tables 6.1, 6.2, and 6.3, the calculated additional drawdown or head decline is increased by increased the pumping rate. The additional drawdown value of each pumping well from the third management plan is higher than the additional drawdown that resulting from first and second management plans, and the lowest additional drawdown is from the second management plan.

## Measure for Effective Management and Conservation

Figure 6.22 shows the water level hydrograph during different management plans at the observation well # 10 in Al-Matta area (central area). As shown in the figure the water level in the observation well during the period of 1999 is 515 m, which will be reduced to 435 m at the end of the year of 2050 by implementing the first management plan. The net drawdown during the planning period (1999-2050) will be 80 m. The water level conditions at the end of the year of 2050 will be improved by adapting the second management plan. The water level at the observation well in 2050 will be 475 m and the net drawdown will be reduced to 40 m by implementing the second management plan. On the other hand, by implementing the third management plan, the water level of the observation well # 10 will be reduced from 515 m in 1999 to 395 m in 2050, which means that, the net drawdown during the planning period (1999-2050) will be increased to 120 m. However, by implementing the fourth management plan, which is the combination of the second and third management plans, the water level of the observation well will be improved at the end of the

Table 6.2. Additional drawdown resulting from the second management plan.

| Well's Name | Drawdown (m) | | | | |
|---|---|---|---|---|---|
| | 2010 | 2020 | 2030 | 2040 | 2050 |
| 1 | 1.45 | 1.59 | 1.73 | 1.88 | 2.02 |
| 2 | 1.45 | 1.59 | 1.73 | 1.88 | 2.02 |
| 3 | 1.45 | 1.59 | 1.73 | 1.88 | 2.02 |
| 4 | 1.19 | 1.31 | 1.43 | 1.54 | 1.66 |
| 5 | 0.51 | 0.56 | 0.61 | 0.66 | 0.71 |
| 6 | 1.06 | 1.17 | 1.27 | 1.38 | 1.48 |
| 7 | 1.02 | 1.12 | 1.22 | 1.32 | 1.42 |
| 8 | 0.34 | 0.37 | 0.41 | 0.44 | 0.47 |
| 9 | 1.45 | 1.59 | 1.73 | 1.88 | 2.02 |
| 10 | 0.94 | 1.03 | 1.12 | 1.21 | 1.31 |
| 11 | 1.02 | 1.12 | 1.22 | 1.32 | 1.42 |
| 12 | 1.02 | 1.12 | 1.22 | 1.32 | 1.42 |
| 14 | 0.51 | 0.56 | 0.61 | 0.66 | 0.71 |
| 15 | 1.45 | 1.59 | 1.73 | 1.88 | 2.02 |
| 16 | 1.53 | 1.68 | 1.84 | 1.99 | 2.14 |
| 17 | 1.36 | 1.50 | 1.63 | 1.77 | 1.90 |
| 18 | 1.02 | 1.12 | 1.22 | 1.32 | 1.42 |
| 19 | 0.55 | 0.61 | 0.66 | 0.72 | 0.77 |
| 20 | 0.43 | 0.47 | 0.51 | 0.55 | 0.59 |
| 21 | 0.55 | 0.61 | 0.66 | 0.72 | 0.77 |
| 22 | 1.45 | 1.59 | 1.73 | 1.88 | 2.02 |
| 23 | 1.53 | 1.68 | 1.84 | 1.99 | 2.14 |
| 24 | 1.36 | 1.50 | 1.63 | 1.77 | 1.90 |
| 25 | 1.45 | 1.59 | 1.73 | 1.88 | 2.02 |
| 26 | 1.36 | 1.50 | 1.63 | 1.77 | 1.90 |
| 27 | 1.36 | 1.50 | 1.63 | 1.77 | 1.90 |
| 1-1 | 1.19 | 1.31 | 1.43 | 1.54 | 1.66 |
| 1-2 | 1.19 | 1.31 | 1.43 | 1.54 | 1.66 |
| 1-3 | 1.19 | 1.31 | 1.43 | 1.54 | 1.66 |
| 1-4 | 1.19 | 1.31 | 1.43 | 1.54 | 1.66 |
| 1-5 | 1.19 | 1.31 | 1.43 | 1.54 | 1.66 |
| 2-1 | 1.19 | 1.31 | 1.43 | 1.54 | 1.66 |
| 2-2 | 1.19 | 1.31 | 1.43 | 1.54 | 1.66 |
| 2-3 | 1.19 | 1.31 | 1.43 | 1.54 | 1.66 |
| 2-4 | 1.19 | 1.31 | 1.43 | 1.54 | 1.66 |
| 2-5 | 1.19 | 1.31 | 1.43 | 1.54 | 1.66 |
| ALHDA | 0.51 | 0.56 | 0.61 | 0.66 | 0.71 |
| HARAT ANOZ | 0.51 | 0.56 | 0.61 | 0.66 | 0.71 |
| AL-ARAMTHAE | 0.51 | 0.56 | 0.61 | 0.66 | 0.71 |

Table 6.2. Continued.

| Well's Name | Drawdown (m) | | | | |
|---|---|---|---|---|---|
| | 2010 | 2020 | 2030 | 2040 | 2050 |
| AL-ASKAN | 1.28 | 1.40 | 1.53 | 1.66 | 1.78 |
| ATHRAS | 0.70 | 0.77 | 0.84 | 0.90 | 0.97 |
| BOSSOR | 0.51 | 0.56 | 0.61 | 0.66 | 0.71 |
| COLLEGE-1 | 0.77 | 0.84 | 0.92 | 0.99 | 1.07 |
| COLLEGE-2 | 0.77 | 0.84 | 0.92 | 0.99 | 1.07 |
| COLLEGE-3 | 0.77 | 0.84 | 0.92 | 0.99 | 1.07 |
| GRA'A | 0.51 | 0.56 | 0.61 | 0.66 | 0.71 |
| AL-GRISH | 1.02 | 1.12 | 1.22 | 1.32 | 1.42 |
| AL-GTHAI | 0.51 | 0.56 | 0.61 | 0.66 | 0.71 |
| AL-HADIKA | 0.51 | 0.56 | 0.61 | 0.66 | 0.71 |
| AL-HNAIA-1 | 0.34 | 0.37 | 0.41 | 0.44 | 0.47 |
| AL-HNAIA-2 | 0.34 | 0.37 | 0.41 | 0.44 | 0.47 |
| HOILAN | 0.51 | 0.56 | 0.61 | 0.66 | 0.71 |
| AL-HOMOR | 0.51 | 0.56 | 0.61 | 0.66 | 0.71 |
| AL-KATHER | 0.51 | 0.56 | 0.61 | 0.66 | 0.71 |
| KMAS | 0.51 | 0.56 | 0.61 | 0.66 | 0.71 |
| AL-MOLIDA | 0.51 | 0.56 | 0.61 | 0.66 | 0.71 |
| AL-MOSHIGH-1 | 0.51 | 0.56 | 0.61 | 0.66 | 0.71 |
| AL-MOSHIGH-2 | 1.02 | 1.12 | 1.22 | 1.32 | 1.42 |
| AL-MOSHIGH-3 | 0.51 | 0.56 | 0.61 | 0.66 | 0.71 |
| AL-MOSHIGH-4 | 1.02 | 1.12 | 1.22 | 1.32 | 1.42 |
| AL-MOTLQ-1 | 0.34 | 0.37 | 0.41 | 0.44 | 0.47 |
| AL-MOTLQ-2 | 0.34 | 0.37 | 0.41 | 0.44 | 0.47 |
| AL-MOREDSIHA | 0.51 | 0.56 | 0.61 | 0.66 | 0.71 |
| AL-QUSAIHA | 0.51 | 0.56 | 0.61 | 0.66 | 0.71 |
| AL-RAGHI-1 | 1.02 | 1.12 | 1.22 | 1.32 | 1.42 |
| AL-RAGHI-2 | 1.02 | 1.12 | 1.22 | 1.32 | 1.42 |
| AL-RAGHIA | 1.02 | 1.12 | 1.22 | 1.32 | 1.42 |
| AL-ROKANI | 0.51 | 0.56 | 0.61 | 0.66 | 0.71 |
| AL-SALHIA | 0.51 | 0.56 | 0.61 | 0.66 | 0.71 |
| AL-SHAMALI-D | 0.51 | 0.56 | 0.61 | 0.66 | 0.71 |
| AL-SHAMALI-K | 0.51 | 0.56 | 0.61 | 0.66 | 0.71 |
| AL-SHOQA-A | 0.51 | 0.56 | 0.61 | 0.66 | 0.71 |
| AL-SHOQA-S | 0.51 | 0.56 | 0.61 | 0.66 | 0.71 |

Table 6.3. Additional drawdown resulting from the third management plan.

| Well's Name | Drawdown (m) | | | | |
|---|---|---|---|---|---|
| | 2010 | 2020 | 2030 | 2040 | 2050 |
| 1 | 1.76 | 2.19 | 2.62 | 3.05 | 3.48 |
| 2 | 1.76 | 2.19 | 2.62 | 3.05 | 3.48 |
| 3 | 1.76 | 2.19 | 2.62 | 3.05 | 3.48 |
| 4 | 1.45 | 1.80 | 2.16 | 2.51 | 2.86 |
| 5 | 0.62 | 0.77 | 0.92 | 1.08 | 1.23 |
| 6 | 1.30 | 1.61 | 1.93 | 2.24 | 2.56 |
| 7 | 1.24 | 1.55 | 1.85 | 2.15 | 2.45 |
| 8 | 0.41 | 0.52 | 0.62 | 0.72 | 0.82 |
| 9 | 1.76 | 2.19 | 2.62 | 3.05 | 3.48 |
| 10 | 1.14 | 1.42 | 1.69 | 1.97 | 2.25 |
| 11 | 1.24 | 1.55 | 1.85 | 2.15 | 2.45 |
| 12 | 1.24 | 1.55 | 1.85 | 2.15 | 2.45 |
| 14 | 0.62 | 0.77 | 0.92 | 1.08 | 1.23 |
| 15 | 1.76 | 2.19 | 2.62 | 3.05 | 3.48 |
| 16 | 1.87 | 2.32 | 2.77 | 3.23 | 3.68 |
| 17 | 1.66 | 2.06 | 2.46 | 2.87 | 3.27 |
| 18 | 1.24 | 1.55 | 1.85 | 2.15 | 2.45 |
| 19 | 0.67 | 0.84 | 1.00 | 1.16 | 1.33 |
| 20 | 0.52 | 0.64 | 0.77 | 0.90 | 1.02 |
| 21 | 0.67 | 0.84 | 1.00 | 1.16 | 1.33 |
| 22 | 1.76 | 2.19 | 2.62 | 3.05 | 3.48 |
| 23 | 1.87 | 2.32 | 2.77 | 3.23 | 3.68 |
| 24 | 1.66 | 2.06 | 2.46 | 2.87 | 3.27 |
| 25 | 1.76 | 2.19 | 2.62 | 3.05 | 3.48 |
| 26 | 1.66 | 2.06 | 2.46 | 2.87 | 3.27 |
| 27 | 1.66 | 2.06 | 2.46 | 2.87 | 3.27 |
| 1-1 | 1.45 | 1.80 | 2.16 | 2.51 | 2.86 |
| 1-2 | 1.45 | 1.80 | 2.16 | 2.51 | 2.86 |
| 1-3 | 1.45 | 1.80 | 2.16 | 2.51 | 2.86 |
| 1-4 | 1.45 | 1.80 | 2.16 | 2.51 | 2.86 |
| 1-5 | 1.45 | 1.80 | 2.16 | 2.51 | 2.86 |
| 2-1 | 1.45 | 1.80 | 2.16 | 2.51 | 2.86 |
| 2-2 | 1.45 | 1.80 | 2.16 | 2.51 | 2.86 |
| 2-3 | 1.45 | 1.80 | 2.16 | 2.51 | 2.86 |
| 2-4 | 1.45 | 1.80 | 2.16 | 2.51 | 2.86 |
| 2-5 | 1.45 | 1.80 | 2.16 | 2.51 | 2.86 |
| ALHDA | 0.62 | 0.77 | 0.92 | 1.08 | 1.23 |
| HARAT ANOZ | 0.62 | 0.77 | 0.92 | 1.08 | 1.23 |
| AL-ARAMTHAE | 0.62 | 0.77 | 0.92 | 1.08 | 1.23 |

Table 6.3. Continued.

| Well's Name | Drawdown (m) | | | | |
|---|---|---|---|---|---|
| | 2010 | 2020 | 2030 | 2040 | 2050 |
| AL-ASKAN | 1.55 | 1.93 | 2.31 | 2.69 | 3.07 |
| ATHRAS | 0.85 | 1.06 | 1.26 | 1.47 | 1.68 |
| BOSSOR | 0.62 | 0.77 | 0.92 | 1.08 | 1.23 |
| COLLEGE-1 | 0.93 | 1.16 | 1.39 | 1.61 | 1.84 |
| COLLEGE-2 | 0.93 | 1.16 | 1.39 | 1.61 | 1.84 |
| COLLEGE-3 | 0.93 | 1.16 | 1.39 | 1.61 | 1.84 |
| GRA'A | 0.62 | 0.77 | 0.92 | 1.08 | 1.23 |
| AL-GRISH | 1.24 | 1.55 | 1.85 | 2.15 | 2.45 |
| AL-GTHAI | 0.62 | 0.77 | 0.92 | 1.08 | 1.23 |
| AL-HADIKA | 0.62 | 0.77 | 0.92 | 1.08 | 1.23 |
| AL-HNAIA-1 | 0.41 | 0.52 | 0.62 | 0.72 | 0.82 |
| AL-HNAIA-2 | 0.41 | 0.52 | 0.62 | 0.72 | 0.82 |
| HOILAN | 0.62 | 0.77 | 0.92 | 1.08 | 1.23 |
| AL-HOMOR | 0.62 | 0.77 | 0.92 | 1.08 | 1.23 |
| AL-KATHER | 0.62 | 0.77 | 0.92 | 1.08 | 1.23 |
| KMAS | 0.62 | 0.77 | 0.92 | 1.08 | 1.23 |
| AL-MOLIDA | 0.62 | 0.77 | 0.92 | 1.08 | 1.23 |
| AL-MOSHIGH-1 | 0.62 | 0.77 | 0.92 | 1.08 | 1.23 |
| AL-MOSHIGH-2 | 1.24 | 1.55 | 1.85 | 2.15 | 2.45 |
| AL-MOSHIGH-3 | 0.62 | 0.77 | 0.92 | 1.08 | 1.23 |
| AL-MOSHIGH-4 | 1.24 | 1.55 | 1.85 | 2.15 | 2.45 |
| AL-MOTLQ-1 | 0.41 | 0.52 | 0.62 | 0.72 | 0.82 |
| AL-MOTLQ-2 | 0.41 | 0.52 | 0.62 | 0.72 | 0.82 |
| AL-MOREDSIHA | 0.62 | 0.77 | 0.92 | 1.08 | 1.23 |
| AL-QUSAIHA | 0.62 | 0.77 | 0.92 | 1.08 | 1.23 |
| AL-RAGHI-1 | 1.24 | 1.55 | 1.85 | 2.15 | 2.45 |
| AL-RAGHI-2 | 1.24 | 1.55 | 1.85 | 2.15 | 2.45 |
| AL-RAGHIA | 1.24 | 1.55 | 1.85 | 2.15 | 2.45 |
| AL-ROKANI | 0.62 | 0.77 | 0.92 | 1.08 | 1.23 |
| AL-SALHIA | 0.62 | 0.77 | 0.92 | 1.08 | 1.23 |
| AL-SHAMALI-D | 0.62 | 0.77 | 0.92 | 1.08 | 1.23 |
| AL-SHAMALI-K | 0.62 | 0.77 | 0.92 | 1.08 | 1.23 |
| AL-SHOQA-A | 0.62 | 0.77 | 0.92 | 1.08 | 1.23 |
| AL-SHOQA-S | 0.62 | 0.77 | 0.92 | 1.08 | 1.23 |

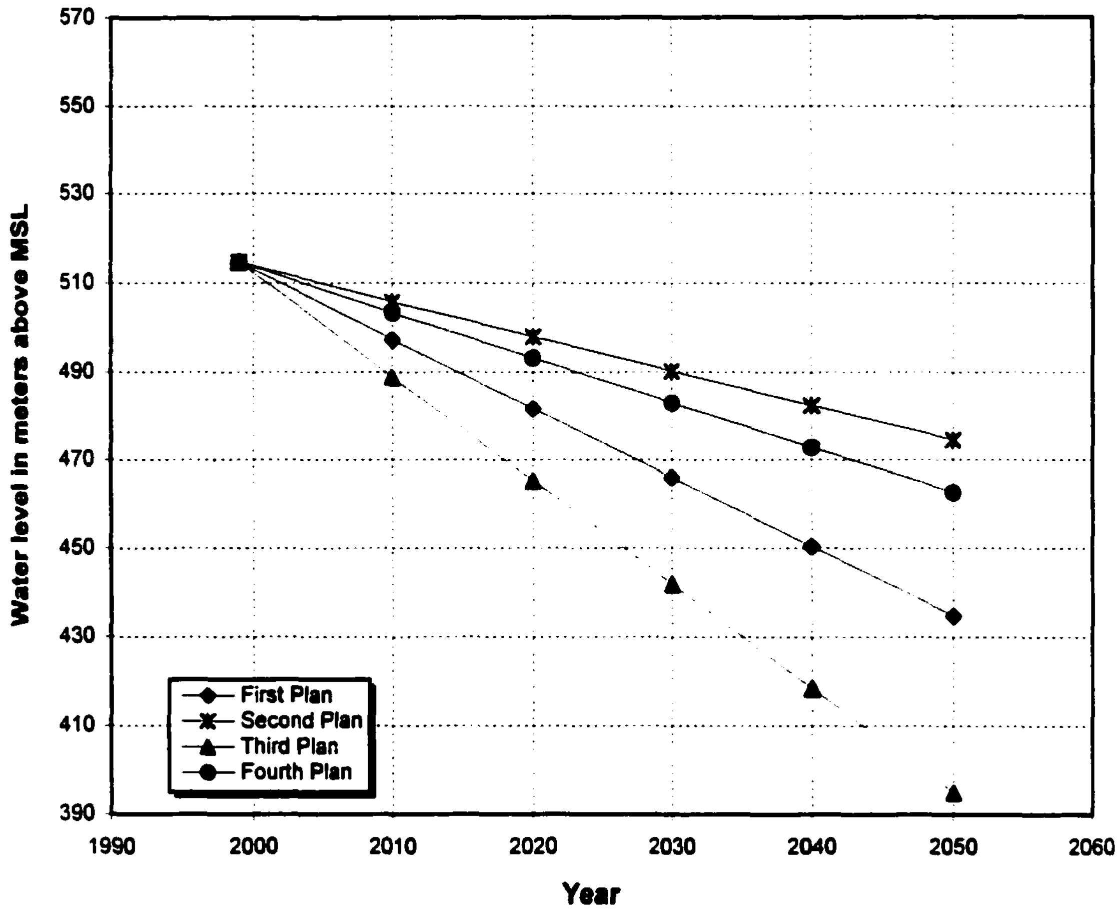


Figure 6.22. Water level at the observation well #10 during different plans.

2050. The water level will be 463 m at the end of 2050 and the resulting change in the hydraulic head (drawdown) will be 52 m, which will improve the water level by 28 m compared with the first management plan. Also, by adapting the fourth management plan, the water level at the observation well will be improved by 68 m compared with the third management plan.

The water level hydrograph at the observation well # 21 (5-km south of the Al-Matta area) during different management plans is shown in Figure 6.23. The water level in the observation well during the period of 1999 is 529 m. When the first management plan is implementing, the water level will be reduced to 466 m in 2050. However, by implementing the second management plan, the conditions of the water levels will be improved to 498 m. When the third management plan is implementing, the water level will be reduced to 434 m. However, by implementing the fourth management plan, the water level will be improved to 488 m. From the above simulations, the net drawdown during the planning period (1999-2050) will be 95 m in the case of the third management plan. The net drawdown will be reduced to 63 m by implementing the first management and if the second or fourth management plan is implementing, the net drawdown will be reduced to 32 m and 42 m, respectively.

Figure 6.24 shows the water level hydrograph during different management plans at the observation well # 2-1 in Unayzah city (30 km south of Buraydah city). As shown in the figure the water level in the observation well during the period of 1999 is 549 m, which will be reduced to 508 m at the end of the year of 2050 by implementing the first management plan. The net drawdown during the planning period (1999-2050) resulting by implementing the first management plan will be 41 m. The water level conditions at the end of the year of

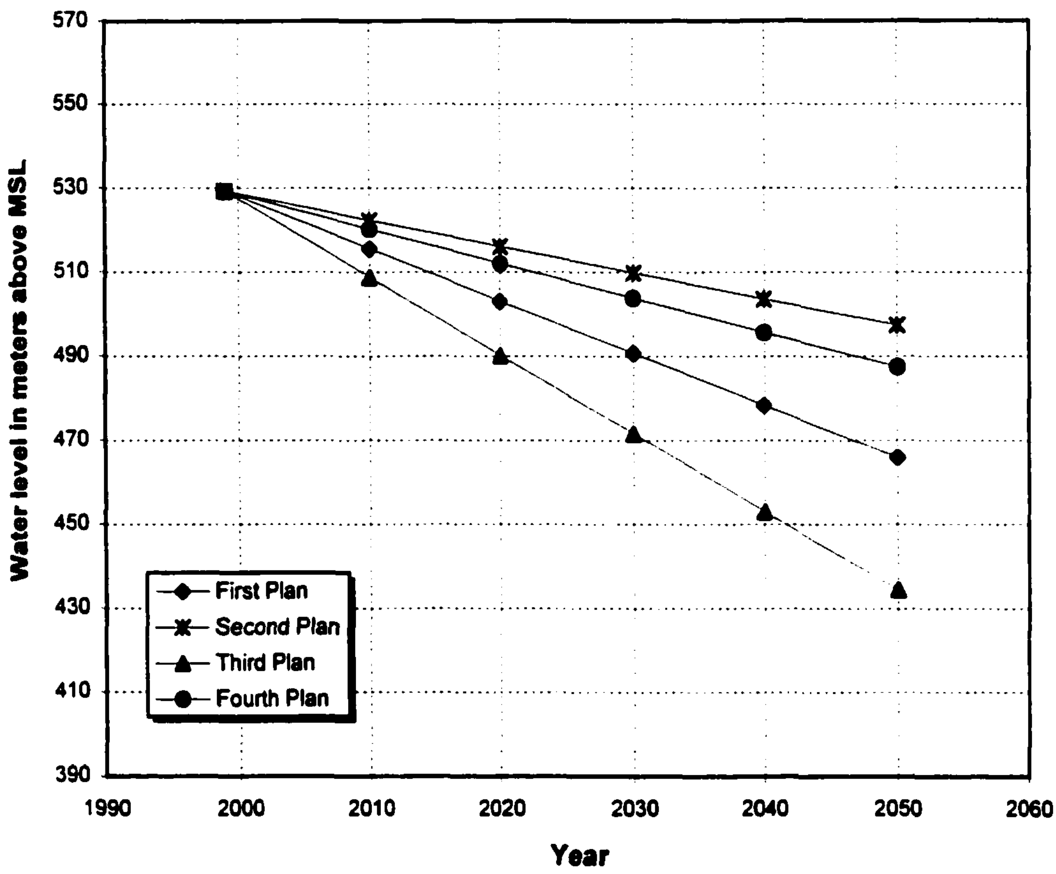


Figure 6.23. Water level at the observation well #21 during different plans.

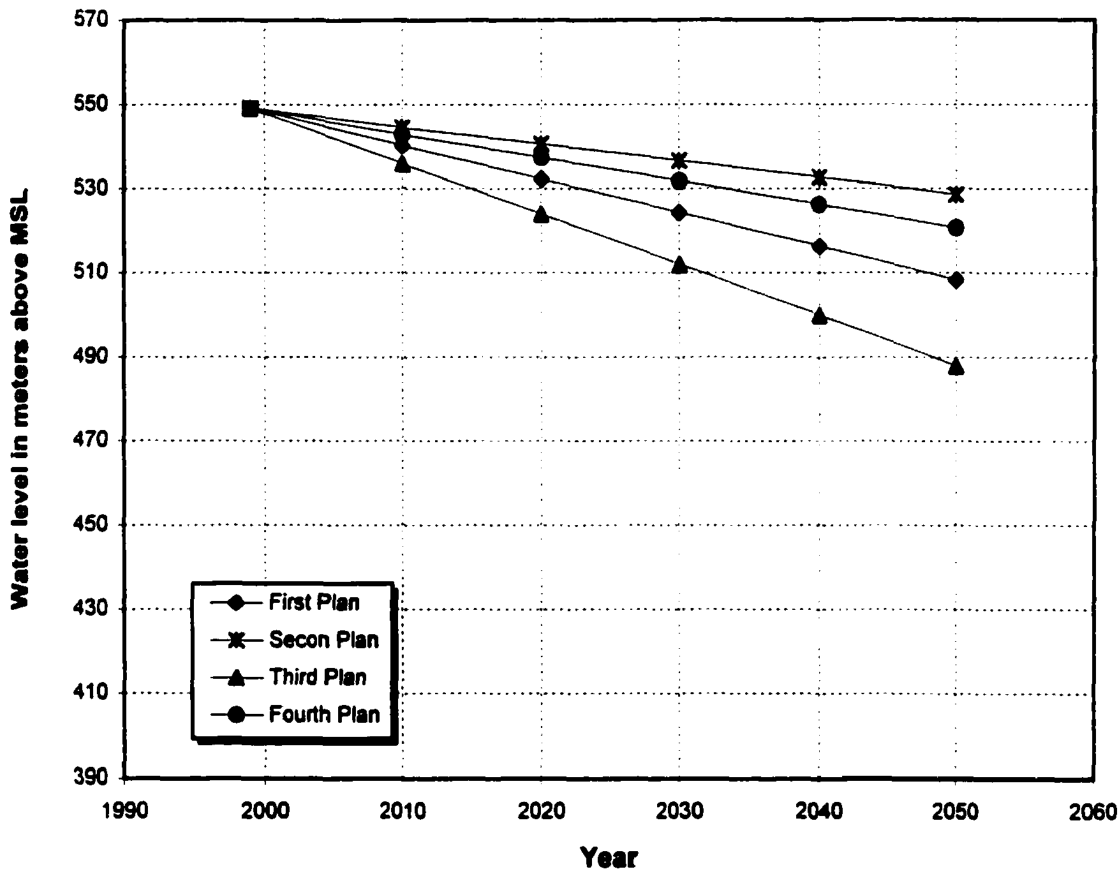


Figure 6.24. Water level at the observation well #2-1 during different plans.

2050 will be improved by implementing the second management plan. The water level at the observation well in 2050 will be 529 m and the net drawdown will be reduced to 20 m by implementing the second management plan. However, by implementing the third management plan, the water level of the observation well # 2-1 will be reduced from 549 m in 1999 to 488 m in 2050, which means that, the net drawdown during the planning period (1999-2050) will be increased to 61 m. If the fourth management plan is implementing, the water level condition will be improved to 521 m by the of 2050, and the net drawdown will be 28 m, which means that the water level will be improved by 33 m compare with the third management plan.

From the above simulation results, it is evident that implementing the fourth management plan improves the conditions of water levels for the whole study area, compared with the first and third management plans. Where the fourth management plan reduces the net drawdown by 50% of the net drawdown that results from the first management plan, and reducing the net drawdown by 130% of the net drawdown that resulting from the third management plan. From the above it seems that it is very important to implement the fourth management plan for the Al-Qassim area.

The findings of groundwater flow investigations show negative impacts of high groundwater withdrawals on groundwater levels of the Saq aquifer. The cost of pumping groundwater from Saq aquifer is going to be higher with decreasing water level, so each management plan will have different cost of pumping according to the condition of water level that results from it. Also, as a result of increasing pumping, the water quality of the Saq aquifer will be poor. In other words, when the water level in the Saq aquifer drops, groundwater will leak from the other formations that have worse water quality into Saq aquifer, so the quality of groundwater in the Saq aquifer will be degraded (Norconsult, 1984).

In addition to the above, the excessive groundwater withdrawal from a large number of wells will lead to lack of water from the Saq aquifer which is not renewable. This will seriously affect the future suitability of the groundwater for domestic and agricultural purposes. Improving water management and conservation are needed to in the Al-Qassim region. Groundwater withdrawal from existing wells in future should be maintained at the present level, if not reduced. This can be achieved by implementing different effective conservation plans to reduce the present and future water demands whether the demands are from domestic or agricultural consumption.

# CHAPTER 7. CONCLUSIONS AND RECOMMENDATIONS

## Conclusions

The hydraulic properties of the Saq aquifer were obtained by a pumping test at the Agricultural Research Center. The values obtained were in the range of the hydraulic properties that were obtained by the Ministry of Agriculture and Water (MAW, 1984). The transmissivity was estimated as 1.25 $m^2$/min, while the transmissivity that was obtained by the Ministry of Agriculture and Water was in the range 0.024 to 1.62 $m^2$/min (MAW, 1984). The storage coefficient from this study was estimated as $2.77 \times 10^{-4}$, while the storage coefficient that was obtained by the Ministry of Agriculture and Water was in the range $1.3 \times 10^{-3}$ to $2.5 \times 10^{-5}$ (MAW, 1984).

A quasi-three-dimensional simulation model was developed using the groundwater flow model MODFLOW (McDonald and Harbaugh, 1988). The computer simulation performed gives a good match for most of the study area. The computer model assumes that the aquifer is homogenous and isotropic. The best computer match has been obtained using a uniform value of 2.8 m/day for the hydraulic conductivity and a value of $4.6 \times 10^{-7}$ $m^{-1}$ for the specific storage were assigned at all the nodes.

Four management plans were considered using different discharge rates for a planning period of 51 years (1999-2050). The first management plan assumes that the present trend of increase in the water extraction rates through the existing wells continue until the end of year 2050. The second management plan was based on the assumption that the rate of increase in water extraction will be reduced by 50% of the first management plan. The third management plan allows that the rate of increase in water extraction will be increased by 50 % of the first management plan. The fourth management plan is the combination of the second and third management plans.

The results of implementing the four different management plans show that the water level in the central area where observation well # 10 is located, during the period of 1999 is 515 m, will be reduced to 435 m at the end of the year of 2050, by implementing the first management plan. The net drawdown during the planning period (1999-2050) will be 80 m. The water level conditions at the end of the year of 2050 will be improved by adapting the second management plan. The water level at the observation well in 2050 will be 475 m and the net drawdown will be reduced to 40 m by implementing the second management plan. On the other hand, by implementing the third management plan, the water level of the observation well # 10 will be reduced from 515 m in 1999 to 395 m in 2050, which means that, the net drawdown during the planning period (1999-2050) will be increased to 120 m. However, by implementing the fourth management plan, which is the combination of the second and third management plans, the water level of the observation well will be improved at the end of the 2050. The water level will be 463 m at the end of 2050 and the resulting change in the hydraulic head (drawdown) will be 52 m, which will improve the water level by 28 m compared with the first management plan. Also, by adapting the fourth management plan, the water level at the observation well will be improved by 68 m, compared with the third management plan.

From the above simulation results, it is evident that implementing the fourth management plan improves the conditions of water levels for the whole study area, compared with the first and third management plans. Where the fourth management plan reduces the net drawdown by 50% of the net drawdown that results from the first management plan, and reduces the net drawdown by 130% of the net drawdown that resulting from the third management plan.

From the above it seems that it is very important to implement the fourth management plan for the Al-Qassim area, because the Al-Qassim region as mentioned before is the most agricultural region of the nation, so development of the Al-Qassim region is expected to be expanded in the future. As the result of the expansion in the development of the Al-Qassim region, the water demand will be increased and this increase in the water demand can be met by implementing the fourth management plan, which allows the rate of increase in water extraction to increase by 50% of the normal rate. Also, by implementing the fourth management plan, the condition of water level will be improved, compared with the first and third management plans as the result of managing the distance between the wells themselves. In other words, the pumping wells should be as far away from each other as possible.

## Recommendations

The findings of groundwater flow investigations show negative impacts of immoderate groundwater withdrawals on groundwater levels of the Saq aquifer. This will seriously affect the future suitability of the groundwater for domestic and agricultural purposes. Improving water management and conservation are needed to in the Al-Qassim region. Groundwater withdrawal from existing wells in future should be maintained at the present level, if not reduced. This can be achieved by implementation different effective conservation plans to reduce the present and future water demands whether that demand is from domestic or agricultural consumption.

The domestic and agricultural water consumption can be reduced through implementing different conservation programs as suggested below:

***Public education***

The first step of this program is to create some programs that help the people who work at the Ministry of Agriculture and Water to learn and understand the system of water resources and how to allocate water resources of each region. The second step is to educate the public about the scarcity of their water resources by conducting some lectures at the Ministry of Agriculture and Water, by distributing some brochures to the people, or by conducting some programs at the Television. Prior to implement any conservation program, it is very important to know whether it is socially acceptable or not and this can be achieved by public education. Educating the people about water management may help decreasing water consumption, whether that water consumption from domestic or agricultural use.

***Water saving devices***

Implementation of new water saving devices in kitchens and bathrooms such as some devices that can be installed in the shower, flush toilet, and washer to minimize water delivery can reduce the domestic water consumption. Also, controlling the leakage from the piped water can save some of water consumption. Estimates indicate that a significant portion of water supplied (50%) is lost to leaks (Al-Ibrahim, 1990).

***Metering and billing***

Installations of metering in each household to control the amount of water consumption can help reducing water consumption. Water pricing, whether that water comes from desalination of seawater or from groundwater, in all Saudi Arabia regions should be based on an increasing block-rate system with different block rates. By using different block rates, the cost of water increases with increasing water consumption. This approach can save a lot of wasteful water.

***Reuse of wastewater***

Wastewater can be used after treatment for municipal landscape irrigation, non-food production and crops, and for industrial purpose. Also, wastewater can be used as a recharge source to the groundwater after treatment. Using wastewater for irrigation and industrial purposes can reduce water demand. Recently, about 175 farms in Riyadh city use treated sewage water for irrigation (Al-Ibrahim, 1990). Also, in Jubail and yanbu cities, treated wastewater is used for industrial purpose.

***Decrease agricultural consumption***

The agricultural consumption can be reduced by effective maintenance of the irrigation system, the application of the efficient irrigation schedule, and by using modern methods such as drip and sprinkler irrigation. Using these modern methods for irrigation can save a large amount of water. Al-Ibrahim (1990) showed that sprinkler irrigation uses 42% less water and drip irrigation uses 62% less water than the surface irrigation system.

Limiting the number of wells in each farm will help to manage water resources in the area. Also, if the farm is very large, which needs more than a well, the Ministry of Agriculture and Water can give the owner a permit to drill another well but this well should not be drilled to the Saq aquifer. The owner can drill another well into any formation located above the Saq aquifer. This approach can save a lot of water from the Saq aquifer as well as protect the Saq aquifer from degrading.

Reducing the agricultural lands will decrease water demand by agricultural purpose. This can be achieved by controlling on each farm, the specific amounts of crops produced. The Kingdom of Saudi Arabia is the only one who purchases farmers' crops. Of course they can market their products everywhere but they will not get as much as they can get from the government. Also, decreasing the cost of crops that are taken by the government will reduce the agricultural lands and as a result of that the water demand by agricultural purpose will be reduced.

From the above, it seems that serious efforts are needed by responsible government agencies, as well as private agencies associated with the distribution, treatment, and use of water, to adopt effective conservation programs.

# APPENDIX. ADDITIONAL FIGURES

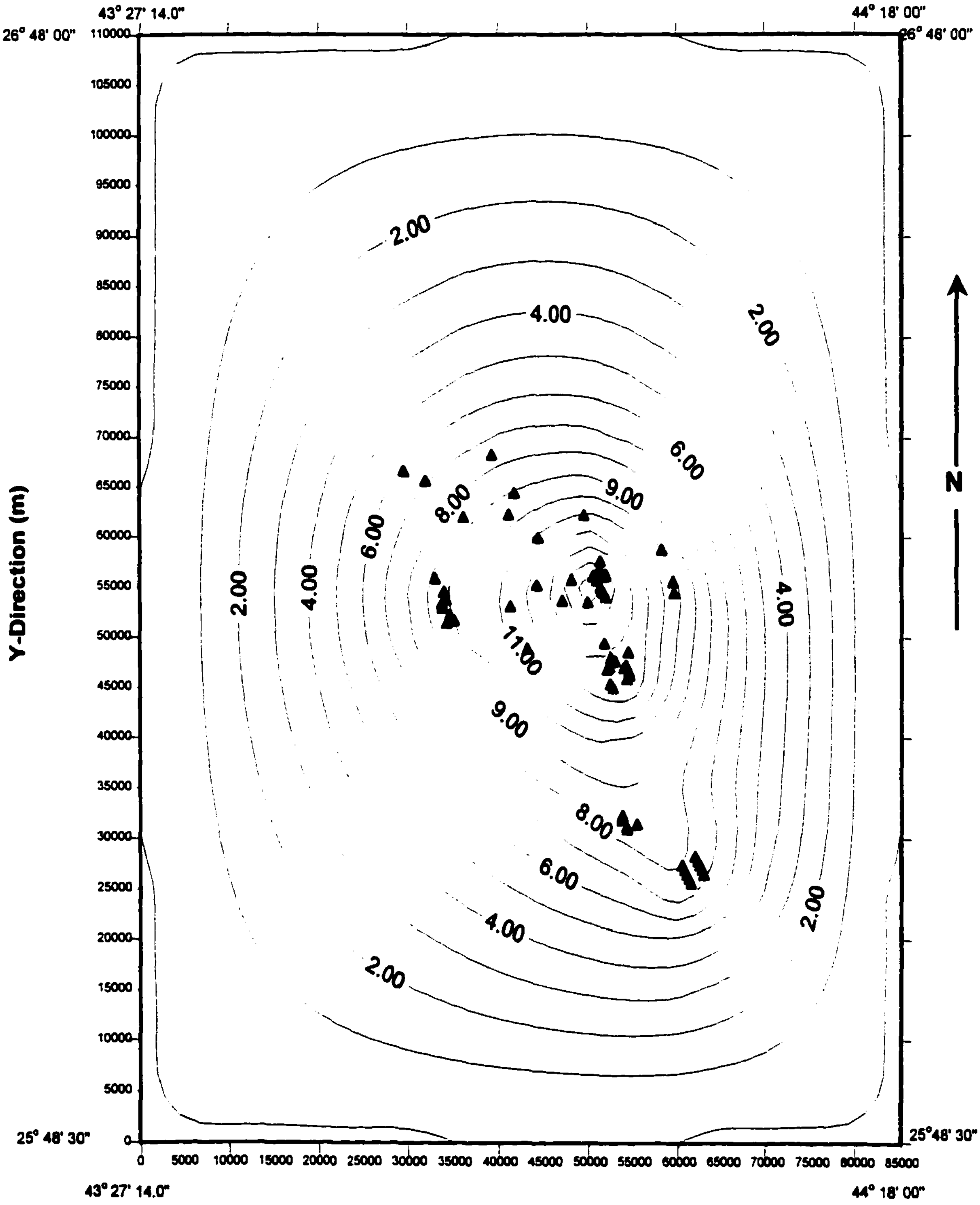


Figure 1. Resulting hydraulic head changes (drawdown) for the first management plan during the period of 2010.

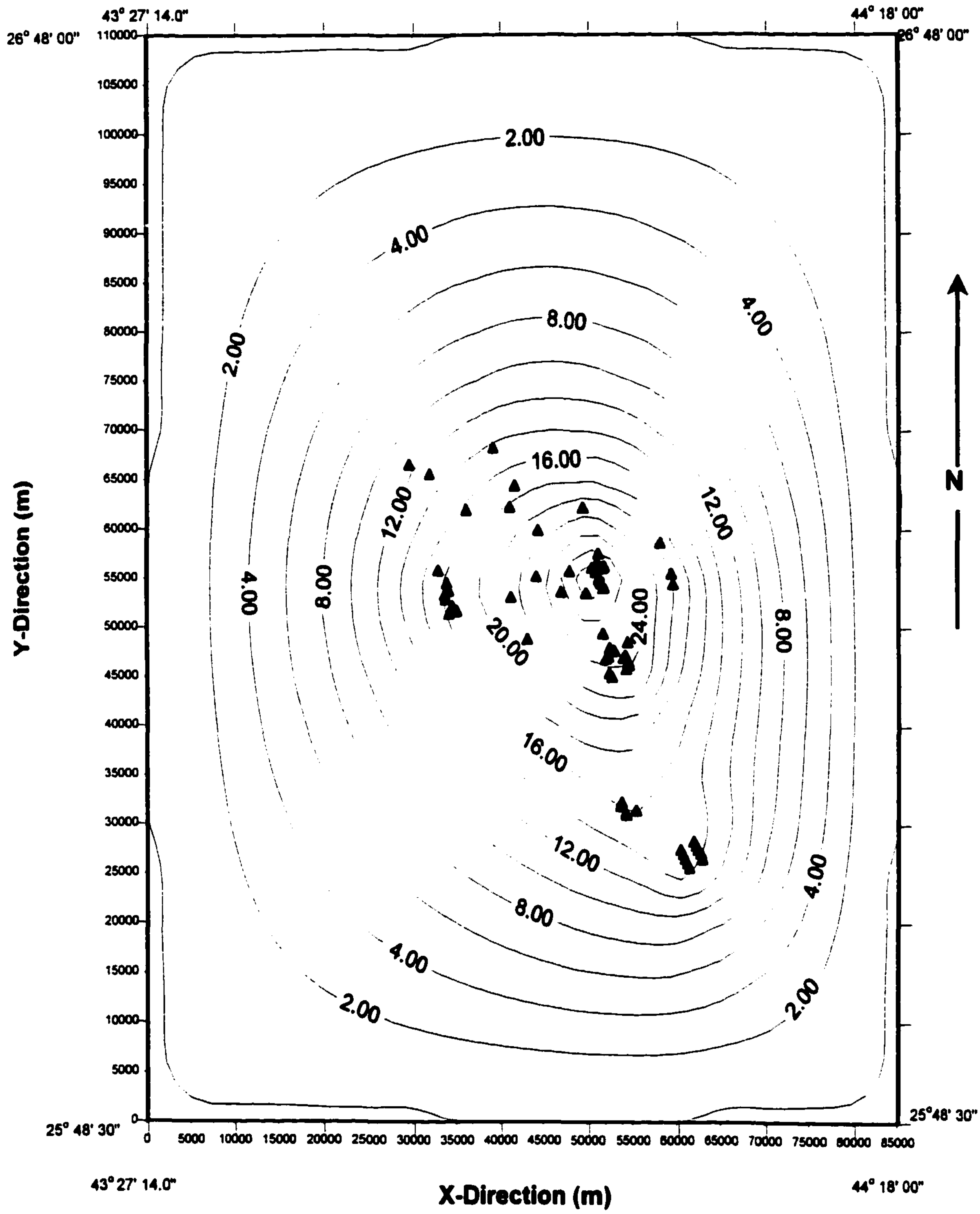


Figure 2. Resulting hydraulic head changes (drawdown) for the first management plan during the period of 2020.

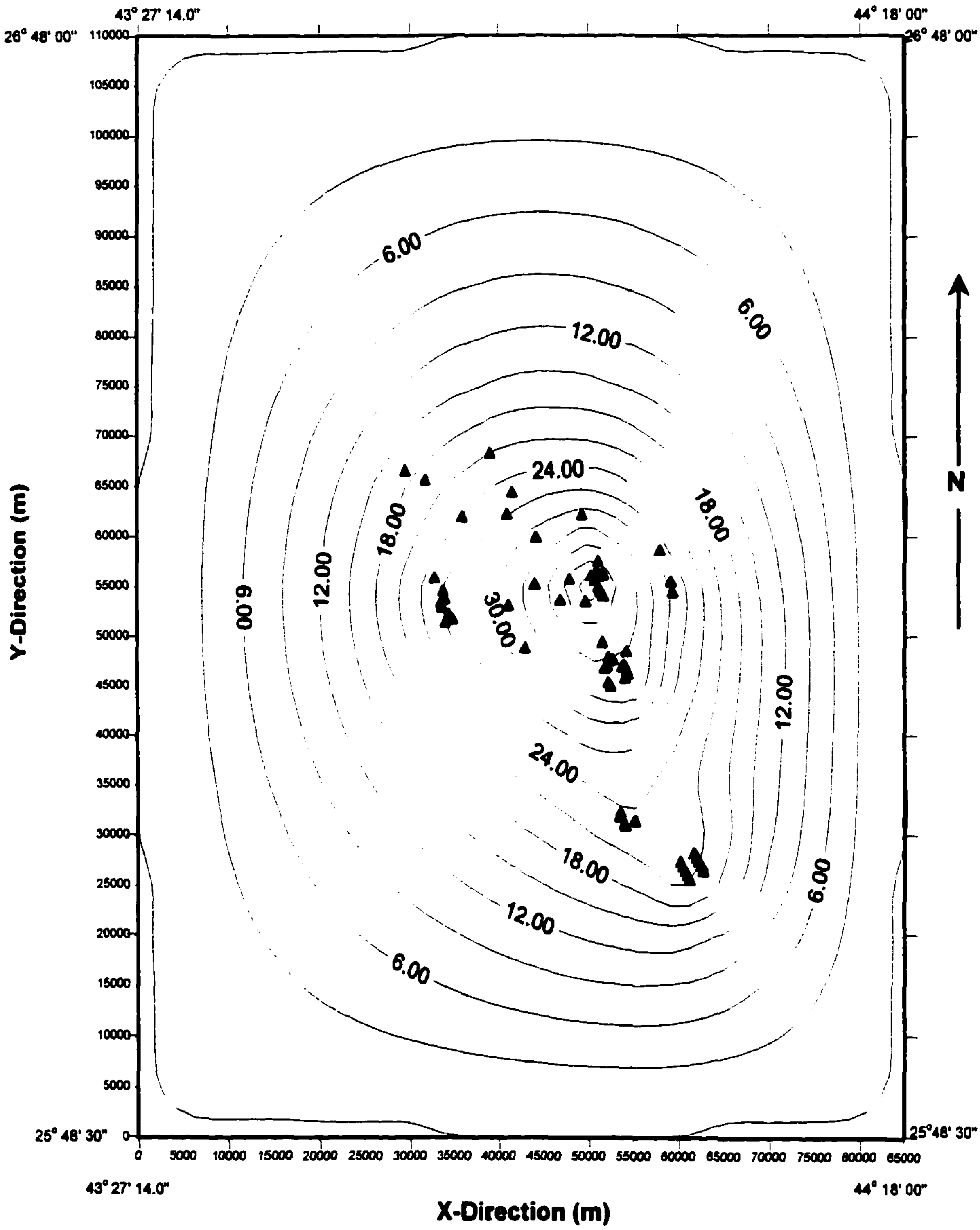


Figure 3. Resulting hydraulic head changes (drawdown) for the first management plan during the period of 2030.

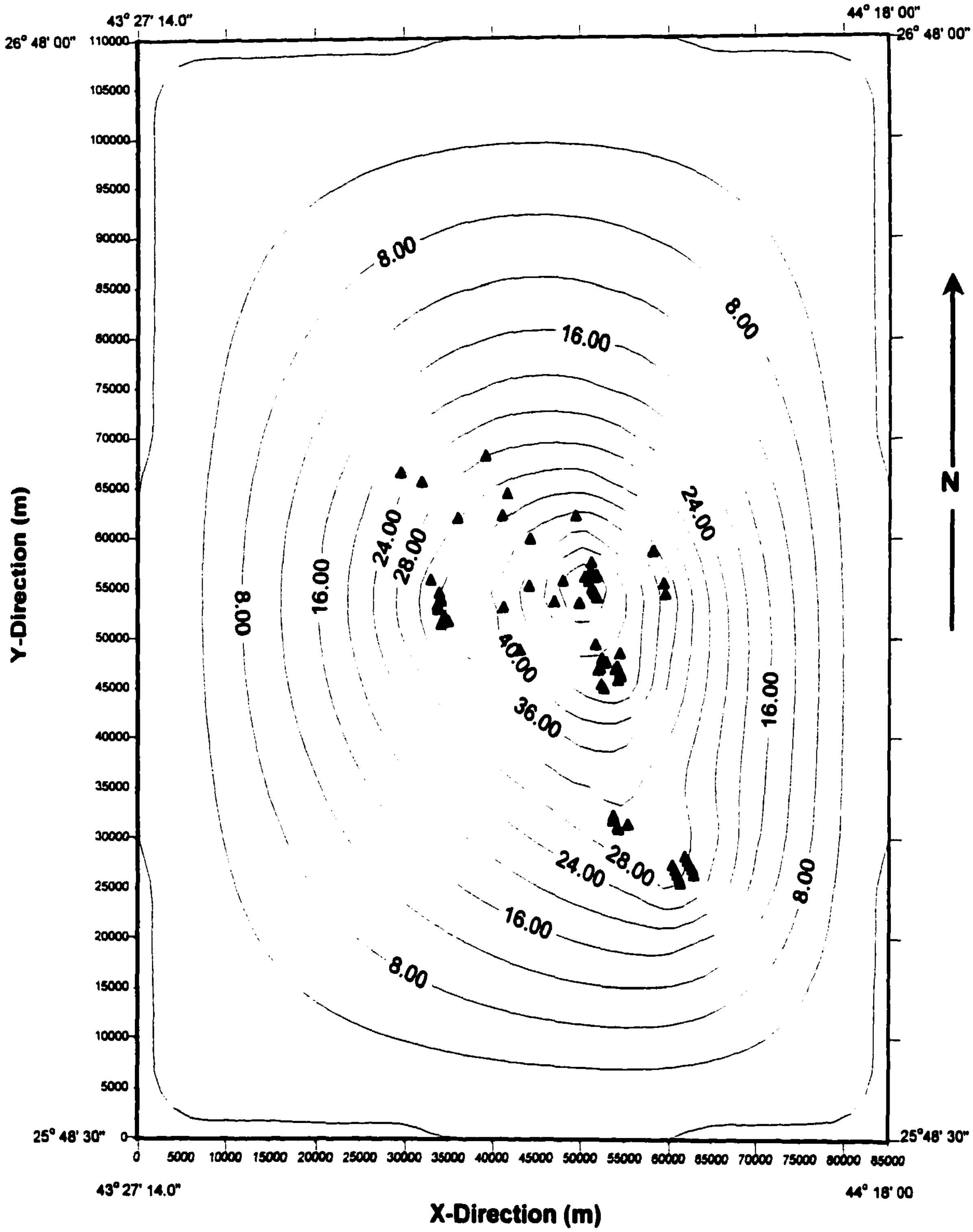


Figure 4. Resulting hydraulic head changes (drawdown) for the first management plan during the period of 2040.

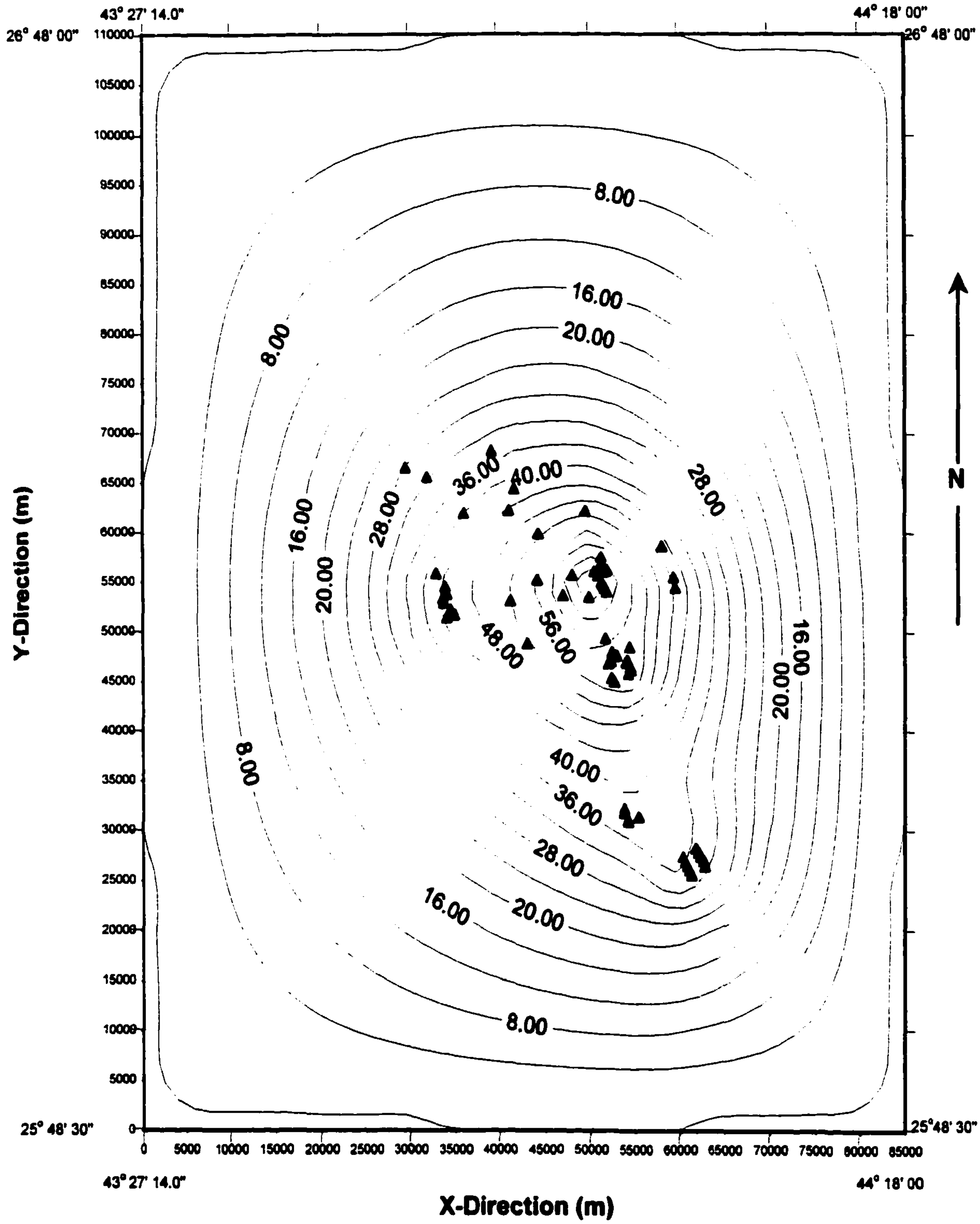


Figure 5. Resulting hydraulic head changes (drawdown) for the first management plan during the period of 2050.

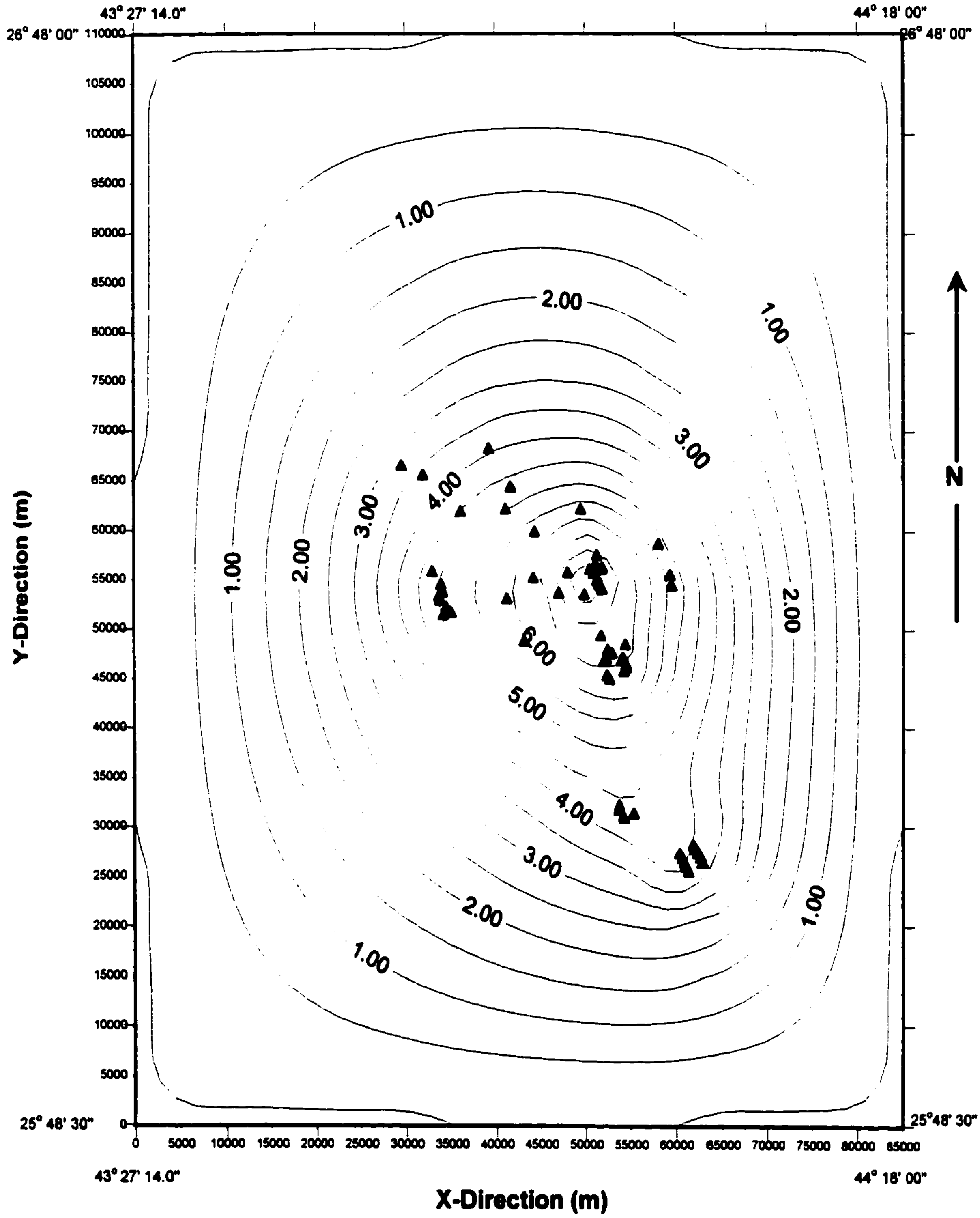


Figure 6. Resulting hydraulic head changes (drawdown) for the second management plan during the period of 2010.

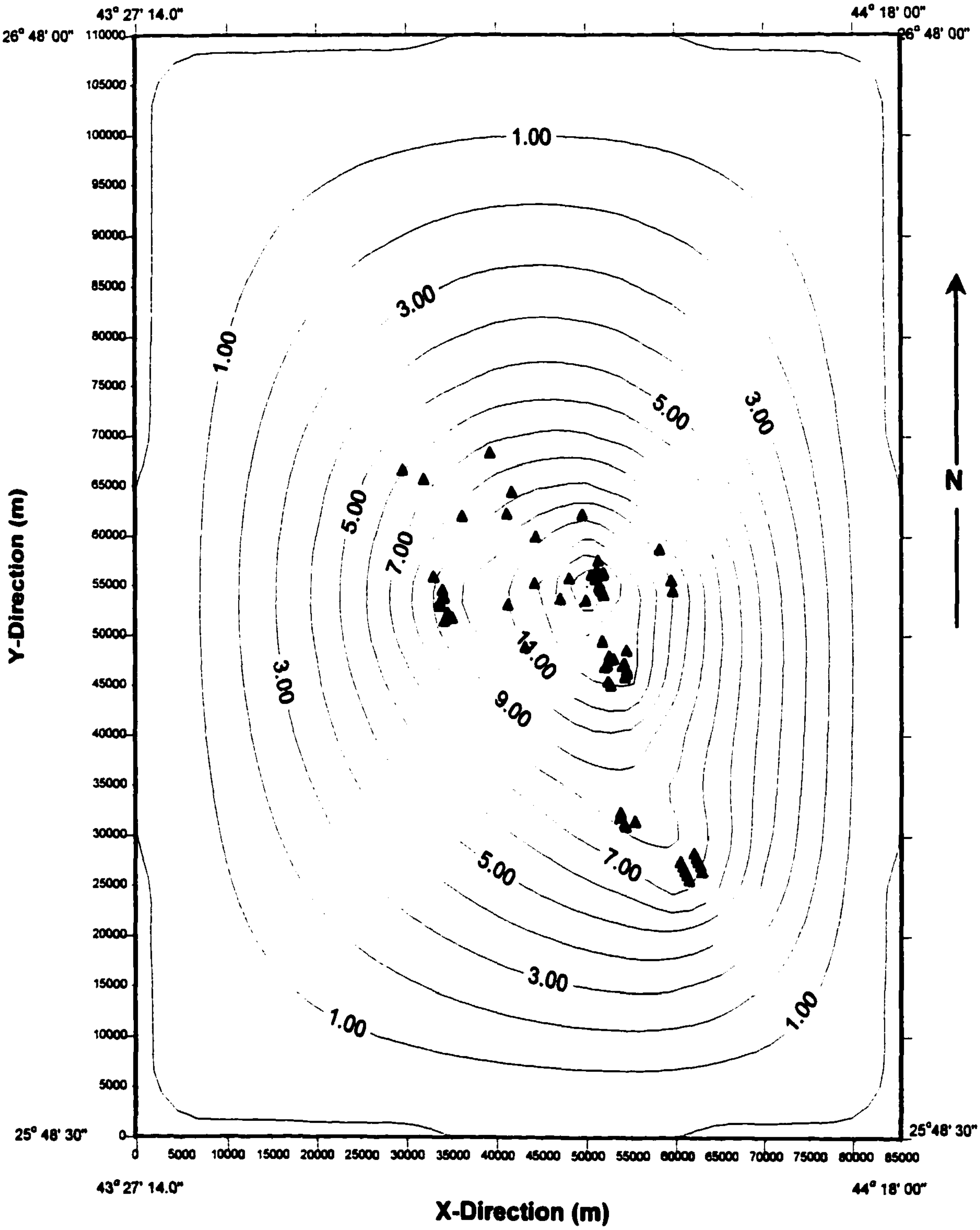


Figure 7. Resulting hydraulic head changes (drawdown) for the second management plan during the period of 2020.

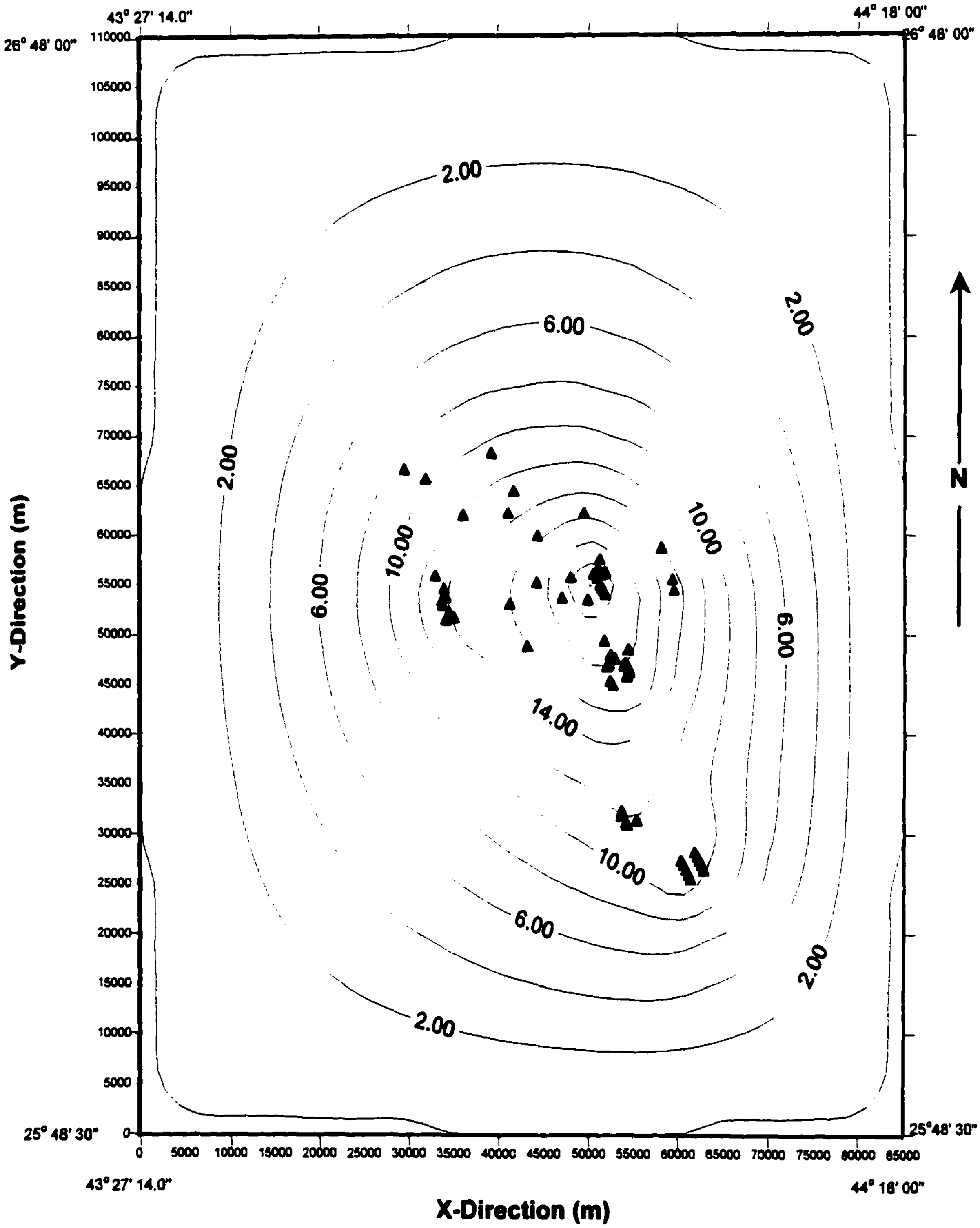


Figure 8. Resulting hydraulic head changes (drawdown) for the second management plan during the period of 2030.

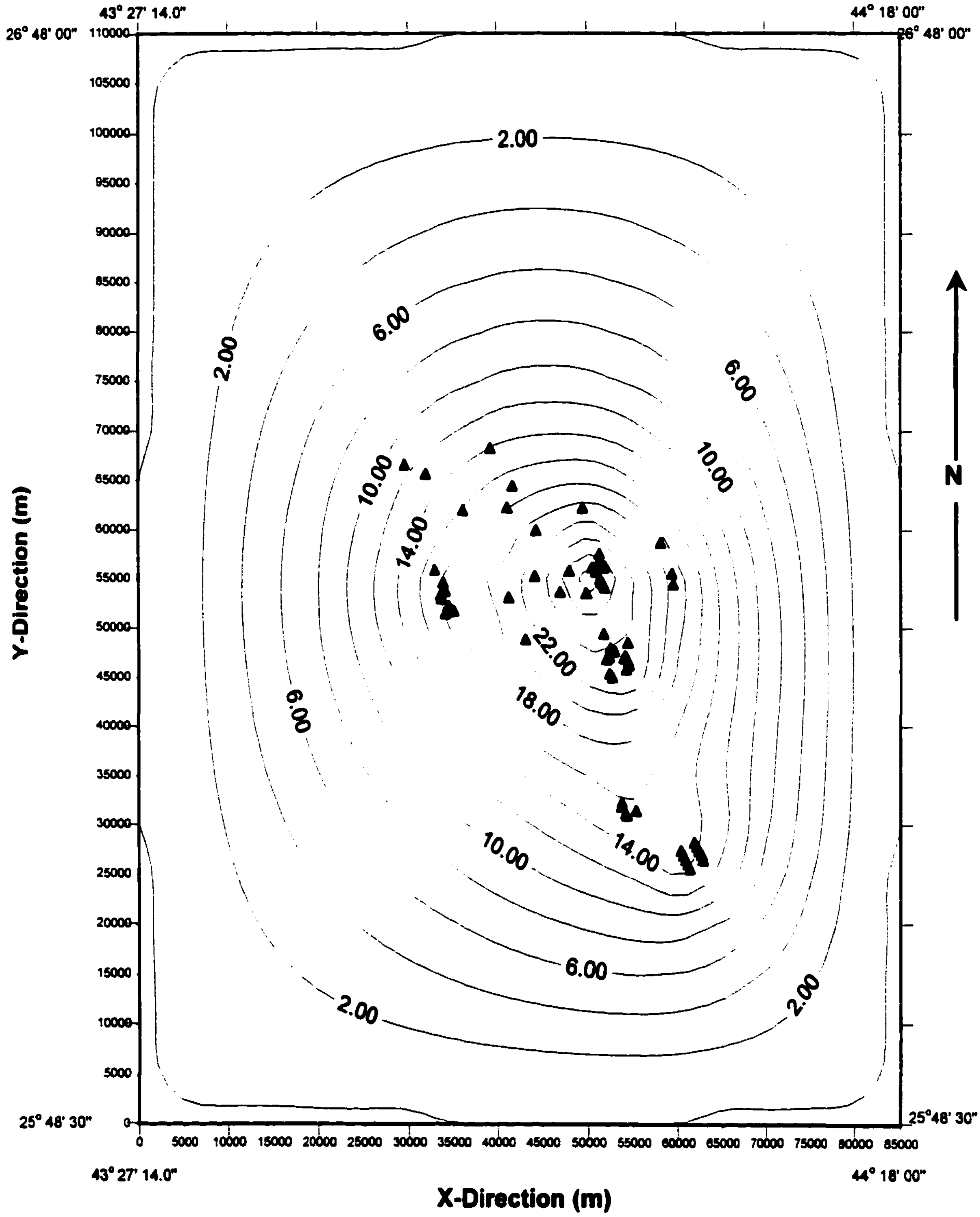


Figure 9. Resulting hydraulic head changes (drawdown) for the second management plan during the period of 2040.

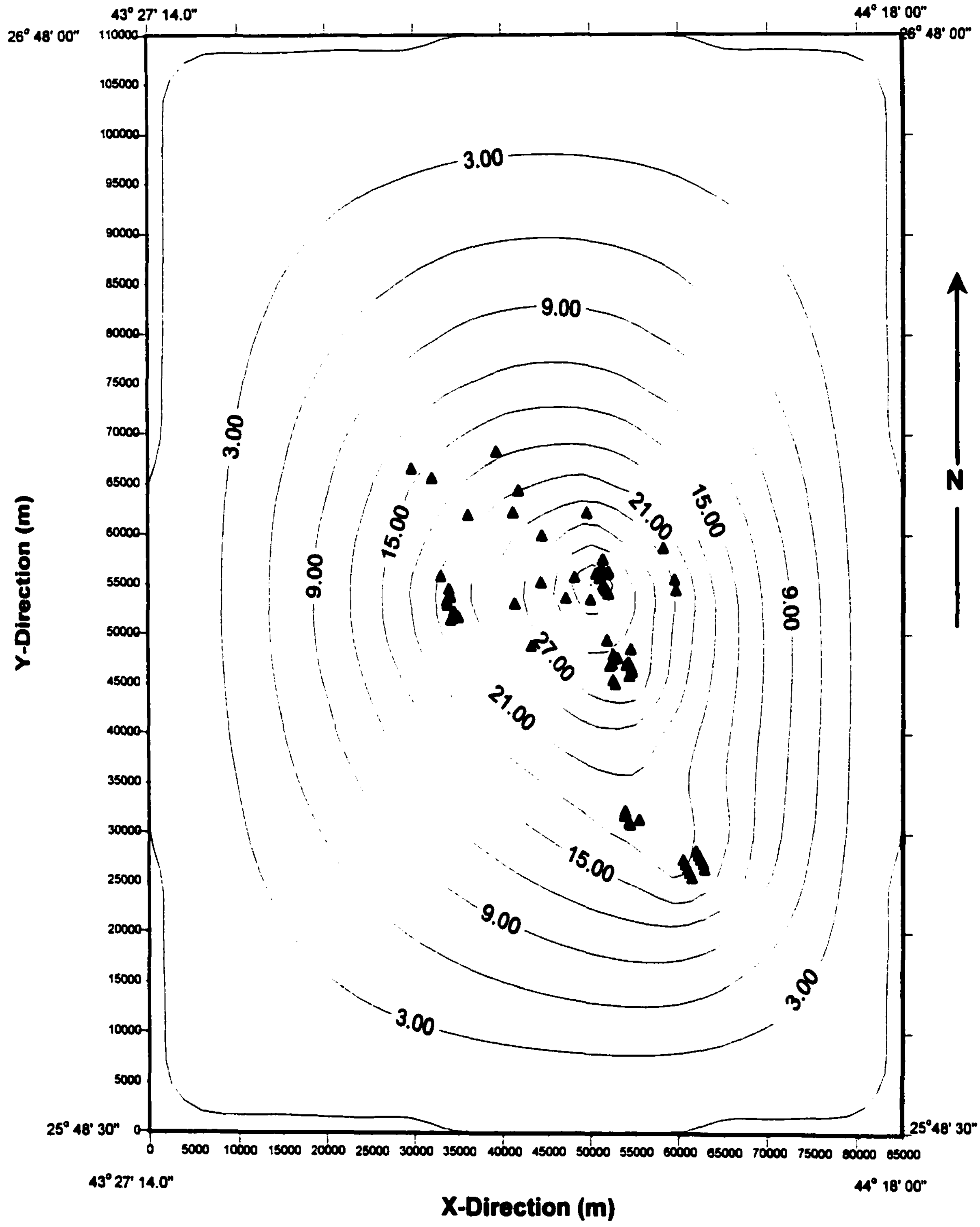


Figure 10. Resulting hydraulic head changes (drawdown) for the second management plan during the period of 2050.

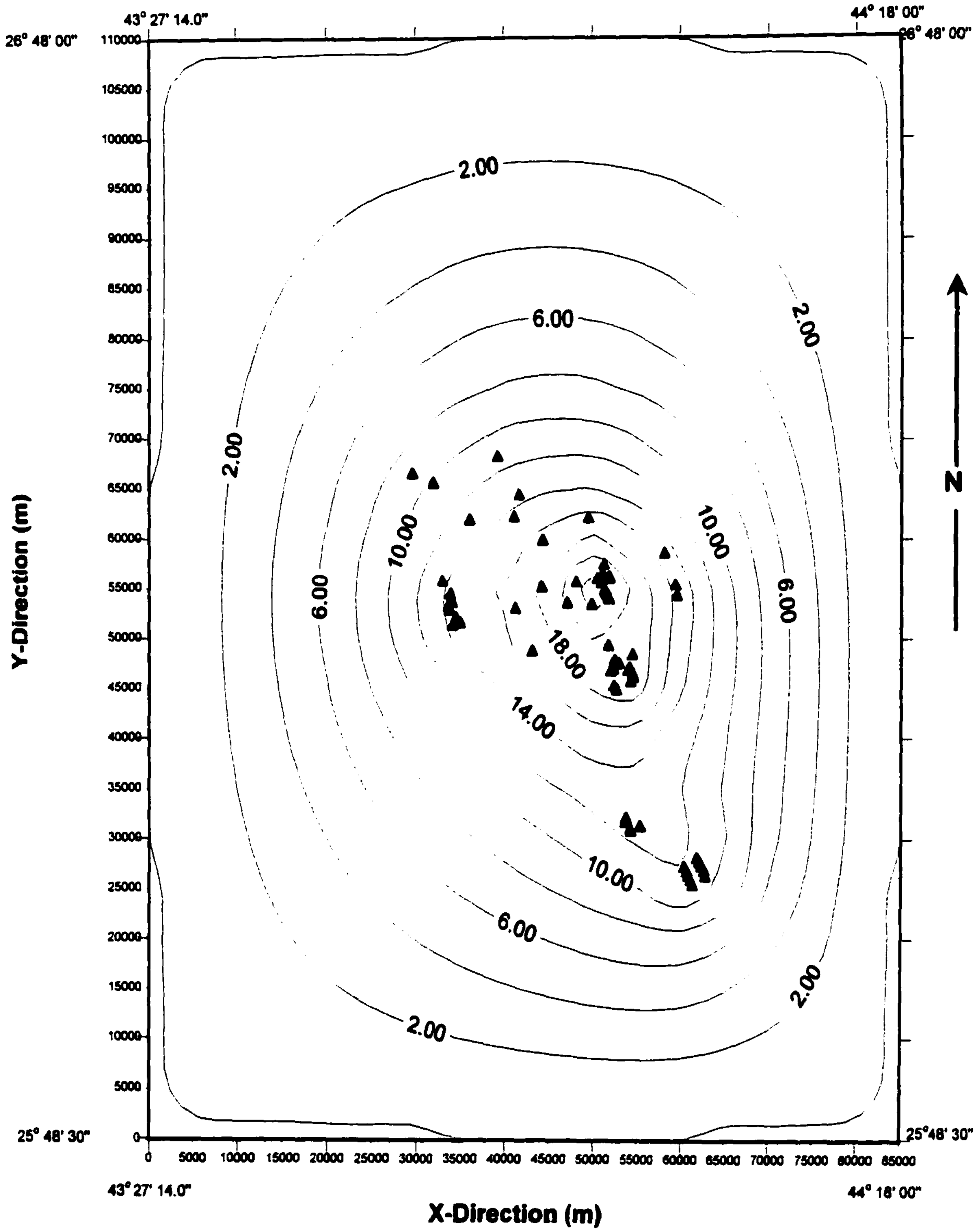


Figure 11. Resulting hydraulic head changes (drawdown) for the third management plan during the period of 2010.

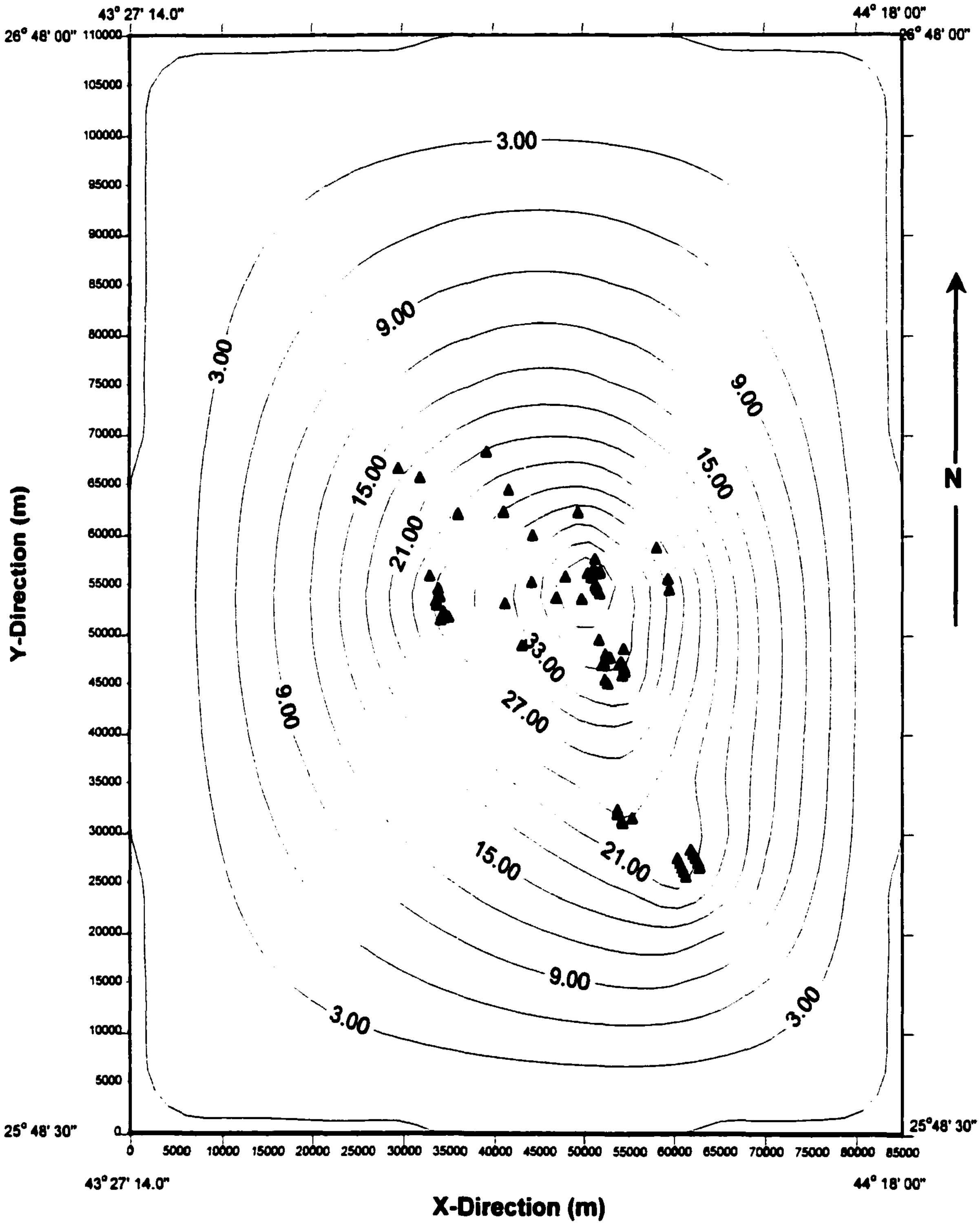


Figure 12. Resulting hydraulic head changes (drawdown) for the third management plan during the period of 2020.

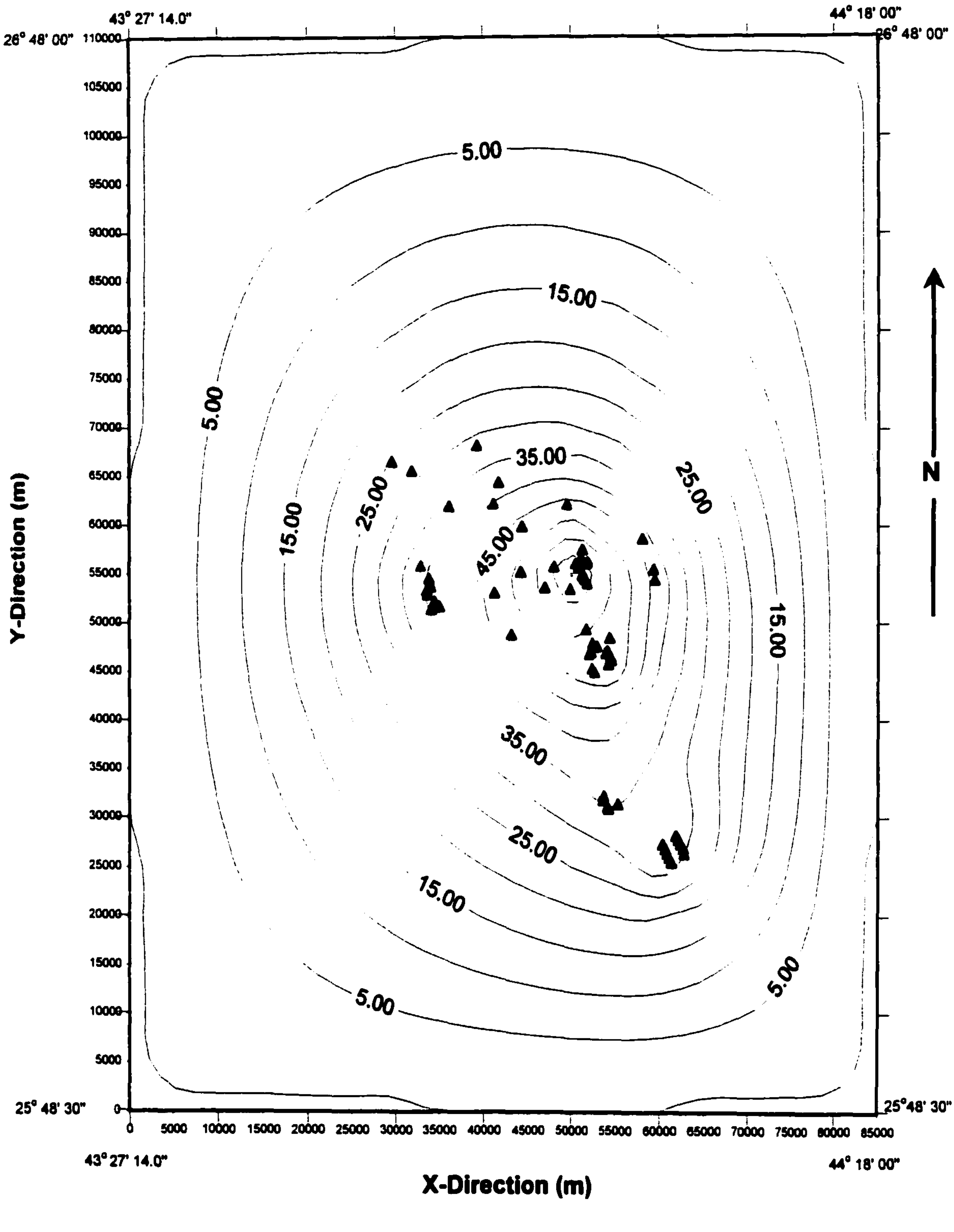


Figure 13. Resulting hydraulic head changes (drawdown) for the third management plan during the period of 2030.

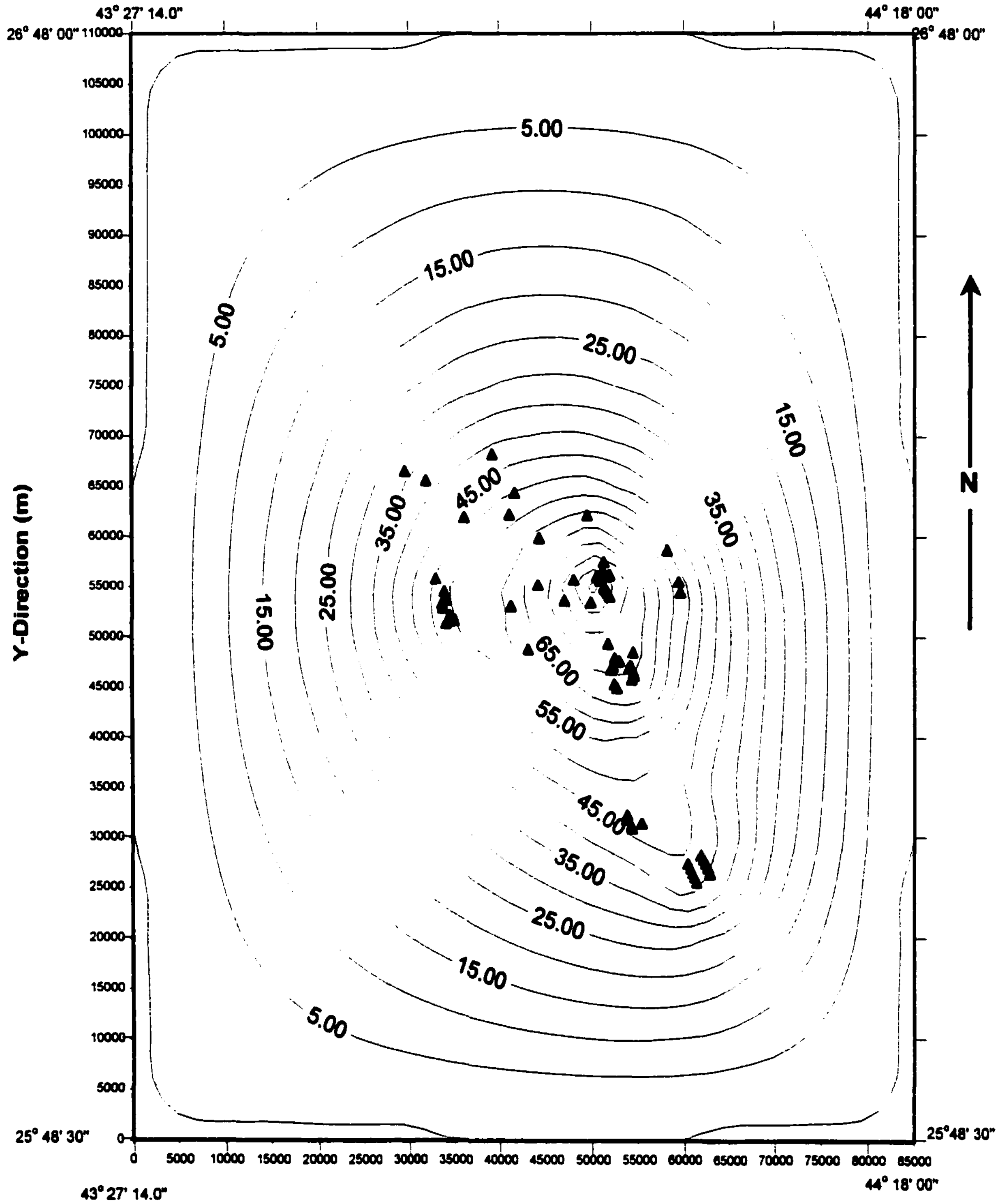


Figure 14. Resulting hydraulic head changes (drawdown) for the third management plan during the period of 2040.

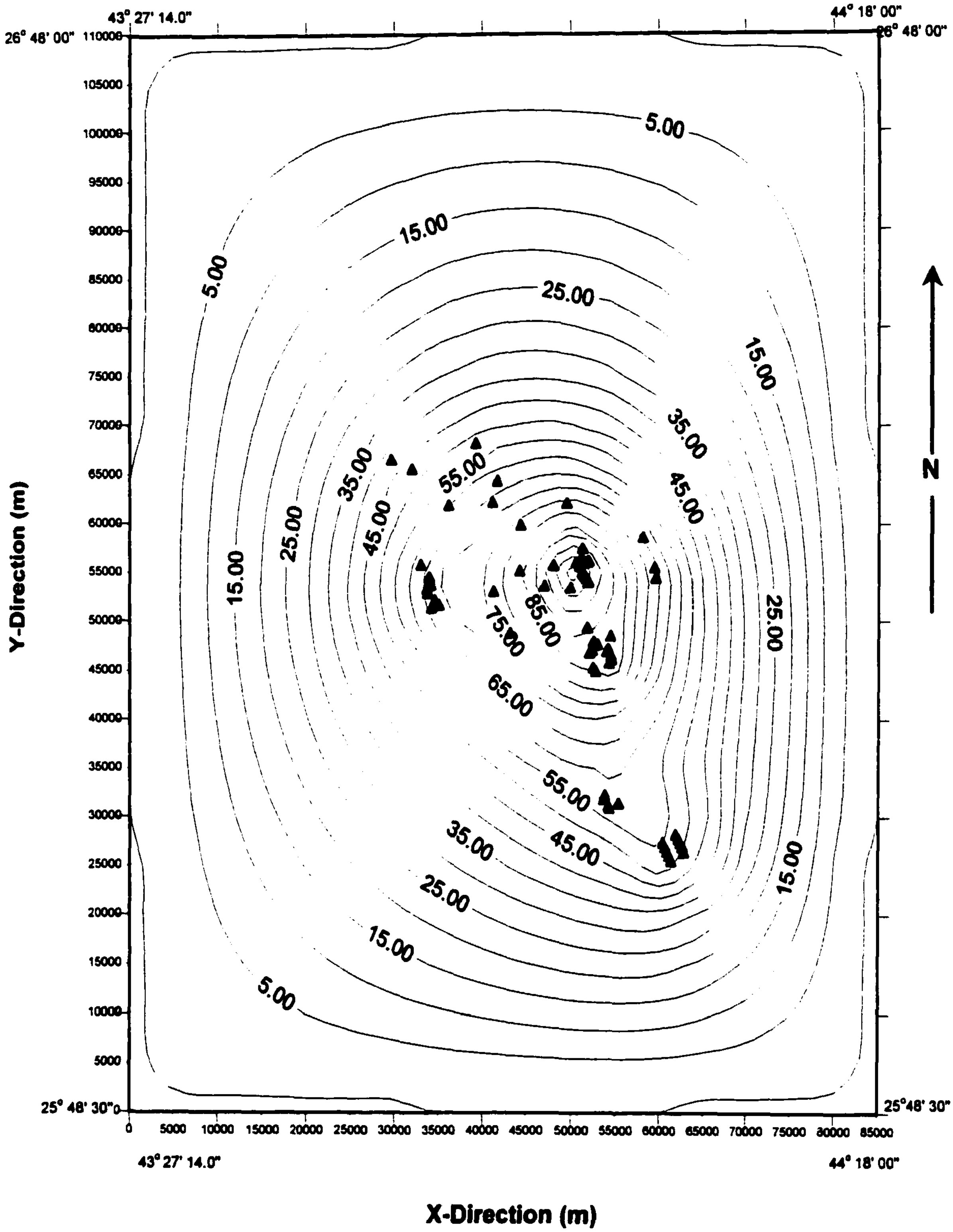


Figure 15. Resulting hydraulic head changes (drawdown) for the third management plan during the period of 2050.

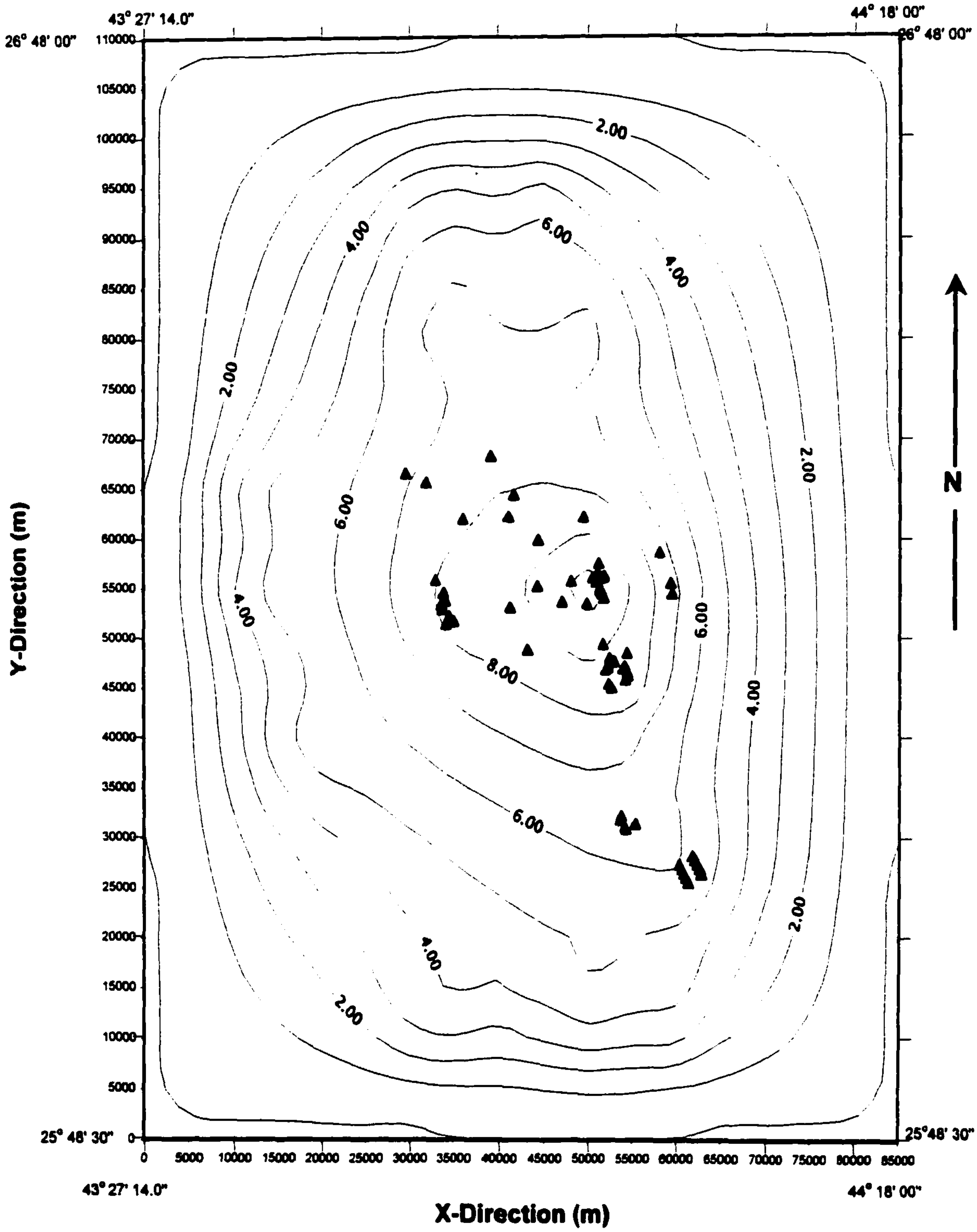


Figure 16. Resulting hydraulic head changes (drawdown) for the fourth management plan during the period of 2010.

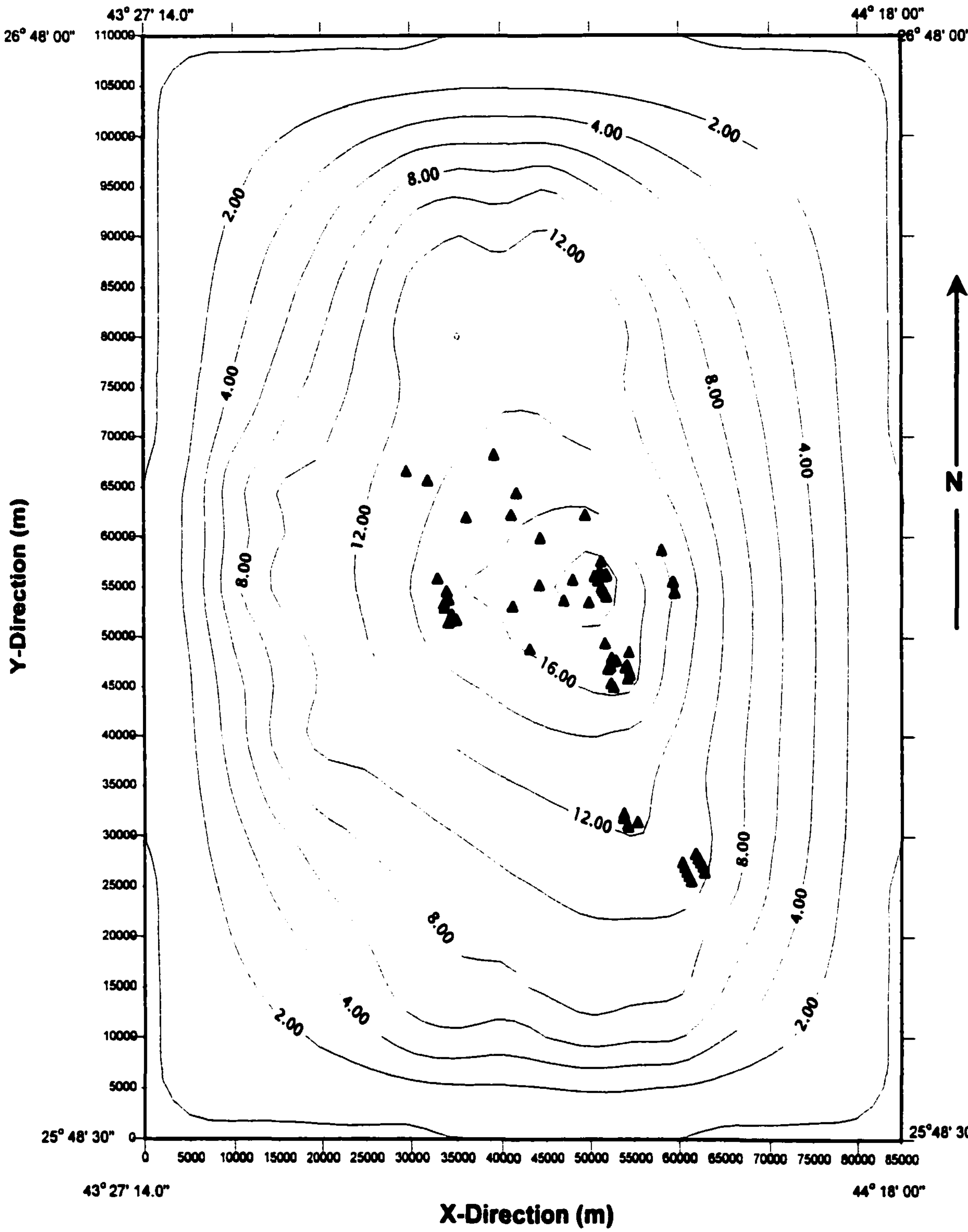


Figure 17. Resulting hydraulic head changes (drawdown) for the fourth management plan during the period of 2020.

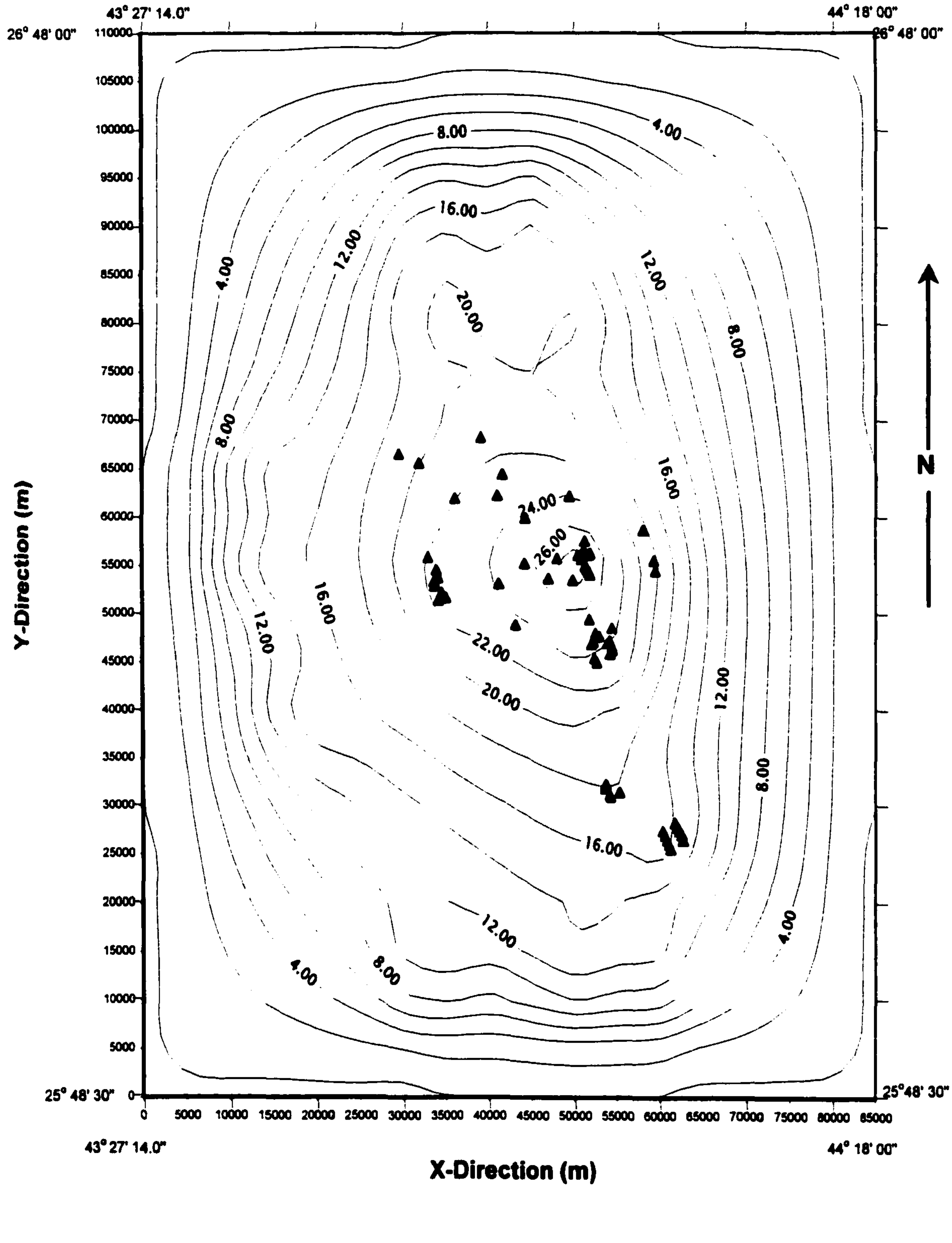


Figure 18. Resulting hydraulic head changes (drawdown) for the fourth management plan during the period of 2030.

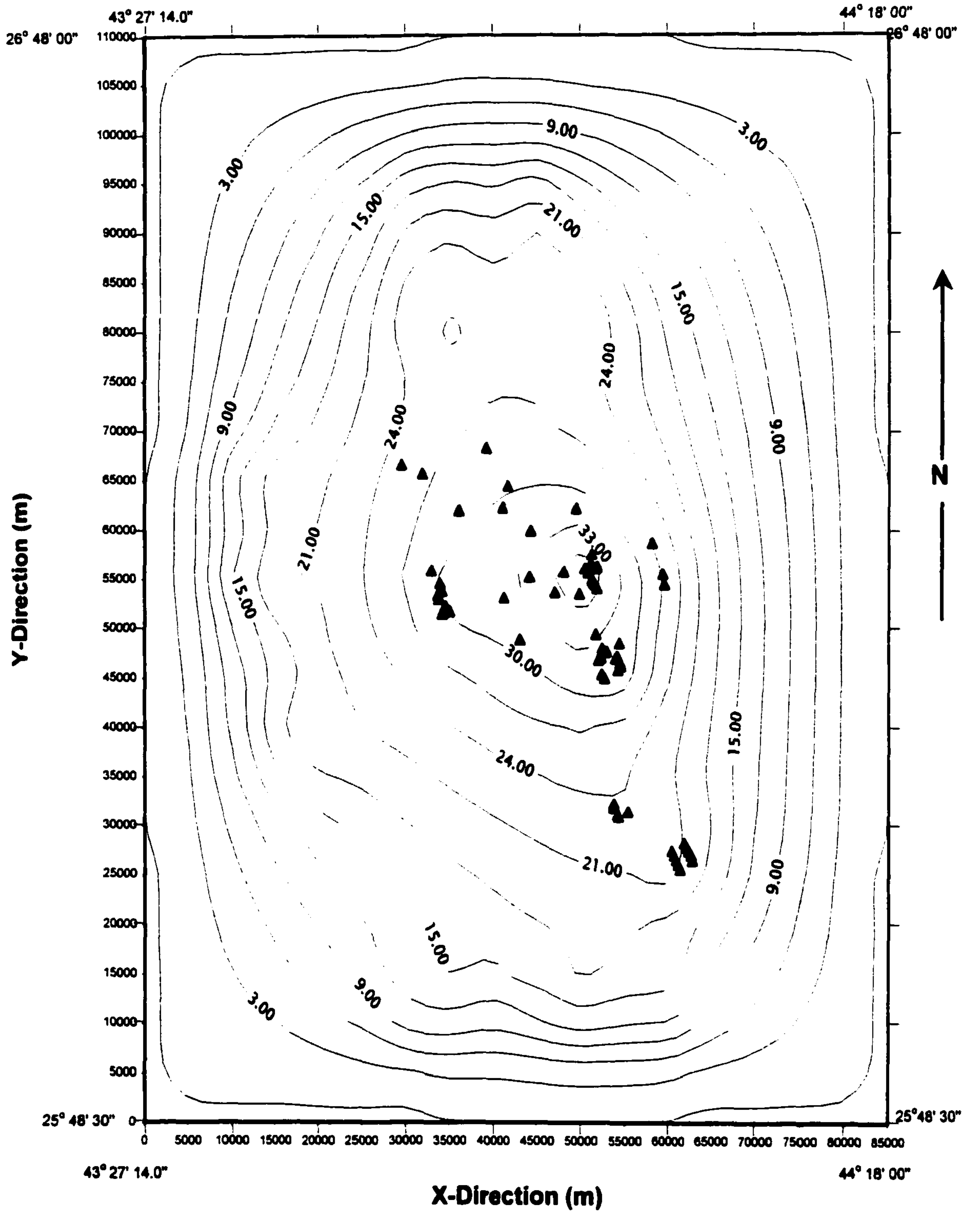


Figure 19. Resulting hydraulic head changes (drawdown) for the fourth management plan during the period of 2040.

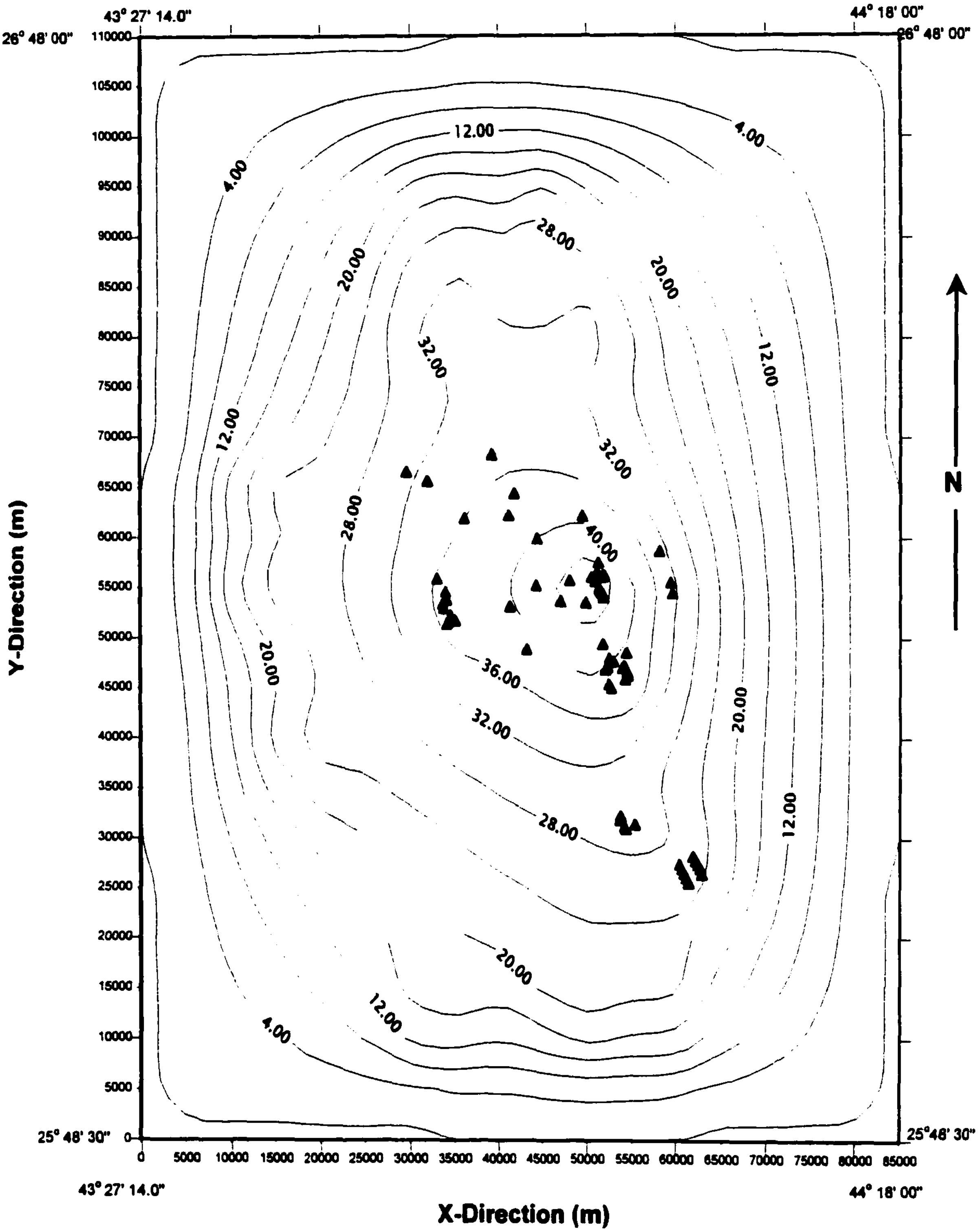


Figure 20. Resulting hydraulic head changes (drawdown) for the fourth management plan during the period of 2050.

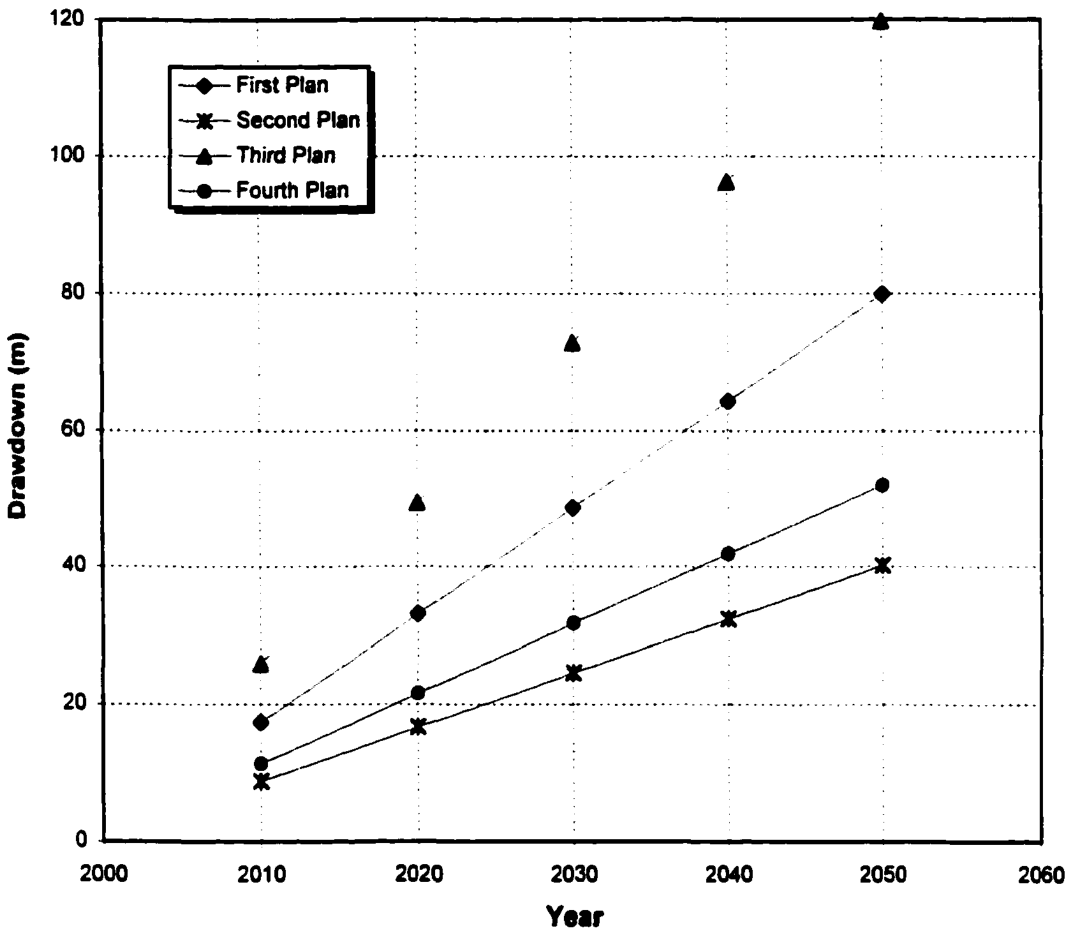


Figure 21. Drawdown at the observation well #10 during different plans.

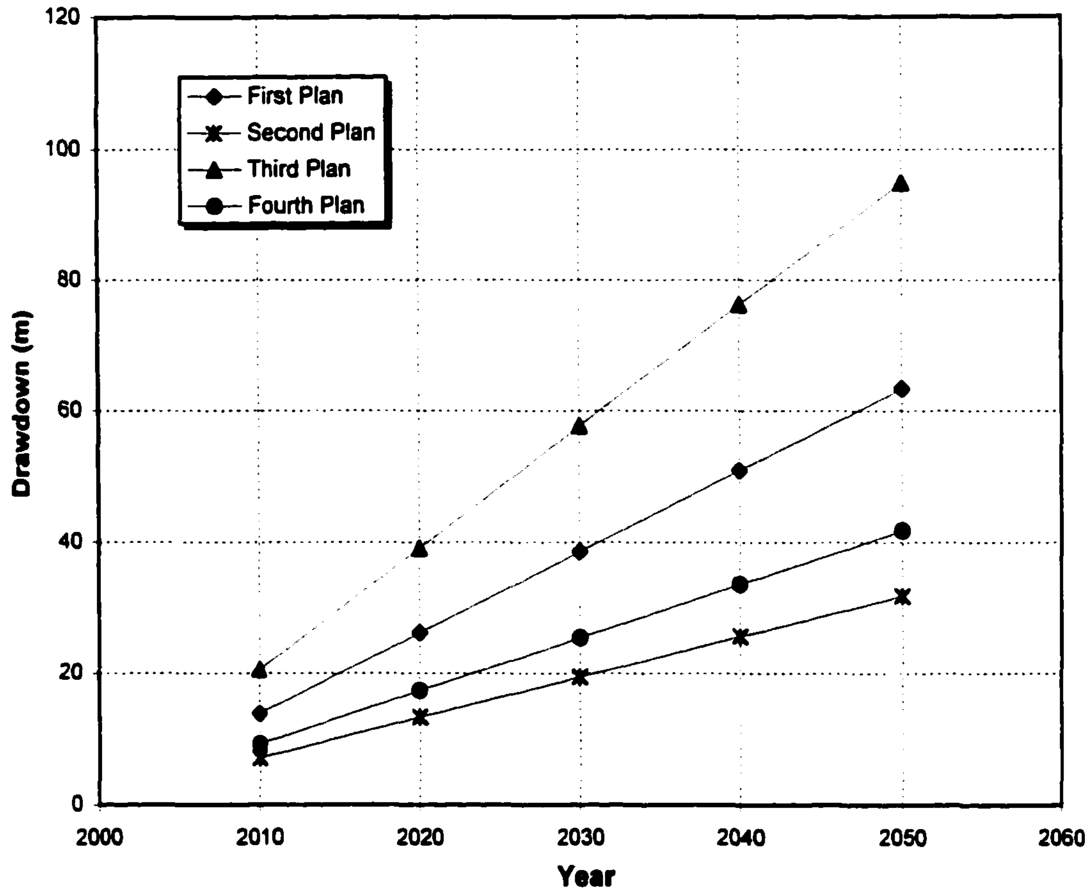


Figure 22. Drawdown at the observation well #21 during different plans.

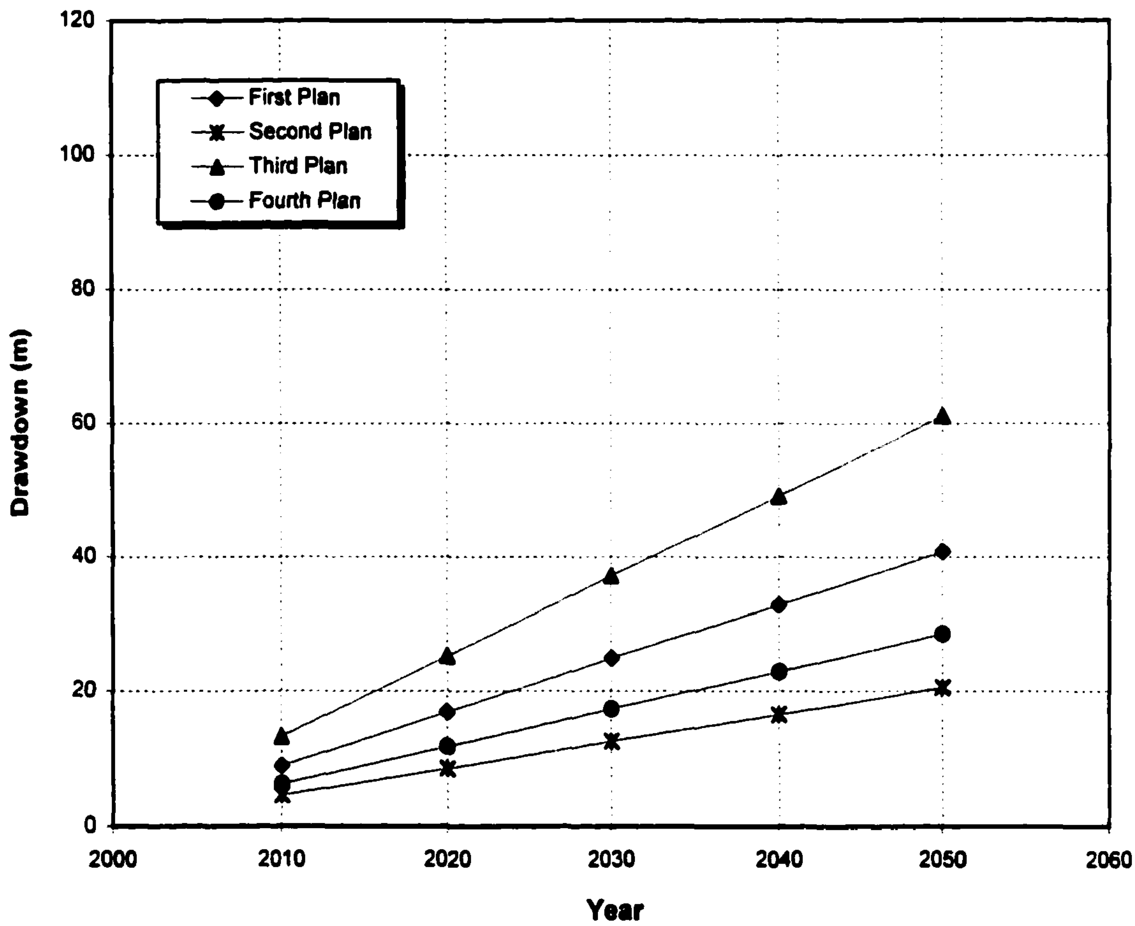


Figure 23. Drawdown at the observation well #2-1 during different plans.

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