Chapter

Aquifer Characterization: The Case of Hawassa City Aquifer

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Abstract

Hydrogeologists and other water experts agree on that the effective groundwater management requires: firstly, a good understanding of the aquifer system; secondly, identification of practical measures to control abstraction; and thirdly, improvement in groundwater resource through artificial recharge. A 16 years' pumping test and drilling lithology data and productive 29 wells were used to characterize the aquifer parameters of the Hawassa City, Ethiopia. The aquifer system was characterized physically, potentially, spatially, quantitatively, and qualitatively using AquiferTest software by applying Moench method to pumping test response data considering the basic assumptions in the model. Weathered and fractured pumice, basalt Scoriaceous rocks, fine-to-coarse-grained sand, and weathered ignimbrites are major water-bearing formations found from the analysis. High porosity and permeability due to these fractures are found to be a risk for the easy contamination of the ground water from surface wastes especially at the shallow aquifer water areas. Spatially, the southern corner and the lake shore of the city were identified as a huge potential area. Percentage of recovery results are 95–100% and transmissivity varies from 4.77×10^{-4} m^2/s to 1.75×10^{1} m^2/s. This follows the general pattern of increasing value from east to west, that is, the value increases from the upper part of the basin to the lower. Moreover, the annual ground flow vector map of the area was developed using static water level data to see the direction of subsurface flow in the area. Accordingly, a large magnitude of water flowing from the central and west directions to the lake shore is identified showing similar profile with the surface flow.

Keywords: Hawassa City, pumping test, AquiTest, Moench method, aquifer characterization

1. Introduction

1.1 Aquifer characterization

Characterization of hydraulic properties of an aquifer involves the use of existing pumping test data, hydrogeological map, geologic map, soil map, lithology obtained from well logs, aquifer thickness, water table depth, structures and surface water features, etc., so as to analyze the lateral distribution and nature of the aquifer.

Pumping test analysis and well logs were used to identify the aquifer system of Tarmaber formation by the author [1]. Accordingly, the formation is categorized as fractured aquifer where the dominant aquifer types are confined-double porosity and single plane vertical aquifer. The double porosity aquifers are related to deeply drilled wells reflecting presence of large and narrow fracture systems with high permeability but with lower storage capacity. Transmissivity varies between 0.5 and 1400 m^2/day.

1.2 Pumping test, slug test, and recovery measurement

1.2.1 Pumping test

Aquifer pumping test involves posing artificial stress on the hydrogeological system by pumping water from a well and measuring the changes in water levels in the pumped well and nearby observation wells. The response of the hydraulic head in the aquifer can be used to estimate transmissivity or hydraulic conductivity in the particular aquifer. The data from the pumping tests are used to calculate the specific capacity (specific capacity = Q/s, where Q = yield and s = drawdown) of the well.

The total drawdown is the algebraic sum of the individual drawdowns during the constant rate of pumping. The total drawdown can be estimated as:

$$TDD_W = DWL - SWL \quad (1)$$

where TDD_W is total drawdown, DWL is dynamic water level, and SWL is static water level.

In addition to estimating hydraulic properties of an aquifer system such as transmissivity and hydraulic conductivity, a step-drawdown test is made to evaluate well performance criteria such as well loss and well efficiency. All conventional well hydraulic theories are based on the assumption that laminar flow conditions prevail in the aquifer during pumping.

In our study area Lake Hawassa catchment, pumping tests are most commonly conducted following the development works usually for 24 h. The objective of the pumping test is to evaluate the production capacity of the well and the aquifers and to decide on the capacity and the position of the production well. Moreover, the results of the pumping test are of great value to be used in the well operation and maintenance apart from being used for future ground water study and research purposes. A pumping well with a pump that allows to control the pumping rate, one or more observation wells close enough to see the influence of the pumping well (mostly in the pumped well or control well itself), some means of measuring water levels in the observation wells at specific times throughout the course of the test; using automatic pressure transducers or manually using depth meters.

1.2.2 Slug tests

Multiple well pump tests are not always feasible—there may not be any observation wells, and it may cost too much to put new wells in or it could be that we are dealing with a contaminated system, and everything we pump out of the well have to be hauled away and treated, which need more investment. There are alternative methods that involve piezometers and a general set of tests called "slug" tests. These tests involve introducing or removing a known quantity of water (a "slug" of water) from a piezometer and measuring the time it takes to recover to the initial static water level [2].

1.2.3 Recovery measurement

After a pump test is performed for the specified time period, the well is shut off and recovered data (heads in the observation well at times after the pump is shut off) are collected. The recovery is the rate at which water in the well returns to its static water level after the pumping is turned off. The recovery measure is another estimate of the well yield. Percentage of recovery can be estimated by the following relationship:

$$PR = 100 \times (DWL - MRWL)/TDD_W \tag{2}$$

where PR is percentage recovery, DWL is dynamic water level, MRWL is the maximum recovery of water level, and TDD_W is total drawdown.

1.2.4 Specific capacity

Specific capacity is known as well performance test estimated by assuming the well is pumped at a constant rate long enough to establish the equilibrium drawdown; within the well, there is a combination of the decrease in hydraulic head (pressure) and a pressure loss due to well loss. Specific capacity is defined as:

$$Sc = Q\ /TDD_w \tag{3}$$

where Sc is specific capacity, Q is the pumping rate, and TDD_w is the total drawdown in the well due to both aquifer drawdown and well loss.

Well loss is created by the turbulent flow of water through the well screen and into the pump intake. Specific capacity is estimated by discharge on a linear x-axis and drawdown on a linear y-axis and measuring the slope of the straight line fit.

1.2.5 Analyzing and evaluating pumping test data

Different hydrogeologists [2, 3] suggested very similar procedures for analyzing and evaluating pumping test data. In general, it is as much an art as a science. It is a science because it is based on theoretical models that the hydrogeologist must understand and thorough investigations must be conducted into the geological formations in the area of the test. It is an art because different types of aquifers can exhibit similar drawdown behaviors, which demand interpretational skills on the part of the hydrogeologist.

During an aquifer test, the hydraulic head in the aquifer declines as the time of pumping increases. Analysis of hydraulic head decline, or drawdown, allows for the estimation of aquifer hydraulic properties. For instance, authors [4] in the study of aquifer parameters estimation in basaltic terrain and the application of wireless sensor networks at Chikhaldara region, India; identified a pumping test as the best available method to evaluate aquifer parameters. The tests were performed at 20 locations using the local farmers' well pumps. The pumping phase of the tests had a short duration of 60–210 min; the recovery phase of the tests had a longer duration of 90–300 min. Three methods were adapted to estimate the aquifer parameters in a basaltic terrain. Out of the three methods, two were conventional or analytical curve matching techniques (the study is found in [5, 6]). The other technique was a numerical method. Moreover, this study determined the flow direction of sub-surface water using static groundwater level data within a basin from the past 20 years (1972–1992); an annual average water level map was constructed (with respect to the above mean sea level).

1.2.6 Pumping tests and methods of analysis

Among the main techniques are analytical/conventional methods and numerical methods. Analytical/conventional methods involve one of the curve matching, finding inflection points, or for special cases and fitting straight lines to the pumping test data [4].

Models for the interpretation of pumping test data were initiated under constant pumping test rate and equilibrium conditions for confined and unconfined aquifers. Since then, different methods have been designed for pumping test analysis. Reliable estimates of the hydraulic parameters controlling an unconfined aquifer's capacity to store and transmit water are generally obtained by pumping test analysis with one or more analytical models, of which authors [5, 7–14] are the most popular. Nowadays, the entire computation procedures and hydrological equations are typically written into computer programs.

However, each of the methods is based on basic assumptions relating to geologic formation, the basic types of well, such as well diameter, dug well and bore well. Therefore, it is important to choose the right method of interpretation based on the field conditions [3].

The study by Mishra and Kuhlman [6] discussed concisely the issue of which model for which well conditions. According to this study, analytic and semi-analytic solutions are often used by researchers and practitioners to estimate aquifer parameters from unconfined aquifer pumping tests. The nonlinearity associated with unconfined (i.e., water table) aquifer tests make their analysis more complex than confined tests.

As the method by Cooper and Jacob [5] is a simplification of the Theis method solution, the pumping well should fully penetrate a confined, homogeneous, and isotropic aquifer. Single well tests from partially penetrating wells in unconfined aquifers depart greatly from the Theis model. Moreover, unconfined aquifer tests are affected by vertical anisotropy and specific yield in addition to transmissivity and storage coefficient. These additional parameters control vertical gradients that are created by partial penetration and drainage from the water table. Likewise, leakage from adjacent confining beds also could affect transmissivity estimates, which likely will be overestimated by the Cooper-Jacob method [15].

The study in Neuman [7] presented a physically based mathematical model that treated the unconfined aquifer as compressible and the water table as a moving material boundary. Newman's approach describes the aquifer delayed response was caused by physical water table movement; therefore, it was proposed to replace the phrase "delayed yield" by "delayed water table response." Besides this, the model exhibits three distinct drawdown segments as shown in **Figure 1**.

Early-time response is controlled by the transmissivity and elastic storage coefficient and is analogous to the response of a confined aquifer, and the water table

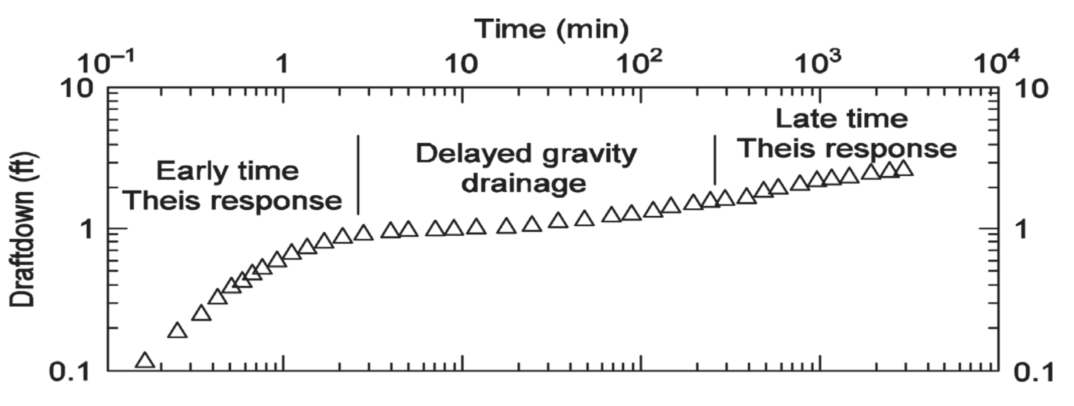


Figure 1.
The three distinct drawdown segments in an unconfined aquifer (from [16]).

does not drop significantly. Late-time response is a function of transmissivity and specific yield (drainable porosity). Release of water is due to drainage from formation over large area water table decline slows and flow is essentially horizontal. At intermediate time, the response is controlled by the aquifer's vertical hydraulic conductivity. The release of water is from gravity drainage and slope of time-drawdown curve relative to Theis curve decreases.

After comparative analysis of various methods for determination of specific yield, the author in [8] concluded that the water table response to pumping is a much faster phenomenon than drainage in the unsaturated zone above it.

The analytical model developed by Moench [14] combines and extends the work of Boulton [13] and of Neuman [7, 8] to account for the release of water from the unsaturated zone above the water table. In spite of the possible limitations inherent in the assumption, the Neuman model has been used successfully by many hydrogeologists in analysis of pumping tests conducted in water table (unconfined aquifers). One of the primary features of the model is that it allows drawdown to vary continuously in the vertical as well as the horizontal directions, thus retaining the full three-dimensional, axisymmetric character of the flow regime. Another feature is that the model accounts for aquifer compressibility. However, the use of Neuman type curve fitting for unconfined aquifer conditions has sometimes led to values of specific yield that are unrealistically low (plus sometime too high) compared to volume-based calculations.

Moreover, although both the Boulton and Neuman models could account for the compressive characteristics of an aquifer by assuming the pumped well is infinitesimal in diameter, it becomes impossible to account for effects of well bore storage, thereby limiting the usefulness of the models for accurate evaluation of specific storage. This assumption necessitates that observation wells be located at large distances from the pumped well to reduce the influence of well bore storage. Unfortunately, this last requirement makes it difficult to record accurate early-time measurements due to small drawdowns at large distances.

The study by Neuman [7] attributed the inability of Neuman's models to give reasonable estimates of specific yield (S_y) and capture this observed behavior near the water table due to the disregard of "gradual drainage." To resolve this problem, the instantaneous moving water table boundary condition used by Neuman was replaced with one containing a Boulton [13] delayed yield convolution integral. The study by Neuman [7] recommended the composite analysis of pumping test data and grouping of corresponding time drawdown data for parameterization as opposed to the analyses of individual drawdown curves.

The Moench solution, presented in AquiferTest V. 2.55, is an extension of the Neuman solution for drawdown in a homogeneous anisotropic confined or unconfined aquifer with fully or partially penetrating pumping and multiple observation wells. The Moench solution also allows for water in the overlying unsaturated zone to be released either instantaneously in response to a declining water table or gradually as approximated by Boulton's convolution integral.

1.2.7 AquiferTest software application for pumping test data analysis

There are a number of software programs that can be used to complete the data analysis of aquifer test drawdown data that include, but are not limited to, AQTESOLV, AquiferTest, WTAQ, and AquiferWin32.

In the analysis of a multiple pumping test conducted in a layered unconfined aquifer (harbor area of Antwerp, Belgium), the use of two computer programs was presented: AquiferTest and WTAQ to investigate and compare previous results obtained for transmissivity, hydraulic conductivity specific yield, and storage coefficient. The study made use of the Theis-type [14] curve method in AquiferTest applicable to both partially and fully penetrating wells. This was used to calculate dimensional drawdowns that are compared with time-drawdown data from 23 observation points to estimate the hydraulic properties of a finite, layered unconfined aquifer situated in the harbor area of Antwerp. The study concluded that AquiferTest and WTAQ form an excellent pair for the analyses of single or multiple pumping tests in unconfined aquifers.

An assessment was made for the hydraulic properties of the Ethiopian Ashange formations applying AquiferTest software. In the study, a total of 70 wells raw pumping test data were analyzed and used besides their respective lithological log to determine hydraulic property of Ashange formation. This study has done identification, analysis, and interpretation of aquifer system hydraulic properties of the geologic formation using the secondary well pump test data, lithological log, and data of hydro geological field observations. Among the different stages of pumping tests, constant rate pumping tests lasting between 5 and 72 h and recovery tests were used to determine transmissivity, hydraulic conductivity, and storativity values. The study analyzed single pumping test data mainly using Theis time-drawdown graphic method by which aquifer properties have been calculated. The pump test data including measured and calculated ones have been organized and processed using the Aquifer test software version 3.5. Arc GIS 9.2 and Global mapper 11 were also used for mapping in that study. As a result, the study finally identified the aquifer characteristics of the Ashange formation with respect to depth of the boreholes, age, and variation of its spatial distribution and groundwater potential.

2. Geological and hydrogeological setting

In this phase of the research work, the aquifer type and water-bearing formations of borehole sites are generalized on the basis of lithological logs developed from well cutting logs collected. For the study, 29 boreholes were used to understand the Hawassa City aquifer.

The main water-bearing geological formation in the Hawassa City ground water system is classified along with the respective water-bearing thickness. The northeast part of the city has water-bearing formation of pumice ash and sand at depth of 14–20 m, weathered and fractured basalt formations at a depth 23–40 m, weathered pumice and rhyolite (42–54 m), and black and red scoria (60–66 m).

The north part of the city has sand (25.52–29 m), trachyte (29–39 m), and the volcanic origins' rocks (39–42 m) and (39–50.5 m). This shows that the area is likely dominated by volcanic rocks for depth below 39 m.

The lake shore (east and southeast of the Hawassa city) covers slightly rhyolite (7.15–9 m), scoria (9–12 m), dominant weathered basalt (12–27 m) and course sand scoriaceous basalt that covers up to 39 m depth of the area. As the well site goes apart to the west direction, the hydrogeology appears different for the whole lake shore; the water striking depth is increasing, and ash with sand formation (23.58–31 m), fractured basalt (49.43–57 m), and ash with scoriaceous basalt (60–69.24 m) are recurrently reported. The far southern part of Hawassa city (*Gara Riqata area*) where relatively the deepest wells of this study are located, the water striking point gets deeper and the major aquifers recognized are pumice type of fractured, weathered and course-grained (18–32 m), highly weathered pumice (32–58 m), fine-to--medium-grained sand (66–72 m), silty sand and weathered rhyolite (79–94 m), fractured pumice (94–102 m), weathered pumice (102–120 m), fine-to-medium-grained sand (120–166 m), weathered pumice (166–172 m) and fine-grained sand (184–196 m) are dominant of which sand covers the largest formation.

Around the western part of the city (the industry zone), the water striking point is the deepest of the study area. Highly fractured and weathered scoriaceous formation dominates the water-bearing strata (52–84 m). The central areas generally fractured basalt (12–21.5 m), sand and ignimbrite (22.64–33.54 m), scoria and pumice (27.38–38.20 m), and highly weathered ignimbrite (39.27–45 m).

About 30–60 m ignimbrites and pumice are dominant in large area of the central part. These ignimbrite and pumice of the rift floor are well jointed while in some cases, it is massive and pumiceous. Where it is well jointed, it has a high or moderate permeability, but in the other part, it has low permeability.

The relationship between lithology and aquifer characteristics is used to understand the qualitative and quantitative aspects of the hydrogeology in these areas. The study by Glenn and Duffield [17] established the estimate of the representative range of hydraulic properties (horizontal and vertical hydraulic conductivity, storativity, specific yield, and porosity) of aquifers and aquitards in relation to the formation type using values reported in different literatures. These tabulated values are used to understand the hydraulic properties of the study area.

Therefore, the dominant water-bearing formations (weathered pumice, scoria, fractured basalt, and sand of different types) possess large pores. Pumice and fractured basalts strata, which are common relatively in the shallower formations, are devoid of primary openings but possess secondary openings in the form of fractures and joints. These features aid in the infiltration of surface water. Besides, pores and fractures in laterites and fractures and joints in basalts act as reservoirs of groundwater.

Highly fractured and weathered scoriaceous formation dominates the water-bearing strata (52–84 m), and the fine-to-course-grained sand is the main water source in depth beyond 100 m. Furthermore, lack of confining rocks like clay in the area studied indicates that groundwater occurs in phreatic, unconfined conditions in the weathered basalts that outcrop at the surface.

Looking into representative values, aquifers in the area are high hydraulic conductivity units and large porosity which will produce higher and more sustained well yields than an aquifer where the clean sands and gravels are compartmentalized by interbedding with clay and other low hydraulic conductivity units.

2.1 Aquifer physical properties of Hawassa City

The results show (**Table 1**) the depth ranges from 25 m to 200 m below the surface. The pumping phase of the tests had a duration of 1440 min; the recovery phase of the tests had a duration of 45–240 min. Constant rate of discharge was applied for each of the wells. These constant discharge rates are from 3.0 l/s (for Gara Riqita 6) to 66 l/s (for Gara Riqita 1). Total drawdown varied from 0.03 m (for Zewdu Village) to 12.36 m (for HU Techno Village) and average of 2.53 m.

2.1.1 Specific capacity

The specific capacity of the wells as the ratio of the yield to the total drawdown is determined using Eq. (1). These two parameters (TDDw and Sc) along with the discharge rate are calculated and tabulated for 29 wells as shown in **Table 1**.

As per **Table 1**, values of specific capacity range from 0.54 l/s/m to 2200 l/s/m. Maximum values are toward the southwest part of the city (at Hawassa University Referral Hospital) and tend to decline toward the central and then to the northern corner. A decline in specific capacity may indicate declining S or T values due to declining water levels or piezometric surfaces, thus large water level drawdown for the specified discharge rate. It can also be used to determine the distribution of transmissivity in the aquifer. The spatial distribution of specific capacity reveals

Well name	Depth of BH(m)	B (m)	DWL (m)	SWL (m)	TDDW (m)	Q (l/sec)	Sc (l/sec/m)
SNNP council	42	8.00	38.17	34.60	3.57	4.45	1.25
Zewd Village	25	14.15	25.61	5.60	0.03	3.66	122.00
South star Int. H.	52	26	25.61	25.60	0.01	6.50	650.00
Agrostone factory	86	11.40	24.54	18.50	6.04	22.00	3.64
S.police garage	52	25.00	30.30	20.20	10.10	6.00	0.59
Abebe W.private C	41.5	17.00	7.27	5.63	1.64	61.00	37.20
Gara.R1	200	98.00	4.81	2.87	1.94	66.00	34.02
Gara.R4	193	30.00	10.76	10.60	0.16	63.60	397.50
Gara.R5	186	64. 00	14.79	4.46	10.33	64.80	6.27
Gara.R6	168	136.00	27.74	27.72	0.02	3.00	150.00
Zinabu Abera	41.5	11.32	52.13	52.12	0.01	5.00	500.00
Dairy farm	67	14.15	22.30	22.20	0.10	5.00	50.00
South Roads Auto.	37	11.32	46.50	45.70	0.80	7.33	9.16
Moha soft drink	90	70.00	25.67	25.30	0.37	5.24	14.16
Midroc con.	52	17.04	17.82	17.20	0.62	7.00	11.29
Awassa agi.r.cenr	50	30.00	56.73	56.72	0.01	5.00	500.00
TTC	71.5	19.81	25.46	25.39	0.07	20.00	285.71
HU 1 (White house)	86	36.00	27.65	27.50	0.15	22.00	146.67
HU 2 (Techno library)	50	30.00	42.53	30.17	12.36	20.00	1.62
HU3 (IoT village)	58	24.00	29.71	24.80	4.91	20.00	4.07
HU 4 (Staff complex)	50	18.00	30.08	28.00	2.08	22.00	10.58
HU 5 (Green house)	46	18.00	12.10	12.02	0.08	22.00	275.00
Dashen bank	36	16.00	32.10	26.70	5.40	7.00	1.30
ATENET S.C	48	18.00	17.50	16.40	1.10	20.00	18.18
HU Condominium	51	24.00	7.70	7.60	0.10	22.00	220.00
ACA HU	40	18.20	13.55	13.54	0.01	22.00	2200.00
HU (Health sc college)	41	23.50	23.94	15.54	8.40	6.50	0.77
SOS Village	60	32.00	16.66	13.72	2.94	6.66	2.27

Table 1.
Discharge rate, total drawdown, and specific capacity results.

that the increase in values coincides with the storage coefficient or transmissivity value presented in **Table 1**. Higher specific capacity values were also found to coincide with areas where extension fracture systems occur.

Using the total drawdown of the wells, a contour map is developed (**Figure 2**) to see the response of the wells at the end of the pump test duration. This is important to conclude about the potential of the aquifer for discharging.

This map shows, at the final hours, the water level that has been nearly stabilized at the end at about water strike zone for those high potential wells of smaller drawdown. This fluctuation could be due to the difference in the rock type of that

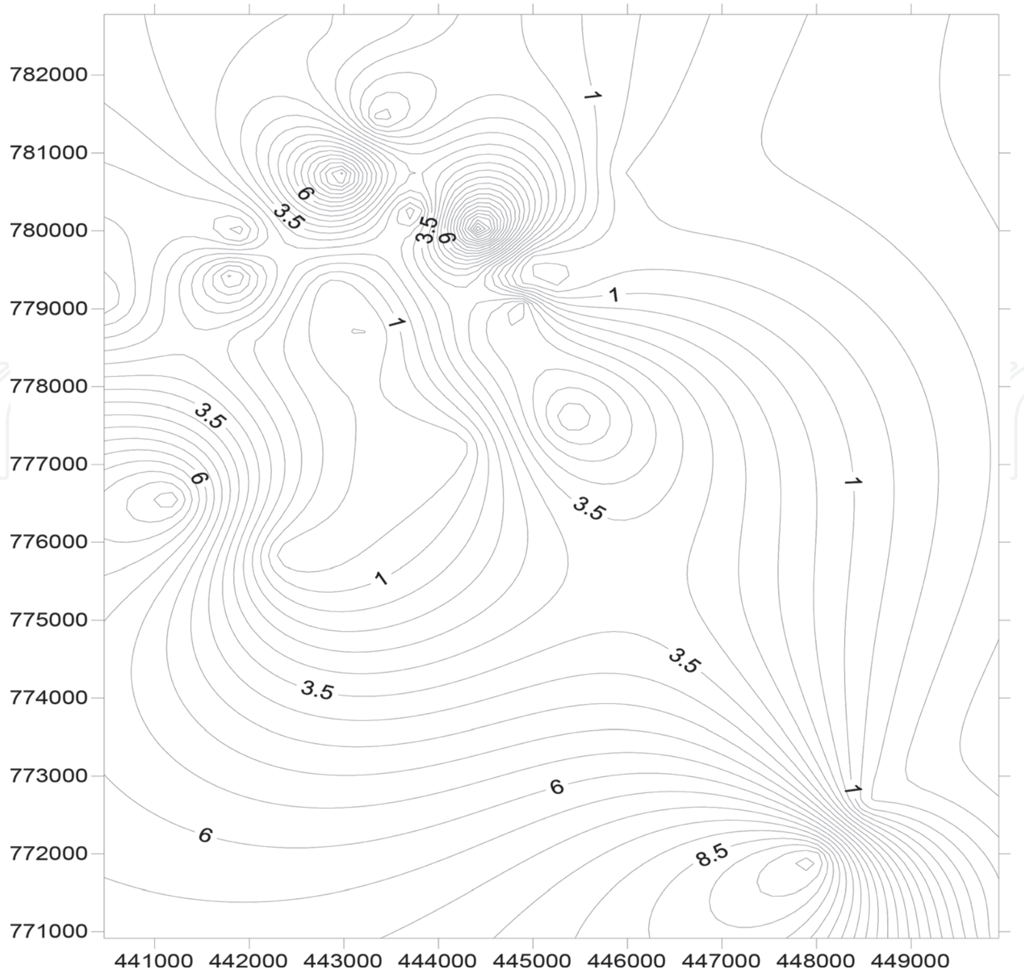


Figure 2.
Contour map of the total drawdowns (UTM Coordinates at Zone 37).

area. Percentage of recovery is also estimated using TDDw and the maximum recovery of water level during pumping test using Eq. (3). The results have 95–100% recovery percentage which reflects high recovery rate. The recovery of these wells is also fast that they recover up to the SWL within few minutes, even in 30 s. The results clearly show that the study area is of high potential of ground water with fast recovery for dewatering of the aquifer.

2.1.2 Saturated aquifer thickness (b)

The thickness values found in the study area range from 8 m to 136 m and average of 30.30 m. Within the study area, the spatial distribution of saturated thickness clearly indicates that the depth and the lakeshore have significant effect on it. As the cutting depth increases and the site getting nearer to the lake shore, the water-bearing formation thickness increases.

2.1.3 Analysis results using Moench method

This hydrogeological analysis method is done to determine the important hydrogeological parameters of the wells using the method selected. Along with the curve, the analysis result displays the important parameters, that is, transmissivity, hydraulic conductivity, aquifer thickness, and storativity (specific yield for unconfined aquifers). The result of the hydraulic parameters determined for the analysis of all the wells are tabulated in **Table 2**.

As presented in **Table 2**, the three parameters are discussed below.

2.1.3.1 Specific yield and storativity

If the aquifer is considered as a confined one, the storativity is determined, and if it is unconfined, its specific yield is determined. The results show that confined aquifers have very low storativity values (much less than 0.01, and as little as 10^{-5}), which mean that the aquifer is storing water using the mechanisms of aquifer matrix expansion and the compressibility of water, which typically are both quite small quantities. Unconfined aquifers have specific yield greater than 0.01 which is about 0.517 for the Hawassa City subsurface.

As per the results, the specific yield is high in the south, west, central, and southwest lake shore parts of the area and low in the east and northeast corner part of the area. The storativity or/and specific yield values generally range from 4.77×10^{-4} to 5.17×10^{-1}. Further, it could be seen that there is a decrease of specific yield in the eastern to southeastern parts and again an increase toward the west and central areas.

2.1.3.2 Transmissivity

Results show that the value of transmissivity varies from 4.77×10^{-4} m^2/s to 1.75×10^1 m^2/s. This follows the general pattern of increasing value from east to west (the lake shore), that is, the value increases from the upper part of the basin to the lower. This also shows a gradual increase of the hydraulic gradient. The high transmissivity coincides with areas where the fractured zone occurs.

This high transmissivity in the study area is a better indicator of the water production capacity of an aquifer than hydraulic conductivity. To see why, if we consider a thin aquifer, for example, a sand bed interbedded (sandwiched) between thick clay layers. The bed has a very high hydraulic conductivity because it consists of clean sand; however, if it is not thick, it will not sustain a large production well (its transmissivity is low).

2.2 Ground water flow dynamics

Annual ground water flow of the Hawassa City aquifer system is determined using wells that are tested at same year and similar season of that year. This is aimed to understand the spatial and temporal regional ground water flow pattern which is essential for managing local and regional groundwater resources, protecting groundwater quality, and delineating wellhead protection zones or drinking water supply source areas. To develop hydraulic head distributions contour map of the area, SWL and DWL data were used from **Table 3**.

From **Table 3**, five batches of wells are selected since their pumping test and completion are undertaken at nearly similar season of that year. In this respect, for 2006, 4 wells; for 2009, 6 wells, for 2012, 5 wells; for 2013, 4 wells; and for 2014, 4 wells are annually grouped along with their SWL and DWL data.

To understand the spatial trend of the flow, contour maps and vector maps are developed (**Figure 3A–J**). During vector map development, the vector orientation is reversed using the command in the Surfer software. Because the SWL and DWL readings are from the top surface downward and the software assumes the values as elevation points otherwise and then wrong flow direction will be identified.

From the above five sets of graphs (**Figure 3A–J**), groundwater moves from higher elevations to lower elevations and from locations of higher pressure to locations of lower pressure.

Well Name	B (m)	T (m^2/s)	Kh (m/s)	Kv (m/s)	S	Sy
SNNP council	8.00	3.5×10^{-3}	4.37×10^{-4}	4.37×10^{-5}	3.5×10^{-3}	
Zewd Village	14.15	2.94×10^{-2}	2.08×10^{-3}	2.08×10^{-4}		94×10^{-2}
South star Int. H.	26.00	1.75×10^{1}	6.73×10^{-1}	6.73×10^{-2}	1.75×10^{-2}	
Agrostone factory	11.40	5.17×10^{-1}	4.53×10^{-2}	4.53×10^{-3}		5.17×10^{-1}
S.police garage	25.00	1.75×10^{-2}	7.00×10^{-4}	7.00×10^{-5}		1.75×10^{-2}
Abebe W.private C	17.00	4.77×10^{-4}	2.80×10^{-2}	2.80×10^{-3}	4.77×10^{-4}	
Gara.R1	98.00	4.85×10^{-2}	4.95×10^{-4}	4.95×10^{-5}		4.85×10^{-2}
Gara.R4	30.00	5.25×10^{-2}	1.75×10^{-3}	1.75×10^{-4}		5.25×10^{-2}
Gara.R5	64.00	5.06×10^{-1}	7.90×10^{-3}	7.90×10^{-4}		5.06×10^{-1}
Gara.R6	136.00	5.15×10^{-3}	3.79×10^{-5}	3.79×10^{-6}	5.15×10^{-3}	
Zinabu Abera	11.32	2.38×10^{-1}	2.10×10^{-2}	2.10×10^{-3}		2.38×10^{-1}
Dairy farm	14.15	1.75×10^{-3}	7.44×10^{-5}	7.44×10^{-6}	1.75×10^{-3}	
Moha soft drink	70.00	5.80×10^{-2}	8.29×10^{-4}	8.29×10^{-5}		5.80×10^{-2}
Midroc con.	17.04	1.59×10^{-3}	9.39×10^{-5}	9.39×10^{-6}	1.59×10^{-3}	
Awassa agi.r.cenr	30.00	5.57×10^{-2}	1.85×10^{-3}	1.85×10^{-4}		5.57×10^{-2}
HU 1 (White house)	36.00	1.59×10^{0}	4.42×10^{-2}	4.42×10^{-3}	1.59×10^{-3}	
HU 2 (Techno library)	30.00	1.75×10^{-1}	5.83×10^{-3}	5.83×10^{-4}		1.75×10^{-1}
HU3 (IoT village)	24.00	1.59×10^{-3}	6.63×10^{-5}	6.63×10^{-6}	1.59×10^{-3}	
HU 4 (Staff complex)	18.00	1.59×10^{-2}	8.84×10^{-4}	8.84×10^{-5}		1.59×10^{-2}
HU 5 (Green house)	18.00	1.75×10^{-2}	9.72×10^{-4}	9.72×10^{-5}		1.75×10^{-2}
Dashen bank	16.00	1.75×10^{0}	1.09×10^{-1}	1.09×10^{-2}	1.75×10^{-3}	
ATENET S.C	18. 00	5.57×10^{-3}	3.09×10^{-4}	3.09×10^{-5}	5.57×10^{-3}	
HU Condom	24.00	1.59×10^{-2}	5.62×10^{-4}	5.62×10^{-5}		1.59×10^{-2}
ACA HU	18.20	1.75×10^{0}	6.25×10^{-2}	6.25×10^{-3}	1.75×10^{-3}	
HU (Health sc college)	23.50	1.75×10^{0}	7.44×10^{-2}	7.44×10^{-3}	1.75×10^{-3}	
SOS Village	32.00	5.17×10^{-3}	1.72×10^{-4}	1.72×10^{-5}	5.17×10^{-3}	
Awassa Flour	20.50	5.33×10^{-3}	2.59×10^{-4}	2.59×10^{-5}	5.33×10^{-3}	

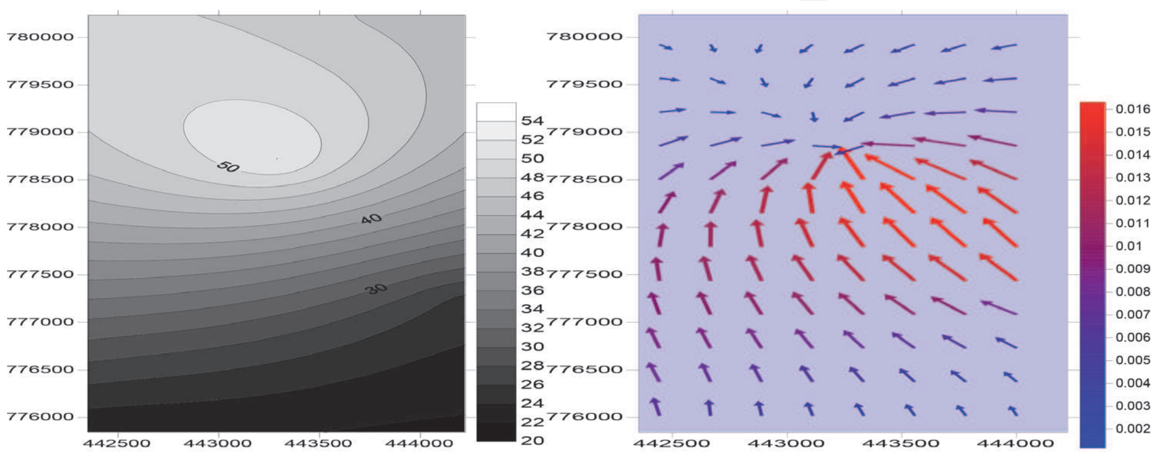
Table 2.
Analysis result of the hydraulic parameters in Hawassa City.

Borehole name	Pumping test time D/M/Y	UTM Esting(m)	UTM Northing(m)	Depth of Well(m)	DWL (m)	SWL (m)	Q (l/sec)
SNNP council	21/04/2011	444359	778478	42.00	38.17	34.60	4.45
Zewd Village	31/12/2007	440465	779086	25.00	25.61	5.60	3.66
South star Int. H.	19/07/2010	442876	779278	52.00	25.61	25.60	6.50
Agrostone factory	12/12/2009	445387	777593	86.00	24.54	18.50	22.00
S.police garage	27/03/2010	442971	780703	52.00	30.30	20.20	6.00
Abebe W.private C	05/09/2009	441936	778609	41.50	7.27	5.63	61.00
Gara.R1	13/08/2012	449214	771791	200.00	4.81	2.87	66.00
Gara.R4	30/06/2012	449926	770917	193.00	10.76	10.60	63.60
Gara.R5	19/07/2012	447977	771948	186.00	14.79	4.46	64.80
Gara.R6	13/07/2012	448528	772643	168.00	27.74	27.72	3.00
Zinabu Abera	30/05/2006	443296	778694	41.50	52.13	52.12	5.00
Dairy farm	04/06/2006	442354	775842	67.00	22.30	22.20	5.00
Moha soft drink	28/05/2006	443745	780233	37.00	46.50	45.70	7.33
Midroc con.	24/05/2009	448915	777121	90.00	25.67	25.30	5.24
Awassa agi.r.cenr	21/12/2007	444865	779285	52.00	17.82	17.20	7.00
HU 1 (White house)	05/11/1998	445957	780765	50.00	56.73	56.72	5.00
HU 2 (Techno library)	03/05/2006	444224	777249	71.50	25.46	25.39	20.00
HU3 (IoT village)	30/04/2013	444975	779643	86.00	27.65	27.50	22.00
HU 4 (Staff complex)	12/06/2013	444444	780020	50.00	42.53	30.17	20.00
HU 5 (Green house)	08/04/2013	444868	779078	58.00	29.71	24.80	20.00
Dashen bank	15/04/2013	444620	779503	50.00	30.08	28.00	22.00
ATENET S.C	11/04/2014	445205	779257	46.00	12.10	12.02	22.00
HU Condom	26/08/2009	441827	779428	36.00	32.10	26.70	7.00
ACA HU	20/06/2009	442431	778944	48.00	17.50	16.40	20.00
HU (Health sc college)	25/03/2014	443374	781427	51.00	7.70	7.60	22.00
SOS Village	28/03/2014	441886	779967	40.00	13.55	13.54	22.00
Awassa Flour	30/03/2014	441190	776556	41.00	23.94	15.54	6.50
SNNP council	08/07/2009	442919	782411	60.00	16.66	13.72	6.66
Zewd Village	19/05/2012	443451	782781	50.00	16.66	13.72	6.66

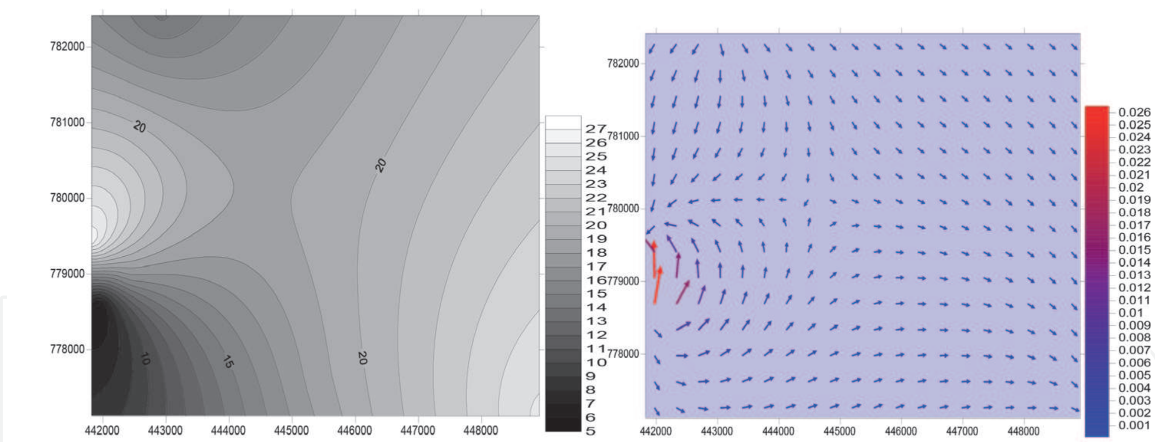
Table 3.
The ground water level data with space and time.

In the vector maps shown, the arrow symbol points in the "downhill" direction of water table and the length of the arrow depends on the magnitude, or steepness, of the slope. A vector is drawn at each grid node; however, some nodes are skipped by changing the frequency setting for the better view of the contour. Since the grid contains dynamic water level data of wells, the direction arrows point in the direction of water flows—from high water elevation to low water elevation. Magnitude is indicated by arrow length. Therefore, the steeper slopes would have longer arrows.

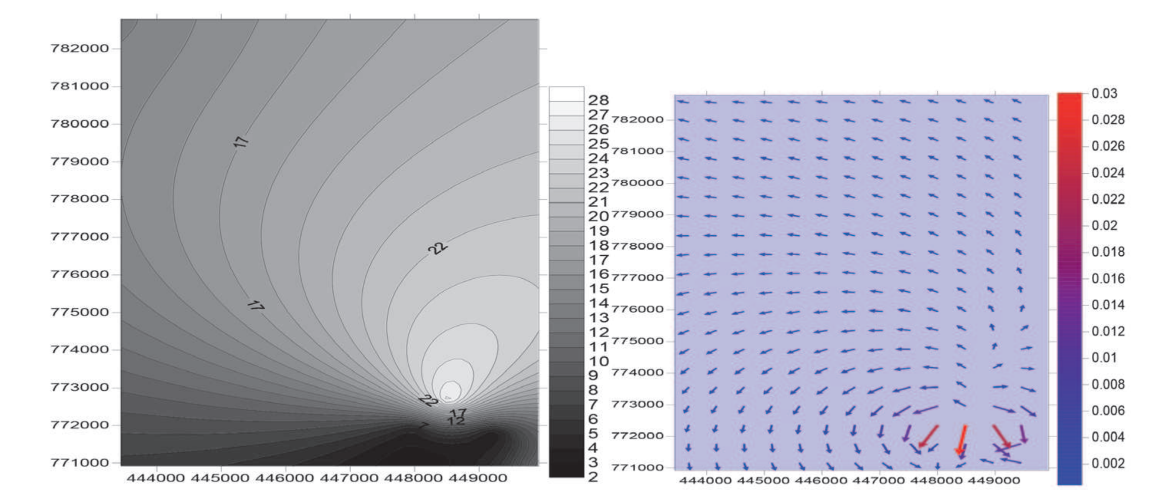
Looking into the map of the study area, SWL and DWL vectors indicate similar trends for each of the years. The results show that for the year 2006, medium to high magnitude of water flowed from the northern and central parts to west and S-W direction. This indicates that there was high discharge from the western and



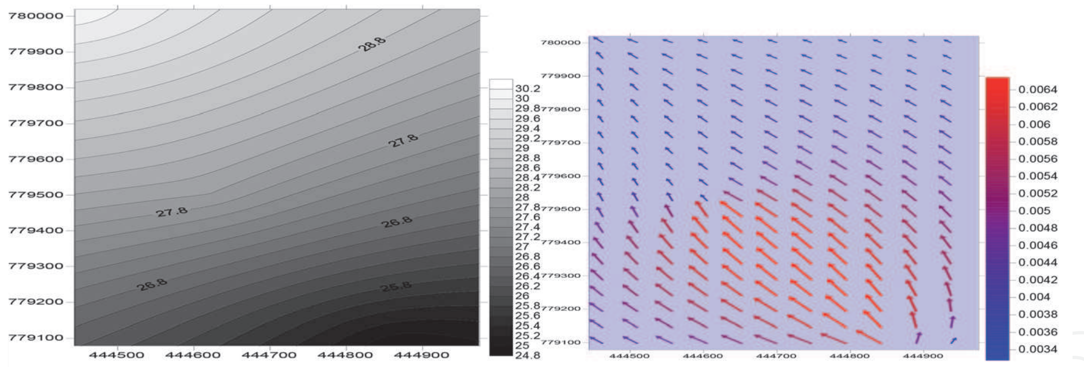
A



B



C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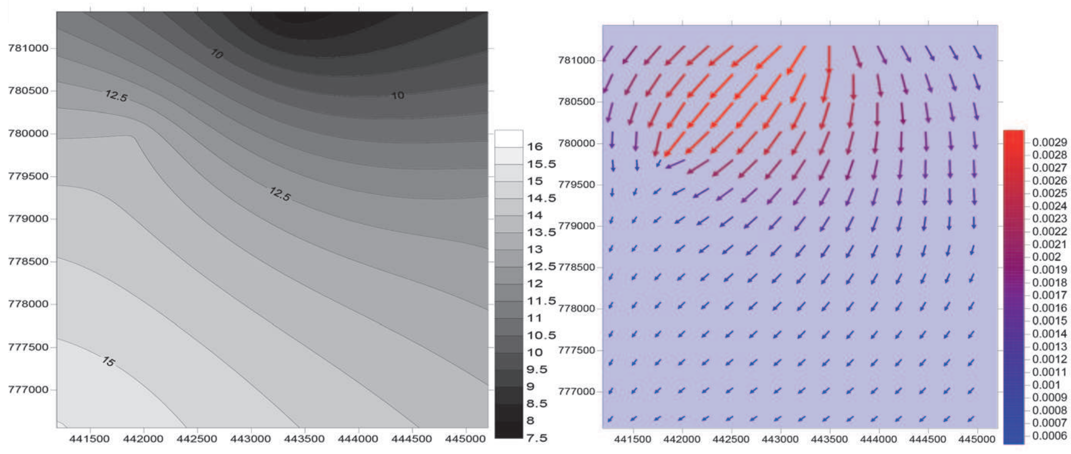
444500 444600 444700 444800 444900
28.8 27.8 27.8 26.8 26.8 26.8
30.2 30 29.8 29.6 29.4 29.2 29 28.8 28.6 28.4 28.2 28 27.8 27.6 27.4 27.2 27 26.8 26.6 26.4 26.2 26 25.8 25.6 25.4 25.2 25 24.8
0.0064 0.0062 0.006 0.0058 0.0056 0.0054 0.0052 0.005 0.0048 0.0046 0.0044 0.0042 0.004 0.0038 0.0036 0.0034

D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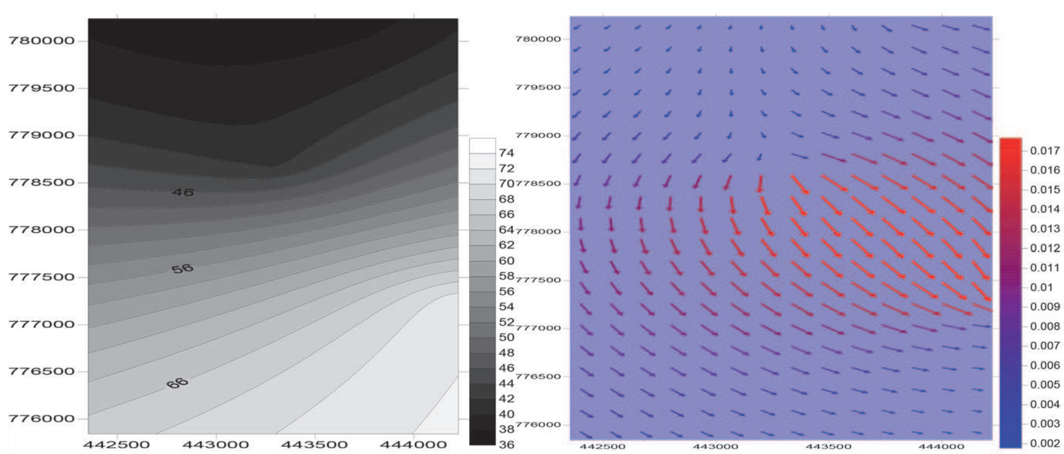
441500 442000 442500 443000 443500 444000 444500 445000
10 12.5 10 12.5 15
16 15.5 15 14.5 14 13.5 13 12.5 12 11.5 11 10.5 10 9.5 9 8.5 8 7.5
0.0029 0.0028 0.0027 0.0026 0.0025 0.0024 0.0023 0.0022 0.0021 0.002 0.0019 0.0018 0.0017 0.0016 0.0015 0.0014 0.0013 0.0012 0.0011 0.001 0.0009 0.0008 0.0007 0.0006

E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442500 443000 443500 444000
46 56 66
74 72 70 68 66 64 62 60 58 56 54 52 50 48 46 44 42 40 38 36
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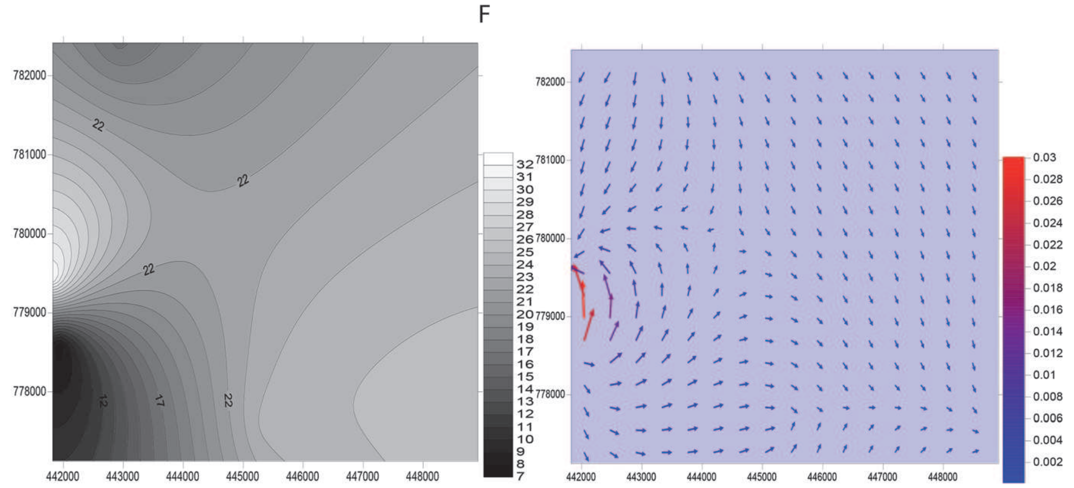
F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32 31 30 29 28 27 26 25 24 23 22 21 20 19 18 17 16 15 14 13 12 11 10 9 8 7
0.03 0.028 0.026 0.024 0.022 0.02 0.018 0.016 0.014 0.012 0.01 0.008 0.006 0.004 0.002

G

DOI: http://dx.doi.org/10.5772/intechopen.91211

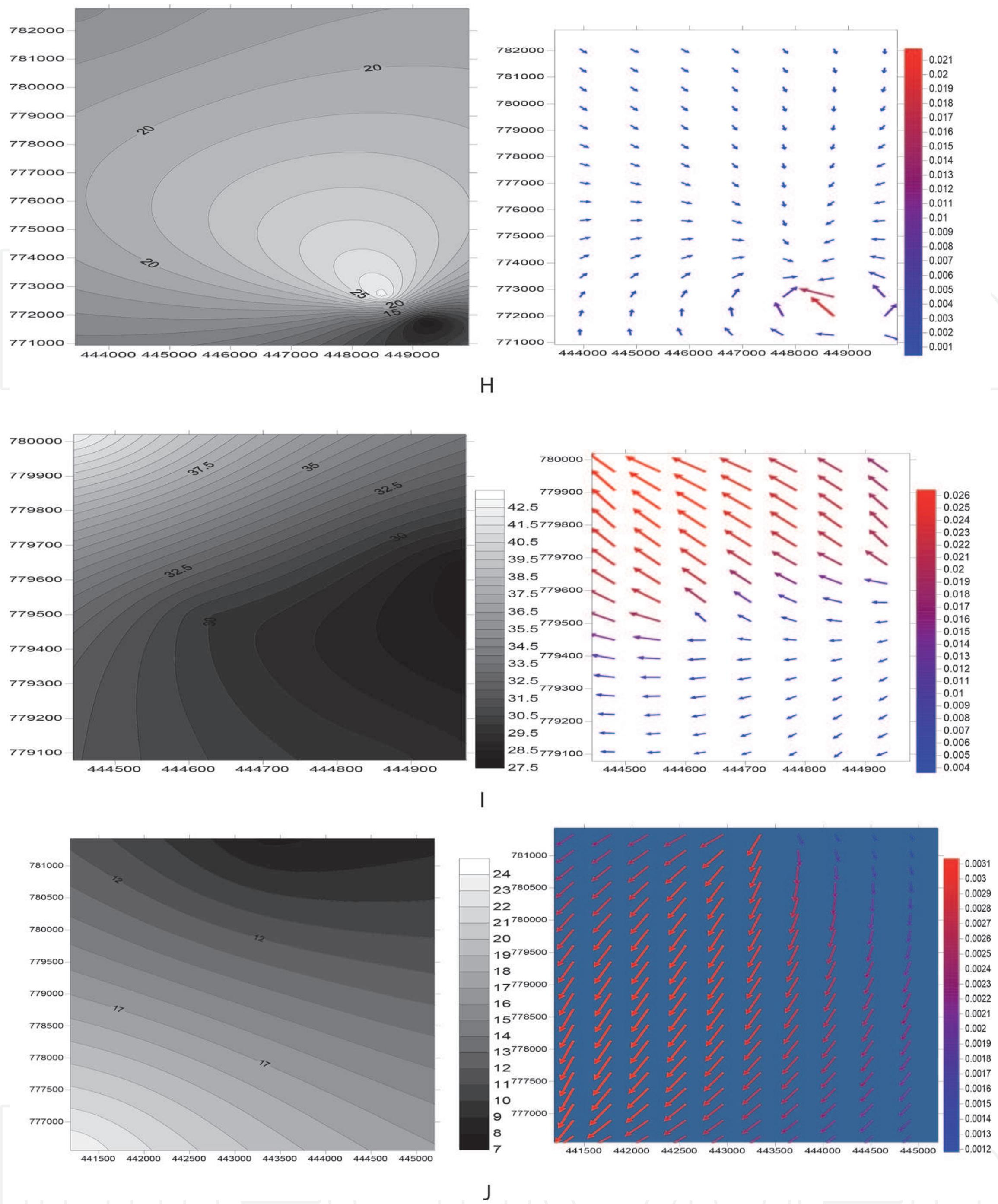

Figure 3.
(A) SWL contour map and vector map showing flow direction (2006) with color scale; (B) SWL contour map and vector map showing flow direction (2009) with color scale; (C) SWL contour map and vector map showing flow direction (2012) with color scale; (D) SWL contour map and vector map showing flow direction (2013) with color scale; (E) SWL contour map and vector map showing flow direction (2014) with color scale; (F) DWL contour map and vector map showing flow direction (2006) with color scale; (G) DWL contour map and vector map showing flow direction (2009) with color scale; (H) DWL contour map and vector map showing flow direction (2012) with color scale; (I) DWL contour map and vector map showing flow direction (2013) with color scale; and (J) DWL contour map and vector map showing flow direction (2014) with color scale.

S-W areas. For the year 2009, the map presented shows turbulence, so the flow direction has no clear trend except for the lake shore area that receives water from the nearby aquifer. For the year 2012, relatively medium magnitude water flows into the Gara Riqata area, which produces huge water discharge for the next year 2013. The two years 2013 and 2014 results clearly reveal that significant amount of

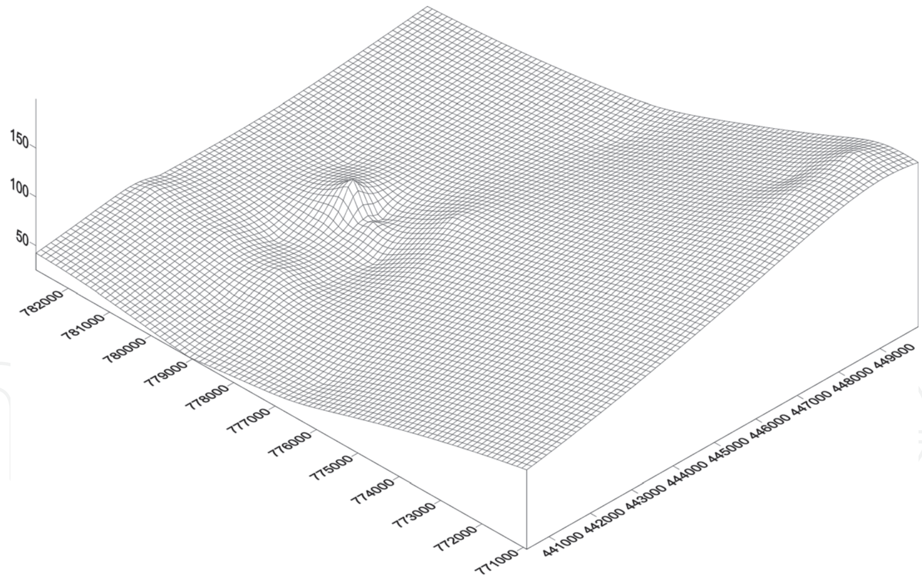

Figure 4.
Well depth wireframe map.

ground water flows from the large area of the city toward the lake shore. Thus, the ground water system feeds the lake which will in turn accelerate the lake level rise. For those months in which the pumping test of the wells conducted (i.e., March, April, and May) large amount of infiltrated water from the discharge spots join the ground water reservoir as this is the time immediately after the rainy season stops in the area. Combining these graphical results and the one for the surface water flow direction (**Figure 3A–J**), groundwater flow direction follows similar tendency of the surface water movement, that is, it follows the surface profile. This also implies the fact that the highlands are recharge areas and the lowland areas as nice spots for discharging.

2.3 Guide to drilling depth in Hawassa City

Using the wire frame and the grid map of the well depth on Surfer 8 Software, one can interpolate the required depth to be drilled at specific GPS location in the study area. This is an important guide for borehole drillers and clients to estimate the depth of the water striking formation at that specific site. To do so, the Surfer 8 Software can be used to display the map as shown in **Figure 4**.

The gridding method in Surfer 8 Software uses weighted average interpolation algorithms. This means that with all other factors being equal, the closer a point is to a grid node, the more weight it carries in determining the Z value at that grid node. The difference between gridding methods is how the weighting factors are computed and applied to data points during grid node interpolation. The coefficient of determination for this analysis is found to be $R^2 = 0.87$, which indicates the strong acceptability of the guide.

To increase the likelihood that these data are honored, one can increase the number of grid lines in the X and Y direction. This increases the chance that grid nodes coincide with data points, thereby increasing the chance that the data values are applied directly to the grid file.

The geological formation at the depth to be drilled and the other parameters determined by this and other studies shall be combined to get more detailed information. Certainly, the more the depth drilled, the better will be the safe yield.

3. Conclusion

The main aquifers tapped by the Hawassa City ground water system is unconfined and semi-confined type since no confining beds like clay are clearly identified up to 200 m depth. Weathered and fractured pumice, basalt scoriaceous rocks, fine-to-coarse-grained sand, and weathered ignimbrites are major water-bearing formations. The first water striking point is the shallowest around the lake shore (west and S-W) and as the well site goes apart to the west direction, the water striking depth is increasing and ash, fractured basalt and ash with scoriaceous basalt are dominating. The Hawassa City ground water system is of high performance and potential due to the very small drawdowns, fast recovery percentage (up to 100%), high transmissivities, and saturated thicknesses of the aquifer. The aquifer materials are highly porous and the high aquifer porosities imply aquifers of high storativity and better yield. The protective capacity of the overburden rock materials in the area is very low. Transmissivity and hydraulic conductivity values are generally high in the lake shore and central parts. Since the aquifer materials in the study area are highly permeable and relatively shallow, the groundwater has a high susceptibility of being contaminated over large area. The ground water flows from the E and S-E parts toward the central and western side of the city with a very similar profile with the surface water flow direction.

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