Chapter 7

Groundwater Modeling

7 Groundwater Modeling

7.1 Introduction

7.1.1 Basic characteristics of Study area

From the viewpoint of groundwater simulation model, the characteristics of the Study area can be summarized as follows:

- Expansive area
- Significant variations in surface relief
- Complex hydrogeological conditions
- Shortage of information about groundwater parameters

7.1.2 Effect of the basic characteristics of model creation

When creating a groundwater simulation model, the model area has to be divided into many small divisions (cells or grid cells). Therefore, in the case of the Study Area− an expansive area encompassing the Rift Valley Lakes Basin− the following issues have to be seriously considered for model division.

When a model is created to cover the entire Study Area, and is divided into small cells, (e.g., a cell of 1km or less on both sides) the number of grid cells in the model will be more than 141,000. A model with this number of cells will need enormous time for calibration, and the high precision calibration will be practically impossible.

On the other hand, if a model is created to cover the whole Study area using big size cells, e.g., 5 km or more on both sides, the number of grids in the model can be reduced into less than 5,700. But 1 grid cell represents an area of 25 square kilometers and then it will be still impossible to achieve a high precision calibration.

The effect of large variations in relief on the cell size in the model is similar to that of the large size of the Study Area. If a model is created with relatively big cell sizes, it would make an actually continuous geological stratum be discontinued. If the model area is divided into smaller size grid cells, the problem of model calibration will emerge as mentioned above.

The complexity of the geological condition and hydrogeological condition has similar effects to those of intensive relief change, affecting the layer division and parameter specification in the model. The effect of specifying minutely divided cells is the same as mentioned above. In the case of specifying large cell size, different geological features had to be combined into one grid cell and thus correct parameter specification will become very difficult.

In order to fit the created groundwater simulation model to actual geological and hydrogeological conditions in the target area as much as possible, a lot of existing hydrogeological data will be necessary for aquifer classification and parameter specification. Even the same aquifer would have a very large range of values of hydraulic parameters. For example, only a few sets of data have revealed that the transmissibility values of the lacustrine sediment aquifer shows a large variation, from 81.8 to 2,080 m^2/day. If more surveys are conducted into the same aquifer of the lacustrine sediment, it is certain that the range of transmissibility would be larger. Therefore, it is easy to imagine how difficult the aquifer parameter determination will be if sufficient data is not available.

7.2 Selection of modeling area

Taking the above mentioned characteristics of the study area into consideration, to achieve balance among the factors of model cell size, the extent of the model target area, change in relief and complexity in geology, construction of four groundwater simulation models was planned in this study to evaluate groundwater in different areas.

In this Study Area with very little hydrogeological information, 10 wells were curried out for the purpose of collecting aquifer parameters.

The criterion for model area selection is that the model should cover a high priority area for the formulation of groundwater development plan in this study.

As a result of comprehensively consideration of all the above issues, Bilate River basin was selected as the target area for the first groundwater modeling.

Bilate River sub-basin, as shown in Figure 7.1 is a tributary basin of Lake Abaya. To delineate the basin boundary, a set of 90 m mesh DEM (Digital Elevation Model) data − SRTM from USNASA was used as the basis and a GIS (Geographic Information System) hydrology tool was used to analyze the topography.

The study team has planned to create 3 models in Ziway east and west area, and Abaya east area. But, when the ground water model (GWM) area selection is discussed, the Professor Tenalem suggests combining the Ziway east and west area as one model and then selecting another two (2) model areas. Following the suggestion of Professor Tenalem the model area selection was changed as follows:

- Model_2: the whole Ziway-Shalla sub-basin area
- Model_3:Gidabo-Galana sub-basin in Abaya-Chamo sub-basin (east Lake Abaya area)
- Model_4: Amessa Guraoha-Kulfo Gina in Abaya-Chamo sub-basin (west Lake Abaya area)

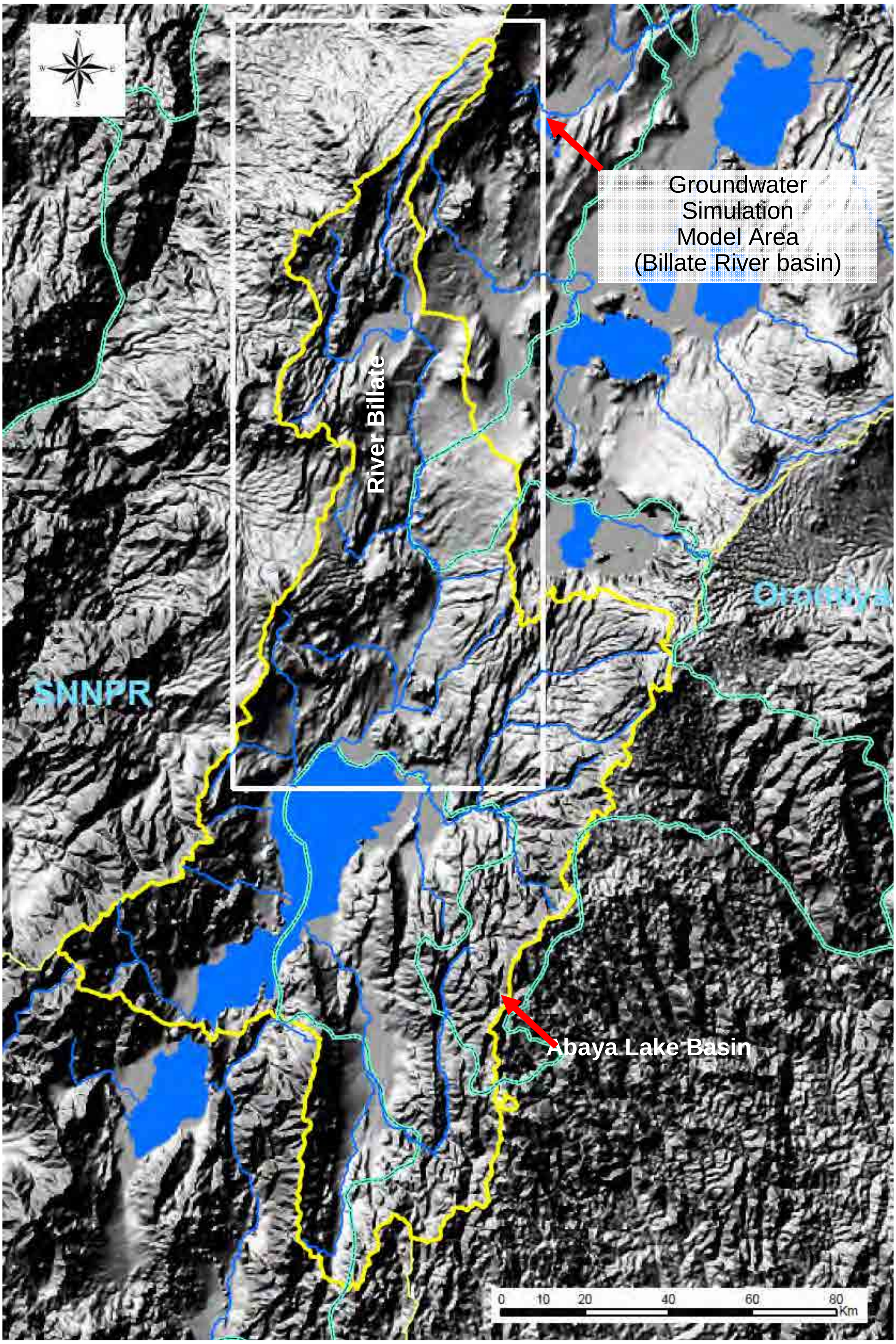


Figure 7.1: Model Area and Abaya Lake Basin

7.3 Method of Groundwater Recharge Analysis

A number of parameters and variables are necessary for creation of a groundwater simulation model. One of the most important variables is groundwater recharge amount. How the groundwater recharge amount is determined can cause significant differences in the model simulation result.

For groundwater recharge calculation, many methods have been developed. The simplest method is to use an empirical equation developed in some other areas of similar topographic and geological features. However, it is generally difficult to obtain an accurate result with this method. Therefore, the empirical equation method is not adopted in this analysis.

The most precise analysis method may be by creating a program to link the groundwater level fluctuation with amount of precipitation. What makes this method precise is that the method employs calculation of the groundwater recharge on a daily basis. However, application of this method requires availability of groundwater level observation records.

Shortage of information about groundwater parameters in the Study Area has been mentioned earlier. Up to present, there has been no groundwater level monitoring conducted anywhere in the Study Area.

Three wells were drilled and groundwater level meters were installed in those wells for groundwater level monitoring (measured every hour). The observation results from the three observation wells are shown in Figure 7.2 to Figure 7.4.

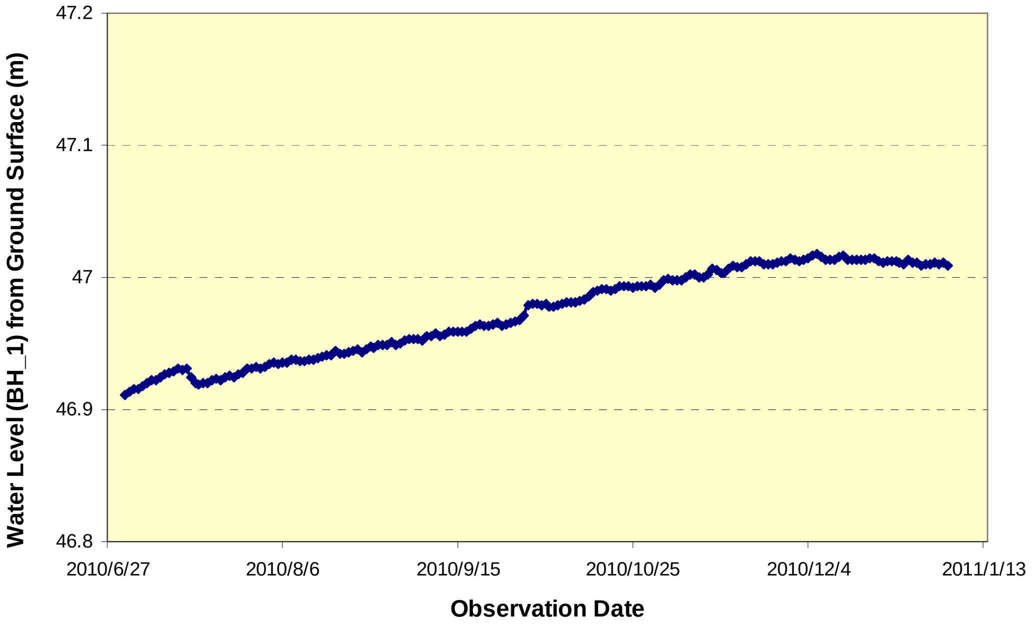


Figure 7.2: Groundwater Level Fluctuation at Site No.- 1

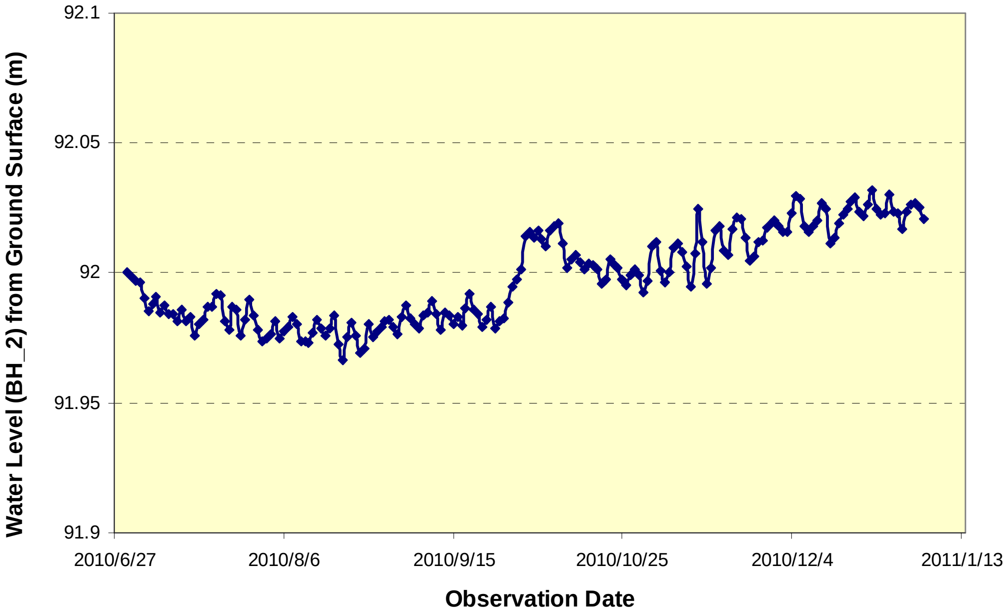


Figure 7.3: Groundwater Level Fluctuation at Site No.- 2

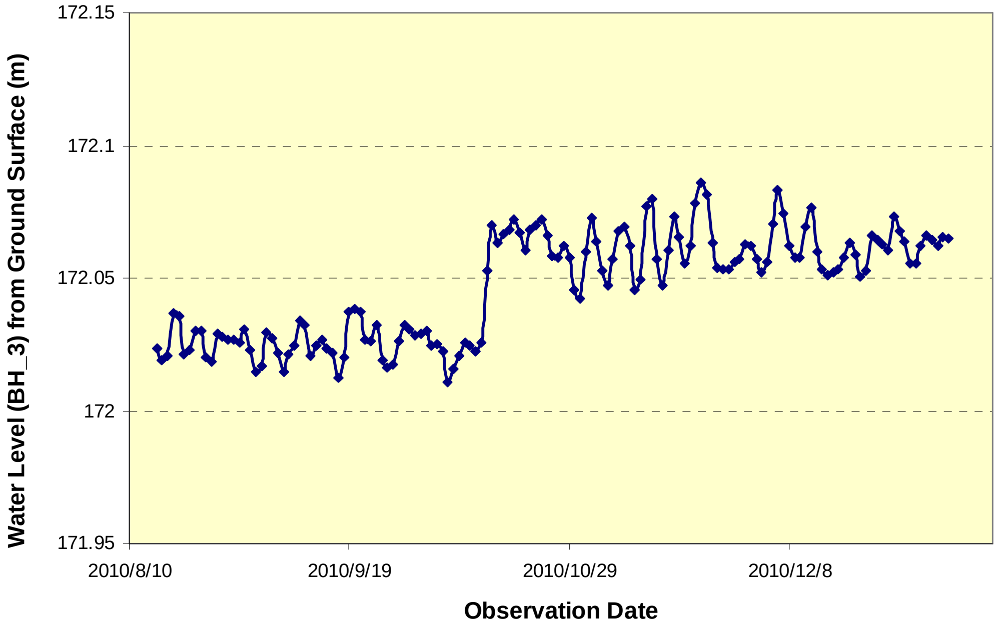


Figure 7.4: Groundwater Level Fluctuation at Site No.- 3

As shown in the above figures, the three observation wells were completed and groundwater level observation was started the in the middle of 2010. Even though the observation period is relatively short, it covered both rainy and dry seasons. Therefore, if the groundwater in the target aquifer of the wells receives recharge from precipitation, the groundwater level will rise in the rainy season and fall in the dry season. However, this kind of tendency can not be found from all three wells. The groundwater level fluctuation in the wells in the last half of the year is as small as 10 cm. Moreover, regardless of the precipitation, the groundwater levels in the rainy season seem lower than in the dry season even though the fluctuation range is very small.

The reason that the groundwater level shows no response to the precipitation and that the range of fluctuation is small can be explained by the aquifer type. All the three observation wells are screened over a relatively deep zone, and then the water level observation was conducted for the deep aquifer. Between the deep aquifer and shallow aquifer exists an aquiclude which hydraulically separates the two aquifers to make the deep one a confined aquifer. Therefore, the observed aquifer cannot get recharge directly from precipitation.

The other fact that groundwater level being a little higher in the dry season than in the rainy season is an abnormal phenomenon. One reason can be the groundwater use in rainy reason is more than in dry season but this assumption is also difficult to be taken as a real case. Therefore, the fact can not be properly understood or explained at this stage, with only this short period of monitoring records. The reason may be made clear after several years when more data has been accumulated.

All the same, observation wells play an important role in geological survey and aquifer parameter determination, but can not be used for groundwater recharge analysis.

The method of linking groundwater level fluctuation with precipitation can not be employed because of the shortage of groundwater level observation data in unconfined aquifers. And the empirical equation method was not selected either because it will not be very precise. Finally, a method of relatively high precision, water resource balance analysis, is selected for the estimation of groundwater recharge amount.

7.4 Water balance in groundwater simulation model area

7.4.1 Factors for water balance analysis

Groundwater recharge amount is not only necessary for groundwater model construction, but also important for water resources evaluation, and for formulation of the future groundwater development plan. Therefore, water resources balance has to be properly analyzed.

When considering the water balance in an area, the balance equation can be expressed as follows:

$$\Delta W = W_R - W_C$$

where

ΔW: Increase or decrease in amount of water resource in the area. When the recharge amount is larger than consumption amount, water resource amount increases, otherwise there is no change or it decreases.

W_R: Water resource recharge in the area.

W_C: Water resource consumption in the area.

Water resource recharge amount W_R includes recharges from all available recharge sources, such as:

- Recharge to surface water and groundwater from precipitation
- Inflow from rivers from outside the basin
- Inflow from groundwater from outside the basin

Water resource consumption amount W_C also includes consumptions from all available consumption sources, such as:

- Evaporation or evapotranspiration
- Outflow by rivers to outside the basin
- Outflow by groundwater to outside the basin
- Water utility

Within the 7 factors given above, only evaporation amount can be easily obtained from the records of meteorological stations in the target area. River flow (discharge) amount also can be obtained from hydrological observation stations, even though river discharge is generally difficult to precisely measure and calculate because there are no real time (in seconds or minutes units) observation systems and not enough verification of H-Q curve in the study area. Generally the real time observation can boost the record precision by as high as 5%, but only daily observation would lead to an error of as big as 100% or more.

As for groundwater flow, there is no method for real observation. Estimation of groundwater flow requires creating a groundwater model with the use of aquifer structure and groundwater level information.

Thus, the issue is to consider a possible method to conduct water balance analysis that does not need data on river flow and groundwater flow.

From the viewpoint of basin characteristics, if the target area is a “closed basin”, that is, the basin is hydraulically independent from other basins, it will have no river flow connecting the target basin with the other basins. So the factor of river flow, in and out of the target basin, can be neglected in the water balance analysis.

For groundwater flow, the water table is known to generally follow the topography with gentler fluctuation. So the highest groundwater level will be found along the basin boundary (chain of mountain ridges), and then there would be no, or a very small amount of groundwater flow between the target basin and the other basins.

As described above, if a closed basin is selected for the water resource balance analysis, the factors of river flow (in and out of target basin) and groundwater flow (in and out) can be neglected. The necessary factors can be limited to recharge to surface water and groundwater from precipitation, evapotranspiration and water use. This method not only makes the analysis easier, but also improves the precision of the analysis.

7.4.2 Selection of water balance analysis area and period

The selected model area, Bilate River basin, is a tributary basin of Lake Abaya as shown in Figure 7.1. Abaya lake basin is a closed basin independent from the surrounding basins. Therefore, the one factor absolutely necessary for groundwater modeling, groundwater recharge amount can be determined by water resources balance analysis within the whole Abaya Lake basin.

When conducting water resources balance analysis, the amount of water resource may increase or decrease according to the balance of recharge and consumption as shown in the water balance equation. On the other hand, the related factors, groundwater and surface water recharge, evaporation and others are changing every day, month and year. That is, in some years or months or days, the recharge from precipitation is larger than consumption, then the water resource in the basin increases to cause the lake water level and groundwater table rise. And in some other years or months or days, the recharge is smaller than consumption, then the water resource in the basin decreases to cause the lake water level and groundwater table fall. If the period of water balance analysis is set to the unit of year, month or day, precipitation data, lake water level data and groundwater level data of corresponding unit will be necessary. But as mentioned above, there is no past groundwater level observation data, and the groundwater observation records from the observation wells drilled in this study are not suitable for the recharge analysis.

From the viewpoint of hydrologic cycle, the situation will be different. If a long-term water resource recharge amount and consumption amount are considered in the hydrologic cycle, the recharge amount is exactly equal to the consumption amount. Therefore, in the long-term hydrologic cycle, the lake water level is stable without fluctuation. The groundwater table also is stable. In this case, the water balance equation becomes:

$$W_R - W_C = 0$$

where,

W_R: Recharge amount for water resource in the target area.

W_C: Consumption amount of water resource in the target area.

Because this method does not need groundwater level observation data that is not available, the water balance analysis is conducted using all available data averaged over a long period.

A precondition for using long term analysis method to omit the data of groundwater level observation is that the main water resource consumption body, Lake Abaya, maintains its water level at a certain level up to now.

However, the well discussed issue of global climate change indicates that the recharge may largely increase or decrease anywhere in the world. Then the local water resource may become more or less. In addition, due to the increase of population and farmland and other water use, the water balance of the area may have become disordered as to cause lake water levels to go down in some areas in the Rift Valley1).

Then before conducting the water balance analysis, it is necessary to confirm if the water level of Abaya Lake has really gone down.

The confirmation was conducted using daily lake water level observation data from the three stations. As shown in Figure 7.5, two of the stations Arba Minch and Gidecho are located in the target area of Abaya Lake basin and the other one is located in adjacent Lake Chammo.

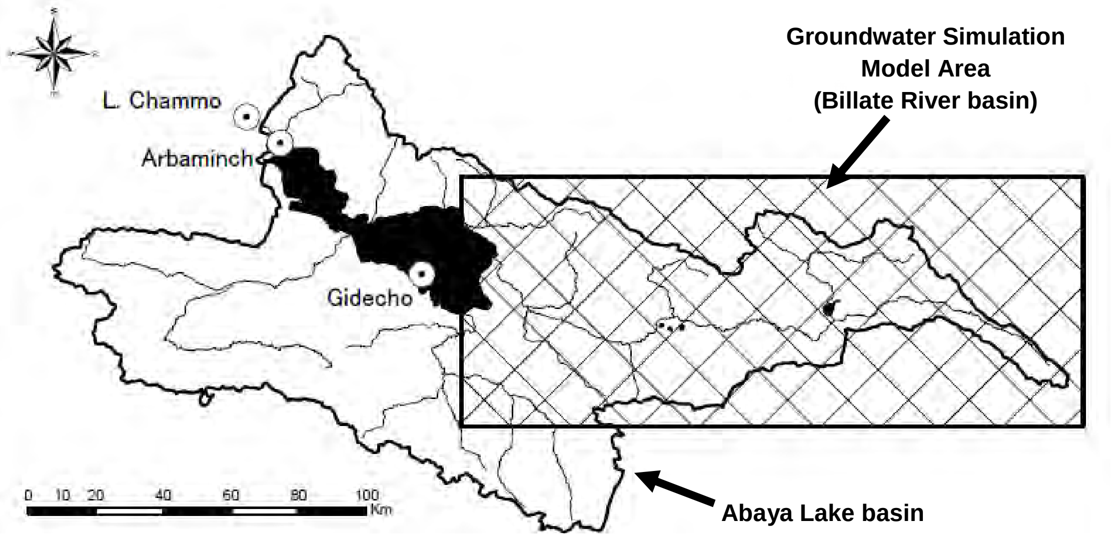


Figure 7.5: Locations of Lake Water Level Observation Stations

The relatively long period of lake water level observation results are shown in Figure 7.6 to Figure 7.8.

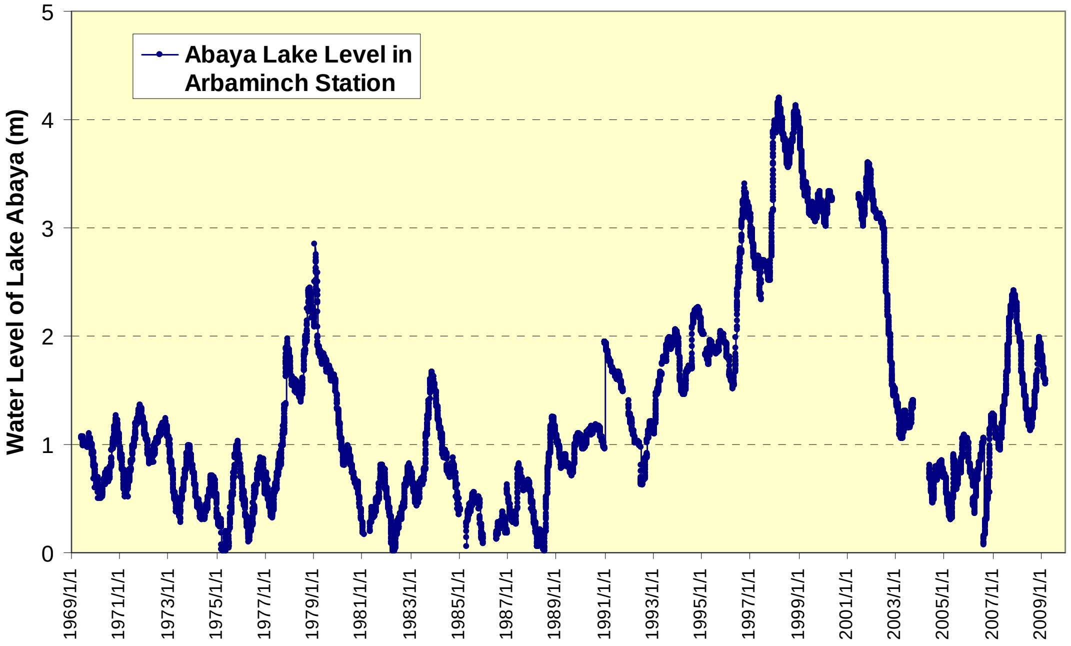


Figure 7.6: Water Level Fluctuation in Abaya Lake (station Arbaminch)

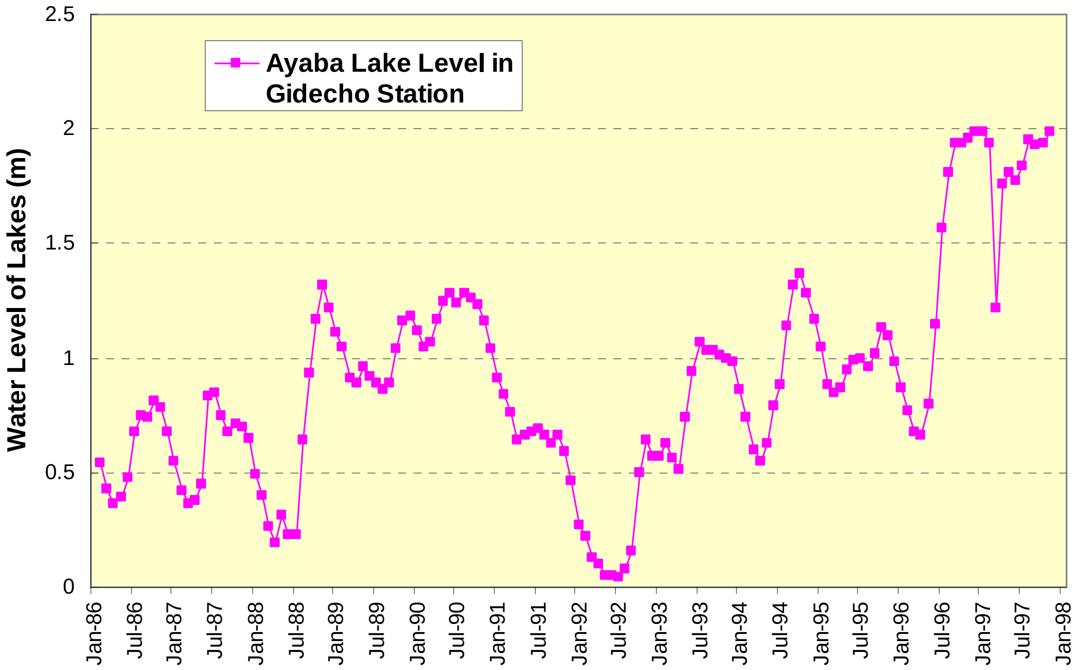


Figure 7.7: Water Level Fluctuation in Abaya Lake (station Gidecho)

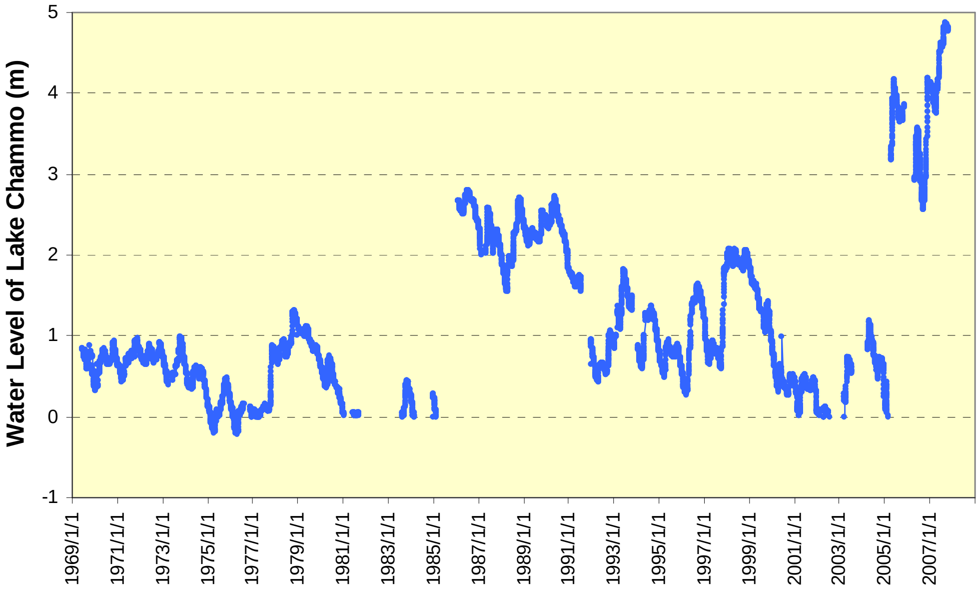


Figure 7.8: Water Level Fluctuation in Chammo Lake (station Chammo)

As shown in Figure 7.6 to Figure 7.8, a tendency of decreasing water level can not be clearly detected from any of the stations. At least during the observation period from 1969 to 2009, there is no evidence to say the lake water level is going down. On the contrary, the lake water level seems to rather rise slightly. If the water level increase is true, its effect on the result of water resource balance analysis using long period average method should be considered.

As shown in the water balance equation, lake water level increase is a result of more recharge amount than consumption amount. If the consumption amount increases, the recharge amount should also increase. The recharge to Lake Abaya includes river flow and groundwater flow. Both river flow and groundwater flow are possibly increased. In this case, when the average values of long term water balance analysis result are adopted, there should be no problem of over-estimating groundwater recharge amount. And then, when the model is used for the evaluation of future groundwater development plan, the possibility of over-estimating the groundwater potential will be lower and consequently to cause some environmental problems due to groundwater use in future.

As the result of the examination described above, the long term average method is employed for the water balance analysis.

7.4.3 Precipitation analysis

Precipitation is the only recharge source for not only Abaya Lake basin, but also to the Rift Valley Lakes basin, and to almost all closed basins in the whole world. Therefore, the water balance analysis was started from the analysis of precipitation.

The groundwater simulation model created this time is one of the four models planned in this study. The target basin is located in the central part of the Rift Valley Lakes Basin. Considering the schedule of modeling, the analysis of precipitation should not be limited to the Abaya Lake basin, but should be conducted for the whole Rift Valley area.

a. Available data

Two kinds of data have been collected, the original data from local meteorological stations (hydraulic department in the ministry of water and energy) and the data from database of

WMO (World Metrological Organization). The original data is the daily record and the WMO data is the monthly summary data.

Table 7.1: Available Precipitation Data

Station Name	Easting	Northing	Elev(m)	Source	Duration	MD_1	MD_2
Abaya	291678	577137	603	Original	2008 - 2010	20.7%	20.7%
Arba Minch	344789	672779	1191	Original	1974 - 2010	6.8%	1.0%
Awassa	442096	780355	1697	Original	1981 - 2010	0.0%	0.0%
Bilate	399203	754131	1360	Original	1980 - 2010	4.3%	4.3%
Buie	450453	923019	2039	Original	1987 - 2010	6.7%	2.3%
Chencha	416719	861173	1951	Original	1989 - 2010	10.5%	5.4%
Dilla	422590	709317	1528	Original	1954 - 2010	43.9%	3.5%
Hageremarim	415096	622728	1849	Original	1984 - 2010	10.9%	10.9%
Hossana	374967	834713	2295	Original	1981 - 2010	10.6%	3.2%
Jinka	228681	641683	1413	Original	1981 - 2010	3.5%	3.5%
Konso	328245	589727	1353	Original	1984 - 2010	8.8%	8.8%
Mirababaya	365418	696524	1237	Original	1982 - 2010	3.1%	3.1%
Shashemene	455838	795805	1934	Original	1981 - 2010	7.5%	7.5%
Wajifo	361003	713565	1228	Original	2000 - 2010	7.4%	7.4%
Werabe	411394	867806	2045	Original	2006 - 2010	15.9%	15.9%
Wolaitasodo	361882	757347	1978	Original	1981 - 2010	2.2%	2.2%
Yabelo	400210	539835	1787	Original	1987 - 2010	2.2%	2.2%
Ziway	468772	876938	1649	Original	1982 - 2010	4.7%	4.7%
Abonsa	380200	798700	2128	WMO	1965 - 1976	15.3%	15.3%
Adamitulu	469823	886464	1663	WMO	1908 - 1989	52.7%	5.5%
Alaba-Kulito	399368	808353	1778	WMO	1973 - 1983	6.1%	6.1%
Asela	514297	878727	2406	WMO	1966 - 1988	25.7%	14.6%
Awassa	442096	780355	1697	WMO	1972 - 2000	12.6%	6.2%
Bokoji-Farm	527407	832179	2782	WMO	1971 - 1984	12.5%	12.5%
Butagira	431375	897420	2077	WMO	1972 - 1987	20.8%	9.5%
Chencha	416719	861173	1951	WMO	1972 - 1983	9.7%	9.7%
Durame	377700	800000	2077	WMO	1973 - 1984	8.3%	8.3%
Gatto	324334	614120	1277	WMO	1973 - 1984	7.6%	7.6%
Geresse	310893	655677	2315	WMO	1973 - 1984	2.8%	2.8%
Gidole	318278	624579	2178	WMO	1954 - 1971	35.2%	16.7%
Jinka Bacco	228681	641683	1413	WMO	1970 - 1984	7.8%	7.8%
Kamba	298315	669937	1884	WMO	1974 - 1984	22.0%	14.2%
Kella	444472	912526	1921	WMO	1972 - 1984	0.6%	0.6%
Kofelle	476356	782064	2679	WMO	1955 - 1982	23.8%	14.7%
Konso	328245	589727	1353	WMO	1971 - 1983	5.1%	5.1%
Kore	492305	797928	2773	WMO	1968 - 1984	7.8%	7.8%
Koshe	448000	885000	1893	WMO	1974 - 1984	9.8%	9.8%
Merab Abaya	365418	696524	1237	WMO	1972 - 1984	16.0%	16.0%
Shonae	384500	789000	1966	WMO	1973 - 1984	4.2%	4.2%
Teltele	321500	559850	1414	WMO	1970 - 1979	3.3%	3.3%
Yirga Chefe	412345	680506	1853	WMO	1966 - 1984	10.1%	10.1%

Easting & Northing: Coordinate of precipitation observation station in projection Adindan UTM zone 37N.
Elev: Elevation of the station (mamsl)
MD_1: Percentage of missing data for the whole observation years.
MD_2: Percentage of missing data except those years without any observation data.

b. Data check and completion

The WMO data is officially released after data check and modification, so there is little error. However, the original data is a raw data with some errors. If the data verification and correction are not conducted before using the data, it could produce wrong analysis result.

The followings are some examples of data check and modification.

Buie Station: precipitation data for 2008/06/18 is stated “5. 2. 7 mm”. Clearly, the two decimal points is due to a mistake in data input. However, it has to be examined which decimal point is wrong and should be deleted. When the data is compared with the data of the day before and the day after, the former has a precipitation of 0 mm and the latter 20.7mm. Therefore, 5.27 mm was estimated as the correct value.

Arbaminch Station: precipitation data for 9/09/15 is stated “0. 013 mm”. When it is compare with all the other data, it can be confirmed that the data was never measured to that accuracy, namely, three decimal places. Therefore the value is modified to 1.3 mm.

Zeway Station: precipitation data for 2008/11/02 is 142..5 mm. This is thought as a simple input mistake and then the value was modified to 142.4 mm.

In addition to the necessity of data verification and correction, for most stations there are some missing data. If the analysis is carried out without compensating the missing data, the analysis result would give smaller values than the real ones.

As shown in Table 7.1, all collected data, except for those of Awassa station, have missing data. Especially for Dilla station, the data for almost half the observation period is missing.

For those stations with missing data, the data was checked to classify the type of missing data. In the case of the data missing for a whole year, that year can be simply eliminated from the data series for analysis. If a part of data of a year is missing, the problem becomes a little complex. In the first place, it is impossible to recover the missing data but if the data for the corresponding whole year were eliminated from the analysis, the available data for water balance analysis could become very limited in some cases.

Therefore, data compensation should be conducted. Several kinds of methods are available, such as correlation method, average method using the data from adjacent stations, and self-averaging method. In this analysis, the self-averaging method was used. The process of the method is to use the averaged value of the same date in other years to estimate the missing data.

c. Precipitation analysis

c.1 Average precipitation

The average precipitation in Rift Valley Lakes basin was summarized using the complemented data. The analysis results of WMO monthly precipitation data is shown in Table 7.2 and Figure 7.9. The analysis results of original daily precipitation data in Abaya Lake basin is shown in Table 7.3 and Figure 7.10.

Table 7.2: Summary of WMO Precipitation Data Analysis Result

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Abonsa	34	57.5	93.6	124.7	103	85.5	159.2	167.9	124.9	60.5	47.4	6.9
Adamitulu	12.4	30.8	38.3	56.2	64.9	65.9	113.2	101.1	79.4	17.8	5.5	4.3
Alaba-Kulito	19.7	32.2	90.9	116.7	127.3	70.1	123.7	119.4	113.7	68.1	38.1	16.1

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Asela	22.8	54.2	93.6	105.4	128.7	141	223.2	242.8	190.8	58.9	21.5	9.9
Awassa	28.9	43.2	69.7	95.7	115.6	97.2	125.1	116.9	116.5	83.4	29.5	17
Bokoji-Farm	29.6	42.8	75.5	80.6	100.4	113.7	198.5	174.3	90.6	55.1	19.3	10
Butagira	32.2	67.8	107	91.3	130.2	92.7	157.8	163.2	113.2	41.3	17.3	10
Chencha	44.9	49.6	94.7	163.6	181.2	88.7	135.5	104.9	111.7	169	69.8	18
Durame	43.6	24.3	91.3	87.1	137.9	88.4	135.8	161.4	130.4	81.1	37.3	12.6
Gatto	29.5	51.5	116.2	173.8	169.3	48.2	43.3	61.8	117.3	89.3	127	18.6
Geresse	27.8	44.3	146.8	186.8	315.9	119.4	162.3	171.3	160.3	216.4	99.3	25.9
Gidole	28.7	71.6	114.9	172.5	123.4	77.2	73.7	109.8	95	197.6	69.4	56.3
Jinka Bacco	38.6	70	105.8	179.9	166.9	107.3	101.8	121.2	133.4	168.3	125.5	32.8
Kamba	29.8	42.8	99.5	158.4	208.6	101	132.8	103.5	152.6	177.8	66	15.8
Kella	36.4	55.5	85.9	103	120.2	149.3	237.5	226.4	144.4	57.8	16	5.2
Kofelle	40.3	59.6	117	140	89	107.8	146.6	150.8	142.6	93.9	56.2	24.5
Konso	11.3	19.5	33.1	69	56.3	16.4	25.1	24.1	40.4	61.1	38.3	6.5
Kore	39.3	57.6	101.2	111.1	113.6	89.7	177.3	182.1	137.9	83.5	29	22.6
Koshe	27.9	49.2	86.2	94.9	123.5	99.5	196.7	225.4	131.5	58.4	9.1	0.3
Merab Abaya	21.1	18.1	43.6	79	105.4	51	93.8	50.4	74.4	83.6	61.4	7.4
Shonae	67.6	86.5	143.9	129	171.6	143.5	221.2	224.3	196.9	107.8	51.3	20.9
Teltele	37.6	39.8	77.4	138.4	123	27.4	10.2	15.3	34	113	66.2	11.6
Yirga Chefe	27.8	41.7	122.6	293.1	295.8	136.4	100.8	124.3	242.8	300.9	103.1	13.1
Minimum	**11**	**18**	**33**	**56**	**56**	**16**	**10**	**15**	**34**	**18**	**6**	**0**
Maximum	**68**	**87**	**147**	**293**	**316**	**149**	**238**	**243**	**243**	**301**	**127**	**56**
Average	**32**	**48**	**93**	**128**	**142**	**92**	**135**	**137**	**125**	**106**	**52**	**16**

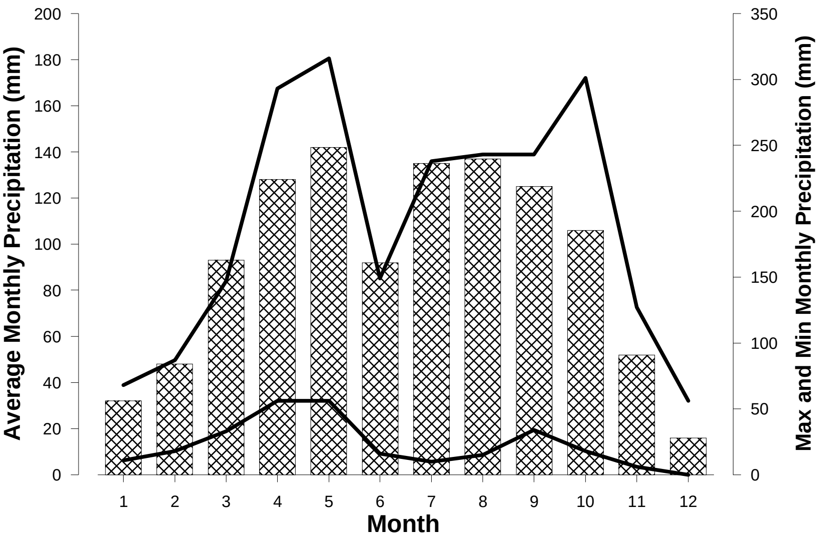


Figure 7.9: Maximum, Average and Minimum Monthly Precipitation of WMO Data

Table 7.3: Summary of Original Precipitation Data Analysis Result for Abaya Lake Basin

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Abaya	34.3	8.1	92.8	102.7	134.5	90.3	78.4	35.3	58.9	69.1	32.2	28.1
Arba_Minch	30.4	33.9	61.8	149.5	152	62.1	45.9	49	83.9	114.5	59.7	37.5

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Bilate	31.7	34.5	60.2	112	109.5	75	88.7	70.3	71.5	73	38.9	29.4
Chencha	55.2	52.2	128.8	191.6	147.5	89	119.8	119.3	131.5	168.4	84.4	65.8
Dilla	41	42.9	104	194.2	182.1	113.3	105.7	108.5	151.8	162.1	72.4	36.1
Hageremarim	14.5	20.5	72.4	187.1	205.6	67.3	35	40.8	52.4	121.8	69.2	18.5
Hossana	30.5	51.7	107.7	141.8	143.9	118.7	150.5	174.8	151.3	82.8	21.9	18.2
Konso	26	35.2	86.4	178.4	110.9	35.7	21.2	34.2	58.9	94.8	55.5	45.2
Mirabaaya	25.2	24.9	54.7	104.5	109.8	69.9	50.8	52.8	56.1	75.9	55.8	31.7
Shashemene	23.2	33.5	75.5	121	103.6	66.2	98.1	92	112.4	71.7	21.9	16.1
Wajifo	27.5	18.1	97	174.9	170.9	108.1	136	203.9	90.4	97.1	45.5	53.7
Werabe	36	72.2	75.1	88.6	155.4	145.3	209.1	223.3	148.7	65.2	71.2	9.3
Wolaitasodo	30.7	42.9	81.1	163	183.4	131.3	179.7	187.8	111.9	90	56.1	39.2
Yabelo	23.1	27.4	84.9	147.7	92.9	12.3	10.6	9	34	94.8	48.5	21.2
Minimum	**15**	**8**	**55**	**89**	**93**	**12**	**11**	**9**	**34**	**65**	**22**	**9**
Maximum	**55**	**72**	**129**	**194**	**206**	**145**	**209**	**223**	**152**	**168**	**84**	**66**
Average	**31**	**36**	**84**	**147**	**143**	**85**	**95**	**100**	**94**	**99**	**52**	**32**

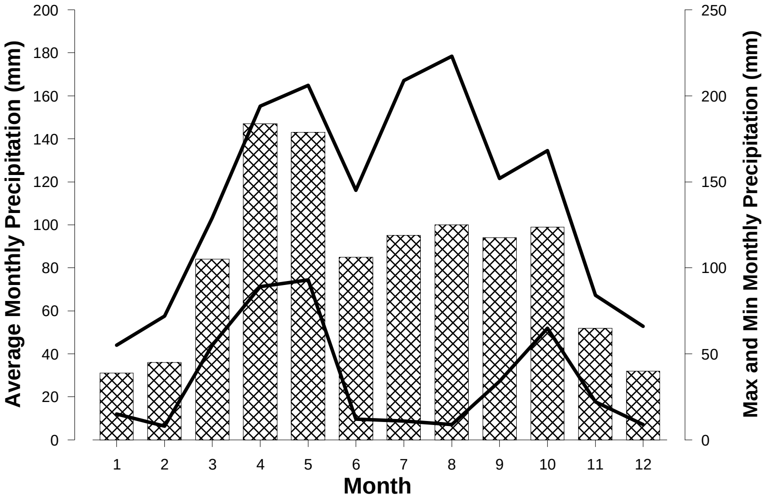


Figure 7.10: Maximum, Average and Minimum Monthly precipitation of Original data.

Analysis results for all complemented precipitation data are summarized in Table 7.4 and Figure 7.11.

Table 7.4: Summary of All Precipitation Data Analysis Results

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Minimum	11	8	33	56	56	12	10	9	34	18	6	0
Maximum	68	87	147	293	316	149	238	243	243	301	127	66
Average	31	43	90	135	143	89	120	123	113	103	52	22

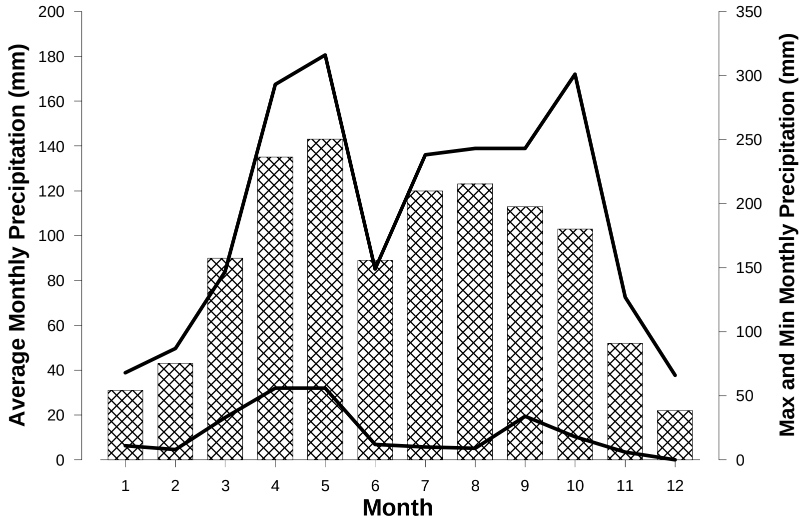


Figure 7.11: Maximum, Average and Minimum Monthly precipitation of All Available Data

c.2 Analysis of correlation between precipitation and elevation

One characteristic of the model area is the intensive change in ground surface relief as mentioned in the beginning of this chapter. This variation in relief affects not only the construction of the groundwater model, but also the distribution of precipitation. As in the common sense of hydrology, precipitation increases with elevation. So the relationship between the precipitation and the elevation will be examined here.

As shown in Figure 7.12, a weak relation can be found that the precipitation increases with the elevation. However, when the degree of correlation is calculated, the result showed no clear relationship.

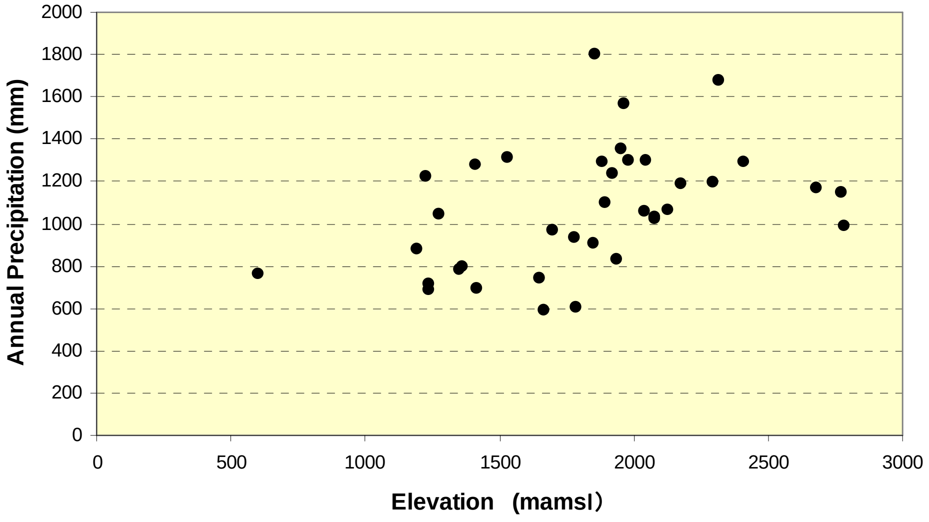


Figure 7.12: Relation between Precipitation and Elevation

Another method was used to continue the analysis. The ground surface was divided into seven elevation groups with a step of 250m in altitude. Then, the precipitation was divided into each elevation group and summarized as average precipitation. The result of the analysis is shown in the Table 7.5 and Figure 7.13.

Table 7.5: Relation between Groups of Precipitation and Elevation

Elevation	Average rain	No. of Stations
1250	854	5
1500	919	5
1750	904	4
2000	1175	11
2250	1111	6
2500	1388	3
>2500	1101	3

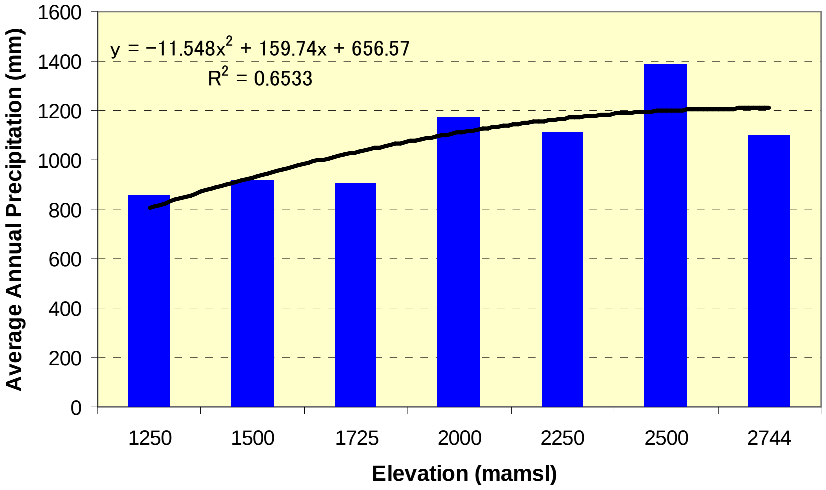


Figure 7.13: Relation between Groups of Precipitation and Elevation

The result of quadratic correlation analysis is shown in Figure 7.13. The coefficient of correlation is 0.808 and is not very high.

A linear equation was also employed to calculate the correlation. The result is:

$$\text{precipitation} = 0.271 \times \text{elevation} + 523.82$$

And the correlation coefficient is 0.78, and is lower than the quadratic.

If a clear correlation is identified between the precipitation and the elevation, the relation will be used to calculate the precipitation in the target area. In this case, no clear correlation was confirmed. Therefore, the traditional method of Thiessen division was used to estimate and summarize the yearly precipitation in the target area – Abaya Lake basin.

c.3 Total precipitation in Abaya Lake Basin

Figure 7.14 shows the result of Thiessen division based on the data of precipitation observation stations within and surrounding the Abaya Lake basin. Within Abaya Lake basin, both original daily data and WMO summary data are available. In this case the original data was used.

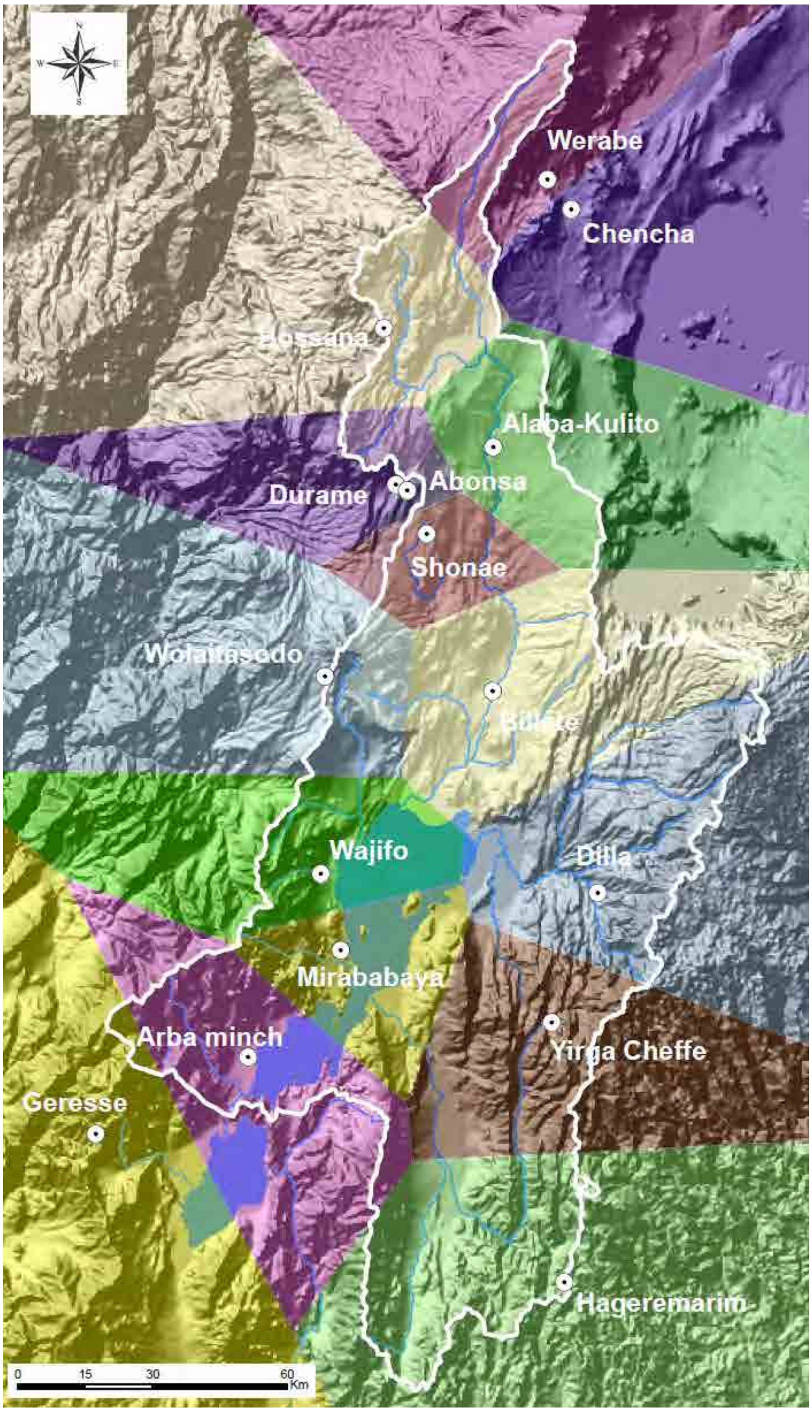


Figure 7.14: Thiessen Division for Precipitation Stations in and Surrounding Abaya Lake Basin.

Table 7.6 shows the result of precipitation analysis summarized for Abaya Lake basin.

Table 7.6: Precipitation Analysis Result Summary in Abaya Lake Basin

Station	**Y_rain(mm)**	**Area(m2)**	**T_Area_rain (m2)**
Abonsa	1065	89,676,671	95,505,655
Alaba-Kulito	936	1,104,599,009	1,033,904,672
Arba minch	880	1,348,454,025	1,186,639,542
Bilate	795	2,506,841,025	1,992,938,615
Chencha	1354	15,321,558	20,745,390
Dilla	1314	2,224,857,655	2,923,462,959
Durame	1031	241,282,405	248,762,160
Geresse	1676	68,625,363	115,016,108
Hageremarim	905	1,781,895,764	1,612,615,666
Hossana	1194	912,104,307	1,089,052,543
Mirababaya	689	1,331,509,830	917,410,273
Shonae	1565	700,921,861	1,096,942,712
Wajifo	1223	1,132,222,199	1,384,707,749
Werabe	1299	442,933,004	575,369,972
Wolaitasodo	1297	611,071,994	792,560,376
Yirga Chefe	1802	1,785,376,549	3,217,248,541
Total		**16,297,693,219**	**18,302,882,933**

Y_rain :	Yearly average precipitation.
Area :	Area of corresponding Thiessen division in Abaya Lake basin
T_Area_rain :	Yearly average precipitation in each Thiessen division area.

As shown in Table 7.6, the difference of precipitation is large for the 16 stations in and surrounding the Abaya Lake basin. The minimum is 689mm/year and the maximum is 1,802 mm/year, the difference is as large as about 3 times. The Thiessen division method results indicates the total precipitation of 18,302.9 Mm^3 in the Abaya Lake basin.

7.4.4 Water resource consumption analysis

In a closed basin, almost all water resource consumption is from evaporation, except for infinitesimal groundwater flow from the deep aquifer to outside the basin. Therefore, evaporation amount is the most important factor for consumption analysis.

a. Available data

Compared to the precipitation observation stations, only a few stations in Rift Valley basin have been observing evaporation. Figure 7.15 shows the location of the four stations with evaporation records.

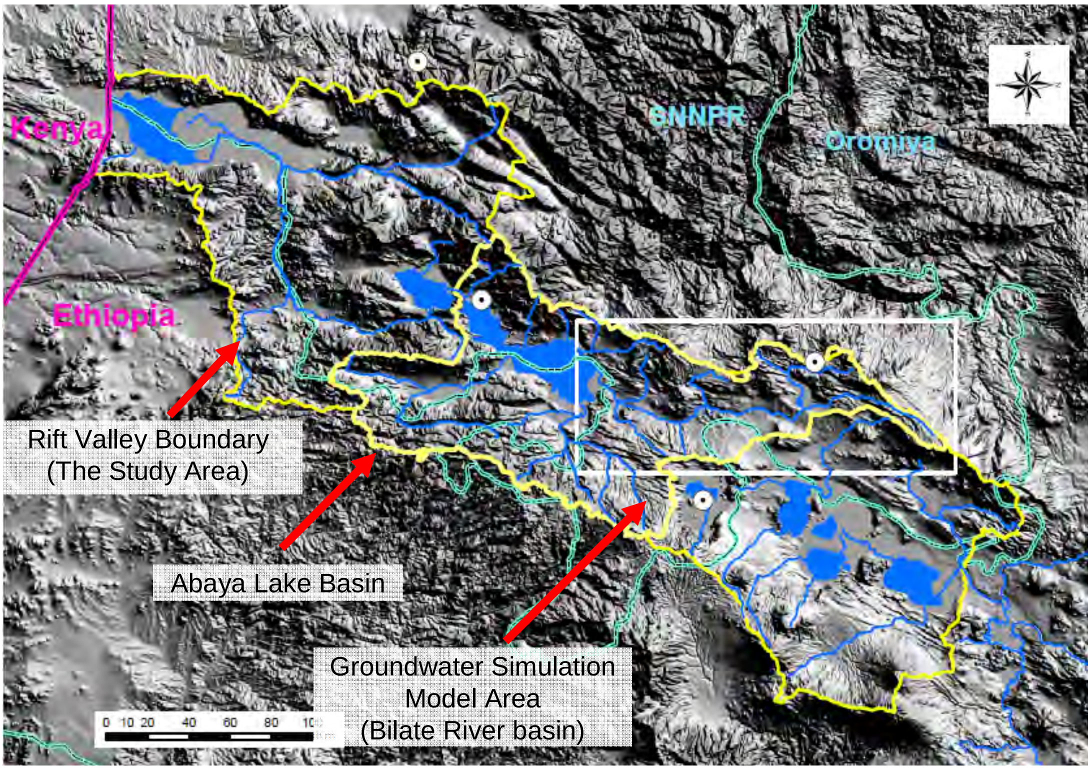


Figure 7.15: Location of Stations with Evaporation Records.

Table 7.7 shows the observation period and ratio of missing data.

Table 7.7: Available Evaporation Data in Rift Valley

Station	Duration	Missing_Data	MD_pcnt
Arba_Minch	2006 - 2010	617	42.2%
Awassa	1986 - 2010	1,032	11.3%
Hossana	2004 - 2010	1,414	55.3%
Jinka	1989 - 2009	1,605	20.9%

b. Data check and completion

Similar to the process of precipitation analysis, the data verification and compensation were conducted before the use of the data. Some examples of data modification are as follows:

Jinka Station: Evaporation amount for 2001/05/23 is stated as “6. 50. mm”. Clearly, the last decimal point is an input mistake. Therefore, the decimal point was deleted to correct the data as 6.5mm.

Awassa Station: Evaporation amount for 2004/09/21 is stated as “2. 6. 2mm”. One of the two decimal points must be an input mistake and should be deleted. After comparing the evaporation values for the day before and the day before that (2.87 and 3.0mm, respectively), the correct value was judged to be 2.62mm.

In addition to the small number of available stations, the short period of observation and numerous missing data adds to the problem. In the same way as precipitation data modification, self-averaging method was used for data complementation.

Table 7.8 shows the monthly and yearly average of evaporation amount in the Rift Valley based on the four available stations.

Table 7.8: Monthly and Yearly Average of Evaporation in Rift Valley

Month	Arba_Minch	Awassa	Hossana	Jinka	Average
Jan	188.4	191.4	130.9	137.5	162.1
Feb	173.1	193.3	147.1	137.9	162.9
Mar	219.2	193.4	186.5	139.7	184.7
Apr	147.3	161.7	148.2	116.7	143.5
May	129.1	165.2	118.9	104.3	129.4
Jun	146.9	152.1	111.4	95.3	126.4
Jul	126.4	132.1	105.3	96.1	115
Aug	146.6	137.1	89.3	104	119.3
Sep	135.7	131.7	106.6	121	123.8
Oct	143.1	151.6	135.2	112.3	135.6
Nov	154.8	174.5	166.3	111.6	151.8
Dec	136.6	179.2	145.6	118.1	144.9
Min	126.4	131.7	89.3	95.3	115
Max	219.2	193.4	186.5	139.7	184.7
Average	153.9	163.6	132.6	116.2	141.6
Total	1,847	1,963	1,591	1,395	1,699

The precipitation values in Abaya Lake basin show a difference of as large as three times but the difference in evaporation values between the stations is relatively small. When comparing the minimum amount of 1,395 mm/year and the maximum of 1,963 mm/year, the difference is less than 50%.

c. Relation between evaporation and elevation

Analysis was conducted to confirm if there is any correlation between evaporation and elevation. As shown in Figure 7.16, no relationship can be found between them.

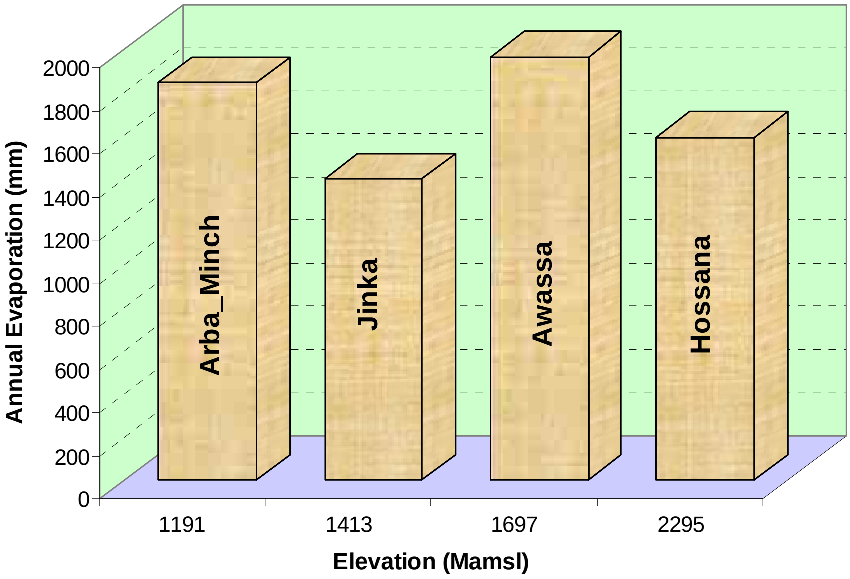


Figure 7.16: Relation of Annual Evaporation and Elevation

d. Evaporation from lake water surface

Within the Abaya Lake basin, Lake Abaya is the biggest Lake, and there are also some small lakes or ponds. The locations of those lakes and corresponding evaporation observation stations are showing in Figure 7.17.

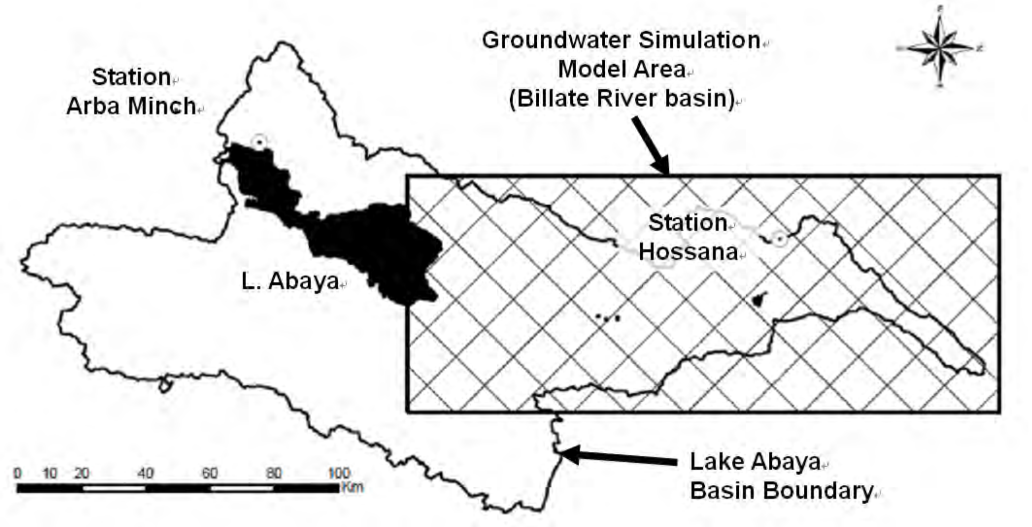


Figure 7.17: Distribution of Lakes in Abaya Lake Basin

The evaporation amount from all the lakes in Abaya Lake basin were calculated using the yearly evaporation values from the nearest meteorological stations that were selected based on the physical proximity shown in Figure 7.17. The result is summarized in Table 7.9.

Table 7.9: Evaporation from Lakes in Abaya Lake Basin

Name	Area（km2）	Evap_Station(m)	Evap_Lake(Mm2)
Lake Abaya	1094.81	1.847	2022.1
Water	6.35	1.591	10.1
Water	1.09	1.591	1.7
Water	0.77	1.591	1.2
Water	0.66	1.591	1.1
Total	**1103.68**	--	**2036.2**

Evap_Station: Yearly average evaporation amount in the nearest meteorological station.
Evap_Lake: Evaporation amount from lake’s water surface.

The evaporation amount from lake water surface in Table 7.9 includes direct precipitation on the lake's water surface. Evaporation is not related to recharge from river flow or groundwater flow. Since the aim of the consumption analysis is to obtain groundwater recharge amount, the precipitation should be eliminated from the consumption analysis process. The net evaporation amount, that is, recharge from river flow or/and from groundwater flow to the lakes are summarized in Table 7.10.

Table 7.10: Summary of Net Evaporation of Lakes in Abaya Lake Basin

Name	Area（km2）	Evap-Prec(m)	Evap_Lake(Mm2)
Lake Abaya	1094.81	0.967	1058.7
Water	6.35	0.397	2.5
Water	1.09	0.397	0.4
Water	0.77	0.397	0.3
Water	0.66	0.397	0.3
Total	**1103.68**	--	**1062.2**

Evap - Prec: Difference of evaporation and precipitation in the corresponding stations.

Evap_Lake: Net evaporation amount from lake's water surface.

The total annual net evaporation amount from the lakes in Abaya Lake basin was calculated to be 1,062.2 M m3.

e. Consumption from river water surface

As shown in Figure 7.18, Abaya Lake basin contains many rivers.

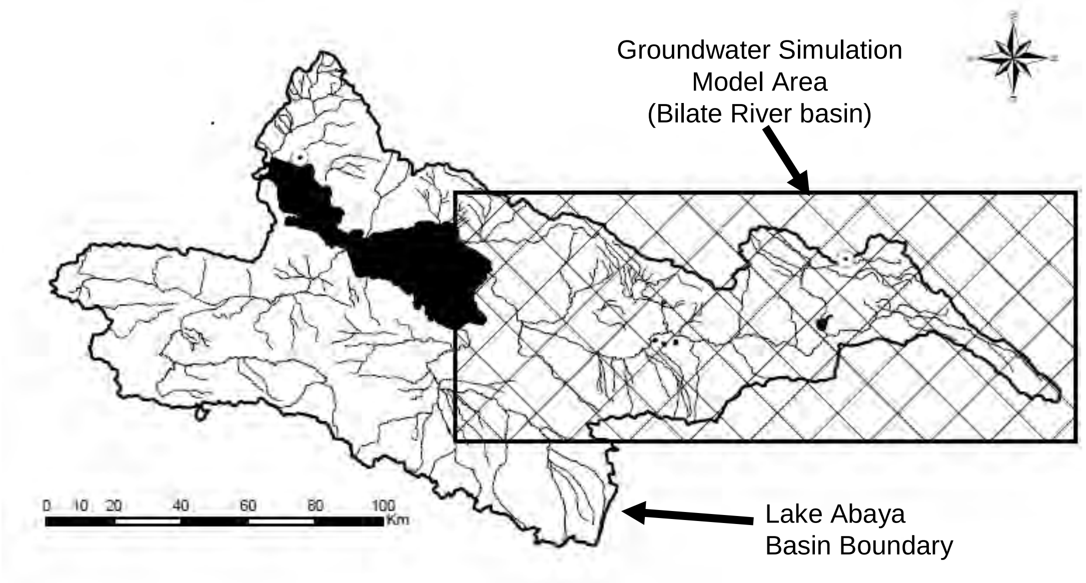


Figure 7.18: Distribution of Rivers in Abaya Lake Basin

Two parameters are necessary to calculate evaporation amount from river water surface:

- River water surface area ＝ river length × river width
- Evaporation amount for each river or each section of rivers

River length and width are necessary for river water surface area calculation. River length is easy to obtain through the GIS length calculation function. On the other hand, the width, as well known, changes in each section of a river due to many factors such as relative position in the river (upstream or downstream), the length of the river, the topography of the river course. There is no way to get the changing width values exactly for a river, other than by conducting a very detailed survey.

In the GIS data file of those rivers from Halcrow 2008$^{1)}$, the rivers are classified into two types: major rivers and streams. The major rivers include: Bilate (257km), Gelana (175km), Gidabo (131km) and some other major rivers. The streams include many small rivers with their length ranging from several kilometers to tens of kilometers.

Generally, the river width is somehow proportional to river length. That is, longer rivers are generally wider than shorter rivers. Therefore, the river width was specified as follows:

- 10m (5 rivers) for rivers with river length >100km.
- 8m (3rivers) for rivers with river length between 50～100km.
- 5m (over 300 rivers) for rivers with river length <50km.

Very few meteorological stations have evaporation records as described above. There are only two such stations within Abaya Lake basin. The yearly evaporation amount from these two stations is quite similar, with values of 1,847mm (Arba Minch) and 1,591mm (Hossana). The difference between the two evaporation stations is only less than 15%. And also the relation between evaporation and elevation was not identified as described above. Therefore, there is no way to exactly specify yearly evaporation amount for each part of rivers. Thus, evaporation from river water surface was calculated for all the rivers using yearly average evaporation amount of the two stations. The calculation process is shown in Table 7.11.

Table 7.11: Specification of Parameters for Calculation of Evaporation from Rivers

R_Length	**R_Width**	**R_#**	**T_R_Length**	**R_Area**	**Evapo**
>100	10	3	564.8	5.648	9.7
40 - 100	8	8	389.5	3.116	5.4
<40	5	184	2108	10.54	18.1
Total	**--**	**195**	**3062.3**	**19.304**	**33.2**

R_Length : River length (km)
R_Width : River width (m)
R_# : Number of rivers
T_R_Length : Total length of rivers (km)
R_Area : Total area of rivers (km^2)
Evapo: Total evaporation amount from river water surface (Mm^3)

In the same way as in lake water surface evaporation amount calculation, the calculation result summarized in Table 7.11 includes precipitation directly fallen on river water surface. This amount should be taken out to make the evaporation values exactly equal to the recharge from river discharge or/and groundwater flow. The direct precipitation amount onto the river is also impossible to calculate exactly for the same reason as evaporation. On the other hand, as compared with the evaporation amount from lake water surface of 1,062.2 Mm^3 , the total evaporation amount from the river surface is 33.2 Mm^3, only 3% of the former. Therefore, even if the specified values for the rivers may not be so exact, the effect would be very minor as to be negligible. Anyway, the same method as in evaporation specification was employed for direct precipitation specification. That is, the averaged value of precipitation from the two stations, which were also used for evaporation amount specification, was taken as the factor for all the rivers. The calculation equation is given below:

$$
\begin{aligned}
E_{R\_net} &= TE_R\ (m^3) - Area_R\ \ (m^2) \times 1.037\ (m) \\
&= 33.2 \times 10^6 - 19,304,629 \times 1.037 \\
&= 13.2\ (Mm^3)
\end{aligned}
$$

whhere

E_{R_net} : Net evaporation consumption from river water surface.
TE_R : Total evaporation amount from the Table 7.11.
$Area_R$: Total river surface area.

When the calculated net evaporation amount from river water surface is compared with the net evaporation amount from lake's water surface (1,062.2Mm^3), it is only 1.2%. Therefore, even though the specification of evaporation and precipitation amount on river water surface may not be sufficiently exact, the error will be less than 1% for the total water resources consumption estimation.

f. Consumption for irrigation

If groundwater is used for irrigation, some extra cost is needed for electricity or fuel, so it is supposed that not so many farmers will use, or be able to use groundwater irrigation. The result of interview survey in this study also supported this assumption.

On the other hand, when river water is used for irrigation, its ratio may be small compared to the total river discharge. Otherwise, the river flows to lakes will be reduced and the lake water level will go down. However, as reviewed earlier, up to 2010, there is no sign of decrease in the lake's water level.

The information about the use of irrigation water is even scarcer than meteorological data. In the field survey on irrigation amount, it was confirmed that no irrigation amount was recorded at any of more than 10 zonal or Woreda irrigation offices visited during the survey. The information on irrigation water use is, as a result, limited to the following:

1) In most areas, irrigation is conducted only in the dry season
2) The frequency of irrigation is from twice to 5 times a year for most farmlands.

Based on past experience and a document from FAO[2)], the water surface area due to irrigation can remain only for several hours after irrigation. Therefore, evaporation from irrigation water only occurs at the same rate of evaporation as for the first two days.

According to the results of discussion above, the consumption from irrigation water use is summarized in Table 7.12.

Table 7.12: Calculation of Evaporation for Irrigation

Name	**Amaro**	**Gamo Gofa**	**Konso**	**Sodo**
Area（km^2）	1557.23	12163.89	2322.62	830.1
Irri_Area（ha）	3175	5542	3918	1615
#_Times	4			
D_Evapo（m）	0.01			
T_Evapo （Mm^3）	1.27	2.22	1.57	0.65
Ratio(m^3/km^2)	643.4	84.4	432.1	1205.3
Ratio$_A$($m^{3/}km^2$)	**338.4**			

Area: Total area of interviewed administrative unit (zone or Woreda)
Irri_Area: Area of irrigated farm land in the corresponding administrative unit.
#_Times: Specified number of irrigation times based on the interview.
D_Evapo: Specified daily evaporation amount in the dry season.
T_Evapo: Water consumption from irrigation system in each interviewed administrative unit.
Ratio : Total water used for irrigation divided by the area of each administrative unit.
Ratio$_A$: Total water used for irrigation divided by the area of the whole interviewed administrative units.

Figure 7.19 shows the relation of Abaya Lake basin and administrative districts where the interview surveys were conducted. At four interviewed zonal irrigation department offices, two (Amaro and Gamo Gofa) extend over the target basin of Abaya Lake.

Using the results shown in Table 7.12, the total irrigation water consumption amount in Abaya Lake basin was calculated by the equation below:

$$\text{Ratio}_A\ (338.4m^3\ /\ km^2)\ \times\ \text{Area of Abaya Lake Basin}\ (16{,}298\ km^2)\ =\ 5.\ 5\ Mm^3/\ \text{year}$$

This amount is smaller than the net water consumption amount from river water surface, and is less than 0.5% when compared with the evaporation from lake water surface.

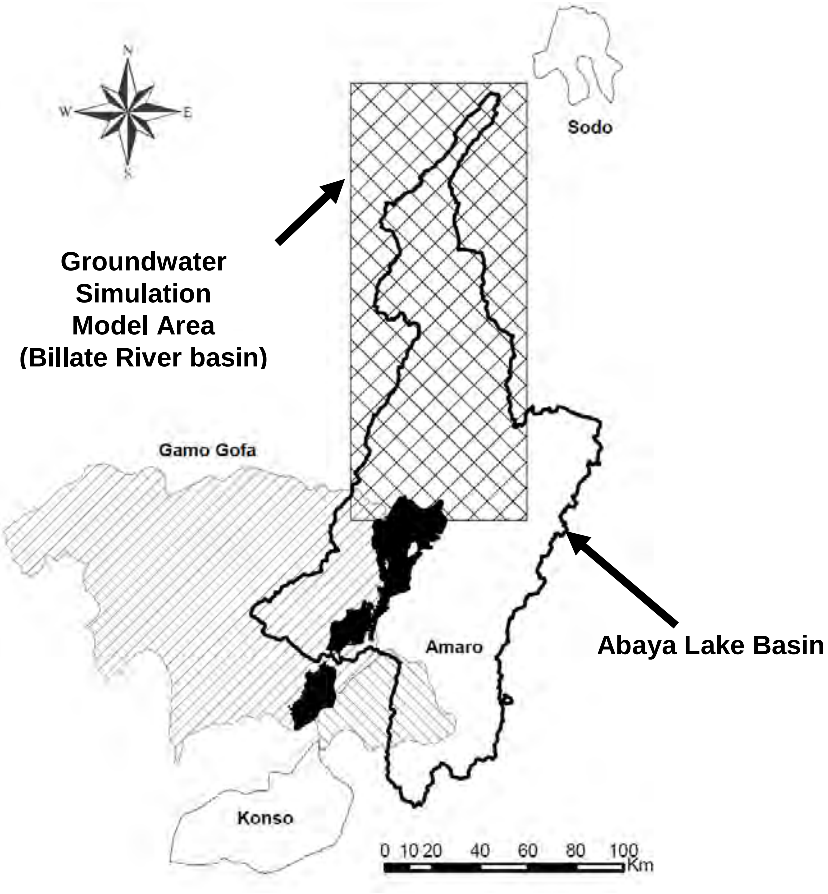


Figure 7.19: Relation of Surveyed Irrigation Area and Groundwater Simulation Model Area

g. Industrial and domestic water use

Other than the water for irrigation, water resource is consummated by production water use and domestic water use. According to the reference report1), amount of domestic water use is different from rural area and urban area. In rural area, the unit water use is set at 10 liters per day per capita from unprotected sources and in urban area it is 50 liters per capita per day from piped systems. Because there is not enough additional data for production and domestic water use estimation, the calculation of production and domestic water use was based on the estimation result from the reference report1).

The production and domestic water use in the whole Rift Valley basin is estimated1) as 82Mm^3 in 2005. The total population in Rift Valley basin in 2005 is 8.9 million. It is obvious that both production and domestic water use are related to the population. The population in 2005 in the administrative districts covering Abaya Lake Basin is 5.75 million as shown in Figure 7.20. However, not all the population in these administrative districts lives in Abaya Lake Basin. Thus, the population within the Abaya Lake basin was calculated by subtracting the population of administrative districts extending outside the boundary. The division was conducted by separating the population by the proportion of administrative area in and out of the lake basin boundary.

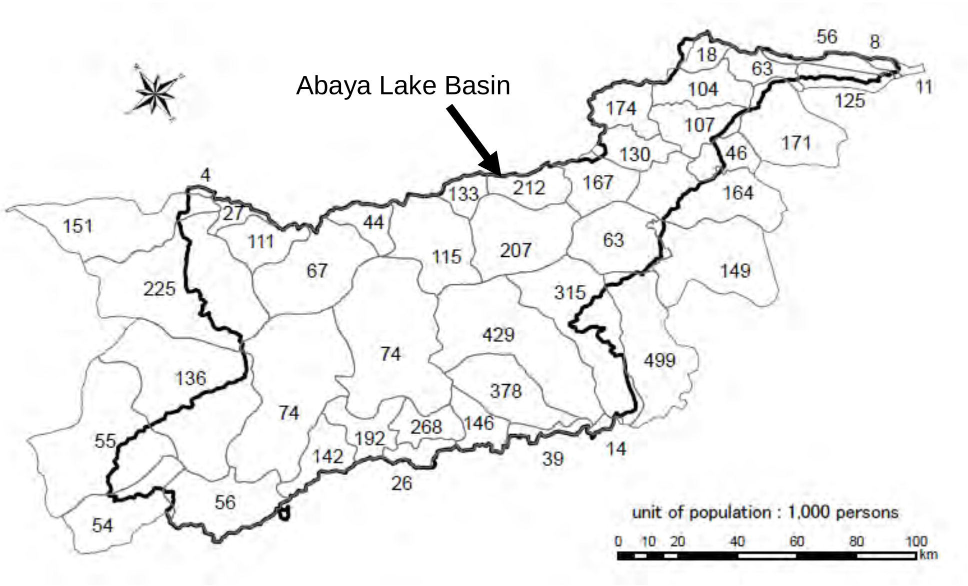


Figure 7.20: Population Distribution in Abaya Lake Basin

The calculation results of the population in Abaya Lake basin is 4.00 million. It is 45% of the whole population in the Rift Valley Lakes Basin. This ratio and the total production and domestic water use amount values were used to estimate water use consumption. The resultant production and domestic water use amount is 36.9Mm^3/yaer in total within Abaya Lake Basin.

The production and domestic water use is larger than water consumption from river water surface and irrigation, but it is still less than 3.5% of consumption from lake's water surface evaporation.

All the water resources consumption has been analyzed by the procedure descried above. All consumption amounts are summarized in Table 7.13.

Table 7.13: Summarizing of Water Resource Consumption Analysis Result

Type	Amount (Mm3)	Percentage
Net evaporation from lakes	1062.2	95.03
Net evaporation from Rivers	13.2	1.18
Water use for irrigation	5.5	0.49
Industrials and domestic use	36.9	3.3
Total	**1117.8**	**100**

7.4.5 Groundwater recharge analysis

The purpose of water balance analysis is to calculate groundwater recharge amount in the groundwater simulation model area. In a long period of the hydrologic circle, the recharge amount of water resources equals to the consumption amount of water resources in a closed basin. The Abaya Lake basin is a closed basin and the total water resource consumption amount is 1,117.8 Mm^3 within the basin is given in Table 7.13. Therefore, the total recharge amount of water resource in the basin should be the same value of 1,117.8 Mm^3.

However, this recharge amount contains both river flow and groundwater flow components. So, to obtain the groundwater recharge amount, the total water resource consumption amount has to be separated into the two components.

a. River discharge analysis

To separate surface runoff (river discharge) and groundwater flow, an analysis should be conducted to calculate either surface run off amount or groundwater recharge. Since the information about aquifer structure and aquifer parameters is quite limited as mentioned in the beginning of this chapter, the calculation is started from river discharge analysis.

a.1 River discharge division

The river discharge observation data collected from 16 stations are available for river discharge analysis. Location of those hydrological stations is shown in Figure 7.21.

In the same way as in the analysis of precipitation and evaporation data, check and modification of the data was carried out before using the river discharge data.

Some examples of the modification are given below:

Gombera (Hossana) Station: monthly maximum discharge is stated as "6. 87 Mm^3" for 1998/8, and the average discharge is 8.558Mm^3 in the same month. This average discharge is not only larger than the maximum value, but also the biggest in 6 year's observation period. Therefore, the values for monthly maximum and average were judged to have been mistakenly substituted. Then the two values were exchanged for correction.

There are two types of hydrological observation stations, the river discharge stations and spring discharge observation stations. If it is a river discharge station, the observation records should have a big range of fluctuation following the seasonal change in precipitation. On the other hand, spring water is 100% supplied from groundwater, so that the discharge fluctuation is much smaller than in river discharge record. Based on this hydrological common sense, the type of station L. Abaya_Lantie is judged as wrongly given as river discharge station, because the range of fluctuation is much smaller than other rivers.

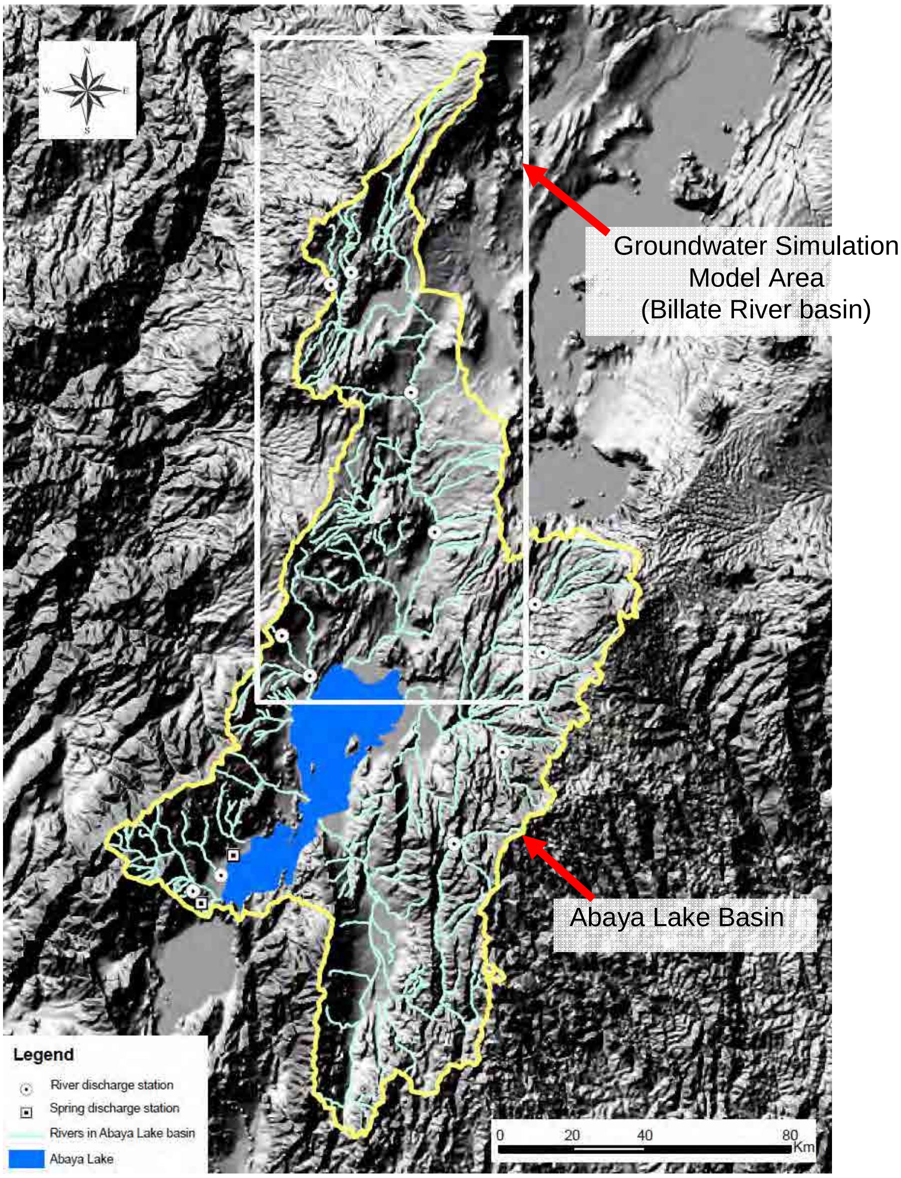


Figure 7.21: Distribution of Hydrological Stations in Abaya Like Basin

Table 7.14: Available River Discharge Data in Abaya Lake Basin

Name	Type	Elevation	Duration	MD_1	MD_2
40 Spring	Spring	1366	1980 - 1998	8.30%	8.30%
Bedessa	River	1521	1986 - 2003	2.30%	2.30%
Bilate_Alabkulito*	River	1716	1971 - 2002	3.90%	3.90%
Bilate_Tena*	River	1493	1980 - 2002	50.70%	37.00%
Gidabo	River	1683	1976 - 2000	6.00%	6.00%
Gombera	River	2292	1987 - 1992	16.70%	16.70%
Guder	River	2292	1987 - 2000	11.30%	11.30%
Hamessa Nr. Humbo	River	1630	1985 - 2003	11.00%	11.00%
Hammessa Nr. Wajifo	River	1306	1980 - 2003	13.90%	13.90%

Name	Type	Elevation	Duration	MD_1	MD_2
Hare	River	1186	1980 - 2003	8.70%	8.70%
Kola	River	1849	1975 - 2003	4.60%	4.60%
Kulfo	River	1468	1975 - 2003	7.50%	7.50%
L. Abaya_Lantie	Spring	1182	1985 - 2000	4.70%	4.70%
Upper Gel	River	1862	1980 - 2000	8.30%	3.80%
Weira/Bat	River	2188	1993 - 1999	2.40%	2.40%

The monthly average discharge for all river discharge stations were analyzed using compensated data set. The result is shown in Table 7.15 and Figure 7.22.

Table 7.15: Monthly Average Discharge of River Stations in Abaya Lake Basin

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Bedessa	1.8	1.1	1.3	3.2	7	6.8	7.2	6.5	10.6	13.1	7.7	3.3
Bilate_Alabkulito*	2.8	3.4	6.4	14.6	19.8	23.5	38.2	73.1	81.6	52.1	17.4	5
Bilate_Tena*	7.8	8.7	21.9	31.9	46.1	59.8	76.5	81.7	99.5	86.4	20.5	7.1
Gidabo	6.9	5.9	7.7	14.8	26.2	21	21.5	31	33.3	36.8	17.4	9.9
Gombera	0.1	0.1	0.1	0.1	0.4	0.8	1.1	3	2.9	1.1	0.2	0.1
Guder	0.2	0.4	0.8	1.8	3.3	3.3	6	11	8.5	6.6	1	0.3
Hamessa (Humbo)	0.3	0.3	0.2	0.7	1.6	1.8	3.4	4.5	2.7	2	1.3	0.6
Hamessa (Wajifo)	1.4	1.9	2.3	13.6	22.1	15	21.2	26	10.6	10.4	1.4	1.5
Hare	3	2.5	2.8	6.1	11.8	7.2	7.5	8.6	7.7	10.5	5.4	3.7
K.&A.Outl	8.2	15.2	24.1	54.9	94.5	40.9	29.1	42.3	33	57.7	16.1	9.7
Kolla_Aleta	4.2	2.5	2.3	4.9	12.5	12.5	14.6	20.6	16.2	13.4	7.9	5.1
Kulfo	7.1	7	5.4	16.2	25.4	15.6	24.1	20	18.2	24.5	18.7	7.4
Uppesr Gellana	3.5	2.3	2.4	8.4	23.8	16.9	9.4	7.9	12.5	21.3	10.9	4.9
Weira	1.1	1.7	4.3	9.1	18.2	16.6	26.9	52.3	27.8	23.4	5.3	1.1
Average	**3.5**	**3.8**	**5.9**	**12.9**	**22.3**	**17.3**	**20.5**	**27.8**	**26.1**	**25.7**	**9.4**	**4.3**

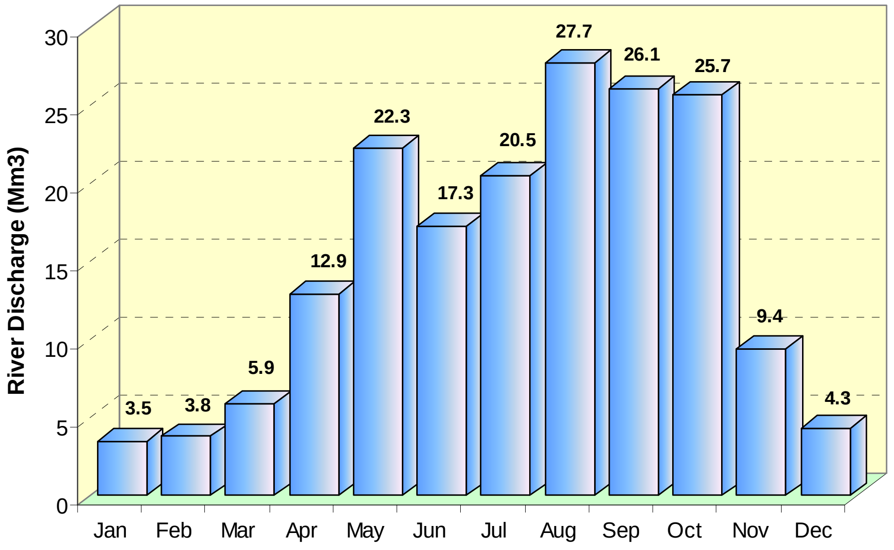


Figure 7.22: Monthly Average River Discharge

According to the precipitation analysis result, there are two seasons in Rift Valley area, dry season from December to February of next year and rainy season from March to November. In dry season, the monthly average precipitation is less than 50mm. this small precipitation is not enough to maintain the river discharge, so the river discharge in dry season should be considered as the base flow. That is, it is being recharged from groundwater water. The average monthly discharge of all the analyzed river stations for the months of December to February is 3.87Mm^3.

The topography in the target basin and in the entire Rift Valley area, is characterized by its large variation as mentioned before. Rivers in the area of this intensive relief generally flow on the bottom of valley to be recharged by groundwater in both sides of the valley. Therefore, the river flow can be maintained even in the dry season. And also the river is getting groundwater recharge in all seasons. If the groundwater recharge to rivers is considered in more detail, it is easy to suppose that the recharge amount in the rainy season is more than that in dry season, because compared with the river water level fluctuation, groundwater level fluctuation is generally bigger in different season.

There is no groundwater level observation data to understand groundwater level change in dry and rainy seasons, so it is impossible to calculate the increased amount of groundwater recharge to rivers. Then the base flow analysis result (refer to Table 7.15 and Figure 7.22), based on the average monthly discharge from December to February, was taken as the constant value for yearly groundwater recharge to the rivers. Since the base flow is sustained all round a year, the total annual amount of average groundwater recharge was calculated. The equation is given below:

$$\text{Monthly average base flow } (3.87\ \text{Mm}^3) \times \text{Number of months } (12)$$

$$= 46.4\ (\text{Mm}^3/\text{year})$$

The yearly groundwater recharge to the river discharge can be obtained from the result of the above equation, to be 46.4(Mm^3/year). Then, the ratio of groundwater recharge to the total river discharge can be calculated as below:

Yearly average base flow amount (46.4 Mm^3) / Yearly average river discharge (179.5 Mm^3) ＝ 25. 8％

b. Groundwater recharge analysis

In the closed basin of Abaya Lake basin, the water resources recharge amount equals to water resources consumption amount in a long hydrologic period. The water resources consumption includes different components such as evaporation from water surfaces of lakes and rivers, evaporation from irrigation water and other water use. On the other hand, the water resources recharge is all provided from precipitation, but being separated into two components:

1) Recharge to groundwater (base flow and directly flow to Abaya Lake)
2) Recharge to rivers (Run off)

The ratio of base flow and run off has been analyzed above, then the only unclear component is the direct groundwater flow from mountain area to plain area, and finally to the lake. This amount can be considered very small because the hydraulic gradient is estimated as very small in the plain area between mountains and Abaya Lake.

If the groundwater level observation data exists, the groundwater flow can be calculated by Darcy Law as:

$$Q = A \times i \times K$$

Here:

Q : Groundwater flow amount.

A: Cross-sectional area of flow

I : Hydraulic gradient

K: Hydraulic conductivity.

Because the plain area between Abaya Lake and surrounding mountains is flat and the hydraulic gradient is generally gentler than the ground surface, the hydraulic gradient can be considered small. Then the groundwater flow into Abaya Lake is also smaller.

If the groundwater directly flowing into Abaya Lake can be considered very small, then the recharge to groundwater can be considered as approximately equal to the base flow amount.

Then, the groundwater flow amount can be calculated by the equation below:

Total water resources consumption amount (1117.8 Mm^3/year) ×

Ratio of base flow in total river discharge (25.8％)

= 289. 2 (Mm^3/year)

To convert the unit of groundwater recharge to mm/year, the area of the Abaya Lake basin can be used as follows:

Groundwater recharge amount (289.2Mm^3) / Total area of Abaya Lake basin (16,298km^2)

＝ 17. 7 (mm/year)

Because neither groundwater nor rivers can receive recharge from precipitation in lake body area, the average groundwater recharge amount can be recalculated by excluding the area of the lake from the total area of the basin as follows:

Groundwater recharge amount (289.2 Mm^3) /

Area of Abaya Lake basin except for Abaya Lake water surface area (15,203 km^2)

＝ 19. 02 (mm/year)

b.1 Spring discharge analysis

As shown in Table 7.16, 2 of the 16 river discharge observation stations actually observe spring discharge. Since the flow from springs are 100% from groundwater recharge, these two spring stations can be used to verify and modify the calculated groundwater recharge through water balance analysis.

Figure 7.23 shows the monthly average discharges and their fluctuation for the two spring discharge observation stations of 40 spring and L. Abaya_Lantie.

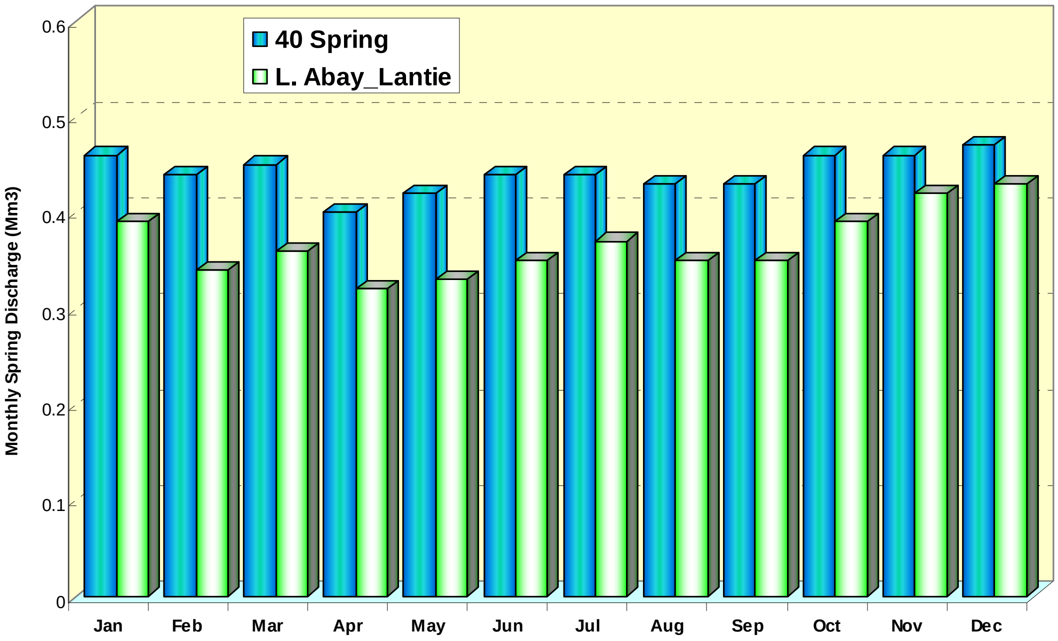


Figure 7.23: Monthly Average of Spring Discharge form Two Stations.

When compared with the fluctuation of discharge for rivers shown in Figure 7.23, the pattern of fluctuation is thoroughly different. The reason is clear, as mentioned above, that the majority (74%) of river discharge is from runoff and all the spring discharge is from groundwater.

Table 7.16: Stability Analysis of Spring Discharge

Station	Minimum	Month	Maximum	Month	Average
40 Spring	0. 4	Apr.	0. 47	Dec	0. 44
L. Abay_Lantie	0. 32	Apr.	0. 43	Dec	0. 37

Unit: Mm^3

Discharge from springs is very stable, with only 10% (40 Spring station) and 15% (L. Abaya_Latien) difference between the maximum and minimum values. Compared with the river discharge with the maximum value appearing in August, the maximum value in spring discharge stations occur in December. Form the hydrogeological viewpoint, the change of spring's discharge depends on groundwater level in the recharge area of the spring. The groundwater level in the recharge area of the spring's should follow the fluctuation of precipitation. That is, it should be higher in rainy season and lower in dry season. Then, the fact that maximum discharge occurs in April, the end of the dry season, in both springs are difficult to comprehend. This fact is difficult to explain within the framework of hydrogeological common sense and mechanism of groundwater flow. Since the difference is quite small, as mentioned above, the analysis can be continued without dealing with this matter now. After the accumulation of information about the groundwater in this area in future, a proper reason may be sought after.

Before estimating groundwater recharge amount in the recharge area corresponding to the location of spring discharge observation stations, the delineation of recharge area boundary has to be conducted. In the same way as in the basin boundary delineation for Abaya Lake basin and Bilate River basins, SRTM (90m mesh DEM) and hydrology function of a GIS program were used for the boundary delineation. The result is shown in Figure 7.24.

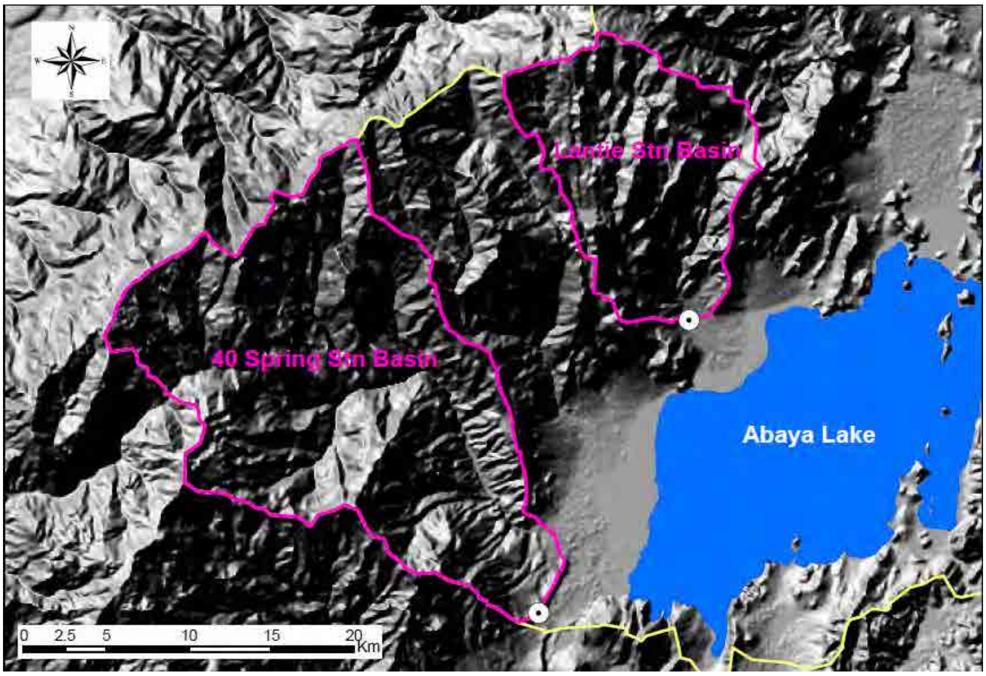


Figure 7.24: Spring Discharge Observation Stations and Corresponding Recharge Area

Before spring discharge analysis, it may be necessary to know the mechanism of springs. Most springs occur somewhere near the borders of mountains and plains. Groundwater flows from high places to lower places in mountain areas. Generally groundwater level is deep from ground surface. When groundwater flows to somewhere near the plain area, the groundwater level becomes shallower. On the other hand, if the aquifer with big enough permeability can continue in the plain area, no spring will occur, all groundwater will go down into the ground until it reaches the lakes. However, if the aquifer is poor with very lower permeability (very small K value shown in the previous equation - Darcy's Law), groundwater flow will become very slow. Another case could be a fault exists along the border of mountain and plain areas. Anyhow, if the groundwater flow amount reaching the lower part, that is plain part, is smaller than groundwater flow amount from upper mountain side, groundwater will accumulate near the border. Groundwater level will then go up, even equaling or a little over ground surface to emerge as a spring.

Because geologically there are no aquifers or fault zones that are completely impermeable, having a spring at a site does not mean that no groundwater will flow further down to the plain area or even into the lake body. Thus, the discharge amount is controlled not only by the extent of recharge area, but also by the aquifer or fault's permeability.

Based on the above mentioned mechanism of spring occurrence, discharge from the two spring stations were analyzed and the result is summarized in Table 7.17.

Table 7.17: Groundwater Recharge Analysis by the Spring Discharge

Station	Basin_area	A_Dishcharge	D_Average
40 Spring	394. 6	5. 3	13, 431. 3
L. Abay_Lantie	169. 9	4. 4	25, 897. 6

Basin_area (km^2) : Area of the basins (refer to the Figure 7.24)
A_Dishcharge (Mm^3/Year) : Annual discharge (refer to the Figure 7.24).
D_Average (m^3/Km^2/year) : Average discharge.

As shown in Table 7.17, the difference in average discharge between the two springs is about 100%. The reason can be considered as follows:

1) The permeability of aquifer or fault zone that makes the spring appear is different
2) There are some rivers within the recharge area of the spring and the base flow to the rivers is different.
3) The spring side of 40 springs, which has smaller average discharge amount, exists under a cliff area and as given by the name 40 springs are distributed there. However, the discharge is not measured from all the 40 springs.

Therefore, the value from the station of 40 springs can be considered smaller than the real groundwater recharge amount. Then the value from the station of L. Abaya_Lantie can be considered to be better for groundwater recharge amount evaluation. Using the analysis result from the station of L. Abaya_Lantie, the yearly average recharge (mm/year) can be calculated by the equation below:

Yearly average groundwater recharge amount (mm/year)

= Yearly average groundwater recharge (25, 897 m^3/km^2/year)

/ Recharge area (169.9 km^2)

= 25.9 mm/year

If this value (25.9mm/year) is compared with the result of water resources balance analysis for the whole Abaya Lake basin area (17.7mm / year) or for the area except lake water surface area (19.02mm/year), the value from spring analysis is bigger.

The reason can be considered as follows:

When river discharge was separated into base flow and run off, the value of base flow was determined based on the dry season when the groundwater level is lowest in a year. Actually in the rainy season, groundwater level will increase much more than river water level as the result of percolation of precipitation. Then the base flow should be bigger than in the dry season. That is, the result from the water balance method should be considered as the lowest limit value of groundwater recharge.

c. Adopted groundwater recharge value

In spite of limited availability of data, all possible measures such as data verification and data compensation were undertaken to improve the reliability and accuracy of the data. The arranged data was used for groundwater recharge amount analysis by the two different methods.

The analysis produced the two values of 19.02mm/year (from water balance analysis method) and 25.9mm/year (from spring discharge analysis method).

The water balance analysis was conducted by taking the whole Abaya Lake basin as the target area, and using the data from as many stations as possible. Therefore, the result can be considered to be the representative of the generally features of the whole basin, and the effect of missing record or input mistake from some stations is expected to be reduced. But the dry season average base flow amount was used for river discharge components separation. This base flow value specification may have caused the groundwater recharge amount result to be smaller than the real value.

The spring analysis method was conducted using two sets of spring discharge data. The stability of the data indicates relatively high reliability of the data. However, the area of analysis is only about 1% of the entire target area. As mentioned in the beginning of this chapter and as explained in the process of water balance analysis, the topographic, geological conditions, climate condition and some other conditions change significantly in the target. Thus it is difficult to consider that the result is suitable for the whole target area.

In fact, there is no way to logically balance the advantages and disadvantages of results from different analysis methods. Therefore, the simple way of taking an average of the two analysis results was used to determine the groundwater recharge value for adoption. The groundwater recharge amount for the Abaya Lake basin is calculated below:

(19.02mm/year + 25.9mm/year) / 2 = 22.46 mm/year

As described above, there is a possibility of underestimating the groundwater recharge using either water resource balance method or spring discharge method. Therefore, when this value is used in the groundwater simulation model and then for evaluation of water resources in the development plan, the risk of overestimating the groundwater potential will be small.

7.5 Groundwater simulation model (Bilate River sub-basin)

This is the first groundwater simulation model of the four models planned to be prepared in this study. As described above, the model area was selected in consideration of all the various factors together, such as extent of model domain, available data, and priority area for the future groundwater development plan formulation. The model area is Bilate River basin located in the northern part of the Abaya Lake basin and central part of Rift Valley Lakes Basin.

Groundwater recharge amount is one of the indispensable parameters, and has been calculated in the previous sections using all available methods.

Many other parameters or conditions are also necessary to construct the model. This will be described in the following sections.

7.5.1 Model domain and grid specification

As shown in Figure 7.25, the model domain covers the whole Bilate River basin. The spatial extent of the domain is as follows:

- Projection: Adinda UTM zone 37N
- Easting: 355000 - 429000 (74km)
- Northing: 719000 – 903000 (184km)

The area of the model domain is a little smaller than the Abaya Lake basin:

74km(east-west) × 184km (north - south)＝ 13,616 km^2

The model domain covers not only Bilate River basin, but also some area outside the Rift Valley Lakes Basin (northern west), and area outside of Abaya Lake basin (northern east). Within Abaya Lake basin, the model domain covers some small river basins other than Bilate River basin. These are Amesa River basin (southern west) and Gidabo River basin (southern east).

The model is created using the world famous groundwater simulation program, MODFLOW. It was developed by the U. S. Geological Survey (USGS) and the source code can be freely downloaded from the USGS website. Modflow employs the finite difference method for numerical solution. This method requires specifying the model domain as a rectangle shape, then dividing the domain into small rectangle shape cells. Cells in the model are specified as square shape with the length of each side to be 1 km (1000m). Therefore, the number of cells is 74 in west – east direction and 184 in north – south direction. The total number of cells is 13,616, being the same as the model domain area in km^2.

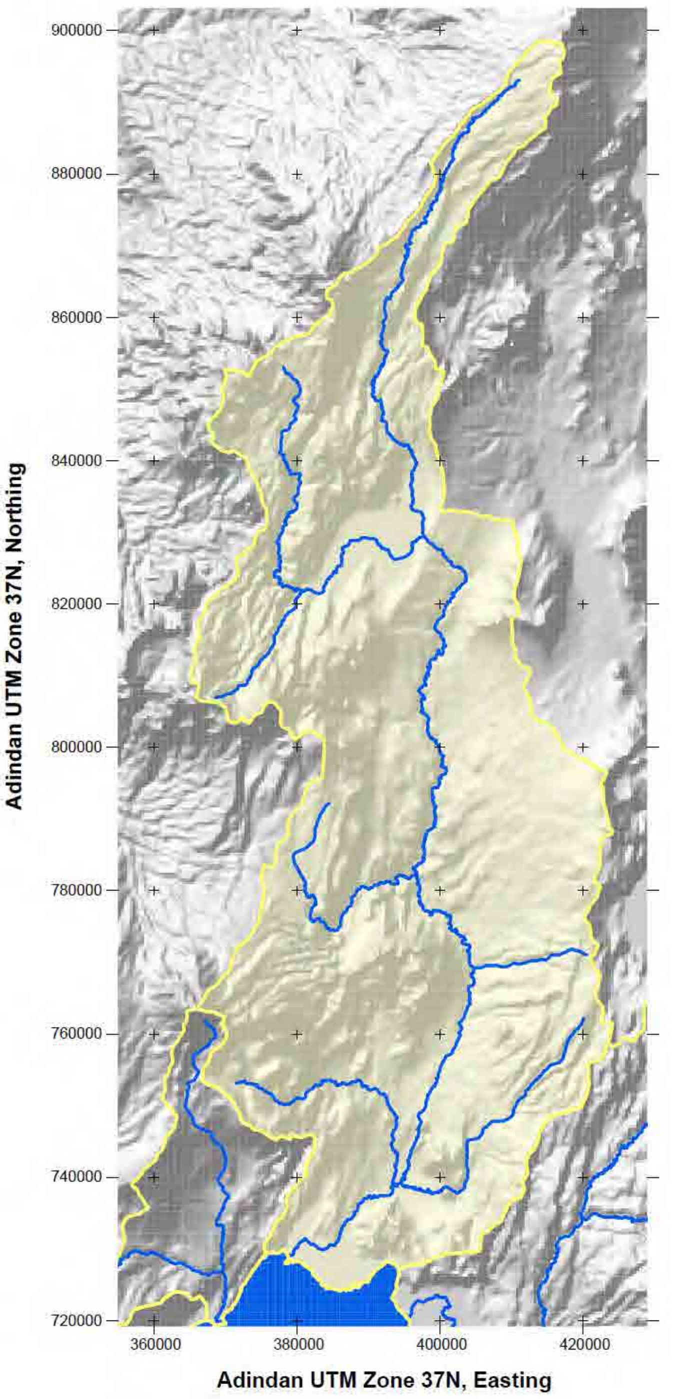
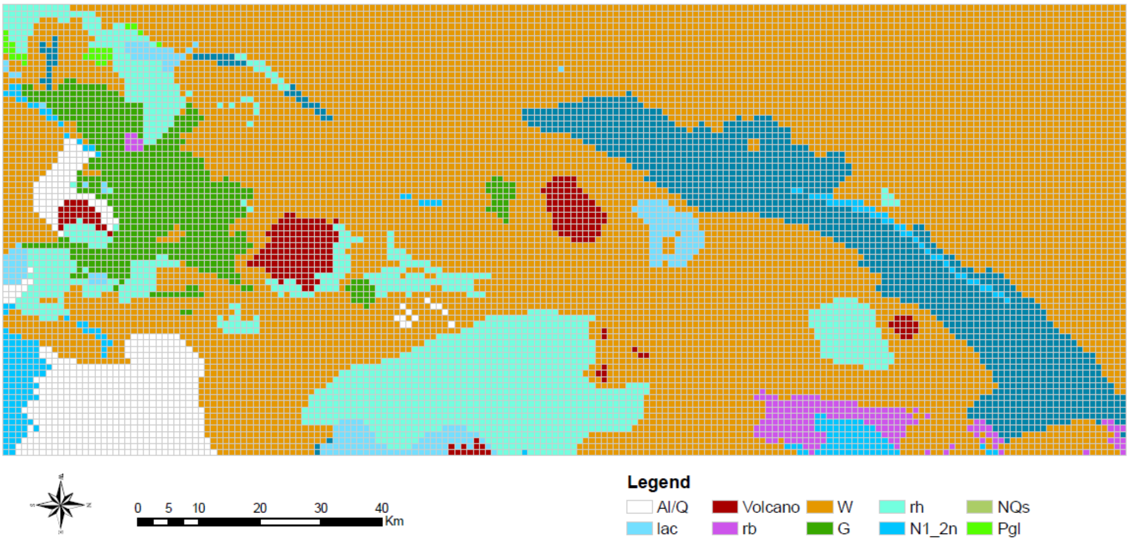


Figure 7.25: Bilate River Basin and GWM Domain.

a. Aquifer classification

Six model layers were specified in the model based on the eight geological profiles (Refer to the part of Geology) created by a member responsible for geological survey in the Study Team, The top of the first layer is the ground surface and bottom of the last layer is set to at the elevation of 700 m (mamsl). Layer1 to layer5 correspond to different types of geological strata and the last layer (layer6) corresponds to the basement rock as an aquiclude.

As shown in Figure 7.26, because of the very complex geological condition, it is impossible to specify same type of aquifer(s) into the same model layer. Thus, all layers except layer 6 have to be defined as corresponding to different types of aquifers.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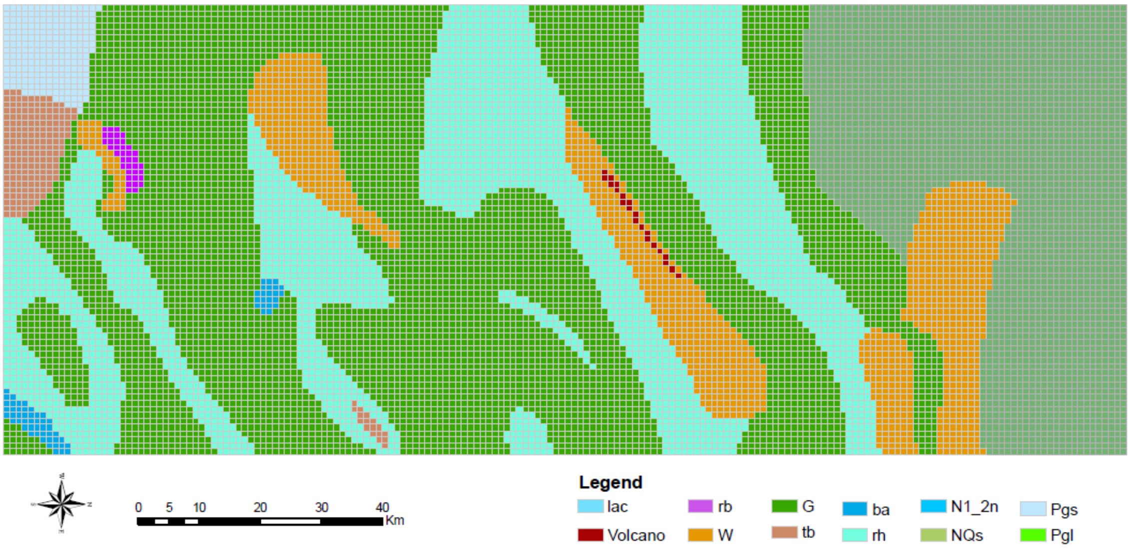
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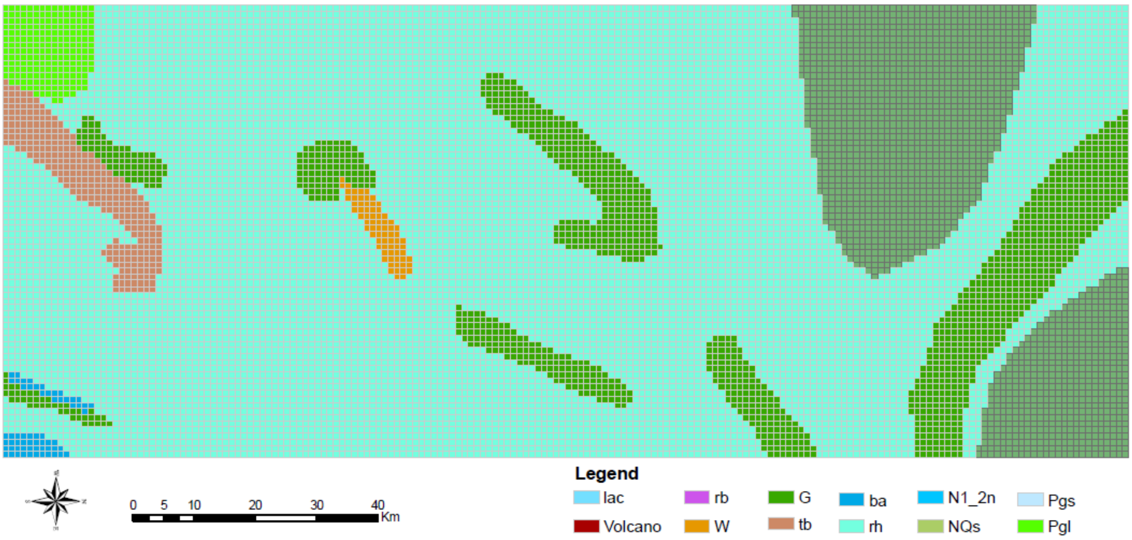
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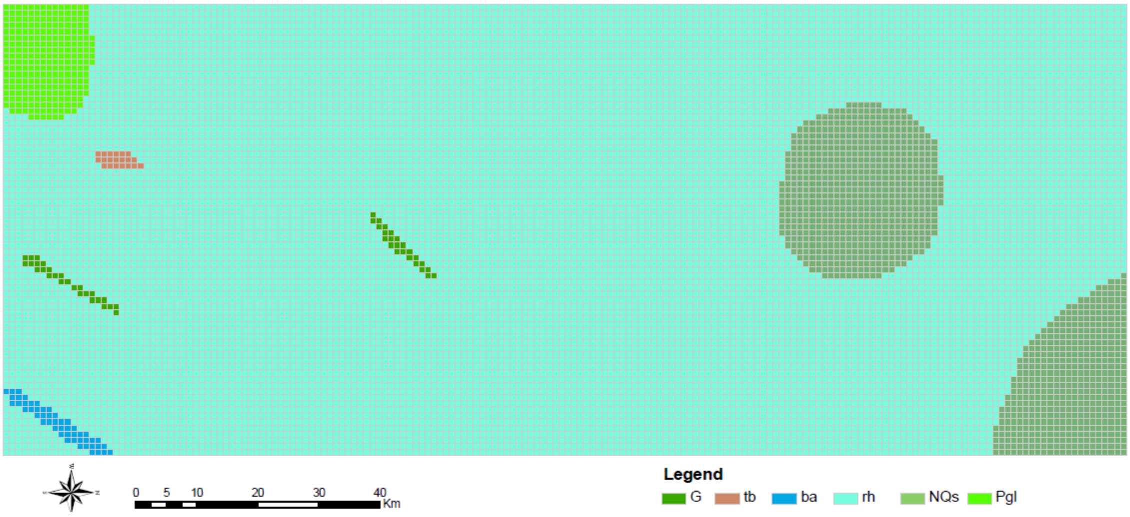


Figure 7.26: Aquifer Specification in Model Layers (in creation)(1&2 layers, 3 layer, 4 Layer, 5 layer from upper part)

b. Layer Thickness Specification

The same data set (SRTM: 90 m mesh DEM from USNASA) used for basins boundary delineation was used to specify the elevation of the top of layer1. Top elevation specification for other layers was basically followed the geological profiles in consideration of the continuity of the model layers. Figure 7.27 and Figure 7.28 shows two main vertical sections in the model in west − east direction (row 87) and north − south direction (column 37), respectively.

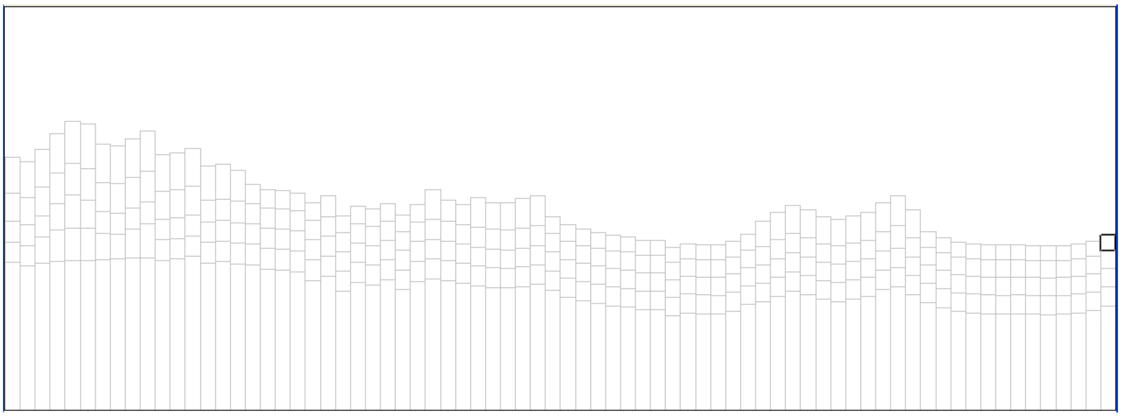


Figure 7.27: Cross Section of Layer Specification (Row 87)

Scale: Vertical : Horizontal = 1: 15

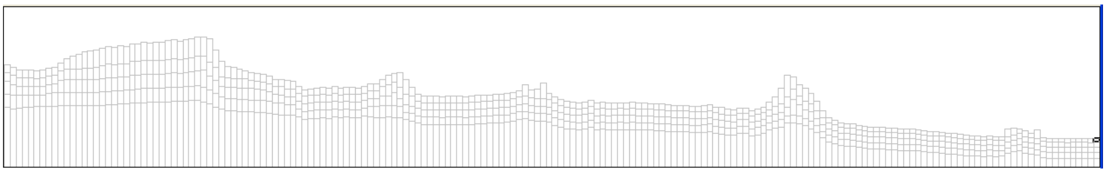


Figure 7.28: Vertical Section of Layer Specification (Column37)

Scale: Vertical : Horizontal = 1: 15

c. Boundary condition specification

c.1 Constant head boundary cell

As shown in Figure 7.26, the most important boundary condition in the Bilate River basin groundwater simulation model is surface water bodies of main rivers and the lakes. If all rivers and lakes are taken into consideration, majority of cells in layer 1 will be specified as constant head boundary and that will only few cells for calculation. Therefore, only the main rivers and Abaya Lake were specified as constant head boundary. The surface water features and cells specified as constant head boundary are shown together in Figure 7.29.

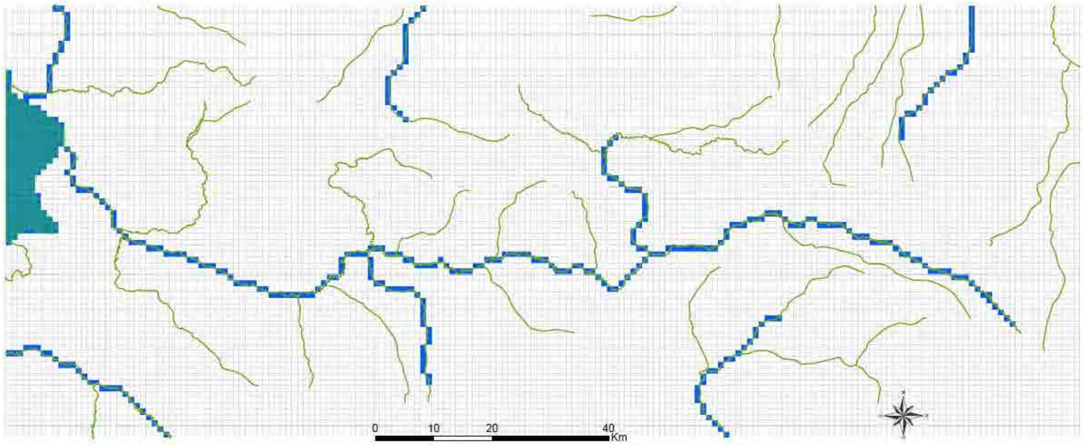


Figure 7.29: Surface Water Features and Constatnt Head BoundaryCells

Layer Separation for Constant Head Boundary Cell and Thickness Adjustment Figure 7.30 shows 2 dimentional specification of constant head boundaries in plan view. On the other hand, in cross section, the thickness of the layers range from tens of meters to over 100 m while the rivers and lakes have much smaller thickness in comparison. If the constant boundary is set to the cells in layer 1, the whole thickness of the cell will have to have constand values of water heads, which is not realistic. Therefore, layer 1 was separated into 2 layers, layer 1 and layer 2. these two layers have attribution to the same geological features (aquifers) and the bottom elevation of the newly created layer2 was set at layer1 in the geological profile. The purpose of separating the layer1 in geological profile into two model lyaers is simply to specify constant head boundary conditions in a more realistic manner. The thickness specification criterion for layer1 in the model is as follows:

- Constant head boundary cells : 20m
- All other cells : from ground surface to 10m above the bottom of layer2.(variable)

One example of layer 1 and 2 specificaiton is shown in Figure 7.30.

c.2 Water level specification in constatnt head boundary cells

Specification of water levels for constant head boundary cells in Abaya Lake area: water levels in cells covering Abaya Lake was specified at 1200m, because the highest elevation of central point of cells within the Aaya Lake area is 1198 (mamsl).

Specificatiiin of water levels for constant head boundary in river cells: water levels was basically specified at 10m lower than the central point elevation in each cell. In case downstream water level becomes higher than the water level upstream, the water level was adjusted to make the downstream one lower by at least 0.5m.

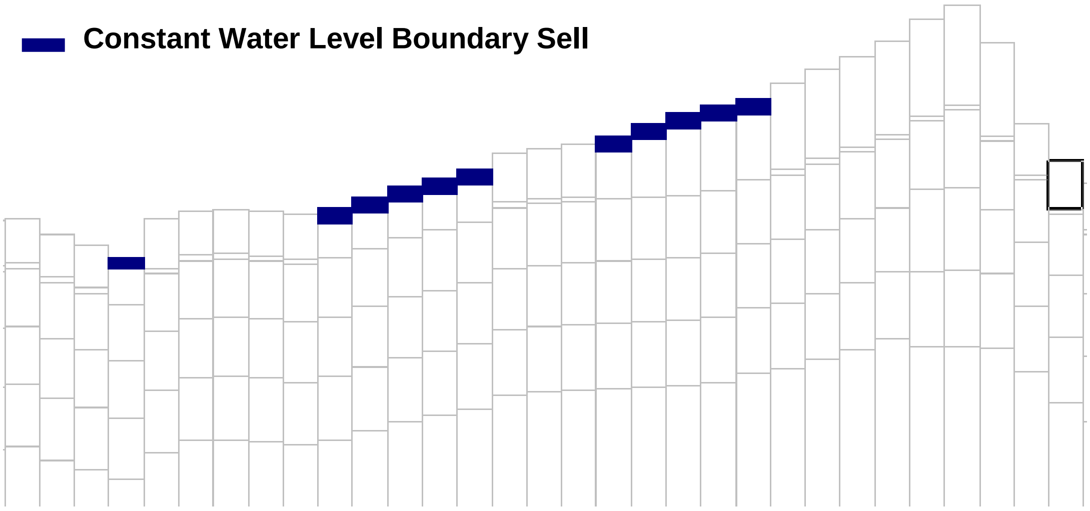


Figure 7.30: Layer Separation for Constant Head Boundary Cell and Thickness Adjustment.

(Row: 113; Column: 41 to 72)

c.3 Layer property

Layer 1: Unconfined aquifer

Layer 2: − layer 6: Confined aquifer

7.5.2 Parameter specification

a. Hydraulic conductivity

a.1 Horizontal hydraulic conductivity

Specification of hydraulilc conductivity values is essential for groundwater simulation model creation. However, there was no information on this parameter in Rift Valley basin before this survey. Of 3,078 wells in the well database, only JICA wells have the values of hydraulilc conductivity. On the other hand from the well database, all the wells that have some relevant information about aquifer parameter are summarized in Table 7.18.

Table 7.18: Summarizing of Aquifer Information from Wells in Rift Valley

Parameter	Number of data	Range	Average
Depth (m)	1322	2 - 305	54.1
Q (l/sec)	473	0.01 - 47	2.9
SWL (m)	190	0 - 344	29.7
DWL (m)	67	0.02 - 263	57.8
TDD (m)	48	0 - 120	21.6
T (m^2/day)	22	2. 5 - 3801	535.4
T_Screen_length (m)	241	2.8 - 62.8	18.5
Aquifer Type	81	-	-

Within the Rift Valley well database, the closest information to hydrolic conductivity is T (Transmissibility). Only 22 of 3,078 wells in the database have T values. In any case, these information are the most commonly available data in the database to be used for hydraulic conductivity specification. Thus, these information was taken as the basis for hydraulilc conductivity specification in the model.

In the geological map of the Rift Valley, geological features are classified into about 50 types. This number is more than those of available well data. If the aquifer type is specified according to the geological classification, most of aquifers in the model will not have any hydrologic conductivity values due to shortage of values. Therefore, the aquifer type in the model was specified by combining the similar aquifer types of the geological classification. And the combination is based on the criteria of both lithology and geologic age. The aquifer combination resulted in 12 aquifer types as shown in Table 7.19.

Table 7.19: Specified Aquifer Types in the Model

Layer_1&2	Layer_3	Layer_4	Layer_5
Al/Q			
lac			
N1_2n			
Volcano	Volcano		
rb	rb		
W	W	W	
	tb	tb	tb
	ba	ba	ba
Ngs	Ngs	Ngs	Ngs
Pgl	Pgl	Pgl	Pgl
G	G	G	G
rh	rh	rh	rh

Even though the geological features have been combined and specified into the model, as shown in Table 7.20, the same aquifer may have different thickness and different Transmissibility in diffeeerent locations. Such variations generally make the model hard to converge. Then more time will have to be spent to conduct a very intensive calibratioin.

If sufficient aquifer parameter informtion was obtained in the model area, it would be possible to reduce time for model calibratioin. Not only the parameter for different type aquifers, but also the aquifer information for the same aquifer but in different locations are desired. However, as mentioned above, only 22 wells have aquifer parameter information.

The most viable way to specify the aquifer parameter is using average values for main aquifer types to specifing the initial aquifer parameter values. The lithofacies corresponding to all aquifer types specified in the model and the aquifer parameter informtion (T) are summarizaed in Table 7.20.

Table 7.20: Specification of Aquifer Parameter in the Model

Symbol	**Main Lithofacies**	**Transmissibility（m2/day）**	**Initial_specification（m2/day）**
AL/Q	Fine sand or mud	90.2 - 388	248
Lac	Lacustrine sediment	10 - 2080	1,081
N1_2n	Rhyolite	2.5 - 376.5	190
Volcano	Volcanics	1980 - 3801	2,891
rb	basalt	64 - 79	72
W	Volcanics & sedimentary rocks	2 - 3801	1,907
Tb	Scoria	158.7	158.7
Ba	Basalt	64 - 79	72
Ngs	Basalt	64 - 79	72
Pgl	Basalt	64 - 79	72
G	Welded tuff	12.5 - 914	52
Rh	Rhyolite	2.5 - 376.5	190

The aquifer parameter speciffication given in Table 7.20 is only for layer1 to layer 5. the layer 6 that corrsponds to the basement rock, was given a very small hydaulic conductivity value of 1E-8 m/day for all cells.

a.2 Vertical hydraulic conductivity

It has been shown in the groundwater level observation result of the observation wells drilled in this survey, that the water in wells with screens installed at about 100m depth do not show any response to precipitation and evaporation. This indicates that the aquifer neither get recharged directly from rainfall, nor consumption from evaporation. The aquifers at that depth are very strongly confined aquifers. Therefore, the initial vertical hydraulic conductivity for layer1 to layer 5 was specified as 1E-3 m/day. Layer 6, which corresponds to the basement rock, was given the same value as horizontal hydraulic conductivity 1E-8 m/day all cells.

b. Effective porosity

Effective porosity was set as 0.1 uniformly to all layers.

c. Other parameters

Most variables for model specification, such as groundwater recharge amount as described above and withdrawal amount of wells that will be described later, were calculated using average values of all relative factors. Therefore, the data is not enough to set variables for different years or different months. On the other hand, one main purpose of this modeling, the first one of the four models planned in this study, is to confirm the process of analysis of relevant factor’s to obtain necessary variables for model specification. Then, the steady state modeling was selected as the model calculation method this time.

When steady state flow as the calculation method is employed, several parameters such as Specific Storage, Storage Coefficient, and Specific Yield are not necessary to be specified.

Then those parameter's specifications remain to be analyzed and specified to when the model is used for groundwater prediction.

7.5.3 MODFLOW packages

Not only parameters, but also various kinds of packages are necessary for groundwater simulation by the program of MODFLOW.

a. GHB package

In MODFLOW program, the frame (perimeter cells) of model domain is automatically specified as impermeable boundary. If a cell on the model frame just happens to fall on the basin boundary, the groundwater flow within the cell will be very small, and there will not be any problem if they remain impermeable. However, if the cells on the model frame do not correspond to the basin boundary, the groundwater will not be able to flow across the model frame. This condition, therefore, is expected to cause some errors in model calibration.

To prevent this kind of error, the GHD (General Head Boundary) package has been developed and the package is used in this model. Many cells along the model frame were specified GHB boundary except those cells with constant water head boundaries and well cells.

b. Recharge package

The reason that groundwater can continue flowing without causing a cell to be dry in the model is that there is enough groundwater recharge amount. So the groundwater recharge amount specification is indispensible for construction of a proper model. Just for this reason, all available methods were used in groundwater recharge amount analysis as described in the previous sections of this chapter.

Within this model domain, all the groundwater recharge is originated from precipitation and the amount of precipitation is generally different according to the elevation. As a common sense in hydrology, more precipitation usually occurs in high elevation areas. However, the precipitation analysis did not indicate clear relation between the precipitation and the elevation.

Thus the groundwater recharge was specified by the method given below.

1) Calculate the total groundwater recharge amount in the model domain by multiplying the average groundwater recharge amount value obtained through the hydrological analysis in previous sections by the model domain area.

   Average groundwater recharge (22.46 mm/year) × Model domain area 13, 616 (km^2)

   $= 305.8\ Mm^3 / year$

2) Following the basic model unit of day and meter to calculate daily groundwater recharge amount.

   Daily groundwater recharge amount = 305.8 (Mm^3 / year) / 365 (days)

   = 0.84 Mm^3 /day

3) Assign the total daily groundwater recharge to each cell in the model according to the criterion that the groundwater recharge amount in cell is proportional to the elevation of the cell.

Because the recharge can only occur in the top layer that is a unconfined aquifer as being revealed by the water level observation results, all the groundwater recharge is specified on layer1.

Figure 7.31 shows the groundwater recharge specifications in the model.

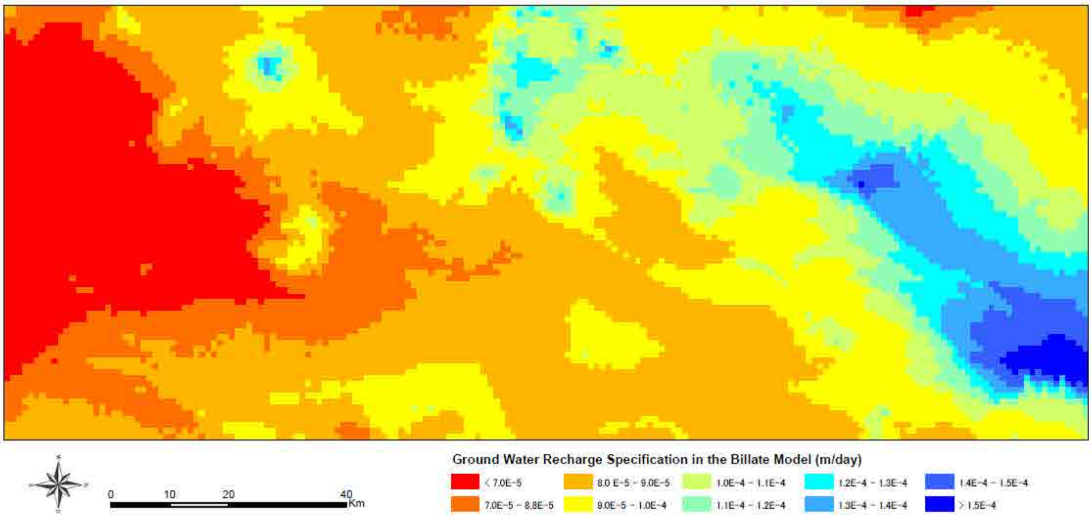


Figure 7.31: Result of Groundwater Recharge Specification

c. Well package

Groundwater is considered as the main water supply source for future water development plan. A lot of wells are used now for groundwater withdrawal. It has been confirmed that 667 wells from well database are distributed in the model domain. The information on those wells is summarized in Table 7.21.

Table 7.21: Information of Wells in the Model Domain

Item	Well Depth	Service Population
Number	425	283
Percent	63.7%	42.4%
Range	2 - 260	63 - 20,000
Average	75.4	1,489

Figure 7.32 shows the distribution of wells in the model domain.

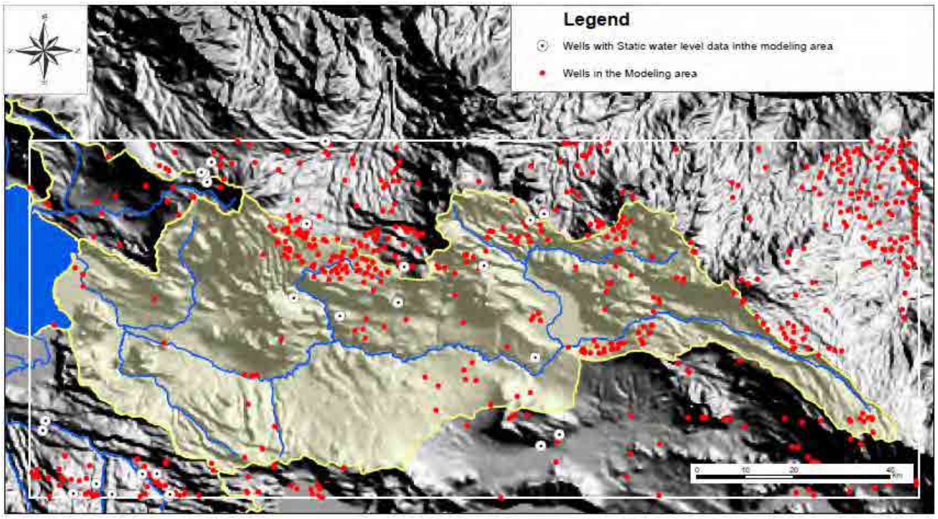


Figure 7.32: Distribution of Wells in Model Domain.

Two kinds of variables are needed to use the well package: well depth and withdrawal amount. To which layer a well should be assigned is based on the well depth and layer thickness. The withdrawal amount is needed to specify the groundwater use in those well cells.

In the well database 425 of the 667 wells have information on well depth. The depth of the wells ranges relatively widely, from 2 to 260m. The deepest wells can penetrate layer 4 in the model. The average well depth was calculated to be 75.4 m. This value was assigned to the remaining 242 wells without depth information.

As describe above, constant head boundary have been specified to the main Abaya Lake area and river area. Single model cell has an area of 1 Km2. according the coordinates information several shallow wells had to be located in constant boundary cells. This kind of well specification is unallowable because the program will be confused if the water level should be kept constant as given by constant head boundary and has to change according to the well withdrawal amount. Therefore, in this case, the shallow wells were specified to the lower layer of layer2. In addition, as described above, if a cell was set as a constant head boundary, the cell thickness would be smaller than other cells, being 20 m thick.

After setting wells to proper layers, it is necessary to set the withdrawal amount for each well. However, there is no information about withdrawal amount for any wells in the study area. On the other hand, as shown in Table 7.22, about 40% of wells (283 of 667) have information of serviced population. Thus this information was taken as the basis for estimation of withdrawal amount. The criteria for withdrawal specification are given in Table 7.22. The criterion setting is based on the estimated unit water use values from Halcrow’s report1).

Table 7.22: Specification of Groundwater Use Amount for Different User Groups

Service Population	Service Unit: ℓ /day/capit
<500	15
500 - 1000	20
1000 - 1500	30
1500 - 2000	40
>2000	50

The groundwater withdrawal amount was assigned to each well cell using the value of served population multiplied by the corresponding service unit given in Table 7.22.

For those wells without service population information, the average values of served population, 1,489 were uniformly assigned and then the corresponding service unit of 30 ℓ/day/capita was used to calculate the withdrawal amount of 44.67m^3/day.

Groundwater withdrawal amount assigned to each layer is summarized in Table 7.23; the number of well cells is also given in the same table.

Table 7.23: Summarizing of Specifications of Well Package

Layer	Layer _1	Layer _2	Layer _3	Layer _4	Total
Number of Cell	489	19	50	14	572
Withdrawal (m3/day)	24, 572	2, 111	5, 693	1, 569	33, 944

Figure 7.33 to Figure 7.36 shows the well package specification in each layer of the model.

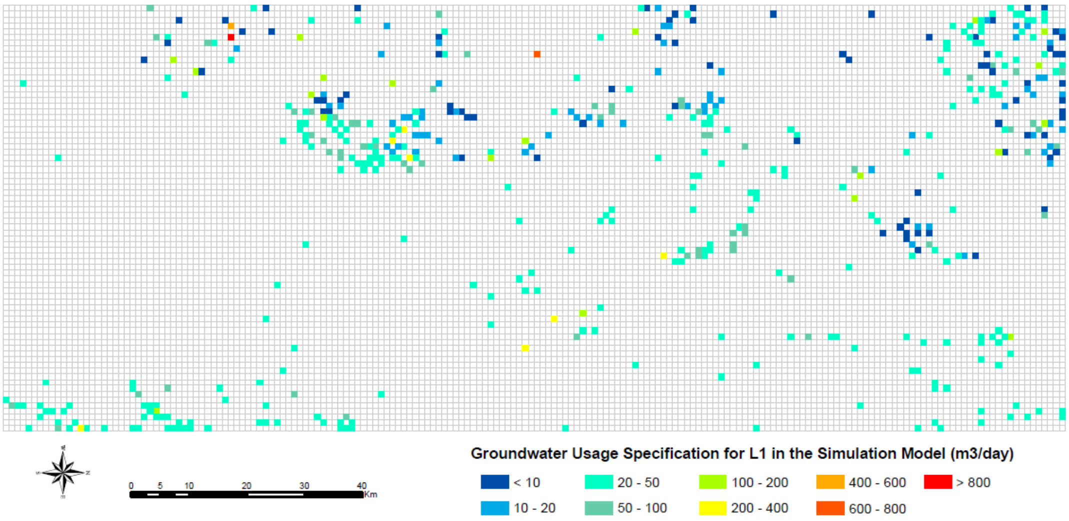


Figure 7.33: Result of Well Package Specification for Layer 1.

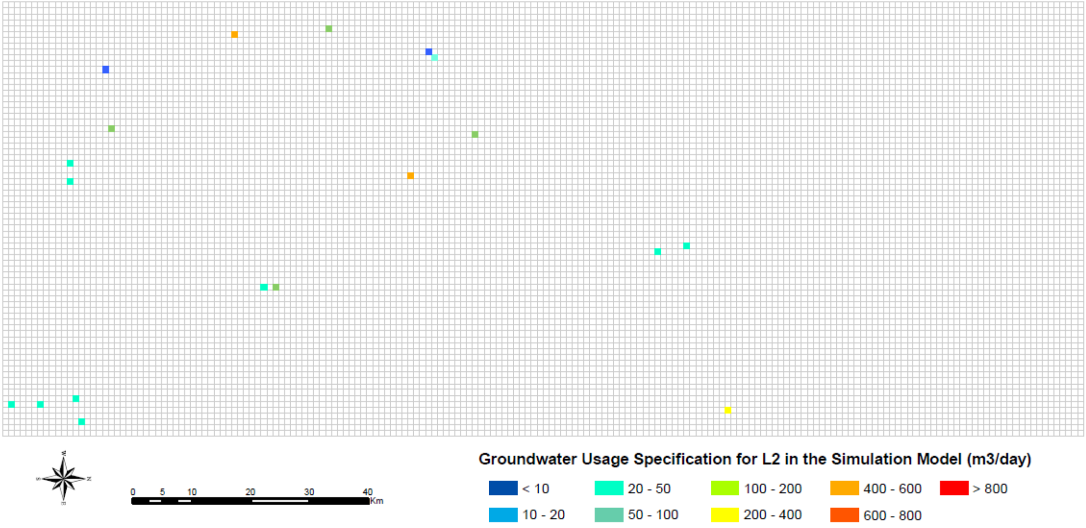


Figure 7.34: Result of Well Package Specification for Layer 2.

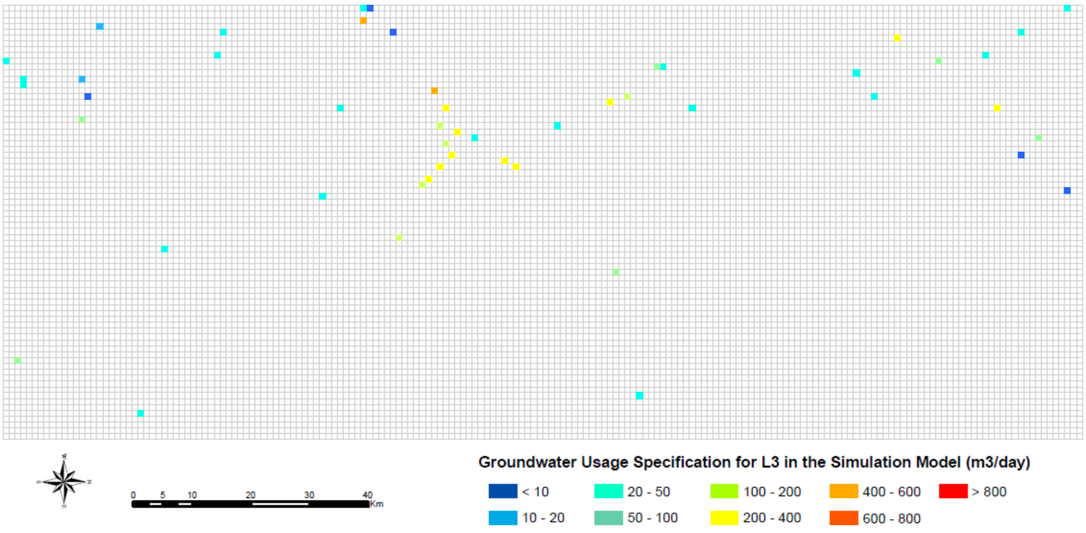


Figure 7.35: Result of Well Package Specification for Layer 3.

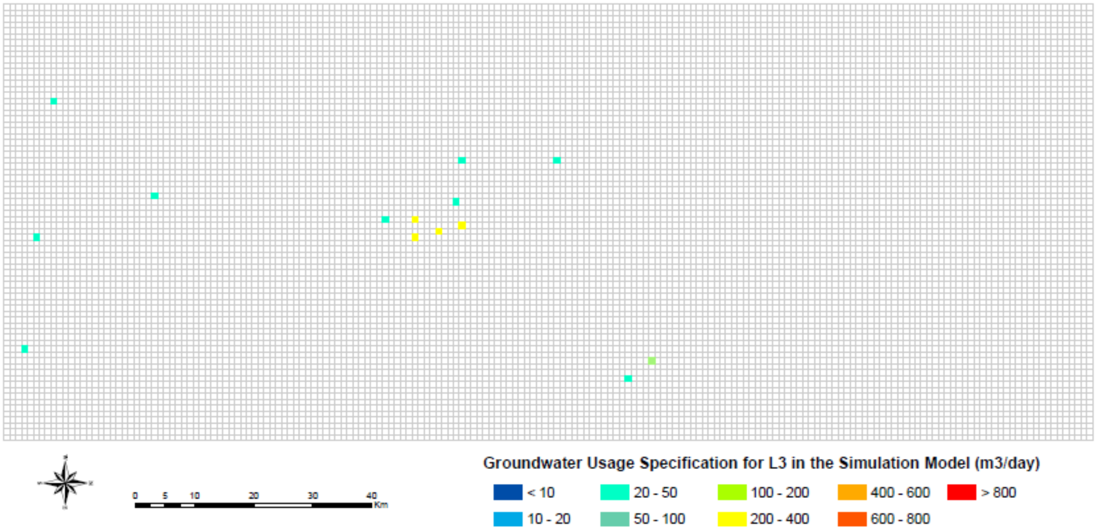


Figure 7.36: Result of Well Package Specification for Layer 4.

7.5.4 Model calibration and result

The steady state flow calculation was used for model calibration this time. Another method of transient flow calculation will be used next time when the model is used for groundwater development plan evaluation. In principle, the two methods of steady state flow and transient flow can be used for model calibration in different visions.

Steady state flow method is compared to a macro-scopic calculation method effective to check the model fitting to a certain degree. Simulation time span for this method is set as infinite to check if water level can stabilize under the conditions of given parameters and specified variables in the model. For steady state flow method, the initial water level specification is not important except those in constant head boundary cells.

Another method of transient flow calculation can be compared to a micro-scopic calculation method, generally used not only for model calibration but also for groundwater evaluation in a limited time span and changing variables such as groundwater recharge amount and withdrawal amount from wells. By the transient flow method the water level in the model domain will change acceding to the specifications of the variables, so that the method can be used to examine if the water level drawdown caused by new pumping wells will stay within an acceptable range. That is, if the groundwater development plan can be ensured for water supply without environmental problems.

As for the model calibration, the most important issue is to check if the model can converge under all specified parameters and variables in different packages. In most cases, if the model does not converge, some problems exist in parameters or variables specification, errors would occur when steady state flow method is used. However, for most cases, even there are some unsuitable specifications in parameters or variables, the error will not occur if the transient flow method is used. Because the transient flow method as mentioned above, is run for a limited time span. So, even some errors exist in parameter setting, it will not be recognized by the program, because the effect of the error will not become big enough in the limited time.

Therefore, the steady flow method is generally used for the first time calibration to check or to ensure the convergence or stability of the model.

In an area with very complex geological condition and hydrogeology condition, like in the modeled area, aquifer parameters may not constant everywhere in the same aquifer, but will change quite large range as shown in Table 7.20, so that the method of specifying same parameter to whole aquifer is surely not fit the natural condition. Then the parameters need to be adjusted cell by cell. For this purpose, a supplementary program is needed and has been created. Even though the calibration can be supported by the supplementary program, still a lone time was taken for over 40 times calibration.

Model calibration result, as shown in Figure 7.37 does not only ensure the convergence of the model but also give the groundwater level distribution in the model area fit the characteristic of reliefs and other conditions.

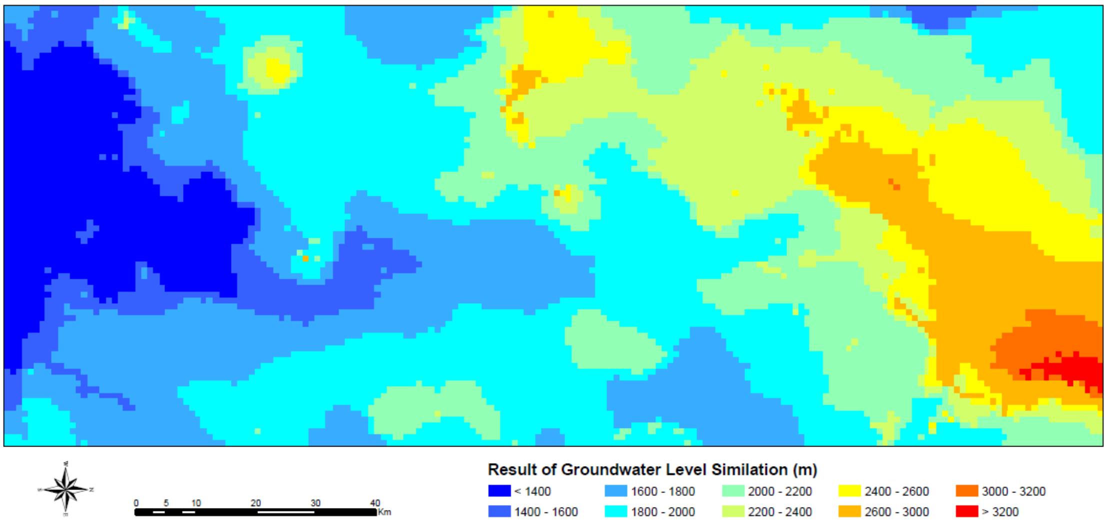


Figure 7.37: Result of Model Simulation Using Steady Flow Method.

7.6 Groundwater simulation model (Ziway-Shalla sub-basin)

The target area of the second groundwater simulation model is set as Ziway-Shalla basin.

7.6.1 Model domain and grid specification

Ziway lake basin includes the surrounding lakes of Langano, Abijata and Shalla. Figure 7.38 shows the topography and Ziway basin boundary.

As shown in Figure 7.39, the model covers the whole Ziway Lake basin with the extent as follows:

- Projection: Adinda UTM zone 37N
- Easting：396000 – 546000 (150km)
- Northing：775000 – 937000 (162km)

The model domain area is:

$$150\text{km(east-west)} \times 162\text{km (north - south)} = 24{,}300\ \text{km}^2$$

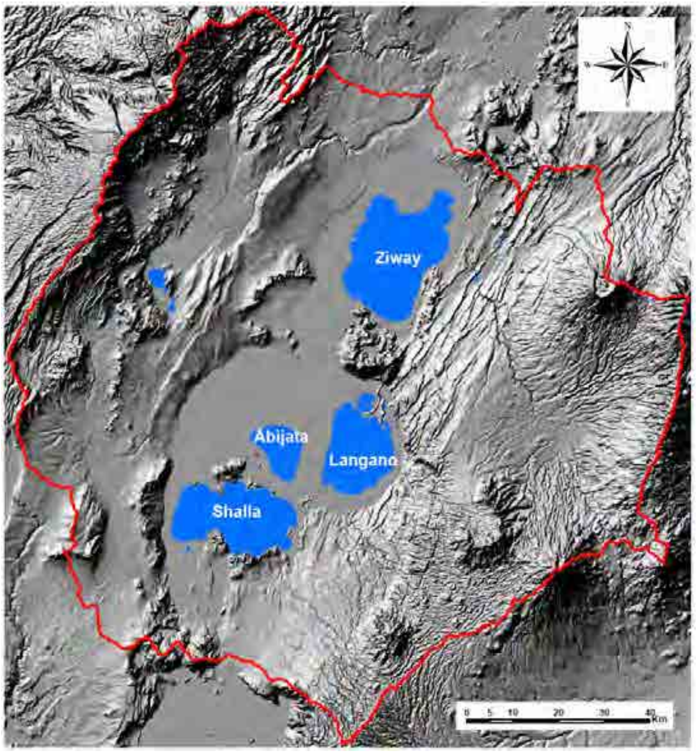


Figure 7.38: Topography and Lake’s Boundary of Ziway-Shalla Area

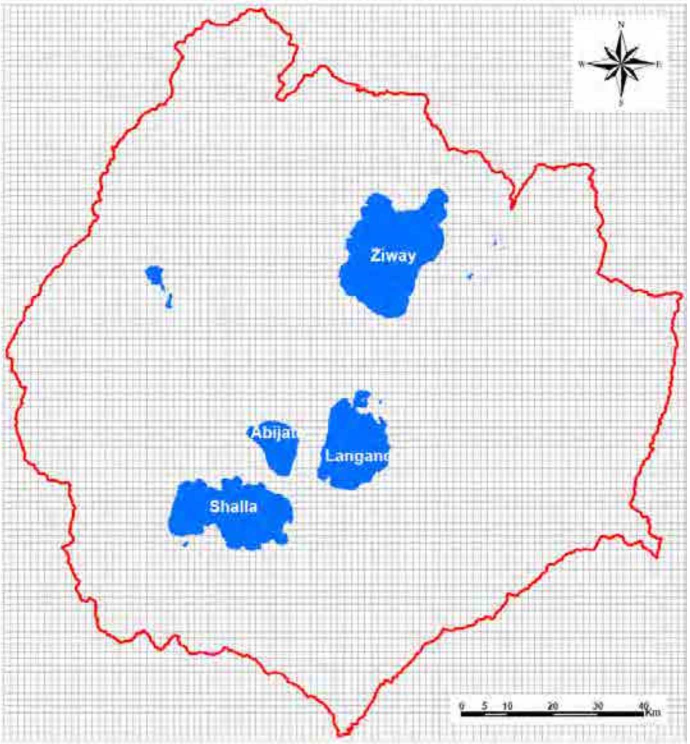


Figure 7.39: Ziway –Shalla sub basin and GWM Domain

The same as model_1 for Billate River basin GWM, the model_2 is created using the most world famous groundwater simulation program, Modflow, which is developed by the U. S. Geological Survey (USGS).

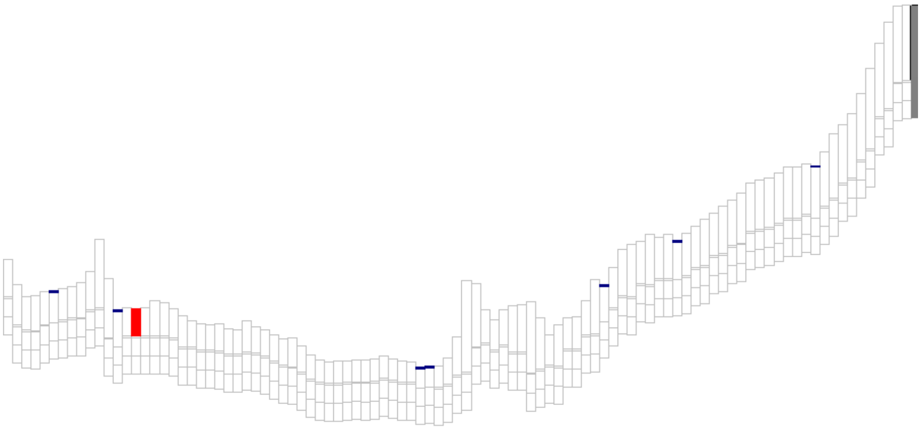
Following the request of the Modflow based groundwater simulation program, the model domain has to be divided into small rectangle grids. Considering the model size and available data for model creation, the girds are specified as square with length of 1.5 km (1500m) on each side. Therefore, the number of grids is 100 in an east – west direction and 108 in a north–south direction. The total number of grids is 10,800.

a. Layer classification

In the vertical direction the model was classified into 4 layers.

The DEM (Digital Elevation Model) of SRTM (Shuttle Radar Topography Mission; USNASA) was used for top elevation specification of layer1 and basins boundary delineation. Top elevation specification for other layers is basically following the geology profiles with the consideration of the continuity of the layer (the same procedure were used for later groundwater models, model_3 and model_4 in eastern and western side of Lake Abaya).

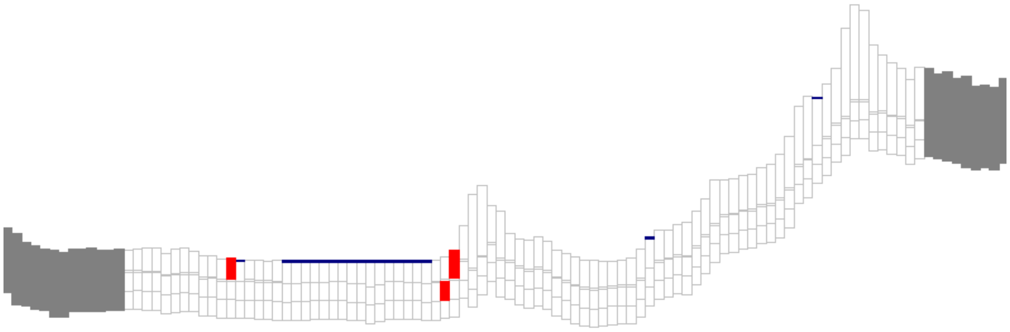
Figure 7.40 and Figure 7.41 show 2 main sections in the Ziway basin model in an east–west direction (51 rows) and a north–south direction (58 columns), respectively.



No color: Active cells; Red color: Well cells; Blue color: Constant head cells; Grey color: Inactive cells

Figure 7.40: Cross Section of Layer Specification (51 rows) in Ziway Basin Model

Scale: Vertical: Horizontal = 1: 30



No color: Active cells; Red color: Well cells; Blue color: Constant head cells; Grey color: Inactive cells

Figure 7.41: Vertical Section of Layer Specification (58 Columns) in Ziway Basin Model

Scale: Vertical: Horizontal = 1: 30

b. Boundary condition specification

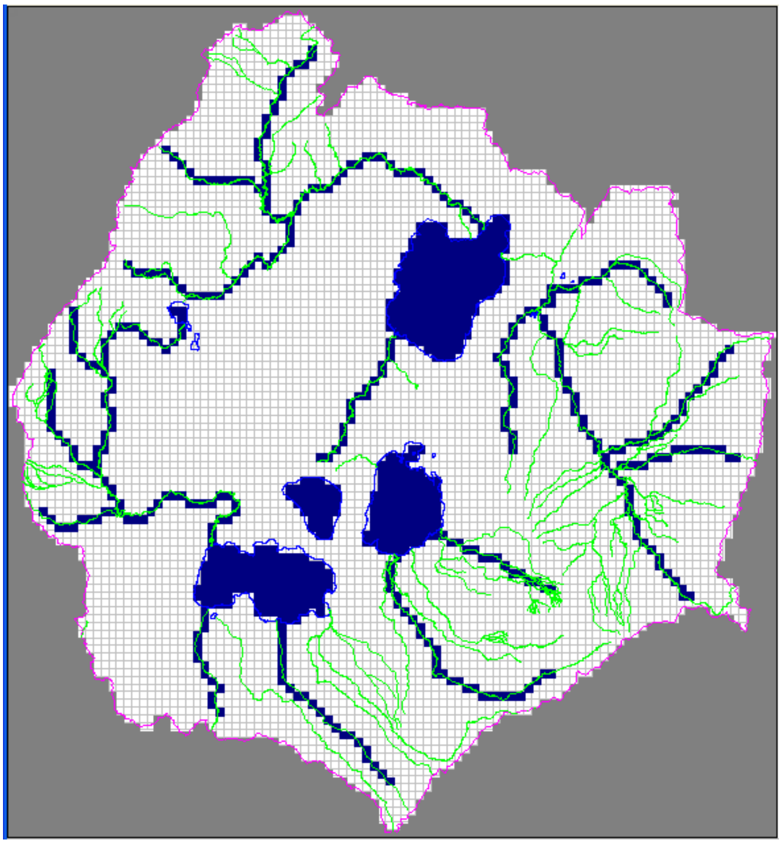
1) Inactive boundary cell

In the Model_1, no inactive boundary cell was set into the model domain. However, the professor Tenalem suggested to set the outside of the lake basin as inacitve boundary cell, following this suggestion, the outside of the Ziway basin were specified as inactive boundary cell. And this kind of specification is also used for all the other models.

2) Constant Head Boundary Cell

Many rivers and lakes distribute in Ziway Lake basin and play a great role for groundwater movement and groundwater level fluactuation. However, if all rivers and lakes are taken into consideration, majority cells in layer 1 will be specified as constant head boundary to make the calculation cells become too few. Therefore, only the main rivers and Lakes were specified as constant head boundary.

The boundary specification for Ziway basin model is shown in Figure 7.42.



Grey color: Inactive cells; Blue color: Constant head cells; No color: Active cells

Figure 7.42: Boundary Specification in Ziway Lake GW Model

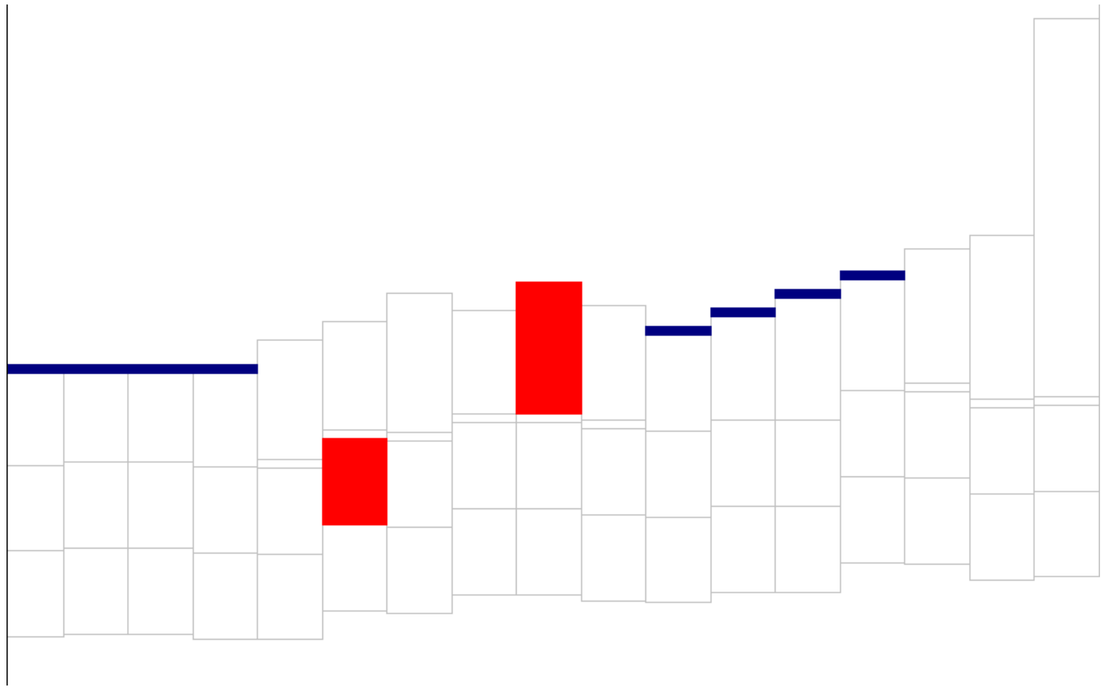
3) Layer Separation for Constant Head Boundary Cell Thickness Adjustment

The main rivers and lakes were specified as constant head boundary, however, considering the thickness of layer, from tens of meters to over 100 m, it will be far different from the natural condition, if the constant boundary is set to the cells in layer 1. Therefore, layer 1 is separated into 2 layers, layer 1 and layer 2.

Layers 1 and 2 have the same correspondation to geology features (aquifers), and the bottom elevation of layer2 is corresponding to layer1 in geology profile. The purpose of separating layer1 in the geology profile into 2 layers in the groundwater simulation model is just for constant head boundary specification. And the thickness specification criterion for layer1 in the model is as follows:

- Constant head boundary cells : 10 m
- All other cells : from ground surface to 10m above the bottom of layer 2.

One example for layer 1 and 2 specificaiton is shown in Figure 7.43.



No color: Active cells; Red color: Well cells; Blue color: Constant head cells

Figure 7.43: Layer Separation for Constant Head Boundary Cell Thickness Adjustment

(Row: 37; Column: 61 to 77)

3) Water Level Specification in Constatnt Head Boundary Cells

Specification of water level for constant head boundary in Ziway Lake area: water level in cells covering Ziway Lake and other lakes are specified according to the elavtion value from SRTM DEM as follows:

- Lake Ziway : 1639 m
- Lake Abijata : 1577m
- Lake Shalla : 1555m

Specification of water level for constant head boundary in river cells: water level is basically specified as 2 m lower than the central point elevation of the cell. In case the downstream water level becomes higher than the upstream water level, the water level is adjusted to make the downstream side lower than the upstream side by at least 0.5m.

7.6.2 Parameter specification

a.1 Layer property

Following common sense in hydrogeology, the layer properties were set as follows:

Layer 1: Unconfined aquifer

Layer 2 – layer 4: Confined aquifer

a.2 Hydraulic conductivity

1) Horizontal Hydraulic Conductivity

As described in PR(2), all available data has been summarized to get values of the hydraulic conductivity for different lithofacies in Rift Valley as shown in Table 7.24.

Table 7.24: Specification of Aquifer Parameter in the Model

Symbol	Main Lithofacies	Transmissibility (㎡/day)	Average (㎡/day)
AL/Q	Fine sand or mud	90.2 - 388	248
Lac	Lacustrine sediment	10 - 2080	1,081
N1_2n	Rhyolite	2.5 - 376.5	190
Volcano	Volcanics	1980 - 3801	2,891
rb	Basalt	64 - 79	72
W	Volcanics & sedimentary rocks	2 - 3801	1,907
Tb	Scoria	158.7	158.7
Ba	Basalt	64 - 79	72
Ngs	Basalt	64 - 79	72
Pgl	Basalt	64 - 79	72
G	Welded tuff	12.5 - 914	52
Rh	Rhyolite	2.5 - 376.5	190

2) Vertical Hydraulic Conductivity

Following the geological structure in the Rift Valley area, the vertivcal hydraulic conductivity is generally much smaller than the horizontal hydraulic conductivity. The vertical haydraulic conductivity is uniformly specified as 0.00001 m/day for all 4 layers.

a.3 Effective porosity

Effective porosity is set as 0.1 uniformly to all layers.

a.4 Other parameters

Some other parameters such as Specific Storage, Storage Coefficient, and Specific Yield are also included in the Modflow program. However those parameters are used for transient flow simulation. At the prersent moment, the model is run by steady flow method for model calibration. Therefore, those parameters are going to be specified after July, 2011, before the groundwater level fluctuation prediction.

7.6.3 Model package

a.1 Recharge package

The specification of groundwater recharge is based on the result of hydrological analysis. The total water resources consampation amount is calcualted by summarizing the evaporation amount of all the lakes in the Ziway Lake Basins as shown in Table 7.25.

Table 7.25: Summarizing of evaporation amount from lakes in Ziway Basin

Name	Area_Km^2	M_Station	Pan_(mm)	Evapo(Mm^3)
Ziway	422.9	Kulumsa	2988	1,263.60
Langano	139.2	Kulumsa	2988	415.9

Langano	94.2	Awassa	1963	185
Abijata	87.3	Awassa	1963	171.4
Shalla	309.8	Awassa	1963	608.1
Others*	27.8	--	--	31.265
Total	**1,081.20**	--	--	**2,675.27**

M_Station: correspoding meteorological stations for evaporation amount calculation.
Pan_(mm): annual average evaporation amount for eaach meteorological station.
Evapo(Mm^3): evaporation amount from the corresponding area for each lake.

The separation of water resources comsumption amount to surface water and groundwater is based on the base flow index (BFI) calculation result for the 3 lakes in the model areas. The available lakes, flow stations for BFI canalysis, and corresponding BFI values are shown in Table 7.26.

Table 7.26: Calculated BFI in Ziway Lake Basin

Basin	Station	BFI
Ziway	Meki_Meki Village	0.6
Langano	Gedemso_Langano	0.65
Shalla	Djidu_Childern	0.27

Station: the river flow observation station used for BFI calculation.

The average BFI for the whole model area is calcualted by weighted average method:

$$\text{Average BFI} = \Sigma(\text{Area}_i \times \text{BFI}_i) / (\text{Total Area})$$

Here:

Area_i : lake’s area for each of the three lakes.

BFI_i : BFI calculation result for each lake (refer to hydraulogical analysis).

Total Area: Sum of the area of the three lakes

The result of the average BFI calculation using the equation above is 48.37%. And then the groundwater recharge amount for Ziway Basin can be calcualted as

$$\text{Total annual evaporation amount} \times \text{Average BFI}$$

$$= 2{,}675.27 \times 0.4837$$

$$= 1{,}294.1(Mm^3/\text{year})$$

Because the units for the GWM are set as meters for length and days for time in the Ziway basin, the above amount is divided by 365 (days) to obtain a daily average recharge amount of 3,545,471m^3.

The groundwaer recharge is basiclly from precipitaion and the precipitaion is differrent in each location. In the moutanous area, precipitaion generally increases with elevation. Therefore, the recharge amount is not allocated to each active cell uniformly, but allocated by the criterion that the groundwater recharge amount in cell is proportional to the elevation of the cell. Figure 7.44 shows the groundwater recharge specifications in the Ziway groundwater simulation model.

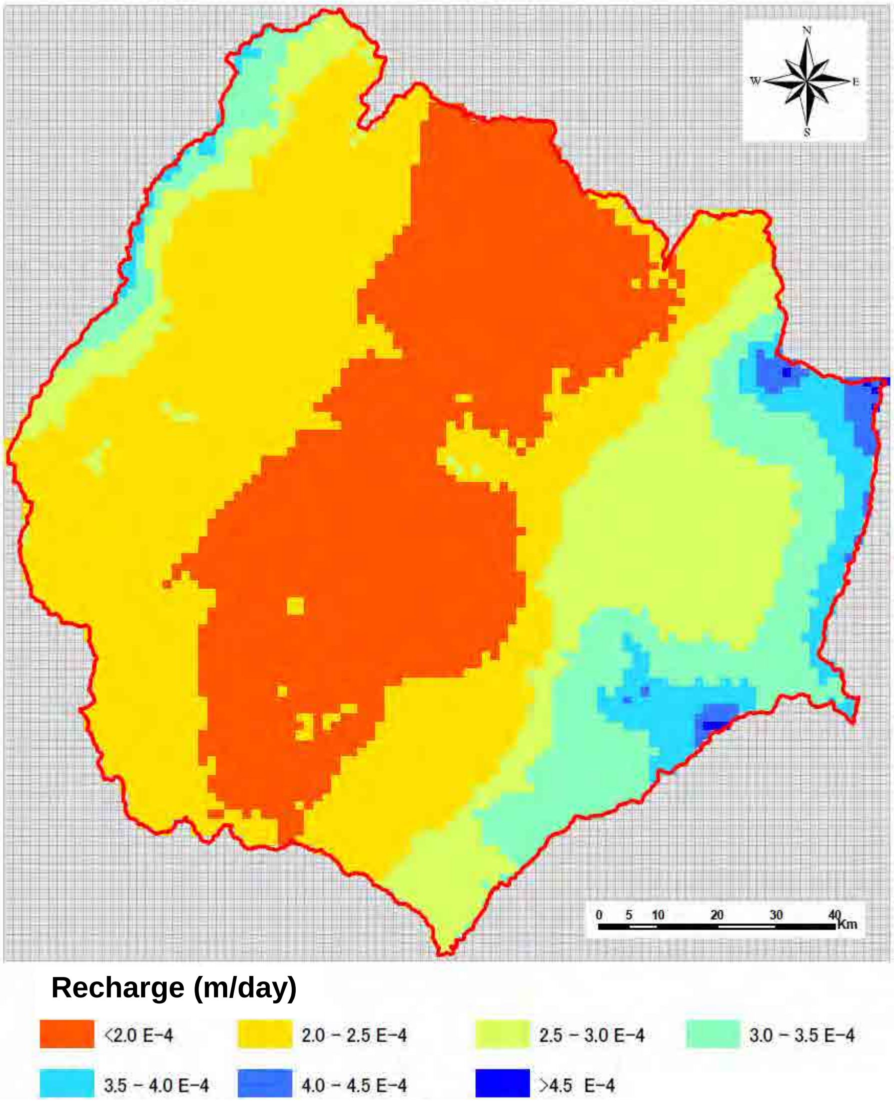


Figure 7.44: Groundwater Recharge Specification in Ziway Basin Model

a.2 Well package

Based on the GIS database, 317 wells can be confirmed in the Ziway basin. Using the same procedure as described in well package specification in Model_1, those wells were assigned into each layer as shown in Figure 7.45 to Figure 7.48.

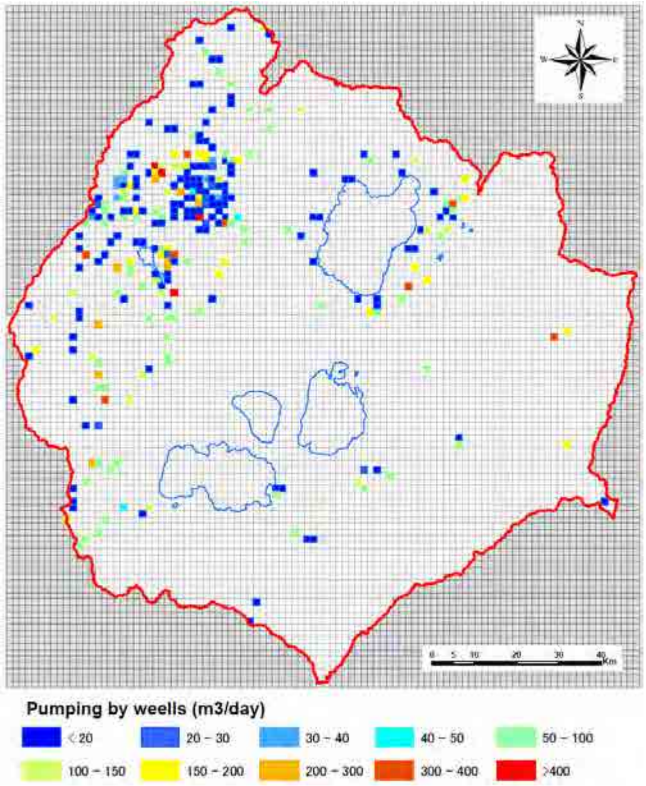


Figure 7.45: Well Package Specification for Layer 1 of Ziway Basin Model

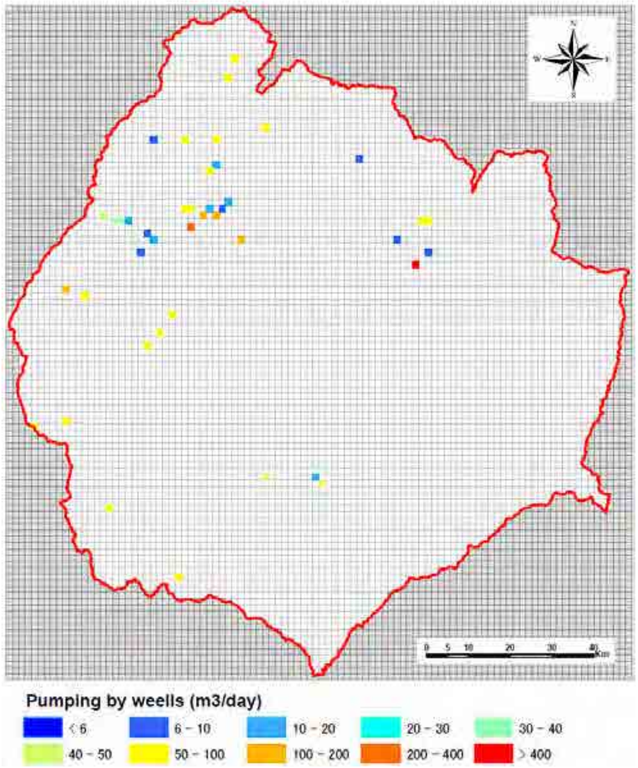


Figure 7.46: Well Package Specification for Layer 2 of Ziway Basin Model

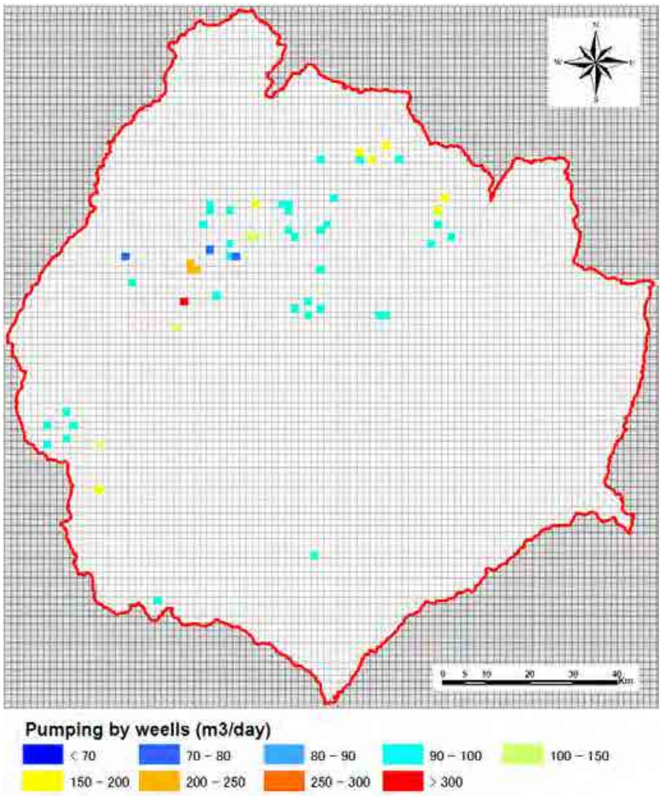


Figure 7.47: Well Package Specification for Layer 3 of Ziway Basin Model

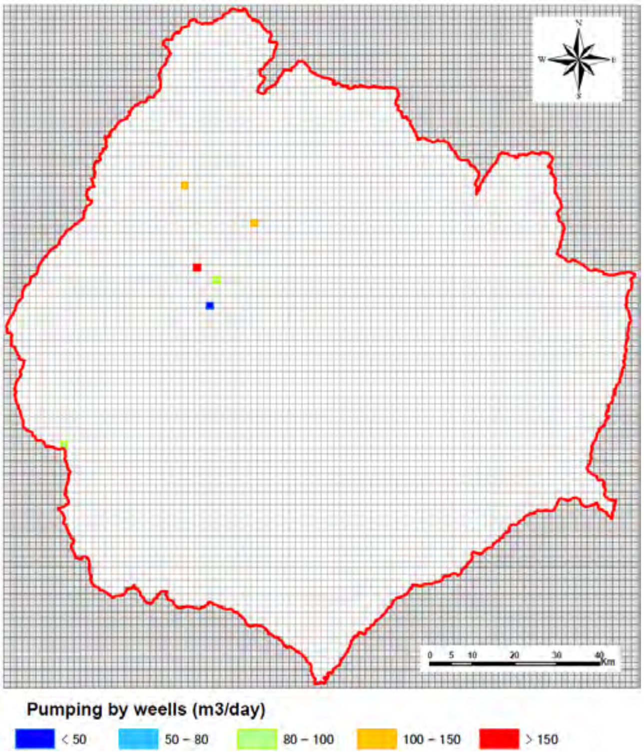


Figure 7.48: Well Package Specification for Layer 4 of Ziway Basin Model

7.6.4 Model calibration and result

The calculation method of steady flow is used for model calibration this time, because the steady flow method is generally used for the first time calibration to check or to ensure the convergence or stability of the model.

As the model calibration result, the groundwater level (head) distribution of the top layers (layer_1) was extracted and shown in Figure 7.49. From the result, it can be confirmed that not only the model has got convergence, but also the calculated groundwater level fits the characteristics of relief in the model area.

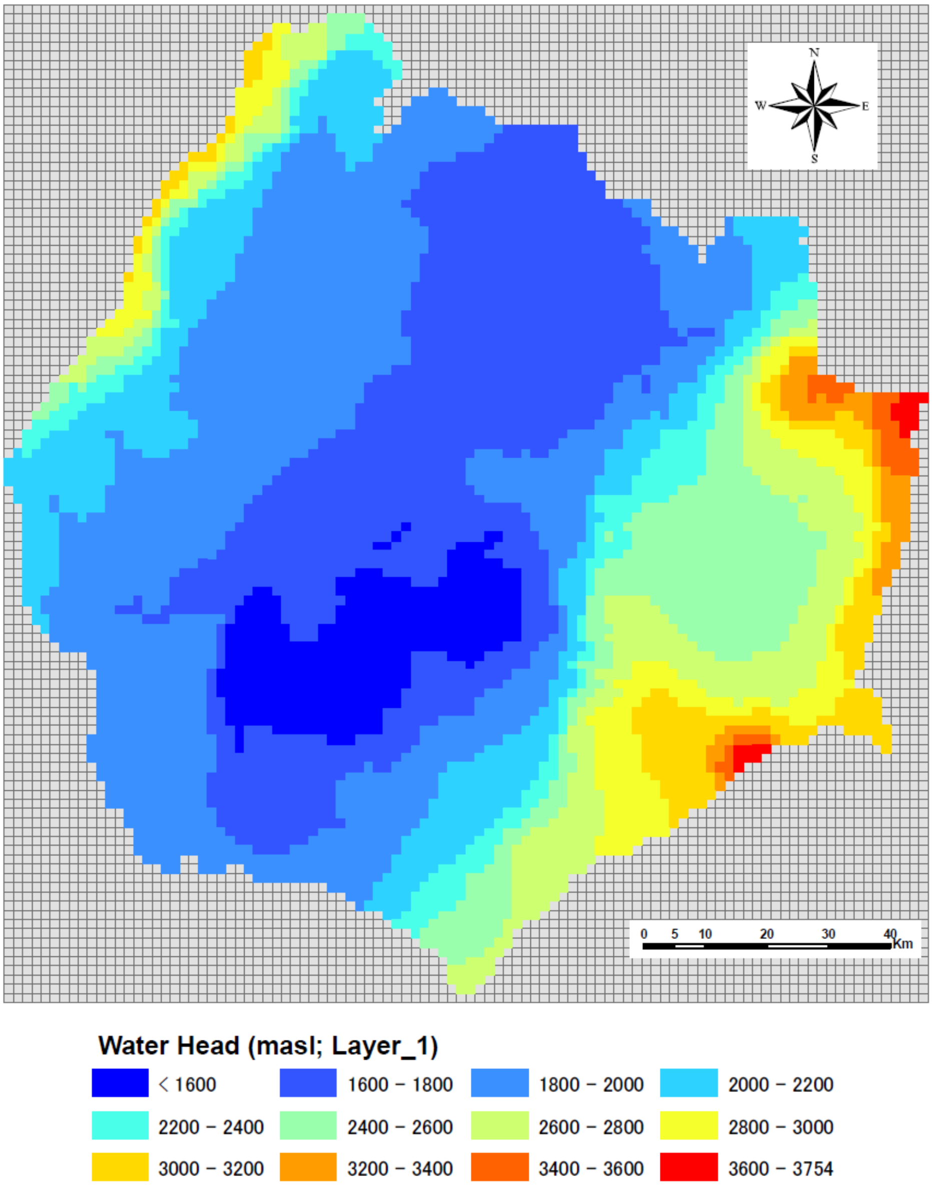


Figure 7.49: Result of Ziway Basin Model Simulation (Layer 1&2)

7.7 Groundwater simulation model (Gidabo-Galana sub-basin, Eastern Lake Abaya area)

The target area of the third groundwater simulation model is decided as the eastern side of Lake Abaya basin

7.7.1 Model domain and grid specification

Figure 7.50 shows the topography and eastern Lake Abaya basin boundary.

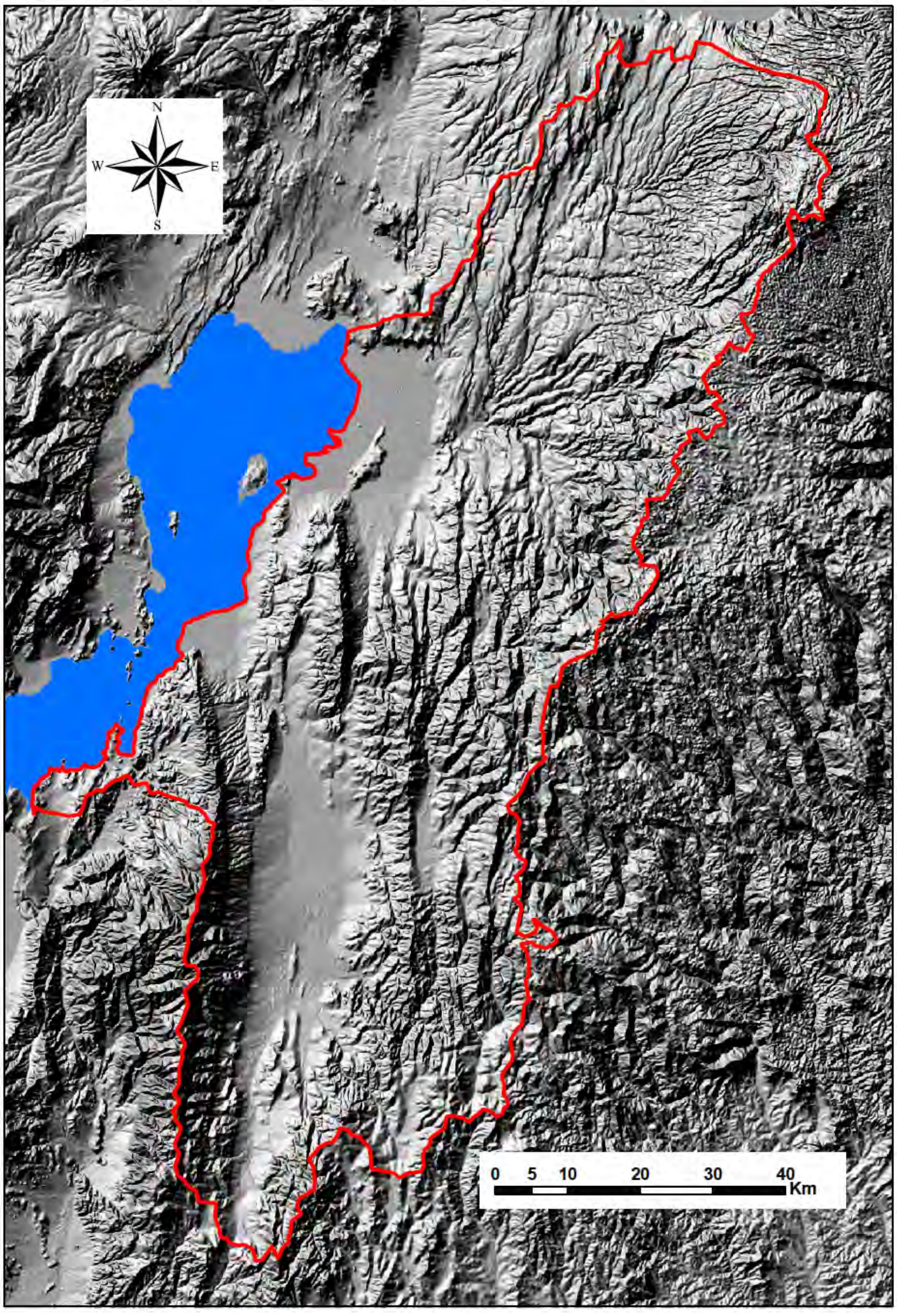


Figure 7.50: Topography and Basin's Boundary of Eastern Abaya Lake Area

As shown in Figure 7.51, the model covers eastern Abaya Lake basin with the extent as follows:

- Projection: Addenda UTM zone 37N
- Easting：350000 – 461000 (111km)
- Northing：598000 – 768000 (170km)

The model domain area is:

$$111\text{km(east-west)} \times 170\text{km (north - south)} = 18{,}870\ \text{km}^2$$

The girds in the model domain are specified as square with length of 1 km (1000m) to each side. Therefore, the number of grids is 111 in an east–west direction and 170 in a north–south direction. The total number of grids is the same as the value of square kilometers of 18,870.

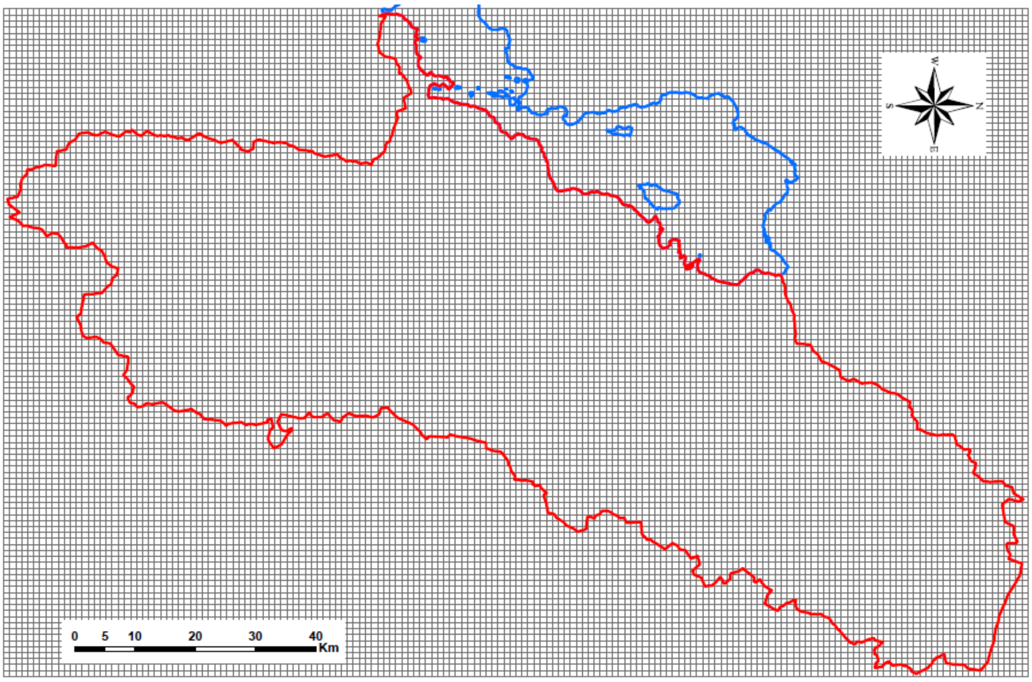
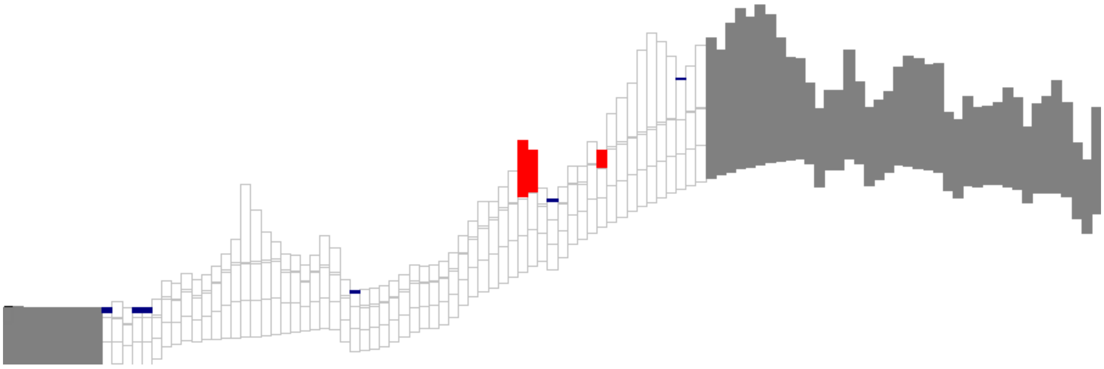


Figure 7.51: Basins' Boundary and GWM Domain of Eastern Abaya Lake Area

a. Layer classification

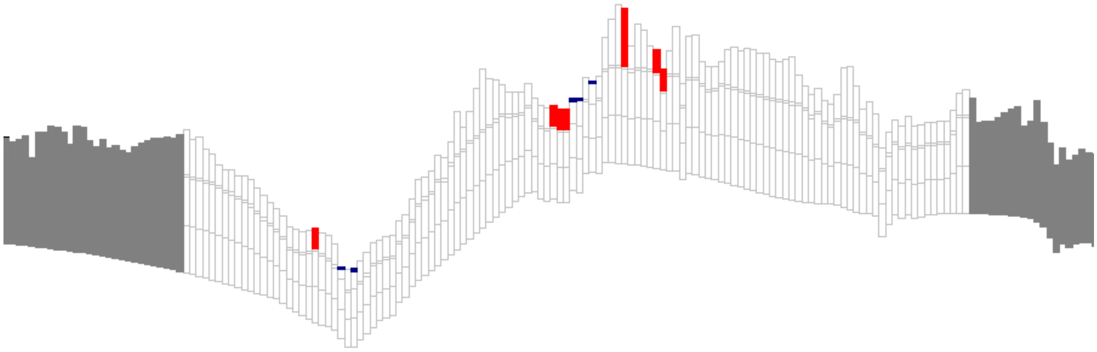
The same like Ziway basin model, the model was classified into 4 layers in vertical a direction. Figure 7.52 and Figure 7.53 show 2 main model sections in east–west direction (99 rows) and north–south direction (62 columns), respectively.



No color: Active cells; Red color: Well cells; Blue color: Constant head cells; Grey color: Inactive cells

Figure 7.52: Cross Section of Layer Specification (99 Rows) in Eastern Abaya Lake Basin Model.

Scale: Vertical: Horizontal = 1: 20



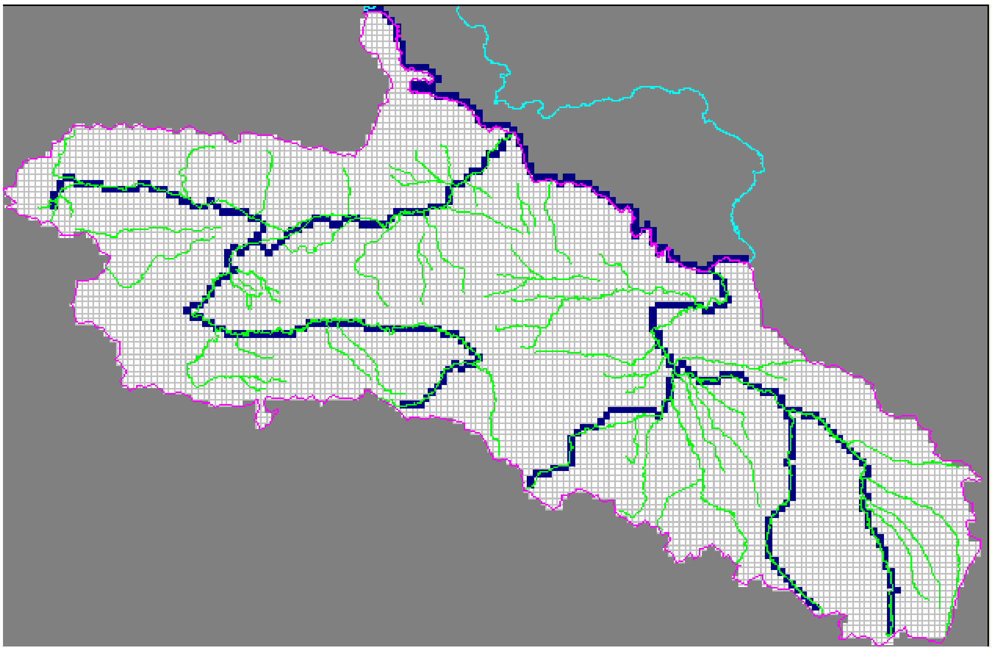
No color: Active cells; Red color: Well cells; Blue color: Constant head cells; Grey color: Inactive cells

Figure 7.53: Vertical Section of Layer Specification (62 Columns) in Eastern Abaya Lake Basin Model.

Scale: Vertical: Horizontal = 1: 40

b. Boundary Specification

The same as Ziway basin model, the outside part of eastern Lake Abaya basin were specified as inactive boundary. The river and lake area were specified as constant head boundary and the other cells were set as active boundary. The boundary specification in the top layer is shown in Figure 7.54.



Grey color: Inactive cells; Blue color: Constant head cells; No color: Active cells

Figure 7.54: Boundary Specification in Eastern Abaya Lake Basin Model

The same as model_1 and model_2, considering the river and lake's depth is much smaller than the aquifer's depth the constant boundary cell's depth was specified as 10m.

The water head in the constant head boundary is taken from SRTM DEM data using the same method of head level specification and modification as described in model_1 and model_2.

7.7.2 Parameter specification

a.1 Layer property

Layer 1: Unconfined aquifer

Layer 2 – layer 4: Confined aquifer

a.2 Hydraulic conductivity

1) Horizontal Hydraulic Conductivity

The same as model_1 and model_2, lithofacies identification for each layer is based on the existing geology map for layer 1 and 2, and geological profiles for other layers. The hydraulic conductivity specification is based on the summarizing result of pumping tests in the whole Rift Valley area as shown in Table 7.24.

2) Vertical Hydraulic Conductivity

The vertical haydraulic conductivety is uniformlly specified as 0.00001 m/day for all the 4 layers

a.3 Effective porosity

Effective porosity is set as 0.1 uniformly to all layers.

a.4 Other parameters

All other parameters necessary only for transient flow simulation are not specified at this moment. And those parameters will be specified before the groundwater fluctuation prediction.

7.7.3 Model package

a.1 Recharge package

When model_1 was created, the detailed analysis was conducted for obtaining the groundwater recharge amount for the whole of Lake Abaya basin. Because the model area of eastern Abaya area belongs to the Abaya Lake basin, the analysis result and procedure for model_1 recharge amount specification was adopted here for model_3's recharge specification. Figure 7.55 shows the groundwater recharge specifications in the eastern Lake Abaya area groundwater simulation model.

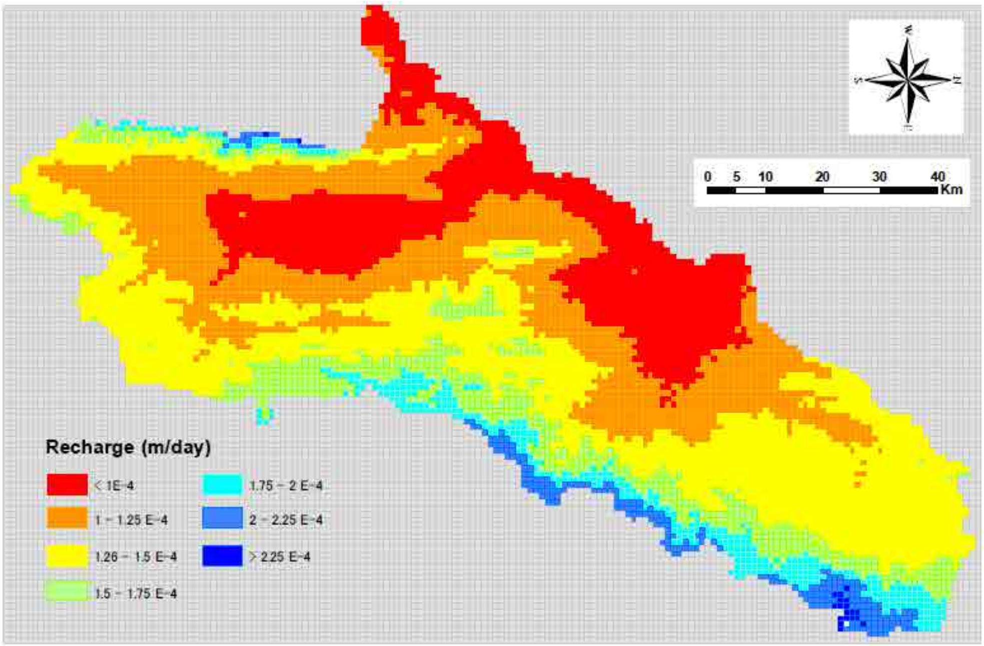


Figure 7.55: Groundwater Recharge Specification in Eastern Abaya Lake Basin Model

a.2 Well package

Based on the GIS database, 640 wells have been confirmed in the eastern Lake Abaya basin. Using the same procedure as described in well package specifications in Model_1 and 2, those wells were assigned into each layer as shown in Figure 7.56 to Figure 7.58.

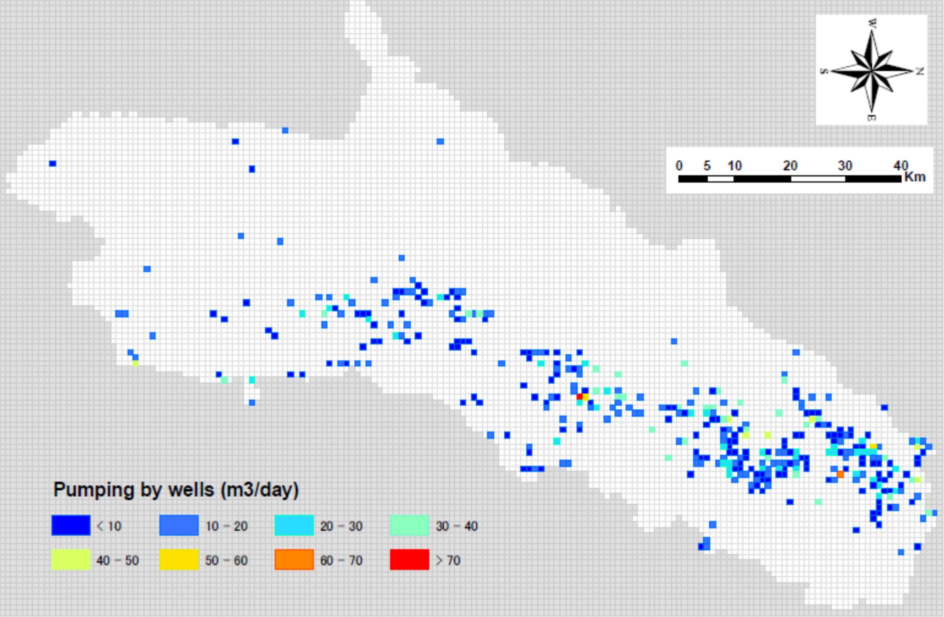


Figure 7.56: Well Package Specification for Layer 1 of Eastern Abaya Lake Basin Model

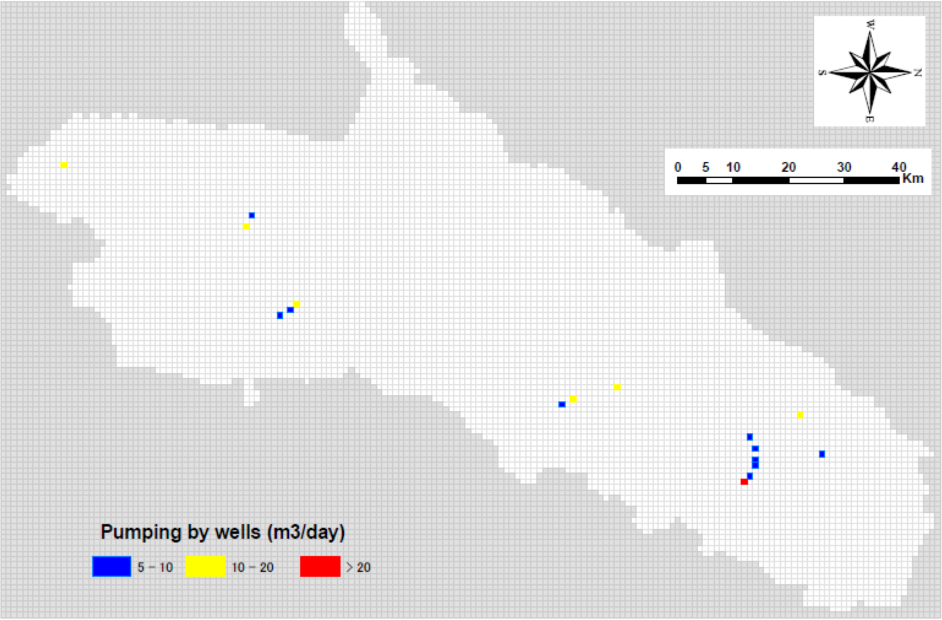


Figure 7.57: Well Package Specification for Layer 2 of Eastern Abaya Lake Basin Model

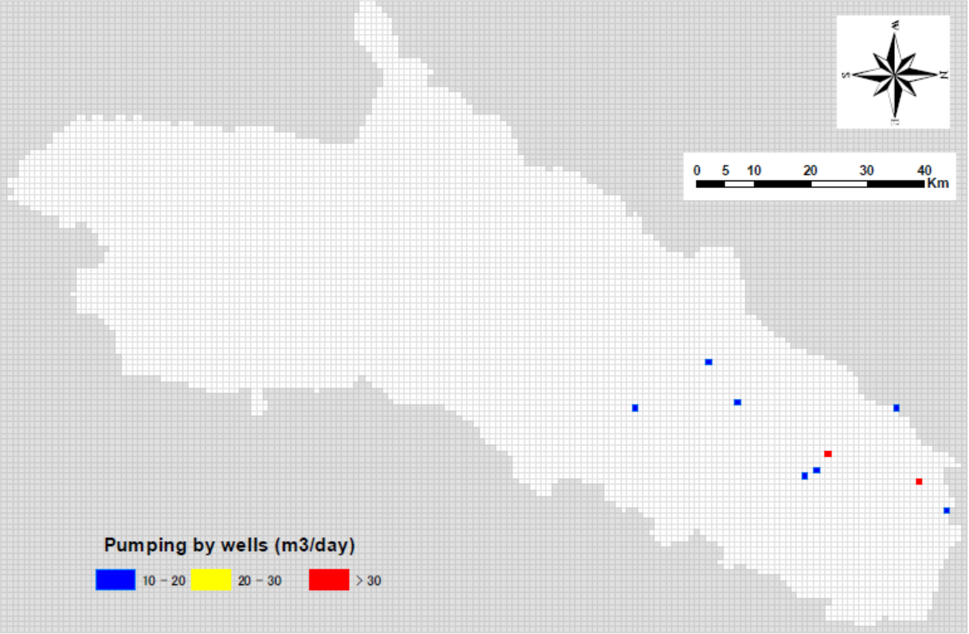


Figure 7.58: Well Package Specification for Layer 3 of Eastern Abaya Lake Basin Model

7.7.4 Model calibration and result

To make sure the model’s stability and fitness, the calculation method of steady flow is used for model calibration.

As the model calibration result, groundwater level (head) distribution of the top layers were extracted and shown in Figure 7.59. From the result, it can be confirmed that not only the model has got convergence, but also the calculated groundwater level fits the characteristics of relief in the model area.

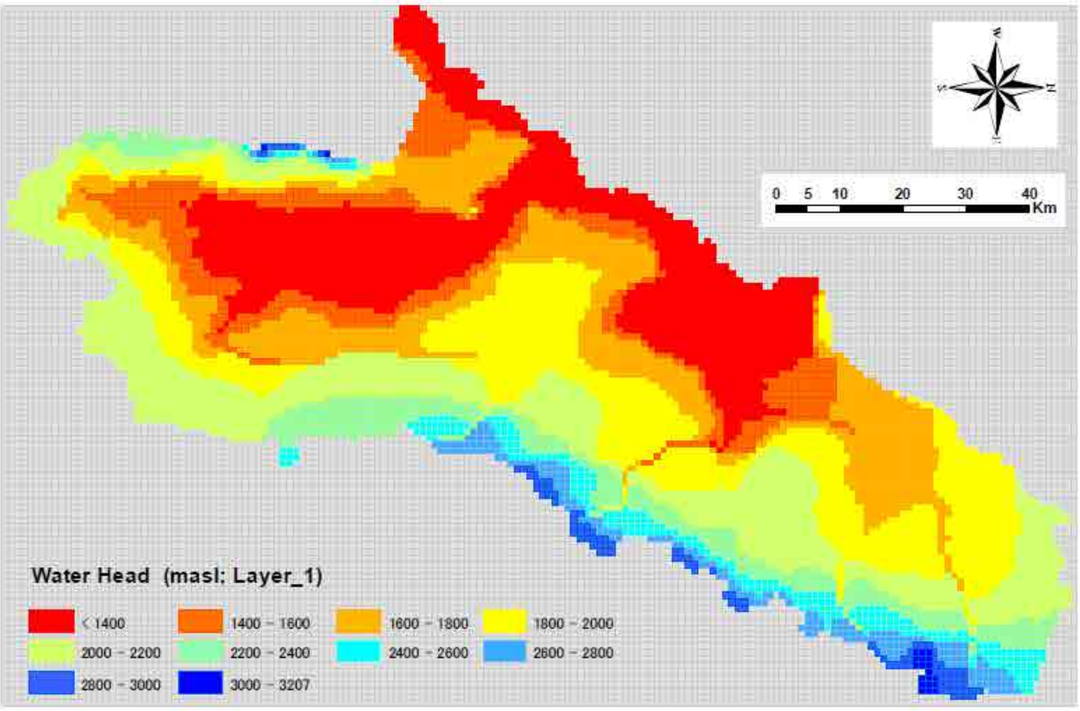


Figure 7.59: Result of Eastern Abaya Lake Basin Model Simulation (Layer_1)

7.8 Groundwater simulation model (Amessa Guraoha-Kulfo Gina sub-basin, western Lake Abaya area)

The target area of the fourth groundwater simulation model is set as western area of Abaya Lake basin.

7.8.1 Model domain and grid specification

Figure 7.60 shows the topography and Western Lake Abaya basin boundary. As shown in Figure 7.60, the model area has a long and narrow shape and lies in a north-eastern to south-western direction. If the model domain is specified the same as the 3 former models to be in due north or due east direction, a lot of grids outside of the model area would be involved in the model domain. So the model domain is specified as 30 degrees from north direction following the orientation of the western Lake Abaya basin area.

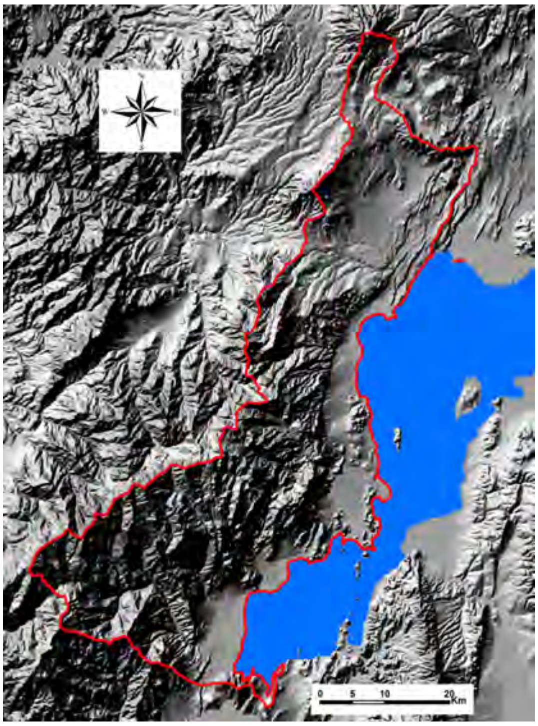


Figure 7.60: Topography and Basin's Boundary of Western Abaya Lake Area

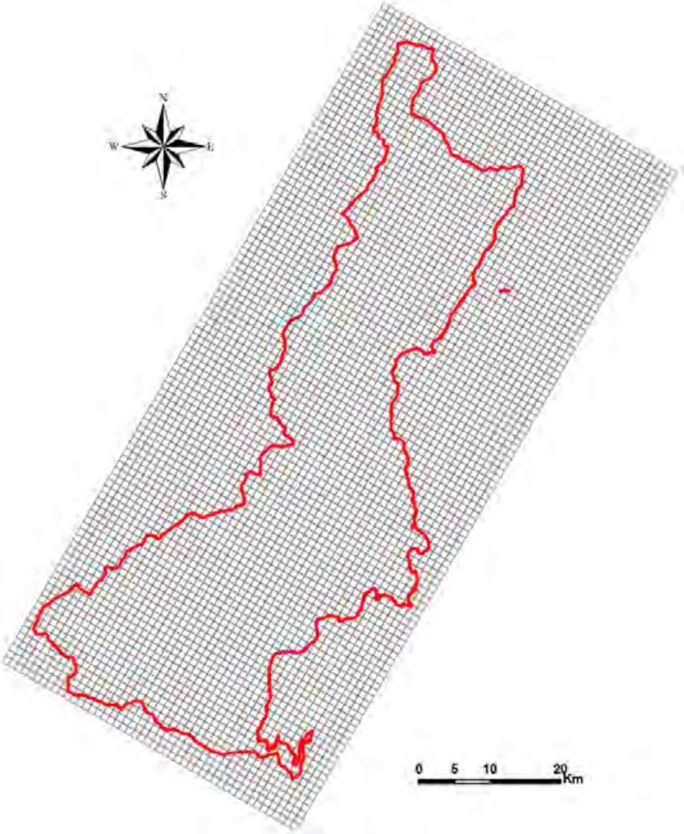


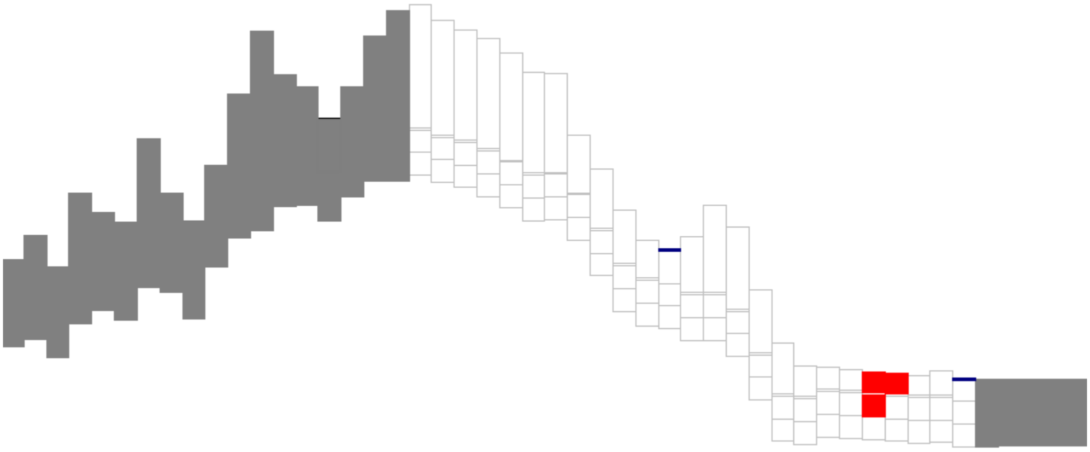
Figure 7.61: Basins' Boundary and GWM Domain of Western Abaya Lake Area

As shown in Figure 7.61, the western Lake Abaya basin model was created following the shape of model area to be a long and narrow rectangle. The grids in the model domain are specified as square with each side to be 1km (1,000m). The model domain is divided into 108 grids in the long direction (north-eastern to south-western), and 48 grids in the narrow direction (north-western to south-eastern). Therefore, the total area in the model domain is

$$48(\text{km}) \times 108\ (\text{km}) = 5{,}184\ \text{km}^2$$

a. Layer Classification

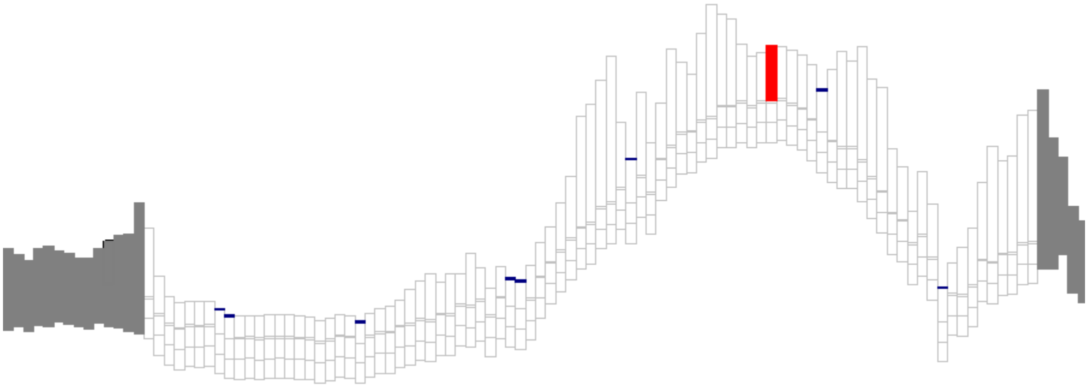
The same as with the former groundwater simulation models, the western Lake Abaya basin model was classified into 4 layers in vertical direction. Figure 7.62 shows the section in northwestern–southeastern direction (67 rows). And Figure 7.63 shows the section in northeastern–southwestern direction (21 columns).



No color: Active cells; Red color: Well cells; Blue color: Constant head cells; Grey color: Inactive cells

Figure 7.62: Cross Section of Layer Specification (67 Rows) in Model_4.

Scale: Vertical: Horizontal = 1: 10



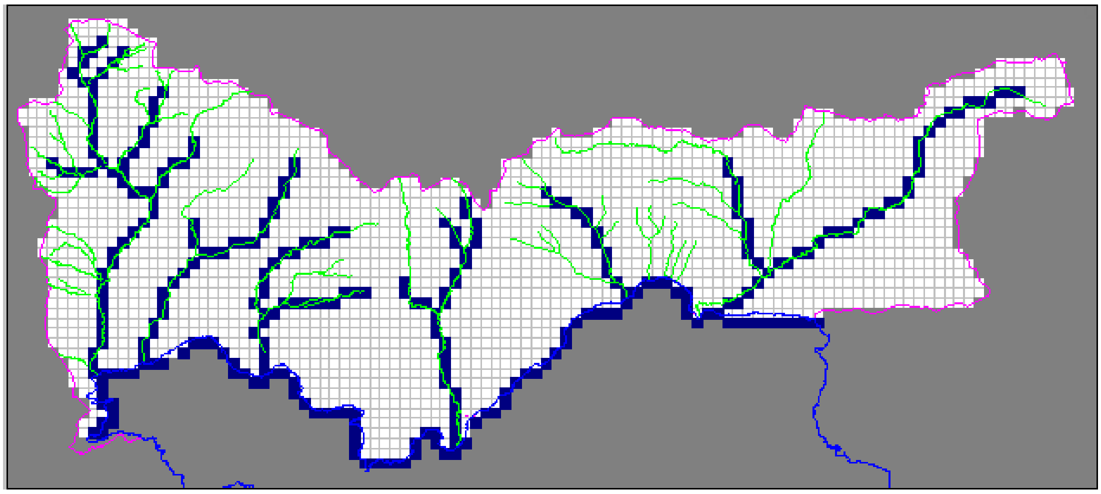
No color: Active cells; Red color: Well cells; Blue color: Constant head cells; Grey color: Inactive cells

Figure 7.63: Vertical Section of Layer Specification (21 Columns) in Model_4.

Scale: Vertical: Horizontal = 1: 20

b. Boundary specification

The same method is taken as the specifications of the former models boundary for the western Abaya lake basin model boundary specification. Figure 7.64 shows the boundary specification in top layer of western Abaya lake basin model.



Grey color: Inactive cells; Blue color: Constant head cells; No color: Active cells

Figure 7.64: Boundary Specification in Western Abaya Lake GW Model

7.8.2 Parameter specification

As the absolute necessary parameter specification, the following parameters were specified by the same procedure as the former models.

- Layer property
- Hydraulic conductivity
- Effective Porosity

Also other parameters like specific storage and specific yield will be set before the groundwater fluctuation prediction.

7.8.3 Model package

a.1 Recharge package

The method and procedure of recharge amount specification is the same as the model of western Abaya lake basin, because both models belong to the Lake Abaya. Figure 7.65 shows the result of recharge specification in the model area.

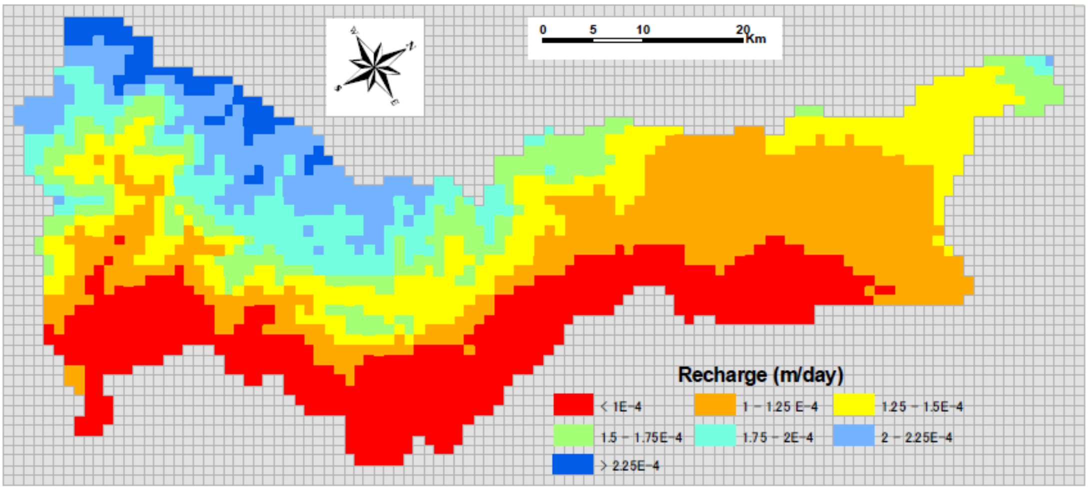


Figure 7.65: Groundwater Recharge Specification in Western Abaya Lake Model

a.2 Well package

122 wells can be confirmed from the GIS database in western Abaya lake basin area. Using the same procedure as described in well package specification in former models, those wells were assigned into each layer as shown in Figure 7.66 and Figure 7.68.

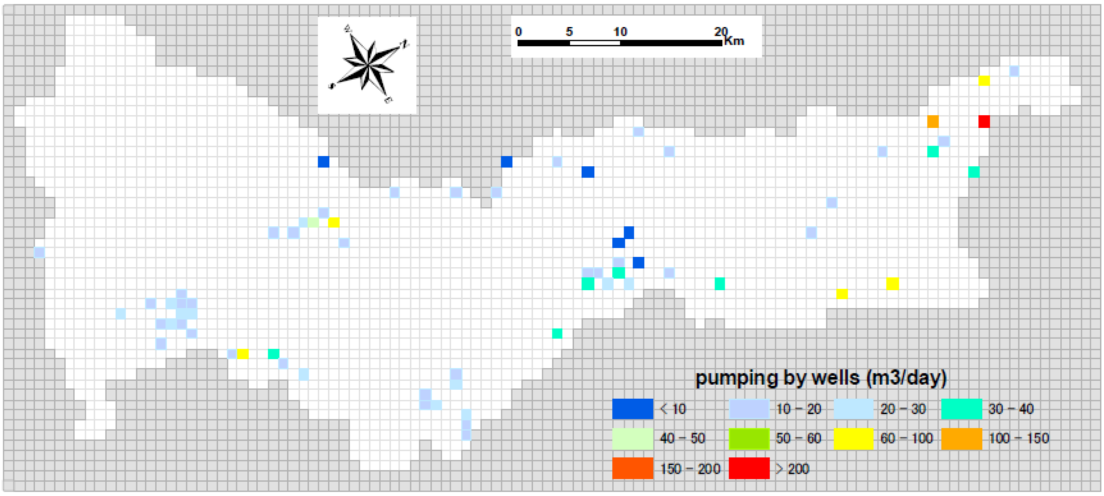


Figure 7.66: Well Package Specification for Layer 1 of Western Abaya Lake Basin Model

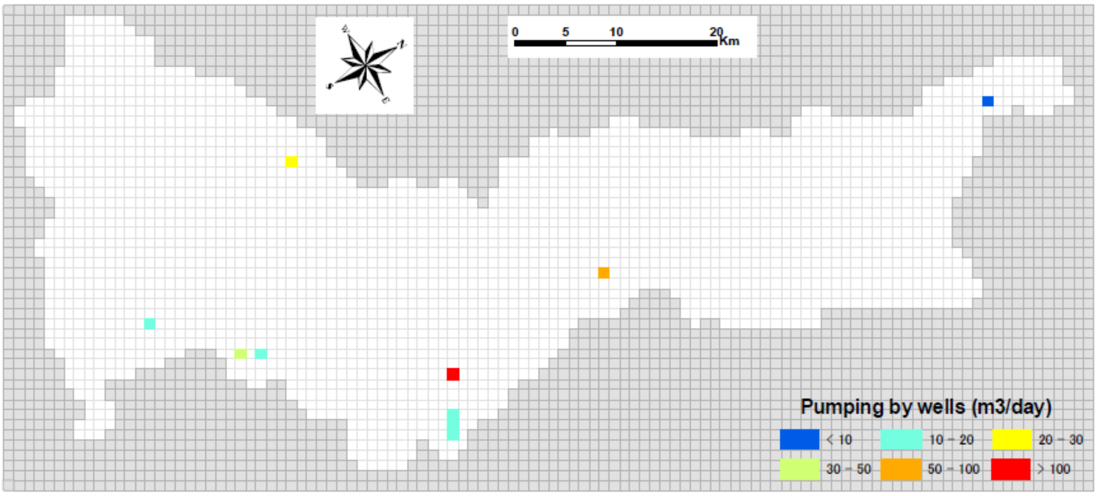


Figure 7.67: Well Package Specification for Layer 2 of Western Abaya Lake Basin Model

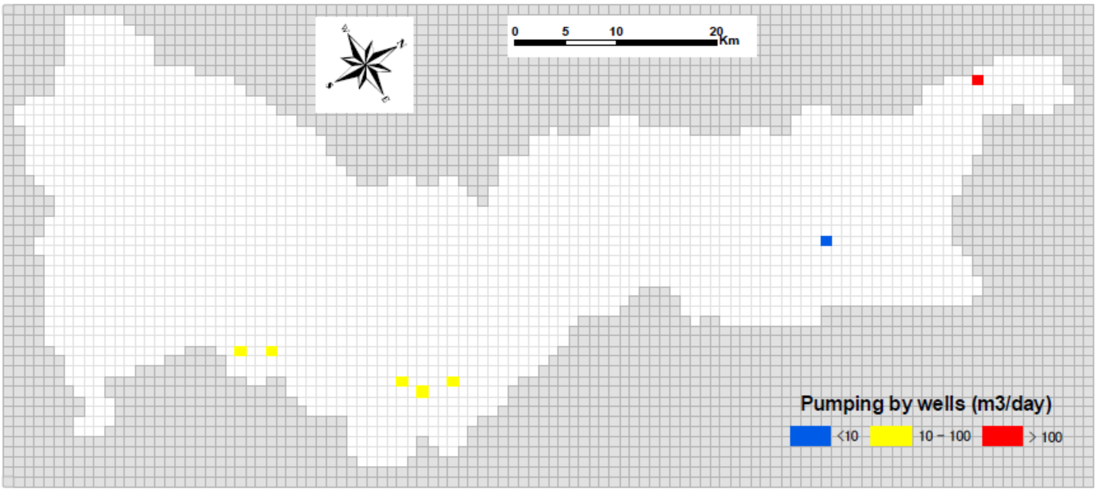


Figure 7.68: Well Package Specification for Layer 3 of Western Abaya Lake Basin Model

7.8.4 Model calibration and result

Steady flow method was used for model calibration. And the model calibration result, the groundwater level (head) distribution of the top layer (layer_1) was extracted and shown in Figure 7.69. From the result, it can be confirmed that not only the model has got convergence, but also the calculated groundwater level fits the characteristics of relief in the model area.

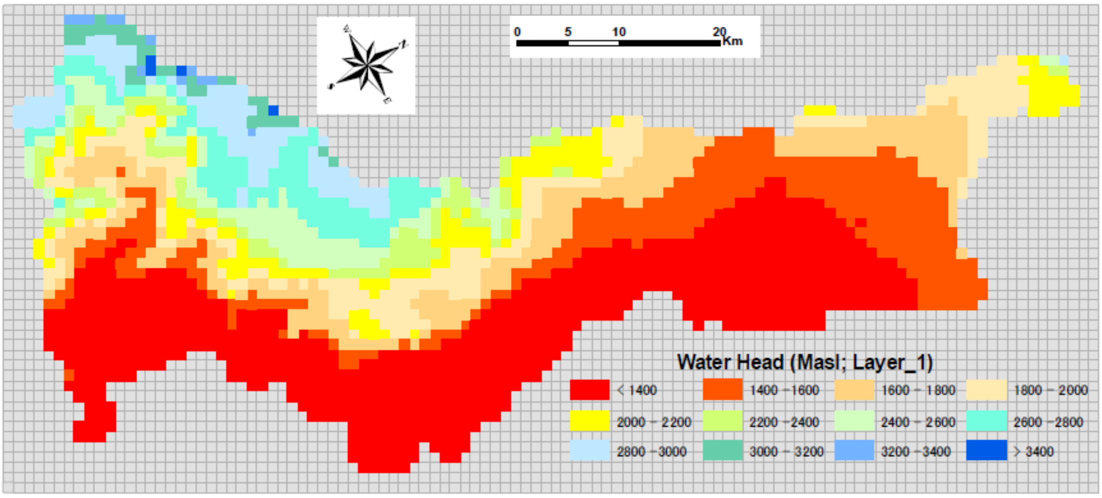


Figure 7.69: Result of Western Abaya Lake Basin Model Simulation (Layer 1)

Reference

1). Rift Valley Lakes Basin Integrated Resources Development Master Plan Study Project. Halcrow Group Limited & Generation Integrated Rural Development (GIRD) Consultants、2009.

2). Crop evapotranspiration - Guidelines for computing crop water requirements - FAO Irrigation and drainage. Richard G. Allen, Luis S. Pereira, Dirk Raes and Martin Smith; 1998.