Chapter 4
Hydrogeology

CHAPTER 4 HYDROGEOLOGY

Hydrogeological conditions in the Internal Drainage Basin (IDB) were investigated by using the following survey results:

(1) Collecting the existing data
(2) Conducting the inventory survey of existing water supply facilities
(3) Remote sensing survey
(4) Geophysical survey
(5) Test borehole drilling survey

4.1 Existing Data Sources

In order to investigate the hydrogeological condition, the Study Team collected existing borehole data and materials contained it: The collected materials are followings:

- MoW Borehole Catalogue (Whole Tanzania)
- DDCA Borehole Catalogue
- RWSSP-WADATA (2002, Shinyanga region)
- Water Supply and Health Project in Marginal Areas (2002, Dodoma region)
- Arusha Region Water Master Plan (2000, Arusha region and Manyara region)
- Tabora Region Water Master Plan (1978, Tabora region)
- The Study on the Groundwater Development for Hanang, Singida Rural, Manyoni and Igunga Districts (1998, JICA Study)
- The Feasibility Study on Monduli Town and the Surrounding Area Water Supply (1995, JICA Study)
- Water Supply Facility Data requested from JICA expert to each district.
- Borehole Completion Form

A borehole database and a water supply facilities database have been compiled from these data in this study.

4.1.1 Borehole Database

The borehole database was established by the Study Team based on the MoW borehole catalogue adding and correcting with other borehole information. The item of the database is listed in Table 4-1. MoW Borehole Catalogue, which was assembled borehole data in the survey area uniformly, is used as basic data to understand the hydrogeological structure in IDB. The feature of this catalogue is as below.

- ✓ 3,456 borehole data since 1937 in this catalogue for 6 regions as the study area.
- ✓ Abandoned boreholes, such as dry holes or high saline water wells, are mentioned in this catalogue.
- ✓ Drilling depth, static water level, water struck depth, water yield, drawdown depth and aquifer

geology are described.

- ✓ Borehole position is not mentioned but only village name due to the difficulties in identifying the location.
- ✓ There are many deficit items in the table.

Insufficient items in the borehole catalogue were filled through the other borehole information with time-consuming effort.

The basic rules of adding and correcting data are described below.

- ✓ Borehole completion forms were recognized as correct. The records different from the completion form were corrected.
- ✓ If the borehole catalogue based on the borehole completion forms had some obvious mistakes, the data were corrected with reference to the previous water resources master plans or the borehole completion forms as the original data source. For example, some borehole catalogue data had been described in feet and gallon unit.
- ✓ Village name was corrected to match to the corresponding one in the census list. Additionally, division name and ward name were added in this database.

Table 4-1
Item of Borehole Database

No.	Items	Type
1	Serial Number	Number
2	Region	String
3	District	String
4	Division	String
5	Ward	String
6	Village	String
7	Longitude (E)	Number
8	Latitude (S)	Number
9	Sub-village	String
10	Borehole Number	String
11	Year	Number
12	Location Village	String
13	Depth (m)	Number
14	Static Water Level	Number
15	Water Struck (m)	String
16	Yield (m^3/h)	Number
17	Drawdown (m)	Number
18	Nature of Aquifer	String
19	Quality Standard	String
20	Remarks	String

4.1.2 Water Supply Facilities Data

As for water supply ratio, the data shown in Table 4-2, which is published in 2005 by WaterAid (NGO of United Kingdom), was adopted for this study. The distribution of water supply ratio in IDB is shown in Figure 4-1. The water supply ratio is the ratio of population served by improved water sources to the total population in each district.. This ratio is based on the same data as Table 2-4 (Chapter 2). However, Table 4-2 do not include the urban areas such as Singida town, Manyoni town, etc. because this study focuses on the rural areas of IDB.

According to Table 4-2 or Figure 4-1, the water supply ratios of Sikonge and Igunga in Tabora region are very low, but Arumeru in Arusha region is very high.. This result is reflected in the potential evaluation for groundwater development.

Table 4-2 Ratio of Households with Access to Improved Water Source

District	Population	% Using improved	Breakdown by type of source (%)			
			Piped	Protected	Unprotected	Other
Arusha Region	854,491	**63.4**	52.6	10.8	39.5	0.8
Monduli	160,521	**39.2**	29.1	10.1	60.7	0.1
Arumeru	421,495	**81.8**	71.5	10.3	16.8	1.4
Karatu	168,514	**61.3**	53.3	8.00	38.6	0.1
Ngorongoro	122,838	**30.8**	12.9	17.9	69.1	0.1
Dodoma Region	1,478,782	**50.3**	38.6	11.7	49.6	0.1
Kondoa	409,877	**36.5**	28.9	7.6	63.5	0.1
Dodoma Rural	431,001	**50.8**	39.8	11.0	49.2	0.0
Dodoma Urban	173,631	**38.2**	19.6	18.6	61.8	0.0
Manyara Region	896,886	**33.7**	22.2	11.5	65.8	0.5
Babati	260,664	**48.7**	36.7	12.0	51.3	0.0
Hanang	185,081	**40.3**	30.3	10.1	59.7	0.0
Mbulu	218,159	**16.5**	3.6	12.9	83.5	0.0
Simanjiro	99,672	**36.6**	16.2	20.4	62.4	1.0
Kiteto	133,310	**18.1**	14.0	4.1	79.7	2.2
Shinyanga Region	2,540,578	**33.7**	6.0	27.6	65.7	0.6
Maswa	279,466	**31.7**	12.7	19.0	68.3	0.0
Shinyanga Rural	275,357	**26.5**	0.6	26.0	69.1	4.3
Kahama	528,840	**32.6**	3.0	29.6	67.3	0.1
Meatu	241,389	**36.1**	5.4	30.6	63.8	0.2
Shinyanga Urban	60,755	**60.6**	19.3	41.3	36.9	2.5
Kishapu	226,136	**9.6**	3.2	6.4	90.3	0.1
Singida Region	938,081	**33.9**	10.3	23.6	66.1	0.0
Iramba	334,355	**29.7**	10.3	19.4	70.3	0.0
Singida Rural	379,613	**38.1**	4.7	33.4	61.9	0.0
Manyoni	167,164	**33.6**	23.9	9.8	66.3	0.0
Singida Urban	56,949	**32.0**	6.5	25.5	68.0	0.0
Tabora Region	1,490,581	**11.8**	0.5	11.3	88.1	0.0
Nzega	385,877	**20.5**	0.0	20.5	79.5	0.0
Igunga	303,952	**5.0**	0.3	4.7	94.8	0.2
Uyui	276,793	**10.4**	1.1	9.3	89.6	0.0
Sikonge	123,493	**4.0**	0.1	4.0	96.0	0.0
Tabora Urban	60,118	**10.9**	5.3	5.7	89.1	0.0

Source: Water Aid (2005): Water and Sanitation in Tanzania

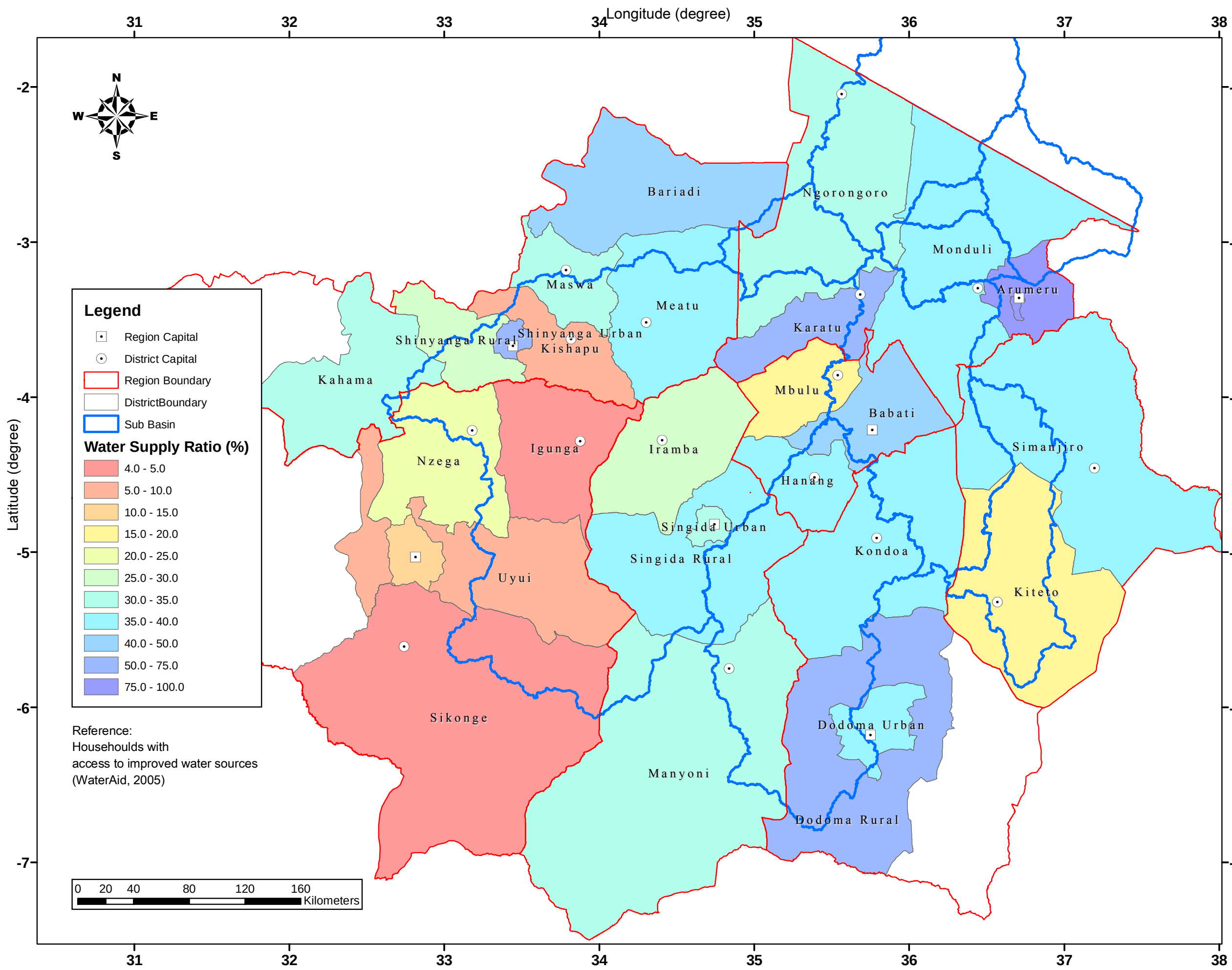


Figure 4-1 Rural Water Supply Ratio by District in IDB

Database of water supply facilities was developed to grasp the usage condition of water resources. JICA Expert for MoW (2005 – 2006), requested all District Water Engineers to fill out a datasheet about water supply facilities in 2005. The Study Team collected the data from each District Water Engineer regarding to IDB and assembled the database for hydrogeological analysis.

The aggregated result of the database is shown in Table 4-3. The ratio of water resource type in each region is shown in Figure 4-2. Piped Borehole, H/P Borehole and Dug well is recognized as using groundwater. Dam, Charco Dam and Gravity scheme (river or spring) is recognized as using surface water. Whereas the dependence rate for surface water in Arusha Region is 80%, other regions are highly depending on groundwater.

Table 4-3 Aggregated Result of Water Supply Facilities

Region	District	Village	Piped Boreholes			H/P Boreholes			Dug Well			Dam			Charco Dam			Gravity Scheme		
			F	N/F	Ratio (%)	F	N/F	Ratio (%)	F	N/F	Ratio (%)	F	N/F	Ratio (%)	F	N/F	Ratio (%)	F	N/F	Ratio (%)
Arusha	Monduli	65	17	0	100.0	1	0	100.0	1	0	100.0	60	0	100.0	0	0	0.0	28	0	100.0
	Karatu	45	0	0	0.0	15	1	93.8	9	0	100.0	0	0	0.0	1	0	100.0	0	0	0.0
	Arumeru	146	8	0	100.0	4	0	100.0	0	0	0.0	4	0	100.0	0	0	0.0	126	0	100.0
	Ngorongoro	37	3	0	100.0	0	0	0.0	0	0	0.0	0	0	0.0	0	0	0.0	15	0	100.0
	Sub-total	***293***	***28***	***0***	***100.0***	***20***	***1***	***95.2***	***10***	***0***	***100.0***	***64***	***0***	***100.0***	***1***	***0***	***100.0***	***169***	***0***	***100.0***
Manyara	Babati Rural	43	0	1	0.0	61	16	79.2	6	1	85.7	0	0	0.0	0	0	0.0	13	4	76.5
	Babati Urban	14	1	0	100.0	15	1	93.8	0	0	0.0	0	0	0.0	0	0	0.0	11	2	84.6
	Hanang	63	0	3	0.0	4	10	28.6	8	6	57.1	1	0	100.0	0	0	0.0	20	0	100.0
	Kiteto	48	21	0	100.0	0	0	0.0	2	0	100.0	0	0	0.0	0	0	0.0	6	0	100.0
	Mbulu	71	0	0	0.0	33	12	73.3	62	25	71.3	0	0	0.0	0	0	0.0	8	0	100.0
	Simanjiro	47	19	2	90.5	42	9	82.4	237	14	94.4	6	0	100.0	6	0	100.0	15	0	100.0
	Sub-total	***286***	***41***	***6***	***87.2***	***155***	***48***	***76.4***	***315***	***46***	***87.3***	***7***	***0***	***100.0***	***6***	***0***	***100.0***	***73***	***6***	***92.4***
Dodoma	Dodoma Rural	131	84	55	60.4	0	0	0.0	165	17	90.7	6	0	100.0	0	0	0.0	0	0	0.0
	Dodoma Urban	9	9	0	100.0	0	0	0.0	22	0	100.0	0	0	0.0	0	0	0.0	1	0	100.0
	Kondoa	171	83	15	84.7	5	0	100.0	98	6	94.2	5	0	100.0	7	0	100.0	96	7	93.2
	Sub-total	***311***	***176***	***70***	***71.5***	***5***	***0***	***100.0***	***285***	***23***	***92.5***	***11***	***0***	***100.0***	***7***	***0***	***100.0***	***97***	***7***	***93.3***
Shinyanga	Maswa	103	2	2	50.0	0	0	0.0	0	0	0.0	23	3	88.5	0	0	0.0	0	0	0.0
	Meatu	64	2	0	100.0	0	0	0.0	392	37	91.4	1	0	100.0	1	0	100.0	0	1	0.0
	Kishapu	103	4	1	80.0	0	1	0.0	172	0	100.0	9	0	100.0	7	0	100.0	0	0	0.0
	Shinyanga Urban	26	33	36	47.8	185	51	78.4	0	0	0.0	8	0	100.0	0	0	0.0	0	0	0.0
	Shinyanga Rural	106	19	0	100.0	0	0	0.0	207	0	0.0	4	4	50.0	0	0	0.0	0	0	0.0
	Sub-total	***402***	***60***	***39***	***60.6***	***185***	***52***	***78.1***	***771***	***37***	***95.4***	***45***	***7***	***86.5***	***8***	***0***	***100.0***	***0***	***1***	***0.0***
Singida	Singida Municipal	19	23	15	60.5	59	5	92.2	249	175	58.7	13	1	92.9	178	4	97.8	0	0	0.0
	Singida Rural	146	33	30	52.4	40	25	61.5	230	194	54.2	4	0	100.0	8	0	100.0	0	0	0.0
	Iramba	125	40	3	93.0	159	59	72.9	56	71	44.1	0	0	0.0	16	12	57.1	0	0	0.0
	Manyoni	73	42	7	85.7	16	10	61.5	9	29	23.7	13	0	100.0	5	4	55.6	1	0	100.0
	Sub-total	***344***	***138***	***55***	***71.5***	***274***	***99***	***73.5***	***544***	***469***	***53.7***	***30***	***0***	***100.0***	***207***	***20***	***91.2***	***1***	***0***	***100.0***
Tabora	Igunga	43	3	0	100.0	11	17	39.3	8	6	57.1	5	0	100.0	15	0	100.0	0	0	0.0
	Nzega	128	7	0	100.0	0	0	0.0	1	0	100.0	7	0	100.0	0	0	0.0	5	0	100.0
	Uyui	29	3	0	100.0	12	4	75.0	12	14	46.2	2	0	100.0	0	0	0.0	0	0	0.0
	Sikonge	53	0	0	0.0	0	0	0.0	38	13	74.5	2	0	100.0	2	0	100.0	1	0	100.0
	Sub-total	***253***	***13***	***0***	***100.0***	***23***	***21***	***52.3***	***59***	***33***	***64.1***	***16***	***0***	***100.0***	***17***	***0***	***100.0***	***6***	***0***	***0.0***
Total		**1,889**	**456**	**170**	**72.8**	**662**	**221**	**75.0**	**1,984**	**608**	**76.5**	**173**	**7**	**96.1**	**246**	**20**	**92.5**	**346**	**14**	**96.1**

F: Functioning N/F: Not Functionaing

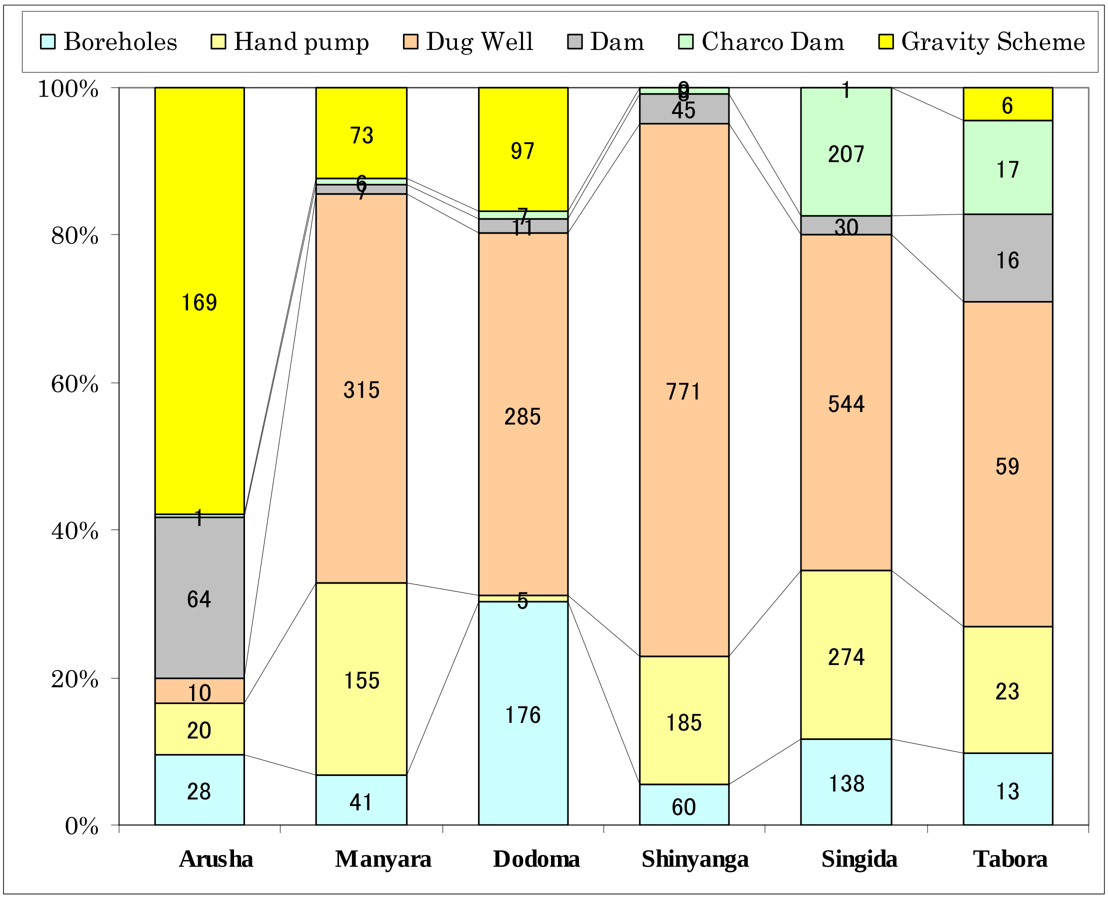


Figure 4-2 Water Source Type of Each Region

To express the relationship mentioned previously, Figure 4-3 was presented. According to this graph, all regions in IDB are classified into three groups: 1) high dependence rate with surface water (Arusha region), 2) low surface water dependence and higher piped borehole ratio region (Dodoma region), and 3) low surface water dependence and low piped borehole water supply ratio. Manyara, Singida, Shinyanga, and Tabora regions can be recognised to be depending on the point water supply facility such as hand pump well or dug well.

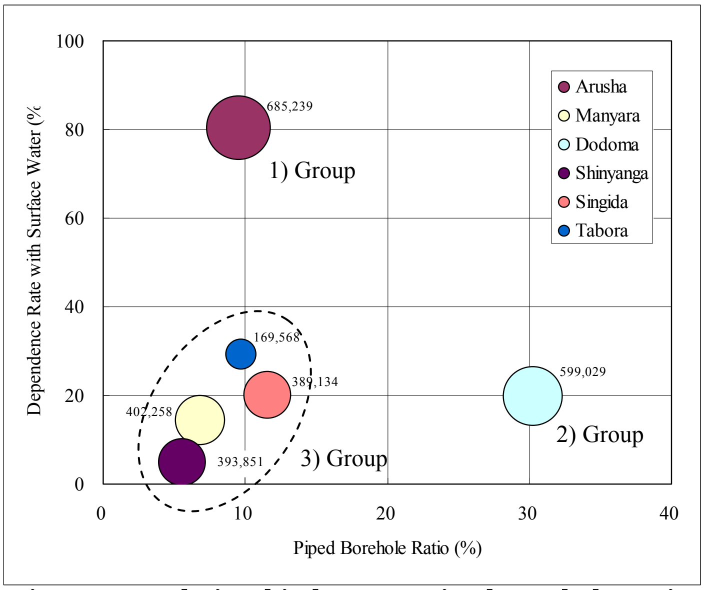


Figure 4-3 Relationship between Piped Borehole Ratio and Dependence Rate for Surface Water

(*Numbers beside circles show the population with water supply services.)

4.2 Hydrogeological Investigation

4.2.1 Inventory Survey of Existing Water Supply Facilities

In order to obtain one of the basic information for hydrogeological conditions in IDB, the inventory survey of existing water supply facilities was conducted. 500 villages in IDB were selected for the inventory survey from the borehole catalogue, because the result of the inventory survey was to be applied to the analysis of the hydrogeological conditions in IDB. The Survey team measured the positions of boreholes, water level of the well and water qualities at the field. Almost all of the collected existing data had no position data so that the main purpose of inventory survey was to check the borehole positions. However, when survey team visited the selected village, there were many cases that the target boreholes had not been existed. In this case, survey team tried to select alternative water source such as dug well or dam or spring.

Total number of villages and the distribution of surveyed points are shown in Figure 4-4 and Table 4-4 respectively.

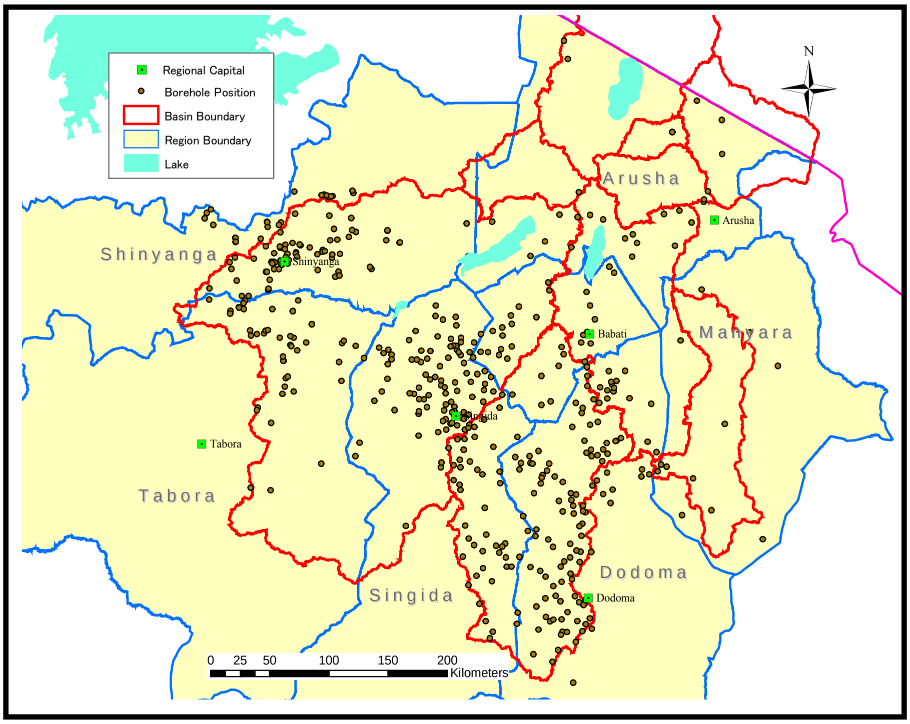


Figure 4-4 Distribution Map of Surveyed Points for Existing Water Supply Facilities Inventory Survey

Table 4-4 Numbers of Surveyed Villages and Points in Each District for the Inventory Survey

Rigion	District		Planed village No.	Surveyed village No.	Surveyed Point No.
Singida	1	Iramba	49	49	53
	2	Manyoni	27	26	28
	3	Singida Rural	41	41	44
	4	Singida Urban	23	23	24
Tabora	5	Igunga	29	22	27
	6	Nzega	11	11	17
	7	Sikonge	1	1	1
	8	Uyui	2	2	2
Shinyanga	9	Kishapu	14	11	17
	10	Maswa	13	10	17
	11	Meatu	7	7	8
	12	Shinyanga Rural	22	22	28
	13	Shinyanga Urban	26	23	31
Arusha	14	Arumeru	5	5	5
	15	Karatu	8	8	8
	16	Monduli	17	17	17
	17	Ngorongoro	4	4	4
Manyara	18	Babati	23	23	23
	19	Hanang	18	18	18
	20	Kiteto	6	6	6
	21	Mbulu	25	25	25
	22	Simanjiro	7	7	7
Dodoma	23	Dodoma Rural and	51	49	51
	25	Kondoa	71	70	73
Total			**500**	**480**	**534**

The results of the existing water supply facilities (boreholes) survey are shown in the Database. Some important results related to economic condition of well construction are shown in below.

(1) Drilling Depth Distribution

Drilling depth distribution of existing borehole is shown in Figure 4-5. Although each borehole has different condition, this distribution indicates the actual depth of the aquifer depth in IDB. The drilling depth is shallower in the western part and central part than the south-eastern and the north-eastern part of IDB.

Table 4-5 Drilling Depth in Each Area

Areas	Drilling Depth (m)
Arusha region (except Karatu district)	100 - 200
Kiteto and Kondoa district	80 - 200
Karatu, Mbulu, Babati, Simanjiro and Hanang district	40 - 100
Dodoma and Manyoni district	80 - 180
Singida, Iramba district	40 - 140
Igunga, Nzega, Uyui and Sikonge district	20 - 100
Shinyanga, Kishapu, Meatu and Maswa district	20 - 60
Western part of Hanang and Eastern part of Singida	80 - 200

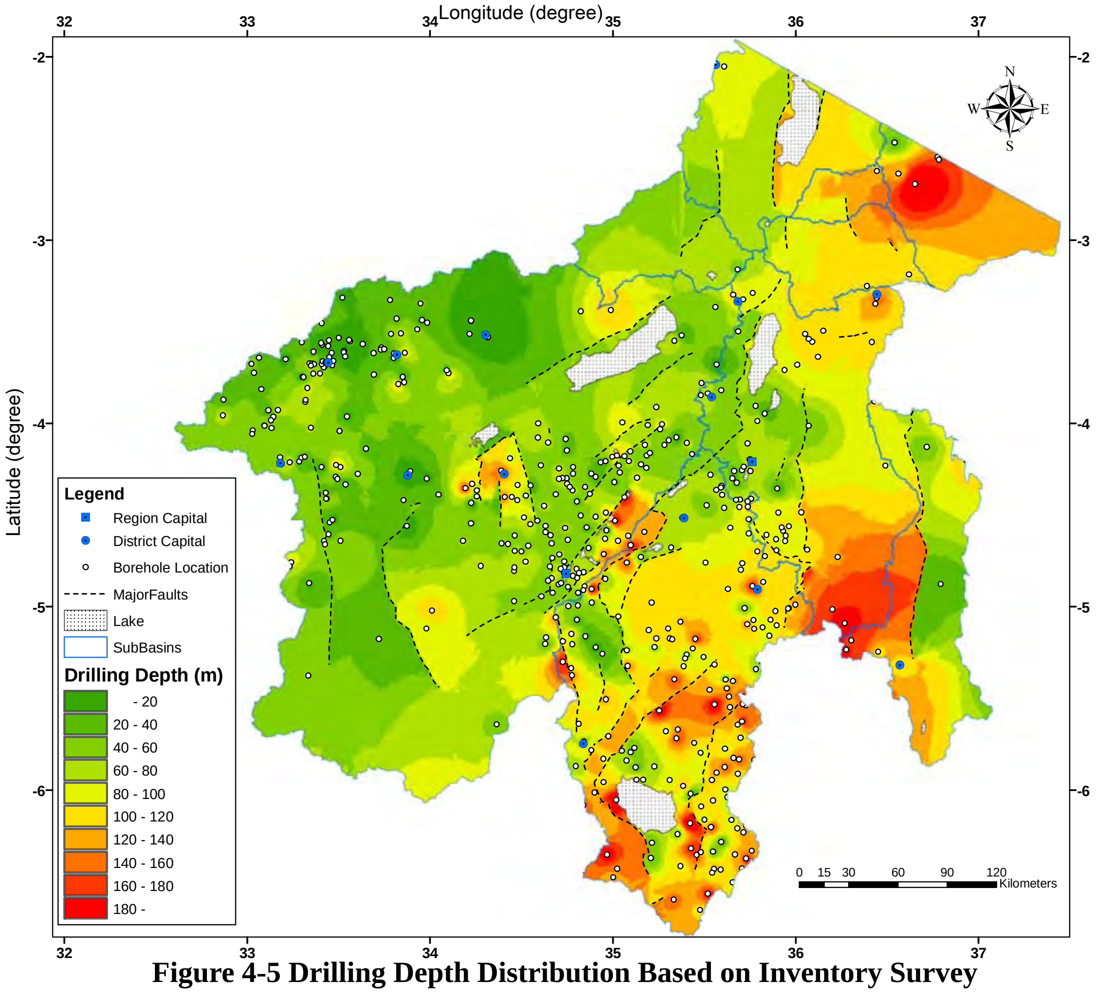


Figure 4-5 Drilling Depth Distribution Based on Inventory Survey

(2) Static Water Level Distribution

Static water level distribution of existing boreholes is shown in Figure 4-6. This distribution is including the results of test borehole drilling survey in the study. The features of static water level distribution are shown in Table 4-6.

Table 4-6 Static Water Level Distribution in IDB

Areas	Static water level
Arusha region (except Karatu district)	50 – 100
Kiteto and Kondoa district	40 - 100
Simanjiro, Karatu, Mbulu, Babati district	15 - 30
Western part of Dodoma region and North-eastern part of Manyara region	100 - 140
South-western part of Manyara	25 - 40
Singida, Iramba, Igunga, Nzega, Uyui and Sikonge district	5 - 20
Shinyanga, Meatu, Kishapu and Maswa district	5 - 15
Hanang, eastern part of Singida, western part of Kondoa and eastern part of Dodoma district	30 - 50

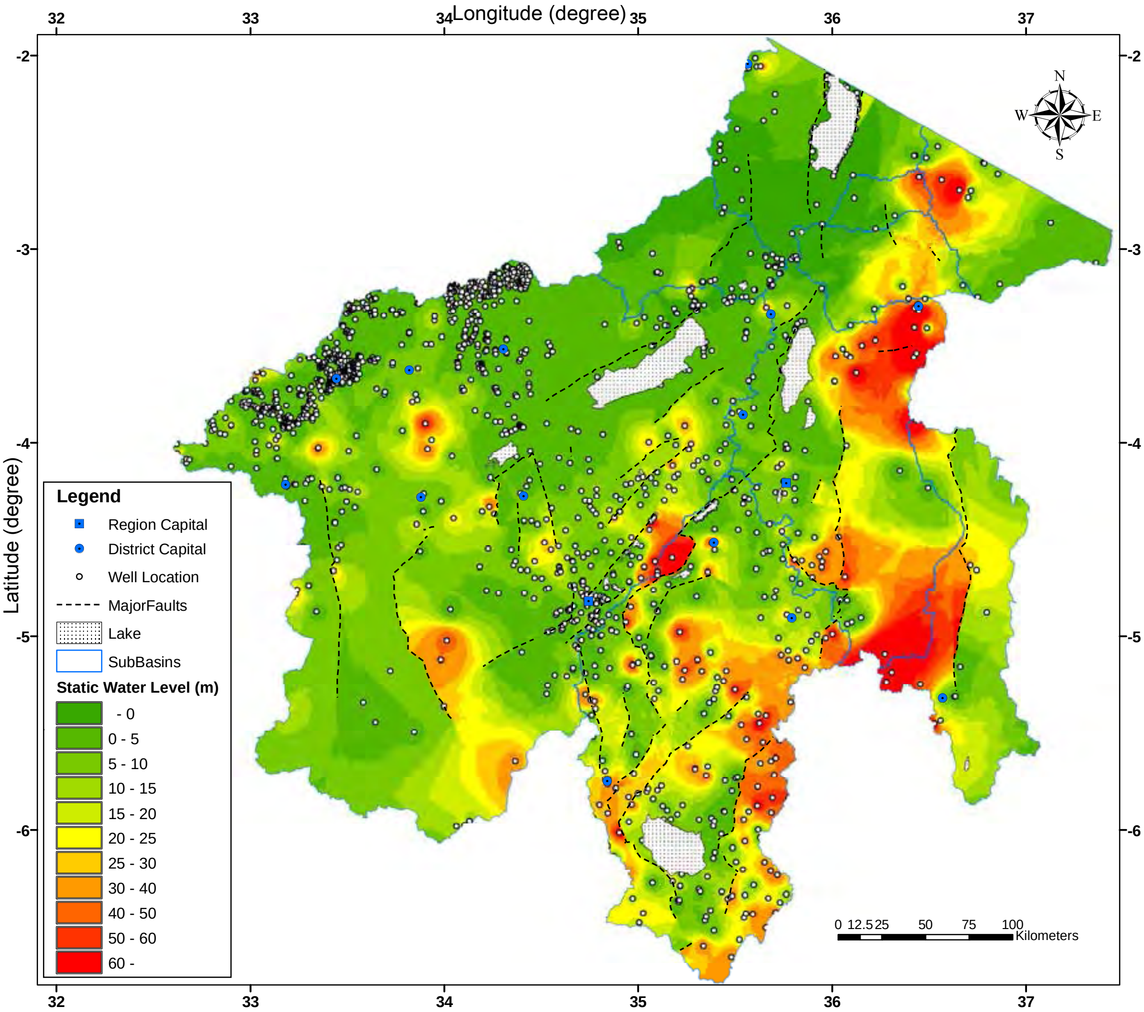


Figure 4-6 Static Water Level Distribution in IDB

4.2.2 Remote Sensing Survey

(1) Purpose

The objective of the survey is to grasp the geo-morphological characteristics in IDB.

(2) Methods

Thirteen scenes of LANDSAT ETM data were analyzed for the surveys to understand vegetation, surface water, soil moisture (groundwater distribution) and land covers in IDB.

(3) Results

SAVI image and VSW image are shown in Figure 4-7 and Figure 4-8 respectively. During January and February when LANDSAT data were acquired, high vegetation index features the two types of areas. One corresponds to high elevation area (above EL1500-2000m) and the other corresponds to the south-western part of IDB along railroad (about EL1000-1400m). The latter also corresponds to smooth topographic characteristic area where is covered by thick weathering zone of granitic rocks.

VSW image shows that high soil index distributes in the northern part of IDB, high water index distributes in eastern low elevation area. Almost all of the large lakes and swamps in magenta colour suggest mixed spectra of soil and water because of shallow water depth.

Figure 4-9 shows land cover map that was produced by VSW image and SAVI image.

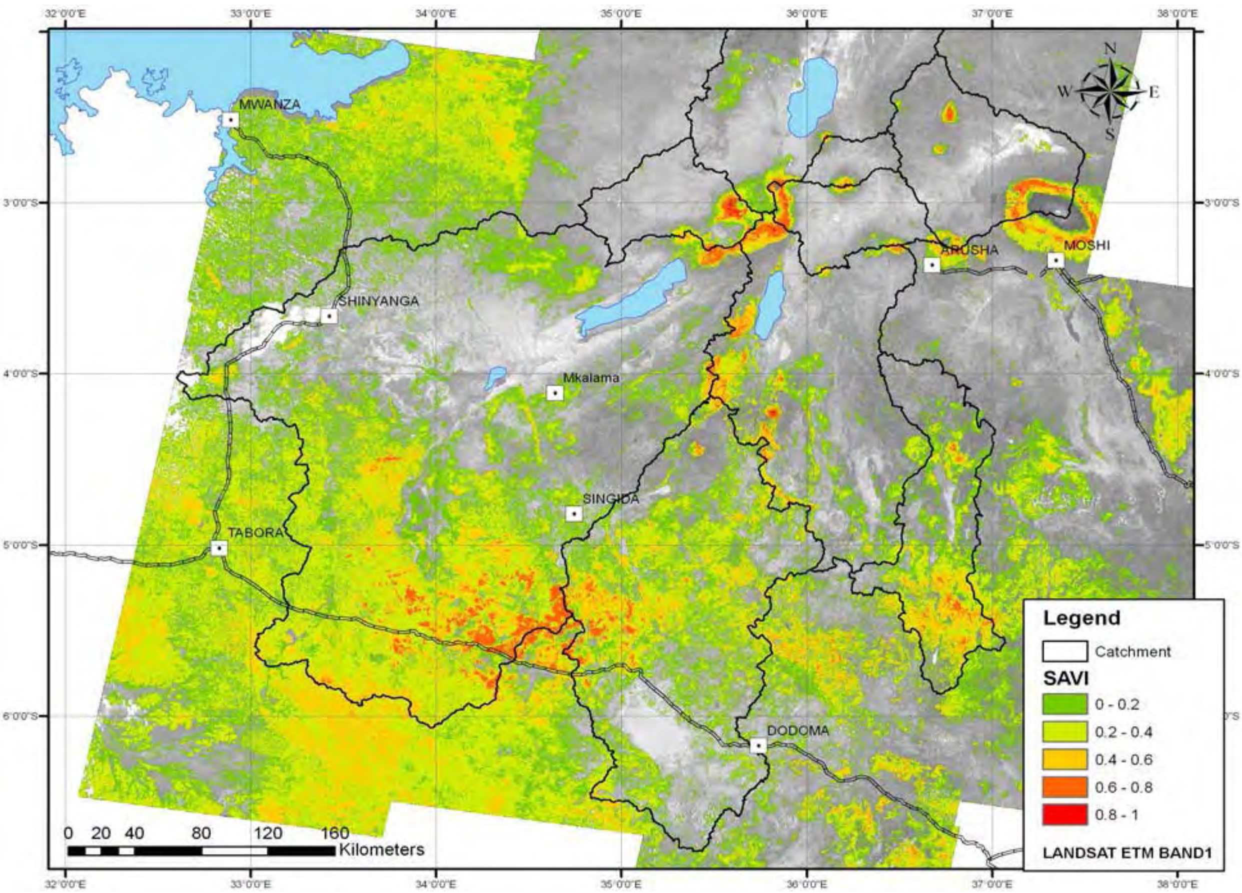


Figure 4-7 SAVI (Soil Adjusted Vegetation Index) Image

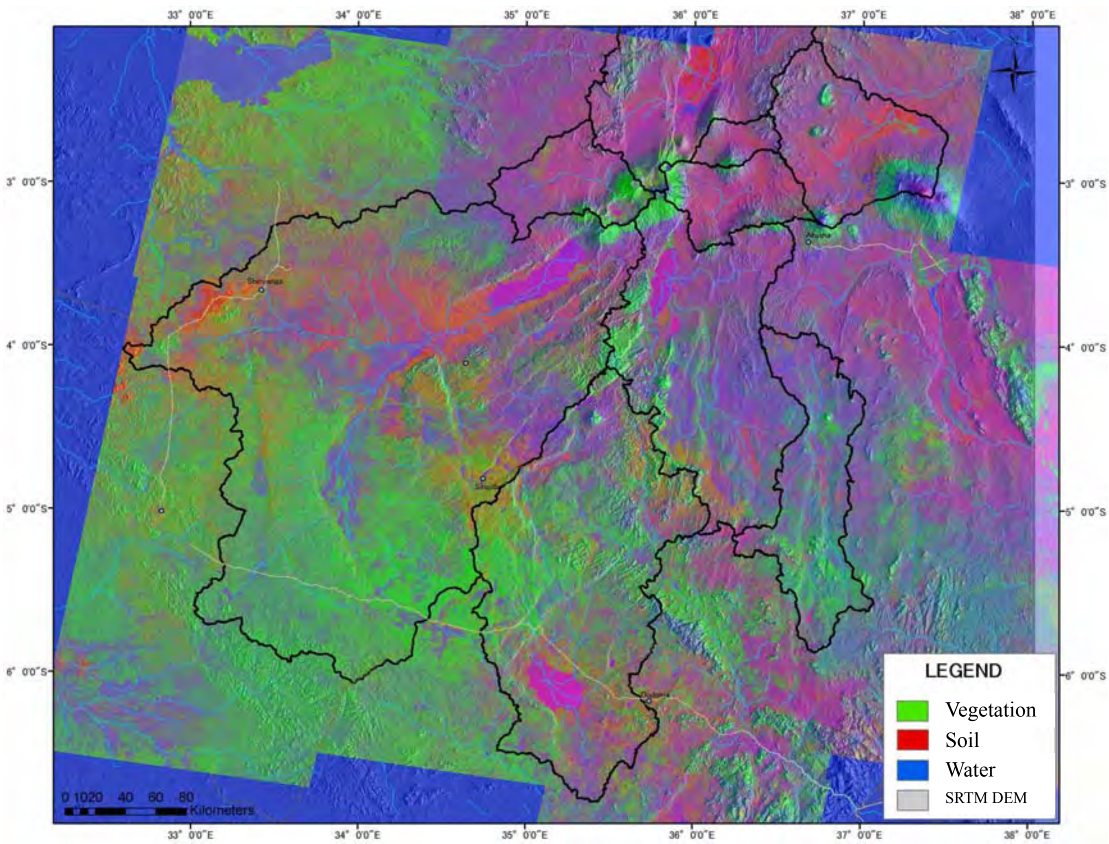


Figure 4-8 VSW Image (V; Vegetation, S; Soil, W; Water and Moisture)

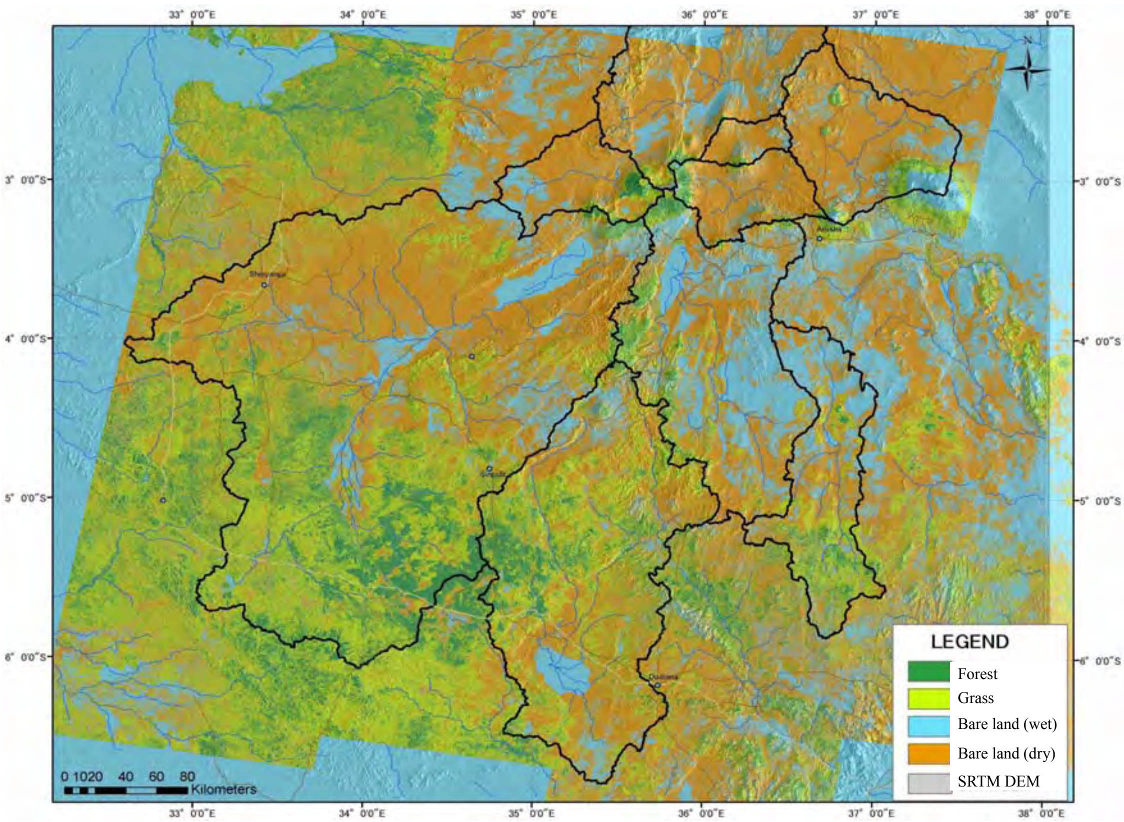


Figure 4-9 Land Cover Map

4.2.3 Geophysical Survey

(1) Purpose of Survey

The purpose of this geophysical survey is shown as follows:

- ✓ To figure out the geological structure of the whole IDB.
- ✓ To select the site of test borehole drilling.
- ✓ To clarify the aquifer structure around the survey points.

(2) Survey Method

Two kind of survey, namely, the geological structure survey and the drilling site survey were implemented by using geophysical survey. As for the geological structure survey, Vertical Electrical Sounding (VES) was adopted. For the drilling site survey, VES was conducted three points in each village principally, and two-dimensional resistivity survey or magnetic survey was conducted in several villages.

Since horizontal layered structure is assumed in VES analysis, VES can provide vertical variation of resistivity. Two-dimensional resistivtiy survey can analyse not only vertical resistivity structure but also horizontal. Although most of all fresh bedrocks have quite high resistivity, an actual resistivity of the strata usually are dominated by the resistivity of the groundwater in pore spaces. Pore spaces in fault and fracture zones are often larger than the pore spaces of the original rocks. Such a zone with high water content: namely, fracture zone, usually has considerably low resistivity. Therefore, resistivity should be dealt with an effective index for detecting anomalous zones in strata for groundwater exploration.

Magnetic survey can detect the magnetic anomaly caused by magnetic susceptibility of rocks. In this time, magnetic survey was adopted to detect fracture zone in the rocky area.

(3) Survey Quantity

In the area where is expected to have horizontal layered structure such as soft sediment area, VES was conducted because of its high accuracy. On the other hand, magnetic survey was mainly conducted together with VES for the survey in rocky areas. Two-dimensional survey was adopted for two sites which have much complicated geological structure.

The number of survey points by survey items is shown in Table 4-7.

Table 4-7 Number of Survey Points for Geophysical Survey

Purpose	Survey Technique	Quantity
Geological Structure	Vertical Electrical Sounding	114 points
Investigation for Test Borehole Drilling Site	Vertical Electrical Sounding	76 points
	2-D Resistivity Survey	2 lines
	Magnetic Survey	12 places

(4) Survey Result

1) Geological Structure Survey

The survey points of VES are shown in the Figure 4-10.

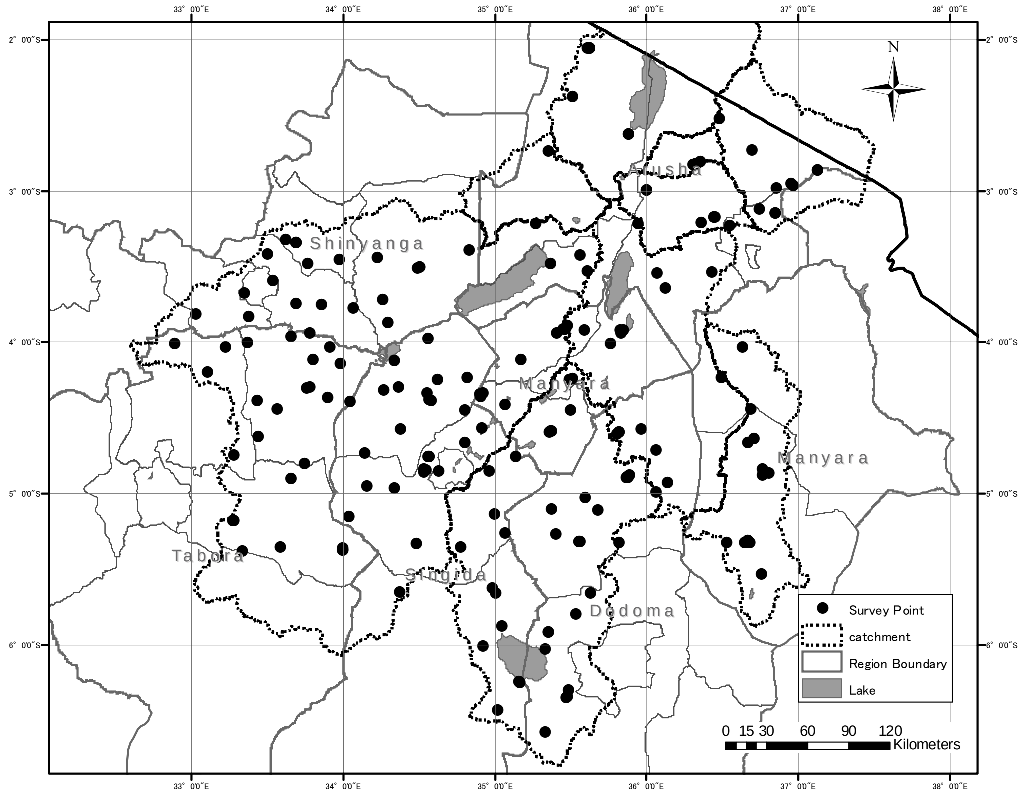


Figure 4-10 Location Map of Survey Points for Vertical Electrical Sounding

i) Relationship between Resistivity and Geology

The resistivity values resulted from VES were compared with the geology confirmed by the test borehole drilling as shown in Table 4-8.

Table 4-8 Comparison between Geology and Resistivity Value by VES

Geology		Range	Average (Ωm)
Igneous Rock	Granite	35.8 - 2000	472
	Weathered Granite	87.9 - 355.4	189
	Strongly weathered granite	7.5 - 7.5	8
Metamorphic Rock	Gneiss	357.9 - 5000	2331
	Weathered Gneiss	10.5 - 864.1	212
	Strongly weathered gneiss	8.4 - 8.4	8
	Schist	357.9 - 357.9	358
Volcanic Rock	Basalt (Lava)	83.3 539.0	311.2
	Pyroclastic Deposit	105.2 180.9	143.1
	Tuff Breccia	13.5 141.1	60.7
	Agglomerate	19.9 677.1	245.3
Sedimentary Rock	Banded Iron-stone	43.7 - 43.7	44
	Tuff	12.4 - 147.5	92.1
Soft-sediment	Gravel with sand	34.2 - 52.4	43
	Sand with gravel	12.9 - 12.9	13
	Medium sand with gravel	4.0 - 22.9	11
	sand	2.1 - 82.2	31
	Clayey sand	18.5 - 27.9	23
	Sandy Clay	2.6 - 12.9	8
	Clay	1.2 - 4.7	3

ii) Resistivity Analysis Pattern and Aquifer

Typical patterns of resistivity analysis results in IDB are categorized by following three patterns

Pattern 1: High (Middle) - Low - High

This pattern is typical for igneous rock and metamorphic rock area. Since the survey was conducted in dry season, first layer from the surface had relatively higher resistivity. Low resistivity of the middle layer is estimated as weathered layer or fracture zone, however when the resistivity is less than 10 ohm-m, the layer may be clay or contain salty groundwater. The deepest layer shown high resistivity is presumed to be bedrock. Although the possibility of water struck is low in the bedrock, fissure water can be expected in granite area.

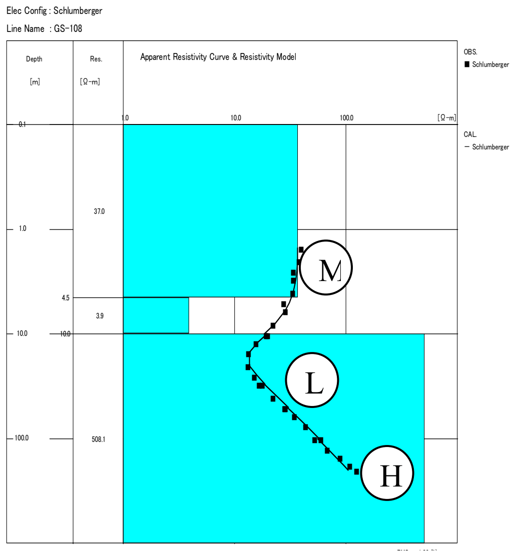


Figure 4-11 Typical Resistivity Structure -Pattern 1-

Pattern 2: Middle (High) - Low

This pattern is typical for soft-sediment area. When the value of low resistivity layer is less than 10 Ωm, it can be regarded to be clay layer or contained salty groundwater. It is difficult to get fresh water in this very low resistivity site. In the soft-sediment area, there is no high resistivity layer up to 200 m of exploration depth in this VES.

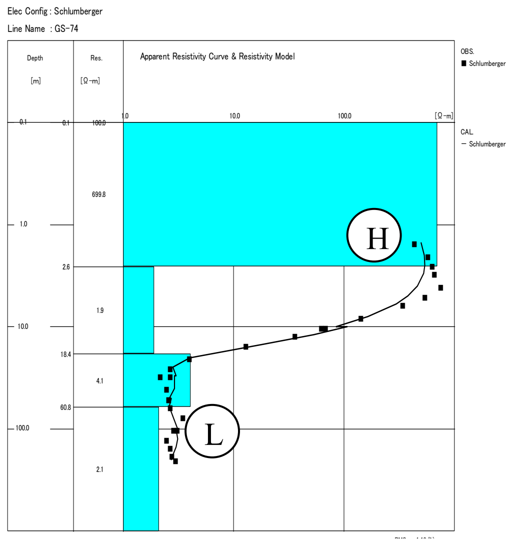


Figure 4-12 Typical Resistivity Structure -Pattern 2-

Pattern 3: Low (Middle) - High

This pattern is typical for granite area with shallow weathered zone. Weathered layer which shows low resistivity is very thin. And very high resistivity (over 500 Ωm) appears immediately. The high resistivity shows intact rock. Possibility of groundwater is very low.

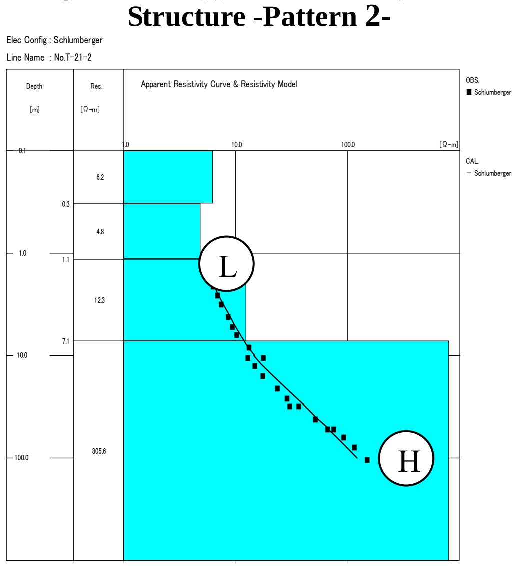


Figure 4-13 Typical Resistivity Structure -Pattern 3-

iii) Resistivity Distribution by VES

Based on the geophysical survey, resistivity distribution is illustrated focusing on the bedrock as shown in Figure 4-14. The distribution of resistivity is well-corresponded to geology which has resistivity as shown in Table 4-9.

Table 4-9 Resistivity Range and Geology

Resistivity (↑ m)	Area	Bedrock geology	Remark
Very High (800-2000)	Kondoa, Shinyanga, Kishapu Meatu, Maswa	Granitic rock	Few fault and lineament
	South of Babati	Metamorphic rock	-
High (500-800)	Singida, Iramba, Hanang, West of Uyui, Sikonge	Granitic rock	-
	Mbulu, Kiteto, Karatu	Metamorphic rock	-
Middle (200-500)	Bahi, Manyoni, East of Uyui	Granitic rock	-
	Simanjiro	Metamorphic rock	-
Low (100 – 200)	Monduli, Ngorongoro, Arumeru	Volcanic rock	-
Very Low (10 – 100)	South of Shinyanga, South of Kisyapu, Igunga, Nzega	Soft-sediment	Not encountered bedrock until 200m

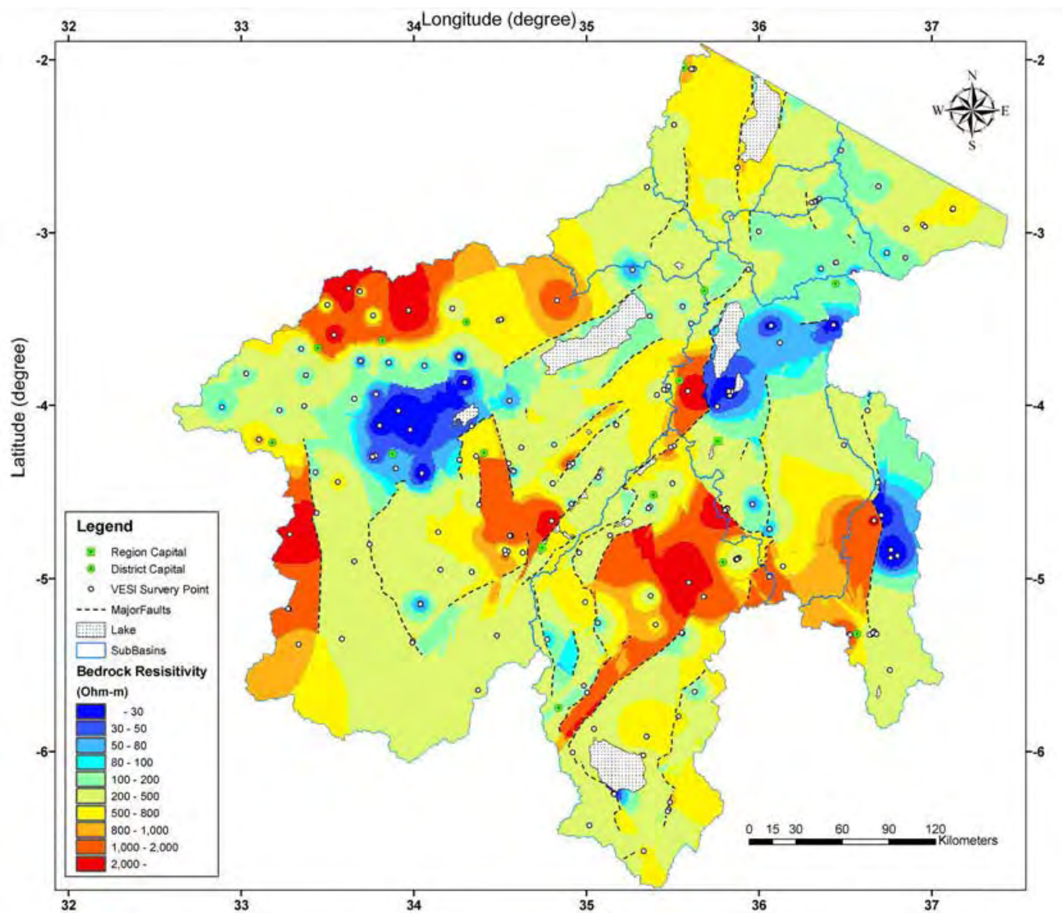


Figure 4-14 Distribution of Bedrock Resistivity Based on Geophysical Survey

On the other hand, a distribution of the bedrock depth based on VES results is shown in Figure 4-15. The feature of the distribution is described in below Table. These are also well-corresponding to the geological distribution.

Table 4-10 Feature of Bedrock Depth Distribution

Very shallow area	Very deep area
Shinyanga, Meatu, Maswa, Uyui, Manyoni, Singida Kondoa, Mbulu and Kiteto	Manonga river and Wembere river area
	Magugu (Babati district)
	Ndedo and Makame (Kiteto district)

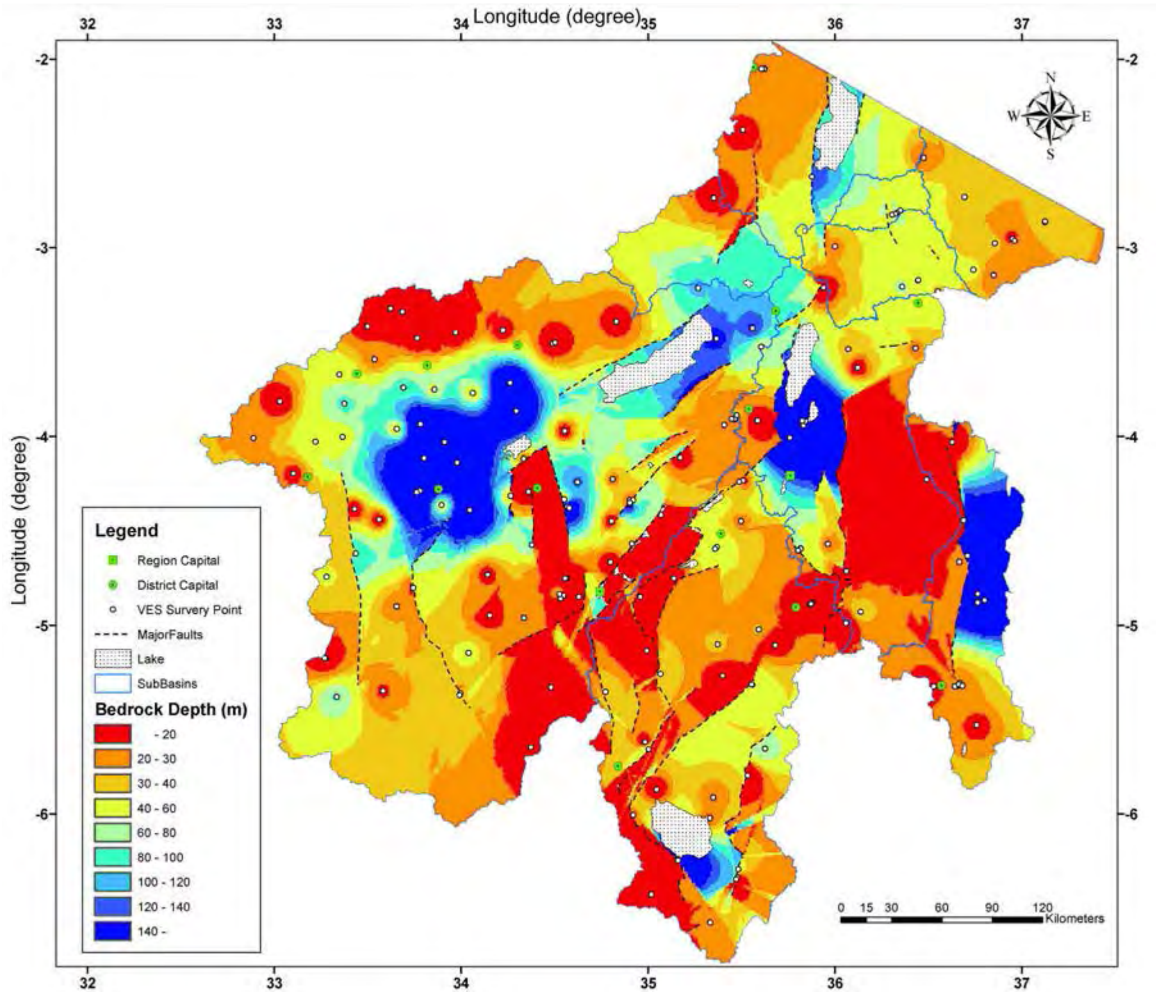


Figure 4-15 Distribution of Bedrock Depth Based on Geophysical Survey

2) Survey for Selection of Test Borehole Drilling Sites

Two methods, three techniques, of geophysical survey were adopted to select test borehole drilling sites. The Vertical Electrical Sounding (VES) was carried out to figure out the outline of geological structure in the candidate areas. When the site wasn't horizontal layered structure, two-dimensional resistivity survey or Magnetic survey was carried out at appropriate line in the candidate areas. Finally, the test drilling sites were determined on the basis of this survey result, including accessibility and topographic feature. The location of the sites are shown in Figure 4-16.

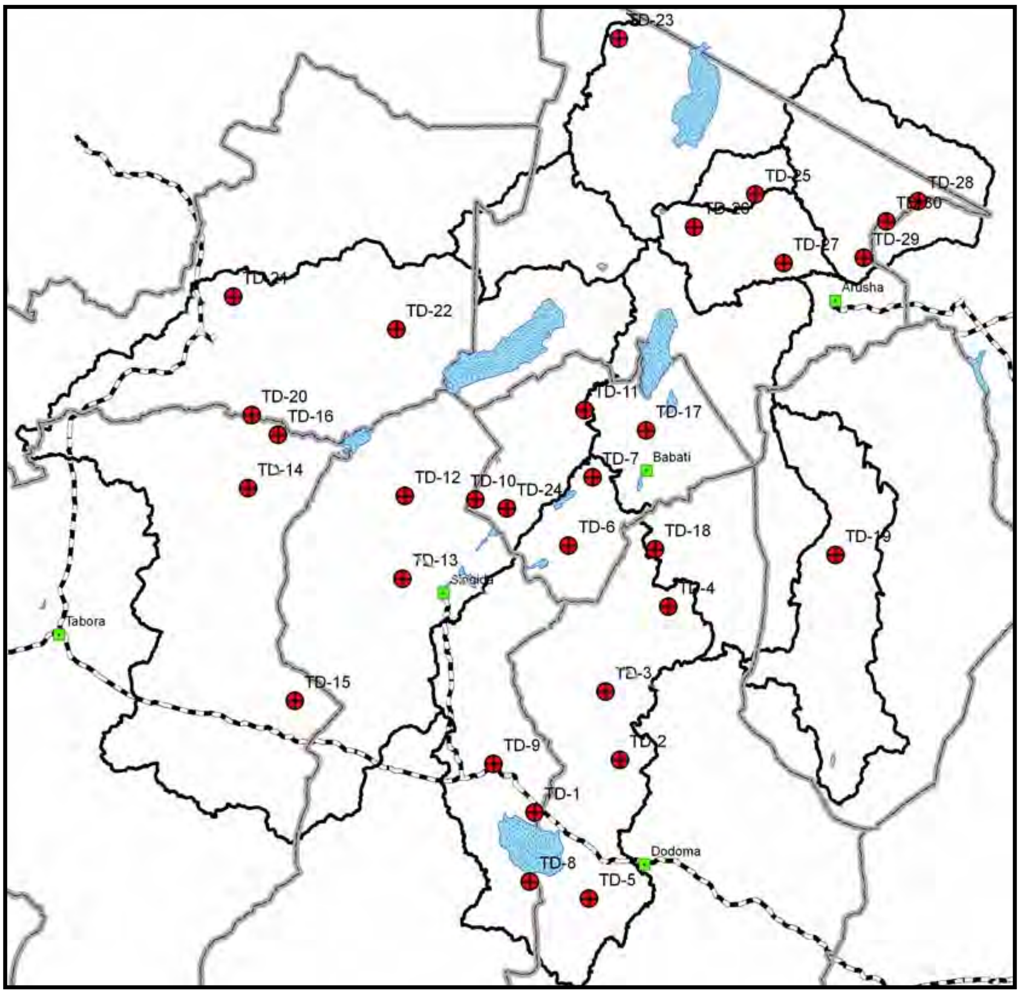


Figure 4-16 Location of Test Borehole Drilling Points

4.2.4 Test Borehole Drilling Survey

(1) Purpose

This survey was carried out to obtain the following information: geological condition, geological structure, groundwater condition, aquifer contents, complement for the existing borehole data, and monitoring on groundwater level and water quality.

This information obtained from the survey is to be fundamental data for establishment of hydrogeological map and evaluation of the groundwater potential in IDB.

(2) Specification of Survey

Test borehole drilling survey consists of drilling work, logging test, well construction and pumping test. This survey was carried out under the following specification:

1) Drilling

Rotary boring method was applied for the soft soil layer and "Down the Hole Hammer" drilling method was applied for the weathered or hard rocks. Casing pipe and suitable drilling fluid were used properly to maintain the borehole wall. The drilled diameter of borehole was 250mm for the rotary drilling and 200mm for the down the hole hammer drilling. Groundwater level and groundwater electric conductivity were measured when the first water strike was found. After completion of the drilling, the geophysical borehole logging was carried out.

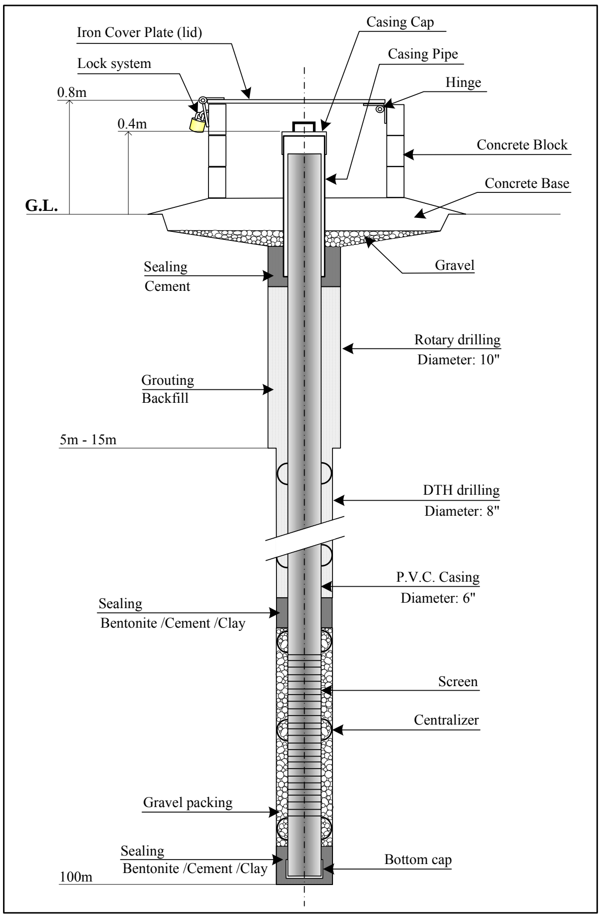


Figure 4-17 Schematic Diagram of Well Structure

2) Well Construction

i) Standard Well Structure

The standard well structure is shown in Figure 4-17.

ii) Casing Diameter

The diameter of the casing pipe was determined as 150 mm which is enough to install a standard submersible pump to conduct the pumping test.

iii) Geophysical borehole logging

Geophysical borehole logging was conducted before installing casing pipe to detect aquifer and to determine the screen position in the borehole. Resistivity logging and natural gamma logging were used for the logging. Resistivity logging can measure the resistivity value along the borehole. Natural gamma logging can measure the strength of gamma ray along the borehole. These logging data can be used for the estimation of stratigraphy and aquifer.

iv) Screen Pipe

PVC pipe with slit (Slot width: 1 mm) was used as the screen pipe. Setting depth and length of the screen pipe was determined based on the results of the drilling and the geophysical borehole logging.

v) Filter Packing and Sealing

Gravel which was siliceous material, clean and well-rounded was used for filter packing. Its grain size is 3 to 8 mm. The range of filter packing section was at least between more than 2m upward and downward of the screen. The sealing at least one (1) m range was put on the top and bottom of the filter packing section. The residual soil was used for the backfilling.

vi) Protection

Cementation was conducted around the mouth of the borehole to fix and protect the casing and to prevent rainfall water intrusion. Finally, the protection box with lock was set up.

3) Well Development

After well construction, the well development was conducted by air lifting. The well development was continued until the clear water recovered. The water level in borehole was measured 3 hours later after completion of the well development.

4) Pumping Test

After the completion of well development of each test borehole, pumping test were implemented. The purpose of pumping test is to estimate the critical yield and aquifer coefficients. The pumping test consists of the step drawdown test, the constant rate pumping test and the recovery test. Outline of pumping test is summarized in the table below.

Pumping Test	Specification	Measuring duration	Result of testing
Step draw down test	5 steps	Each step: 2 hours	Critical yield
Constant rate pumping test	Constant discharge: 80 % of the critical yield	48 hours	Hydraulic conductivity, Transmissivity, Storativity
Recovery test	Measure the water level until settled	At least 12 hours	Hydraulic conductivity, Transmissivity

(3) Results

The result of the test borehole drilling survey is summarized in Table 4-11.

Table 4-11 Results of Test Borehole Drilling Survey

Boring No.	National BH No.	Region	District	Village	Drilling Depth (GL- m)	Well Depth (GL- m)	Presumed Target Aquifer	Aquifer					Water level (m)	Critical Yield (m^3/hour)	Water Condition	
								Nature of Aquifer	Depth (GL- m)	Hydraulic Conductivity (m/min)	Transmissivity (m^2/min)	Storativity			Electrical Conductivity (mS/m)	Fluorid (mg/l)
TD-1	654/2006	Singida	Manyoni	Lusilile	100	40	Sediments	Fractured granite	16.4-22.3, 28.2-37.05	—	—	—	12.05	—	1,190.0	0.555
TD-2	640/2006	Dodoma	Dodoma Rura	Kongogo	105	100	Weathered/ Fractured rock	Fractured granite	57.5	4.16E-04	1.59E-02	8.29E-01	29.39	22.0	90.1	1.590
TD-3	636/2006	Dodoma	Kondoa	Bubutole	80	80	Weathered rock	Fractured granite	44, 65	7.02E-05	9.16E-04	1.64E-01	28.3	3.6	158.2	1.187
TD-4	381/2006	Dodoma	Kondoa	Loo	100	100	Fractured rock	Fractured gneiss	47.5-55, 75	1.13E-04	3.39E-03	9.48E-01	6.47	6.0	106.3	0.049
TD-5	638/2006	Dodoma	Dodoma Rura	Nholi	105	103	Fractured rock	Weathered/ Fractured gneiss	80-90	5.11E-04	1.53E-02	6.75E-01	14.51	15.0	163.3	0.330
TD-6	366/2006	Manyana	Hanang	Numbeta	120	74	Weathered volcanic rock	—	—	—	—	—	N/W.L.	—	—	—
TD-7	371/2006	Manyara	Babati	Bermi/Seloto	80	78	Fault	Weathered/ Fractured gneiss	42-45, 58-74	5.99E-03	1.76E-01	2.11E-03	31.2	33.1	17.3	0.560
TD-8	637/2006	Singida	Manyoni	Ikasi	120	120	Fault	Weathered/ Fractured granite	42-48, 70-76, 95-100	1.42E-05	1.10E-03	4.39E-02	30.9	15.0	261.0	0.273
TD-9	162/2006	Singida	Manyoni	Ilalo	135	135	Fractured rock	—	—	—	—	—	N/W.L.	—	—	—
TD-10	372/2006	Manyara	Hanang	Hirbadaw	147.5	147.5	Fracture zone	Fractured granite	115-130	3.57E-06	8.54E-05	1.99E-01	31.75	1.0	82.4	0.354
TD-11	370/2006	Manyara	Mbulu	Tlawi	101	100	Fracture zone	Fractured schist	63-86	3.35E-05	7.91E-04	2.85E-01	11.2	5.6	79.7	0.180
TD-12	651/2006	Singida	Iramba	Misingi	100	100	Fractured/ weathered rock or sediments	Fractured granite	44-92	2.15E-03	6.36E-02	7.64E-01	7.0	20.4	84.8	4.650
TD-13	642/2006	Singida	Singida	Sepuka	45	42	Weathered rock	Fractured granite	40	9.90E-05	5.84E-04	2.34E-02	3.2	1.6	136.6	3.138
TD-14	161/2006	Tabora	Igunga	Igogo	100	100	Weathered rock	—	—	—	—	—	N/W.L.	—	—	—
TD-15	650/2006	Tabora	Uyui	Nkongwa	60	60	Sediment or weathered rock	Weathered/ Fractured granite	30-37, 47-58	1.81E-04	4.27E-03	1.88E+00	7.7	4.7	384.0	1.270
TD-16	644/2006	Tabora	Igunga	Kininginila	80	80	Sediments	Calcareous Clay	62-68	—	—	—	40.5	—	1,600.0	—
TD-17	652/2006	Manyara	Babati	Mapea	80	80	Sediments	Clayey sand/ Weathered gneiss	27, 40, 72	7.61E-05	2.68E-03	2.20E-01	8.38	4.7	195.1	7.910
TD-18	385/2006	Dodoma	Kondoa	Masange	70	69	Fractured rock	—	—	—	—	—	68.9	—	—	—
TD-19	635/2006	Manyara	Kiteto	Makeme	75	72	Fractured rock	Fractured gneiss	44-50, 68	9.87E-04	2.71E-02	6.29E-01	35.5	16.0	1090.0	0.991
TD-20	653/2007	Shinyanga	Kishapu	Ngofila	75	75	Sediments	Sand	50	3.20E-05	9.61E-04	9.61E-03	4.33	0.8	687.0	34.950
TD-21	522/2007	Shinyanga	Maswa	Mwasayi	70	70	Fractured or weathered rock	Weathered/ Fractured granite	35	6.67E-06	3.14E-04	8.20E-02	4.3	2.4	414.0	1.410
TD-22	523/2007	Shinyanga	Meatu	Mwangudo	100	62	Fractured or weathered rock	—	—	—	—	—	N/W.L.	—	685.0	26.500
TD-23	526/2007	Arusha	Ngorongoro	Loliondo	100	75	Fractured or weathered rock	Sediment	65, 70, 80, 85	1.36E-03	4.52E-05	2.50E-03	13.09	4.0		
TD-24	527/2007	Manyara	Hanang	Bassotu	100	100	Fractured rock	Fractured schist	52, 60, 70	—	—	—	—	—	—	—
TD-25	520/2007	Arusha	Longido	Orkejuloongishu	50	45	Fault	—	—	—	—	—	N/W.L.	—	—	—
TD-26	518/2007	Arusha	Monduli	Engaruka Chini	130	115	Sediment	—	—	—	—	—	N/W.L.	—	—	—
TD-27	519/2007	Arusha	Monduli	Mfereji	100	98	Fractured or weathered rock	—	—	—	—	—	N/W.L.	—	—	—
TD-28	524/2007	Arusha	Longido	Olmolog	100	90	Fractured or weathered rock	—	—	—	—	—	N/W.L.	—	—	—
TD-29	521/2007	Arusha	Arumeru	Uwiro	105	100	Fractured rock	Weathered/Fractured basalt, agglomerate	30, 45, 60	3.17E-05	2.15E-03	1.12E-01	25.5	8.6	95.3	15.390
TD-30	525/2007	Arusha	Longido	Tingatinga	130	129	Sediment	—	—	—	—	—	N/W.L.	—	—	—

4.3 Hydrogeological Condition by Geological Unit

In this section, hydrogeological condition in IDB is expressed based on each geological unit. Stratum aquifer is expected to be in the Tertiary and recent sediment area. Other rocky areas, which are granitic rock, Metamorphic rock, and volcanic rock areas, are expected as fissure aquifer.

4.3.1 Granitic Rock Area (gs, gs-a, gs-b)

Granite is distributed widely in Shinyanga, Tabora, Singida, and Dodoma Region. Granite is a coarse grained igneous rock. Characteristically, granite is easy to be weathered and has many fractures near the surface. Weathered granite forms sandy state near surface. Clay mineral called "Kaoline" derives from weathered granite. The low land such as pocket or small basin accumulates this clay called "Mbuga". This is good material for brick. Additionally, fractures occur not only vertical but also horizontal in granitic rocks. Many small hills of granite called "Inselberg" with more resistant rock masses, which formed through weathering process, are observed in granite area.

This granite area was mainly formed in Archean period. The granite was uplifted, followed by weathering and erosion of the uplifted mountain, and finally pediplain was formed. Inselberg is a remaining hill in such a pediplain.

Inselberg in Singida

Groundwater in weathered zone, which can be regarded as stratum water, and fissure water in fissure zone are expected in the granite area. However, both of the aquifers are different from ordinary aquifer in stratum like sand or gravel layer. It is more complex structures. Therefore, thickness of the weathered layer or the place which has much more fissures has to be investigated for groundwater development. Additionally, it is also known that granite contains relatively much minerals which contain fluoride. Especially, pegmatite is distributed in some places in the granites area. Fluoride is concentrated in pegmatite as fluorite occasionally. The groundwater which passed through this rock has possibility of high fluoride contents.

Granitic rock area is classified into three units in the Geological map, (i.e., "gs", "gs-a" and "gs-b"). These are derived by satellite image analysis and existing geological map. The differences among these units are rough texture (gs), intermediate texture (gs-a) and smooth texture (gs-b) of topographic feature on the satellite images.

(1) Rough texture (gs):

Many inselbergs are remaining in this area. Each inselberg is expected to be a special recharge place for groundwater in rainy seasons. Perimeters surrounding the inselberg or the places which have many faults or lineaments are expected with high possibility of groundwater development. When the investigations are conducted, the existence and direction of faults and lineaments will be confirmed by geological maps or satellite images. In the field survey, both resistivity and magnetic or electromagnetic surveys shall be conducted to confirm the thickness of weathered zone or existence of fissure and faulted zones of the area.

Since the surface of this area is covered by granitic sand with high permeability, the existence of groundwater is expected at the lower part of weathered zone or the upper part of fresh rock. The place which has deep bedrock depth has advantage in such a weathered area. This area can be surveyed by resistivity survey method (electrical sounding). On the other hand, fissure zone can be detected by magnetic or electromagnetic surveys. Although the resistivity survey method can be applied for fissure zone, the magnetic or electromagnetic survey is more effective. On the other hand, the place which has high resistivity (over 500 Ωm) zone from shallow depth is very difficult to get groundwater and not suitable for groundwater development.

Expected drilling depth in this area is 30 to 60 m.

(2) Intermediate texture (gs-a):

This area is covered by thick weathered granite. Therefore, groundwater is expected in the weathered layer. Mainly resistivity survey method is used in this area. If much amount of water is required, fissure zone shall be investigated, but it is more difficult than “gs” area.

Expected drilling depth is 50 to 70 m.

(3) Smooth texture (gs-b):

This flat area is covered by hard sediment layer called “Kilimatinde Cement” which is accumulated by calcite or silicate. Since the Kilimatinde cement has a low permeability, groundwater recharge from the surface is not very much expected. The thickness of Kilimatinde cement is expected to have a maximum 30 m. It needs to confirm the existence of fault or inselberg using geological maps or satellite images for the groundwater development in this area.

Expected drilling depth is 50 to 100 m.

4.3.2 Metamorphic Rock Area, Usagaran system (Xs, Xs-a, Xs-l)

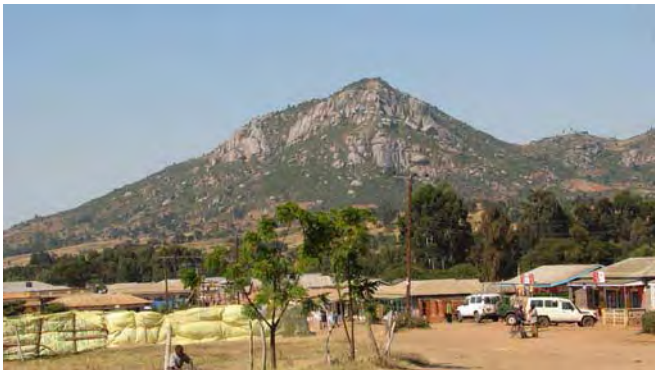
Metamorphic rock called “Usagaran” as a part of the Mozambique metamorphic belt is distributed in the north part of Arusha, Manyara, and Dodoma regions. The areas consist of older granitic and sedimentary rocks were metamorphosed by the orogenic movement of intrusion of granites. Therefore, some large scale foldings are laid in the axis of north-south direction. The rock is mainly gneiss.

Hydrogeological condition is almost the same as that of granite.

Gneiss, which is originated in intrusion of granite, is easier to be weathered than granite, and it forms wide pediplain. Masai Steppe is one of such kind of pediplains. This area has no rainfall gauges but the rainfall in Masai Steppe is supposed to be very small from surrounding meteorological data. Therefore this area is one of the most difficult places for groundwater development.

Usagaran was classified into three units in the Geological map, (i.e., “Xs”, “Xs-a” and “Xs-l”). These were derived by satellite image analysis and existing geological map. The differences among these units are rough texture (Xs), intermediate texture (Xs-a) and smooth texture (Xs-l) of topographic feature on the satellite image.

(1) Rough texture (Xs):



Mountain of Gneiss at Mbulu

Gneiss is distributed in this area. This area is located in a high altitude area. Weathered gneiss is considered to form colluvial deposit around Inselberg. Inselberg in this metamorphic rock area have wider skirts than the one in granite area. Hydrogeological condition is almost the same as the one in granite (gs). Perimeter of the inselberg or the place which has many faults or lineaments is expected to have high possibility of groundwater development.

The place which has deep bedrock depth area has advantage in such a weathered area. This area can be interpreted by resistivity survey. On the other hand, fissure zones can be detected by magnetic or electromagnetic survey methods. Although the resistivity survey can be applied for fissure zone, the magnetic or the electromagnetic survey methods are more effective.

Expected drilling depth is 40 – 80 m.

(2) Intermediate texture (Xs-a):

Stripes on Gneiss at Kiteto

This area is corresponding to gs-a in the granite area. Xs-a is lain like a hilly band along the axis of folding in the Geological map. These hilly areas are expected as a recharge area of groundwater, and the recharged water can be expected to form aquifer in the weathered zone. Therefore, the resistivity survey is used in this area mainly. If much amount of water is required, fissure zone should be investigated, though groundwater development is more difficult in this area than “Xs” area.

Expected drilling depth is 50 to 100 m.

(3) Smooth texture (Xs-l):

River Bed at Kondoa

This flat area is covered by thick weathered layer, and formed pediplain called “Masai Steppe”. In this area, the existing geological map shows scarcely any faults or lineaments. Since the weathered layer has high permeability, groundwater is in the deep part of weathered layer. Resistivity survey is effective for grasping the thickness of weathered layer.

Expected drilling depth is 70 to 150 m.


Outcrop of Dodoman Formation

4.3.3 Dodoman System (D)

Dodoman system, which is the oldest formation in Tanzania, is distributed in the central part of Dodoma region. This consists of the metamorphic rocks which are metamorphosed from sedimentary and granitic rocks in Archean. The rocks are schist, gneiss, and migmatite, etc.

Since the rocks of Dodoman system are very dense and hard to weathering, it forms hilly land around Dodoma town. Hydrogeological condition is almost the same as the one for “gs” area in the granite area. Weathered layer or fracture zone in Dodoman system can be developed for groundwater.

Test borehole drilling (TD-5) was drilled at the end of Dodoman series area and boundary of granite area. TD-5 encountered a fissure aquifer in granite zone of Dodoman System.

Expected drilling depth is 70-120 m.

4.3.4 Nyanzian System (Z)

Nyanzian System consists of metamorphic rock, which was metamorphosed from sedimentary and igneous rocks. It is distributed in the northern part of Tabora region, the southern part of Shinyanga region, the northern part of Singida region, and a part of Manyara region. Discriminative rock is banded ironstone which is distributed in Igunga district, and schist and quartzite are also distributed in this system. Banded ironstone is very dense and hard, groundwater is not expected in the rock. Schist and quartzite are also dense, but some groundwater is expected in fissure part of the rocks. Nyanzian system is surrounded by granite at many places. The place which contacts with granite is expected to have many fractures.

Magnetic or electromagnetic survey is recommended to investigate the fissure zone. Resistivity survey is not suitable for this area, because the weathered zone is expected very thin.

Expected drilling depth is 40-100 m.


Amphibolite and Pegmatite Dike of Nyanzian Formation in Iramba District


Banded Ironstone of Nyanzian Formation in Igunga District.

4.3.5 Volcanic Area (Nv and Nvd)

Lava flow, volcanic ash and pyroclastic flow sediment from the recent volcano in Neogene are distributed in Arusha region and a part of Manyara region. Almost all volcanoes consist of alkaline type volcanic rocks such as alkali basalt or trachyte. These volcanic activities occurred during the same period as the movement of the Great Rift Valley. Hot springs are flown out along the Great Rift Valley, e.g. at the west shore of Lake Manyara and the east of Singida region, etc.

Mt. Oldoinyo Lengai

Volcanic products which contained much fluoride were erupted from some volcanoes locally. Especially, Mt. Oldoinyo Lengai, the active volcano, exploded a special kind of lava called “carbonatite”, which is including much fluoride. Mt. Meru, which is in the back of Arusha town, is presumed to explode carbonatite lava also.

Volcanoes in this area are classified into two kinds; those are old and young volcanoes. Old volcanoes exploded low viscosity lava (i.e., flood basalt), in the wide range. These volcanoes formed very wide volcanic rock area from Mt. Kilimanjaro to Mt. Ngorongoro. Young volcanoes, which are Mt. Oldoinyo Lengai, Mt. Meru, or Mt. Hanang etc., are considered to explode materials which include much fluoride.

Groundwater development in this area is very difficult. It needs much consideration in order to decide a drilling site. However, if an aquifer is found, the yield of the borehole can be expected to be high.

Volcanic products in this area are volcanic ash, scoria, pyroclastic flow and basalt lava. Volcanic ash is in powdery state so that it can easily go up in the sky, and it diffuses to wide area by wind. Scoria is fizzy grain, which comes from several millimetres to several dozen millimetres in diameter. Pyroclastic flow is the phenomena that the eruption products flow down with high speed and with high temperature involving surrounding rocks from the top of volcano. Lava is molten material of rock extruded from volcano, and becomes solidified by cooling rapidly. Volcanic ash has high permeability generally. However, for its fine grain size, when volcanic ash accumulates and solidified with water, it becomes layers with low permeability. Scoria and pyroclastic flow sediments also have relatively high permeability. Basaltic lava has many cracks on the upper and lower part which were facing air and ground, and these parts have high permeability. From these characteristics, volcanic area can be considered to have much possibility of groundwater development because of its high permeability. Additionally, this mountainous area has much rainfall and high water retention capacity. However, a disadvantage in this area is that the water level becomes very deep due to the very thick volcanic ash and pyroclastic sediments, which has high permeability. Therefore, groundwater development is very difficult.

Basaltic materials have relatively low electric resistivity itself. It is difficult to decide the drilling point and its depth by resistivity survey method only. Topographic feature and the position of springs are

very important information for selecting the drilling point.
Expected drilling depth is 100-250 m.

4.3.6 Tertiary and Recent Sediment (N, Nl, and Nf)

Stratum aquifer is expected only in this area. Sand and clay are thickly accumulated in the end of drainage system by surface water flow. In IDB area, a river is never flowing out to the ocean. River water, which dissolved much mineral by passing through the underground, flows into lakes or swamps in the end of each sub-basin and later evaporates there. The water in the lakes or the swamps increases the concentration of the minerals by evaporation, and hence the accumulation of salts of various types happens. Therefore, the groundwater in the lake sediment has denser concentration of such kind of salts.

Villagers are taking salt from edge of Bahi swamp in dry season

Clay layer has very low permeability. It behaves as aquiclude. Sand layer and gravel layer has high permeability. These layers are expected as good aquifer in this area. However, even when a good aquifer is found, the water is expected to be saline.
Vertical electric sounding is suitable to investigate the bedrock depth for this area. Most of these areas have very low resistivity, which shows below 10 Ωm, because of clay minerals. Relatively high resistivity layer, which shows 30 to 50 Ωm, is expected as aquifer.
Expected drilling depth is 30-200 m.

4.3.7 Fault System Related to the Great Rift Valley

The structural feature of fault system within IDB is related to the Great Rift Valley. Many large scale faults trend north-south or northeast-southwest direction in this area. Basically, these faults which are related to the Great Rift Valley are normal fault; the fracture zone of these faults is presumed to store much groundwater.
Some places along the Great Rift Valley have hot springs. Some hot springs are far from active volcanoes. For example, the west shore of Lake Manyara and the eastern

Resistivity survey in close to fault scarp (Test borehole No. TD-8, Ikasi, Manyoni).

valley of Singida Region are far from any active volcanoes. The water quality of the hot springs is always poor, because the water is including much quantity of minerals.

The dip angle and dip direction of the fault should be considered for the drilling site selection for groundwater development. The dip with very steep angle, normal fault, is well suited as a groundwater development site. Therefore, the drilling site shall be selected in very close to the scarp to be within the width of the fault.

Expected drilling depth is 70-200 m.

4.4 Groundwater Flow Analysis

Groundwater flow was analyzed by using static water level of boreholes and water quality data.

4.4.1 Altitude of Static Water Level

The groundwater altitude distribution map was produced by using the existing borehole data, spring data and test borehole drilling data in this study. Groundwater has mainly two kinds of aquifer, confined and unconfined aquifer. The water level of confined aquifer is called piezometric head, and the water level of unconfined aquifer is called natural water table. However, the kinds of aquifers or water levels were not clear in the existing data. Therefore, the difference was neglected in the production of the map. Figure 4-18 shows the distribution map of the altitude of static water level. The altitude of the static water level of each groundwater was calculated from the altitude of wells measured by GPS and their static water levels measured.

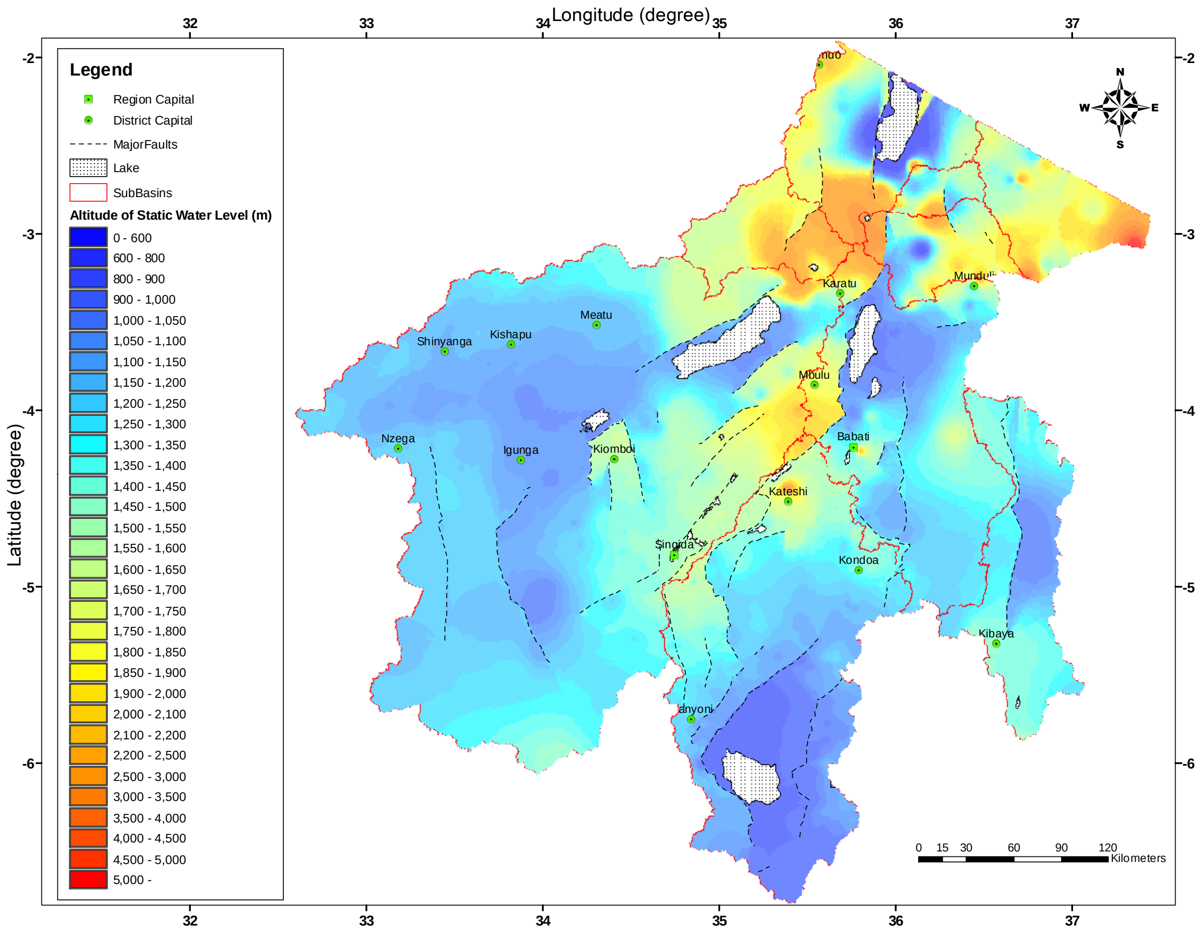


Figure 4-18 Distribution of the Altitude of Static Water Level

4.4.2 Water Quality Hexa-diagram Analysis

Surface water and rain water infiltrates to underground, passes through soil and rock, dissolves minerals from surrounding rock, and flows underground with changing the water quality. Therefore,

water flow can be analyzed by comparing water quality in upstream and downstream of groundwater.
The distribution of water quality hexa-diagram is shown in Figure 4-19. The parameters of water quality are Sodium and Potassium (Na^++K^+), Calcium (Ca^{2+}), Magnesium (Mg^+), Chloride (Cl^-), Bi-carbonate (HCO_3^-), and Sulphate and Nitrate (SO_4^{2-}+NO_3^-). Additionally, the colour of the diagram shows kinds of sources of the water sample; blue colour shows borehole, light blue shows spring, yellow shows shallow well and orange colour shows surface water.
Generally, surface water forms narrow shape as the diagram because the dissolved mineral is few. Shallow groundwater in shallow well includes relatively much bicarbonate. The downstream of groundwater or the stagnant groundwater tends to have wider width of the diagram because of dissolving larger quantity of various minerals. Especially, the widths of Sodium and Chloride components become wider in the downstream side. The dissolutions of Calcium, Magnesium and Sulphate are depending on the geological condition. For comparison, the hexa-diagram of seawater shows cocktail glass shape because the widths of Sodium and Chloride components are wide and others are narrow.

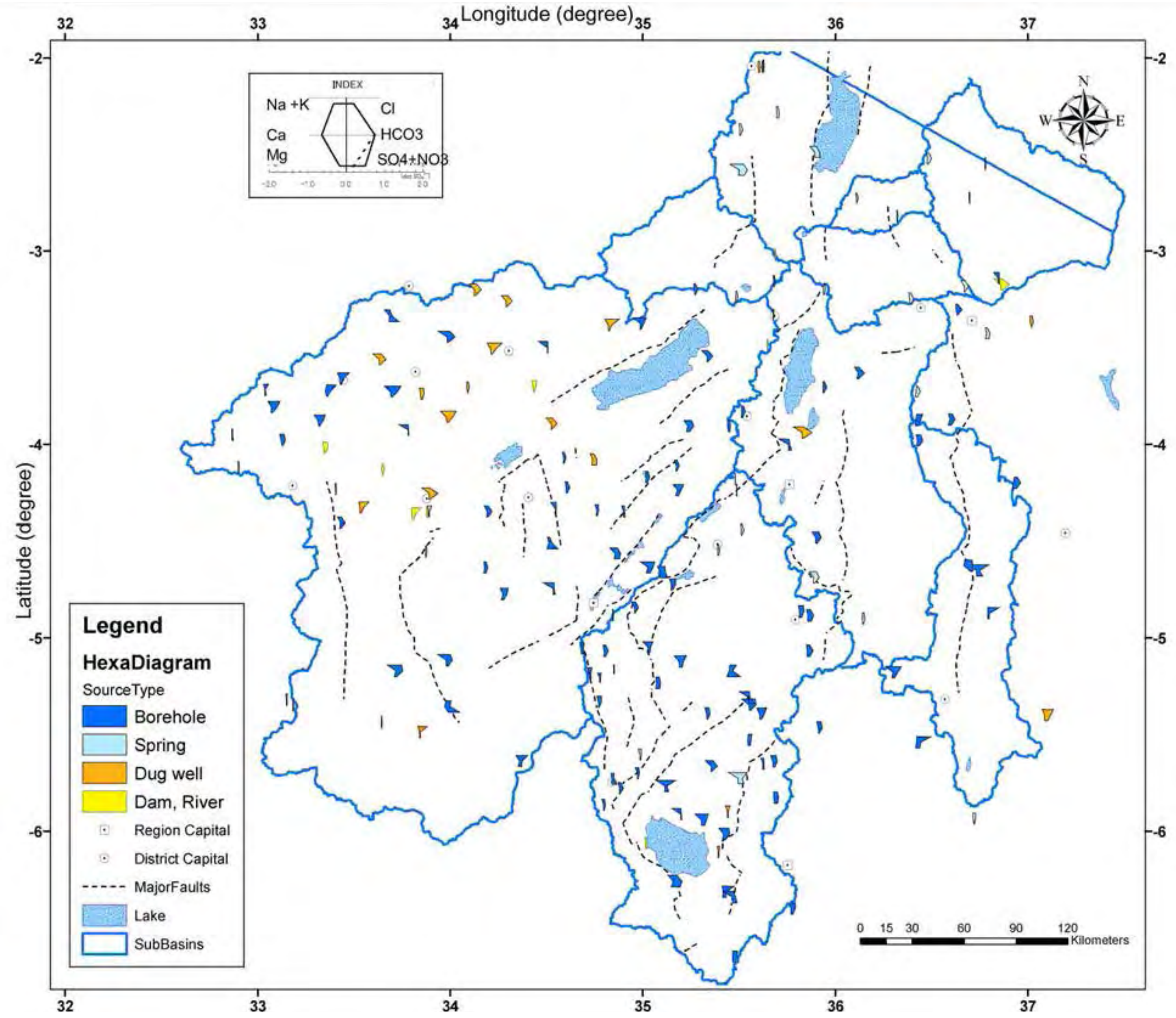


Figure 4-19 Hexa Diagram of Water Quality in IDB

4.4.3 Groundwater Flow

Groundwater is flowing from high position to low position by gravity. This is same as the flow of surface water. Therefore, groundwater flow direction can be provided by tracing the altitude of static water level. Additionally, changing of water quality, which can be recognized by the distribution of hexa-diagram, was considered for groundwater flow analysis. Figure 4-20 shows the groundwater flow map. This map is showing only horizontal direction of the flow, and the length of the arrow is not showing the flow rate.

Groundwater flow velocity is also estimated from the altitude of static water level. the velocity is calculated by following equation, which is Darcy's law.

$$V=K(dH/dL),$$

where, V is the velocity (m/min), K is the hydraulic conductivity (m/min), H is the piezometric head, and L is the distance between two points which the piezometric heads are measured. (dH/dL) is called the hydraulic gradient.

Groundwater flow velocities are calculated at the test borehole drilling site. The result is shown in Table 4-12.

Table 4-12 Groundwater Flow Velocity around Test Borehole Drilling Site

Boring No.	Nature of Aquifer	Hydraulic Conductivity (m/min)	Distance between contour (m)	Interval of the contour (m)	Velocity (m/year)	Remark
TD-2	Fractured granite	4.16E-04	20,399	100	1.07	
TD-3	Fractured granite	7.02E-05	14,439	100	0.26	
TD-4	Fractured gneiss	1.13E-04	8,345	100	0.71	
TD-5	Weathered/Fractured gneiss	5.11E-04	14,484	100	1.85	
TD-7	Weathered/Fractured gneiss	5.99E-03	8,193	100	38.43	Fault area
TD-8	Weathered/Fractured granite	1.42E-05	691	100	1.08	Fault area
TD-10	Fractured granite	3.57E-06	6,005	100	0.03	
TD-11	Fractured schist	3.35E-05	7,108	100	0.25	
TD-12	Fractured granite	2.15E-03	4,426	100	25.53	Fault area
TD-13	Fractured granite	9.90E-05	26,945	100	0.19	
TD-15	Weathered/Fractured granite	1.81E-04	16,653	100	0.57	
TD-17	Clayey sand, Weathered gneiss	7.61E-05	1,841	100	2.17	
TD-19	Fractured gneiss	9.87E-04	370	100	140.40	Sediment area
TD-20	Sand	3.20E-05	24,072	100	0.07	
TD-21	Weathered/Fractured granite	6.67E-06	25,110	100	0.01	
TD-29	Weathered/Fractured basalt, agglomerate	3.17E-05	1,891	100	0.88	

The velocities in the granitic rock and metamorphic rock areas are very slow. On the other hand, the velocity in the fault area is faster.