MINISTRY OF PUBLIC WORKS
THE REPUBLIC OF LIBERIA

THE LIBERIA WATER AND SEWER CORPORATION

THE MASTER PLAN STUDY ON URBAN FACILITIES RESTORATION AND IMPROVEMENT IN MONROVIA IN THE REPUBLIC OF LIBERIA

GROUNDWATER DEVELOPMENT PLAN IN PAYNESVILLE AREA

FINAL REPORT

March 2010

JAPAN INTERNATIONAL COOPERATION AGENCY

YACHIYO ENGINEERING CO., LTD.
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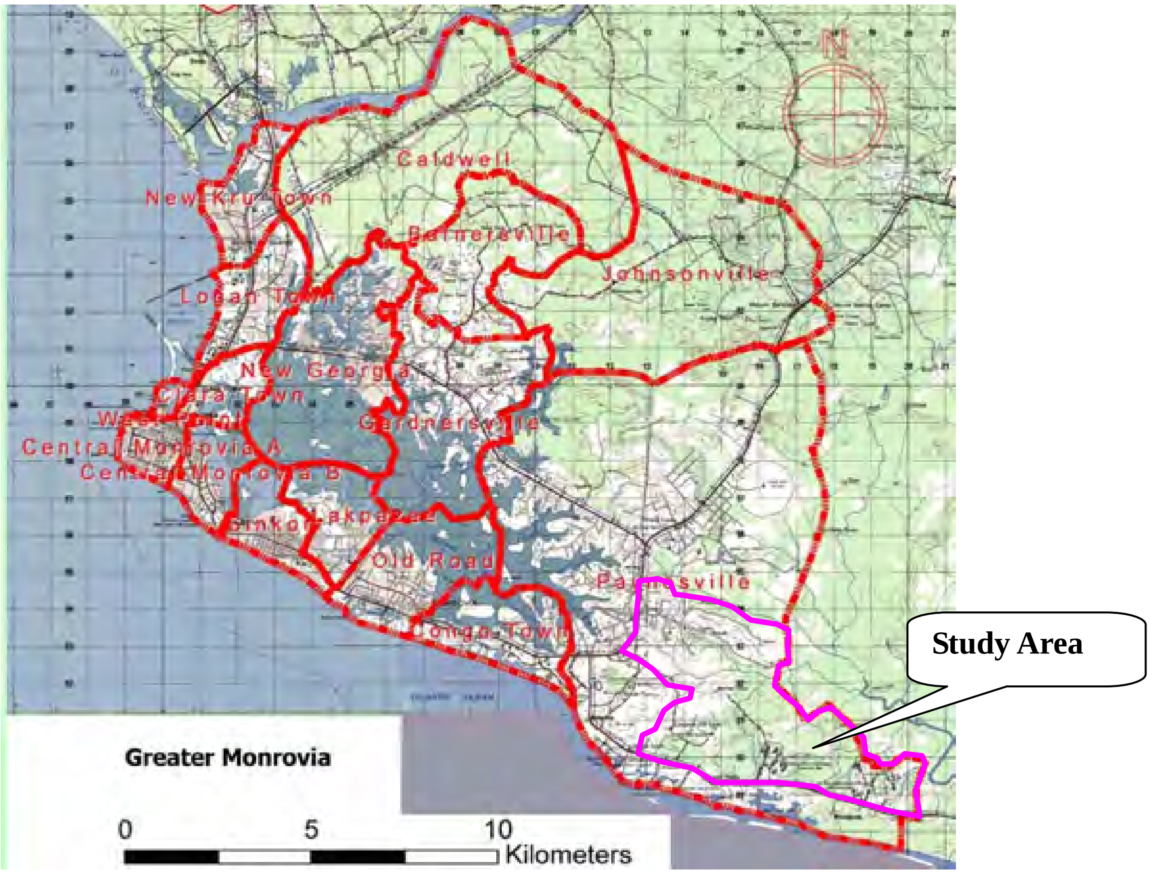
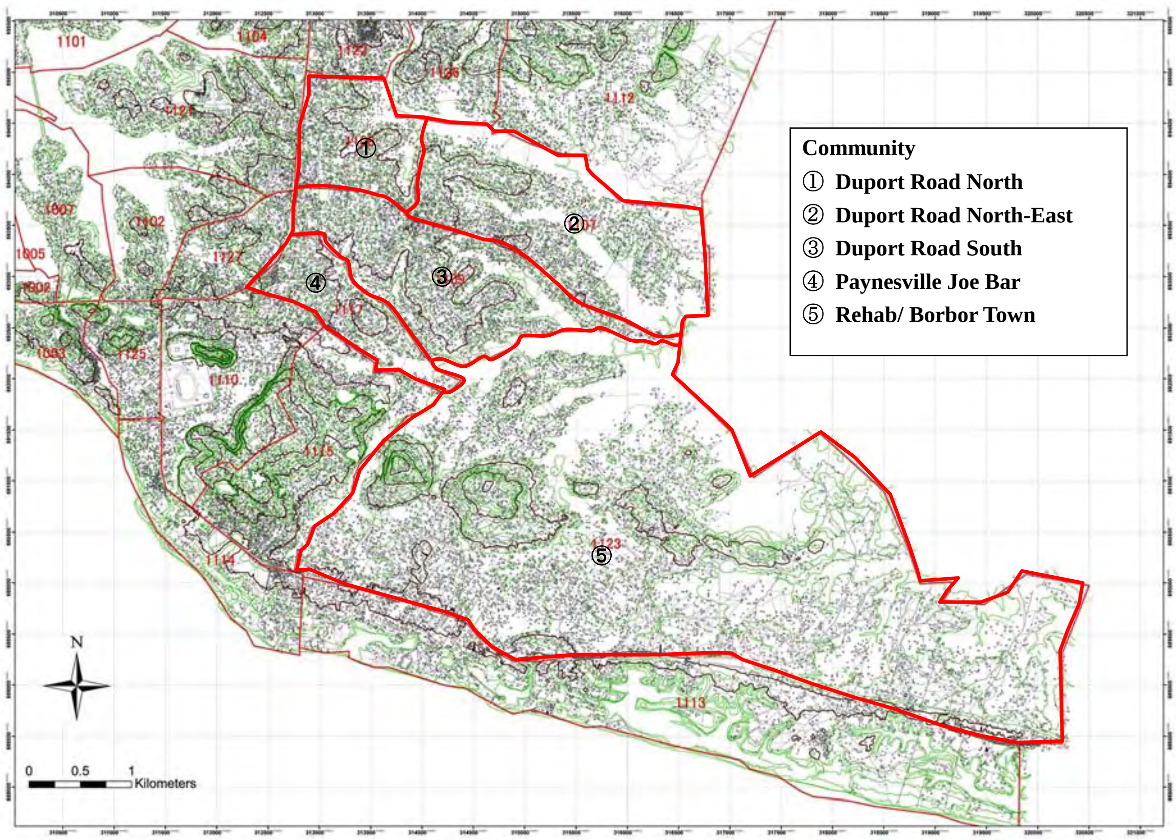
LOCATION MAP



Location Map of Greater Monrovia and Study Area



Map of Study Area

The Master Plan Study on Urban Facilities Restoration and Improvement in Monrovia in the Republic of Liberia

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ABBREVIATIONS

EC	Electric Conductivity
GIS	Geographic Information System
GPS	Global Positioning System
GM	Greater Monrovia
JICA	Japan International Cooperation Agency
LHS	Liberian Hydrological Services
LISGIS	Liberia Institute for Statistics and GeoInformation Services
LWSC	Liberia Water and Sewer Corporation
MLME	Ministry of Lands, Mines and Energy
MPEA	Ministry of Planning and Economic Affairs
MPW	Ministry of Public Works
MTA	Monrovia Transit Authority
VES	Vertical Electric Sounding
WB	World Bank
WG	Working Group
WHO	World Health Organization
WMO	World Meteorological Organization
WSRP	Water and Sanitation Rehabilitation Program
WTP	Water Treatment Plant

1. INTRODUCTION

1.1 Objectives

This study is carried out to examine the implementability of groundwater development project in Paynesville as a grant aid project of Japan for water supply facilities improvement, and to make water development plan in detail by additional investigation. The study is succeedingly conducted as a additional study from "The Master Plan Study on Urban Facilities Restoration and Improvement in Monrovia in the Republic of Liberia" executed as a main project from November .2008 to November 2009. The study includes following items.

1) Electrical sounding
2) Exploratory well drilling
3) Water quality analysis

Following other 2 additional studies are carried out at same time in the main project.

1) Operation & Maintenance and Monitoring of Community-Managed Satellite Water Supply System
2) Environment Impact Assessment of Somalia Drive

1.2 Study Area

The study area includes following 4 communities in Paynesville as shown in **Figure 1.1-1**.

1) Duport Road North-East Community
2) Duport Road North Community
3) Duport Road South Community
4) Paynesville Joe Bar Community
5) Rehab/ Borbor Town Community

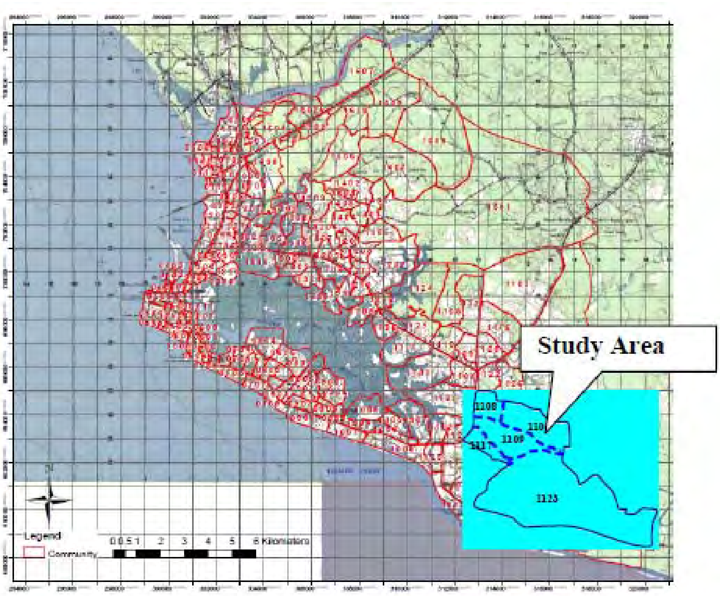


Figure 1.2-1 Location of the Study

1.3 Study Schedule

The study commenced in October 2009 and to be completed in March 2010.

1.4 Investigation Items and Quantity

The investigation items of the study are shown in **Table 1.4-1**.

Table 1.4-1 Investigation Items and Quantity of the Study

Item	Place	Point	Total Quantity	Remarks
Electrical Sounding	12	3 points/ place	36 points	
Exploratory Well Drilling	6	7 wells	Total depth 484m	
Screen/ Casing Installation	6	5wells	Total length 326m	6"Casing
Water Quality Analysis	6	6 wells	38 items x 6 wells	

2. TOPOGRAPHY AND GEOLOGY

2.1 Topography

The study area locates in the south-west part of the Du river watershed. The watershed boundary exist west side and south side of the study area. The future of topography of the study area is shown in **Figure 2.1-1**

The land form classification of the Study area is as follows.

1) Diabase hills (sub-zone 1a; Central hills; sub-zone 1b; North side hill, sub-zone1c; Masurado river south-east hill)
2) Upper to middle stream area of south-west branches of the Du river (zone 2).
3) Soth side narrow plain (zone 3)
4) Low land of the south-west area of Du river (4 zone)
5) Beach zone (5 zone)

The low mound like sand dune is recognized along beach between zone 3 and zone5.
The elevation of watershed ridge and each zone around the study area is as follows.

1) The elevation of watershed ridge is 10 to 18m in west side, and 10 to 16 m in south side.
1) The elevation of sub-zone 1a is 10 to 48m, sub-zone 1b is 10 to 18m, and sub-zone 1c is 8 to 12m.
2) The elevation of zone 2 is 4 to 14m.
3) The elevation of zone 3 is 2 to 8m.
4) The elevation of zone 4 is 2 to 4m.
5) The elevation of zone 5 is 0 to 12m.

The week lineaments are recognized along foot of Diabase low hills. West-north-west to east-south-east direction is predominant. North-east to South-west direction is secondly predominant.

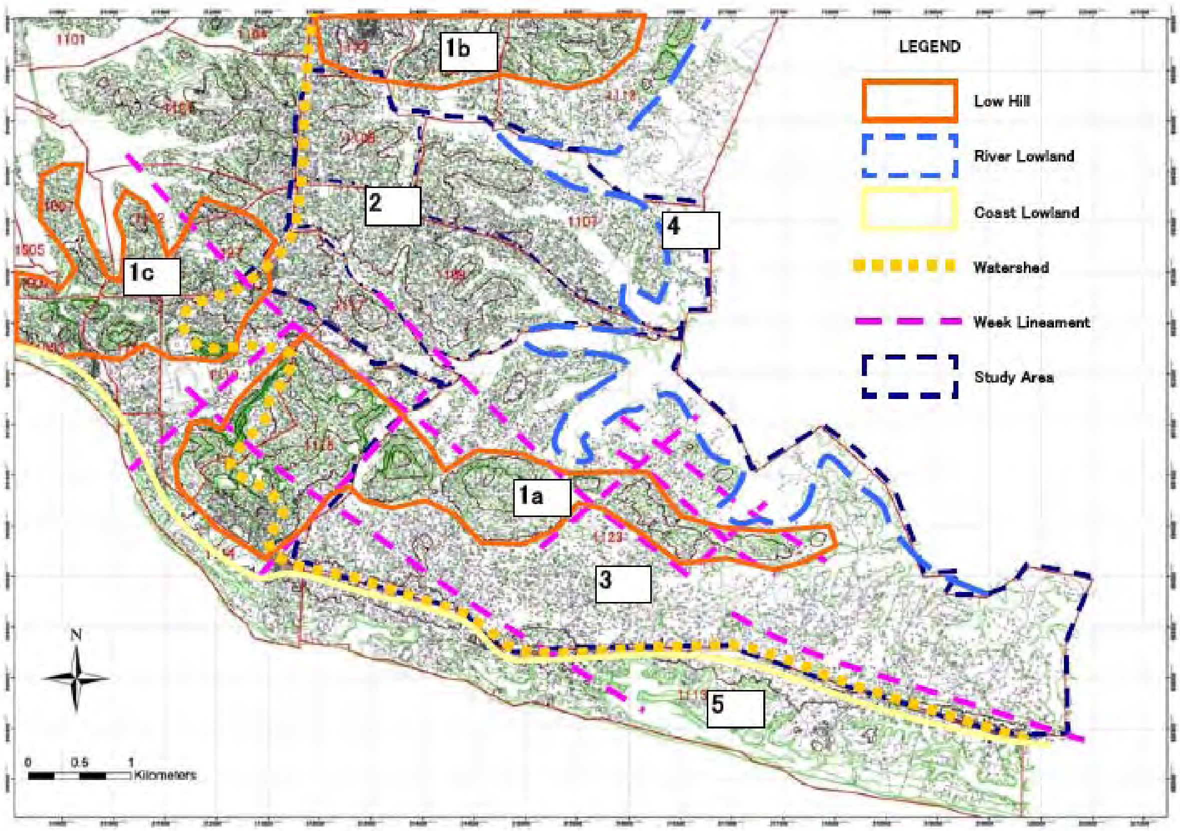


Figure 2.1-1 Feature of Topography of the Study Aria

2.2 Geology

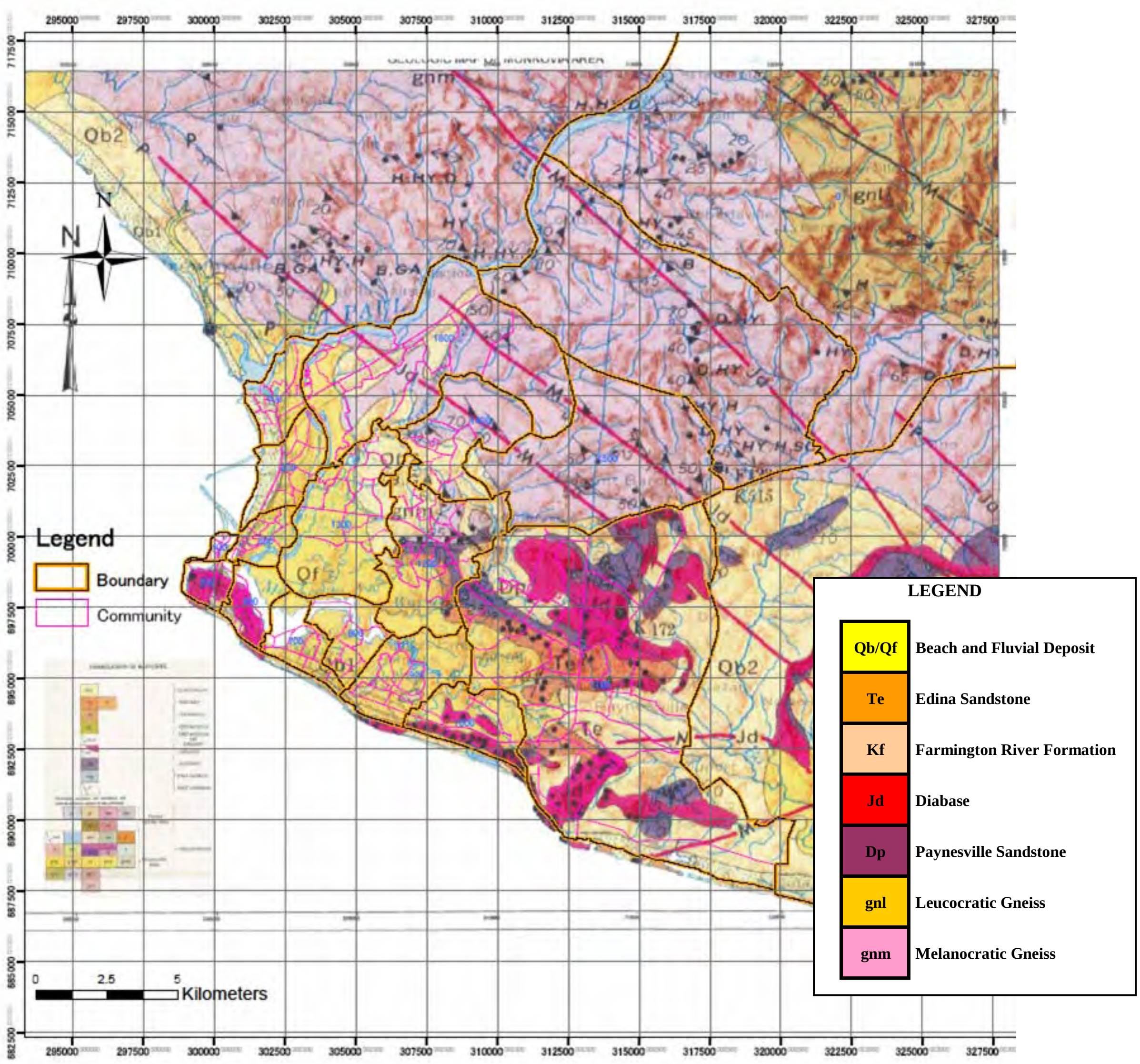
The geology of the greater Monrovia and surrounding area mainly consists of Precambrian Melanocratic gneiss, Devonian Paynesville sandstone, Jurassic Diabase dike, Tertiary Edna sandstone and Quaternary Beach and Fluvial deposits.
The geological composition of the greater Monrovia and surrounding area is shown in **Table 2.2-1**. The geological map of the greater Monrovia and surrounding area is shown in **Figure 2.2-1**.
The Precambrian Melanocratic gneiss is widely distributed as a base rock in north part of the grater Monrovia such as New kru town, North part of Logan town, Caldwell, Barnesville, North part of New Georgia, North part of Gardnesville and Johnsonville.
The Devonian Paynesville sandstone is distributed at central area of New Georgia and at everywhere of Paynesville. The formation is intruded by Jurassic Diabase at everywhere and covered by Tertiary and Quaternary deposit at low flat area.
The Jurassic Diabase is distributed as a dike or intrusive rock with rather large rock body in Central Monrovia A and B, Congo Town and Paynesville. The rock bodies often form row height hill.
The Tertiary Edina sandstone is distributed at front of Paynesville sandstone at central and south east area of New Georgia and at central and partly south area of Paynesville.
The Quaternary deposit is distributed low flat land of all the grater Monrovia area and covers underlying other formations.

The geology of the study area consists of Devonian Paynesville sandstone, Jurassic Diabase dike, Tertiary Edna sandstone and Quaternary Beach and Fluvial deposits.
The Paynesville sandstone is distributed partly forming tinny outcrops in plain area around Diabase low hill (1a sub-zone). The hard outcrops are recognized at VES 19 to VES 20 area. The formation is almost overlaid widely by Quaternary deposit in north-west and central area and Tertiary Edina sandstone in north-west area of the study area.
The Diabase is distributed forming low hills in 1a, 1b and 1c zone. West-north-west to east-south-east directed arrangement of Diabase rock bodies is recognized.
The Edina sandstone is distributed in north-west area of the study area, and overlaid widely by Quaternary deposit in north-east area and central area of the study area.
The Quaternary beach and fluvial deposit is distributed widely in low land and middle area up to watershed boundary overlaying old formations.

Table 2.2-1 Geological Composition of Study Area and Surrounding Area

Era	Period	Symbol	Formation	Description	Remarks
Cenozoic	Quaternary	Qb/Qf	Beach and Fluvial Deposit	Modern beach deposits (seashore sand), Older beach deposits (pure white quartz sand, buff to yellowish-brown sand and silt)	
	Tertiary	Te	Edina Sandstone	Brownish yellow, light-brown, white, medium to coarse grained gritly to conglomeratic quartz sandstone	Generally less than a few meters thick
Mesozoic	Cretaceous	Kf	Farmington River Formation	Brown to dark green massive sandstone, poorly to moderately well sorted, Conglomerate unit at base	No indication in the geological map
	Jurassic	Jd	Diabase	Dark-gray, fine to course grained rock, mainly diabasic but locally gabbroic in texture, chiefly dikes with north-west trending, partly forming sill-like bodies	
Paleozoic	Devonian	Dp	Paynesville Sandstone	Light colored, fine to medium grained, well rounded and well sorted, cross bedded quartz sandstone, subordinate cross bedded reddish brown siltstone and shale	
Precambrian		gnl	Leucocratic Gneiss	Light colored, medium to coarse grained, foliated, commonly banded, rock composition ranging from granite to granodiorite, locally quart diorite	Distribution out of the study area
		gnm	Melanocratic Gneiss	Dark colored, medium grained, moderately foliated, rock composition ranging from diorite to gabbro, including amphibolite and granitic gneiss	

Source: 1/62,500 GEOLOGICAL MAP OF MONROVIA AREA (LISGIS Material)



Source: Geological Map of Monrovia Area (LISGIS materials)

Figure 2.2-1 Geological map of the Grater Monrovia and Surrounding Area

3. ELECTRICAL SOUNDING

3.1 Outline of Electrical Sounding

(1) Objectives and method

The vertical electric sounding (VES) is carried out to grasp widely hydrogeological condition in the study area and to select exploratory well sites. The Schlumberger method is applied as vertical electric sounding in consideration of the method generally performed in Liberia and the method of enforcing a number of people. The field work of vertical electric sounding is carried out by Bezaleel Turnkey Contractors Inc. Liberia from 16th Oct. 2009 to 23rd Oct. 2009.

(2) Location and quantity

The location map of the electrical sounding is shown in **Figure 3.1-1**. The quantity of the sounding is shown in **Table 3.1-1**. The vertical electric sounding is carried out at selected 12 places, 3 points per each place, total 36 points. The current electrode spacing (AB) is set from 2m to maximum 900m, and the potential electrode spacing (MN) is set from 0.66m to 15m at each measurement point. Each point is arranged about 300-500m apart.

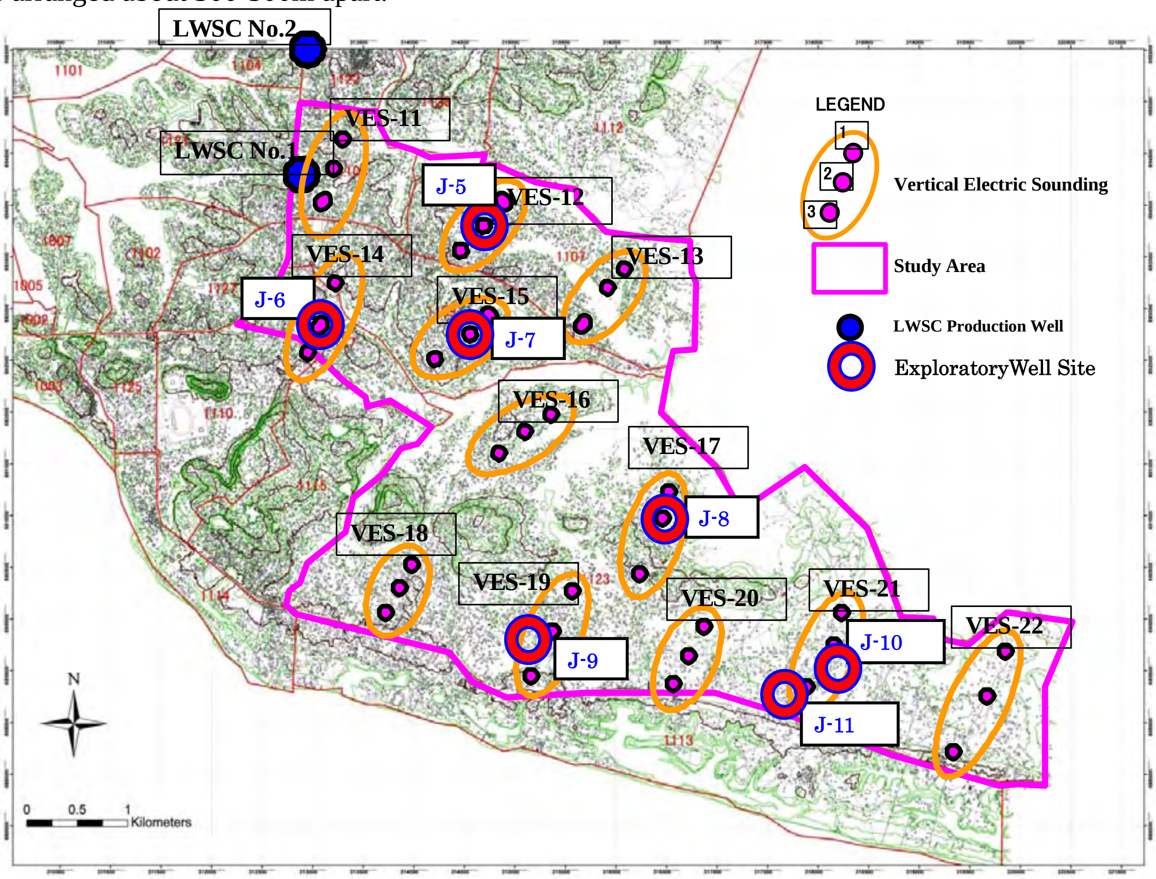


Figure 3.1-1 Location of Electric Sounding

Table 3.1-1 Location and Quantity of Vertical Electric Sounding

VES No.	Sub-No.	Community	UTM Coordinate		Elevation (m)	AB (Max m)	Remark
			Easting	Northing			
VES-11	1	Outland C. / Hammond Field C., Duport Road North	313375	694670	11	400	
	2		313283	694351	11	300	
	3		313216	694045	13	400	
VES-12	1	Cowfield C., Duport Road North-East	314815	694011	10	400	
	2		314629	693842	9	400	Well J-5
	3		314398	693573	8	400	
VES-13	1	Sahra C., Duport Road North-East	316042	693426	6	400	
	2		315888	693171	5	300	
	3		315687	692881	7	400	
VES-14	1	Worldwide C., Duport Road South Block/ G-2., Paynesville Joe Bar	313267	693236	8	400	
	2		313024	692922	11	400	Well J-6
	3		312779	692731	14	400	
VES-15	1	Zubah Town Rehab C., Duport Road South	314762	692979	7	300	
	2		314577	692842	10	400	Well J-7
	3		314117	692584	12	400	
VES-16	1	Zubah Town C., Rehab/ Borbor Town	315388	691973	7	400	
	2		315108	691806	8	300	
	3		314773	691549	6	400	
VES-17	1	Thinkers Village Old Field C., Rehab/ Borbor Town	316538	691257	8	400	
	2		316469	691046	6	400	Well J-8
	3		316061	690534	9	400	
VES-18	1	Rehab C., Rehab/ Borbor Town	314064	690639	8	400	
	2		313901	690363	10	400	
	3		313735	690110	8	400	
VES-19	1	Kendeh Town Old Field C., Rehab/ Borbor Town	315583	690301	7	400	
	2		315381	689999	8	400	Well J-9
	3		315041	689483	10	400	
VES-20	1	Kpayam Town C., Rehab/ Borbor Town	316890	690052	5	300	
	2		316692	689655	6	400	
	3		316584	689416	7	400	
VES-21	1	Ghengbah C., Rehab/ Borbor Town	318196	690119	3	200	
	2		318191	689759	4	400	Well J-10
	3		317835	689388	6	400	Well J-11
VES-22	1	VOA C., Rehab/ Borbor Town	319886	689713	3	400	
	2		319689	689192	4	400	
	3		319408	688710	7	400	

(3) General information related VES interpretation

General information for VES interpretation is as follows. The resistivity of stratum and rock is shown in **Table 3.1-2**.

1) The resistivity of rain shows 1,000-1,500 ohm-m. Generally, the resistivity of groundwater in shallow aquifer shows 50-100 ohm-m, and the resistivity of groundwater in deep aquifer shows 20-50 ohm-m
2) Rock which has less than 100 ohm-m of resitivity has possibility of aquiclude.
3) Rock which has more than 1,000 ohm-m of resistivity has possibility of igneous rock, metamorphic rock or dry condition among aquifer's rock.
4) Rock which has more than 1,000 ohm-m of resistivity under groundwater has possibility of rock belonging to aquiclude except of a kind of gravel layer such as fun gravel.
5) Aquifer saturated groundwater shows 100-1,000 ohm-m except of a kind of gravel layer such as fun gravel.

(Source; Shimura (1984) Method of Electric Sounding, Shoukodo Publish Japan)

Furthermore, there is following information;

a) In case of increase of moisture content at fault or weathered portion, resistivity remarkably decreases. In case of increase of graphite or iron ore content, resistivity clearly decreases.
b) Crackly portion or weathered portion of hard rock shows 100-1,000 ohm-m, and hard weathering clay zone shows less than 100 ohm-m.
c) In case of Tertiary soft rock, conglomerate shows more than 100 ohm-m, sand stone shows 80-100 ohm-m, and alternation portion of sand stone and mud stone shows 20-80 ohm-m.

Table 3.1-2 Resistivity of Stratum or Rock

	Stratum/ Rock	Resistivity (Ohm-m)	
		Dry	Wet
Aquifer	Gravel	1,000-15,000	200-10,000
	Gravel with sand	1,000-7,000	200-5,000
	Sand	300-7,000	100-700
	Conglomerate	300-1,800	100-500
	Sand stone	200-2,500	100-500
Aquiclude	Silt		<100
	Clay		<100
	Marl		<100
	Sale		<100
Non-Aquifer	Tuff breccia	100-1,000	
	Granite	1,000-10,000	
	Andesite	200-10,000	
	Basalt	20,000	
	Crystaline shist	200-20,000	
	Gneiss	200-20,000	
	Limestone	60-500,000	

Source; Shimura (1984) Method of Electric Sounding, Shoukodo Publish Japan

3.2 Results of Electrical Sounding and Interpretation

(1) Results of VES

The appearance resistivity – depth curve and analysis result of each point is shown in **Figure 3.2-1**.
The columnar indication of the vertical electric sounding results is shown in **Figure 3.2-2**.
The classification of resistivity is shown in **Table 3.2-1**.

Table 3.2-1 Resistivity classification

Clasification	Resistivity Range	Description
	Resistivity <50	Silt, clay, mudstone, shale, groundwater of fissure zone
	50 =< Resistivity < 100	Alteration of sand and silt, alteration of sandstone and siltstone or shale, a part of sandstone
	100 =< Resistivity < 500	Sand, sandstone or highly weathered rock
	500 =< Resistivity < 1,000	Weathered or crackly portion of hard rock
	1,000 =< Resistivity	Hard rock

(2) Interpretation of resistivity of the study area

According to the resistivity classification, the general interpretation of resistivity of the study area is as follows.

1) The Resistivity < 50 ohm-m zone shows a possibility of silt, clay, mudstone and shale (Aquiclude). Sometimes groundwater in fissure zone may show very low resistivity (Possibility of Aquifer).
2) 50 =< Resistivity <100 ohm-m zone may show a part of sandstone, alternation of sandstone (Possibility of Aquifer) and mudstone (Aquiclude).
3) The 100 =< Resistivity <500 ohm-m zone shows a possibility of sand and sandstone (Aquifer).
4) The 500 =< Resistivity < 1,000 ohm-m zone shows a possibility of weathered or crackly portion of hard rock and a part of sandstone (Aquifer to Aquiclude).
5) Resistivity =>1,000 ohm-m zone shows a possibility of hard rock (Non-Aquifer).
5) The Resistivity >= 5,000 ohm-m zone shows very hard portion of base rock (Non-Aquifer).

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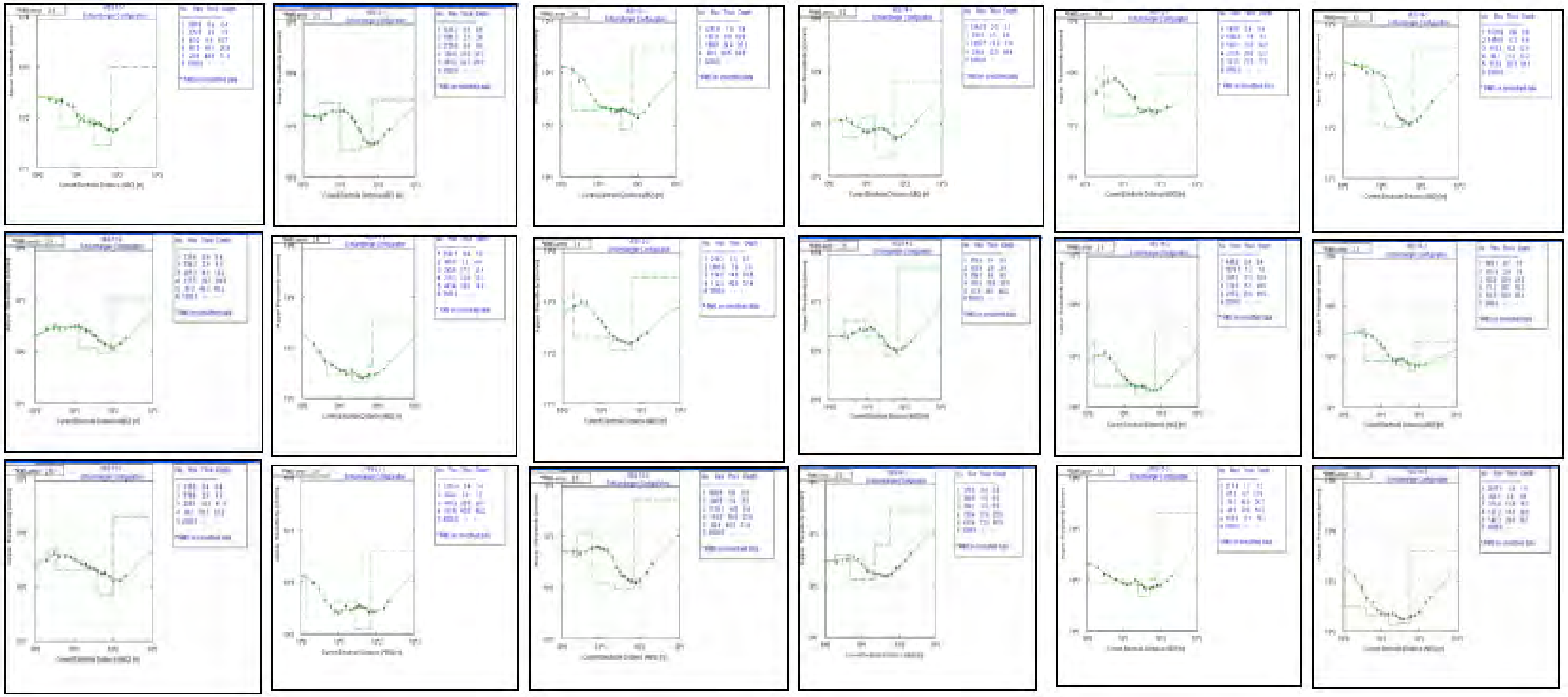


Figure 3.2-1(1) The Appearance Resistivity – Depth Curve and Interpretation Result (1)

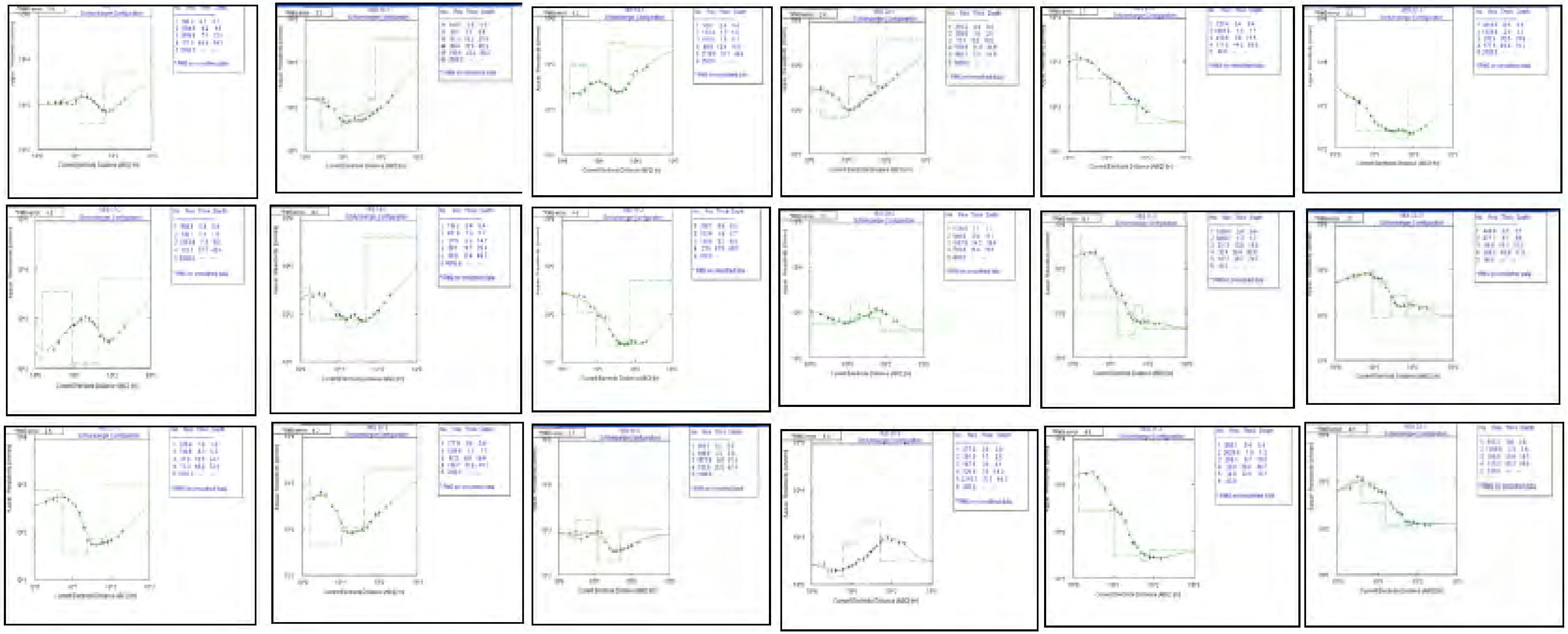


Figure 3.2-1(2) The Appearance Resistivity – Depth Curve and Interpretation Result (2)

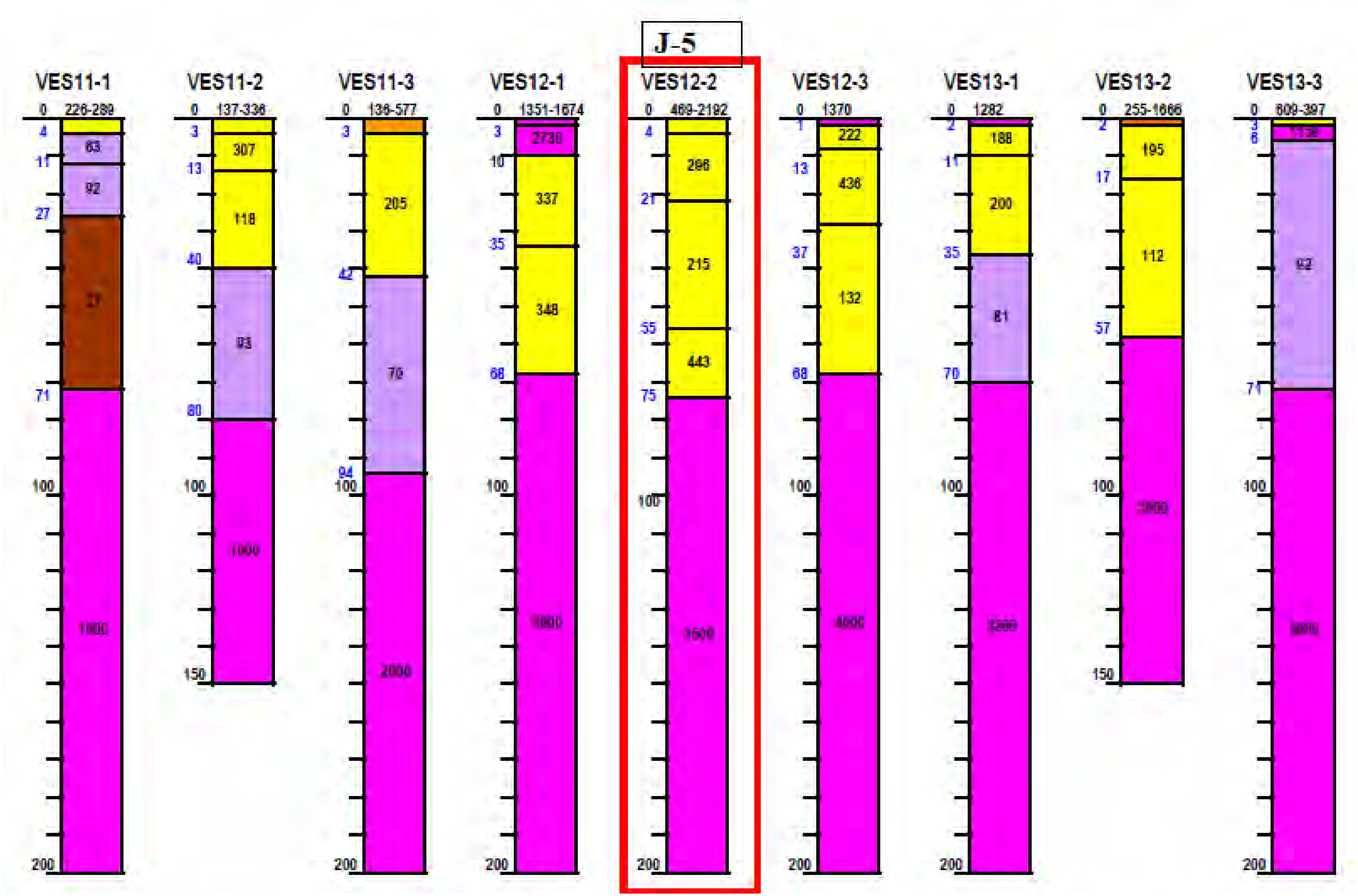


Figure 3.2-2(1) Columnar of Resistivity of VES Sites (1)

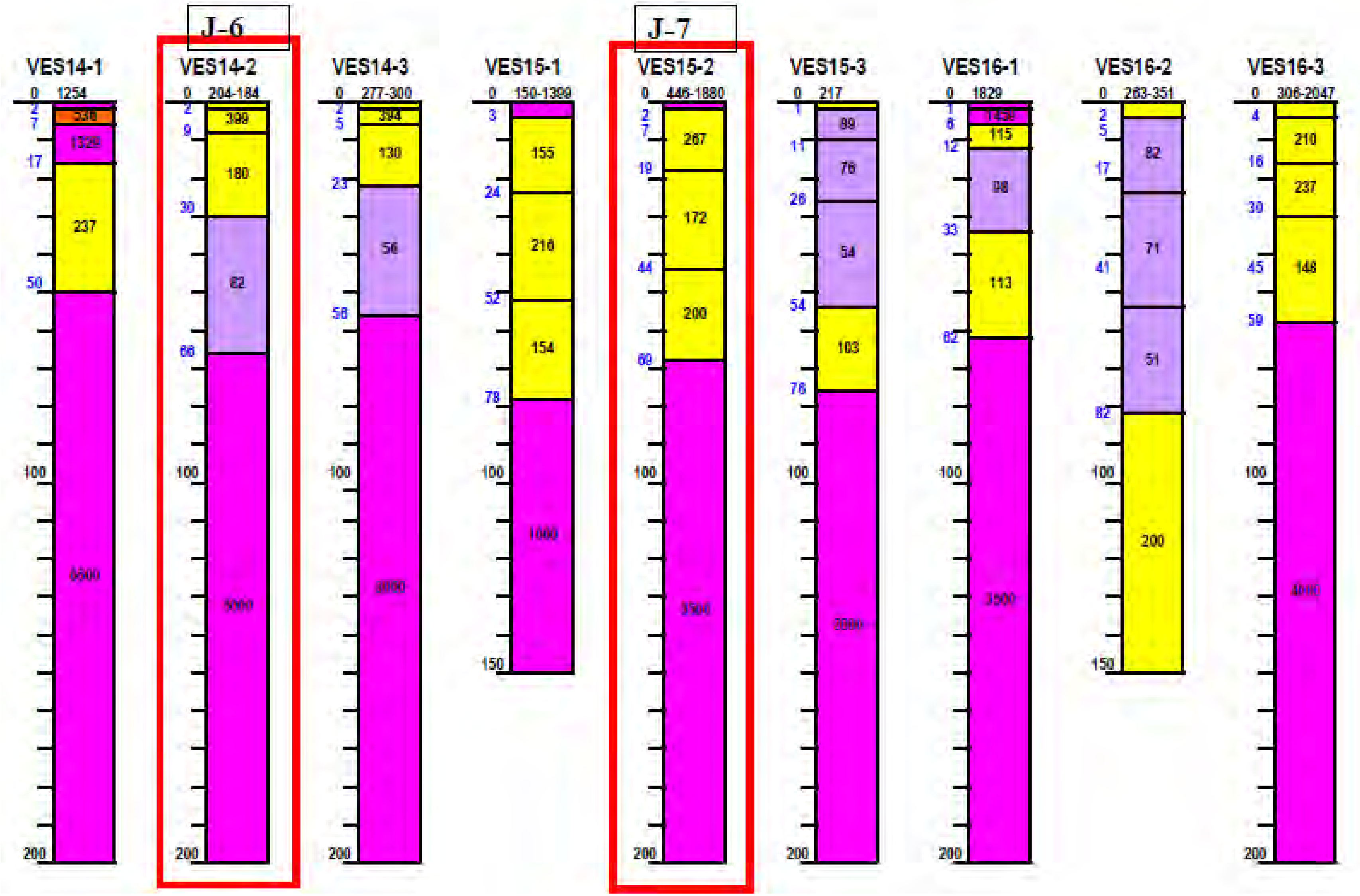


Figure 3.2-2(2) Columnar of Resistivity of VES Sites (2)

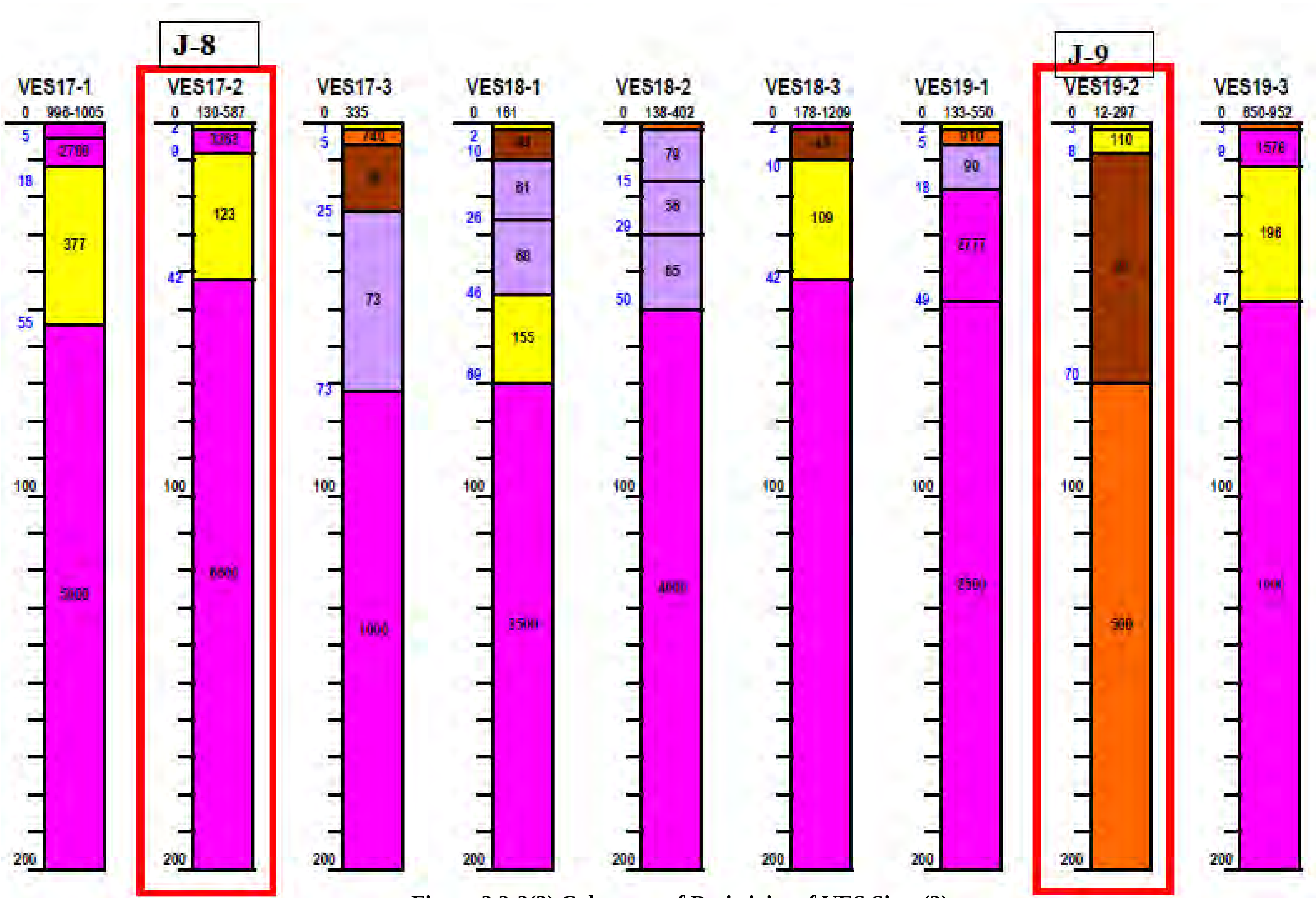


Figure 3.2-2(3) Columnar of Resistivity of VES Sites (3)

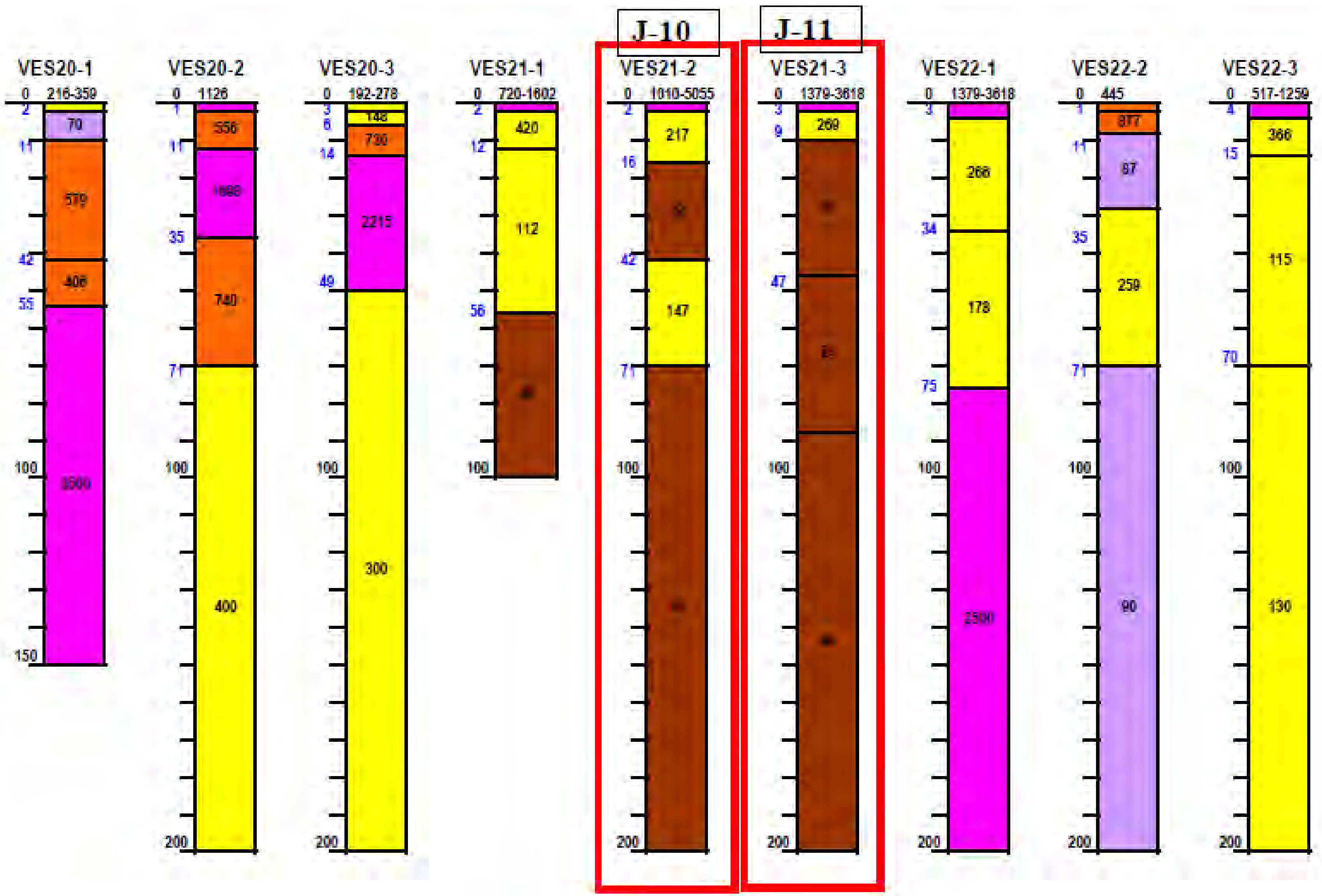


Figure 3.2-2 Columnar of Resistivity of VES Sites (4)

3.3 Hydrogelogical Condition Presumed from Electrical Sounding before and after Exploratory Well Drilling

(1) Presumed hydrogeological condition from VES before exploratory well drilling

The hydrogeological structure presumed from VES results in the study area is summarized as follows.

1) In north west zone of this study area (VES 11 to VES 15 area), sandstone or sandstone predominant alteration are distributed widely. Low resistivity less than 50 ohm-m, which generally indicates fine soil or fine rock, exists only at VES11-1. The hard rock is distributed under 50-94m (Average 70m)
2) In central zone of this study area (VES 16 to VES 19 area), sandstone predominant alteration portions increase more than half compared to north west zone, and thin low resistivity sections indicated less than 50 ohm-m are included. The hard rock is distributed under 42-73m (Average 55m) and becomes shallow compared to the north west zone. VES 7-1 and VES 7-3 locate in diabase distributed area. One shows fine rock condition with less than 100 ohm-m, and another shows weathered or crackly condition with 380 ohm-m. VES 19-2 shows fine rock condition with less than 50 ohm-m up to 70m and crackly hard rock condition with 500 ohm-m under 70m. low resistivity section sometime shows highly crackly portion bearing fresh or brackish water. VES 16-2 shows sandstone predominant alteration condition with less than 100 ohm-m up to 82m and sandstone or weathered/ crackly condition with 200 ohm-m under 82m. These 2 VES points show hard rock is rather deeper than other VES points
3) In south east zone of this study area (VES 20 to VES 22 area), VES results show very varied condition such as hard rock or crackly hard rock condition in VES 20 area, sandstone and fine rock condition in VES 21 area, and sandstone predominant condition in VES 22 area. The hard rock is distributed under 55-75m in VES 20-1 and VES22-1 points, but in other VES points, hard rock becomes deep, it indicates ordinary sandstone predominant or alteration or fine rock condition exist at deeper portion, or sometimes existence of fresh or brackish water in highly crackly rocks.

The geological and hydrogeological condition of the study area presumed from VES results is shown in **Table 3.3-1**. The hydrogeological condition of proposed exploratory well drilling site presumed from VES results is shown in **Table 3.3-2**.

Table 3.3-1 Presumed Hydrogeological Condition of the Study Area

No.	Presumed Condition	Hard Rock Depth (m)
VES11	Possibility of sand or sandstone, or sandstone predominant alteration in upper portion alteration or mudstone/ shale in deep portion (VES11-2 & VES11-3, near LWSC Well No.1) Possibility of alteration or mudstone/ shale (VES11-1)	71-94
VES12	Possibility of sandstone, Resemblance of J-1 condition	68-75
VES13	Possibility of sandstone predominant alteration	57-71
VES14	Possibility of sand or sandstone, or sandstone predominant alteration in upper portion alteration or mudstone/ shale in deep portion Resemblance of VES 11-2 in LWSC Well No.1 area	50-66
VES15	Possibility of sandstone, Resemblance of J-1 condition (VES15-1, VES15-2), Possibility of mudstone/ shale predominant alteration	69-78
VES16	Possibility of mudstone/ shale predominant alteration (VES16-1, VES16-2), Possibility of sandstone (VES16-3)	59-62, deep at VES16-2
VES17	Possibility of sandstone (VES17-2), Possibility of weathered and crackly diabase (VES17-1), Possibility of weathered diabase or hard rock like J-4 (VES17-3)	42-73
VES18	Possibility of mudstone/ shale or fine rock predominant alteration	42-50
VES19	Possibility of silt, mudstone/ shale or crackly rock (VES19-2), Possibility of shallow hard rock (VES19-1), Possibility of sandstone (VES19-3)	47-46, deep at VES19-2
VES20	Possibility of shallow hard rock and crackly hard rock of Paynesville sandstone, Possibility of weathered sandstone with flesh or blackish water in deeper portion (VES20-2, VES 20-3)	55, deep at VES20-2, VES20-3
VES21	Possibility of mudstone/ shale predominant alteration, Possibility of weathered fine rock with blackish water or fresh water in crackly portion	Deep at all points
VES22	Possibility of sandstone or sandstone predominant alteration, Possibility of weathered sandstone or alteration with flesh or blackish water in deeper portion (VES20-2, VES 20-3)	75, deep at VES22-2, VES22-3

Table 3.3-2 Presumed Condition of Proposed Exploratory Well Drilling Site before Drilling

Well No.	Resistivity of VES	Presumed Lithology	Presumed Condition of Aquifer
J-5	215-443 ohm-m up to 75m 3500 ohm-m under 75m	Sandstone or sandstone predominant alteration Hard rock under 75m	Aquifer (Resemblance of J-1)
J-6	180-399 ohm-m up to 30m, 82 ohm-m up to 66m, 5000 ohm-m under 66m	Sandstone at upper portion and sandstone predominant alteration at middle portion. Hard rock under 66m	Aquifer (Resemblance of LWSC Well No.1)
J-7	172-267 ohm-m up to 69m 3500 ohm-m under 69m	Sandstone or sandstone predominant alteration Hard rock under 69m	Aquifer (Resemblance of J-1)
J-8	123 ohm-m up to 47m 6500 ohm-m under 42m	Sandstone or sandstone predominant alteration Hard rock under 42m	Aquifer (Confirmation of a portion with about 100 ohm-m)
J-9	23 ohm-m up to 70m, 500 ohm-m under 70m	Mudstone/ shale or portion of water bearing in cracks, crackly rock with fresh water or blackish water under 70m	Aquitard or Aquifer (Confirmation of a portion with less than 50 ohm-m)
J-10	217 ohm-m up to 16m, 32 ohm-m up to 42m, 147 ohm-m up to 71m, 45 ohm-m under 71m	Sandstone half and Mudstone/ shale half, Fine rock or crackly rock with fresh water or blackish water under 71m	Aquifer or Aquitard (Confirmation of a alteration portion with 100-200 ohm-m and less than 50 ohm-m)

(2) Hydrogeological condition of the study area from VES and exploratory well drilling results

The results of having compared VES with drilled exploratory well is as follows.

1) The resistivity 150-500 ohm-m zone shows sandstone. The water producing capacity is separated into J-1type (VES1-1 and 1-2, Yield: 10-20m^3/day at 8 hours pumping), J-5 type (VES 12-2, Yield: 70-90m^3/day at 8 hours pumping), and J-7 type (VES 15-2, Yield: less than 5m^3/day at 8hours pumping).
2) The resistivity 100-500 ohm-m zone including 100-150 ohm-m zone shows sandstone. The water producing capacity indicates rather high such as J-8 (VESS17-2, Yield: 70-90 m^3/day at 8hours pumping).
3) The resistivity 50-100 ohm-m zone shows sandstone predominant alternation, sometimes indicates intrusion of diabase. The water producing capacity become high incase of intrusion of diabase and having crackly zone around diabase intrusion body such as J-6(VES 14-2, Yield: 150-180m^3/day at 8hours).
4) The resistivity 50-100 ohm-m zone shows shale and fine rock, sometimes indicates intrusion of diabase. The water producing capacity become high incase of crackly or fracture zone in biabase body or around diabase intrusion body such as J-9(VES 17-2, Yield: more than 500m^3/day at 8hours). And J-11(VES 21-3, Yield: 150-170m^3/day at 8hours). But, the low resistivity zone sometimes shows hard diabase without crackly zone such as J-10 (VES 14-2, Yield: less than 5m^3/day at 8hours).

The re-presumed hydrogeological condition of each VES point from above mentioned condition is shown in **Table 3.2-3**.

Table 3.3-3 Re-presumed Hydrogeological Condition after Exploratory Well Drilling

VES No.		VES Pattern Similar to	Condition	Yield (Possibility)	Remarks
11	-1	J-6	Shale, Alternation/ Diabase	△-○	
	-2	J-6	Sandstone、Alternation/ Diabase	○	
	-3	J-6	Sandstone、Alternation/ Diabase	○	
12	-1	J-1, J-7	Sandstone, Hard rock	X－△	
	-2	J-5	Sandstone predominant	△	J- 5
	-3	J-5	Sandstone predominant Sandstone	△	Including (< 150 ohm-m)
13	-1	J-6	Alternation, Sandstone/ Diabase	○	
	-2	J-5, J-8	Sandstone predominant Sandstone	△－○	Including (< 150 ohm-m)
	-3	J-6	Alternation/ Diabase	○	
14	-1	J-1, J-7	Sandstone	X－○	
	-2	J-6	Sandstone	○	J-6
	-3	J-6	Sandstone/ Diabase	○	
15	-1	J-1, J-7	Sandstone predominant	X－○	
	-2	J-7	Sandstone, Hard rock	X	J-7
	-3	J-6	Alternation, Sandstone/ Diabase	○	
16	-1	J-6	Alternation, Sandstone/ Diabase	○	
	-2	J-6	Alternation/ Diabase	○	
	-3	J-5, J-8	Sandstone	△－○	Including (< 150 ohm-m)
17	-1	J-1, J-7	Sandstone	X－○	
	-2	J-8	Sandstone	○	J-8
	-3	J-6	Shale, Alternation/ Diabase	△-○	
18	-1	J-6	Alternation/ Diabase	○	
	-2	J-6	Alternation, Sandstone/ Diabase	○	
	-3	J-5, J-8	Sandstone	△－○	Including (< 150 ohm-m)
19	-1		Shallow hardrock	X	
	-2	J-9	Diabase with crackly zone	◎	J-9
	-3	J-1, J-7	Sandstone	X－○	
20	-1		Shallow hardrock	X	
	-2		Shallow hardrock	X – ?	< 400 ohm-m at deep portion
	-3		Shallow hardrock	X – ?	< 300 ohm-m at deep portion
21	-1		Shale/ Diabase	X – ?	<50 ohm-m at deep portion
	-2	J-10	Diabase hard	X	<50 ohm-m at deep portion
	-3	J-11	Diabase hard, Fracture zone	○	<50 ohm-m at deep portion
22	-1	J-1, J-7	Sandstone	X－○	
	-2	J-1, J-7	Sandstone/ Diabase	X－○?	<50 ohm-m at deep portion
	-3	J-5, J-8	Sandstone	△－○?	Including (< 150 ohm-m)

Remarks; Yield; x: very low, △: low, ○: high. ◎: very high

<< Reference Data>>

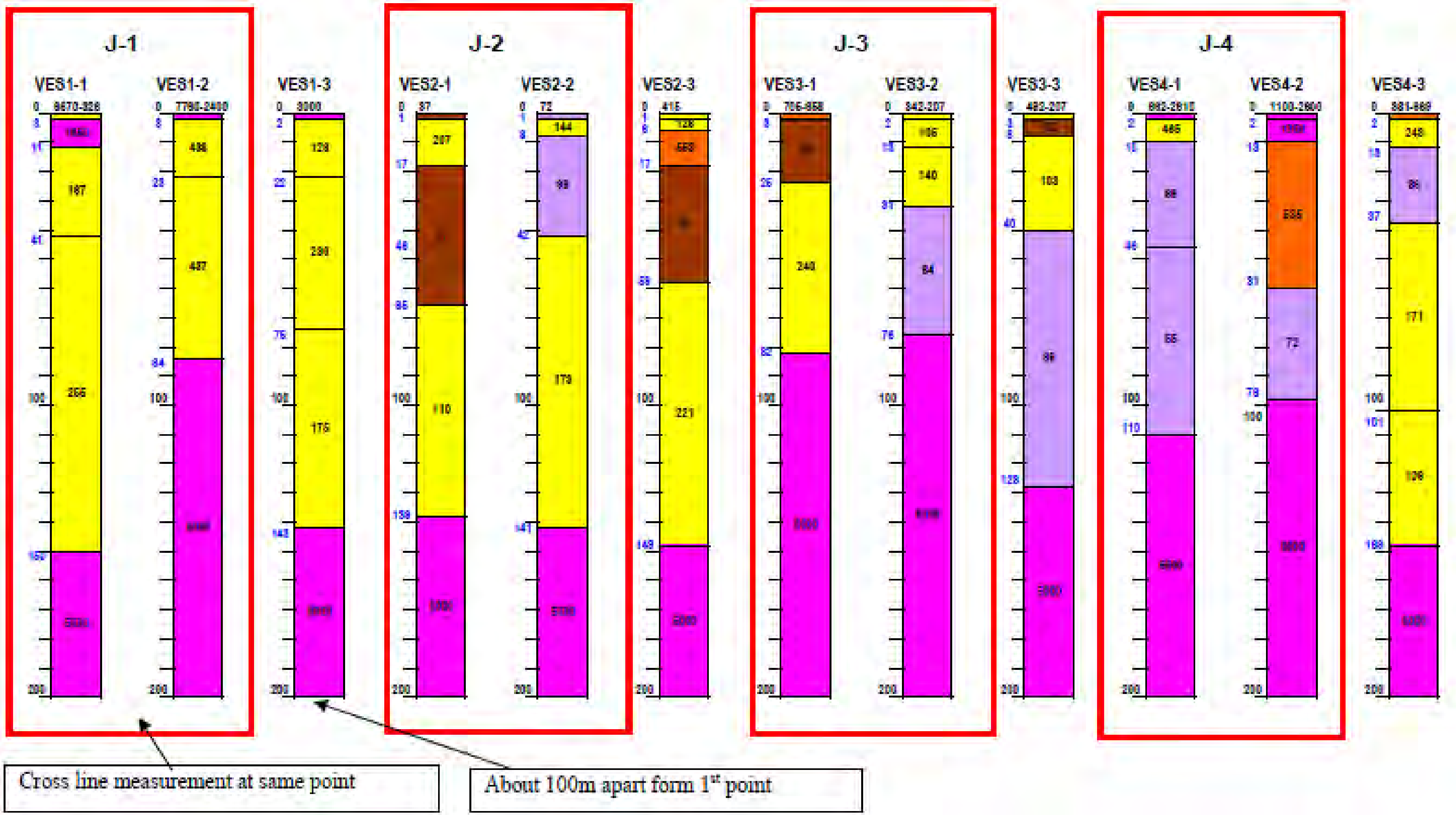


Figure R-1 VES columnar of Phase 1 Exploratory Well Site

<< Reference Data>>

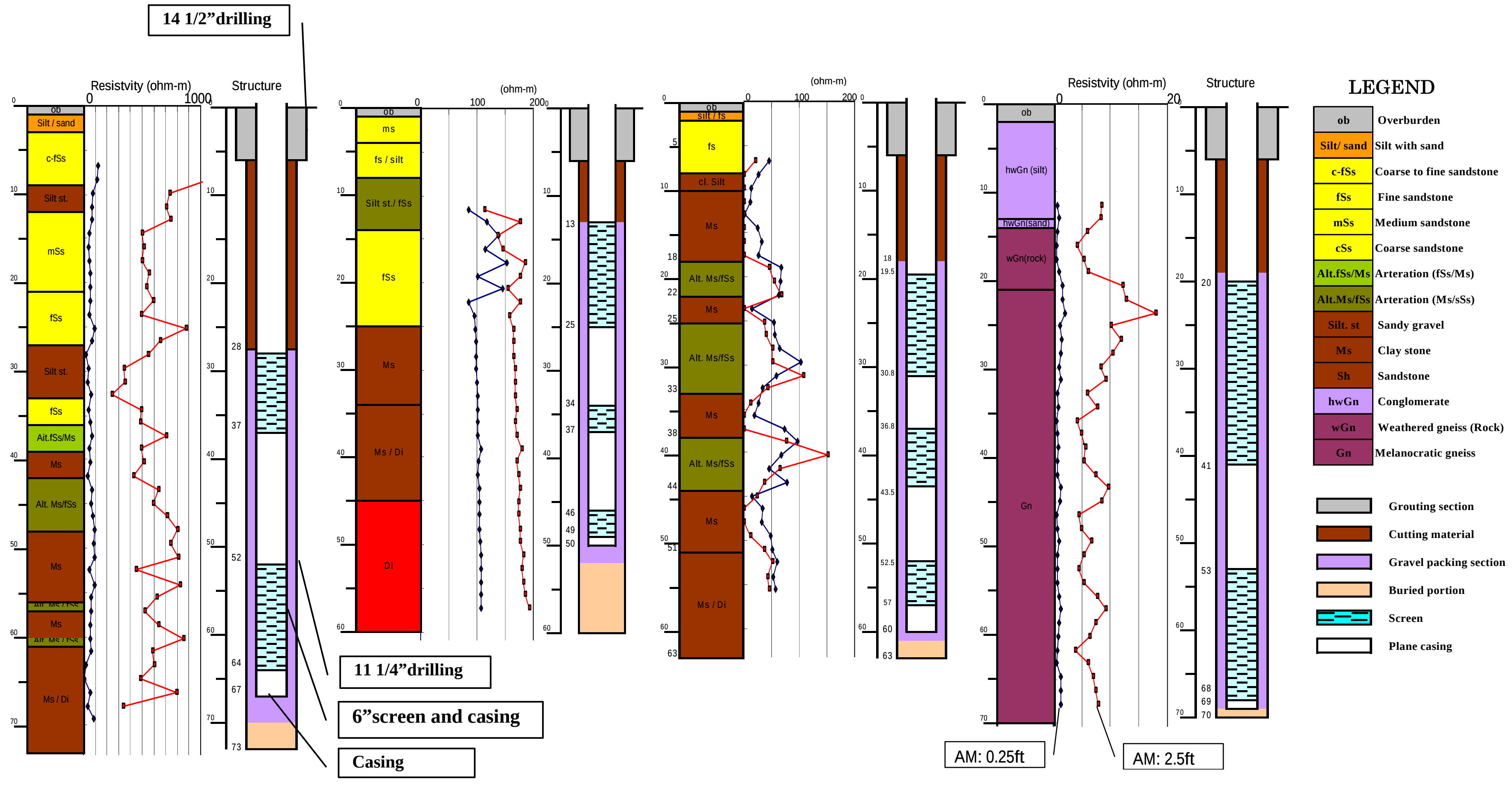


Figure R-2 Lithology, Resistivity and Wellcolumnar of Phase 1 Exploratory Well

<< Reference Data>>

Table R-1 VES result at Existing wells

Existing Well	Lithology	Resistivity of VES	Resistivity of Logging	Yield (L/min)
LWSC Well No.1	Gravel, Conglomerate, Sandstone	118-307 ohm-m (main), 83 ohm-m in deep (by VES11-2)	No data	200m^3/day
J-1	Sandstone dominant, Alteration, Shale	167-438 ohm-m	200 ohm-m to 900 ohm-m, 200-500 ohm-m shows Aquifer	Optimum yield 96L/min
J-2	Shale dominant, Partly sandstone at shallow portion	47-99 ohm-m (main), 144-207ohm-m (upper part)	100-200 ohm-m up to 23m (Aquifer), Stacking the prove in deeper section	Optimum yield 19L/min
J-3	Shale dominant, Partly sandstone at shallow portion	50-64 ohm-m & 105-204 ohm-m	0-100 ohm-m under 10m (Aquitard)	Optimum yield 29L/min
J-4	Hard rock of melanocratic gneiss	55-86 ohm-m including 535 ohm-m a part	0-20 ohm-m (Aquitard)	Optimum yield 6L/min

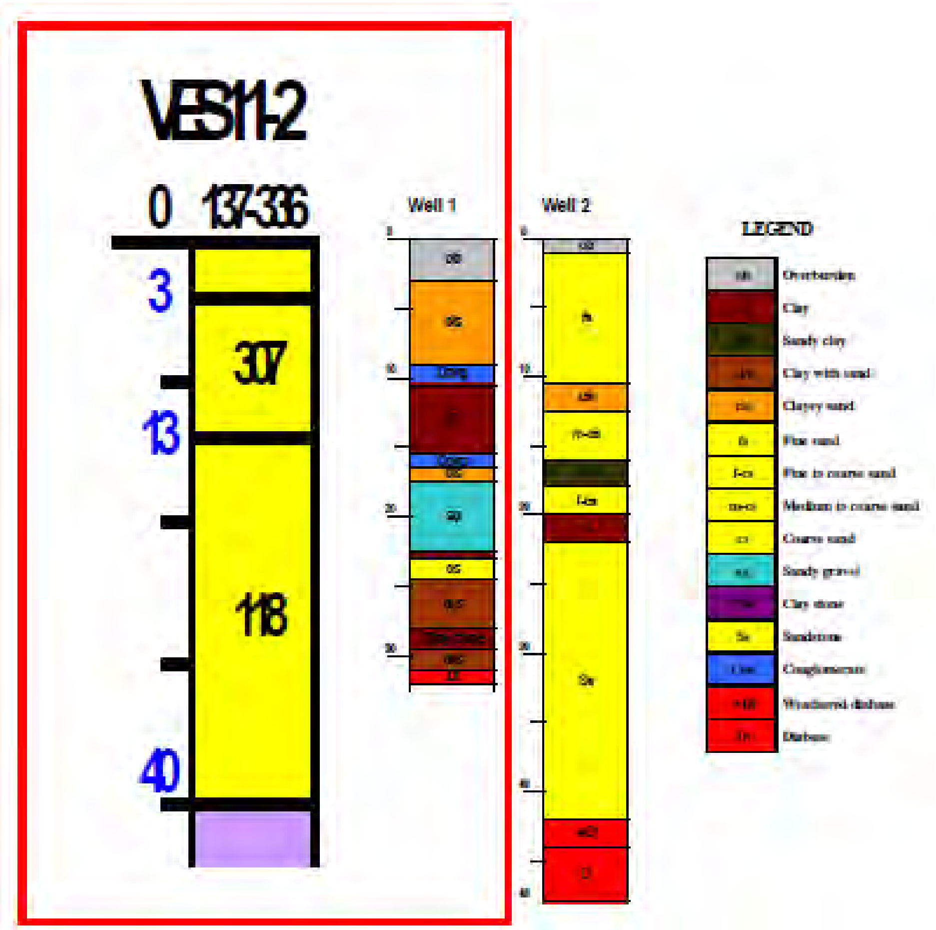


Figure R-3 Relation of VES11-2 and LWSC Production Well No.1

4. EXPLORATORY WELL DRILLING

The exploratory well drilling work, namely the drilling work of 7 wells (Well J-5, J-6, J-7, J-8, J-9, J-10, and J-11) including following works, is carried out to obtain the aquifer structure and aquifer properties including hydraulic parameter in detail at each well site.
The exploratory well drilling work consists of 14 inches and 10 inches drilling work, geophysical logging work, 6 inches screen and casing installation work, gravel packing and grouting work, pumping test work and well head installation work.

4.1 Exploratory Well Drilling Work

(1) Location and Quantity of Drilling Well

The Location of exploratory wells is shown in **Figure 4.1-1**. The Quantity of drilling work is shown in **Table 4.1-1**.
Since water did not come out by Well J-10, Well J-11 was drilled as substitution of J-11.

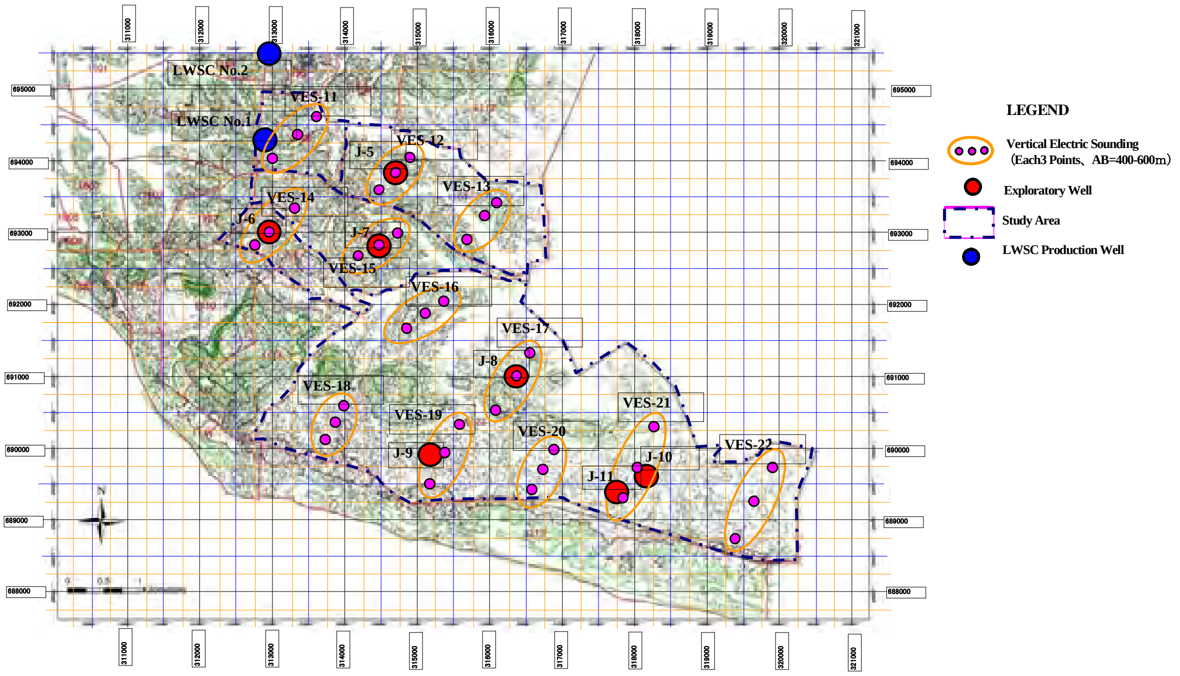


Figure 4.1-1 Location of Exploratory Well

Table 4.1-1 Location and Quantity of Exploratory Well

Well No.	Location (Community)	Coordinates (UTM)		Elevation (m)	Total Depth (m)		Casing Diameter (“)	Remarks
		Easting	Northing		Drilling Depth	Completion Depth		
J-5	Cow field C., Duport Road North-East	314627	693846	9	75.00	44.60	6	VES12-2
J-6	Block G-2 C., Paynesville Joe Bar	313024	692922	11	69.55	64.70	6	VES14-2
J-7	Zubah Town Rehab C., Duport Road South	314570	692844	10	72.00	72.00	6*1	VES15-2
J-8	Thinkers Village Old Field C., Rehab/ Borbor Town	316481	691047	6	72.00	70.80	6	VES17-2
J-9	Kendeh Town Old Field C., Rehab/ Borbor Town	315104	689961	8	51.50	49.50	6	VES19-2
J-10	Ghengbah C., Rehab/ Borbor Town	318166	689552	5	74.00	74.00	6*1	VES21-2
J-11	Ghengbah C., Rehab/ Borbor Town	317779	689379	5	70.00	61.70	6	VES21-3

Remarks; *1; Not casing installation because of very little water producing

(2) Lithology and Electric Logging Result of Drilling Well

The lithological log and electric logging log of J-5 to J-11 is shown in **Figure 4.1-2.** The feature of lithology and electric logging result of each well is summarized in **Table 4.1-2 and Table 4.2-3.**.

As for the electric logging, normal resistivity logging AM=0.25 ft, 2.5 ft, 10ft and spontaneous potential (SP) logging is carried out.

Table 4.1-2 Feature of Lithology and Water Producing Portion During Drilling

Well No.	Lithology	Water Producing Potion during Drilling	Remarks
J-5	0-19m; Quaternary/Tertiary, 19-37m; Sandstone, 37-48m; Diabase, 48-75m; Gneiss	Not clear	Rather little water producing
J-6	0-18m;Quaternary/Tertiary, 18-49m, Diabase, 49-69.65m; Sandstone (hard)	2.5m, 17-19m, 41m, 67m	High water producing
J-7	0-19m;Quaternary/Tertiary, 19-20m; Weathered sandstone, 26-72m; Sandstone (hard) intercalated thin shale layers	Not clear	Very low water producing
J-8	0-16m;Quaternary/Tertiary, 19-29m; Weathered sandstone, 29-72m; Sandstone, 68-71m; Diabase intrusion	11-13m, 24m, 39m, 67m	Rather High water producing
J-9	0-7m;Quaternary/Tertiary, 7-12m; Weathered sandstone, 12-18m; Sandstone, 18-51.5m; Diabase 49-51.5m; Crackly zone	11m, 12m, 23m, 51-52m	Very High water producing
J-10	0-4m;Quaternary/Tertiary, 4-74m; Diabase	Not clear	Very low water producing
J-11	0-8m;Quaternary/Tertiary, 8-56m; Diabase, 56-70m; Weathered Gneiss 56-59m; Fracture zone	22m, 26m,38-52m 57m	High water producing

Table 4.1-3 Electric Logging Result

Well No.	Resistivity and Spontaneous Potential (SP)	Water Producing Portion by Logging	Remarks
J-5	Resistivity 0-1300ohm-m, low up to 37m, becoming very high under37m SP; 0-1000mV, becoming gradually high below section	Not clear indication, Water producing portion; under 37m in Diabase. Same trend resistivity and SP (Device badness)	
J-6	Resistivity; 0->1000ohm-m, 19-29m and 32-40m; high separation of each AM, 40-56m; separation SP; 0-500mV, 25-26m,38-57m; low portion	Water producing portion; 24-27m, 31-40m in Diabase	
J-7	Resistivity ; 0-500ohm-m, 44-53m, 58-72m separation portion Sp; 0-1000mV, Not clear indication of low portion	Not clear indication Same trend resistivity and SP (Device badness)	Very low water producing well
J-8	Rsistivity; 0-4000ohm-m, too high indication, 25-46m; separation portion SP; Device fault	Water producing portion; 25-46m in sandstone	
J-9	Resistivity; 0-1000ohm-m, high separation under 26m, but 10ft shows rather low resistivity. SP; 0-20m; uniform under 20m	Not clear indication	49-51.5m; Crackly zone
J-10	Resistivity; 0-100ohm-m, 18-69m; separation50m SP; 0-1000mV, almost uniform with high voltage	Not clear indication Same trend resistivity and SP (Device badness)	Very low water producing well
J-11	Resistivity; 0-100ohm-m, low resistivity and monotonous up to 50m, high separation under 50m SP; 0-900mV, very high under 58	Not clear indication Same trend resistivity and SP (Device badness)	56-59m; Fracture zone

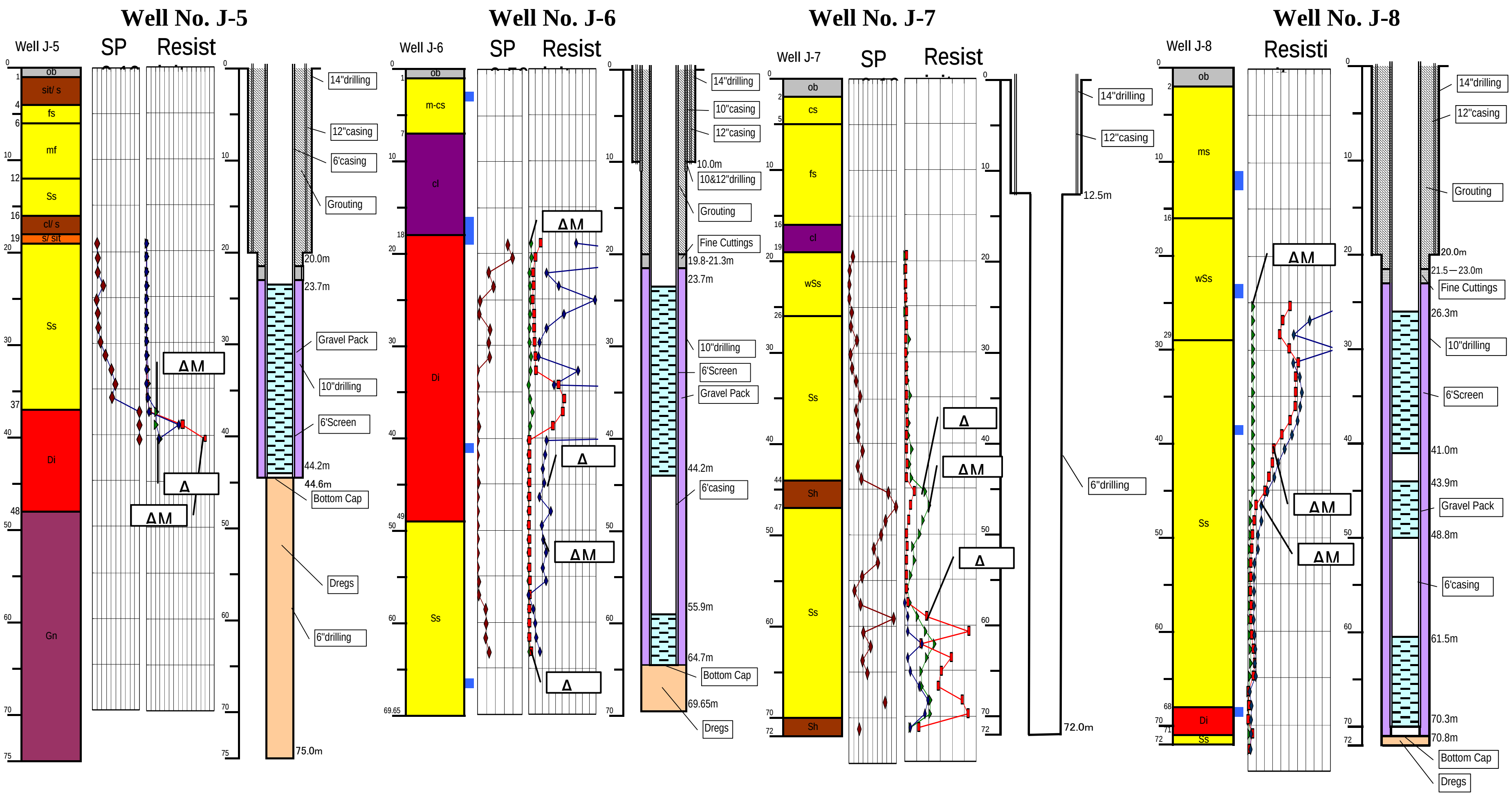


Figure 4.1-2(1) Lithological Log, Electric Ligging Log and Well Structure of Exploratory Well (1)

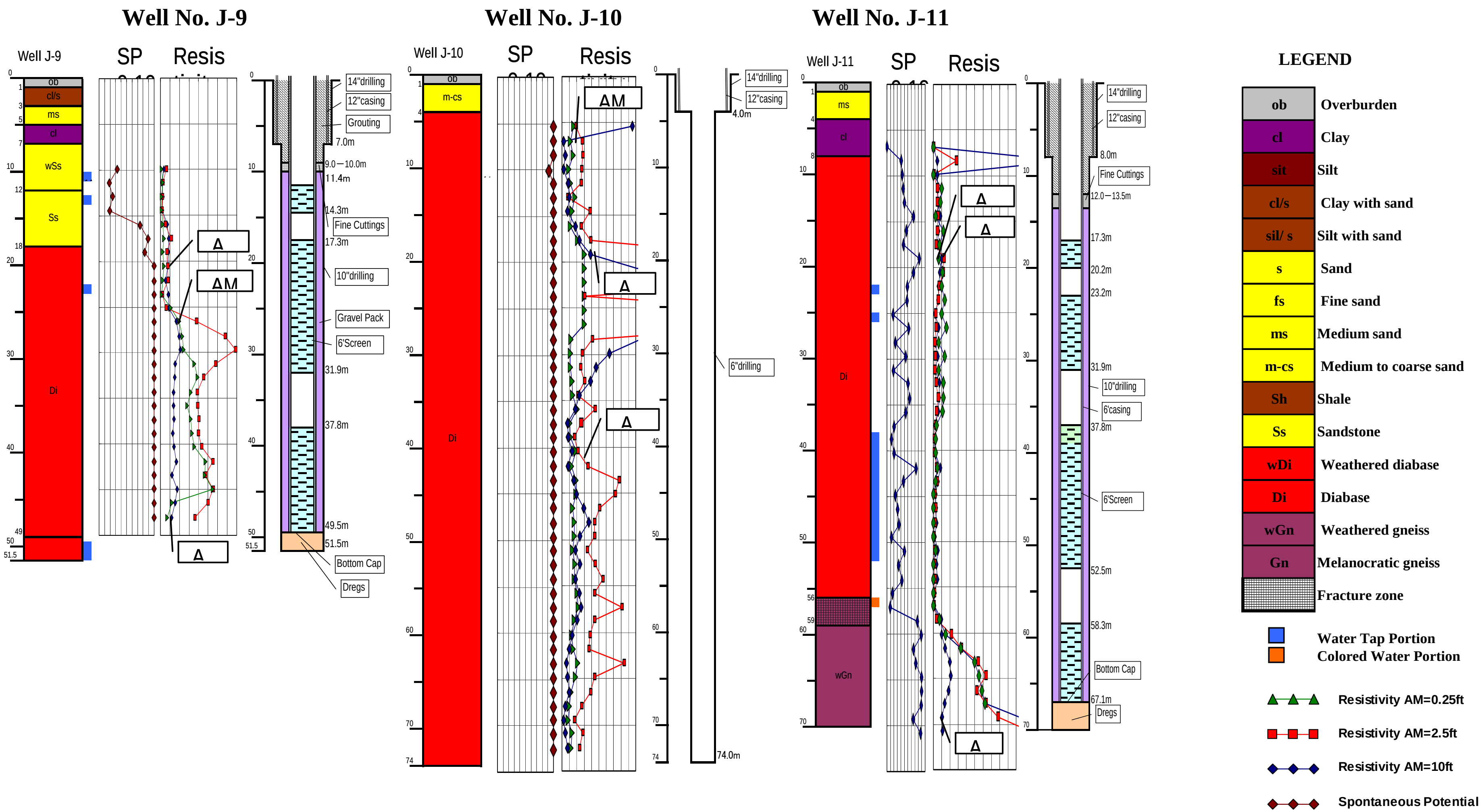


Figure 4.1-2(2) Lithological Log, Electric Ligging Log and Well Structure of Exploratory Well (2)

(3) Screen and Casing Installation, Gravel Packing and Grouting
The well structure of J-5 to J-11 is shown in **Figure 4.1-2.** The quantity of drilling work is shown in **Table 4.1-4**.
The screen of each well is installed in consideration of lithology, electric logging result and water tapping situation under drilling.
J-7 and J-10 remain with the situation of precedence drilling by 6”, and not installation of casing and screen, because of little amount of water under drilling work. The 12” temporary casing for protection of well mouth portion still remains, and well head concrete slab and cover is installed.
Although it tried to perform a backfill, there is a strong request of landowner to leave a well and this remaining procedure was performed at J-7 and J-10 well site.

Table 4.1-4 Quantity of Main Items of Exploratory Well Drilling Work

Item	J-5	J-6	J-7	J-8	J-9	J-10	J-11	Total
Drilling Total depth (m)	75.00	69.55	72.00	72.00	51.50	74.00	70.00	484.05
Well Completion Total depth (m)	44.60	64.00	72.00	70.80	49.50	74.00	61.70	436.60
Drilling diameter (“)	10	10	6	10	10	6	10	
Casing diameter (“)	6	6	6	6	6	6	6	
Casing length (m)	23.9	34.3		41.1	22.8		28.9	273.6
Screen length (m)	21.0	30.0		30.0	27.0		33.0	163.0
Gravel packing (m)	20.9	43.4		44.5	38.1		53.6	200.5
Grouting length (m)	21.0	20.0		22.0	9.0		12.0	24.0

4.2 Pumping Test

The pumping test (Pre-pumping test, Multi-stage pumping test, 72 hours constant discharge pumping test, and Recovery test) is carried out after well development at each exploratory well.

(1) Multi-stage Pumping Test
The summary of the recording result of multi-stage pumping test is shown in **Table 4.2-1**.

Table 4.2-1 Summary of Recording Result of Multi Stage Pumping Test

Well No.	Initial Water Level (m)	Stage	Yield (L/min)	Pumping Duration (min)	Drawdown (m)	Remarks
J-5	4.03	1	18	120	4.12	Depth of pump set: 41.6m, Remarkable drawdown at stage 4
		2	30	240	8.30	
		3	51	360	18.84	
		4	68	385	30.83	
		5				
J-6	5.03	1	74	120	1.45	Depth of pump set: 42.1m
		2	148	240	2.77	
		3	222	360	4.40	
		4	296	480	6.75	
		5	365	600	8.84	
J-7	5.48	1	4	120	2.98	Depth of pump set: 40.7m, Remarkable drawdown at stage 4
		2	8	240	7.56	
		3	12	360	16.21	
		4	16	480	25.54	
		5				
J-8	2.37	1	74	120	4.68	Depth of pump set: 41.7m
		2	150	240	10.29	
		3	225	360	14.52	
		4	300	480	20.05	
		5	373	600	23.06	
J-9	1.83	1	76	120	0.32	Depth of pump set: 41.9m
		2	150	240	0.54	
		3	225	360	0.82	
		4	300	480	1.15	
		5	375	600	1.51	
J-10	0.83	1	6	60	3.98	**Preliminary Test** Depth of pump set: 34.7m
		2	8	240	13.24	
J-11	1.94	1	75	120	1.24	Depth of pump set: 41.8m
		2	150	240	3.27	
		3	225	360	6.01	
		4	300	480	8.58	
		5	375	600	12.90	

The drawdown (s)–time (t) graph and the drawdown (s)–yield (Q) graph of the multi-stage pumping test are shown in **Figure 4.2-2**. The maximum yield and the optimum yield of the each exploratory well estimated from the results of the multi-stage pumping test are shown in **Table 4.2-2**.
The optimum yield is obtained mechanically using the inflection point on the multi-stage pumping test drawdown (s)-yield (Q) curve, such as 42 L/min in J-5, 220 L/min in J-6, 8 L/min in J-7, 200 L/min in J-9, 200L/min in J-9, 8L/min in J-10, 300L/min in J-11 and so on. But J-6, J-11, especially J-9 shows low drawdown. Though J-8 indicates gradually rather large drawdown according to increasing yield, the inflection point is not clear.
In case like this situation, it is necessary to calculate optimum yield or safety yield under a condition of fixed drawdown. The following condition is applied in this report to obtain the calculated optimum yield.

Table 4.2-2 Maximum Yield, and Optimum Yield Obtained by Inflection Point on s-Q Curve

Well No.	Maximum Yield	Optimum Yield
J-5	< 51 L/min	42 L/min
J-6	> 365 L/min	(220 L/min)
J-7	< 16 L/min	8 L/min
J-8	> 373 L/min	Not clear
J-9	> 375 L/min	(200L/min)
J-10	< 11 L/min	8 L/min
J-11	> 375 L/min	(300L/min)

Remarks; (   ) shows uncertain because of low drawdown

1) The yield that can pump up during 8 hours pumping per day with 10 m drawdown in ordinary wells
2) The yield that can pump up during 8 hours pumping per day with 5m drawdown in high water producing well

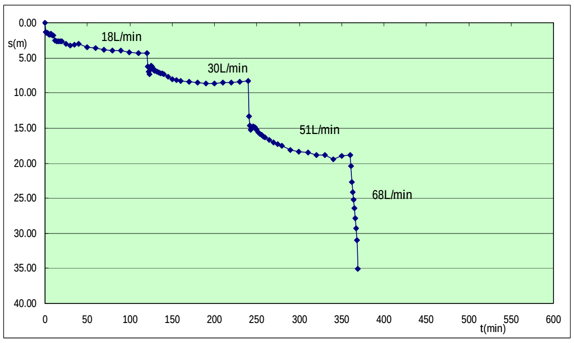
This setting is a procedure to formulate safety plan for groundwater development. The paragraph 2) is considered not to estimate exceed capacity per well on planning because of not confirmation of large yield pumping condition. The calculated safety yield of each well is shown in **Table 4.2-3**. The calculation is carried out under confined aquifer condition and using hydraulic parameters obtained constant discharge pumping test (Refer to **Paragraph (2)**).

Table 4.2-3 Calculated Safety Yield

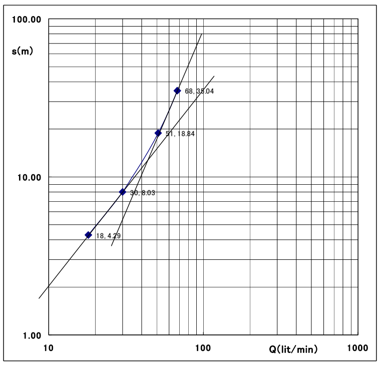
Well No.	Safety Yield	
	L/ min	m^3/ day (in case of 8hours pumping)
J-5	38	18
J-6	355	170
J-7	7	3.4
J-8	183	88
J-9	1236	593
J-10	4	1.9
J-11	336	161

Well No. J-5

Drawdown (s) – Time (t)

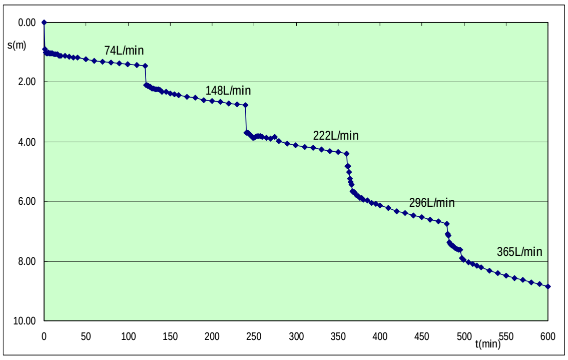


Drawdown (Log s) – Yield (Log Q)

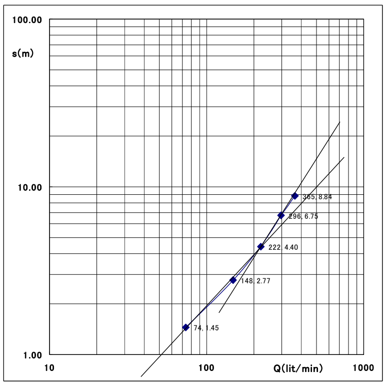


Well No. J-6

Drawdown (s) – Time (t)

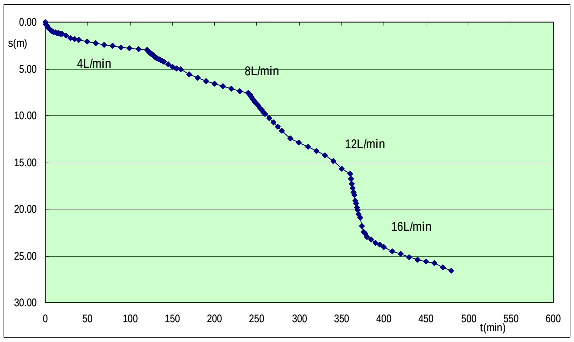


Drawdown (Log s) – Yield (Log Q)

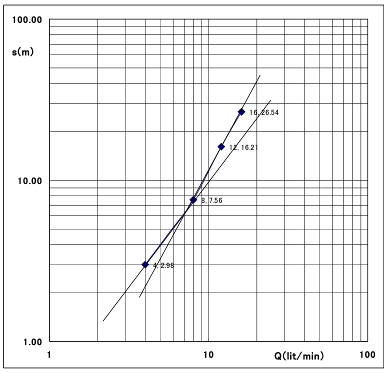


Well No. J-7

Drawdown (s) – Time (t)

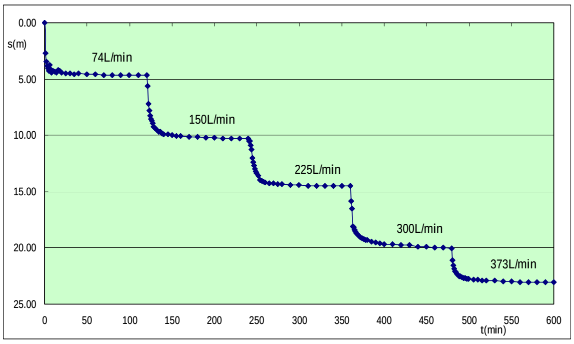


Drawdown (Log s) – Yield (Log Q)



Well No. J-8

Drawdown (s) – Time (t)



Drawdown (Log s) – Yield (Log Q)

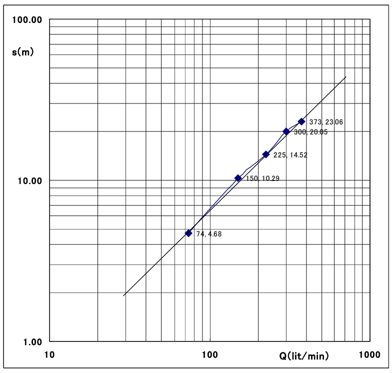
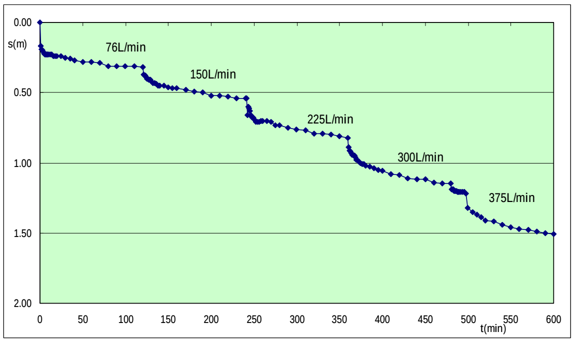
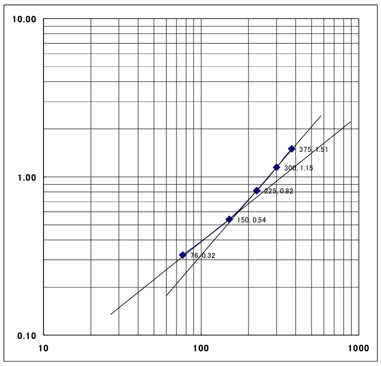


Figure 4.2-1(1) Multi-stage Pumping Test Graph (1)

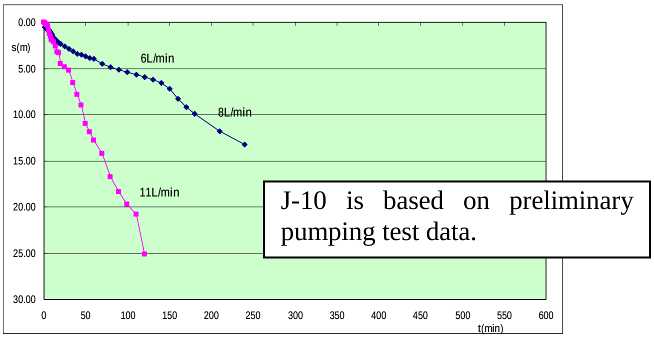
Well No. J-9
Drawdown (s) – Time (t)



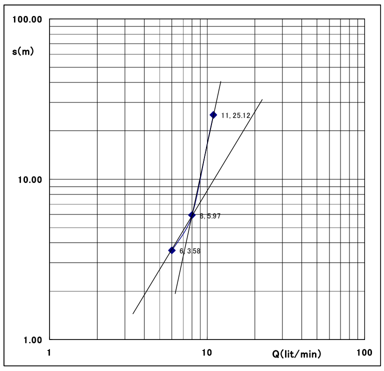
Drawdown (Log s) – Yield (Log Q)



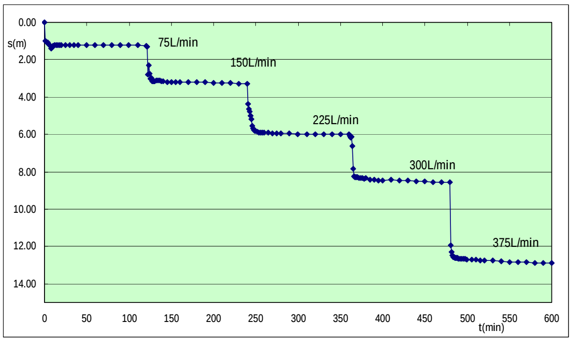
Well No. J-10
Drawdown (s) – Time (t)



Drawdown (Log s) – Yield (Log Q)



Well No. J-11
Drawdown (s) – Time (t)



Drawdown (Log s) – Yield (Log Q)

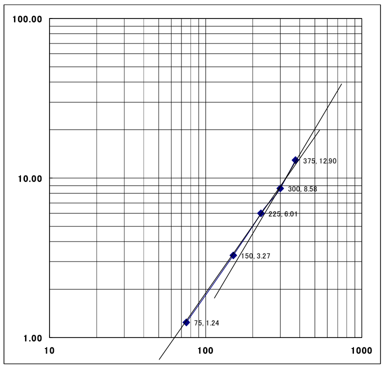


Figure 4.2-1(2) Multi-stage Pumping Test Graph (2)

(b) Constant Discharge Pumping Test and Recovery Test

The summary of the recording result of constant discharge pumping test and recovery test is shown in **Table 4.2-4**.

Table 4.2-4 Summary of Recording Result of Constant Discharge Pumping Test

Well No.	Initial Water Level (m)	Yield (L/min)	Pumping Duration (min)	Drawdown (m)	Remarks
J-5	4.18	40	4320	13.36	Recovery to 0.50m at 8640 min
J-6	5.58	365	4320	12.72	Recovery to -0.02m at 8640 min
J-7	5.77	11.5	4320	21.77	Recovery to 0.01m at 8640 min
J-8	2.39	373	4320	23.66	Recovery to 0.00m at 6720 min
J-9	1.86	375	4320	1.82	Recovery to 0.00m at 5460 min
J-10	0.75	11 (Ave.)	330	25.15	**Preliminary test**
J-11	2.09	375	4320	13.83	Recovery to 0.00m at 7260 min

The drawdown(s)-time(t) graph, Theis's method graph, Cooper & Jacob's method graph, Hantush's method graph, Neuman's Method and Recovery method graph of the constant discharge pumping test and recovery test are shown in **Figure 4.2-2 (1) to 4.2-2 (7).** The estimation of hydraulic parameter by various methods is carried out using the software "Aquifer Test for Windows Version 2.56 of Waterloo Hydrogeologic Inc.". The obtained values of hydraulic parameters by various methods are shown in **Table 4.2-5**. In each well, a set hydraulic parameter value, which indicates most suitable mating with standard curve or line among various method, is selected as an applied value of the well. The selected hydraulic parameter of the constant discharge pumping test and recovery test is shown in **Table 4.2-6.**

Table 4.2-5 Hydraulic Parameters of Each Exploratory Well Obtained from Various Methods

Item		J-5	J-6	J-7	J-8
Transmissivity (m^3/sec/m)	Theis's method	4.30×10^{-5}	4.31×10^{-4}	4.03×10^{-6}	2.91×10^{-4}
	Cooper & Jacob's method	4.30×10^{-5}	3.02×10^{-4}	4.68×10^{-6}	4.72×10^{-4}
	Hantash's method	4.36×10^{-5}	4.31×10^{-4}	4.03×10^{-6}	2.91×10^{-4}
	Neuman's method	4.36×10^{-5}	2.16×10^{-4}	4.03×10^{-6}	2.93×10^{-4}
	Recovery method	4.09×10^{-5}	2.42×10^{-6}	6.56×10^{-6}	2.78×10^{-4}
Storativity	Theis's method	7.86×10^{-2}	7.33×10^{-1}	1.23×10^{0}	1.97×10^{-3}
	Cooper & Jacob's method		8.41×10^{0}	6.62×10^{-1}	1.02×10^{-6}
	Hantash's method		7.50×10^{-1}	1.23×10^{0}	1.97×10^{-3}
	Neuman's method		2.98×10^{-3}	1.38×10^{-4}	1.82×10^{-3}
Permeability Coefficient (m/sec)	Theis's method	2.04×10^{-6}	1.59×10^{-5}	6.77×10^{-8}	9.71×10^{-6}
	Cooper & Jacob's method	2.04×10^{-6}	1.12×10^{-5}	7.87×10^{-8}	1.57×10^{-5}
	Hantash's method	2.07×10^{-6}	1.59×10^{-5}	6.77×10^{-8}	9.71×10^{-6}
	Neuman's method	2.07×10^{-6}	8.00×10^{-6}	6.77×10^{-8}	9.77×10^{-6}
	Recovery method	1.95×10^{-6}	8.98×10^{-6}	1.10×10^{-7}	9.28×10^{-6}
Item		J-9	J-10	J-11	Remarks
Transmissivity (m^3/sec/m)	Theis's method	2.44×10^{-3}	5.07×10^{-6}	3.72×10^{-4}	
	Cooper & Jacob's method	2.05×10^{-3}	6.19×10^{-6}	1.32×10^{-4}	
	Hantash's method	2.44×10^{-3}	5.07×10^{-6}	3.72×10^{-4}	
	Neuman's method	2.44×10^{-3}	4.02×10^{-6}	3.72×10^{-4}	
	Recovery method	2.29×10^{-3}	3.46×10^{-6}	1.89×10^{-3}	
Storativity	Theis's method	1.57×10^{1}	6.66×10^{-1}	6.67×10^{-3}	
	Cooper & Jacob's method	2.86×10^{1}	5.56×10^{-1}	1.87×10^{-11}	
	Hantash's method	1.57×10^{1}	7.68×10^{-1}	6.67×10^{-3}	
	Neuman's method	1.57×10^{1}	9.41×10^{-1}	6.67×10^{-3}	
Permeability Coefficient (m/sec)	Theis's method	5.05×10^{-6}	1.87×10^{-7}	1.03×10^{-5}	
	Cooper & Jacob's method	8.15×10^{-6}	9.38×10^{-8}	3.68×10^{-5}	
	Hantash's method	6.83×10^{-6}	7.68×10^{-6}	1.03×10^{-5}	
	Neuman's method	8.15×10^{-6}	6.10×10^{-6}	1.03×10^{-5}	
	Recovery method	8.15×10^{-6}	5.25×10^{-8}	5.26×10^{-5}	

Table 4.2-6 Selected Hydraulic Parameter of Each Exploratory Well

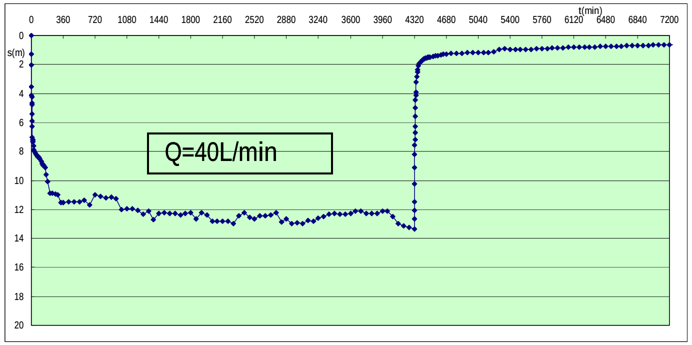
Well No.	Transmissivity		Storativity	Permeability Coefficient (m/sec)
	(m^3/sec/m)	(m^3/day/m)		
J-5	4.30×10^{-5}	3.71	7.86×10^{-2}	2.04×10^{-6}
J-6	4.31×10^{-4}	37.2	7.33×10^{-1}	1.59×10^{-5}
J-7	4.03×10^{-6}	0.35	1.38×10^{-4}	6.77×10^{-8}
J-8	2.91×10^{-4}	25.1	1.97×10^{-3}	9.71×10^{-6}
J-9	2.44×10^{-3}	211	1.57×10	1.16×10^{-4}
J-10	5.07×10^{-6}	0.44	6.66×10^{-1}	1.87×10^{-7}
J-11	3.72×10^{-4}	32.1	1.03×10^{-5}	1.03×10^{-5}

About selected hydraulic parameter from pumping test has still irregular with a extremely high storativity or low strativity, and sometimes there is not reproducibility on check calculation getting the last drawdown in 72 hours pumping test. The adjusted hydraulic parameter which is examined by calculation to become the last drawdown of the constant discharge pumping test under same condition of yield and pumping duration is shown in **Table 4.2-7** together with yield which becomes 5m, 10m and 20m drawdown by 8hours pumping per day. The yield which gives 5m or 10m drawdown by 8 hours pumping par day is considered as a safety yield on ground water development planning,

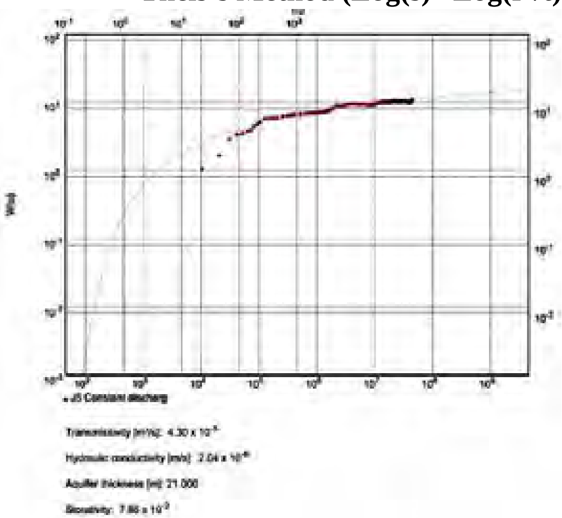
Table 4.2-7 Adjusted Hydraulic Parameter, and Yield at Drawdown 5m, 10m and 15m

Well No.	Transmissivity		Storativity	Permeability Coefficient (m/sec)	Yield per each drawdown (s) (L/min)		
	(m^3/sec/m)	(m^3/day/m)			s=5m	s=10m	S=20m
J-5	4.30×10^{-5}	3.71	8.6×10^{-2}	2.04×10^{-6}	18.8	37.6	75.2
J-6	4.31×10^{-4}	37.2	5.2×10^{-1}	1.59×10^{-5}	178	355	712
J-7	7.50×10^{-6}	0.35	9.0×10^{-2}	3.53×10^{-7}	3.4	6.8	13.6
J-8	2.91×10^{-4}	25.1	1.9×10^{-2}	9.71×10^{-6}	91	183	365
J-9	3.65×10^{-3}	315	6.0×10^{-1}	1.74×10^{-4}	1236		
J-10	5.07×10^{-6}	0.44	3.6×10^{-3}	1.87×10^{-7}	2.0	4.0	7.9
J-11	4.07×10^{-4}	35.2	5.0×10^{-1}	1.03×10^{-5}	168	336	672

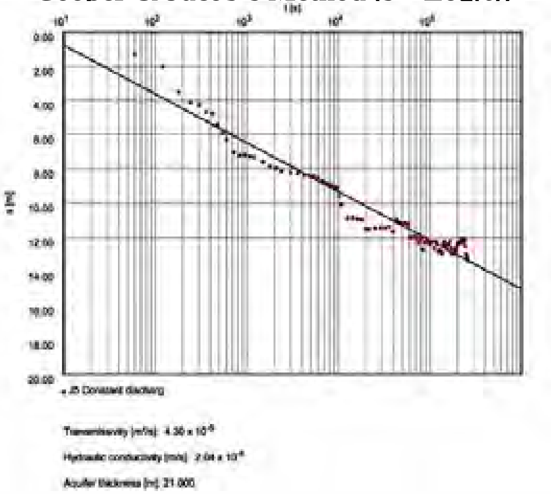
Drawdown (s) - Time (t)



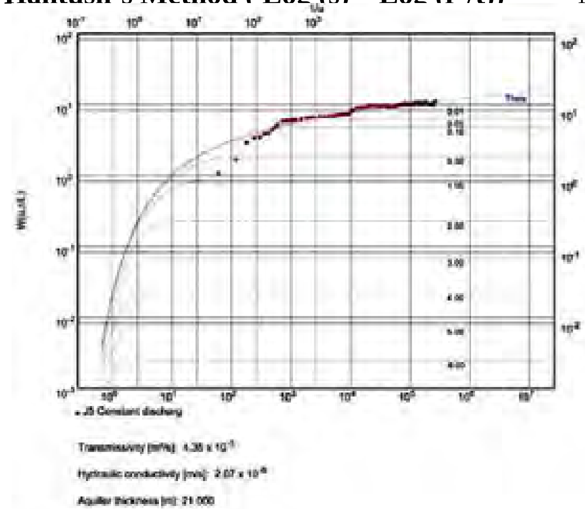
Theis's Method (Log(s) –Log(r²/t))



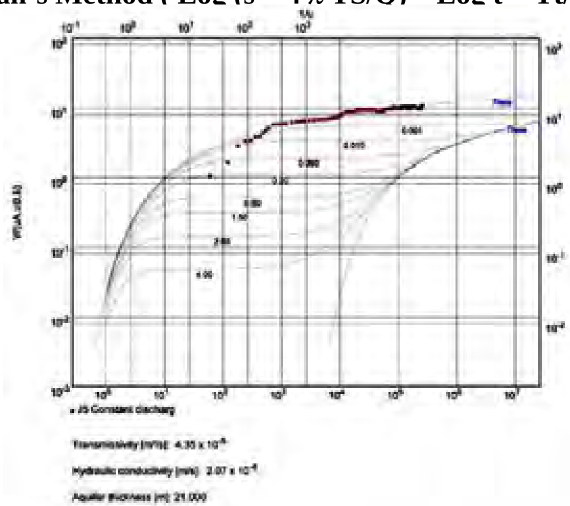
Cooper & Jacob's Method (s – Log(t))



Hantush's Method (Log (s) – Log (r²/t))



Neuman's Method (Log (s = 4 π TS/Q) – Log t = Tt/(Sr²))



Recovery Method (s – Log(t/t'))

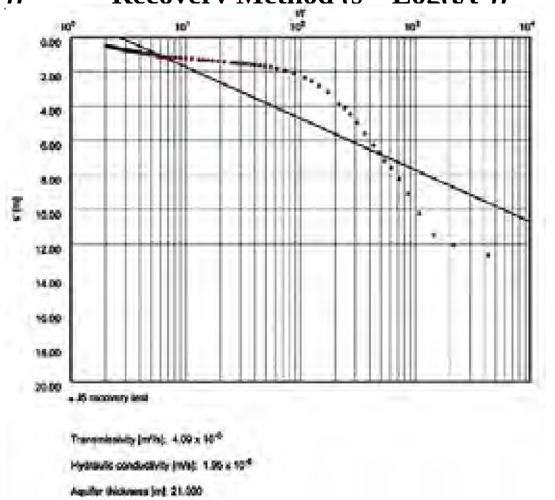
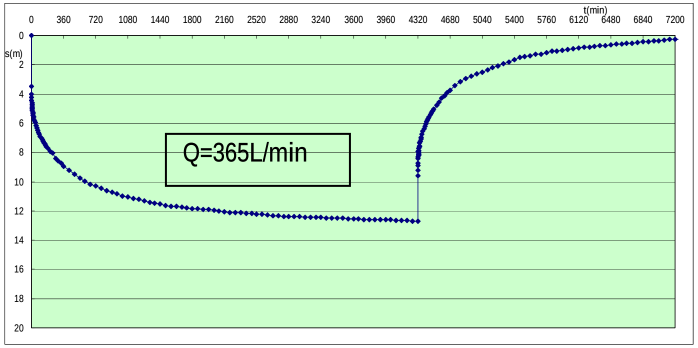
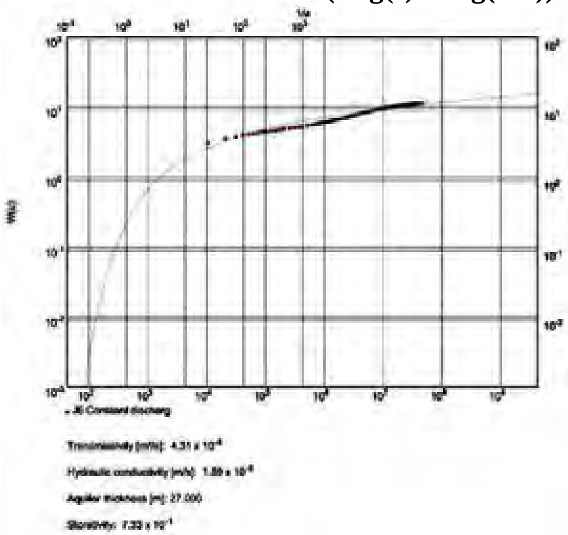


Figure 4.2-2(1) Constant Discharge Pumping Test and Recovery Test Graph of J-5

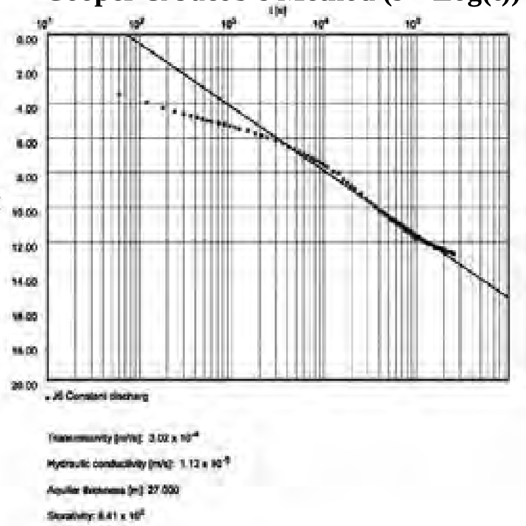
Drawdown (s) - Time (t)



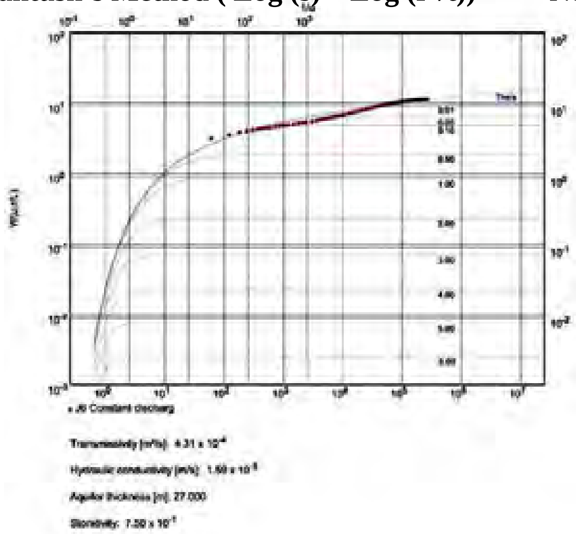
Theis's Method (Log(s) –Log(r^2/t))



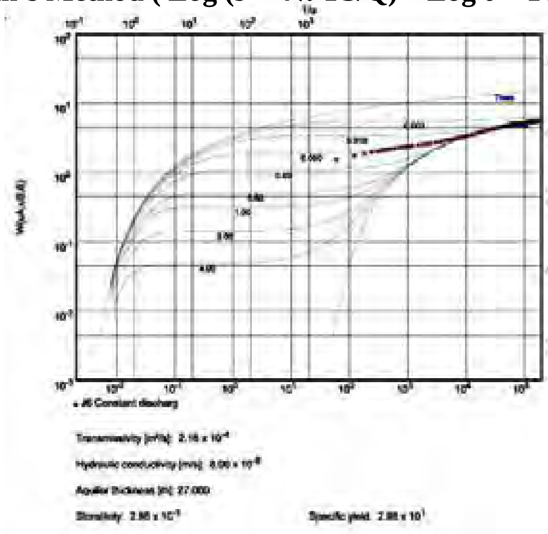
Cooper & Jacob's Method (s – Log(t))



Hantush's Method (Log (s) – Log (r^2/t))



Neuman's Method (Log (s = 4 π TS/Q) – Log t = Tt/(Sr^2))



Recovery Method (s – Log(t/t'))

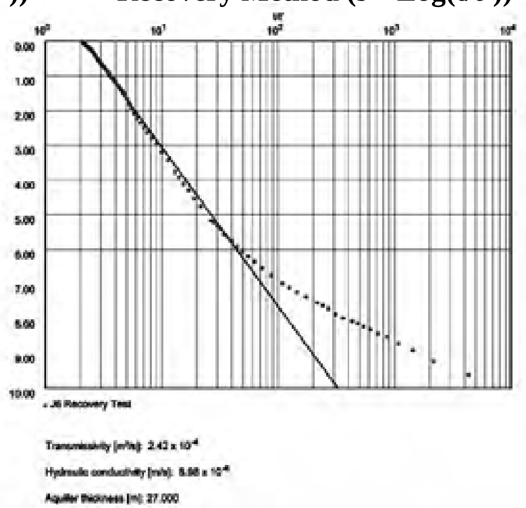
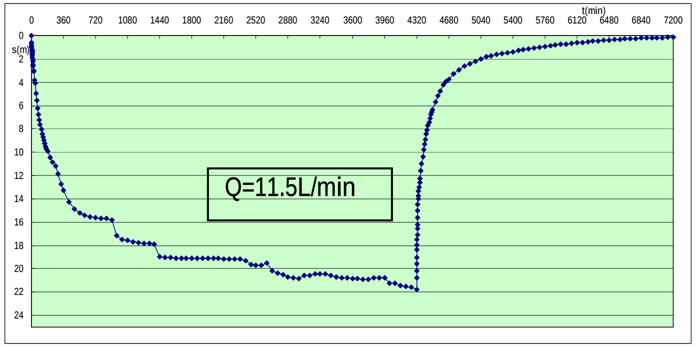
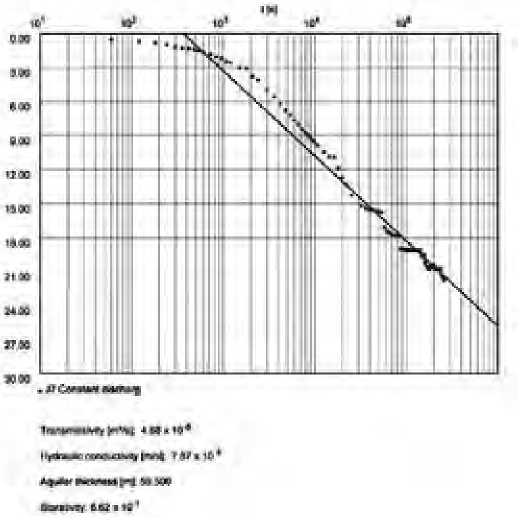


Figure 4.2-2(2) Constant Discharge Pumping Test and Recovery Test Graph of J-6

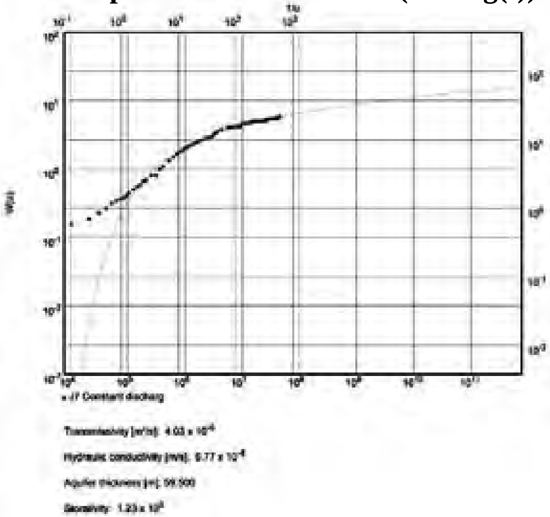
Drawdown (s) - Time (t)



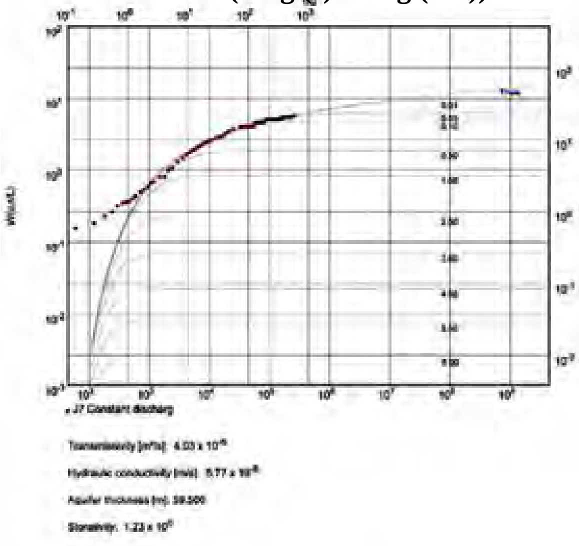
Theis's Method (Log(s) –Log(r²/t))



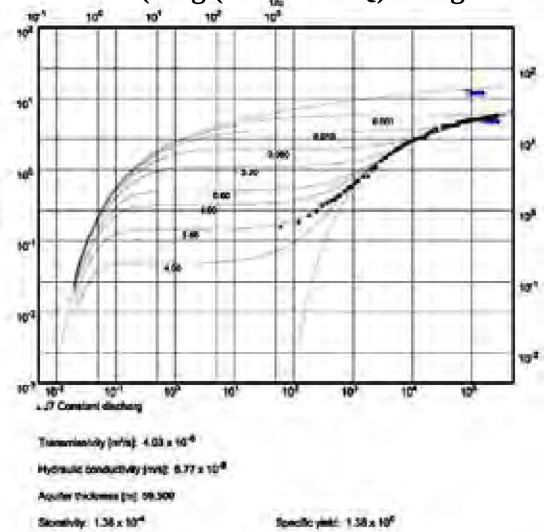
Cooper & Jacob's Method (s – Log(t))



Hantush's Method (Log (s) – Log (r²/t))



Neuman's Method (Log (s = 4 π TS/Q) – Log t = Tt/(Sr²))



Recovery Method (s – Log(t/t'))

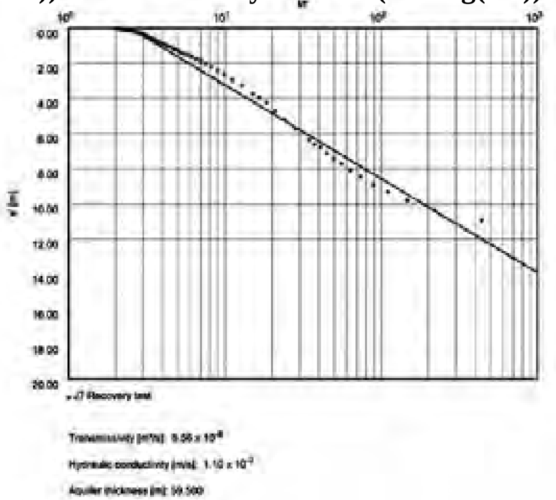


Figure 4.2-2(3) Constant Discharge Pumping Test and Recovery Test Graph of J-7

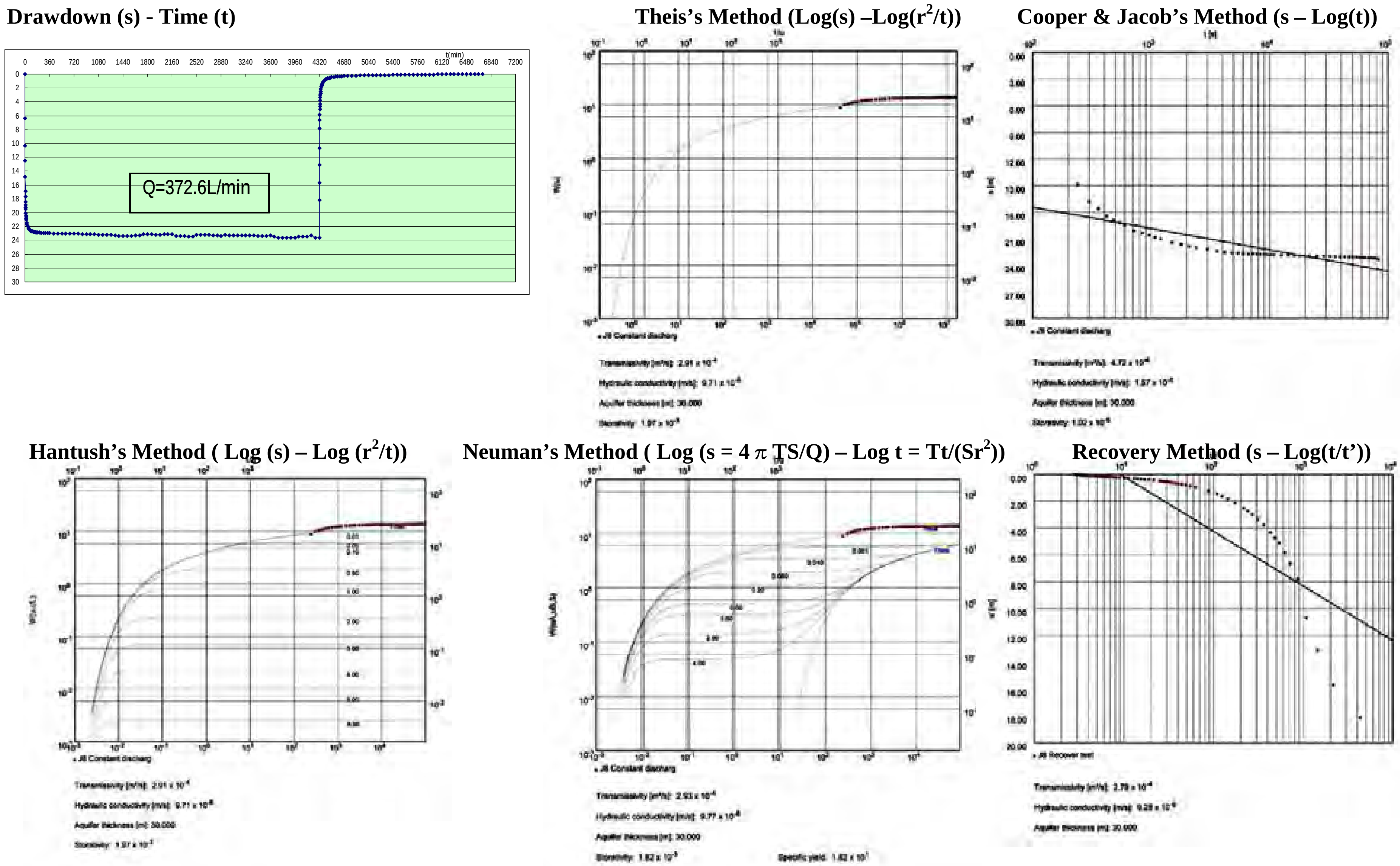
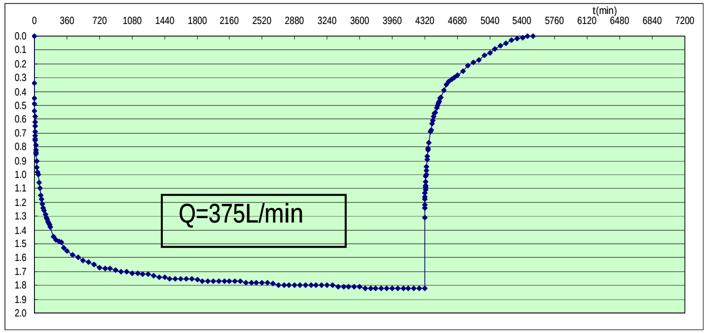
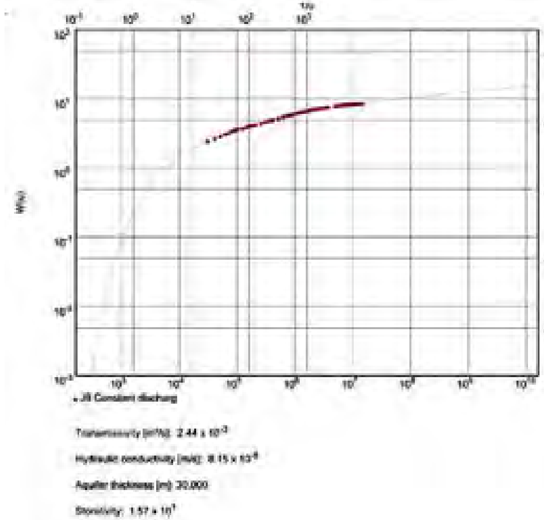


Figure 4.2-2 (4) Constant Discharge Pumping Test and Recovery Test Graph of J-8

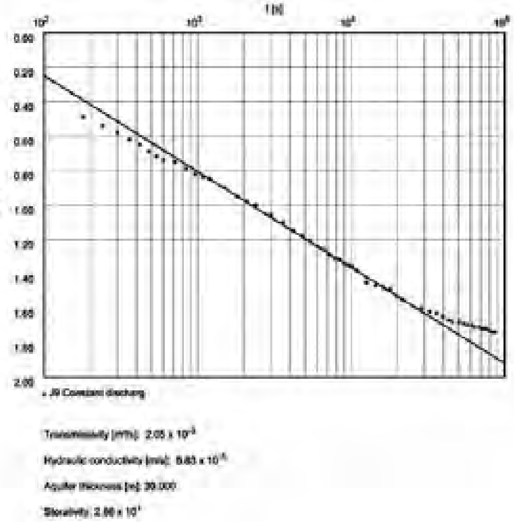
Drawdown (s) - Time (t)



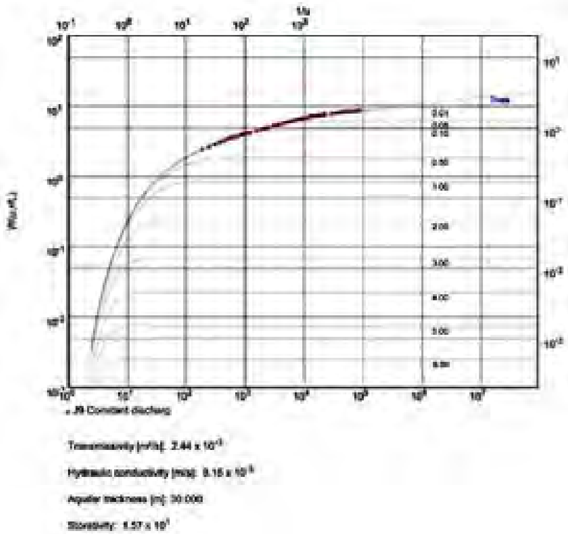
Theis's Method (Log(s) –Log(r^2/t))



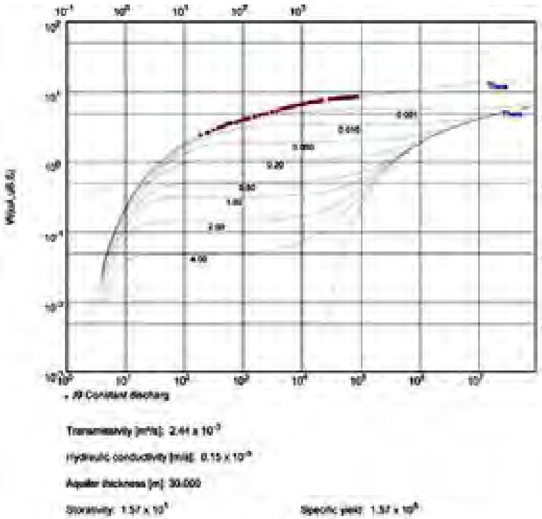
Cooper & Jacob's Method (s – Log(t))



Hantush's Method (Log (s) – Log (r^2/t))



Neuman's Method (Log (s = 4 π TS/Q) – Log t = Tt/(Sr^2))



Recovery Method (s – Log(t/t'))

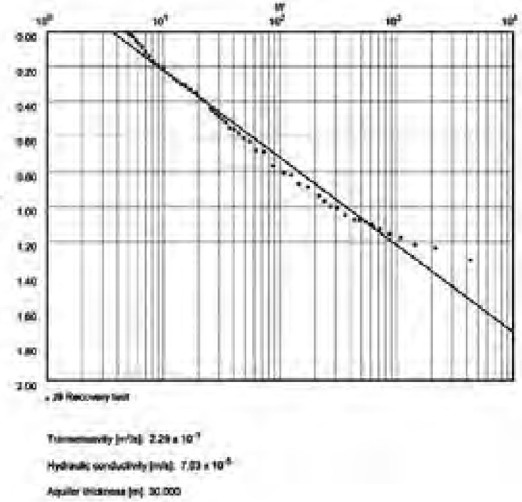
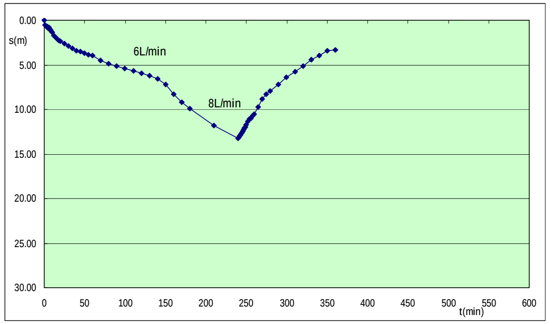
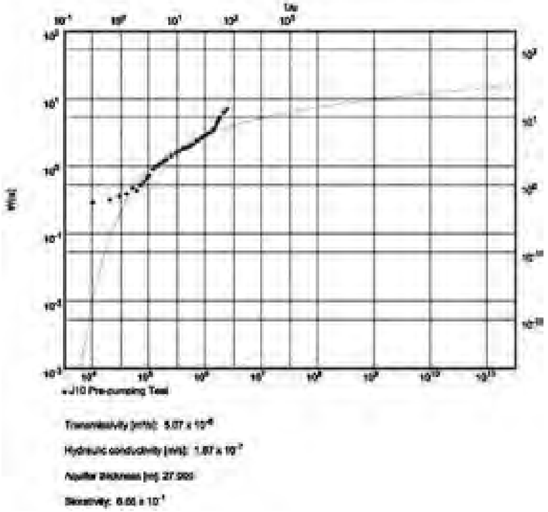


Figure 4.2-2(5) Constant Discharge Pumping Test and Recovery Test Graph of J-9

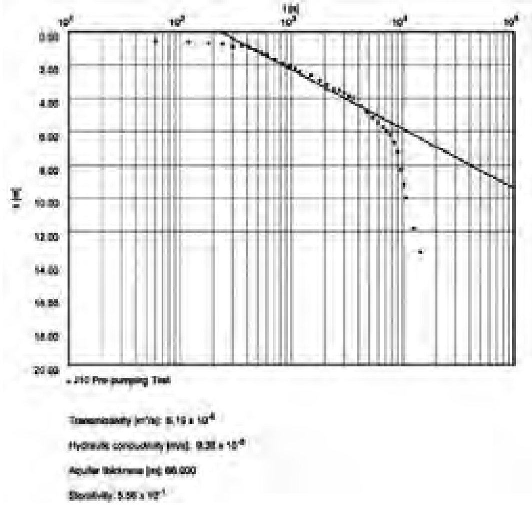
Drawdown (s) - Time (t)



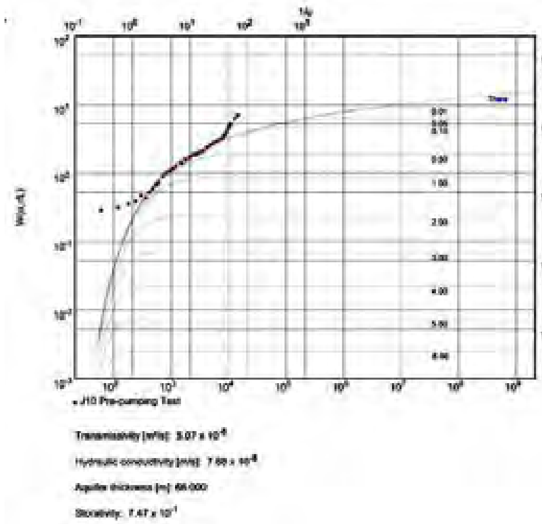
Theis's Method (Log(s) –Log(r²/t))



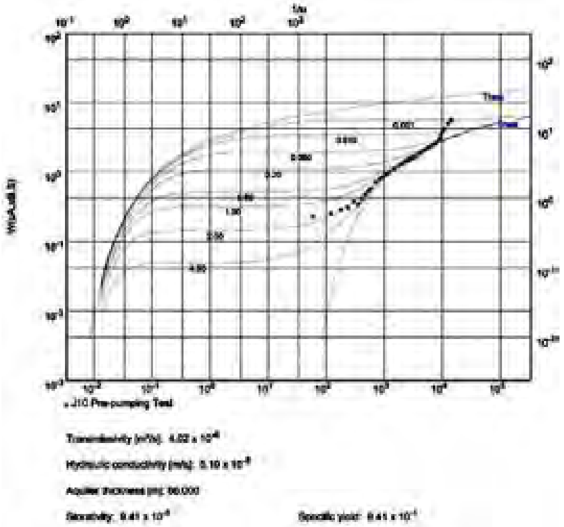
Cooper & Jacob's Method (s – Log(t))



Hantush's Method (Log (s) – Log (r²/t))



Neuman's Method (Log (s = 4 π TS/Q) – Log t = Tt/(Sr²))



Recovery Method (s – Log(t/t'))

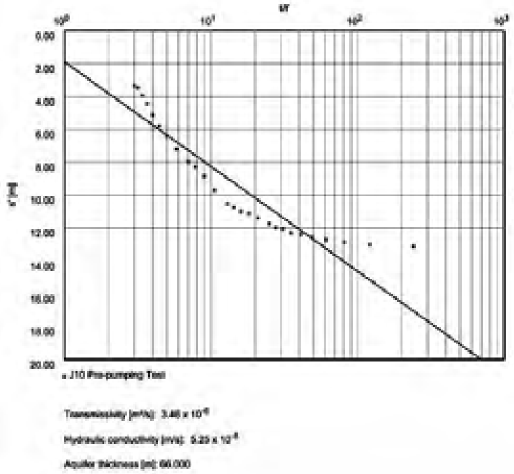
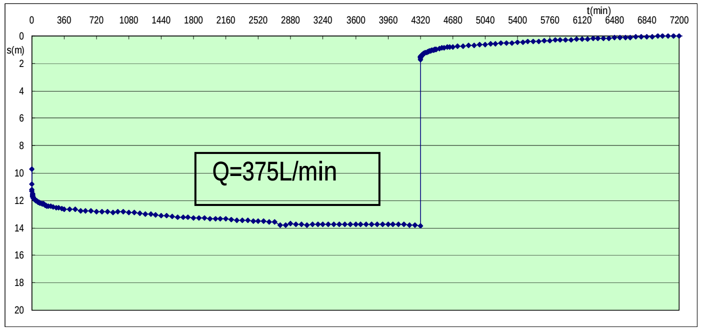
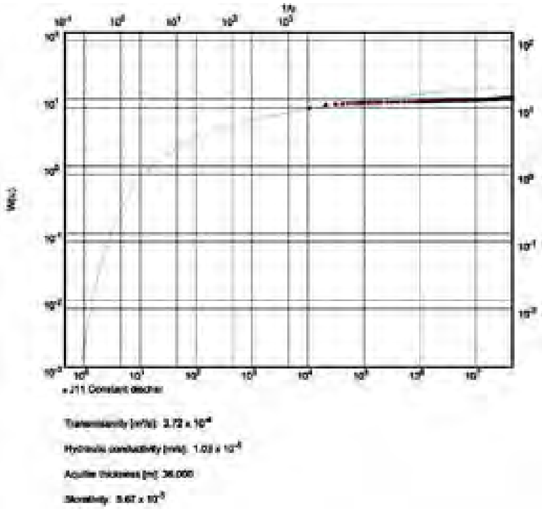


Figure 4.2-2(6) Constant Discharge Pumping Test and Recovery Test Graph of J-10

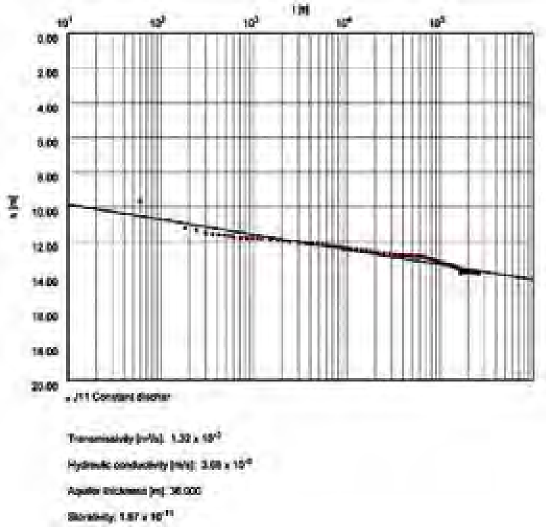
Drawdown (s) - Time (t)



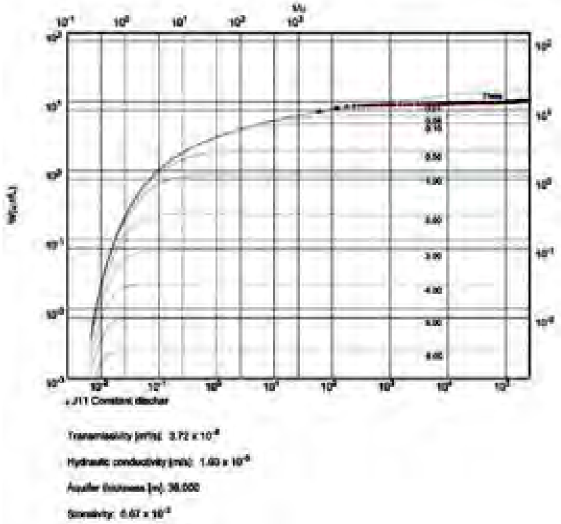
Theis's Method (Log(s) –Log(r^2/t))



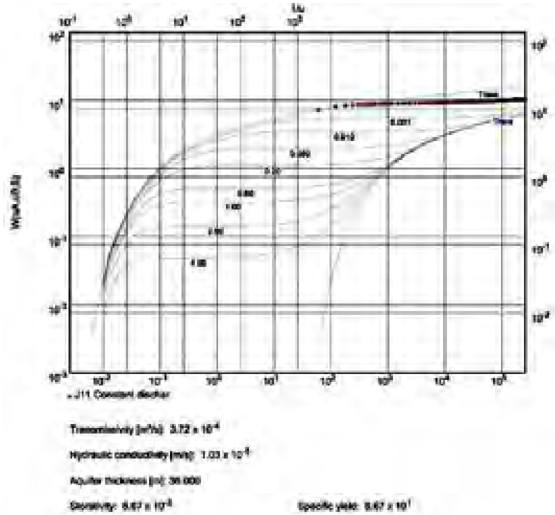
Cooper & Jacob's Method (s – Log(t))



Hantush's Method (Log (s) – Log (r^2/t))



Neuman's Method (Log (s = 4 π TS/Q) – Log t = Tt/(Sr^2))



Recovery Method (s – Log(t/t'))

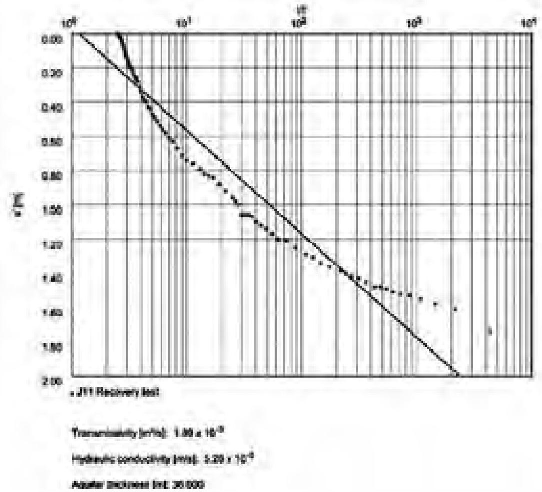


Figure 4.2-2(7) Constant Discharge Pumping Test and Recovery Test Graph of J-11

4.3 Shallow Wells Situation and Influence during Pumping Test

(1) Shallow Wells Situation surrounding Exploratory Wells

The Inventory records of surrounding wells of each exploratory drilling site and an area along central low hills formed by diabase intrusion is shown in **APPENDIX 1**.
The feature of shallow wells' structure, water use and situation of quality as resident consciousness in a) north west part of the study area, b) central and south west part of the study area and c) diabase intrusion area is as follows.

1) Shallow Wells in North West Part of the Study Area
a) Well structure and water level
Dug wells with concrete cover or block cover reach to 89%. The diffusion rate of hand pump is rather low. Dug well with hand pump is 8% and drilled well with hand pump is 0%. Diameter of Dug wells is 0.8 to 1.2m, total depth is 1.7 to 10.6m, average 5.2m. Water level is 0.0 to 6.8m, average 2.0m.

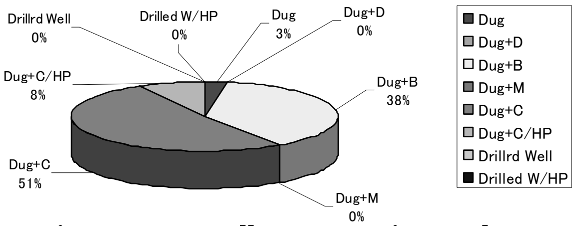


Figure 4.3-1 Well Structure in North West Part

Table 4.3-1 Well Dimension in North West Part

Well Dimension							
Ground Hight (m)		Total Depth (m)		Water Level (m)		WL(Elevation, m)	
Max.	14	Max.	10.58	Max.	6.77	Max.	11.60
Min.	8	Min.	1.68	Min.	0.01	Min.	5.16
Average	11	Average	5.24	Average	2.02	Average	8.41
Median	11	Median	4.99	Median	1.44	Median	7.99
Mode	12	Mode	3.90	Mode	0.33	Mode	—
Total N	37	Total N	35	Total N	35	Total N	35

b) Groundwater use
Drinking water use including domestic water use is 35%, 65% of wells can not use as drilling water. Average water use per well is 13.7 gallon/ day/ person. Average total volume of water use per well is 4,744 gallon/ day.

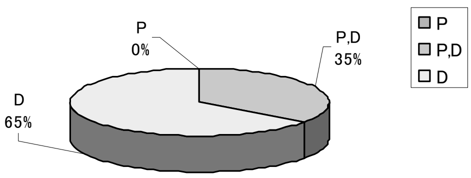


Figure 4.3-2 Use of Water in North West Part

Table 4.3-2 Water Use Volume of Well in North West Part

Water Use					
Person/ Well		Vol./ P. (Gal/day)		T. Volume (Well, Gal/day))	
Max.	1500	Max.	20.0		
Min.	8	Min.	3.0		
Average	346	Average	13.7	Average	4,744
Median	500	Median	15.0		
Mode	500	Mode	15.0		
Total N	37	Total N	37		

c) Dry-up Condition and Quality of groundwater
Dry up well in dry season is 24%, and well in which water level goes down in dry season is 41%. 35% of wells are not recognized any dry up situation. The water quality or problem as resident consciousness is as follows.

i) 27% of wells has bad water quality situation such as cloudy water (8%), colored water (14%), and dirty water (5%).
ii) Contamination such as dust/ leaves/ rubbish blowing in and odor is felt in 52% of wells.

Table 4.3-3 Water Quality of Wells in North West Part (by Field Measurement)

Water Quolity									
Temp. (oC)		pH		EC (mS/cm)		TDS(mg/L)		Turbidity (NTU)	
Max.	29.9	Max.	6.88	Max.	0.720	Max.	191.0	Max.	33.5
Min.	27.0	Min.	4.20	Min.	0.035	Min.	22.0	Min.	0.0
Average	28.0	Average	5.72	Average	0.151	Average	75.4	Average	6.1
Median	27.9	Median	6.05	Median	0.106	Median	66.0	Median	4.4
Mode	27.4	Mode	6.17	Mode	0.058	Mode	49.0	Mode	0.0
Total N	37	Total N	37	Total N	37	Total N	37	Total N	37

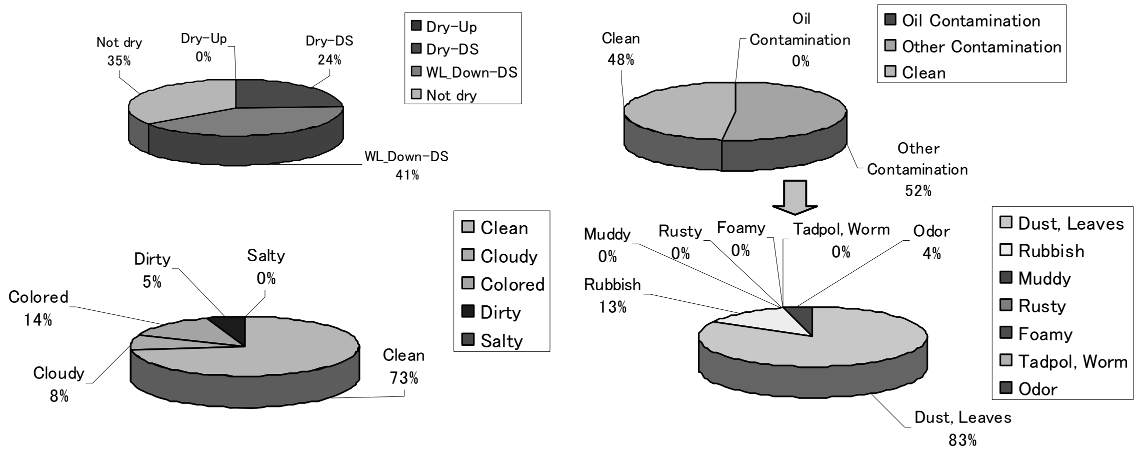


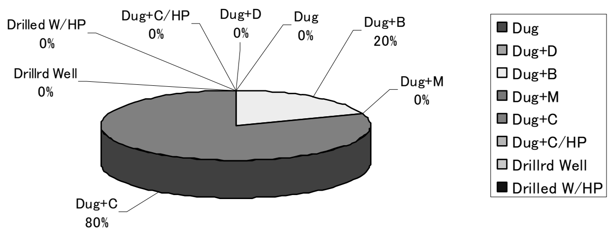
Figure 4.3-3 Dry up Situation and Water Quality Consciousness in North West Part

2) Shallow Wells in Central and South East Part of the Study Area

a) Well structure and water level

Dug wells with concrete cover or block cover reach to 100%. The diffusion rate of hand pump is very low, especially in south east part of the study area. Diameter of dug wells is 0.8 to 1.2m, total depth is 1.1 to 6.9m, average 4.1m. Water level is 0.1 to 2.7m, average 0.7m.

Table 4.3-4 Well Dimension in Central and South East Part



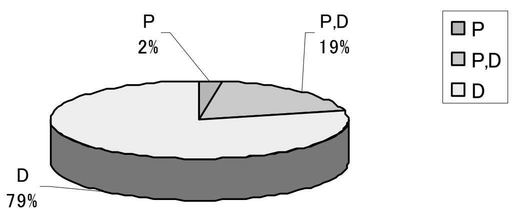
Well Dimension							
Ground Hight (m)		Total Depth (m)		Water Level (m)		WL(Elevation, m)	
Max.	10	Max.	6.92	Max.	2.69	Max.	8.90
Min.	4	Min.	1.06	Min.	0.06	Min.	2.93
Average	6	Average	4.07	Average	0.71	Average	5.61
Median	6	Median	3.89	Median	0.46	Median	5.19
Mode	6	Mode	4.30	Mode	0.10	Mode	—
Total N	41	Total N	41	Total N	41	Total N	41

Figure 4.3-4 Well Structure in Central and South East Part

b) Groundwater use

Drinking water use including domestic water use is 21%, 79% of wells can not use as drilling water. Average water use per well is 12.9 gallon/ day/ person. Average total volume of water use per well is 2,091 gallon/ day.

Table 4.3-5 Water Use Volume of Well in Central and South East Part



Water Use					
Person/ Well		Vol./ P. (Gal/day)		T. Volume (Well, Gal/day))	
Max.	500	Max.	20.0		
Min.	9	Min.	3.0		
Average	162	Average	12.9	Average	2,091
Median	50	Median	15.0		
Mode	50	Mode	15.0		
Total N	40	Total N	40		

Figure 4.3-5 Purpose of Water Use in Central and South East Part

c) Dry-up Condition and Quality of groundwater

Dry up well in dry season is 20%, and well in which water level goes down in dry season is 24%. 56% of wells is not recognized any dry up situation. The water quality or problem as resident consciousness is as follows.

i) 62% of wells has bad water quality situation such as cloudy water(7%), colored water (46%), dirty water (7%) and salty water (2%).

ii) Contamination such as dust/ leaves/ rubbish blowing in, muddy/ rusty/ foamy situation, tadpole/ worm generation, and odor is felt in 54% of wells.

Table 4.3-6 Water Quality of Wells in Central and South East Part (by Field Measurement)

Water Quolity									
Temp. (oC)		pH		EC (mS/cm)		TDS(mg/L)		Turbidity (NTU)	
Max.	31.3	Max.	8.37	Max.	1.000	Max.	641.0	Max.	77.0
Min.	21.6	Min.	4.94	Min.	0.024	Min.	15.0	Min.	0.0
Average	27.8	Average	6.76	Average	0.265	Average	171.5	Average	12.7
Median	28.0	Median	6.85	Median	0.216	Median	140.0	Median	10.6
Mode	28.1	Mode	6.85	Mode	0.216	Mode	140.0	Mode	0.0
Total N	41	Total N	41	Total N	41	Total N	41	Total N	41

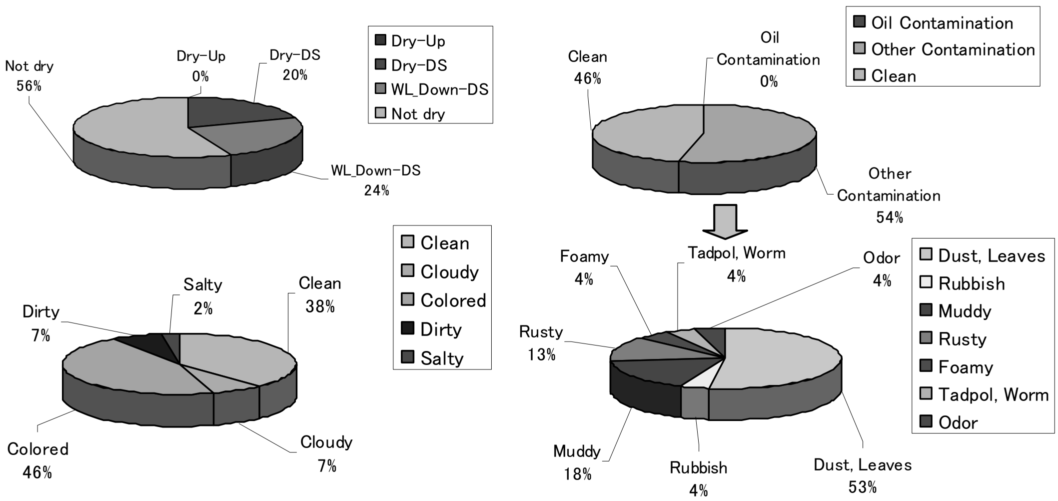


Figure 4.3-6 Dry up Situation and Water Quality Consciousness in Central and South East Part

3) Shallow Wells in Diabase Intrusion Area

a) Well structure and water level

Dug wells with concrete cover or block cover reach to 90%. The diffusion rate of hand pump is low. Dug well with hand pump is 5% and drilled well with hand pump is also 5%. Diameter of Dug wells is 0.8 to 1.2m, total depth is 3.2 to 12.2m, average 6.8m. Water level is 0.3 to 7.7m, average 3.0m.

Table 4.3-7 Well Dimension in Diabase Intrusion Area

Well Dimension							
Ground Hight (m)		Total Depth (m)		Water Level (m)		WL(Elevation, m)	
Max.	27	Max.	12.20	Max.	7.69	Max.	21.95
Min.	6	Min.	3.20	Min.	0.30	Min.	4.45
Average	11	Average	6.83	Average	2.97	Average	8.26
Median	10	Median	7.43	Median	2.40	Median	7.83
Mode	8	Mode	7.85	Mode	—	Mode	—
Total N	24	Total N	24	Total N	20	Total N	20

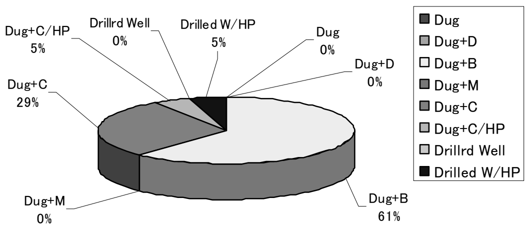


Figure 4.3-7 Well Structure in Diabase Intrusion Area

b) Groundwater use

Drinking water use including domestic water use is only 50%, 50% of wells can not use as drilling water. Average water use per well is 14.7 gallon/ day/ person. Average total volume of water use per well is 6,420 gallon/ day.

Table 4.3-8 Water Use Volume of Well in Diabase Intrusion Area

Water Use					
Person/ Well		Vol./ P. (Gal/day)		T. Volume (Well, Gal/day))	
Max.	500	Max.	15.0		
Min.	25	Min.	8.0		
Average	436	Average	14.7	Average	6,420
Median	500	Median	15.0		
Mode	500	Mode	15.0		
Total N	24	Total N	24		

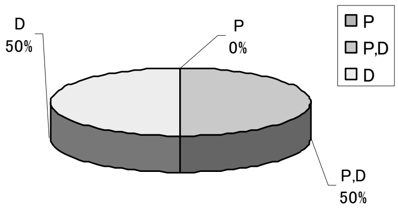


Figure 4.3-8 Purpose of Water Use in Diabase Intrusion Area

c) Dry-up Condition and Quality of groundwater

Dry up well in dry season is 50%, and well in which water level goes down in dry season is 21%. 29% of wells is not recognized any dry up situation. The water quality or problem as resident consciousness is as follows.

i) 21% of wells has bad water quality situation such as cloudy water(13%) and colored water (8%).

ii) Contamination such as dust/ leaves/ rubbish blowing in, foamy situation and tadpole/ worm generation is felt in 42% of wells.

Table 4.3-9 Water Quality of Wells in Diabase Intrusion Area

Water Quolity									
Temp. (oC)		pH		EC (mS/cm)		TDS(mg/L)		Turbidity (NTU)	
Max.	29.0	Max.	7.52	Max.	0.215	Max.	94.0	Max.	19.0
Min.	26.1	Min.	4.85	Min.	0.016	Min.	0.0	Min.	3.0
Average	27.3	Average	5.74	Average	0.059	Average	23.8	Average	2.0
Median	27.2	Median	5.67	Median	0.052	Median	16.0	Median	0.0
Mode	26.8	Mode	5.70	Mode	0.040	Mode	8.0	Mode	0.0
Total N	24	Total N	24	Total N	24	Total N	24	Total N	24

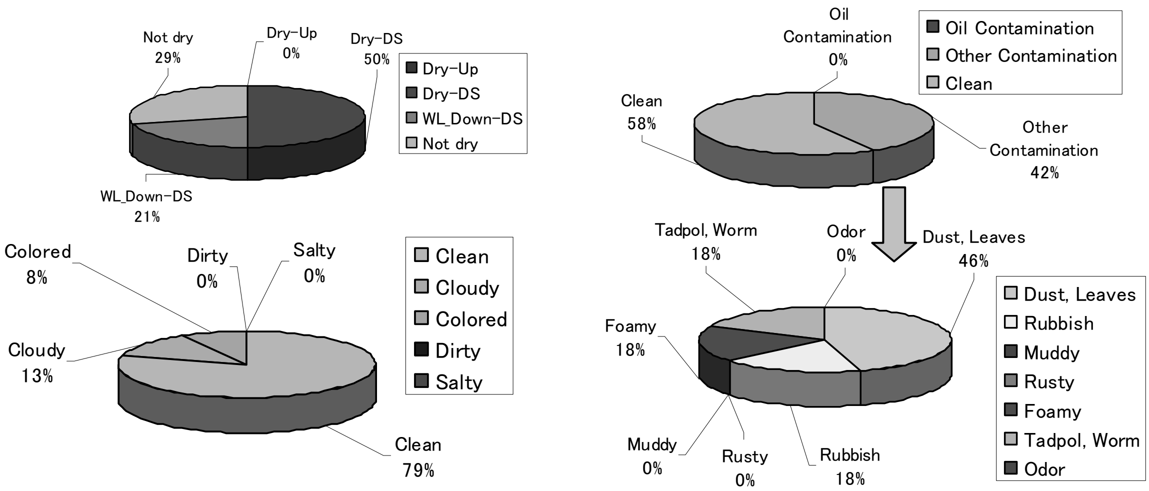


Figure 4.3-9 Dry up Situation and Water Quality Consciousness in Diabase Intrusion Area

(2) Seasonal water level and quality variation

The 2nd well inventory survey was carried out from 24th Feb. 2010 to 28th Feb. 2010 in order to obtain water level and simple water quality by site measurement in dry season. The 1st inventory work was conducted from 27th Oct. 2009 to 6th Nov. 2009 at end of rainy season. The seasonal water level and water quality variation between a rainy season and a dry season is as follows.

1) Seasonal variation in North West Part of the Study Area

The Seasonal variation of water level and simple water quality in North West Part of the Study Area is shown in **Figure 4.3-11.** The record of the 2nd well inventory survey is arranged in **Appendix-II.**

a) Variation of Water Level

The water level goes down in dry season. The variation of water level between rainy season and dry season shows 0.36 to 2.98m, average 1.81m.

b) Water Quality

The PH does not show clearly a trend to change between rainy season and dry season. The graph shows some portion increases and other portion decreases.

The electric conductivity shows the tendency which increases slightly to the rainy season. It can be thought an influence of inflow of surface water with slightly high content of dissolved substitute. Total dissolved solid shows a remarkable difference is not recognized.

The turbidity shows the tendency which increases to the dry season. It may show an influence of increase of insoluble content according to decrease of water level.

2) Seasonal variation in Central and South East Part of the Study Area

The Seasonal variation of water level and simple water quality in Central and South East Part of the Study Area is shown in **Figure 4.3-12.** The record of the 2nd well inventory survey is arranged in **Appendix-II.**

a) Variation of Water Level

The water level goes down in dry season. The variation of water level between rainy season and dry season shows -0.03 to 2.36m, average 1.21m.

b) Water Quality

The PH shows the tendency which increases slightly to the rainy season. The reason is not known. There may be conditions which cannot be easily influenced by rain and surface water about PH.

The electric conductivity shows the tendency which increases slightly to the rainy season. It can be thought an influence of inflow of surface water with slightly high content of dissolved substitute. Total dissolved solid also shows the same tendency.

The turbidity shows the tendency which increases to the dry season. It may show an influence of increase of insoluble content according to decrease of water level.

3) Seasonal variation in Diabase Intrusion Area

The Seasonal variation of water level and simple water quality in Diabase Intrusion Area of the Study Area is shown in **Figure 4.3-13.** The record of the 2nd well inventory survey is arranged in **Appendix-II.**

a) Variation of Water Level

The water level goes down in dry season. The variation of water level between rainy season and dry season shows -4.04 to 5.64m, average 1.88m.

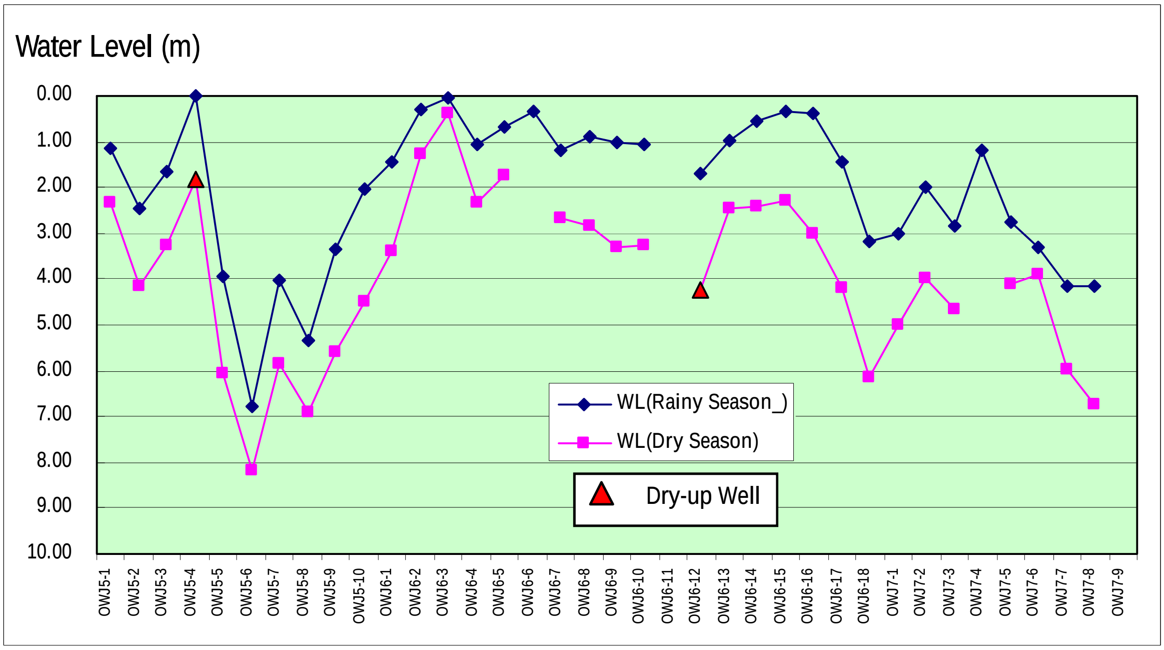
b) Water Quality

The PH shows the tendency which decreases to the dry season. In rainy season, the influence of the rain and surface water with low PH can be considered.

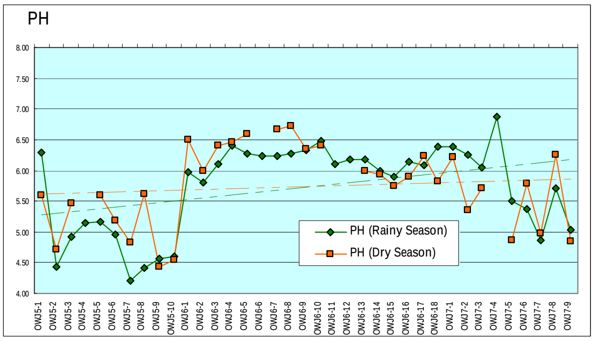
The electric conductivity shows the tendency which increases slightly to the dry season. An influence of increase of dissolved substitute according to decrease of water level is considered.

The turbidity shows the tendency which increases to the dry season. It may show an influence of increase of insoluble content according to decrease of water level.

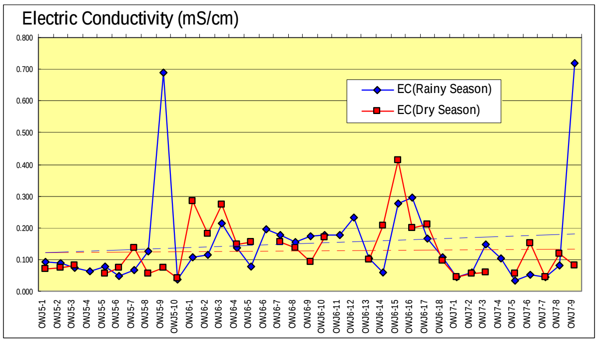
(A) Water Level



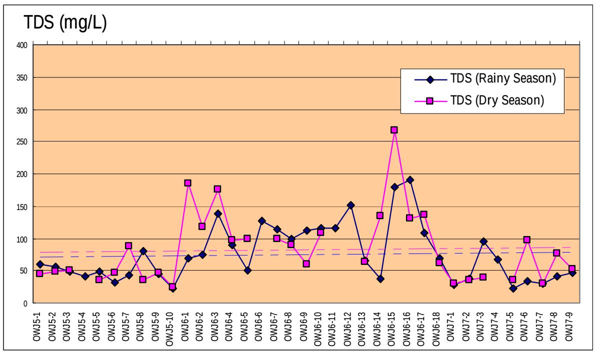
(B) PH



(C) Electric Conductivity



(D) Total Dissolved Solid



(E) Turbidity

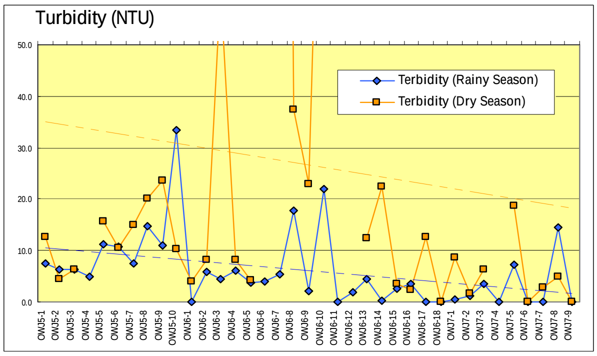
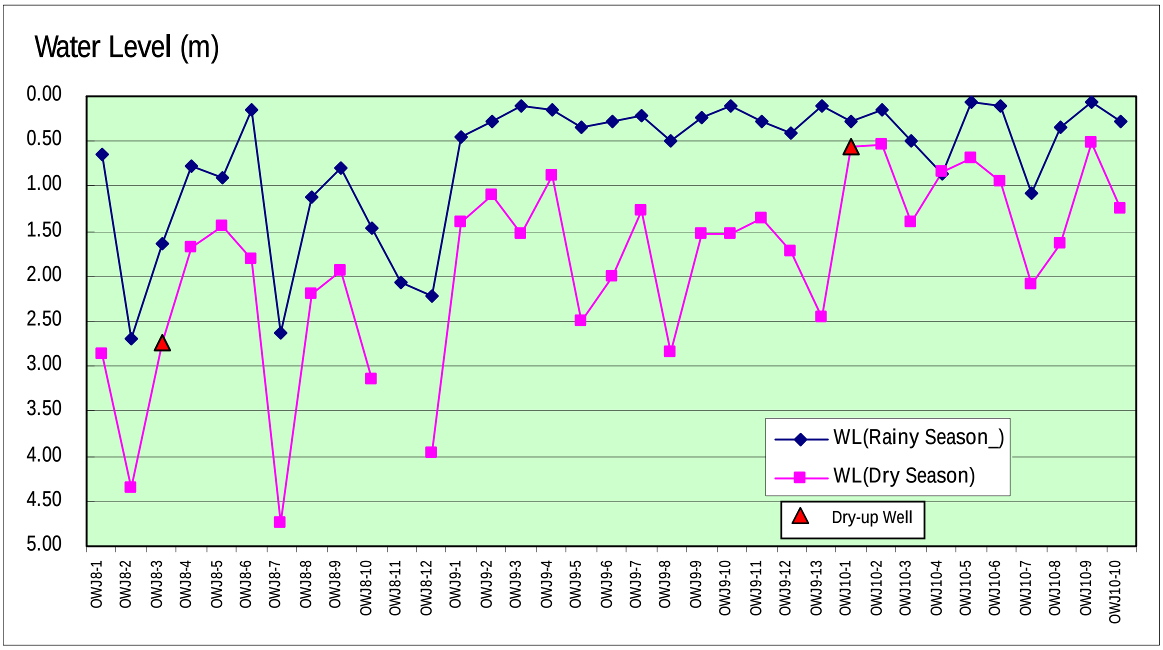
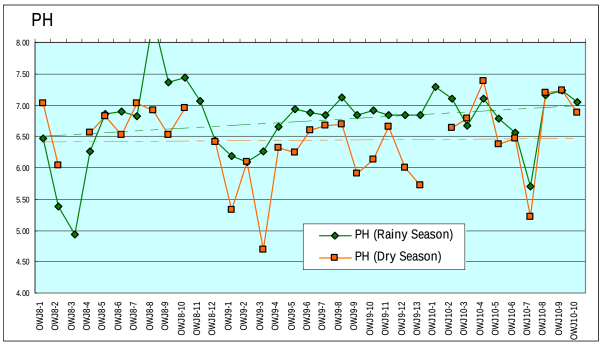


Figure 4.3-10 Seasonal Variation of Water Level and Water Quality in North West Part

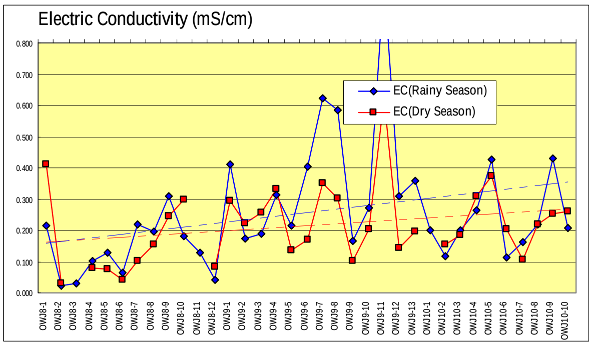
(A) Water Level



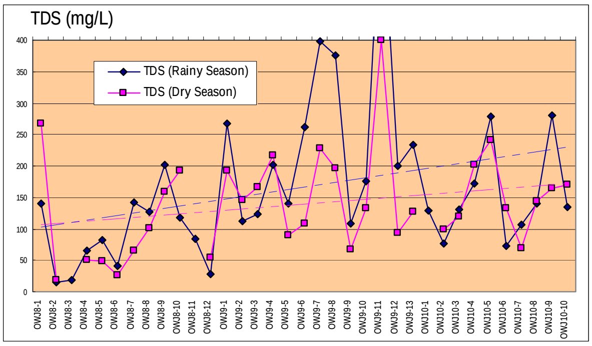
(B) PH



(C) Electric Conductivity



(D) Total Dissolved Solid



(E) Turbidity

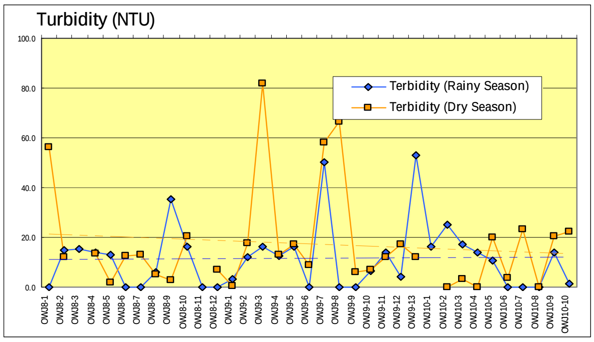
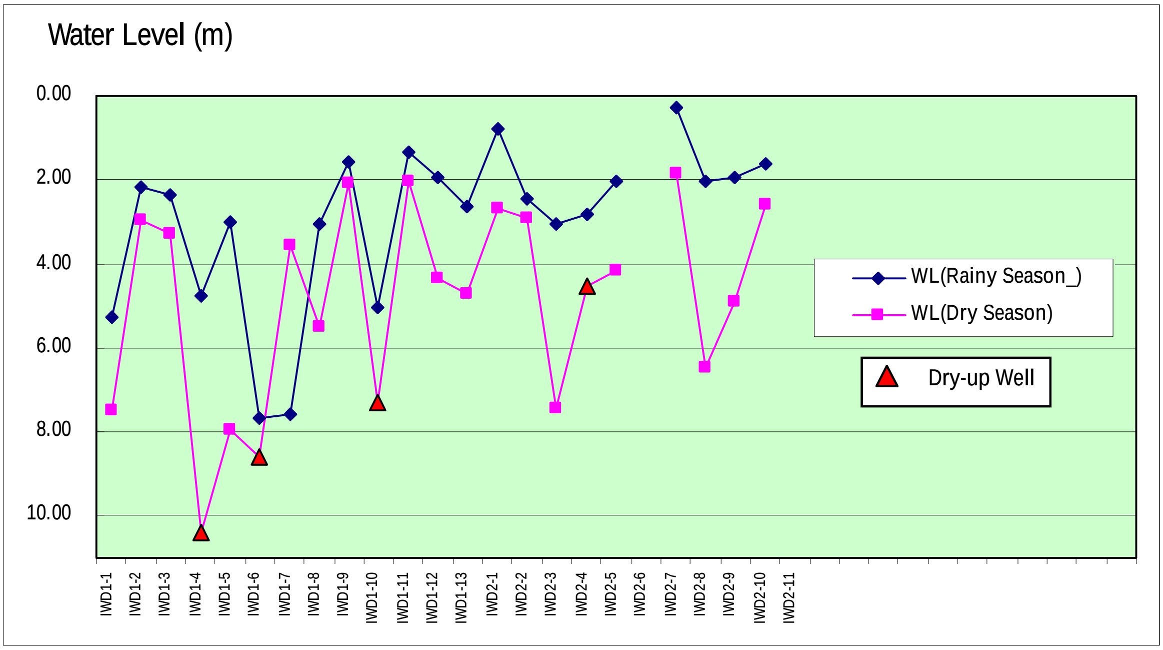
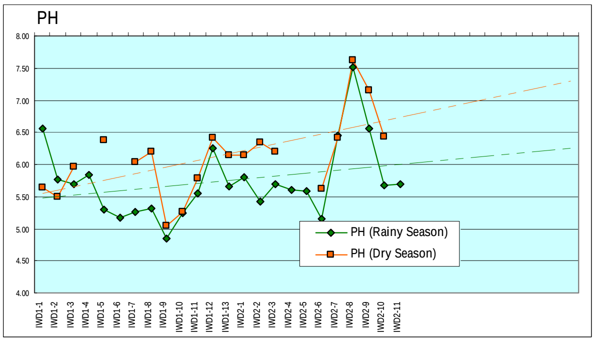


Figure 4.3-11 Seasonal Variation of Water Level and Water Quality in Central and South East Part

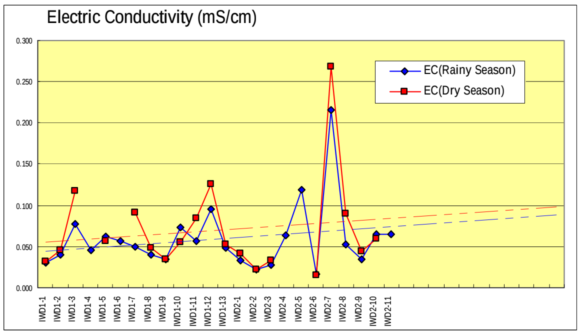
(A) Water Level



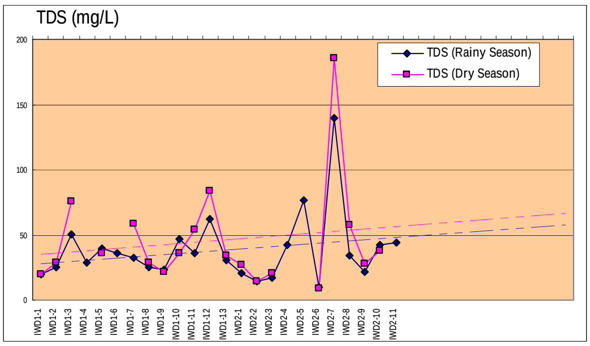
(B) PH



(C) Electric Conductivity



(D) Total Dissolved Solid



(E) Turbidity

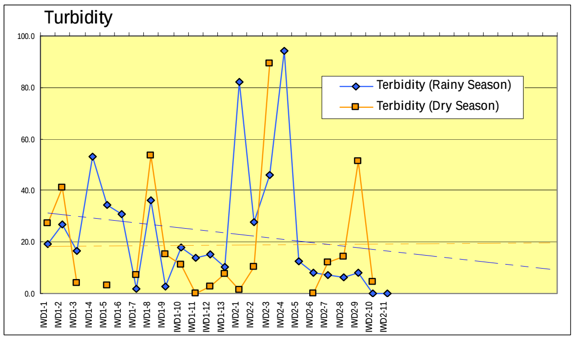


Figure 4.3-12 Seasonal Variation of Water Level and Water Quality in Diabase Intrusion Area

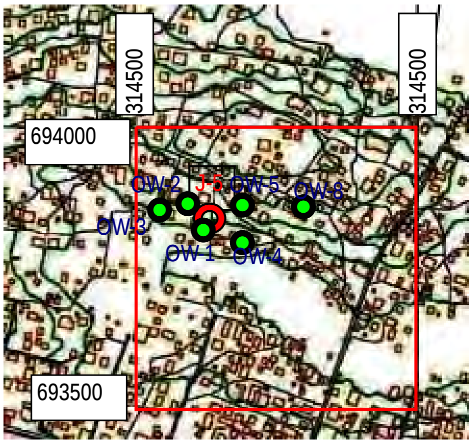
(3) Influence to Surrounding Shallow Wells during Pumping Test

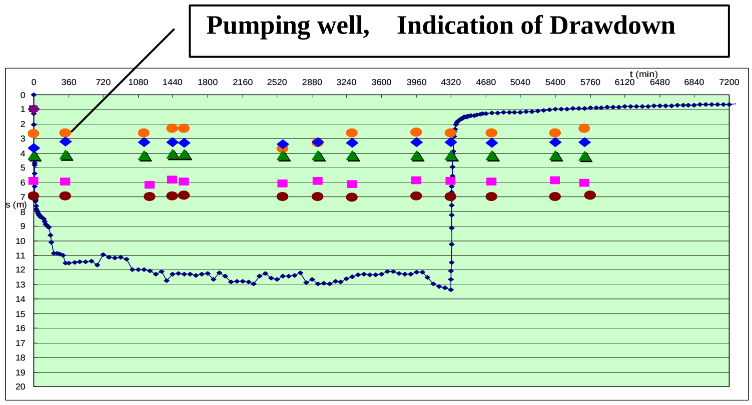
At each drilling well site except for J-10 in which normal pumping test other than preliminary pumping test was not conducted because of very low water producing condition, the observation of water level of surrounding shallow wells during the constant discharge pumping test and recovery test is carried out in order to confirm the situation of influence on existing shallow wells by pumping. The influence on water level of existing shallow wells during pumping test is shown in **Table 4.3-10**. The recording water level of observation shallow wells during pumping test is plotted in **Figure 4.3-11** shown with the location map. Any clear influence is not recognized during pumping test in each well site.

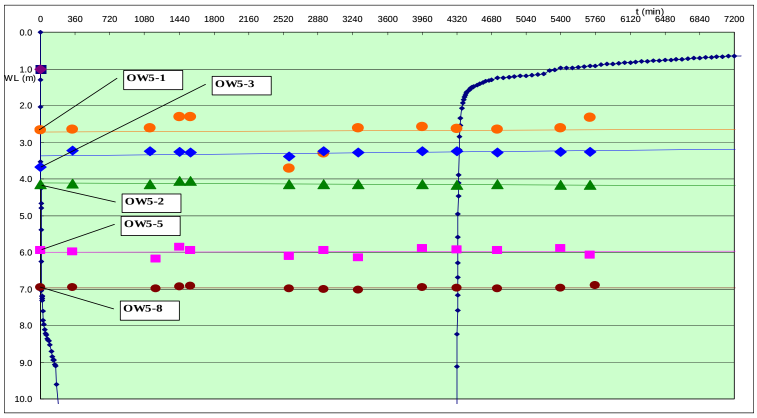
Table 4.3-10 Results of Water Level Observation in Surrounding Shallow Well during Pumping Test

Well No	Description	Influence
J-5	OW5-1 indicates partly water level drops during pumping, but water level recovers at last one day pumping duration. Other wells do not indicate influence of exploratory well pumping.	Not influence
J-6	All observation well indicates slightly rising trend of water level during exploratory well pumping.	Not influence
J-7	All observation wells does not indicate any decline trend of water level during exploratory well pumping.	Not influence
J-8	OW8-2 indicates partly water level declines during pumping, but water level recovers at last few hours pumping duration.	Not influence
J-9	OW9-6 indicates water level declines about 40cm at last one day of pumping duration and after stopping pump. But the trend is not reflected the very first recover situation and the only 1.8m drawdown of the pumping well.	Not clear
J-11	OW11-1 indicates gradually decline about 10cm during pumping. But the trend is not concerned to the drawdown trend of the pumping well.	Not clear

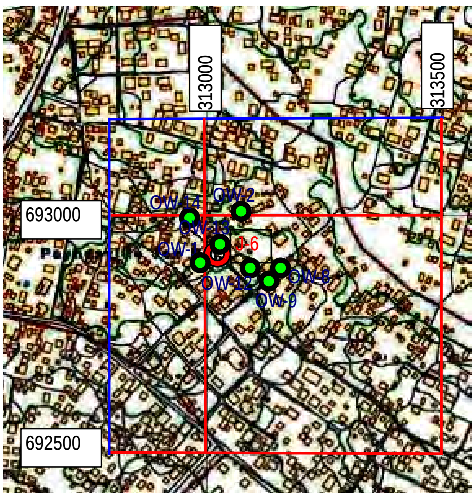
J-5

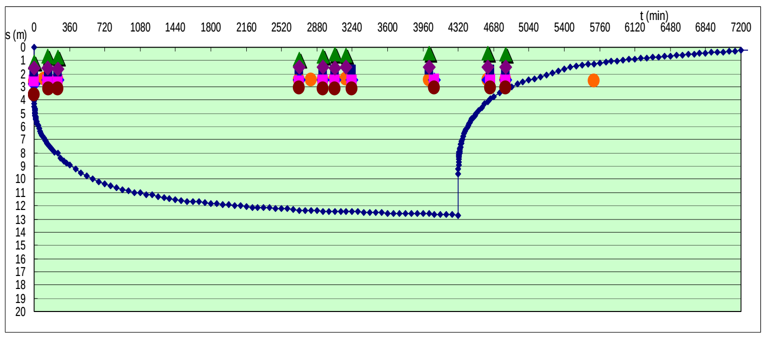






J -6





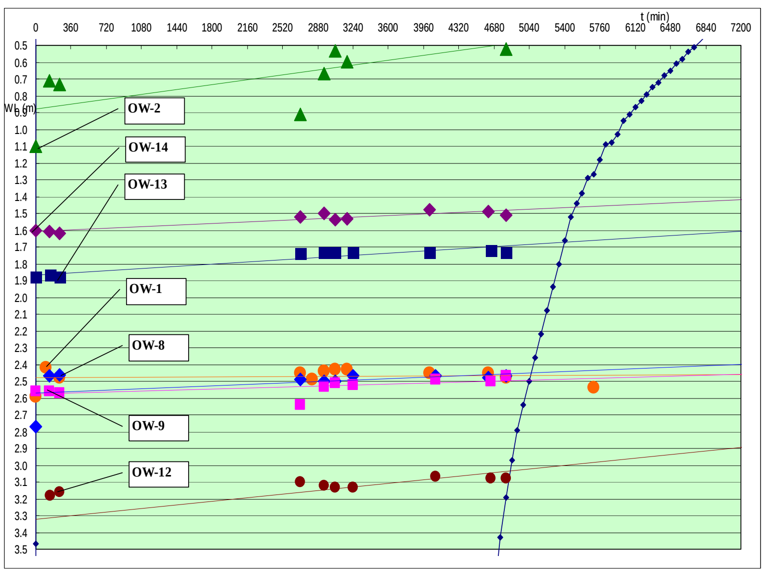
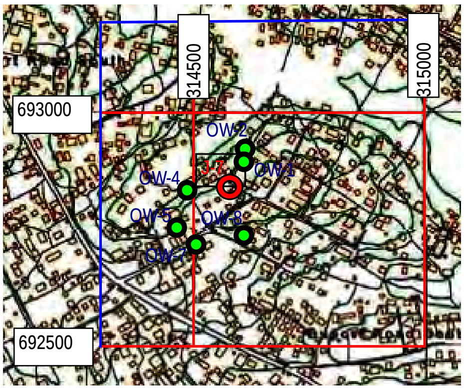
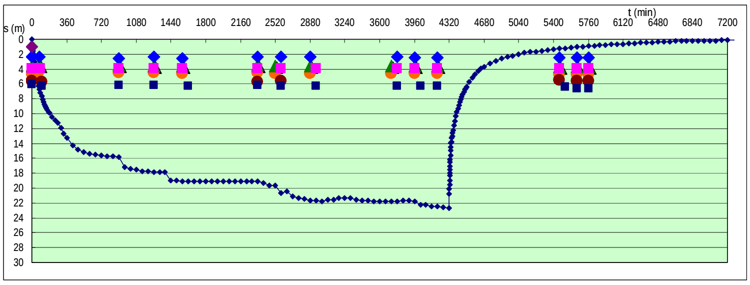
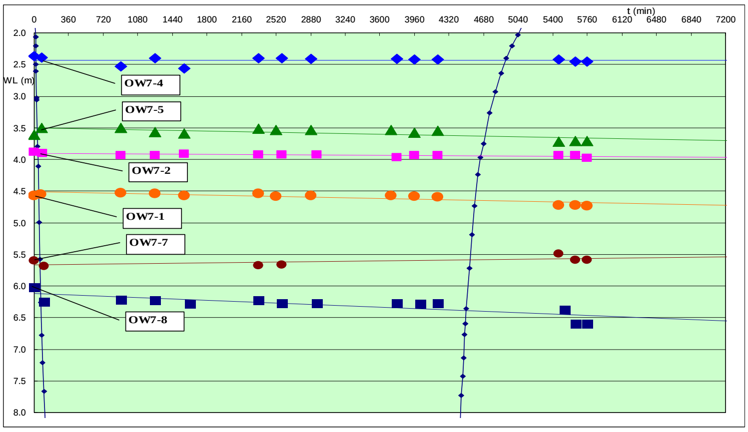


Figure 4.3-13(1) Influence to Existing Shallow Wells during Pumping Test (1)

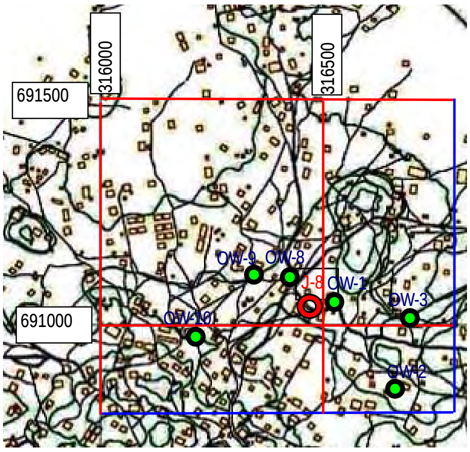
J-7

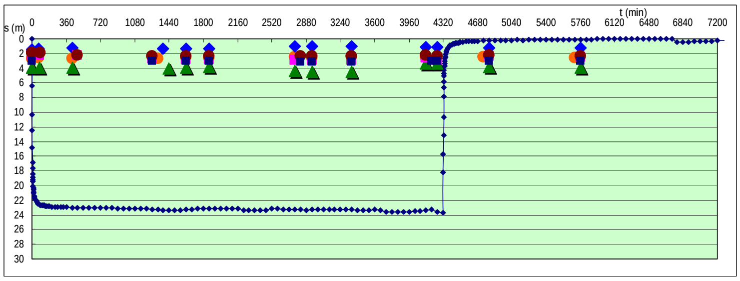






J-8





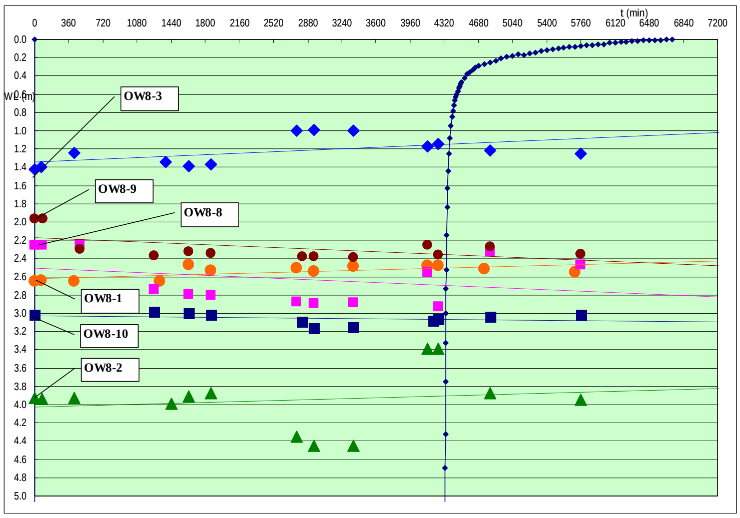
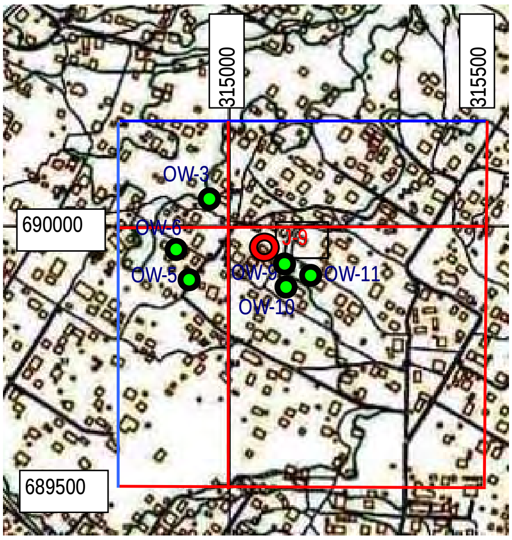
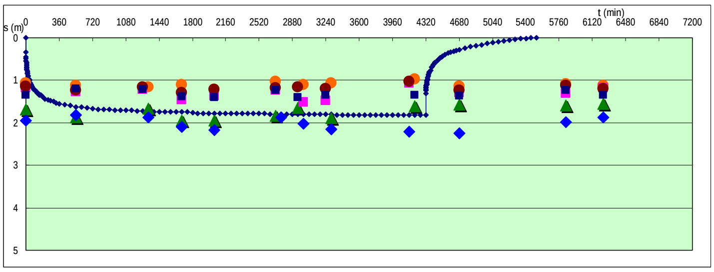
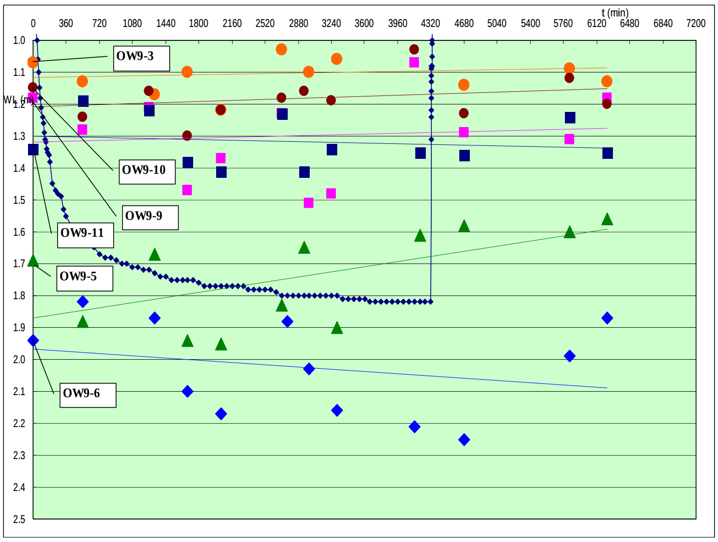


Figure 4.3-13(2) Influence to Existing Shallow Wells during Pumping Test (2)

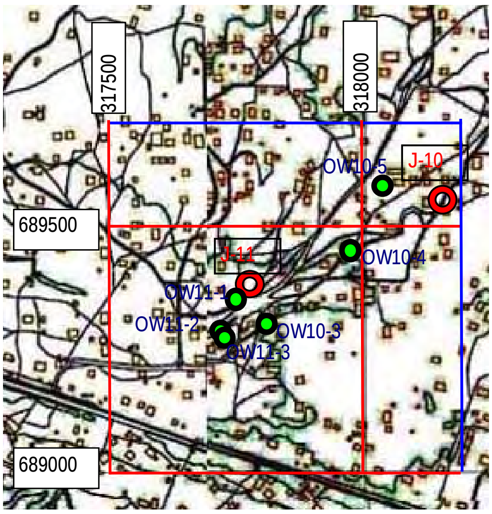
J-9

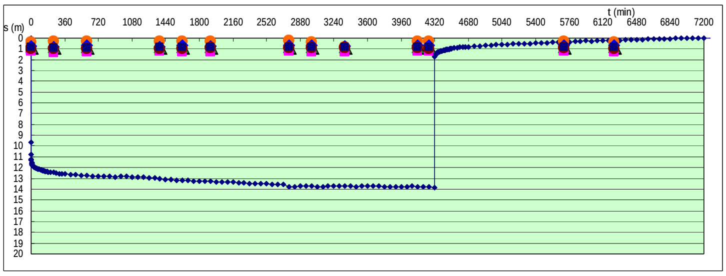






J-11





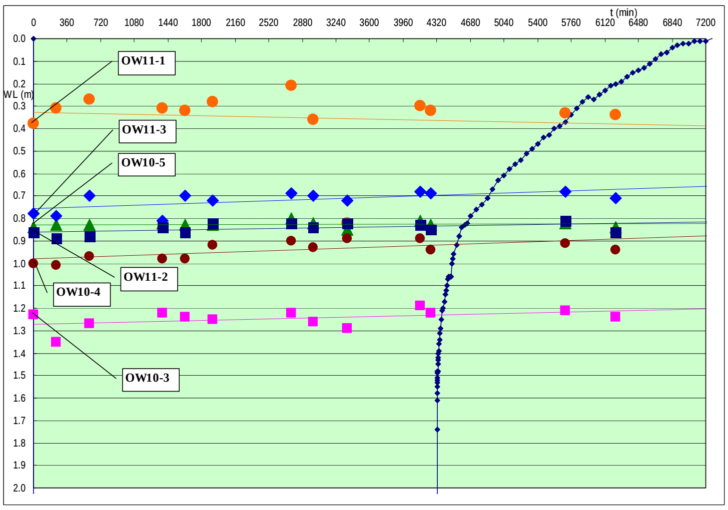


Figure 4.3-13(3) Influence to Existing Shallow Wells during Pumping Test (3)

5. WATER QUALITY ANALYSIS

Water Quality analysis is carried out using sampling water at the last day of constant discharge pumping test. The results of water quality analysis are shown in **Table 5-2**. The situation of the results is summarized in **Table 5-1**.

Table 5-1 Summary of Result of Water Quality Analysis

Well No.	Description	Evaluation	Remarks
J-5	Iron, turbidity, color exceed WHO standard	Nit drinking	Concentration of metal
J-6	Iron, Arsenic, color exceed WHO standard. Total coliforms is detected.	Not drinking	Concentration of metal
J-7	Arsenic exceeds WHO standard. Total coliforms is detected.	Not drinking	Concentration of metal
J-8	PH is slightly low. Other items clear WHO standard.	Almost clean	
J-9	Iron, Nickel, and color exceed WHO standard Total coliforms is detected.	Not drinking	Concentration of metal
J-11	All items clear WHO standard.	Good for drinking water	

Table 5-2 Result of Water Quality Analysis of Exploratory Well

Well No.	J-5		J-6		J-7		J-8		J-9		J-11		WHO Standard
Sampling Date	23-Feb-10	23-Feb-10	2-Jan-10	2-Jan-10	9-Jan-10	9-Jan-10	22-Jan-10	22-Jan-10	11-Jan-10	11-Jan-10	3-Feb-10	3-Feb-10	
Test Organization	Site	Japan	Site	Japan	Site	Japan	Site	Japan	Site	Japan	Site	Japan	
pH (-)	6.55	7.4	7.0	7.7	7.2	8.0	5.6	5.2	7.1	8.0	7.7	8.1	
T (°C)	30.1		28.8		30.9		28.7		27.8		29.3		
Turbidity (NTU)	0.0	29.2	3.8	2.6	10.6	1.6	0.6	0.4	4.4	2.0	4.3	<0.2	5
Color (°)		56.8		42.1		0.7		<0.5		16.5		1.2	15
EC (mS/cm)	0.180		0.255		0.364		0.027		0.318		0.133		
Alkalinity -OH^- (mg/l as $CaCO_3$)		<2		<2		<2		<2		<2		<2	
Alkalinity -CO_3^{2-} (mg/l as $CaCO_3$)		<2		<2		<2		<2		<2		<2	
Alkalinity -HCO^{3-} (mg/l as $CaCO_3$)		62		94		161		6		143		87	
Calcium (mg/L)		14		20.5		19.7		<1		44.5		2	
Magnesium (mg/L)		4		7.1		6.5		<1		5.2		1	
Total Hardness (mg-$CaCO_3$/l)		53		80		76		<1		133		10	
LI (-)		-1.09		-0.46		0.05				0.35		-1.1	
Potassium (mg/L)		6.2		3.6		6.0		0.2		3.1		2.4	
Sodium (mg/L)		10.7		10.7		23.0		1.9		7.4		1.9	
Chlorides (mg/L)		2.2		2.6		1.9		2.7		9.2		3.6	
SO_4^{2-} (mg/L)		6.5		14.9		13.7		<1.0		<1.0		<1.0	250
TDS (mg/L)	116	171	165	206	238	212	18	16	206	214	205	169	1000
NH_4 -N (mg/L)		0.08		0.07		0.12		<0.05		0.12		0.10	
NO_3 -N (mg/L)		<0.5		<0.5		<0.5		<0.5		<0.5		<0.5	11
NO_2 -N (mg/L)		<0.5		<0.5		<0.5		<0.5		<0.5		<0.5	0.9
Silica (mg/L)		93		82		43		13		73		65	
Iron (mg/L)		2.40		0.85		0.01		<0.01		0.53		0.08	0.3
Manganese (mg/L)		0.217		0.118		0.012		0.007		0.104		0.035	0.5
Arsenic (mg/L)		0.007		0.011		0.017		<0.001		0.005		<0.001	0.01
Selenium (mg/L)		<0.001		<0.001		<0.001		<0.001		<0.001		<0.001	0.01
Copper (mg/L)		<0.01		<0.01		0.10		<0.01		<0.01		<0.01	2
Cadmimum (mg/L)		<0.001		<0.001		<0.001		<0.001		<0.001		<0.001	0.003
Chromium (mg/L)		<0.005		<0.005		<0.005		<0.005		<0.005		<0.001	0.05
Cyanide (mg/L)		<0.001		<0.001		<0.001		<0.001		<0.001		<0.005	0.07
Lead (mg/L)		<0.001		<0.001		0.002		<0.001		<0.001		<0.001	0.01
Mercury (mg/L)		<0.00005		<0.00005		<0.00005		<0.00005		<0.00005		<0.00005	0.001
Boron (mg/L)		<0.1		<0.1		0.2		<0.1		<0.1		<0.1	0.5
Barium (mg/L)		<0.07		<0.07		0.09		<0.07		<0.07		<0.07	0.7
Molybdenum (mg/L)		<0.007		<0.007		<0.007		<0.007		<0.007		<0.007	0.07
Nickel (mg/L)		0.010		0.019		0.017		<0.001		0.033		0.003	0.02
Flouride (mg/L)		0.32		0.15		0.53		<0.08		0.15		0.18	1.5
Total Coliforms (CFU/100ml)	0		0		1		0		1		0		
E.Coli. (CFU/100ml)	0		0		0		0		0		0		

6. EVALUATION OF HYDROGEOLOGICAL CONDITION

6.1 Hydrogeological Structure

The Hydrogeological structure of the study area is considered as follows based on the synthesis investigation of the results of electric sounding and exploratory well drilling work carried out in the study. The geological map of the study area is shown in **Figure 6.1-1**, and the geological cross section is shown in Figure 6.1-2.

(1) Distribution of Geological formation and Aquifer

The feature of geological formation of the study area is as follows.

1) The geological formation of the study area consists of Quaternary beach and fluvial deposit, Tertiary Edina sandstone, Jurassic intrusive rock Diabase, Devonian Paynesville sandstone and Precambrian melanocratic gneiss.

2) The Precambrian gneiss does not appear on ground surface in the study area. J-5 and J-11 encountered at deeper section at 48m and more and 56m and more respectively.

3) The Devonian Paynesville sandstone on ground surface of the study area is only recognized at limited narrow area of north-west part of VES 19 in Kendeh town old field community forming hard rock outcrops. J-5 to J-7 located in north-west part of the study area tap mainly the sandstone facies of the formation. J-8 also taps the sandstone facies of the formation at almost all total drilling depth section among Diabase outcrops area. J-9 taps the formation at 7-18m section. In the study area the sandstone facies is predominant in the formation instead of shale facies predominant at J-1 to J-3 site of Phase 1 investigation area of central to north- east part of the grater Monrovia

4) The Jurassic intrusive rock Diabase usually form low hills and distribute rather wide part on ground surface. At other area out of Diabase outcrop zone, the wide distribution situation of Diabase rock bodies is recognized through the lithological log of exploratory wells at also almost flat low plain area at south-east part of the study area.

5) The tertiary Edina sandstone is distributed in north-west part of the study area with 18 to 20m thickness together with Quaternary deposits. The clear classified recognition for the both formation is rather difficult by observation of drilling cutting materials.

In the central area to south-west part of the study area, the Quaternary deposit (partly includes Tertiary deposit become thin, especially at part from north part of VES 19 to VES 20 and VES 21 (Well J-10, J-11) hard rock portion becomes very shallow and the depth estimated less than 10m.

(2) Aquifer Structure

Generally, though the formation of aquifer is considered shown in **Table 6.1-1**, the grasped aspect become change as follows through the study (Phase 2 investigation).

1) The Painesville sandstone does not form uniform aquifer not only at shale or alternation portion but also at inside sandstone facies portion. The sandstone facies portion sometimes has hard rock portion and includes low water producing portion such as J-7. Furthermore the formation has rather limited water producing capacity without some geological structure such as fissure, crackly zone, fracture zone and so on due to itself progress compaction and rather little cavity portion.

2) The Diabase is a hard rock and does not form good aquifer inside fresh rock body, and generally has very low water producing portion in stead condition such as J-10. But at edge portion of intrusion, if some crackly zone or fractured zone was formed, it may become good aquifer. J-9 taps such crackly zone below 48m depth and get high water producing. J-11 taps a fracture zone formed boundary between Diabase intrusion rock body and base rock gneiss. The boundary zone has alteration and

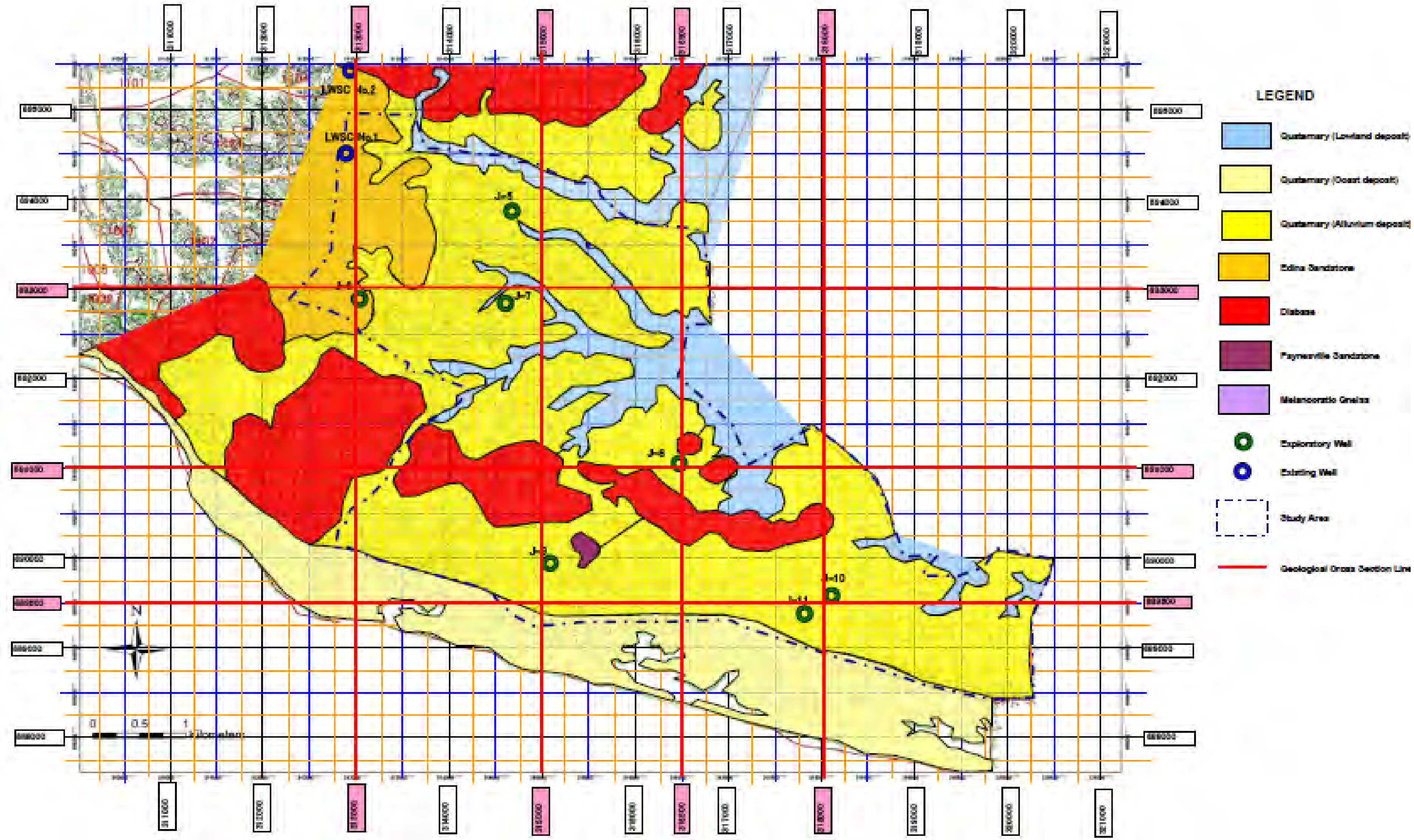


Figure 6.1-1 Geological Map of the Study Area

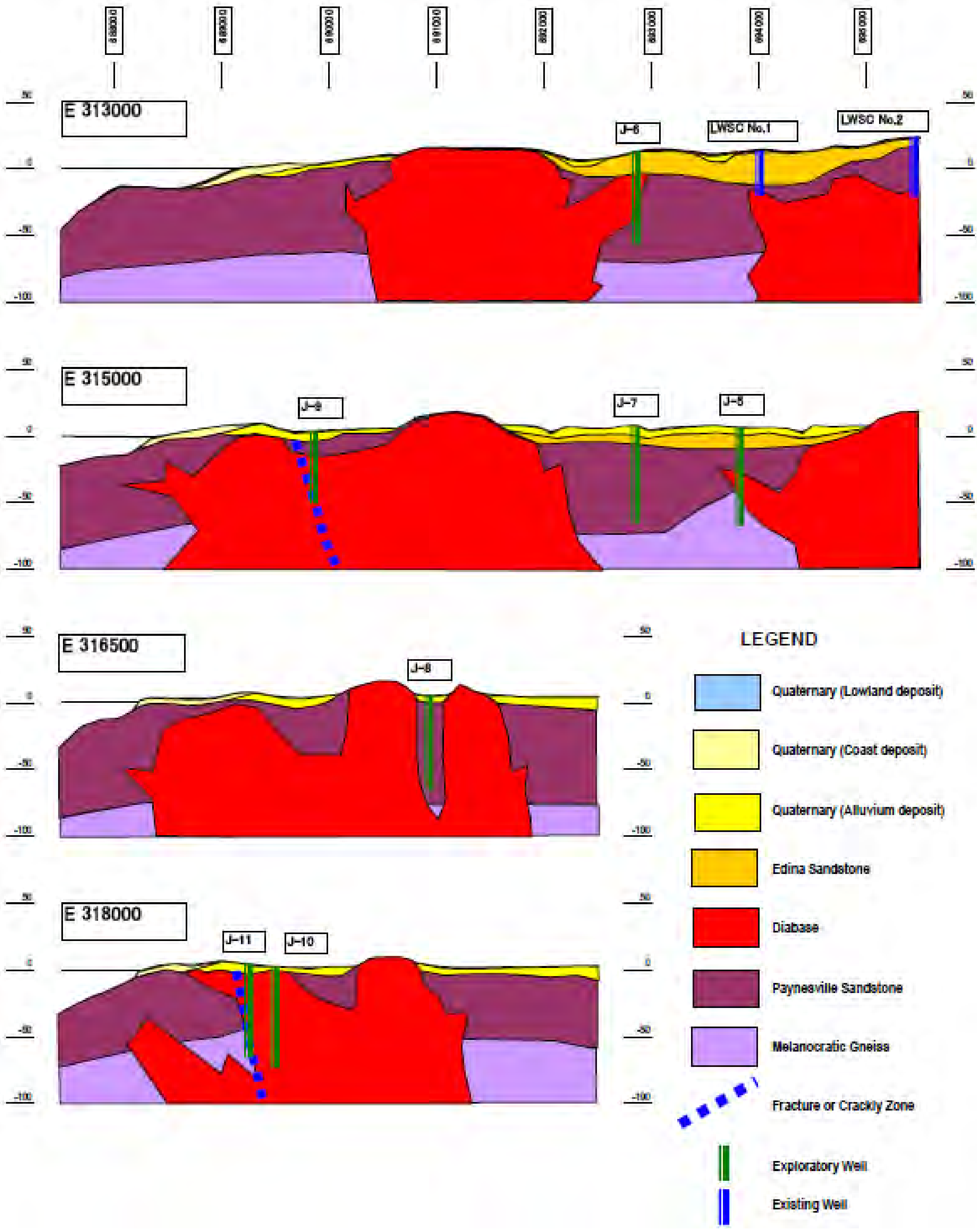


Figure-6.1-2(1) Geological Cross Section of Study Area (1)

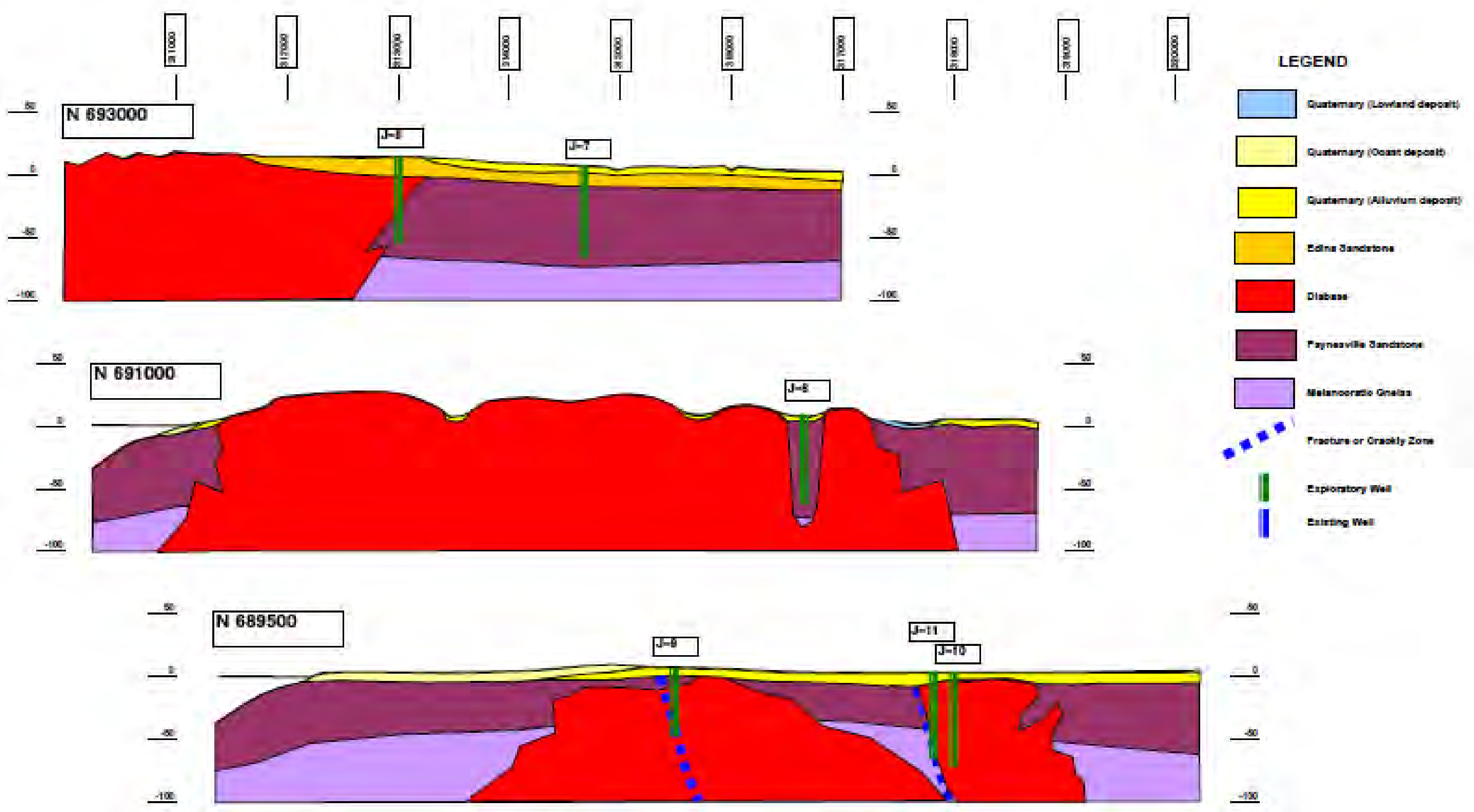


Figure-6.1-2(2) Geological Cross Section of Study Area (2)

Table 6.1-1 Possibility of Aquifer in Each Formation

Symbol	Formation	Feature as Aquifer	Possibility of Aquifer
Qb/Qf	Beach and Fluvial Deposit	Quaternary deposit is supposed to be thinly deposited on the lowlands of the stable basin. Sand strata have possibility of an aquifer for shallow well.	Possible for shallow well
Te	Edina Sandstone	Tertiary sandstone has possibility of an aquifer. However, according to literature, this formation is as thin as several meters.	Possible for shallow well
Kf	Farmington River Formation	Sandstone formation has possibility of an aquifer. However, the distribution of this formation is not well known in the study area.	Unknown in the study area
Jd	Diabase	Generally dike and intrusive rock has not possibility of an aquifer, However, Crackly zone or boundary portion with fissure sometimes storage groundwater.	Unsuitable for well
Dp	Paynesville Sandstone	Sandstone formation has high possibility of an aquifer. Sometimes mudstone and shale layer are intercalated.	Possible for deep well
gnl	Leucocratic Gneiss	Generally this formation is non aquifer because of hard rock of a part of Precambrian craton. Highly weathered or fissure zone has possibility of ground water presence	Unsuitable for well
gnm	Melanocratic Gneiss	Generally this formation is non aquifer because of hard rock of a part of Precambrian craton. Fissure zone nearby fault has possibility of ground water presence	Unsuitable for well

(Source; Phase 1 study)

rather soft portion at gneiss portion owing to alteration and weathering. The high water producing exists in the portion and Diabase rock portion with crackly zone along the fracture zone. J-8 taps almost Paynesville sandstone, but the well locates in a structure zone put between north side Diabase rock body and south side Diabase body apart only 200 to 300m, and the nipped sandstone zone becomes partly soft condition like by weathering. The water producing portions are recognized some upper portions of sandstone and around branch intrusion of Diabase. J-6 also has rather thin Diabase intrusion section, and the water producing portions are recognized at its boundary part.

3) The Tertiary and Quaternary aquifer are distributed in north-west to central part of the study area. The thickness is 10 to maximum 20m in the study area. Mainly the sand portion is predominant in the study area, and sometimes rather thick clay layer intercalated in bottom portion such as J-6. Owing to the limited thickness and distribution, Though it is considered to be difficult to use as the only one target aquifer for urban or semi-urban type groundwater development with rather high water producing demand per well, to use as a source for the compound of shallow aquifer section and deeper section in same well is possible.

(3) Yield Condition of Well

The yield condition of wells in phase 1 study and in this phase 2 study together with existing LWSC wells is shown in **Table 6.1-2**. From **Table 6.1-2** the classification of the yield capacity of well can be obtained shown in **Table 6.1-3.**

- Group A (Transmissivity;>50m^3/day/m, Yield; >200m^3/day on 8hours pumping) contains J-9 and LWSC Well No.1.
- Group B (Transmissivity 10-50m^3/day/m, Yield; 100-200m^3/day on 8hours pumping) contains J-6, J-8,J-11 and LWSC Well No.2.
- Group C (Transmissivity 5-10m^3/day/m, Yield; 10-100m^3/day on 8hours pumping) contains J-1.
- Group D (Transmissivity 1-5m^3/day/m, Yield; 5-10m^3/day on 8hours pumping) contains J-2, J-3 and J-5..
- Group D (Transmissivity <1m^3/day/m, Yield; <5m^3/day on 8hours pumping) contains J-4, J-7 and J-10.

The yield capacity suggests rather higher in fissure or structure zone than the Paynesville sandstone proper portion.

Table 6.1-2 Yield Condition of Wells

Well No.	Transmissivity (m^3/sec/m)	Transmissivity (m^3/day/m)	Storativity	Permeability Coefficient (m/sec)	Yield per each drawdown (s) (L/min) s=5m	s=10m	S=20m
J-1	$1.04x 10^{-4}$	8.99	$2.2 x 10^{-2}$	$4.69 x 10^{-4}$	36.0	72.1	144
J-2	$1.29x 10^{-5}$	1.11	$2.7 x 10^{-2}$	$1.08 x 10^{-6}$	5.7	14.4	22.8
J-3	$3.11x 10^{-5}$	2.69	$4.3x 10^{-2}$	$3.13 x 10^{-6}$	13.0	26.1	52.2
J-4	$4.70 x 10^{-6}$	0.41	$6.3 x 10^{-3}$	$2.23 x 10^{-7}$	2.6	5.3	10.6
J-5	$4.30 x 10^{-5}$	3.71	$8.6 x 10^{-2}$	$2.04 x 10^{-6}$	18.8	37.6	75.2
J-6	$4.31 x 10^{-4}$	37.2	$5.2 x 10^{-1}$	$1.59 x 10^{-5}$	178	355	712
J-7	$7.50 x 10^{-6}$	0.35	$9.0 x 10^{-2}$	$3.53 x 10^{-7}$	3.4	6.8	13.6
J-8	$2.91 x 10^{-4}$	25.100	$1.9 x 10^{-2}$	$9.71 x 10^{-6}$	91	183	365
J-9	$3.65 x 10^{-3}$	315.	$6.0 x 10^{-1}$	$1.74 x 10^{-4}$	1,236		
J-10	$5.07 x 10^{-6}$	0.44	$3.6 x 10^{-3}$	$1.87 x 10^{-7}$	2.0	4.0	7.9
J-11	$4.07 x 10^{-4}$	35.2	$5.0 x 10^{-1}$	$1.03 x 10^{-5}$	168	336	672
LWSC No.1	$4.6 x 10^{-4}$ - $1.2 x 10^{-3}$	40 – 106	$5.0 x 10^{-2}$	$2.5 x 10^{-5}$ - $6.8 x 10^{-5}$	150 – 363	300 - 726	600 - 1,452
LWSC No,2	$2.5 x 10^{-4}$ - $5.2 x 10^{-4}$	21 – 45	$1.0 x 10^{-3}$	$2.5 x 10^{-5}$ - $6.8 x 10^{-5}$	64 - 126	127 - 252	254 - 504

Table 6.1-3 Classification of Yield Capacity of Wells

Group	Transmissivity m^3/day/m	Yield (Safety) L/min	Yield (Safety) m^3/day (8hours)	Well	Remark
A	>50	>400	>200	J-9, LWSC No.1	Fissure, Tertiary
B	10-50	200-400	100-200	J-6,J-8,J-11, LWSC No.2	Fissure, Sandstone
C	5-10	20-200	10-100	J-1	Sandstone
D	1-5	20-100	5-10	J-2, J-3,J-5	Sandstone
E	<1	<20	<5	J-4,J-7, J-10	Hard rock

6.2 Groundwater Potential

(1) Shallow aquifer

The surface geology of the study area indicated on 250m mesh grid is shown in **Figure 6.2-1.** The Quaternary and Tertiary deposit is widely distributed in low to middle height area in the study area. The thickness is 10 to 20m in north-west and central part in the study area., and 5 to 10m in central to south-east part in the study area. Owing to rather thin condition, the Quaternary and Tertiary deposit has not enough capacity to develop as a main aquifer. the Quaternary and Tertiary deposit can be used as a sub aquifer in north-west part of the study area in case of the development of wells combined withdrawal from shallow aquifer and deeper aquifer.

(2) Deeper aquifer

The geology of the taking out the Quaternary and Tertiary deposit area indicated on 250m mesh grid is shown in **Figure 6.2-2.** In consideration with geological structure and results of electrical sounding and exploratory well drilling, the groundwater water potential is presumed as shown in **Figure 6.2-3.**
The evaluation criteria is applied the Classification category of the water producing capacity of wells shown in **Table 6.1.3.**
The high potential is assumed in surroundings along Daiabase intrusive area with geological structures and partly along beach mound elongated along coast.
The indication added water quality information on the same map is shown in **Figure 6.2.4**.

The water quality contaminated zone supposed to be originated ore deposits accompanied with Diabase intrusion activity. There is possibility which appears every place in Diabase intrusion area. It

is necessary to check contamination distribution and to advance adjustment, for example sorting of the development area in detail with new information furthering development.
The production wells are arranged in high water producing capacity zone without water quality contaminated zone.

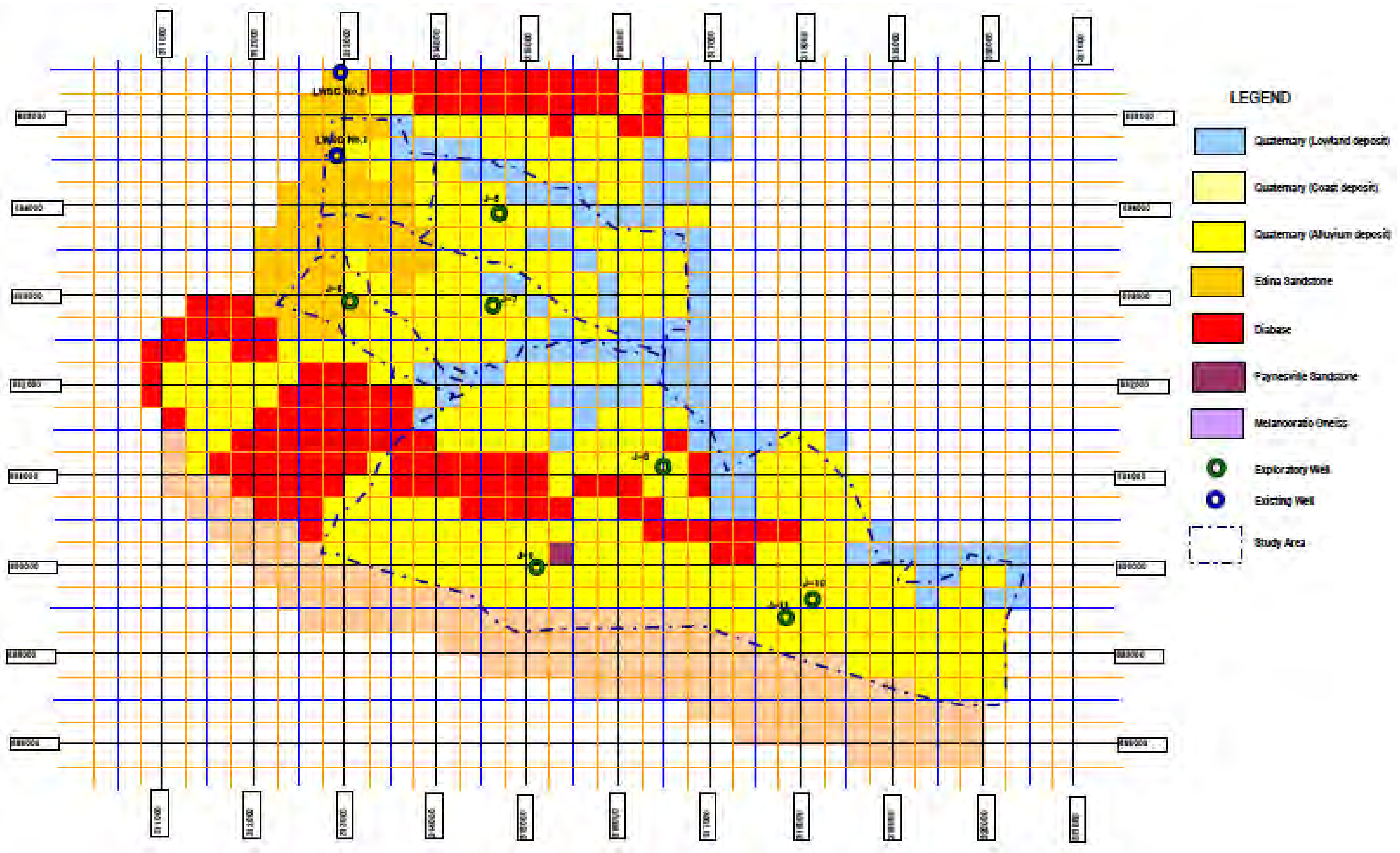


Figure 6.2-1 Geological Distribution of Surface

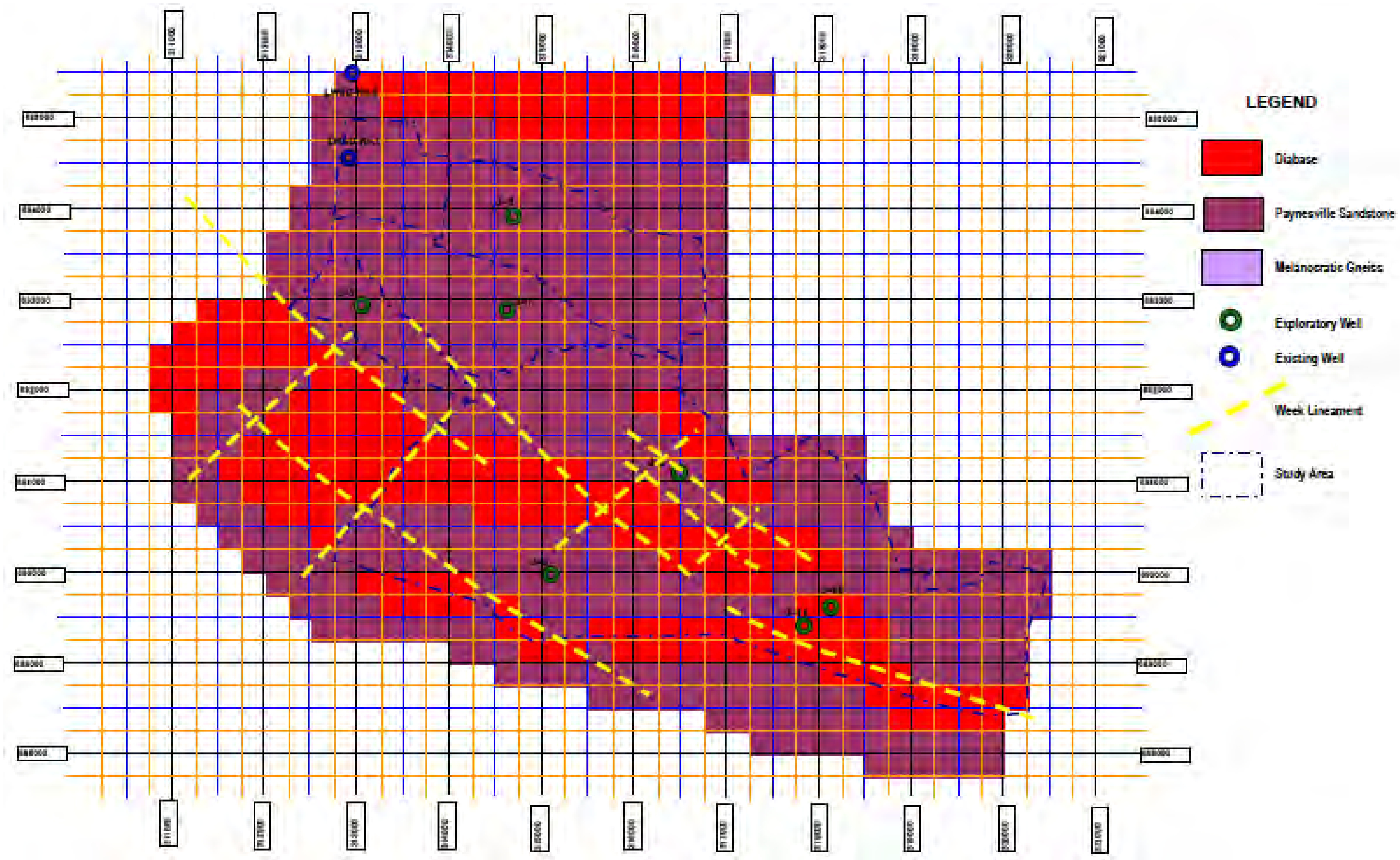


Figure 6.2-2 Geological Distribution of Deep portion

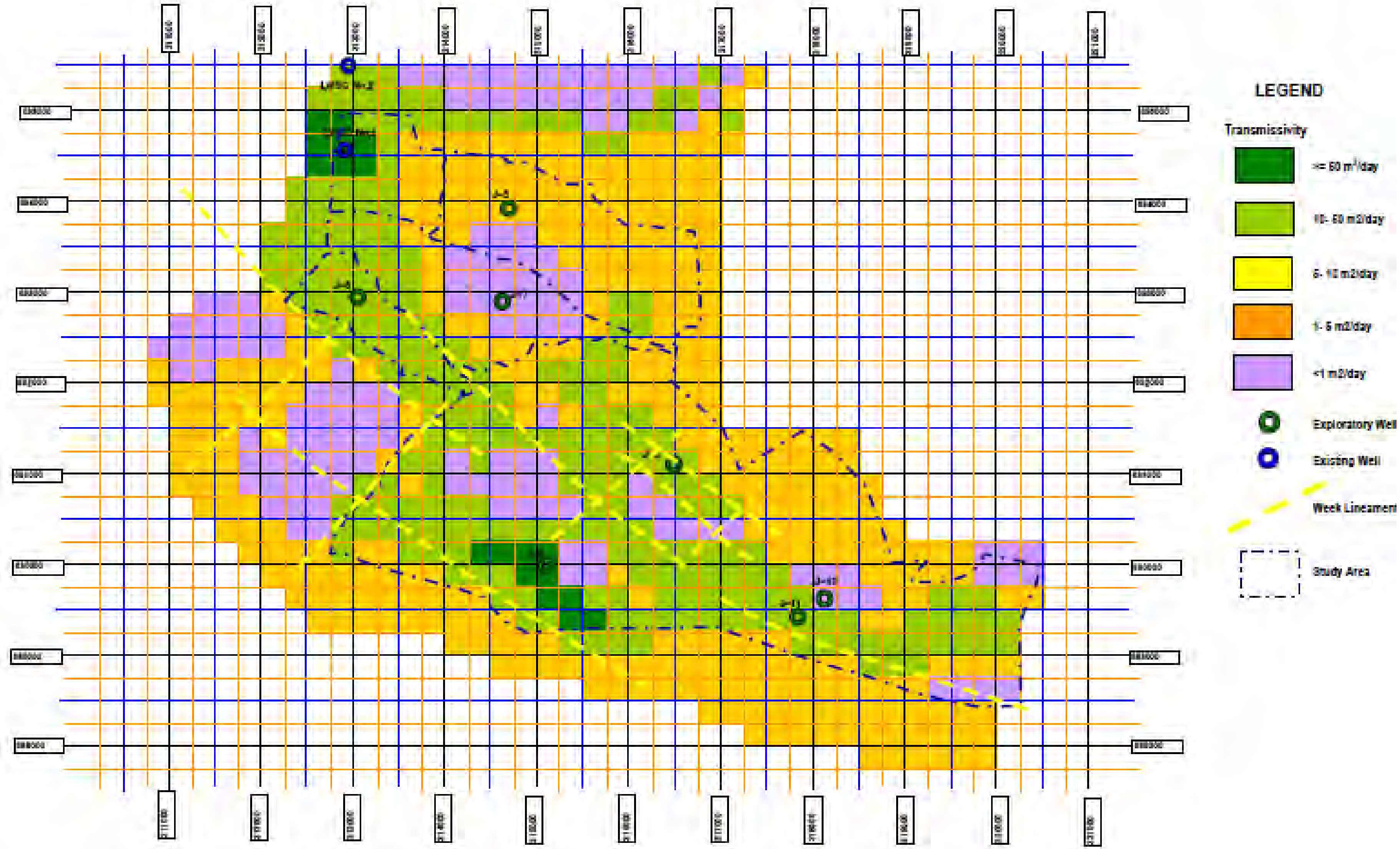


Figure 6.2-3 Groundwater Development Potential Indicated by Transmissivity

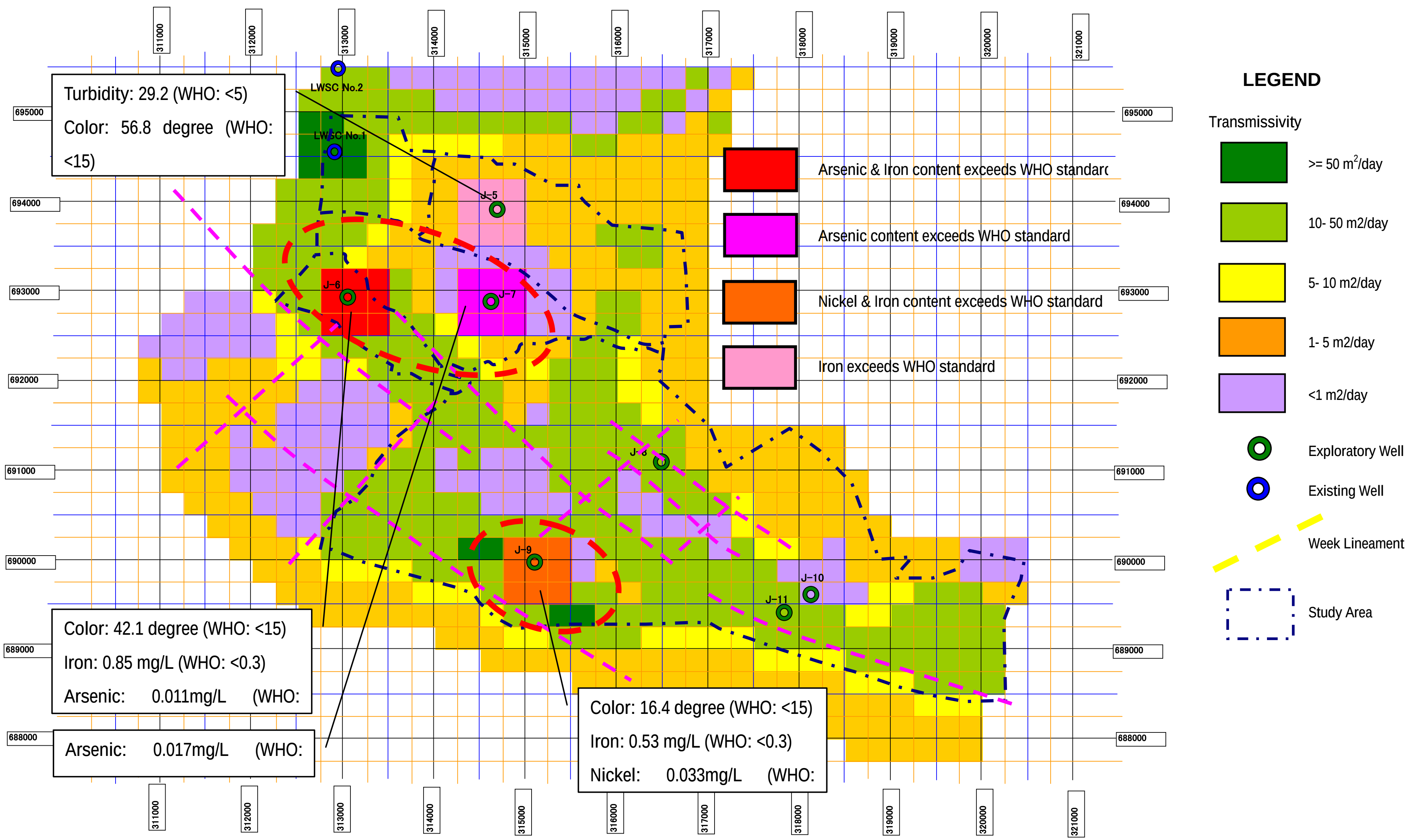


Figure 6.2-4 Groundwater Development Potential and Water Quality Contamination Area

7. GROUNDWATER DEVELOPMENT PLAN

7.1 Direction of Groundwater Development

The direction of groundwater development plan is set up as follows.

1) The structure zone concerning the Diabase intrusion such as crackly zone, fault or fracture zone, and boundary zone with Diabase rock bodies sometimes form fissure type aquifer and water producing capacity is rather high in comparison with the Paynesville sandstone. The structure zone is as a main target to develop ground water. The Pynesville sandstone has possibility of water producing is also a important target.

2) The Tertiary Edina sandstone and Quaternary deposit is also sub target to obtain the ground water from two sources in one well, One is shallow aquifer and main is deeper aquifer.

3) The rank classification for estimation of water producing capacity of well shown in **Table 7.1-1** is applied.

Table 7.1-1 Rank Classification of Water Producing Capacity of Well

Rank	Category based on Transmissivity	Description
A	>= 50m^3/day/m	Yield comparable as LWSC Well No.1 and J-9
B	10-50 m^3/day/m	Yield comparable as LWSC Well No.2 and J-6, J-8 and J-11
C	5-10 m^3/day/m	Yield comparable as Well J-1

4) The sustainable groundwater development is performed. That is, the withdrawal of groundwater exceeding the amount of groundwater recharge by rainfall every year is not performed.

7.2 Groundwater Development Area and Required Amount

The ground water development target area is Duport road north-east community, Duport road north community, Duport road south community, Paynesville Joe Bar Community, Rehab/ Borbor town community. However, according to the result of the study, the following condition is confirmed.

1) The Duport road north east community area has not enough water producing capacity of well.
2) Duport road south community and Paynesville Joe Bar Community has arsenic and partly iron contamination problem.
3) J-9 area of Rehab/ Borbor town community has iron and nickel contamination problem.

For these areas the required water should be supplied from other area, or downsizing of project area is necessary to select. In the study the plan is examined as that all necessary water volume is developed in good producing area, and delivered by water tanker etc.

Table 7.2-1 Required Water Supply Amount of Each Community to Recharge

ID.	Community	Area	Water Supply Amount		Mean Annual Rainfall	Amount of Rainfall	Recharge	Supply Amount/ Recharge
		km^2	m^3/day	m^3/yr	mm	m^3/yr	m^3/yr	%
1107	Duport Road North-East	3.324	1,136	414,458	3,500	11,634,000	1,163,400	36
1108	Duport Road North	1.241	568	207,229	4,300	5,336,300	533,630	39
1109	Duport Road South	2.65	871	317,751	4,000	10,600,000	1,060,000	30
1117	Paynesville Joe Bar	1.018	606	221,044	4,500	4,581,000	458,100	48
1123	Rehab / Borbor Town	15.977	1,211	442,088	4,085	65,266,045	6,526,605	7

The total required amount is 4,391m3/day(.Duport road north-east community; 1,136n3/day, Duport road north community; 568m^3, Duport road south community; 871m^3/day, Paynesville Joe Bar Community; 606m^3/day, and Rehab/ Borbor town community;1211m^3/day).

7.3 Possible Yield

The possible yield for rank classification of producing capacity of well is set as shown in **Table 7.3-1** referring to **Table 6.1-2** and **Table 6.1-3**.

Table 7.3-1 Possible Yield

Item	Rank A	Rank B	Rank C
Possible yield / well (L/nin)	500	350	100
Possible yield / well (m^3/day)	240	168	48
Pumping duration (hour/day)	8	8	8
Drawdown (m)	10-15	10-15	10-15

To 19 wells are necessary incase of rank A well,, 27 wells are required in case of rank B and 92 wells in case of rank C..

7.4 Well Specification

The well structure is shown in **Figure 7.4-1**. Two type well specifications united with amount of yield are prepared, and the selection of specification (well diameter change) of the well is used properly.

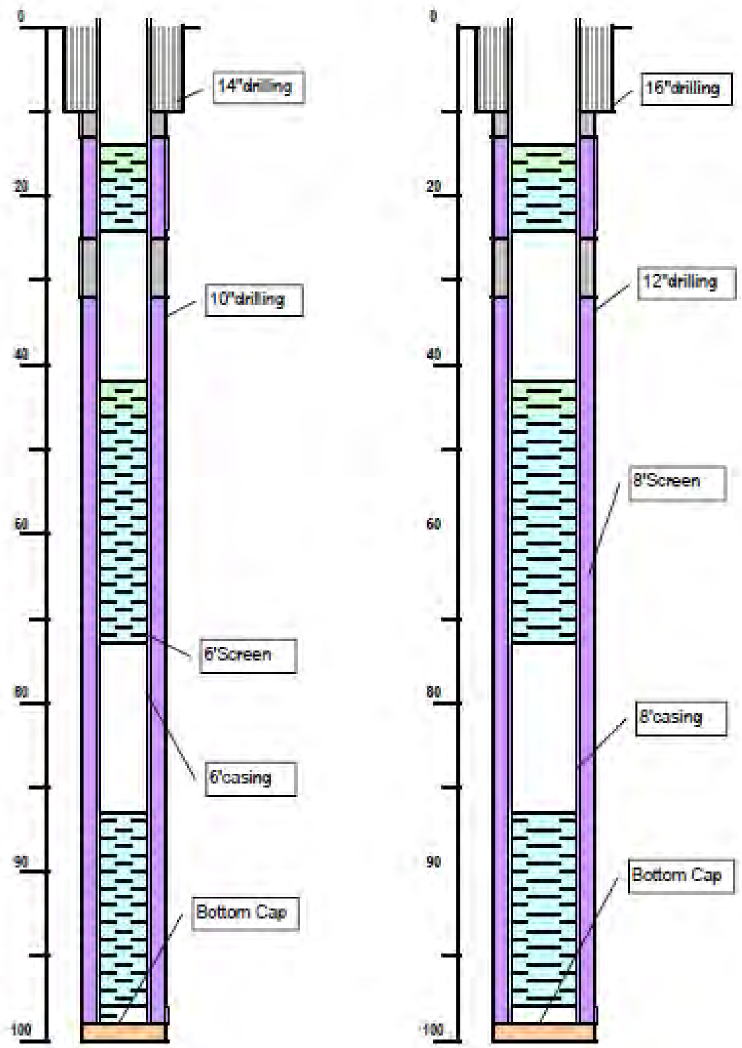


Figure 7.4-1 Standard Structure of Production Well

7.5 Well Arrangement

The well arrangement in case of rank B well is shown in **Figure 7.5-1**.

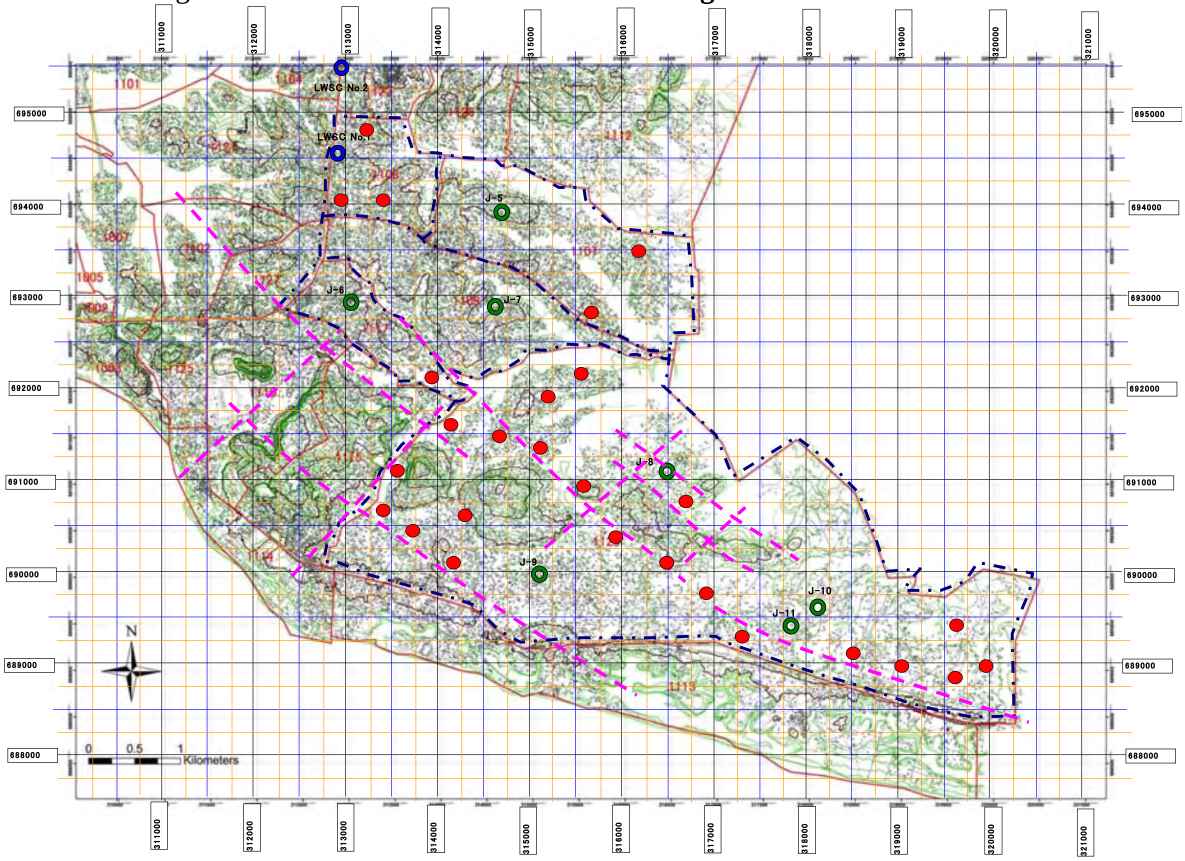


Figure 7.5-1 Arrangement of Production Wells for Groundwater Development Project

7.6 Public Water Tap Work

The public water tap system is installed based on the criteria shown in **Table 7.6-1**. The image of public water tap is shown in **Figure 7.6-1**.

Table 7.6-1 Criteria of Public Water Tap and Hand Pump Installation

Category	Criteria
Public Water Tap Installation	Yield >= 1.5 L/sec & satisfaction of WHO's water quality standard
Hand Pump Installation	0.3 L/sec <= Y <1.5 L/sec & satisfaction of WHO's standard
No Installation	Y < 0.3 L/sec or dissatisfaction of WHO's standard

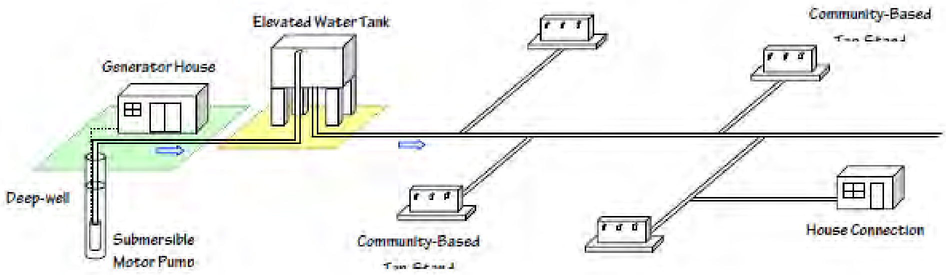


Figure 7.6-1 Image of Water Tap Installation System

8. CONCLUSION AND RECOMMENDATION

8.1 Conclusion

(1) Electric Sounding

Electric sounding is carried out at 12 places, 3points per place, total 36 points in the study area.
In the study area, the following resistivity range suggests following geological distribution. The outline of geological structure can be assumed Combination of the classified resistibity range

Resistivity 100-500 ohm-m; Sand or Sandstone
Resistivity 0-50 ohm-m; Fine sediment or Shale or sometimes Diabase
Resistivity 50-100 ohm-m; Alternation or sometimes Diabase
Resistivity >500 ohm-m; Hard rock

(2) Exploratory Well Drilling

7 exploratory wells are drilled.

1) The Quaternary and Tertiary soft deposit with 18 to 20m depth is distributed in north-west part of t he study area. It becomes thin In central to south-east part of the study area.
2) In north west part, Paynesville sandstone is predominant, sometimes Diabase intrudes. In J-5, gneiss is recognized below 48m.
3) In south west part, Diabase is predominant. In J-11, gneiss is confirmed below 56m.

(3) Yield

1) Safety yield is shown in **Table 8.1-1**.

Table 8.1-1 Safety Yield

Well No.		J-5	J-6	J-7	J-8	J-9	J-10	J-11
Safety Yield	(L/min)	38	355	7	183	1236	4	336
	(m^3/day)	18	170	3.4	88	593	1.9	161

Remarks; Safety yield is a yield at 10m drawdown at 8hours pumping.

2) J-9 has extraordinary yield more than LWSC well No.1. J-6, J-7 and J-11 have high yield as same as LWSC well No.2.
3) In the study, high yield wells is in connection with geological structure zone.
   J-6; Diabase intrusion in Paynesville sandstone
   J-8; Structure zone both side banded by Diabase
   J-9; Crackly zone in Diabase
   J-11; Fracture zone of boundary between Diabase and gneiss with alteration and weathering

(4) Water Quality

Some groundwater contaminations considered to be the ore deposit origin are recognized.

J-5; Iron, turbidity and color exceed WHO standard.
J-6; Arsenic, iron, color and coliforms exceed WHO standard.
J-7; Arsenic exceeds WHO standard.
J-9; Nickel, iron and coliforms exceed WHO standard

(5) Groundwater Development Potential

1) In the study, the groundwater development potential is expressed using a classification criteria of transmissivity concerning yield capacity shown in **Table 8.1-2** (Reinsertion).

Table 8 1-2 Classification of Yield Capacity

Rank	Transmissivity	Yield (Safety)		Well	Remark
	m^3/day/m	L/min	m^3/day (8hours)		
A	>50	>400	>200	J-9, LWSC No.1	Fissure, Tertiary
B	10-50	200-400	100-200	J-6,J-8,J-11, LWSC No.2	Fissure, Sandstone
C	5-10	20-200	10-100	J-1	Sandstone
D	1-5	20-100	5-10	J-2, J-3,J-5	Sandstone
E	<1	<20	<5	J-4,J-7, J-10	Hard rock

2) High yield condition is considered to be in area along Diabase belt. Inside Diabase mass is supposed to be rather low yield.

(6) Problem of Target Area

In **Figure 8.1-1**(Reinsertion), the water quality contamination area is indicated on groundwater development potential map. The problem area is as follows.

1) Paynesville Joe Bar Community to Duport Road South Community;
   Groundwater development is difficult due to contamination containing arsenic, partly iron.
2) Central area of Rehab/ Borbor Town Community;
   Groundwater development is difficult due to contamination containing nickel and iron.
3) Dup0rt Road North East Community;
   Groundwater development is difficult due to low yield capacity and partly high iron content.

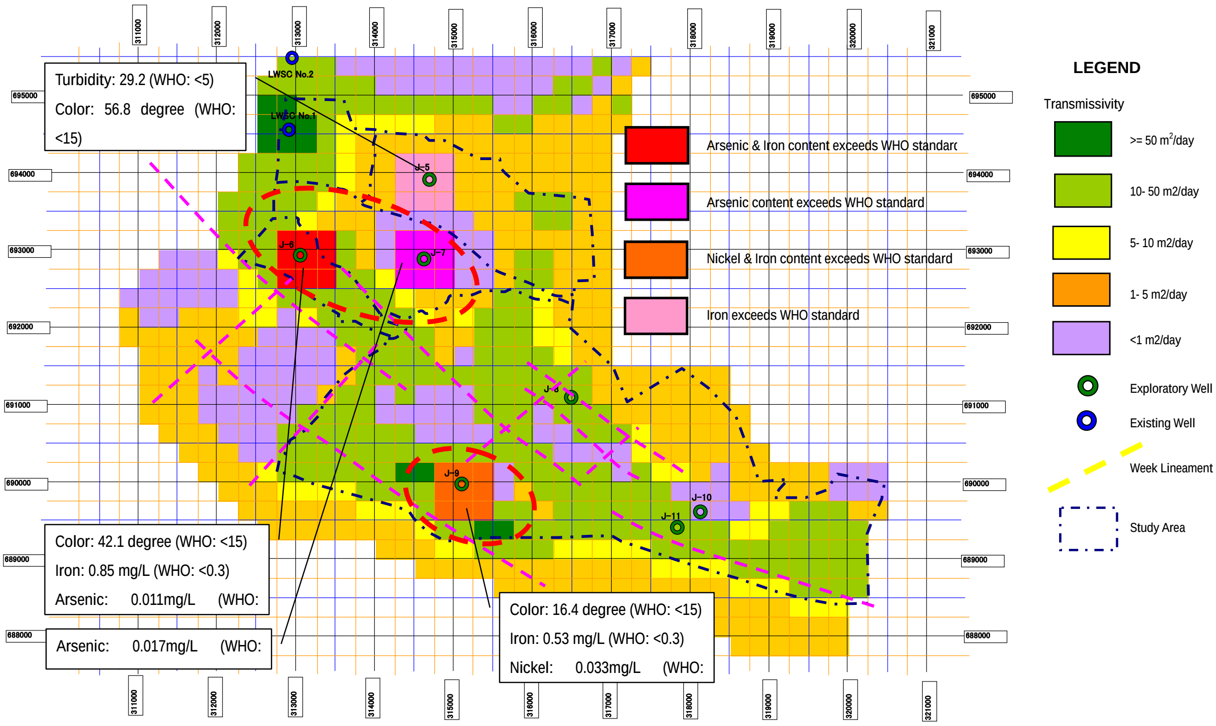


Figure 8.1-1 Groundwater Development Potential and Contamination Area

(7) Groundwater Development Plan

In the report, the groundwater development plan with following direction is proposed.

1) All required volume of 5 communities, that is 4,391 m^3/day, is target for development.
2) Development is carried out in possible area with high yield capacity. It is sometimes apart from community residence.

Necessary well number is 27 in case of rank B yield capacity. In the study the success rate of rank B well is 57%, and it becomes 29% in case of including contamination.

8.2 Recommendation

(1) Investigation of Geological Structure Zone

At present, the success rate of grade B well is rather low. If the full-scale production well construction project is commenced, it generates large amount of useless drilling, The second additional investigation along the foot areas of Diabase belt is necessary to confirm the certain yield capacity and the success rate of well before going into a full-scale project..

(2) Stage Development

The target area is divided and a project is advanced from the high area of the possibility of development.

It starts from Rehab/ Borbor Town Community and amount of water has a margin, and after the possibility of water supply in other areas is checked, next stage development for other areas is advanced.

(3) Device of Well Work and Well Structure

1) Pre-proceeding drilling

At first, 6"pre-proceeding drilling is carried out. After getting information, the size of completion well is decided, and the reaming work is performed up to completion depth.

2) Selection of the well structure united with amount of yield

At some wells with large amount of yield, well diameter is enlarged and it enables to install a big pump, thus, well number can be reduced. However, it is necessary to change the scale of a public water tap system.

3) Well completion with 2 sources from shallow aquifer and deep aquifer.

At some area where the Quaternary and Tertiary deposit are thick and available to use, the screen is set at both of shallow aquifer portion and deeper aquifer portion in a well. In case that well completion work becomes slightly complicated. After preparing temporary steel casing, gravel pack, fine-grained-soil filling, gravel pack, and fine-grained-soil filling are performed through steel casing, and steel casing needs to be extracted.

(4) Establishment and Capacity Development of Water Quality Analysis Organization

In order to judge the propriety of well completion and to lessen futility according to water quality, foundation and training of the organization which can do water analysis speedily are required.