3.4 Drilling Exploration

(1) Quaternary Drilling Exploration

The Study Team carried out Quaternary exploratory drilling to know geological condition and to install groundwater level observation wells.

(a) Location of Drilling and Result

Location of six drilling is shown in Table-3.3 and Figure-3.4. In site selection, items below were considered.

- To be suitable to know hydrogeological characteristics of Quaternary
- To be suitable to know representative groundwater level of Quaternary

Result of drilling exploration is summarized in Table-3.3

Table-3.3 Result of Quaternary Exploration Drilling

Well No.（Site）		**No.1 (Gibraltar)**	**No.2 (Tisquesusa)**	**No.3 (Siberia)**	**No.4 (Sopo)**	**No.5 (Diana)**	**No.6 (Choconta)**
Well depth(m)		196	192	173	150	188	123
Screen depth (GL-m)		73～75 85～121 132～136 149～152 163～166 (Total 48m)	117～120 128～146 152～158 162～186 (Total 51m)	80～92 95～119 124～127 134～137 143～155 (Total 54m)	25～47 57～65 (Total 30m)	41～53 73～82 96～105 126～132 144～147 (Total 39m)	41～60 65～73 120～144 154～175 (Total 72m)
Casing Diameter		8 inch	8 inch	8 inch	8 inch	8 inch	8 inch
Aquifer		Fine sand, sand and gravel （Sabana）	Fine sand (Sabana)	Fine sand (Sabana)	Sand and gravel (Sabana)	Fine sand, silty sand and gravel (Sabana)	Silty sand and gravel, silt (Tilata)
Pumping test	S.W.L[1)] (GL-m)	16.5	76.92	21.94	14.7	17.33	11.07
	Yield (m^3/day)	-[4)]	317	432	605	586	533
	Drawdown	-[4)]	6.43	16.69	5.37	6.99	3.89
	D.W.L[2)] (GL-m)	- [4)]	83.35	38.63	20.07	24.32	14.96
	Specific Capacity (m^3/day/m)	- [4)]	49	26	82	84	137
	Transmissivity (m^2/day)	46	204	30	85	89	159
	Conductivity (m/day)	0.96	4.0	0.56	2.8	2.3	2.2
	Storativity	- [3)]	1.38×10^{-18}	6.82×10^{-2}	- [5)]	1.27×10^{-2}	7.61×10^{-2}

Note
1) S.W.L. :Static water level
2) D.G.L :Dynamic water level
3) Conductivity and storativity were analyzed by Jacob method and recovery method.
4) For Gibraltar well, not pumping test but borehole permeability test was carried out. Therefore, D.W.L, specific capacity, storativity are not calculated.
5) Storativity was not calculated for Sopo well, because drawdown was irregular during pumping test.

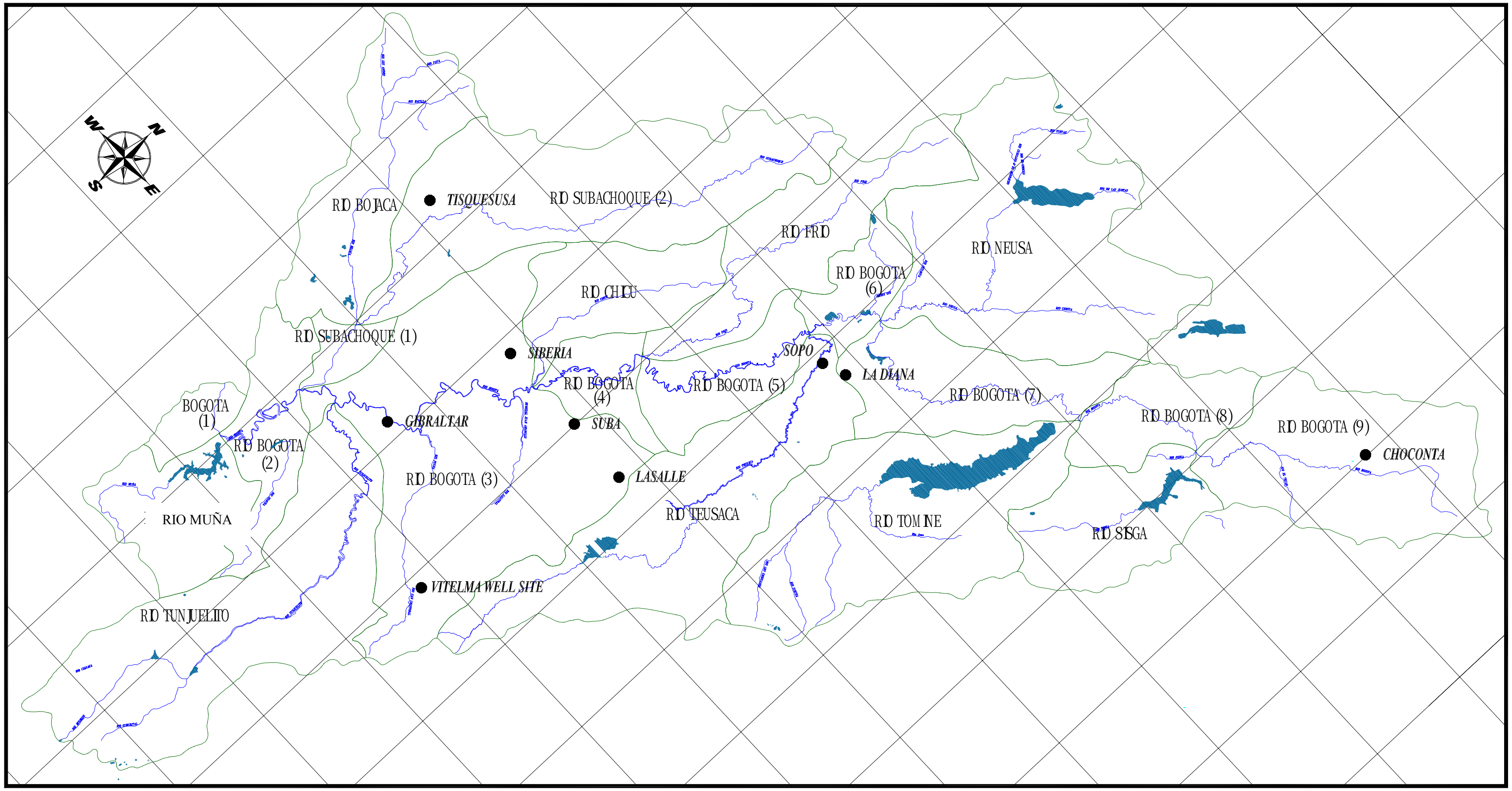

Figure-3.4 Sites of Exploratory Drilling of Quaternary and Cretaceous

Characteristics of Quaternary Aquifer

According to result of exploratory drilling, Sabana and Tilata Formation consist of mainly clayey sediments, and sand and gravel layers are not so many. Only sand and gravel layers become aquifers in Quaternary, which distribute separately in different depth surrounded by thick and low-permeable layers. Within this system, sand and gravel layers has vertical connection of groundwater flow though intermediate low-permeable layers. According to pumping test, specific yield of drilled six wells is 26m^3～84m^3/day/m, and its average is 60 m^3/day/m. This result shows high production capacity of Quaternary aquifer.

(2) Cretaceous Exploratory Drilling

EAAB carried out four of Cretaceous Exploratory Drilling during this Study. The result of the drilling is summarized below.

(a) Location and Result of Drilling

Drilling sites of two wells are shown in Figure-3.4. Result of exploratory drilling is summarized in Table-3.4.

Table-3.4 Result of Cretaceous Exploratory Drilling (1)

	Well No. (Site)	No.1 (La Salle)		No.2 (Suba)		No.3 (Mariscal Sucre)	
	Coordinate of Wells	E:1,006,063/N:1,017,517		E:999,911/N:1,017,839		E:999,214 /N:1,019,352	
	Well depth(m)	270		389		304m	
	Screen depth (GL-m)	60～65、69～75、82～85、87～90、97～106、113～119、134～140、148～151、153～156、172～175、179～188、195～198、202～205、221～224、229～238、248～254、258～261 (Total 84m)		145～148、150～159、166～175、190～199、213～222、228～234、240～246、258～267、283～286、322～325、329～335、341～344、349～355、377～380 (Total 84m)		124, 136, 164, 195, 200, 215, 220, 240, 264, 284, 288,	
	Casing Diameter	8 inch		8 inch		8 – 6 inch	
	Aquifer	Sandstone and shale		Sandstone		Sandstone	
Pumping Test	S.W.L[1)] (GL-m)	-23.92		-23.92		20.09	
	Yield (m^3/day)	1,987		1,987		4,320	
	Drawdown	5.07		5.07		3.91	
	D.W.L[2)] (GL-m)	18.85		18.85		24	
	Specific Capacity (m^3/day/m)	392		392		1,104	
	Transmissivity (m^2/day)	160-192		651		1,729	
	Conductivity (m/day)	1.9-2.3 (0.59～0.71)		7.8 (1.67)		-	
	Storativity	1.44×10^{-11}		1.53×10^{-4}		2.3×10^{-3}	
S tep Down	1 step yield / drawdown	636 m^3/day	4.18m	758 m^3/day	0.87m	1,520 m^3/day	0.88 m
	2 step yield / drawdown	968 m^3/day	8.33m	1,165 m^3/day	1.73m	1,763 m^3/day	1.06m
	3 step yield / drawdown	1,158 m^3/day	11.10m	1,486 m^3/day	2.60m	2,065 m^3/day	1.28m
	4 step yield / drawdown	1,495 m^3/day	18.40m	1,970 m^3/day	4.39m	-	
	5 step yield / drawdown	1,944 m^3/day	35.01m	-		-	-

Note 1) Conductivity and storativity were analyzed by Jacob method and recovery method

2) Two types of conductivity are shown. The first one is (Transmissivity / total screen length), and second one is (Transmissivity / total well length).

Table-3.4 Result of Cretaceous Exploratory Drilling (2)

Well No. (Site)	No.4 (Vitelma Recharge well)	No.5 (Vitelma observation well)
Coordinates of Wells	E: 1,001,326 N: 996,416	E: 1,001,220 N: 996,431
Well depth(m)	300 m	240 m
Screen depth (GL-m)	60～63、73～82、87～96、100～106、114～129、133～136、139～154、167～176、208～211、216～219、252～258、262～265、281～287 (Total length 90m)	113～140、148～151、173～179、199～202、205～208、216～222、233～236 (Total length 72m)
Casing Diameter	8 inch	4 inch
Aquifer	Sandstone, shale	Sandstone, shale
＜Pumping Test＞		
S.W.L[1] (GL-m)	-6.63m	－6.84m
Yield (m3/day)	1,296	-
Drawdown	18.84	12.03
D.W.L[2] (GL-m)	25.47	18.87
Specific Capacity (m^3/day/m)	69	-
Transmissivity (m^2/day)	62-	60
Conductivity (m/day)	0.70 (0.21)	0.68 (0.21)
Storativity	3.4×10^{-4}	3.4×10^{-4}

Note: 1) Conductivity and storativity were analyzed by Jacob method and recovery method
2) Two types of conductivity are shown. The first one is (Transmissivity / total screen length), and second one is (Transmissivity / total well length).
3) S.W.L. of No.4 well is from ground level of No.4 well.

Characteristics of Cretaceous aquifer

From the drilling result, main aquifer of Cretaceous Group in La Salle, Suba and Vitelma drilling sites is Labor Tierna Formation. Labor Tierna Formation consists of mainly sandstone, of which more porous and fractured parts becomes aquifer. Such sandstone distributes in different depths within Labor Tierna Formation. In addition to this, notable fractured zones are developed in Labor Tierna Formation, and such fractured zones sometimes form excellent aquifer. Specific capacity is 56m^2/day in La Salle well, 392m^2/day in Suba well and 69 m^2/day in Vitelma well. According to pumping test, three wells show very high specific capacities. It proves that Guadalupe Group of the drilling sites has high aquifer capacity.

3.5 Groundwater Level Observation

Groundwater level of the Study Area was observed by simultaneous groundwater level observation and by automatic groundwater level recorder. Groundwater level and seasonal fluctuation of it were analyzed in this Study. The result is explained below.

(1) Simultaneous Groundwater Level Observation

(a) Simultaneous Groundwater Level Observation by JICA Study Team and CAR

The Study Team carried out simultaneous groundwater level observation in February, August and December of 2001 and August and November of 2002. Total number of observed wells is around 100, which are currently not in use for pumping. CAR started simultaneous groundwater level observation for entire Study Area since 1998. Fourteen times groundwater observation campaigns for around 370 observation wells were carried out by CAR during 1998 and 2001. The wells used for these observations are currently in use for pumping.

(b) Result of Simultaneous Groundwater Level Observation

Groundwater level distribution and its fluctuation in the Study Area were examined from the result of simultaneous groundwater level observation carried out by CAR and the Study Team. The result of examination is explained below.

Fluctuation of Groundwater level in the Study Area

Groundwater level fluctuation during 1998 to 2001 was analyzed from CAR's result. Average speed of groundwater level fluctuation of observed wells was summarized in histogram shown in Figure-3.5. As shown in Figure-3.5 average speed of groundwater level fluctuation shows range of -6m/year and 6m/year.

Two interpretations for result above are possible.

- Groundwater level is being lowered by the average speed of -0.2m/year,
- Fluctuation speed of -0.2m/year is negligible. It means that groundwater level is already in equilibrium state, and is not in big fluctuation.

In the Study Area, large groundwater development started 20 years ago, since then lowering of groundwater level also started. From the result mentioned above, the lowering of groundwater level by pumping has already reached equilibrium state and serious lowering of groundwater level will not take place any more.

Groundwater Level Distribution of Study Area

Groundwater level distribution was estimated from observation results by CAR and JICA Study Team. More than 90% wells, which were observed by CAR and the Study Team, have Quaternary aquifer, and wells with Cretaceous (Guadalupe) aquifer are few. Moreover, wells with Tertiary aquifer are rare.

(a) Groundwater Level of Quaternary

Assumed groundwater level of Quaternary aquifer was shown in Figure-3.6. As shown in Figure-3.6, groundwater of Quaternary aquifer flows from the border of Bogotá Plain (mountain and hill area) to the center of Bogotá Plain following the gradient of land slope. Groundwater level is low where there are many pumping wells, and it is expected that groundwater flows toward this area from its surrounding area.

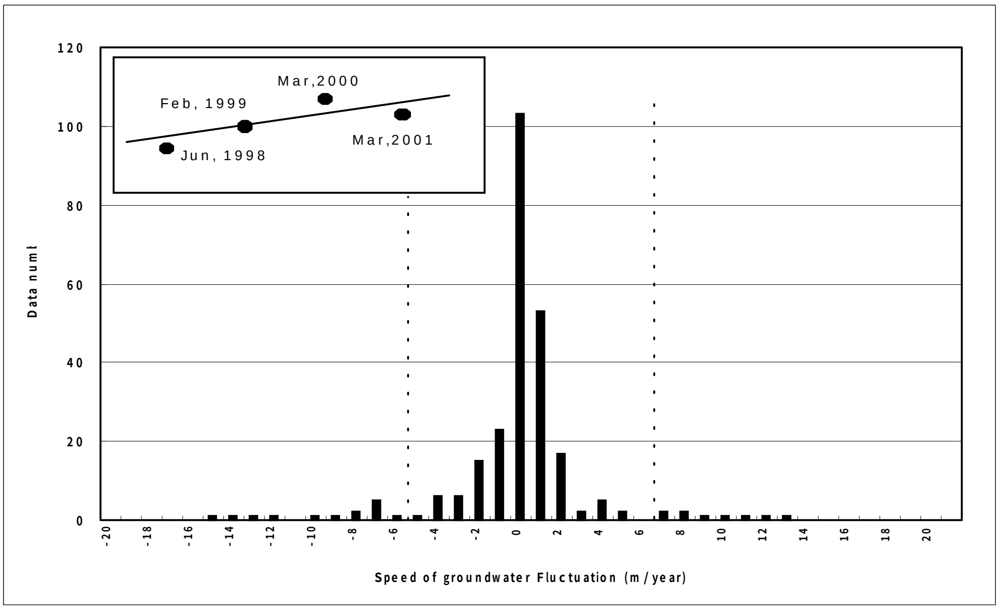

Figure-3.5 Histogram of Speed of Groundwater Fluctuation (m/year)

(b) Groundwater Level of Cretaceous Aquifer

Data of groundwater level of Cretaceous aquifer are few compared with those of Quaternary.

Then, it is difficult to draw groundwater level contour-line covering all over the Study Area. In order to obtain concept of groundwater level distribution, groundwater level was drew based on some assumptions, and this is shown in Figure-3.7.

As shown in Figure-3.7, groundwater of Cretaceous aquifer flows from the NNE to SSW direction following gradient of land slope of Bogotá Plain, and finally flows out from the Study Area.

(2) Result of Continuous Groundwater Level Observation

The Study Team installed automatic groundwater level recorders to 11 existing wells, and groundwater level is currently being automatically observed in these wells.

Table-3.5 Wells for Groundwater Level Continuous Observation

Well No.	Well No.	Coordinates of well	
		E	N
No.1	Gibraltar (Soacha)	988,439	1,005,845
No.2	Tisquesusa (Facatativa)	976,639	1,022,020
No.3	Siberia (Tabio)	991,462	1,017,974
No.4	Sopo (Sopo)	1,011,020	1,037,638
No.5	Diana	1,013,170	1,038,429
No.6	Choconta	1,049,874	1,067,343
No.7	Suba	999,911	1,017,839
No.8	Guadarrama	1,014,772	1,053,702
No.9	Grasco	996,772	1,001,948
No.10	Santa Monica Flowers	977,203	1,014,760
No.11	Dersa	996,772	1,001,948

(3) Monitoring result up-to now is summarized as follows.

The monitoring result shows seasonal groundwater fluctuation of Quaternary aquifer. Fluctuation pattern is different in each well, and seasonal fluctuation is not clear. It seems to be caused by the effect of neighboring pumping wells. The pattern of groundwater level fluctuation in the Study Area is generally complicated. This is caused by the existing pumping wells, which have an influence on groundwater level by artificial yield control.

From the observation result, the trend of the long-term lowering and rising of groundwater level is not recognized. It is considered that lowering of groundwater level of Bogotá Plain by pumping has already reached an equilibrium condition.

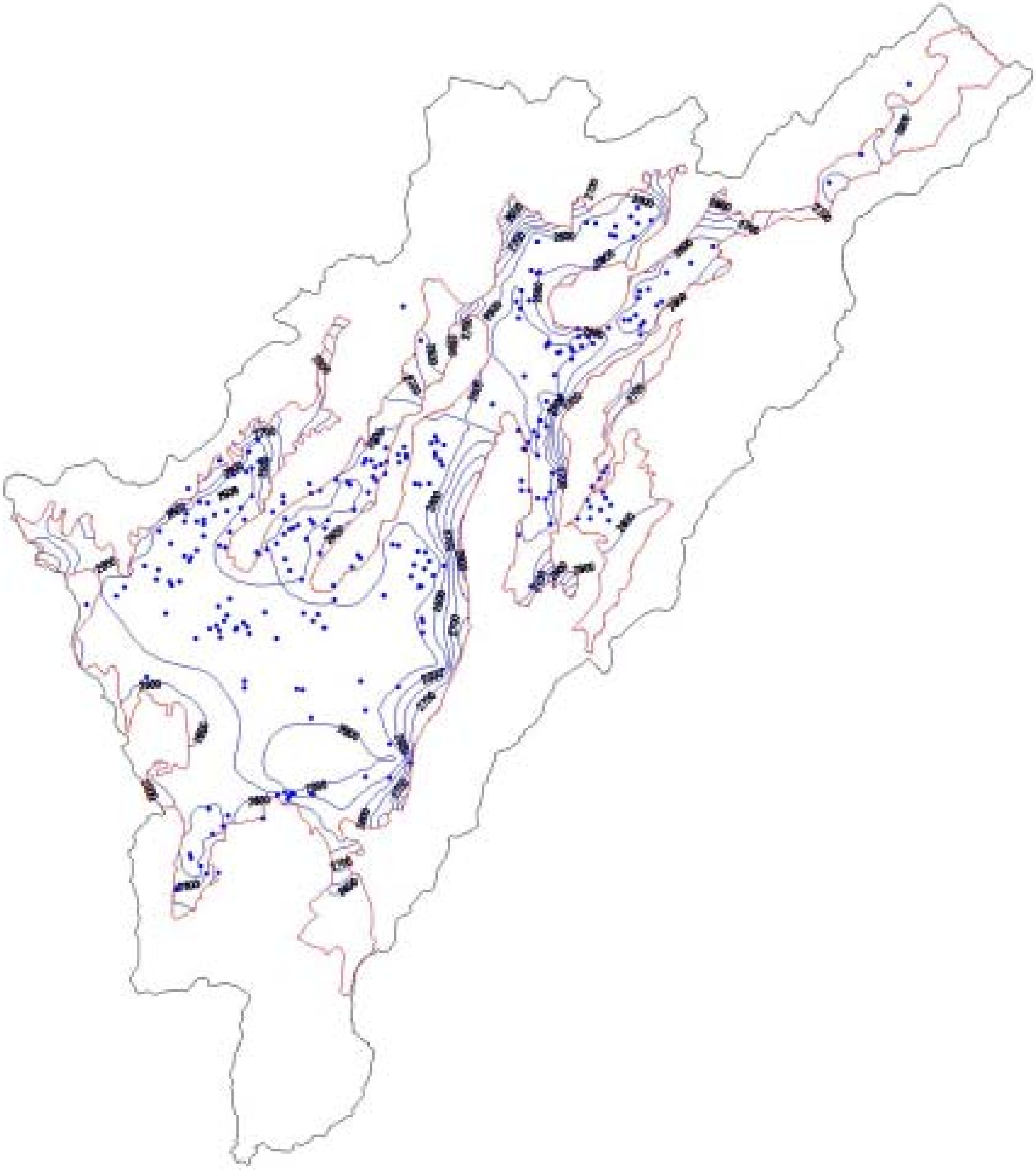

Figure-3.6 Groundwater Level of Quaternary

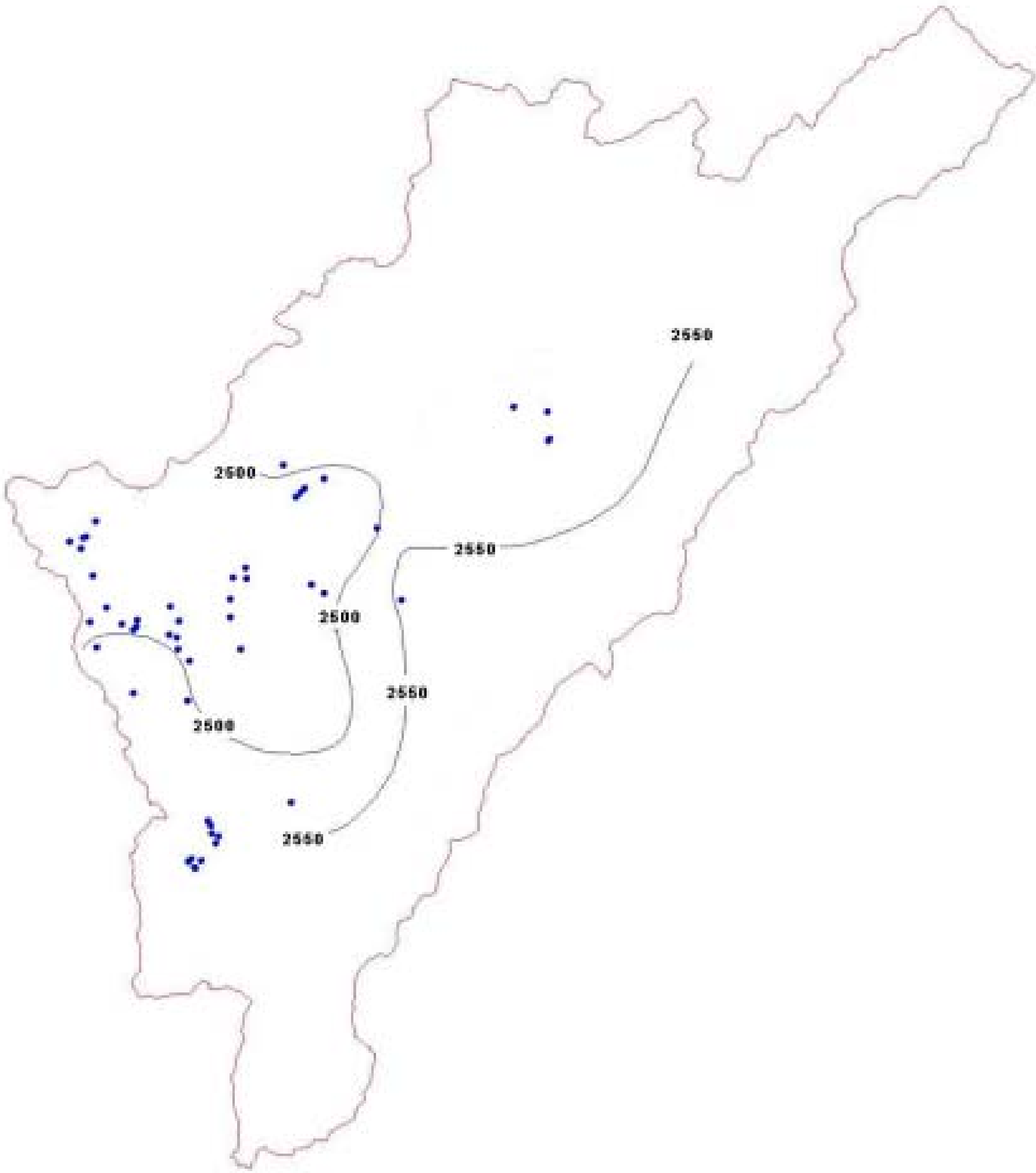

Figure-3.7 Groundwater Level of Cretaceous

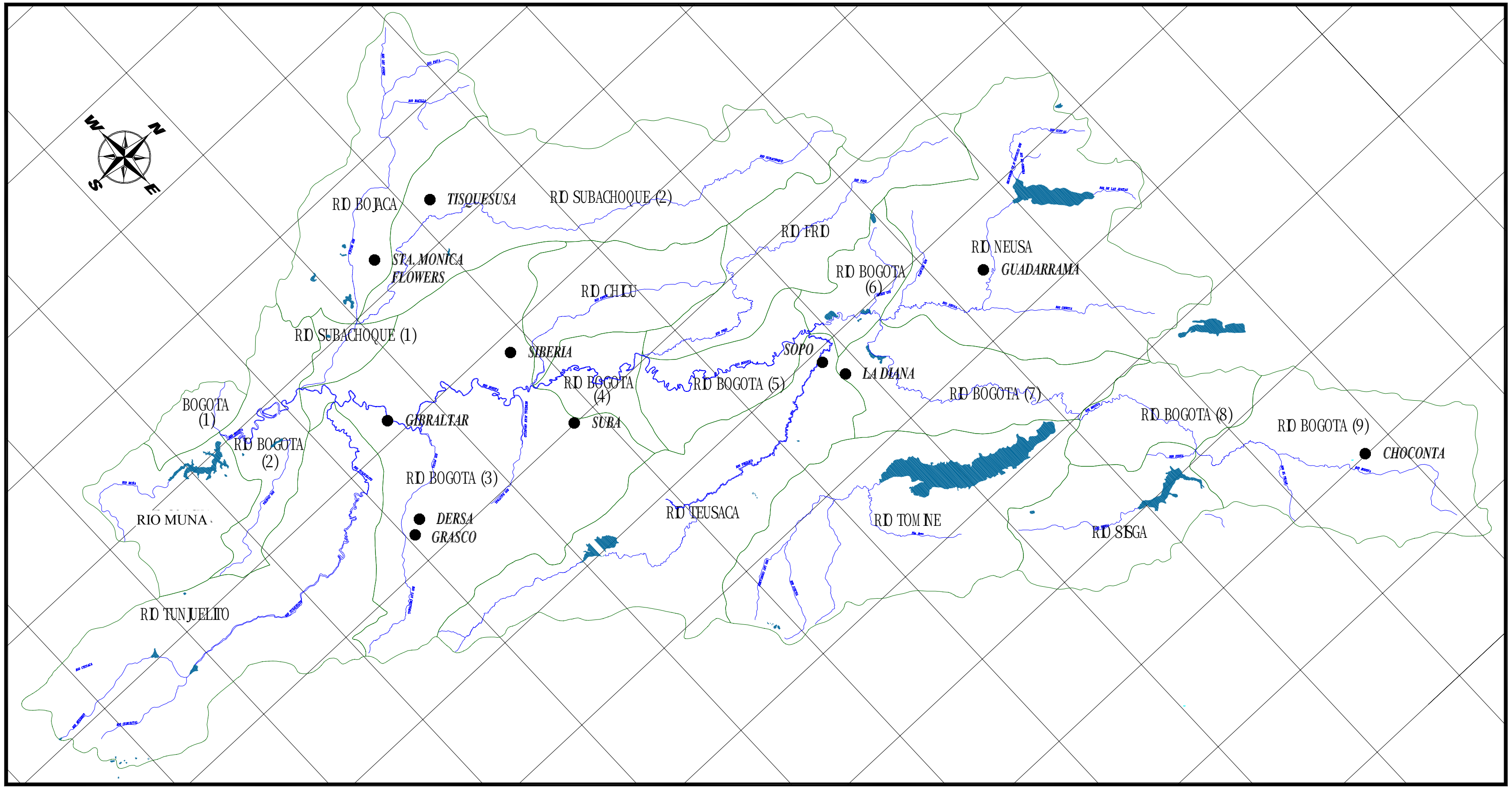

Figure-3.8 Site for Installation of Groundwater Level Recorder

3.6 Water Quality Test for Well

Water quality analysis for well was conducted three times to evaluate the groundwater in Bogota Plain from the environmental and hydrogeological aspects (Phase 1: February - March, 2001, Phase 2: October – November, 2001 and Phase 3: August – September, 2002).

(1) Sampling Location and Test Parameter

The sampling locations for water quality analysis are selected from (i) wells along rivers, (ii) wells in agricultural area, (iii) wells in industrial area, (iv) wells for isotopic analysis and (v) others. Test items were selected for covering 6 categories (chemical parameters related to human health, parameters related to taste, odour and colour, inorganic parameters, organic parameters, agrochemicals, and bacteria).

Table-3.6 Sampling Points for Well Water Quality Test and Items

Items	Phase 1	Phase 2	Phase 3
1. Sampling Points (Total)	99	104	70
- Wells around Rivers	33	33	18
- Wells in Agricultural Areas	5	5	5
- Wells in Industrial Areas	5	5	5
- Wells for Isotopic Analysis	20	20	9
- Wells in Other Areas	36	42	33

2. Analysis Items	Around Rivers	Agricultural Area	Industrial Area	Isotopic Analysis	Other Areas
Chemical parameters related to human health	○	○	○	○	○
	Arsenic, Boron, Cadmium, Chromium, Cyanide, Fluorine, Lead, Total mercury, Nickel, Nitrates, Nitrites, Selenium, Antimony, Barium, Beryllium, Copper, Manganese, Molybdenum, Cupper				
Physical & chemical parameters related to taste/odor/color	○	○	○	○	○
	Color, Odor, Turbidly, Temperature, Langelier index, Conductivity				
Inorganic parameters	○	○	○	○	○
	Aluminum, Ammonia, Chloride, Hardness, Hydrogen sulfide, Iron, Dissolved oxygen (Phase 2 only), pH, Sodium, Sulfates, Dissolved total solid, Zinc, Magnesium, Potassium, Bicarbonate Ion, Carbonate, Calcium, Alkalinity, Acidity				
Organic parameters	--	--	○	--	--
	Toluene, Xylems, Benzene				
Agrochemicals	--	○	--	--	--
	Aldicarb, Carbofuran, Aldrin, Endrin, Dieldrin, Chlordane, Linuron, P, p-DDT, o-p ' DDT, p-p ' DDT, Permetrina, 2-Clorofenol, 2, 4, 6-Triclorofenol, Endosulfan I, Endosulfan II, Endosulfan S042-, Heptachlor, Heptachlorepoxide, Lindane, Metolachlor, Atrazine, Bentazone, Profenofos, Clorpirifos, Triclorfos, 2, 4-D, Methoxychlor, Simazine, Trifluralin, 2, 4-DB, Dichlorprop, Malation, Etil Paration, Metil Paration, 2, 4, 5-T, PCP, Diazinon, Permethrin, 2, 4, 5-TP				
Bacteria	○	○	○	○	○
	Escherichia coli, Coliform bacteria				

○ : tested -- : not tested

(2) Summary of the result

<Water Quality Evaluation in the environmental aspect>

<u>Water quality in Quaternary</u>

The main characteristic is that the water quality items rarely detected in usual groundwater in deep strata were observed at high values widely in the study areas. Benzene, Toluene and Xylene (BTX), which are the evidence of contamination from industry, were not detected in the wells in the industrial area. Similarly, the influence of pesticides was not identified in the agricultural area. By contrasting to Colombian raw water quality standard, the following describes the items, which exceed the standard in its concentration and the number of wells. As a whole, the groundwater in the Study Area does not satisfy the water quality standard and water cannot be utilized for drinking purpose without normal purification process.

- Raw water for domestic use: Color, turbidity, the *coliform bacilli* group, ammonia and pH exceed the standard values in many wells. Therefore, it should be emphasized that the water quality is extremely poor as raw water for planning normal purification process. Though it cannot be said that hydrogen sulfide and iron content exceed the standard since there is no standard exist in Colombia, the concentrations of these substances exceed international standard such as the WHO guideline. Therefore, there is a high risk to drink this water without treatment process and it cannot be expected to use the water relying on its good quality.
- Raw water for agricultural use: Exceed in iron and manganese concentrations was seen many wells. Because Colombian standard does not include hydrogen sulfide and other toxic ions, these issues will be discussed in the later section.
- Raw water for stock-raising use: No groundwater sample exceeded the standard.

Water quality in Cretaceous

Although hydrogen sulfide, manganese, iron and color could not satisfy the standard values, these concentrations are relatively lower in comparison to the ones in Quaternary. It should be emphasized that ammonia was hardly detected in this strata. Therefore, it can be concluded that the water quality differs from the one in Quaternary.

Characteristics of Groundwater Quality

Chromaticity: The standard value of raw water for chlorine sterilized is 20 TCU (human can detect 15 TCU). Approximately 80% of the basins exceed this standard. It is a rare case that deep groundwater exceed in this content. The dissolved organic matters such as humic acid dissolved in the water increases the chromaticity. The values of chromaticity of groundwater in Quaternary strata (25 wells 17 TCU in average), which is mainly formed by old lake sediments, and in Cretaceous strata (10 wells 30 TCU in average), which is formed by oceanic sand layer, were compared. The result reveals that the chromaticity in Quaternary is noticeably high. Hence, the cause of high chromaticity is attributed to deteriorable organic matter.

Ammonium-nitrogen: Ammonium-nitrogen of high concentration was widely detected in the study area. The water standard of the raw water for drinking purpose was 1.0 mg/l, but the average concentrations in 70% of basins exceeded this standard. The average concentration was 4.91 mg/l and 1.12 mg/l in the Quaternary aquifer (25 wells) and Cretaceous aquifer (10 wells), respectively. It is natural to consider a large quantity of ammonia is stocked in deep groundwater layer. It is hard to explain this issue by surface human activity. It is more natural to connect that the ammonia is generated from humic organic matters in the lake sediment. There is a good correlation between chromaticity and ammonia concentration. This support the cause of high concentration of ammonia attributes to organic matters.

Hydrogen sulfide: High concentration of hydrogen sulfide is seen throughout the Study Area. With referring to the WHO standard of 0.03 mg/l, the concentrations of the substance exceed in almost all wells. The average concentration value is 0.804 mg/l and there is no clear deference between strata. Hydrogen sulfide is considered to originate from geological condition because the stocked amount is much higher than the generated amount by surface human activity. Hydrogen sulfide may originate from pyrite and volcanic ash in Tertiary strata.

Iron and manganese: It is obvious that geological features affect both iron and manganese concentrations. The metals distribute through the Study Area in unevenly. However, groundwater in Quaternary strata contains high concentration of the metals. The iron concentration exceed 0.3 mg/l, which is commonly employed value in many countries. This attributes to reduced condition in underground and the same applies to manganese.

Coliform bacillus: C*oliform bacillus* from excretion was detected in more than half basins. The number of basins from which *coliform bacillus* was detected in more than 40% of wells in the basin exceeded 75%. This is probably caused by the fact that the structural problem of wells facilitates the invasion of *coliform bacillus* from ground surface.

Geochemical characteristics

The concentrations of the main eight ions (Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, HCO_3^-, CO_3^{2-}) of water quality samples were expressed on tri-linear diagram and hexa diagram. As a result, the following geochemical characteristics of groundwater were found:

- Groundwater in Quaternary aquifer has the quality of the $Na\text{-}HCO_3$ type that is typical of groundwater in deep-aquifer, which has experienced long underground-flow time, and ion exchange has advanced. On the other hand, the $Ca\text{-}HCO_3$ type without advancement of ion exchange, which appears in groundwater in shallow-aquifer, can be also observed but its number is small.
- The Cretaceous groundwater does not have distinctive characteristics, while $Ca\text{-}CO_3$ is slightly more.
- All study wells were classified by statistical cluster analysis according to total similarity of concentrations of the main eight ions. As a result, wells showing the $Na\text{-}HCO_3$-type quality of water, which is considered to have experienced long flow time, are over 65 %.
- From the water quality of Quaternary aquifer, it is suggested that groundwater flows from the periphery of basin to the center of basin in terms of water quality. Similar results have been obtained in the Cretaceous aquifer.

3.7 Isotopic Analysis

(1) Sampling and analyzed items

Isotopic analysis was carried out based on the samples collected from existing 20 wells in February 2001 (Phase 1) and 10 wells in August 2002 (Phase 3) to estimate the groundwater recharge and its flow mechanism. The wells and analysis parameter are listed in the table below.

Table-3.7 Selected wells for isotopic analysis (Phase 1 and 3)

Item		^{14}C	^{3}H	D and ^{1}H	^{18}O and ^{16}O
Aim for analysis		Age determination of ground water older than 5000 years	Confirmation of ground water of young age about 40 years	Examine the origin, mixture and flow of ground water	
Selection standard		･Select in all aquifer but mainly Cretaceous ･Select wells in the central area of the basin	･Select in all aquifer but mainly Quatenary ･Select wells distributed widely in the study area		
Number of selected wells	Quaternary	1 (5)	14	14	14 (15)
	Tertiary	1	3	3	3
	Cretaceous	3 (4)	3	3	3 (4)
Total		5 (9)	20	20	20(19)

(2) The Result of Isotopic Test

<^{14}C (Carbon fourteen)>

The result of the analysis in 15 wells shows the age of groundwater in the Study Area is approximately between 1,690 and 33,170 years. The aquifer of the samples mainly belongs to Cretaceous strata. The age of the groundwater represents the travelling time from recharging to sampling point. In general, carbonic acid, which is provided into the groundwater in the process of precipitation, penetration and various reaction in *situ*, effects on the concentration of carbon 14. Because the carbon in carbonic acid is “Dead Carbon”, which has already lost ^{14}C, the age of groundwater can be younger than estimated.

By comparing the results of carbon 14 analysis from Quaternary and Cretaceous strata, the age of groundwater in Cretaceous is younger than the one in Quaternary. It is because the wells of Cretaceous strata locate in mountainous regions and the groundwater is rapidly recharged by precipitation in the mountains. On the other hand, wells for Quaternary locate in the centre of the plain. Hence, the travelling period is much longer. Cretaceous layer has higher permeability than Quaternary strata. Hence, the groundwater actively moves in Cretaceous strata. The result of water quality analysis shows groundwater in Quaternary strata strongly has Na-HCO_3 type more than the Quaternary groundwater. This supports the result of isotopic analysis. The groundwater in Vitelma where the pilot study was conducted is classified as the very recent water among 15 samples.

Table-3.8 Result of isotopic analysis

No.	Well ID	Basin	Aquifer	Depth (m)	^{14}C Age (year)	TR	δ ^{18}O(‰)	δ D(‰)
	<Phase I>							
1	246-Ⅱ-A-061	BOGOTA(1)	Saban-Gdlupe	357	14140±50	0.41	-10.67	-60.76
2	227-Ⅱ-D-587	CHICU	G. Guadalupe	1000	8230±40	0.50	-11.61	-78.50
3	227-IV-A-233	SUBACHOQUE	Sabana	-	27150±150	0.37	-11.29	-74.16
4	227 Ⅳ A-299	SUBACHOQUE	Sap-Subacho	500	23650±100	0.39	-8.82	-69.81
5	228-Ⅰ C-252	BOGOTA(2)	Tertiary	170	24180±110	0.38	-10.97	-63.66
6	08-0007	BOGOTA(2)	Guadalupe	450	-	0.40	-11.77	-73.94
7	227-IV-B-561	BOGOTA(2)	Sabana	115	-	Na	-10.95	-43.13
8	11-0010	BOGOTA(2)	Sabana	251.8	-	0.45	-10.22	-86.52
9	22-0078	BOGOTA(2)	Sabana	252	-	0.45	-10.36	-61.42
10	228-Ⅰ-C-019	TUESACA	F. Sabana	135	-	0.49	-10.82	-33.07
11	209-Ⅲ-D-172	BOGOTA(3)	F. Sabana	253	-	0.35	-10.78	-70.70
12	228-Ⅰ-A-509	TUESACA	Sabana	112	-	0.33	-11.00	-70.03
13	209-Ⅲ-D-036	BOGOTA(3)	F. Sabana	82	-	0.56	-11.47	-70.38
14	209-Ⅲ-B-170	NUESA	F. Cacho	-	-	0.42	-10.67	-66.14
15	227-Ⅱ-D-1115?	BOGOTA(2)	Guadalupe	-	-	0.44	-11.48	-41.79
16	227-IV-A-442?	SUBACHOQUE	Sap-Subacho	353	-	0.57	-10.68	-73.77
17	227-IV-B-577?	BOGOTA(2)	F. Sabana	526	-	0.44	-12.49	-68.08
18	227 Ⅳ A-X6	SUBACHOQUE	Tilata	581	-	0.41	-11.91	-75.35
19	16-0003	BOGOTA(2)	F. Sabana	192	-	0.47	-11.36	-66.90
20	10-0011	BOGOTA(2)	F. Sabana	120	-	0.44	-11.55	-54.54
	<Phase 3>							
21	227-Ⅱ-B-028	SUBACHOQUE(2)	G. Guadalupe	70	3630±40		-10.46	
22	227-VI-A-063	SUBACHOQUE(2)	G. Guadalupe	448	33170±380		-10.71	
23	227-Ⅱ-D-802	CHICU	F. Sabana	100	32380±350		-10.51	
24	Vitelma1 EAAB	BOGOTA(3)	Guadalupe ?		4620±40		-10.39	
25	E-2 EAAB	BOGOTA(3)	Guadalupe	389	9430±40		-9.55	
26	JICA1 EAAB	BOGOTA(3)	Sabana	196	29750±270		-10.31	
27	JICA2	SUBACHOQUE(2)	Sabana	192	33110±380		-10.37	
28	JICA5	BOGOTA(7)	Sabana	188	20640±90		-9.51	
29	JICA6	BOGOTA(9)	Tilata	188	1690±40		-10.54	
30	Rio BOGOTA				-		-9.99	

TR: Tritium unit (1 in 1,018 hydrogen atom), Na: Below detection limit, δ : it is represented in parts per thousand in the ratio to SNOW (standard seawater) and + or – shows if it is higher or lower than SNOW.

<^{3}H or Tritium>

Twenty samples have been analyzed in order to determine the tritium concentration. The results showed that all the tritium concentration were less than 0.7 TU, the limit of detection. Considering that the half-life period of tritium is 12.35 years, the groundwater of Bogotá Plain is assumed to be older than 40 years. This result seems appropriate in view of the distance from the recharge area to the sampling wells and the depth of the aquifers (GL- 80m to GL- 1,000 m). Generally, artificial tritium, generated in thermonuclear explosion test, is found more on the Northern Hemisphere and less on the Southern Hemisphere as the test fields are mostly located in the Northern Hemisphere. Also the higher the altitude from the sea level is, the lower the concentration will be. Considering that the Study Area is 2,600 m to 3,000 m above the sea level, since new information is unlikely to be obtained, the tritium analysis was omitted in the Phase 3 study.

<D and ^{18}O (Deuterium and isotopic oxygen)>

The analysis results of deuterium and oxygen 18 in Phase 1 are shown in Figure-3.9. According to the results, water can be classified into the following three types .

The isotope composition of water in the wells No. 1, 2, 5, 6, 9, 11, 12, 13, 14, 18 and 19 are plotted along the approximate line $\delta D = 9.3868\ \delta^{18}O + 35.631$ which is nearly parallel with the global meteorological line ($\delta D = 8\ \delta^{18}O + 10$). Although the meteorological line in Bogota Area is not clear, this line is thought to be close to the global meteorological line in this area.

On the other hand, wells No. 3, 4, 16 and 18 in Madrid district show the approximate line of $\delta D = 1.7844\delta^{18}O - 54.224$ that has a low inclination and intersects with the global meteorological line. It is thought that the penetrated rainwater might be warmed and reacted with the surrounding rocks in isotopic exchange process. The rocks contain approximately 60% of oxygen in atomic composition. Through the reaction of isotopic exchange between water and rocks under this condition, the isotopic ratio of oxygen in water is drawn toward the value of rocks and this results in an increase of ^{18}O. On the other hand, the hydrogen content in the rocks is very low in comparison to that in water. Thus, the isotopic ratio of hydrogen in isotopic exchange reaction is relatively stable and the inclination of the approximate line becomes low.

Moreover, water in Wells No. 7, 8, 10, 15, 17, and 20 is plotted far above the global meteorological line in Figure-3.9. Wells No. 10 and 15 are located near recharge area, which are plotted at the top, and Wells No. 7, 8,17 and 20, which are plotted below them, are located in the city center. It is considered that D and ^{18}O concentrations become enriched through reaction with minerals during groundwater movement in the geological layer and mixing with deeper groundwater.

Sampling locations for oxygen 18 analysis in Phase 3 was distributed in the rim of the Study Area in comparison to Phase 1 study. The result matches in Phase 3 to the one in Phase 1, but the average concentration of ^{18}O is higher in Phase 3. This is probably because many sampling locations are in the area of rock layer of Cretaceous and the groundwater might be under the influenced of rock-rainwater reaction.

From the above analysis results of hydrogen and oxygen isotope, groundwater in the Study Area is basically recycling, originating from the meteoric water in the Study Area, although partial mixing of deeper groundwater might be possible.

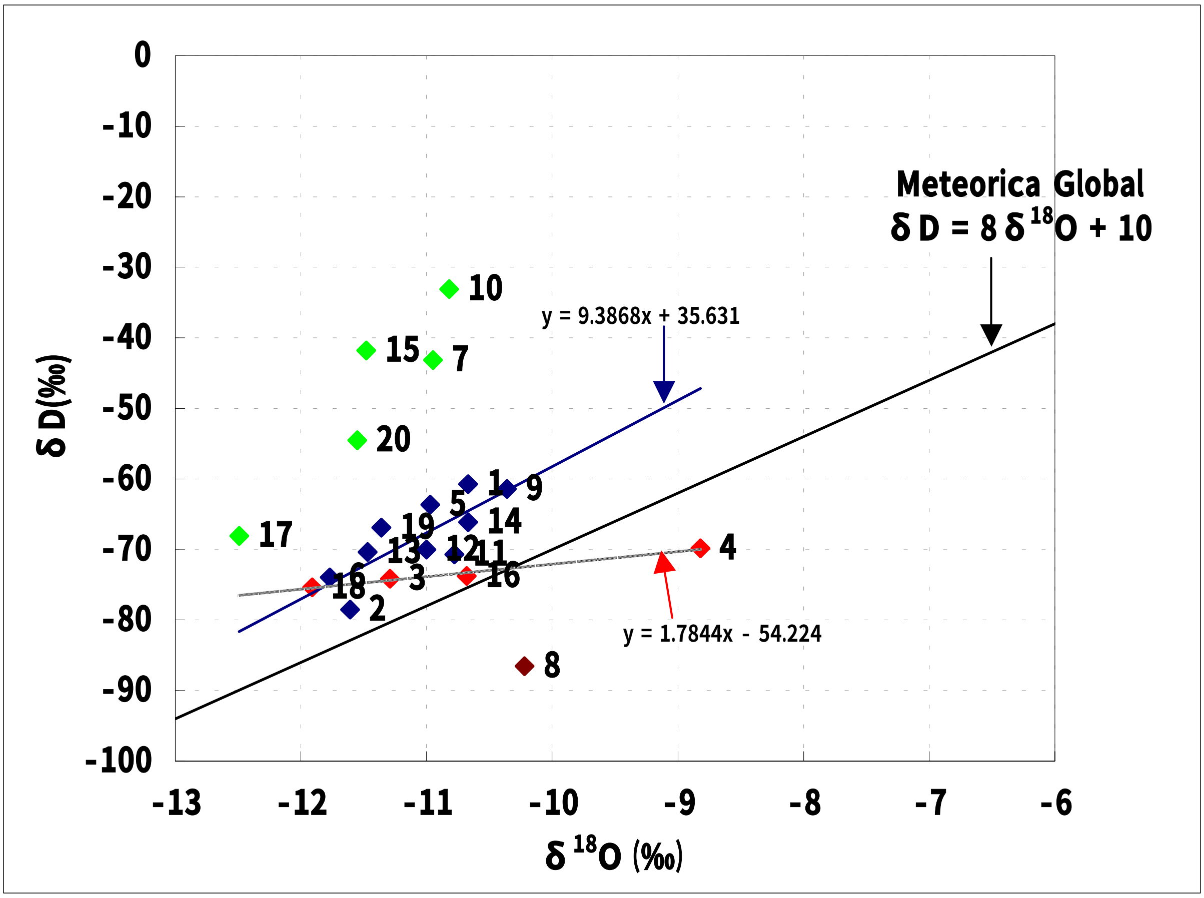

Figure-3.9 Relations between δD and $\delta^{18}O$

3.8 Well Inventory

(1) Outline of Well Inventory

The Study Team carried out Well Inventory survey for all the wells in the Study Area. The Study Team collected well data that had been stored in well Database of INGEOMINAS and well data registered to CAR and DAMA. It is possible to compile most of the wells that exist in the Study Area by putting all the data together. The number of wells that was collected by the Study Team is shown in Table-3.9. The total number of wells in the Study Area is estimated about 7,081 as shown in Table-3.9.

Table-3.9 The Number of Wells in the Study Area

Classification	Well Number	
	Well data with location	Well data without location
Wells recorded in well data-base of INGEOMINAS	3,027	694
Wells registered to CAR	1,672	1,439
Wells registered to DAMA	248	1
Sub Total	4,947	2,134
Total	7,081	

(2) Current Yield from Pumping Wells in the Study Area

Based on this database, the current yield from pumping wells in the Study Area was estimated. This database has 7,081 well data, most of which has information on yield. Daily yield of well is calculated from unit yield and daily operation hours. Daily yield of well was calculated from the formulae below.

Daily yield from well = Unit yield (m^3/day)×Daily well operation hours (hours/day)

The average yield of well data with yield information is 1.54 (l/s). Hence, unit yield of 1.54 (l/s) was assumed for wells data without unit yields information. Average operation hours of wells with information on operation hours are 6.54 hours/day. Hence, daily operation hour was assumed as 6.54 hours for wells without information on daily operation hours.

Total Yield in Study Area

Total yield from the current wells in the Study Area was estimated based on the assumption explained above. The result is shown in Table-3.10. As shown in Table-3.10, total yield from pumping wells in the Study Area is estimated 323,700m^3/day. The estimated total yield is expressed by other unit, 118×$10^6 m^3$/year, 3.75m^3/s, 27.7mm/year.

Table-3.10 Total Yield of Study Area

Classification of Well Data	Well Number	Estimated unit yield (l/s)	Well operation hours in 1 day (hours)	Total yield (m^3/day)
Date with unit yield and daily operation hours	2,644	Known	Known	158,690
Data without unit yield or without operation hours.	4,437	1.54(l/s)	6.54 (hours)	160,800
Total	7,081	-	-	320,490

(3) Well Number and Yield by Geology

Well Database created by the Study Team has information on aquifer type of wells. Most of INGEOMONAS well data of the Well Database has information on aquifer. Based on this information, well number and aquifer of well were analyzed by geology type. The result is shown in Table-3.11.

Table-3.11 The Number and Aquifer of Wells by Geological Type

Geology of aquifer		The number of well		Yield of well	
		Well number	% of total number	Yield (m^3/day)	% of total yield
Quaternary		6,570	92.9	248,830	77.6
Tertiary	Cacho	60	0.8	4,200	1.3
	Guaduas	50	0.7	3,900	1.2
	Other Tertiary	50	0.7	700	0.2
Cretaceous	Labor y Tierna	246	3.5	48,060	15.0
	Pleaners and Dura	90	0.13	14,400	4.5
	Chipaque	15	0.02	400	0.1
Total		**7,081**	**100**	**320,490**	**100**

93% of wells of the Study Area take groundwater from Quaternary aquifer, 2% from Tertiary aquifer, 5% from Cretaceous aquifer. Wells in the Study Area pump up groundwater, 78% from Quaternary aquifer, 3% from Tertiary aquifer and 19% from Cretaceous aquifer. As explained above, most of groundwater is currently pumped up from Quaternary aquifer, and groundwater pumped up from Cretaceous is only little amount. Groundwater pumped up from Tertiary aquifer is extremely limited.

(4) Well Distribution by River Basin

Well number and well yield by river basins were calculated based on Well Inventory Result. The results are shown in Table-3.12 and Figure-3.10. In Figure-3.10, well yields were summed up every 1km×1km mesh. As shown in Figure-3.10, the distribution of wells is partially concentrated in locations. There are many wells concentrating especially in the west of Bogotá City, Subachoque River Basin and Chicu River Basin.

Table-3.12 Total number and yield of Wells by River Basin

Basin	Catchment Area (km^2)	Well number	Well number per area (No/km^2)	Yield (m^3/day)	Yield per area ($m^3/day/km^2$)
Bogota1 –Bogota3	678	1,559	2.3	77,651	114.5
Bogota4 –Bogota6	232	1,141	4.9	45,797	197.4
Bogota7 –Bogota9	557	429	0.8	27,451	49.3
Bojaca	219	311	1.4	21,549	98.4
Chicu	134	1,620	12.0	44,636	333.1
Frio	194	320	1.6	12,476	64.3
Neusa	432	185	0.4	8,333	19.3
Sisga	152	1	0.0	30	0.2
Muna	128	40	0.3	1,298	10.1
Subachoque 1	32	18	0.6	293	9.2
Subachoque 2	386	1,078	2.8	54,751	141.8
Teusaca	353	256	0.7	14,467	41.0
Tomine	368	21	0.7	719	2.0
Tunjuelito	404	103	0.3	11,038	27.3
Total	4,269	7,081	1.7	320,490	75.1

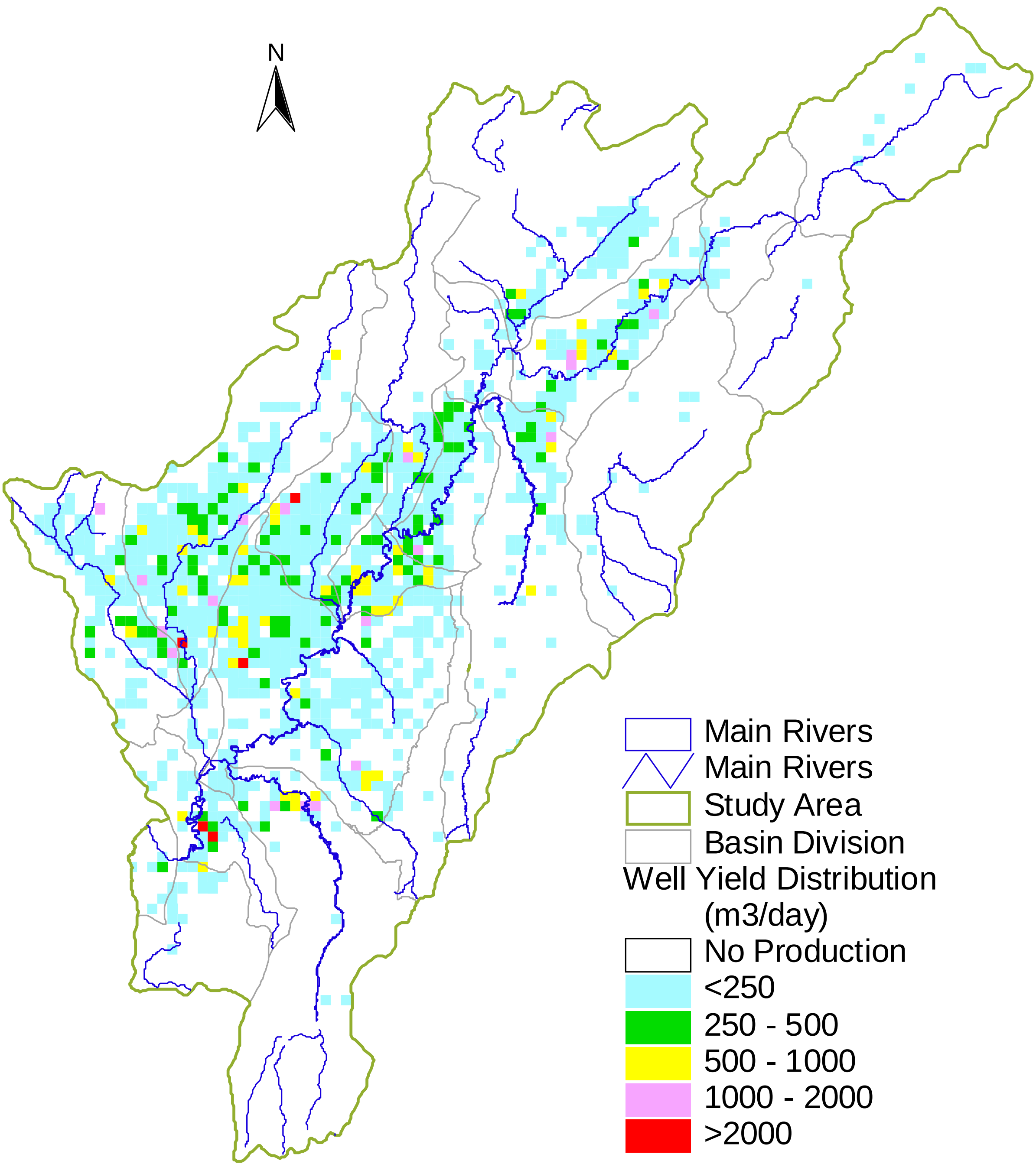

Figure-3.10 Distribution of Yield