4.4 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

Location of six drilling is shown in Table-4.5 and

Figure-4.12. 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

Table-4.5 Location of Quaternary Exploratory Drilling

Well No.		Coordinates	
		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

<u>Well Structure</u>

Total drilling depth of six wells is 1,022m, and average depth of each well is 200m. The final diameter of casing of six wells is 8 inch. Groundwater level recorders were installed for every well. After installation of the recorders, groundwater level is being automatically observed. Six observation have screens for sand and gravel aquifer distributing in clayey formation, which can be called multiple screen structure. Therefore, these wells show mixed groundwater level of different aquifers of Quaternary.

<u>Result of Drilling</u>

Result of drilling is shown in Table-4.6. Pumping tests were carried out immediately after drilling completion. After pumping test of 48 hours pumping, recovery tests were carried out. For Gibraltar well, not pumping test but borehole permeability test was carried out because methane came out from ground water of Gibraltar well.

<u>Geological condition</u>

Five wells were drilled in Sabana Formation of Quaternary. The remaining one well of Choconta site were drilled in Tilata Formation of Quaternary. Sabana Formation is representative formation of Quaternary, which occupies upper half of Quaternary of the Study Area and distributes most of Bogotá Plain. Current pumping by flower companies is mainly from Sabana Formation. On the other hand, Tilata Formation occupies lower half of Quaternary of the Study Area, of which distribution is limited and still not fully known. Silty and clayey layers are dominant in Sabana Formation. In Sabana Formation, sand and gravel layers distribute separately in different depth. This situation corresponds to geological history of Bogotá Plain: Quaternary of Bogotá Plain consists of mainly lake deposits (clay and silt), among which several river sediments (sand and gravel) of different age distribute. Thickness of sand and gravel layers of the drilling points of the Study is 1m to 30m. This thickness is considered to be enough to provide sufficient groundwater to consumers.

Table-4.6 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.

Groundwater level

Groundwater level of drilled six wells is from GL-16m to GL-22m, corresponding to general groundwater level of Quaternary aquifer in Bogotá Plain. On the other hand, groundwater level of Tisquesusa well is GL-76.92m, which is much deeper than the other wells. There are many wells concentrated in this area. Currently it is said that groundwater level of this area is deeper than the other area. The drilling result proved this situation.

Specific yield of wells

Specific yield of drilled six wells is $26m^3$～$84m^3$/day/m, and its average is 60 m^3/day/m. Therefore, 1m drawdown by pumping produces yield of $60m^3$/day, and 10m drawdown by pumping produces yield of 600 m^3/s/day.

Conductivity

Conductivity of six wells of Quaternary is 0.96～4.0m/day (1.1×10^{-3}～4.6×10^{-3}cm/s) , and its average is 2.1m/day (2.4×10^{-3}cm/s). It seems reasonable value because aquifers consist of fine sand, and conductivity of aquifers is concluded favorable. On the other hand, average conductivity of Quaternary calculated for the total well length is 2.0×10^{-4}～1.5×10^{-3} cm/s, and its average is 7.3×10^{-4} cm/s. Conductivity may be said not high but not low for entire Quaternary in the drilling sites.

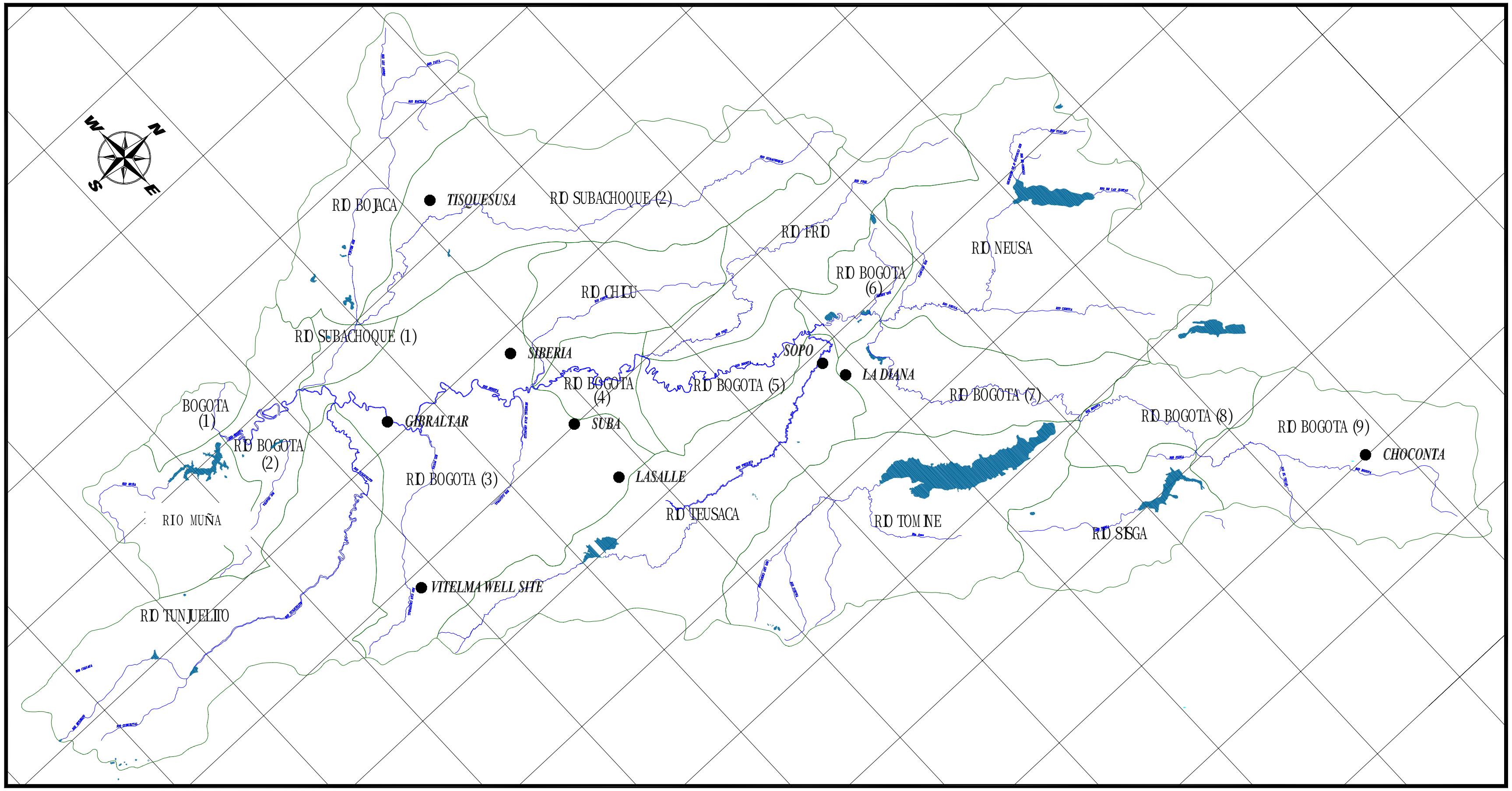

Figure-4.12 Sites of Exploratory Drilling of Quaternary and Cretaceous

Storativity

Storativity of drilled six wells shows 10^{-2} order. This value is a little higher than existing result. On the other hand, Tisquesusa well shows extremely low Storativity of 10^{-18}. From the analyzed storativity, sand and gravel aquifer of Quaternary in the Study Area seems to be between confined and unconfined condition. Sand and gravel aquifers are confined by overlying and underlying low- permeable layers, but not completely confined. Groundwater of sand and gravel layers has connection of vertical flow though intermediate low permeable layers. It means that deep aquifer has connection with shallow aquifer of near ground surface.

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. In drilling sites, sand and gravel aquifers are at most 30m in thickness. These permeable layers and low-permeable layers consist "one" Quaternary aquifer system as a whole. Within this system, sand and gravel layers has vertical groundwater flow though intermediate low-permeable layers.

2) Result of Cretaceous Exploratory Drilling

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

Location of Drilling

Drilling sites of five wells are sown in Figure-4.12. No.1 well is located in the foot of Eastern Hills where groundwater is recharge to Cretaceous Formation. No.2 well is located near Suba Hill. La Salle well and Suba well are arranged on the assumed fault line and near each other. No.3 and No.4 wells are located in Vitelma Intake Site of EAAB in the Eastern Hills. No3 well is for artificial recharge and No.4 is for observation. No. 5 well Mariscal Sucre was drilled near Suba well.

Well Structure

Drilling depth of La Salle well is 270m, Suba well is 389m, Vitelma recharge well is 300m and Vitelma observation well is 280m and Mariscal Sucre well is 304 m. After rotary drilling, electrical-logging and gamma-logging were carried out to identify the location of aquifer for screen installation.

Automatic groundwater level recorder was installed for Suba well. All the Exploratory wells have multiple screens separately in different depth, which take groundwater from different depth of Cretaceous Guadalupe Formation.

Drilling Result

Result of exploratory drilling is summarized in Table-4.7 and Table-4.8.

Geological condition

Geological condition of exploratory wells are summarized in Table-4.9.

Table-4.7 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		N. 1.019.352,937 E: 999. 214,173	
	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		－23.92m		Sandstone	
Pumping Test	S.W.L 1) (GL-m)	+1.75m		-23.92		20.09	
Pumping Test	Yield (m3/day)	1,944		1,987		4,320	
Pumping Test	Drawdown	35.01		5.07		3.91	
Pumping Test	D.W.L 2) (GL-m)	33.26		18.85		24	
Pumping Test	Specific Capacity (m^3/day/m)	56		392		1,104	
Pumping Test	Transmissivity (m^2/day)	160-192		651		1,729	
Pumping Test	Conductivity (m/day)	1.9-2.3 (0.59～0.71)		7.8 (1.67)		-	
Pumping Test	Storativity	1.44×10^{-11}		1.53×10^{-4}		2.3×10-3	
step Down	1 step yield / drawdown	636 m^3/day	4.18m	758 m^3/day	0.87m	1,520 m^3/day	0.88m
step Down	2 step yield / drawdown	968 m^3/day	8.33m	1,165 m^3/day	1.73m	1,763 m^3/day	1.06m
step Down	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
step Down	4 step yield / drawdown	1,495 m^3/day	18.40m	1,970 m^3/day	4.39m	-	-
step Down	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-4.8 Result of Cretaceous Exploratory Drilling (2)

Well No. （Site）	No.4 (Vitelma Recharge well)	No.5 (Vitelma observation well)
Coordinates of Well	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 (m^3/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 No4 well.

Groundwater Level

< La Salle Well >

La Salle well is flowing well. Groundwater level of La Salle well is 1.75m from the ground surface at the time of pumping test. During drilling work, groundwater sprung into well at the depth of 185m, and this caused La Salle well to be flowing well. Groundwater level of La Salle well in December 2001 is almost the same as the groundwater level of the time of the pumping test.

Table-4.9 Geological condition of Well

Well	Geology	Depth (m)	Rock face
La Salle	Colluvial deposit	0-11	Sand, silt, clay
	Tierna Formation	11-100	Sandstone dominant alternation of sandstone and shale
	Labor Formation	100-223	Sandstone dominant alternation of sandstone and shale
	Plaeners Formation	223-268	Shale, partly sandstone
Suba	Colluvial deposit	0-8	Sand, silt, clay
	Tierna Formation	8-77	Sandstone dominant alternation of sandstone and shale
	Labor Formation	77-300	Sandstone dominant alternation of sandstone and shale
	Plaeners Formation	300-365	Shale, partly sandstone
	Dura Formation	365-411	Sandstone dominant alternation of sandstone and shale
Mariscal Sucre	Colluvial deposits	0-48	Soil clay, organic deposits, silt.
	Tierna Formation	48-140	Sandstone white, fine and sorted grain size.
	Labor Formation	140-310	Sandstone gray, and black shale.
	Plaeners Formation	310-427	Silt and sand cracked shale, quartz of fine grain.
	Dura Formation	427-454	Sand fine grain, pyrite and shale.
Vitelma (Recharge well)	Colluvial deposit	0-22	Gravel, sand, silt
	Labor・Tierna Formation	22-180	Sandstone dominant alternation of sandstone and shale
	Chipaque Formation	180-300	Shale
Vitelma (monitoring well)	Colluvial deposit	0-36	Gravel, sand, silt
	Labor・Tierna Formation	36-188	Sandstone dominant alternation of sandstone and shale
	Chipaque Formation	188-240	Shale

< Suba Well >

Groundwater level of Suba well was GL-23.92m at the time of pumping test. During drilling work, drilling water flowed away from well at the depth of 147m. Existence of big fracture is expected at this depth.

<Mariscal Sucre Well>

Groundwater level of this well was 20.09 m, even though the well is relatively near to Suba Well this is towards the flat terrain, no water loss was registered during the drilling work. Therefore the well is far apart from the fractured zone,.

<Vitelma Wells>

Distance between Recharge Well and Observation Well in Vitelma is 122m, and the groundwater level of both wells is about GL-6.8m.

Specific capacity of well

Specific capacity is 56m^2/day in La Salle well, 392m^2/day in Suba well and 69 m^2/day in Vitelma well. Three wells show very high specific capacities. It proves that Guadalupe Group of the drilling sites has high aquifer capacity.

Permeability

Permeability coefficient of screen part is 1.9 - 2.3m/day (2.2×10^{-3} - 2.7×10^{-3}cm/s) in La Salle well, 7.8m/day (9.0×10^{-3}cm/s)in Suba well, and 0.70m/day (8.1×10^{-4}cm/s) in Vitelma well. This result shows that Guadalupe Group of the drilling sites has high permeability.

Storativity

From pumping test result, storativity of the drilling site is 10^{-11} order in La Salle well, 0.25 x10^{-3} Mariscal Sucre, and 10^{-4} order in Suba and Vitelma well. Calculated storativity of three wells are a little different, but it may be suggested that actual storativity may be 10^{-5} - 10^{-6} order for three wells considering error from analysis. This storativity means aquifers of three sites are confined condition.

Step Drawdown Test

Step Drawdown test was carried out with five steps yields in La Salle well and four steps yields in Suba well and three steps Mariscal Sucre. Pumping hours for this test is 3.5 hours' for each step. According to result of step drawdown test, there was not big change in pumping situation during each step. Relation between yield (Q) and drawdown (s) is approximated as shown below.

La Salle well： $s = 2.9\times10^{-3}\times Q+7.8\times10^{-6}\times Q^2$

Suba well： $s = 4.5\times10^{-4}\times Q+9.1\times10^{-7}\times Q^2$

Mariscal Sucre well： $s = 3.9\times10^{-2}\times Q + 6.5\times10^{-4}\times Q^2$

Where,

s : Drawdown (m)

Q : Yield (m^3/day)

Characteristics of Cretaceous aquifer

From the drilling result, main aquifer of Cretaceous Group in La Salle, Suba and Vitelma drilling sites is Labor y Tierna Formation. Labor y Tierna Formation consists of mainly sandstone, of which more porous and fractured parts becomes aquifer. Such sandstone distributes in different depths within Labor y Tierna Formation, and it is difficult to predict the depth of sandstone aquifers before drilling. There was notable groundwater jetting at the depth of 185m of La Salle well, which causes La Salle well to be flowing well. On the other hand, there was big fracture at the depth of 147m of Suba well, and this fracture seems one of main aquifer of this well. As explained above, notable fractured zones are developed in Labor y Tierna Formation, and such fractured zones sometimes form excellent aquifer.

4.5 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 results are explained below.

3) Simultaneous Groundwater Level Observation

Simultaneous Groundwater Level Observation by CAR

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.

Simultaneous Groundwater Level Observation by JICA Study Team

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.

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 result. Using result of about 280 well, observed groundwater levels at each observation well were approximated into one lines by least squares method. These lines show trend of groundwater fluctuation of each observation well during 1998 to 2001.

Average speed of groundwater level fluctuation of observed wells was summarized in histogram shown in Figure-4.13. As shown in Figure-4.13, the average speed of groundwater level fluctuation show range of -20m/year to 15m/year, and most of them distribute between 6m/year and 6m/year. Observed data showing fluctuation speed of more than 6m/year seems abnormal, which has pumping effect. Therefore observed data, which has fluctuation speed of -6m/year to +6m/year, seems reliable without serious pumping effect. By examination of reliable data, matters below were concluded.

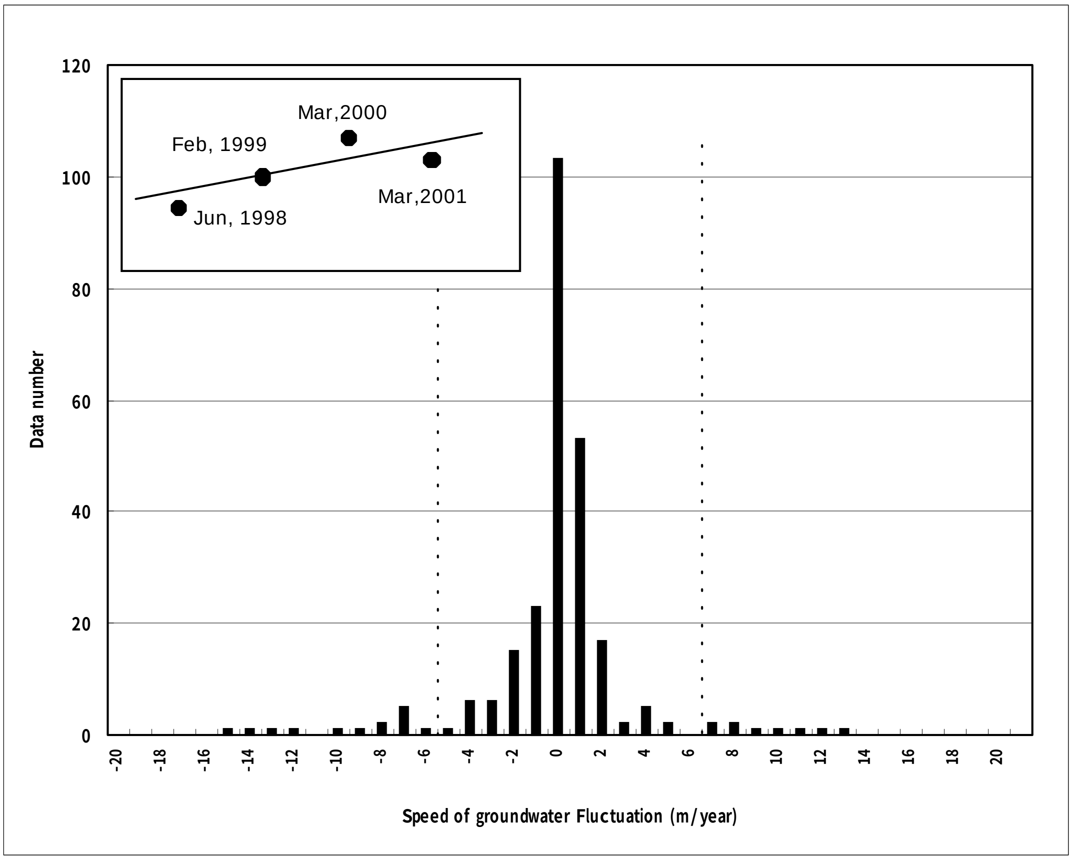

Figure-4.13 Histogram of Speed of Groundwater Fluctuation (m/year)

- Figure-4.13, fluctuation speed ranging between -6m/year and 6m/year shows Gauss distribution, and the average of this distribution is -0.2m/year.
- Distribution above was caused by actual groundwater level fluctuation, pumping effect and errors in observation.
- Two interpretations for result above are possible.
  i) Groundwater level is being lowered by the average speed of -0.2m/year,
  ii) 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. If the amount of pumping is equal or less than the amount of recharge on every specific basin.

4) 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.

Groundwater Level of Quaternary

Assumed groundwater level of Quaternary aquifer was shown in Figure-4.14. Groundwater level of Quaternary aquifer was drawn by procedure below.

- Observed groundwater levels during 1998 to 2001 by CAR were averaged for each observation well. The total number of wells is 277 to 367. Observed data with fluctuation speed more than 6m/year were neglected.
- From the result of simultaneous groundwater levels observation by the Study Team, average groundwater level was obtained for each observation wells. Observed groundwater levels with fluctuation speed of more than 6m during three observation periods were neglected.
- Averaged groundwater level calculated from monitoring result by CAR and JICA Study Team was combined. Based on these data, groundwater level distribution was drawn by interpolation.
- In interpolation of groundwater level, it is assumed that groundwater level of boundary between Quaternary and base-rock (Cretaceous or Tertiary) is GL-15m.

As shown in Figure-4.14, 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 surrounding area. Bojaca and Subachoque area shows this situation.

According to distribution of groundwater level shown in Figure-4.14, groundwater of Quaternary aquifer seems to be flowing within the Study Area.

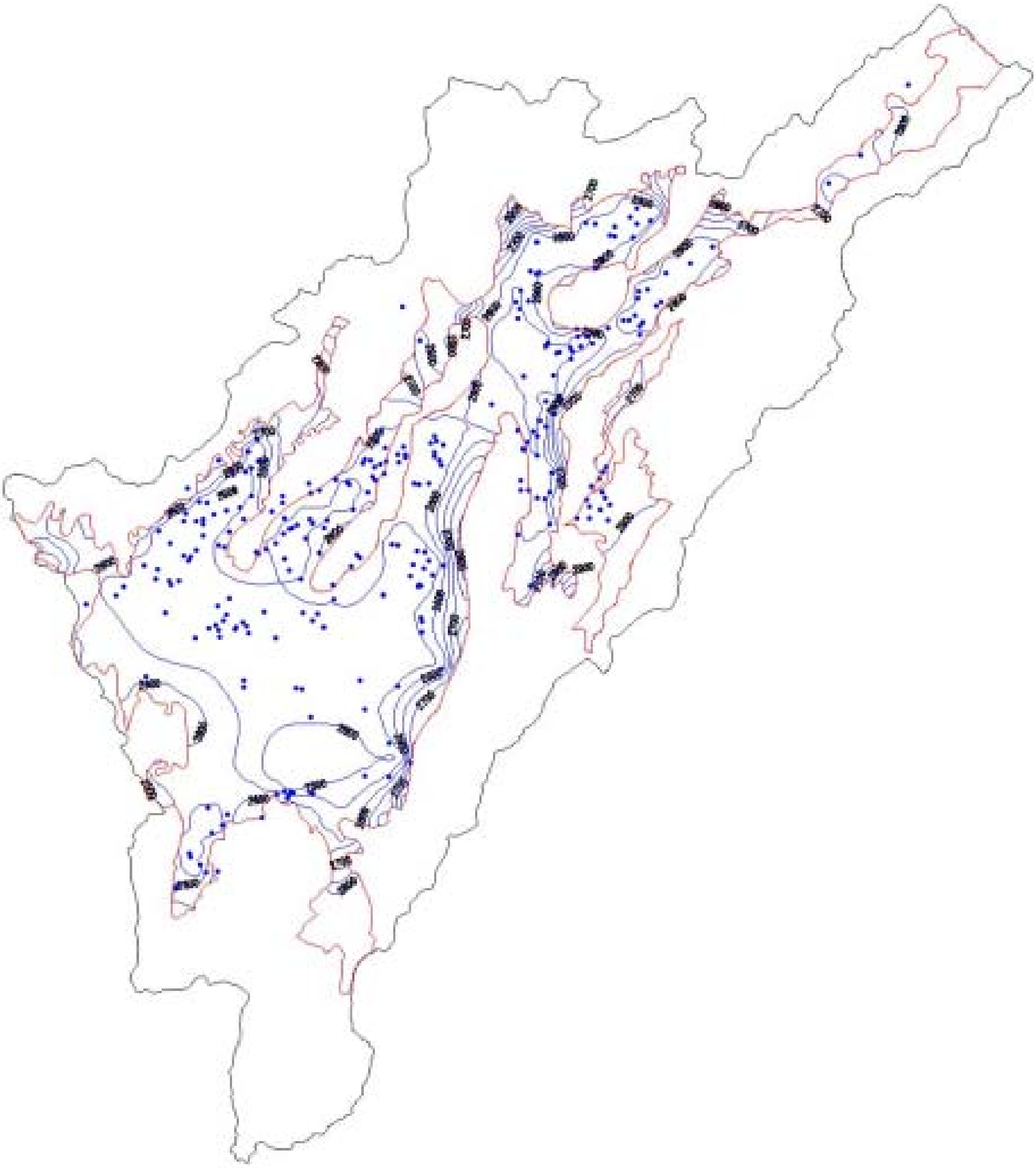

Figure-4.14 Groundwater Level of Quaternary

Groundwater Level of Cretaceous Aquifer

Data of groundwater level of Cretaceous aquifer is 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-4.15. Procedure of making groundwater level contour-line is explained below.

- Average groundwater level for each monitoring well was calculated from monitoring results of CAR and the Study Team. Groundwater level, which has fluctuation speed of more than 6m/year, was neglected.
- Average groundwater level calculated from monitoring result by CAR and JICA Study Team was combined and groundwater level contour line was drawn by interpolation.
- In interpolation of groundwater level, it is assumed that groundwater level of Cretaceous is GL-400m in the border (watershed) of the Study Area.

As shown in Figure-4.15, groundwater of Cretaceous aquifer flows from mountain area bordering the Study Area to the center of Bogotá Plain. Then groundwater flows from NNE to SSW direction following gradient of land slope of Bogotá Plain, and finally flows away from the Study Area.

Groundwater Level of Tertiary

Data of groundwater level of Tertiary aquifer is extremely few, then it is impossible to draw groundwater level contour-line. Groundwater level of Tertiary aquifer should be assumed between those of Quaternary and Cretaceous.

5) 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-4.10 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

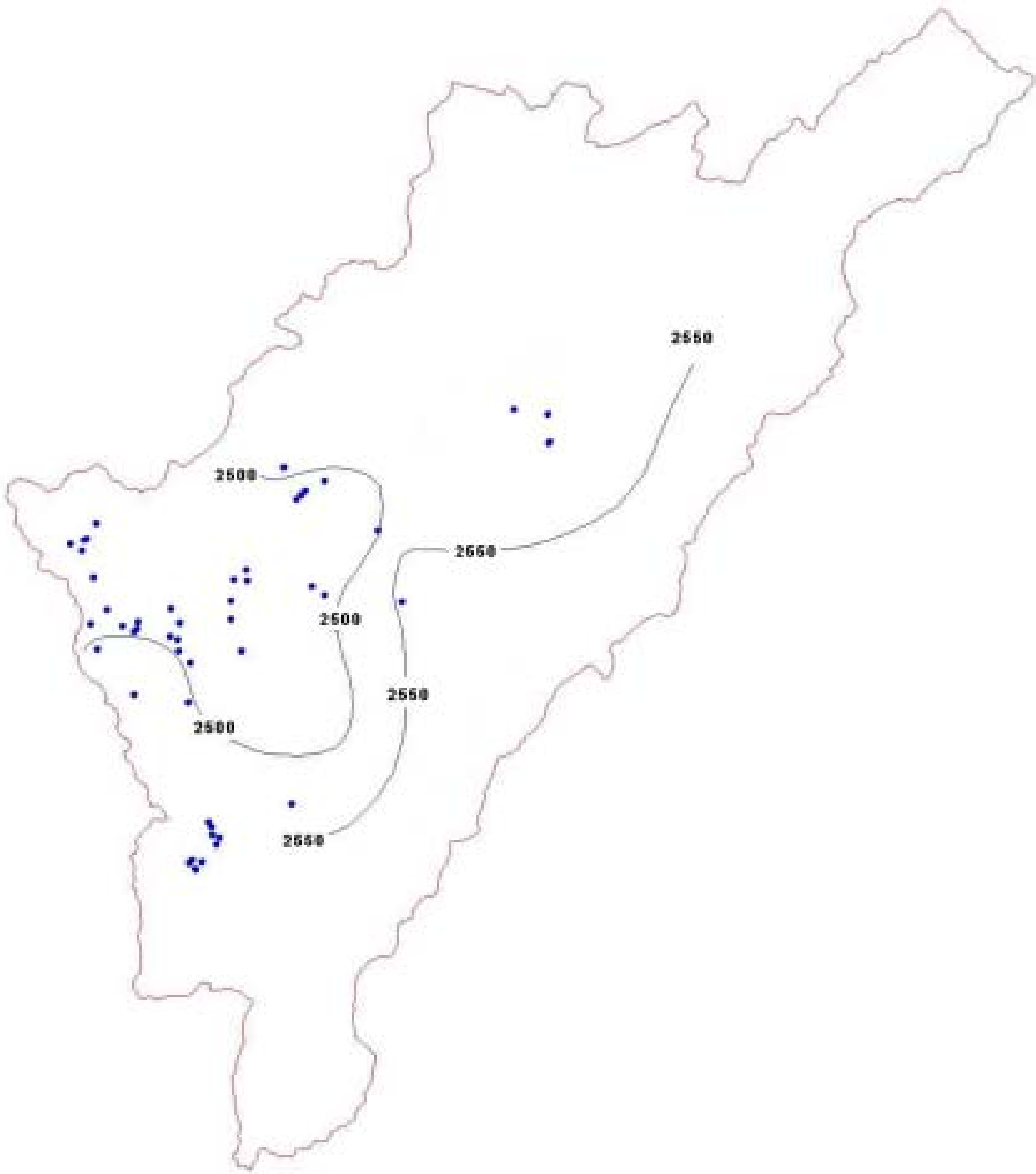

Figure-4.15 Groundwater Level of Cretaceous

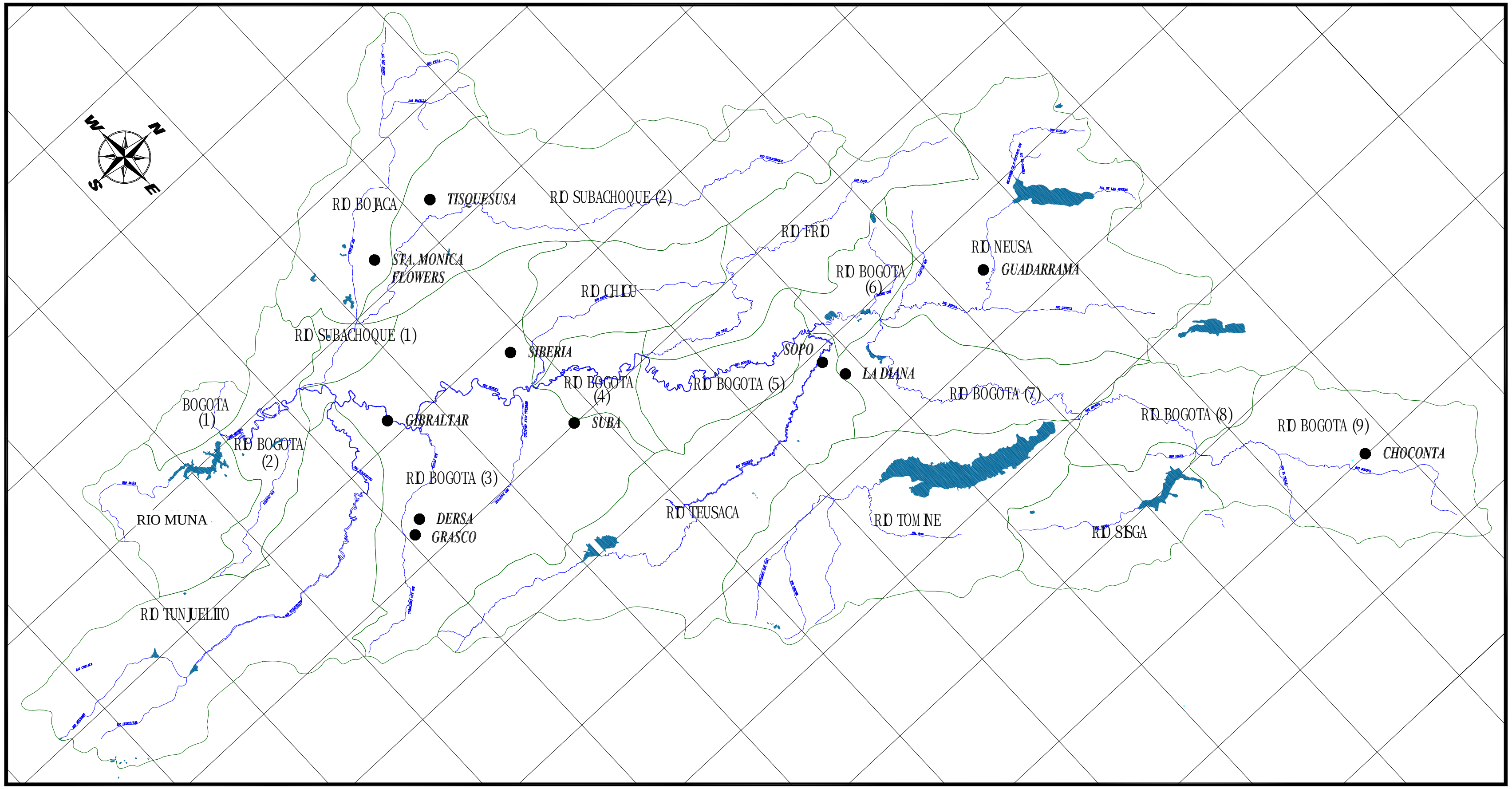

Figure-4.16 Site for Installation of Groundwater Level Recorders

Result of monitoring is shown in Figure-4.17. 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 effect of neighboring pumping wells.
- From observation result, as a whole trend of long-term lowering and rising of groundwater level is not clear. It is considered that lowering of groundwater level of Bogotá Plain by pumping has already reached equilibrium condition.
- Effect of the earth tide was also recorded in every monitoring result with regular vibration of groundwater level of several cm (two cycles per day).
- Groundwater level monitoring should be continued for long period. It is said that groundwater level of Quaternary aquifer is still declining. So far there is no information that proves directly this situation. Hence, groundwater level monitoring by automatic recorder is very important, and this monitoring should be continued after this Study.

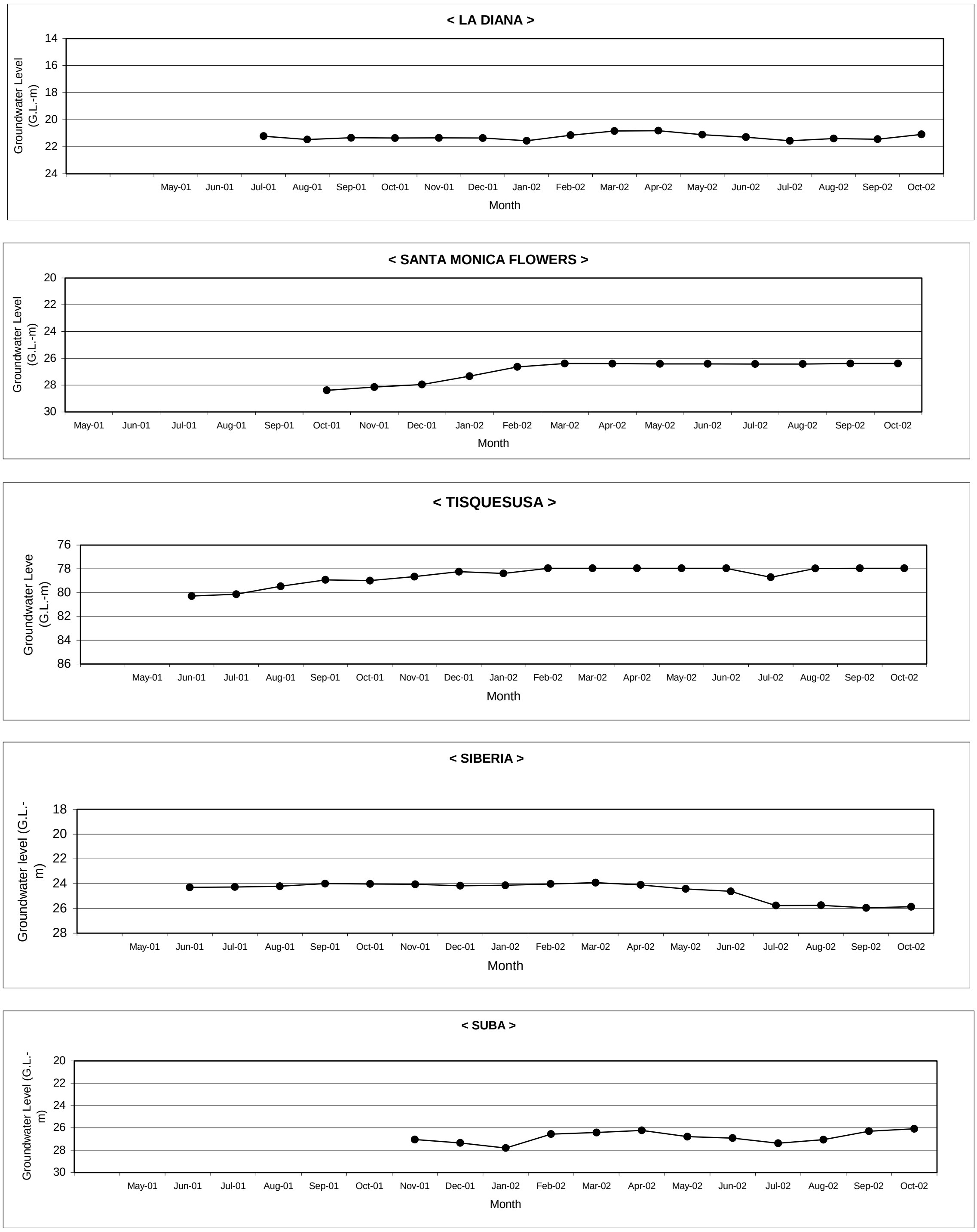

Figure-4.17 The Result of Groundwater Level Monitoring