CHAPTER 3 POTENTIAL FOR WATER RESOURCES DEVELOPMENT

3.1. Surface Water Development Potential

3.1.1. Bogotá River Basin

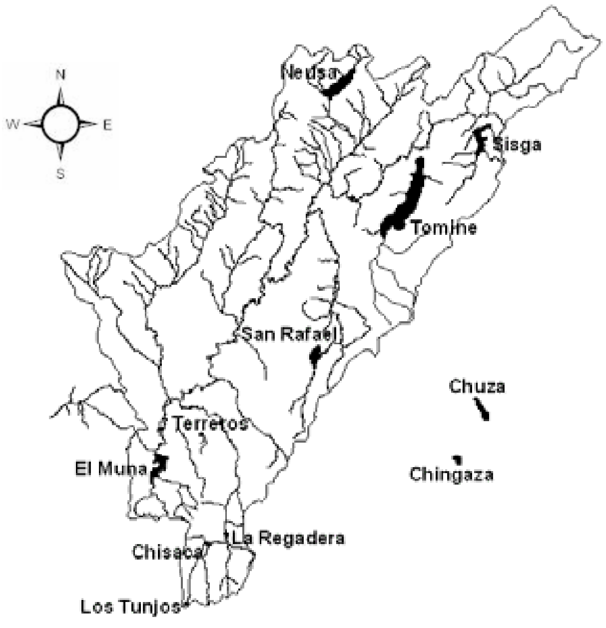
As shown in Table 1.3.20 (in Part 1 Chapter 3), the water demand in year 2000 was already 2.35 x 10^6 m^3/day (27.22 m^3/sec), which is 857.8×10^6 m^3 in annual volume. This is also equivalent to 80% of the total average annual river discharge in the basin of 1,070 x 10^6 m^3. If the residual flow necessary or ecological flow is considered, this used amount has already exceeded the available water resource amount even for years of average flows. According to CAR, the residual flow is defined to be 25% of annual average flow.

(1) Surface Water Development at Present

For the purpose of effective use of water resources, especially the use of high river discharge during high water seasons for dry season, a total of 9 dams and retention ponds were constructed mainly in the upstream (northern part) of Bogotá River Basin. Eight out of these 9 facilities are located within the basin and the remaining Chuza Dam is located outside the basin in the eastern mountain area. The location and size of these dams and retention ponds are shown in Figure-2.3-1.

Dams can only control the volume of discharge in rivers but can not solve the problem of shortage of river discharge to satisfy supply demand. For this reason, a project to convey a large amount of water from Chuza Dam located outside Bogotá River Basin was implemented. Except for the year 1997, when a large scale fall accident occurred inside water conveyance tunnel, the average annual flow over the 12 years from 1988 to 2000 from the dam is 36.89 x 10^9 m^3. This is equivalent to one third of the annual surface water resource generated within Bogotá River Basin under the natural condition. This water conveyance project greatly alleviated the water shortage problem in the basin. Since then, no major water shortage problems have been encountered in the water supply sector except for agricultural water demand.

However, taking into account of the trend of economic and population growth in Bogotá and accompanying rise in quality of life of people are considered, it is expected that new water resources development is necessary after year of 2028. In order to solve this future problem, Acueducto has a plan to introduce more water from outside the basin by expanding the capacity of Chingaza System and the others

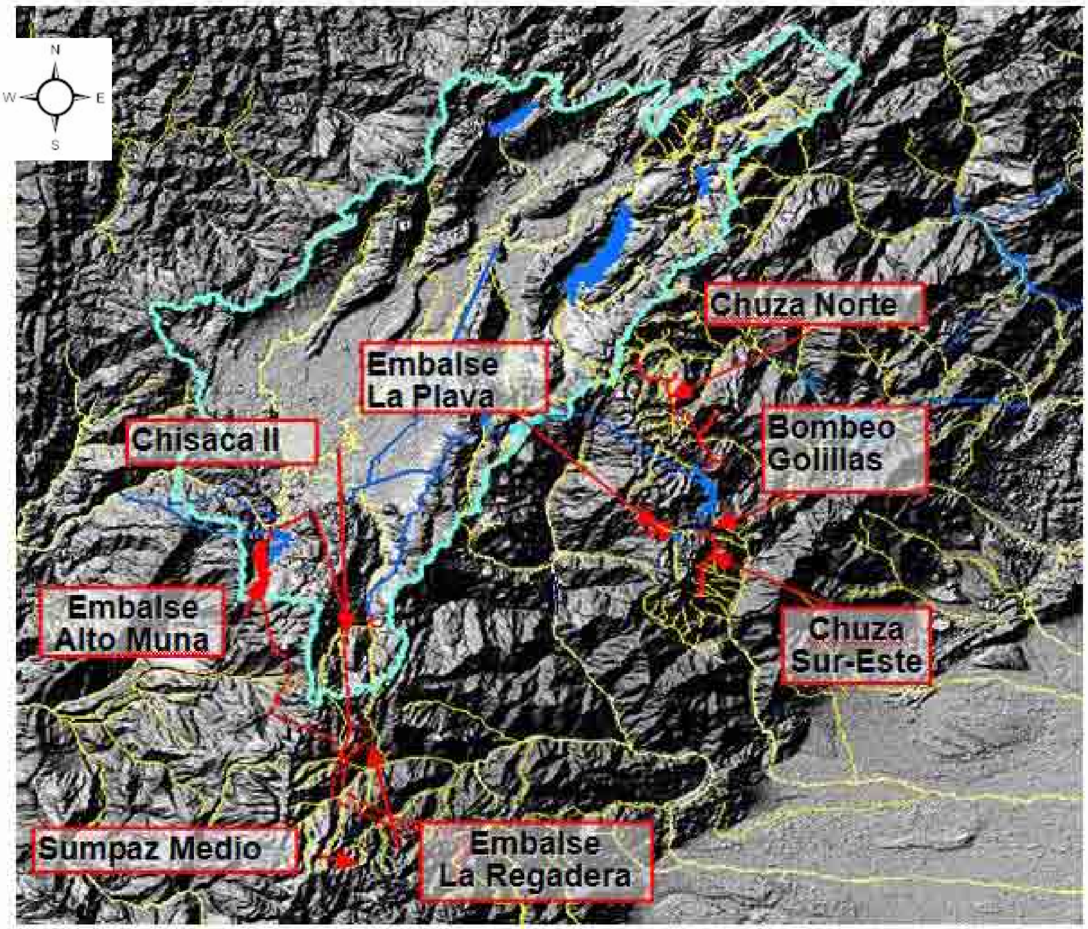


Source: JICA Study Team

Figure-2.3- 1 Location Map of Existing Reservoirs

3.1.2. Other River Basins

According to the water supply expansion plan being discussed in Acueducto, facilities expansion is planned in the Chuza Dam area and also in Sumapaz area, both outside the basin, in order to secure civil water supply. The project names and locations are given in Figure-2.3-2.



Source: JICA Study Team

Figure-2.3- 2 Acueducto Water Supply Expansion Plans and Projects Sites

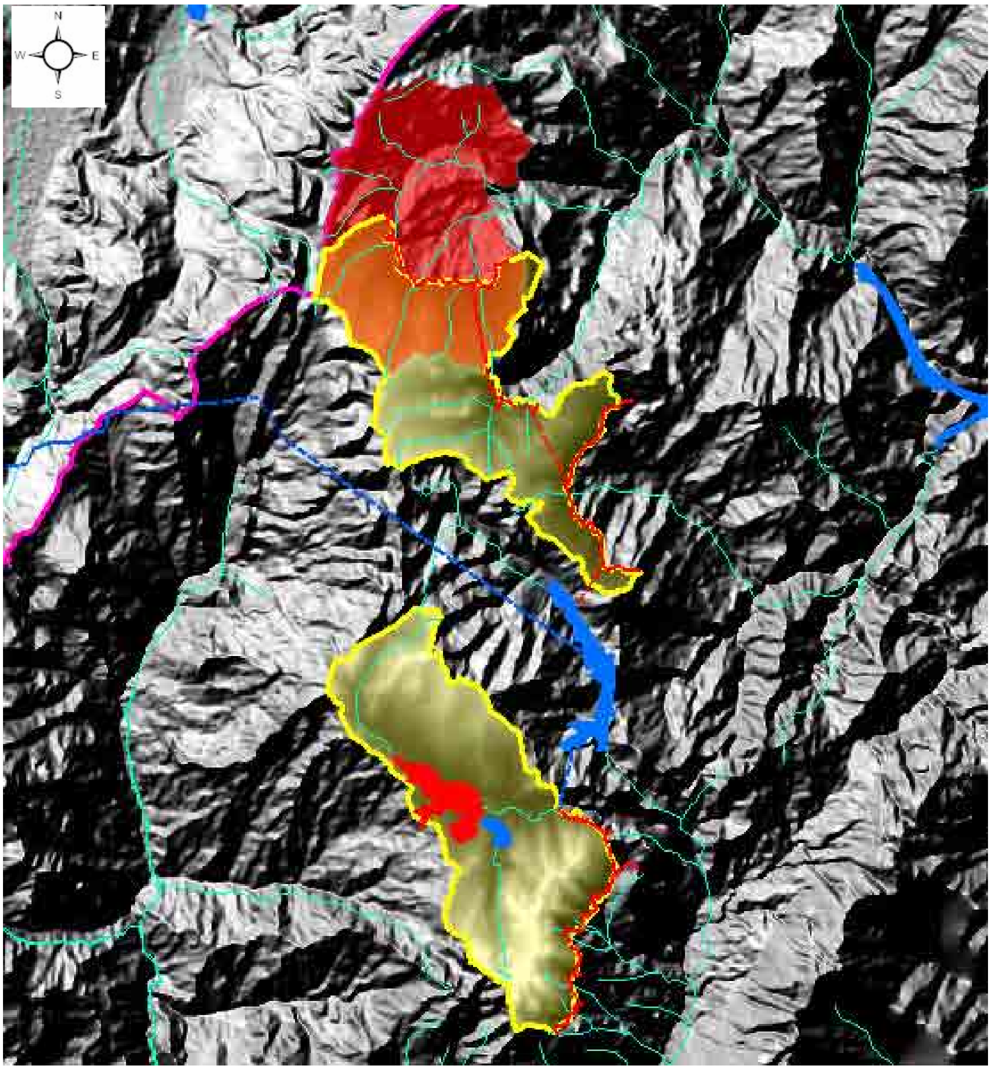
(1) Chingaza Expansion Plan

The catchment area affecting the expansion project in Chingaza lies completely outside Bogotá River Basin. The plan consists of two components of facilities expansion: augmenting the capacity of existing collection facilities in the north of Chuza Dam, and a similar capacity expansion in the south. The catchment areas for the two facilities are shown in Figure-2.3-3.

The average ground elevation in the catchment area is 3,393 m.a.s.l. and the total area is 223 km^2. The river discharge data for the northern part of the planned project site was also collected and examined in the hydrological analysis. The catchment area of this gauging station (as shown in red in Figure-2.3-3) lies within the catchment area of the planned expansion project. Thus the discharge data from this station was used to evaluate the planned expansion project. The code for this gauging station is 3506711 (Sueva-Balcones River) and its data for 28 years from 1971 to 1998 was used to calculate the specific discharge. The value was found to be 38.5 ℓ/sec/km^2. The amount of water to be supplied by this expansion project is, then, calculated as follows:

$$223\,km^2 \times 38.5\,l/\sec/km^2 = 8.5\,m^3/\sec$$

According to the Chingaza Expansion Plan, amount of water to be developed is 6.13 m^3/sec, less than above estimated value, can be realistic in hydrogeological view point.



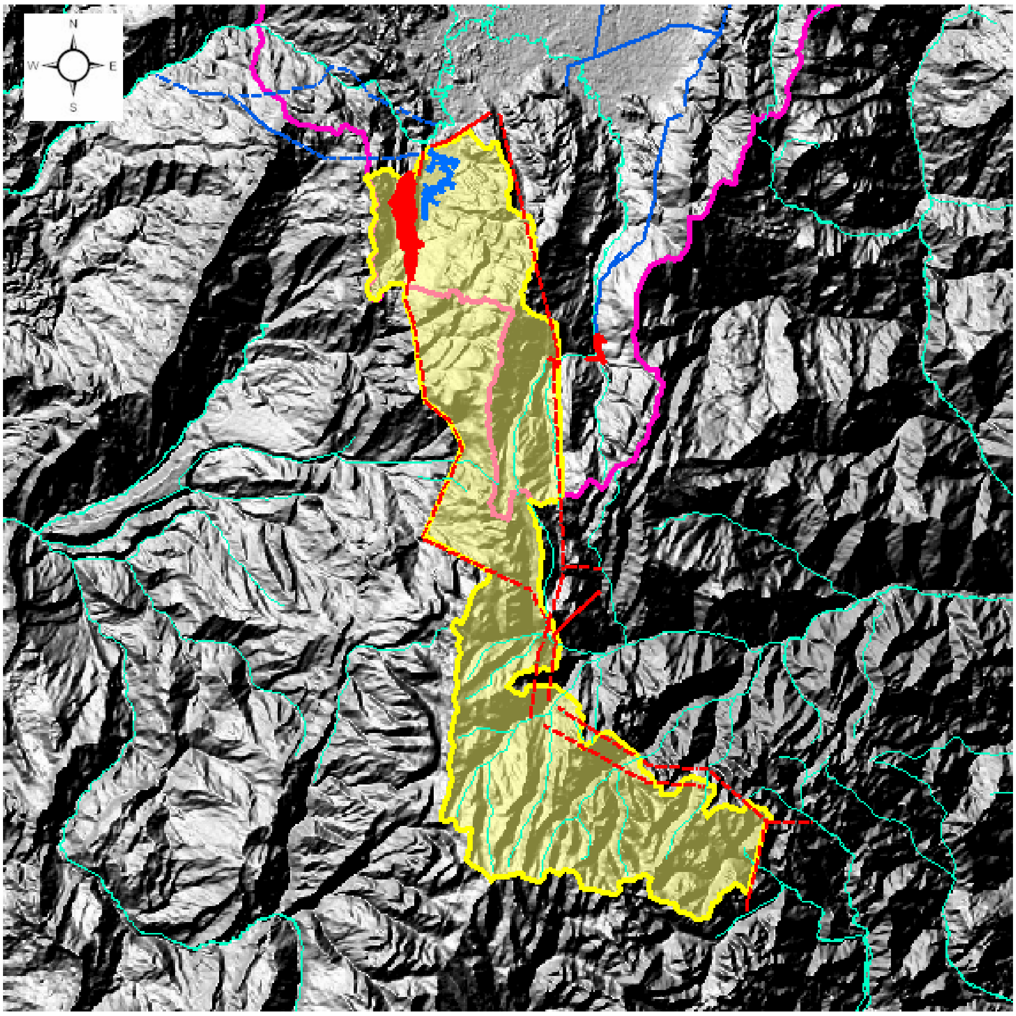
Source: JICA Study Team

Figure-2.3- 3 Catchment Area Affecting the Expansion Project in the East and Catchment for the Gauging Station

(2) Development Plan in Sumapaz

Water resources development plan in Sumapaz area aims to augment water supply capacity by effective utilization of the surface water in Sumapaz area by construction of a dam and related water channels.

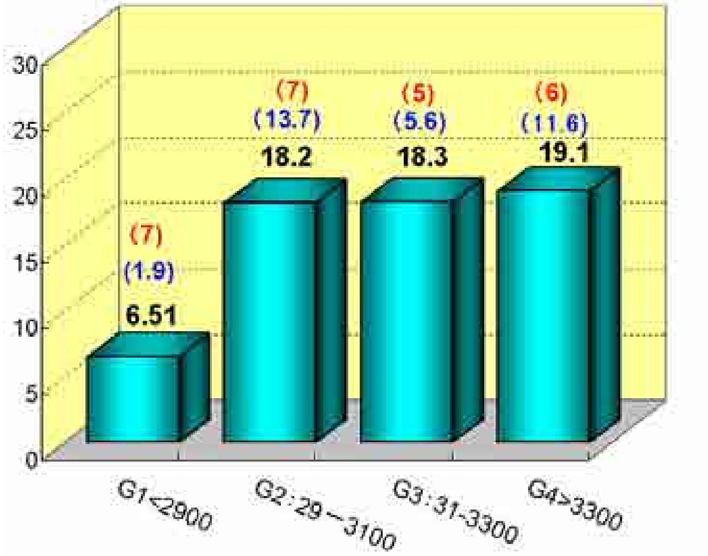
The catchment area affecting this project is shown inFigure-2.3-4. It is located to the south of Bogotá River Basin and most of the catchment areas lie outside the basin with only a small northern portion within the basin. The average ground elevation in the catchment area is 3,434 m.a.s.l and the total area is 678 km^2. It is a general hydrological fact in Sumapaz area that the higher the altitude, the higher the precipitation. This relation is also applicable in Bogotá River Basin as already discussed.



Source: JICA Study Team

Figure-2.3- 4 Catchment Area Affecting the Expansion Project in the South

Based on the various data collected in this JICA study, the relation between specific discharge and altitude was analyzed and is illustrated in Figure-2.3-5.



Note: The figures in black are the average specific discharge for each elevation category in ℓ/sec/km^2, the figure in blue is the standard deviation, the red number of samples

Source: JICA Study Team

Figure-2.3- 5 Relation between Specific Discharge and Altitude

The Development Plan in Sumapaz was evaluated using the relation above. The amount of water that can be collected for implementation of the project can be estimated by multiplying the catchment area by the specific discharge value as follows.

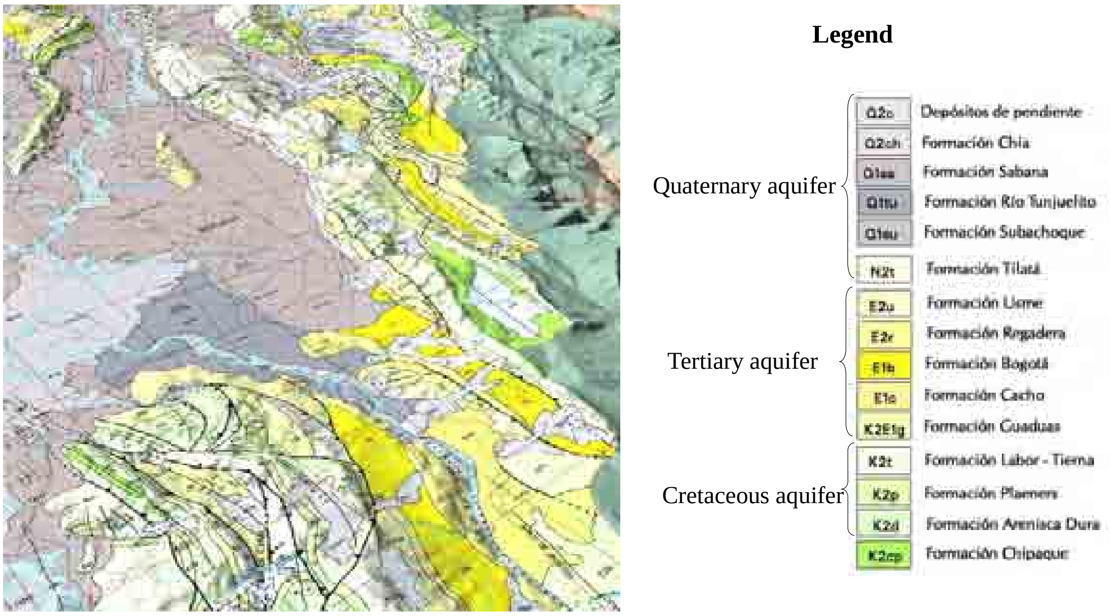
$$678\,km^2\ (Area)\times 19.1\,l/\sec/km^2\ (Specific\ discharge) = 12.95\,m^3\ /\ s$$

3.2. Groundwater

3.2.1. Distribution of Aquifer

As the topographical features in the Study Area reflect geology well, so the distribution of aquifer reflects topographical features inseparably. As for the distribution area of Cretaceous Aquifer, it forms steep mountains generally. As for the distribution area of Tertiary Aquifer, it forms gentle slope of piedmont. As for the distribution area of Quaternary Aquifer, it forms low-lying plain (Figure-2.3-6).

The Tertiary Aquifer is distributed beneath the overlying Quaternary Aquifer, and the Cretaceous Aquifer is further distributed beneath the Tertiary Aquifer continuously, of which relation is observed from the mountain area.



Source: INGEOMINAS arranged by JICA Study Team

Figure-2.3- 6 Relationship of Topography and Aquifer distribution

<u>Groundwater in the rock (fissured media)</u>

From field observation on the slope of large excavation/the tunnel/the mine, groundwater flowing in the rock mass is characterized experientially as explained bellow. These facts provide the useful suggestion on condition of local groundwater storage in rock mass, though regional groundwater flow may be sometimes different form local flow.

i) Groundwater is flowing along the crack in the rock mass (spring from crack).

ii) Some cracks provide much water and others do not provide water, though they are observed in the same fracture plane and the same height.

iii) There may be a gap in the groundwater level in both side of a fault, depending on permeability of the fault, whether it is sealing a flow or control a flowing direction).

iv) Fracture zone along a fault may main route for groundwater flow.

v) Groundwater can flow much though open crack (open crack = tension crack in the broad sense, created under tension stress).

Considering such characteristics of the groundwater in the rock mass in the Study Area, the type of strata and the geological structure, with good capacity of saving groundwater, is assumed as follows.

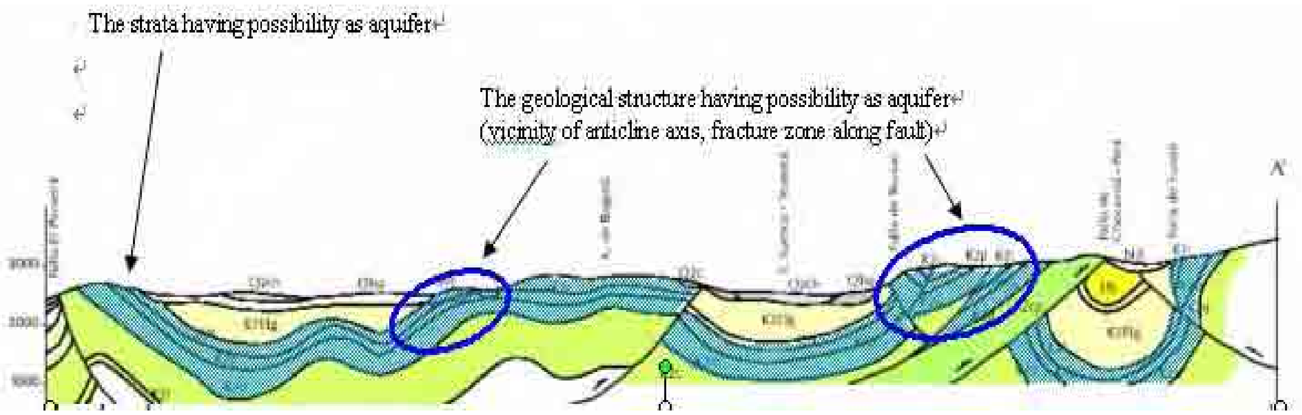
The strata having good condition for storing groundwater

A stratum, which is rich in the crack, will become a capable aquifer, because groundwater is stored in cracks. The Cretaceous rocks consisting of the sandstone, the mudstone, the claystone, and so on is distributed widely in the Study Area. Anticlines and synclines having axis of NNE-SSW or NE-SW direction are running repeatedly in the Study Area. Many cracks will develop more easily in the sandstone than in the other rocks when they suffer a structure movement, because the sandstone is more hard and brittle than the mudstone, the claystone, and so on.

From such a viewpoint, Arenisca Dura Formation and Labor-Tierna Formation may become capable aquifer in the Study Area because they consist mostly of sandstone.

The geological structure having good condition for storing groundwater

Generally, geotectonic position, where many cracks in the rock mass will develop, is fracture zone along a fault. Moreover, open crack often develops in the vicinity of anticline axis, and it can be expected as excellent aquifer. Geological condition mentioned above is desirable for existence of aquifer. However, the catchment basin that can supply enough water to aquifer is also necessary for occurrence of the groundwater. Because the catchment basin of the groundwater (= groundwater basin) is controlled by the hydrogeological structure, area of groundwater basin is sometimes different from area of river basin. But, it often happens that a river basin is same as a groundwater basin in the mountain district which consists of rock mass.



Source: INGEOMINAS

Figure-2.3- 7 Hydrogeological Structure of the Study Area

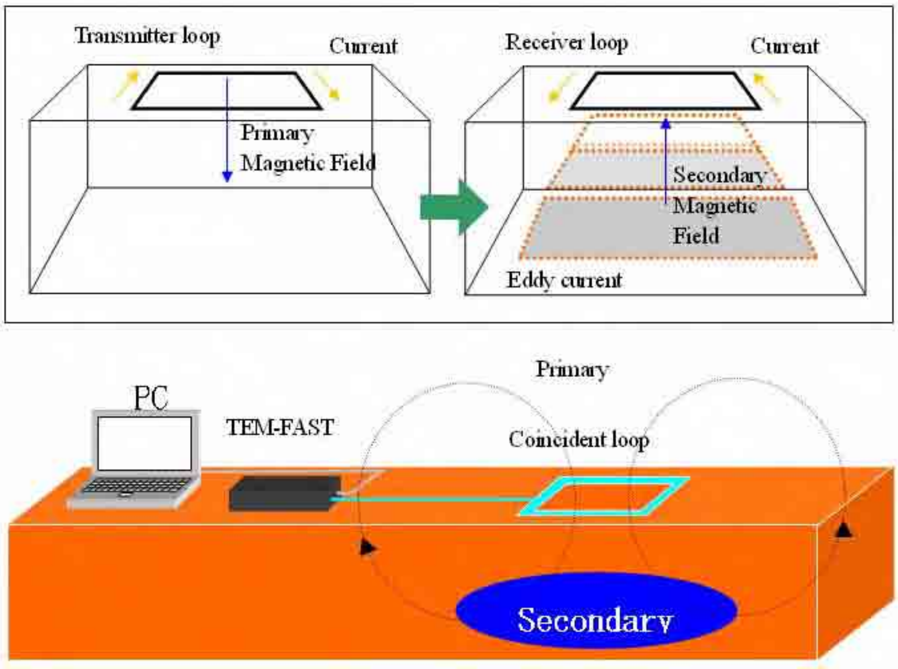
3.2.2. Geophysical Survey

(1) Field Method of Geophysical Survey

(a) Theory

TEM method was applied for geophysical survey in this Study. TEM is one of Electromagnetic (EM) geophysical techniques which induce electrical currents in the earth using electromagnetic induction. A time varying magnetic field is created using a coil or loop of wire on the earth surface. According to Faraday's law of induction, a changing magnetic field will produce an electric field, which in turn will create an electric current. Thus, the primary magnetic field from the transmitter loop will create a secondary electric current in the earth. Finally, we measure the secondary magnetic field produced by those secondary electric currents in the earth.

This method is often referred to as transient electromagnetic exploration (TEM) or time-domain electromagnetic (TDEM) exploration. This method will be referred as TEM in this report.



Source: Rowland B. French, Ph.D, R.G.: Time-Domain Electromagnetic exploration

Figure-2.3- 8 Time Domain Electromagnetic Exploration

(2) Advantage of TEM

The TEM technique has several advantages over the more traditional direct electric-current (DC) resistivity technique and other electromagnetic techniques. TEM does not require earthed electrode, long transmitting dipole, large electrode arrays, big generator, and transmitter. DC resistivity requires long electrode spreading, which is typically three to five times as long as the depth of exploration.

Thus, the investigation to depths of 300 m requires a lateral extent of more than 900 m. In contrast, TEM techniques can obtain exploration depths of several hundred meters with a 200 m transmitter loop.

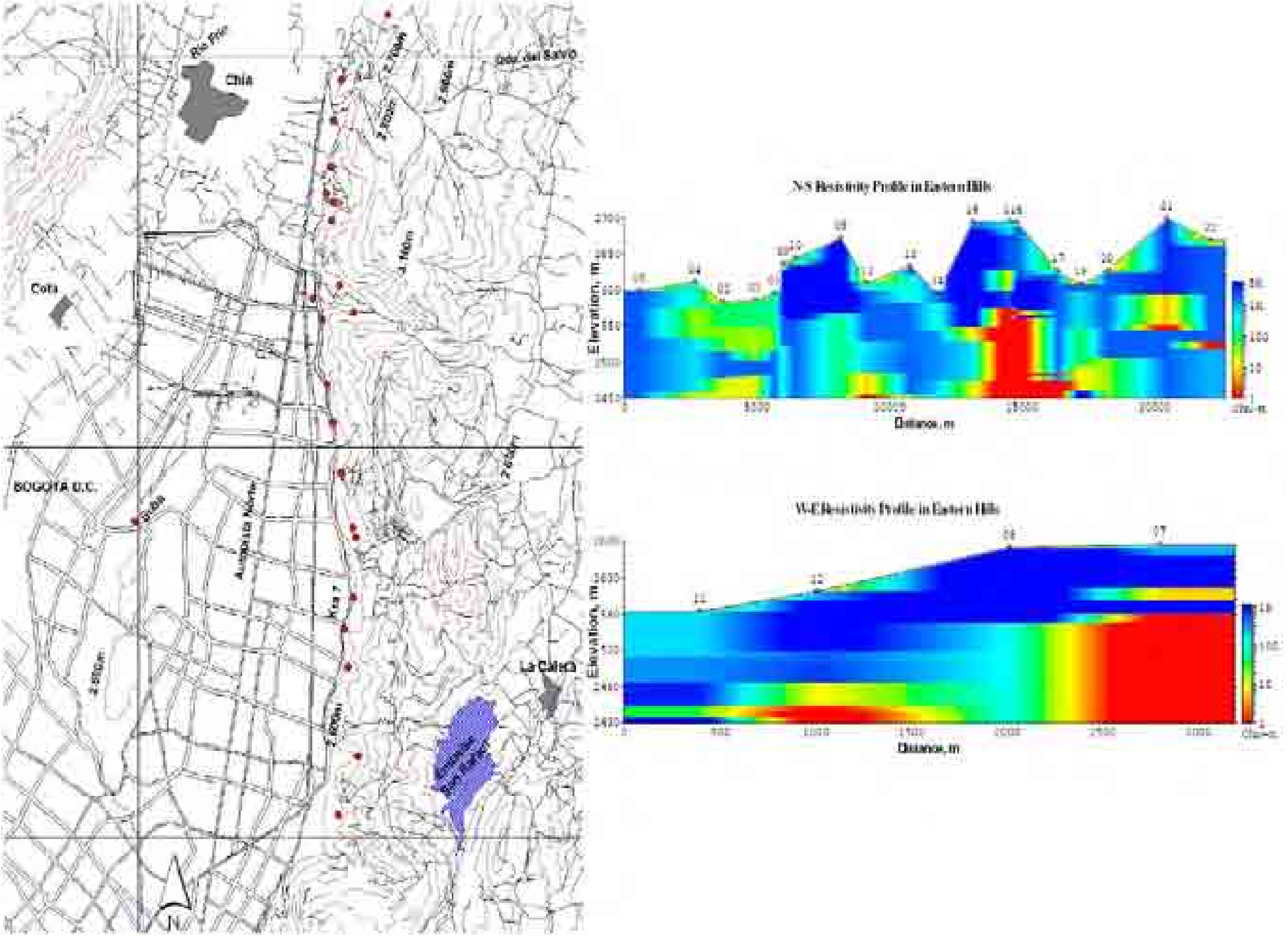
(3) Field Survey

TEM survey was carried out in three areas, Southern Hills, north of Eastern Hills and south of Eastern Hills. TEM survey points are shown in Figure-2.3-9. TEM survey points were arranged carefully because signal of TEM survey was affected by power line, metallic material, generator, vehicles, pipe line, cell phone and wireless devices. An instrument, which is used for this survey with the name of "TEM-FAST", uses a "coincident loop". It means that a same square loop is used for both a receiver loop and a transmitter loop. Three size of a coincident loop such as 25 m, 50 m and 200 m were used in this survey.

(4) Results of Survey

(a) North of Eastern Hills

TEM survey was conducted at 22 points in the Eastern Hills. Luxurious mansions and quarry sites are spotted in the western slope of Eastern Hills. TEM survey was carried out in pasture lands or quarry sites. Most of points in Eastern Hills have been interpreted as two resistivity layer model, which consists of high-resistive first layer and low-resistive second layer.



Source: JICA Study Team

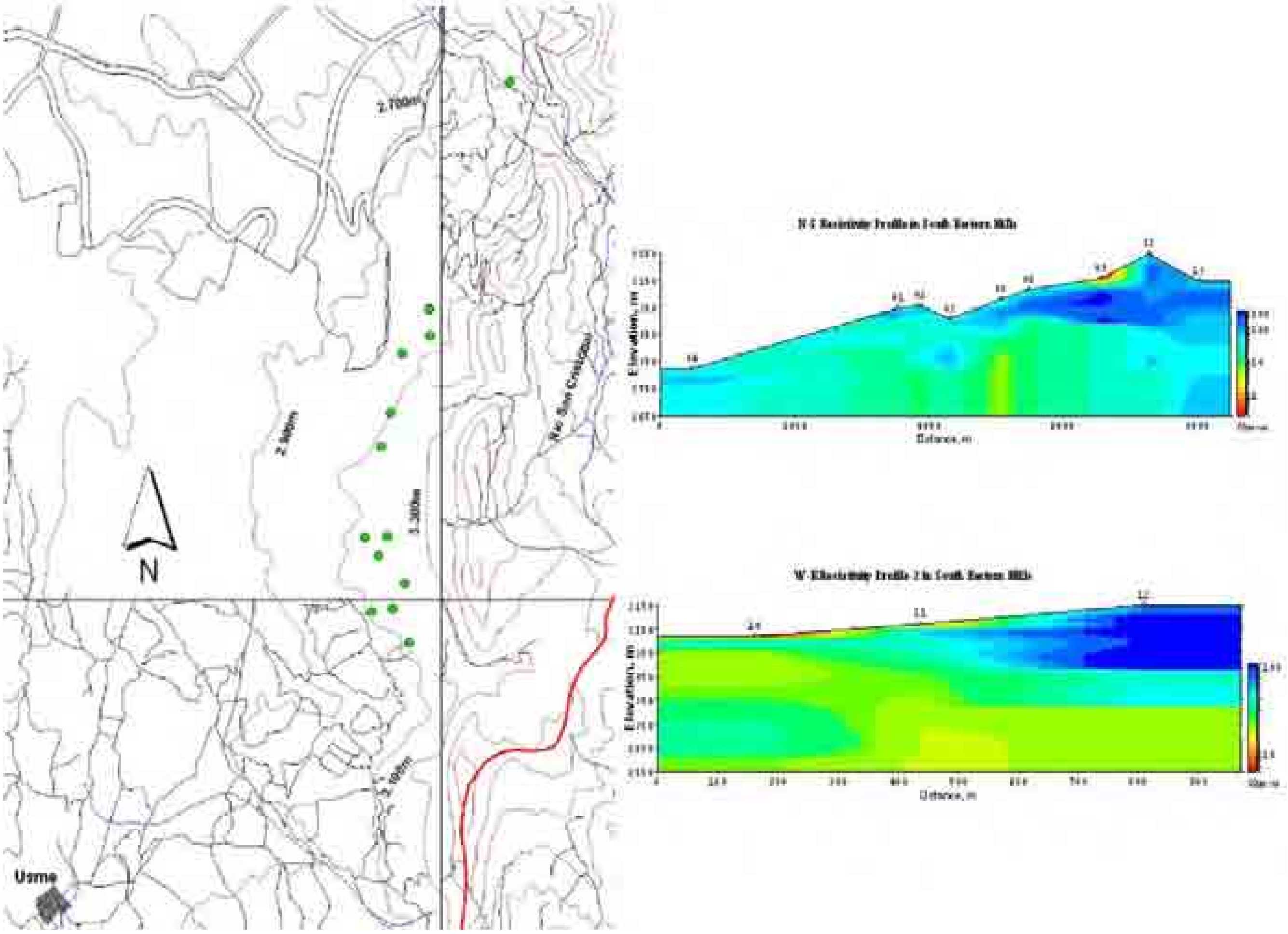
Figure-2.3- 9 TEM Survey Points and Analyzed Results in Eastern Hills

(b) South of Eastern Hills

TEM survey was conducted at 13 points in the h of Eastern Hills. TEM survey was mainly carried out in bush area in the foot of the Eastern Hills. Most of points in south of Eastern Hills have been interpreted as two resistivity layer model, which consists of high-resistive first layer and low-resistive second layer. Generally, the first layer of the observation points, located at higher altitude of the hills, shows higher resistivity and greater thickness. On the other hand, first layer of the observation points, located at lower altitude of the hills, do not show high resistivity, which is contrast to those at higher altitude.

(c) Southern Hills

TEM survey was conducted at 29 points in Southern Hills. Land use of the Southern Hills is roughly classified for two parts. Northern slope of Southern Hills is occupied by settlements, and most of high lands in the south of the settlement are used for pastures. TEM survey was carried out in pasture area. Most of observation points in Southern Hills have been interpreted as two resistivity layer model, which consists of high-resistive first layer and low- resistive second layer. The first layer has extremely high resistivity more than thousands Ωm and its thickness is more than 100 m. The second layer has low resistivity less than 10 Ωm.



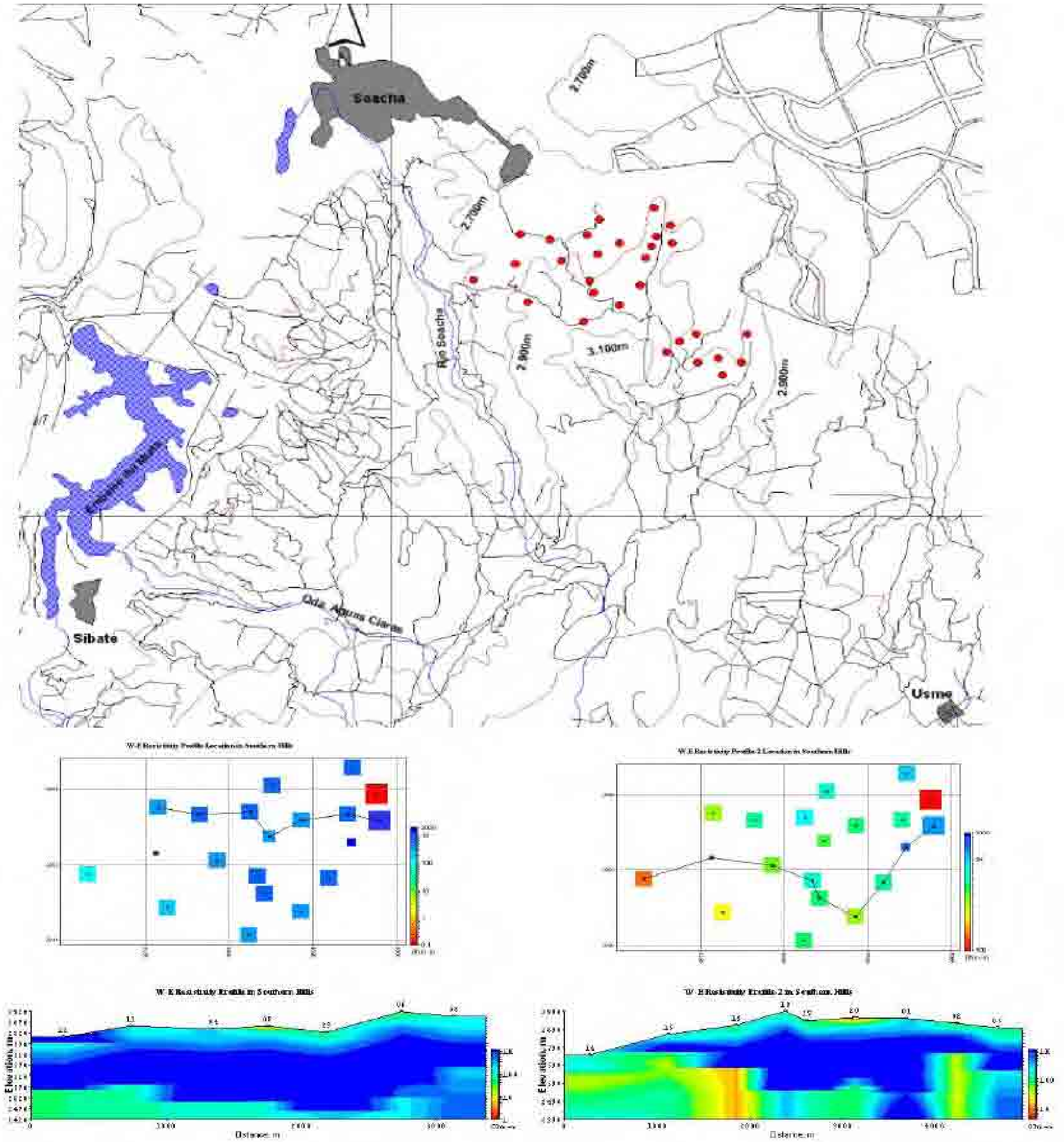
Source: JICA Study Team

Figure-2.3- 10 TEM Survey Points and Analyzed Results in South of Eastern Hills (near Usme)

(5) Interpretation

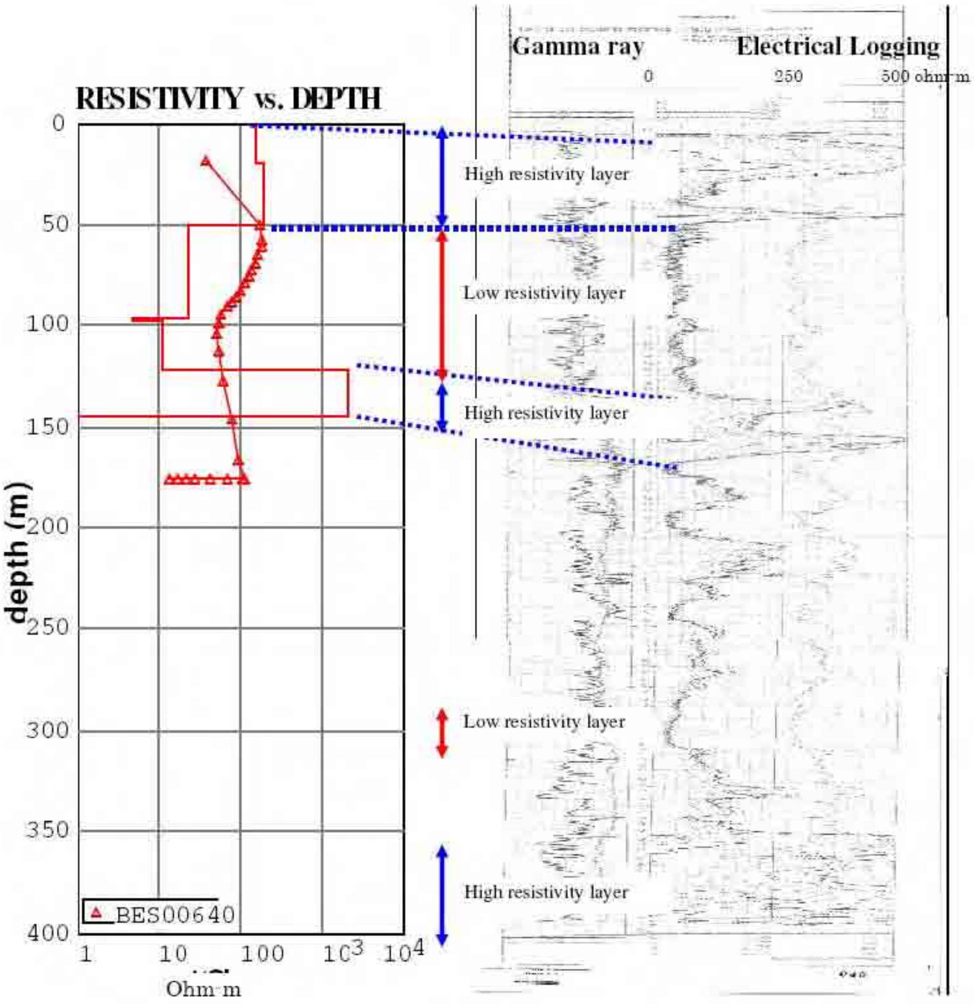
(a) Comparison TEM with Well Log Data

TEM survey was carried out in site of the existing exploratory well in Suba, which was drilled in the previous JICA Study. TEM result was referred to electric logging data for calibration. In Figure 2-3.12, 1D model analyzed as a result of TEM survey, at point No. 6 near exploratory well in Suba, is shown.



Source: JICA Study Team

Figure-2.3- 11 TEM Survey Points and Analyzed Results in Southern Hills



Source: JICA Study Team

Figure-2.3- 12 TEM Result at No. 6

High resistivity zones correspond to the main aquifer of the Study Area, where Cretaceous Guadalupe Group sandstone layer dominates, which is expressed on the right-hand side of the electric well logging chart shown in Figure-2.3-12. Moreover, low resistivity zones correspond to impermeable confining layer of the Study Area, where Guadalupe Group clay formation dominates.

The resistivity structure in the depth of more than 150 m was not acquired by the TEM method in this site. This is caused by electric noises from the high-voltage-power line which surrounds the TEM survey point near the existing well. As far as the resistivity structure down to the depth of 150 m is concerned, the result of TEM survey shows good coincidence with the results of electrical logging of the well.

In the Study area, the sandstone layers of Guadalupe Group would be identified as high resistivity aquifer. On the other hand, the clay formations of Guadalupe Group would be identified as low resistivity confining layers.

(6) Interpretation of Aquifer Distribution

The Eastern and Southern Hills were classified, based on TEM survey, in hydrogeological view points. Criteria for classification are as follows:

- Stratum with electric receptivity more than 100Ωm → It is sandstone, with possibility of aquifer
- Stratum with electric resistibility less than 100 100Ωm → It is shale, with possibility of aquiclude

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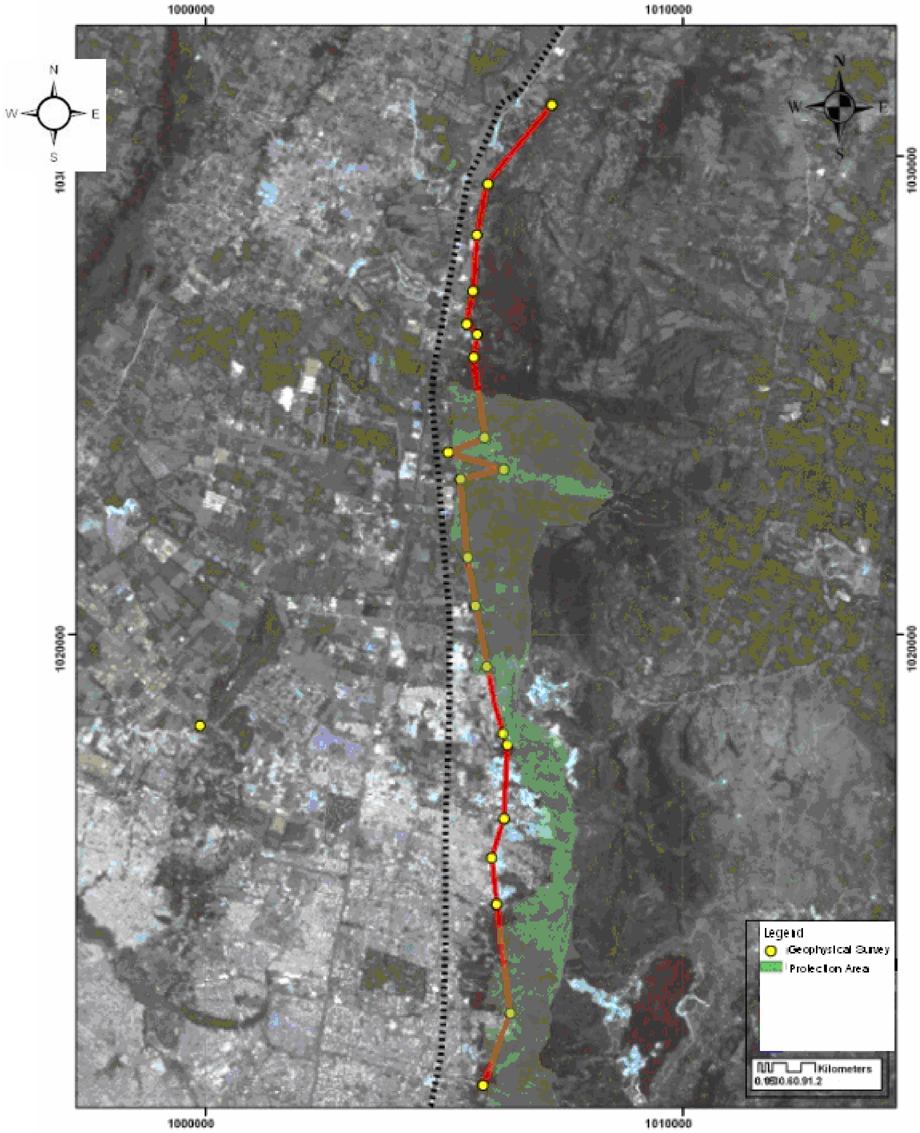
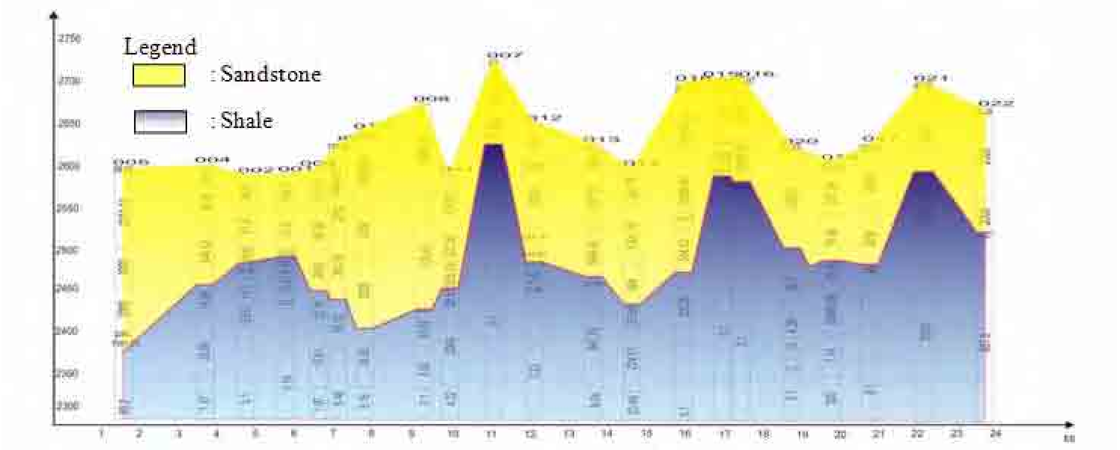
Sandstone and shale makes complicated alternation in the Study Area. In interpretation of TEM result, strata of the Eastern and Southern hills were simplified and classified into only two strata, i) sandstone dominant stratum and ii) shale dominant stratum. The result of these interpretations is shown in Figure-2.3-13, Figure-2.3-14, Figure-2.3-15 and Figure-2.3-16.



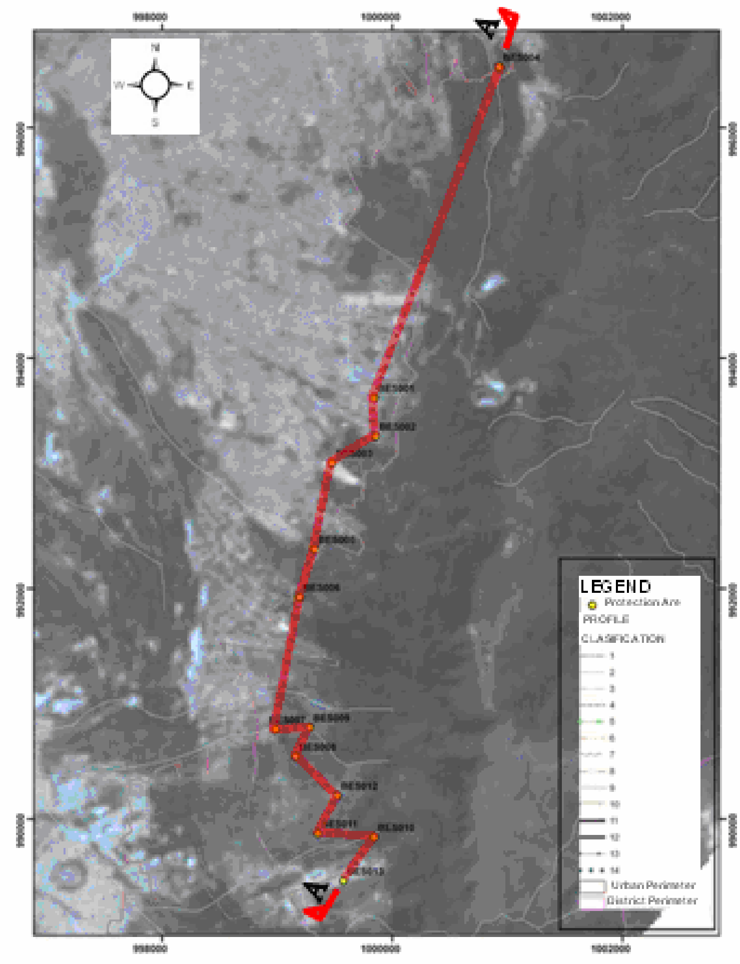
(a) Location Map of Geophysical Exploration (Eastern Hill)



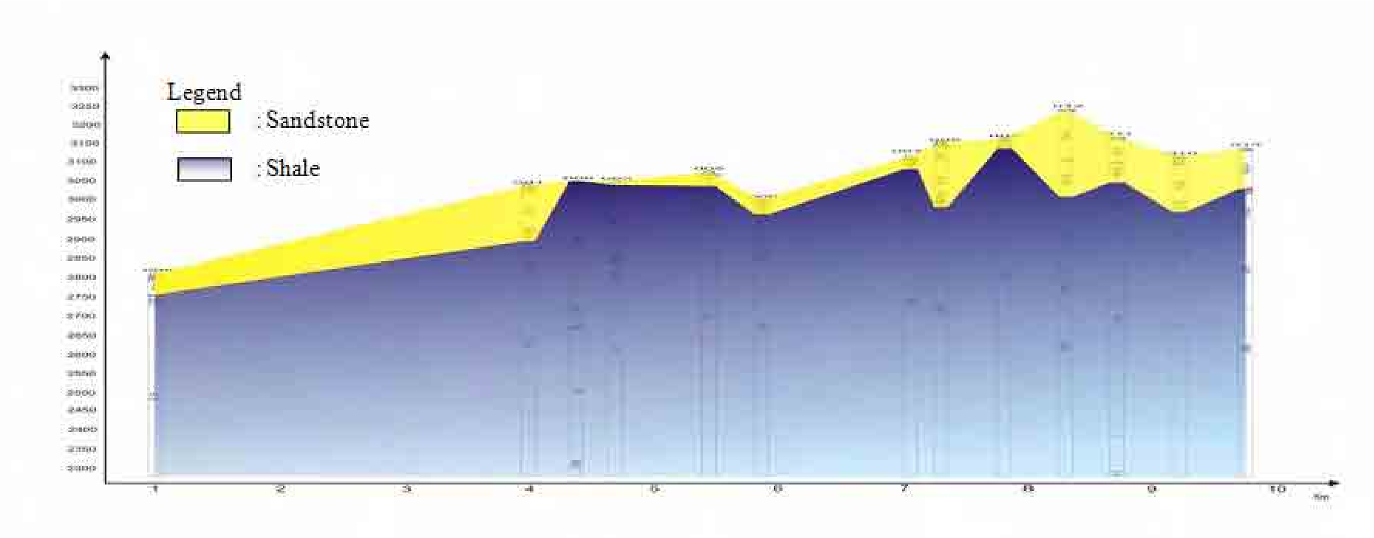
Source: JICA Study Team

(b) Interpreted Geological Section

Figure-2.3- 13 Interpretation of TEM Result (Eastern Hills)



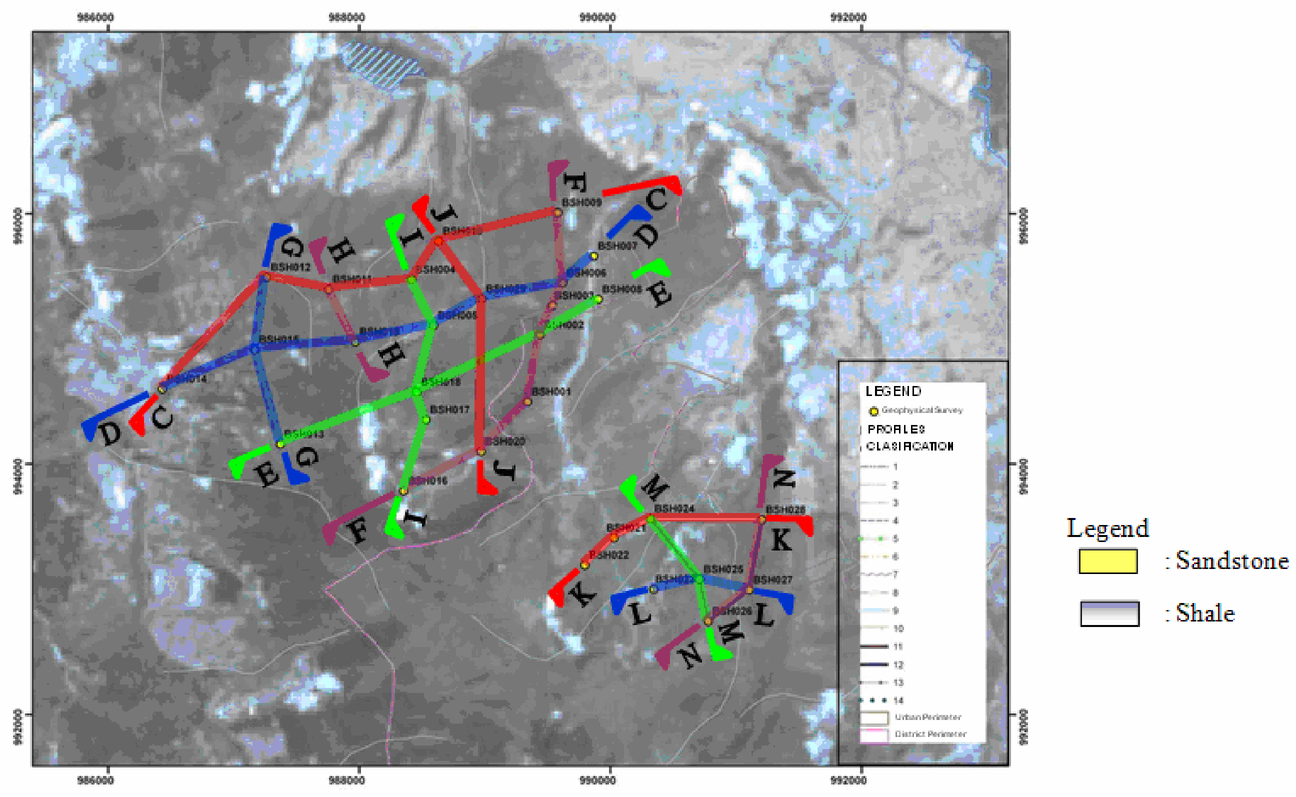
(a) Location Map of Geophysical Exploration (Usme Area)



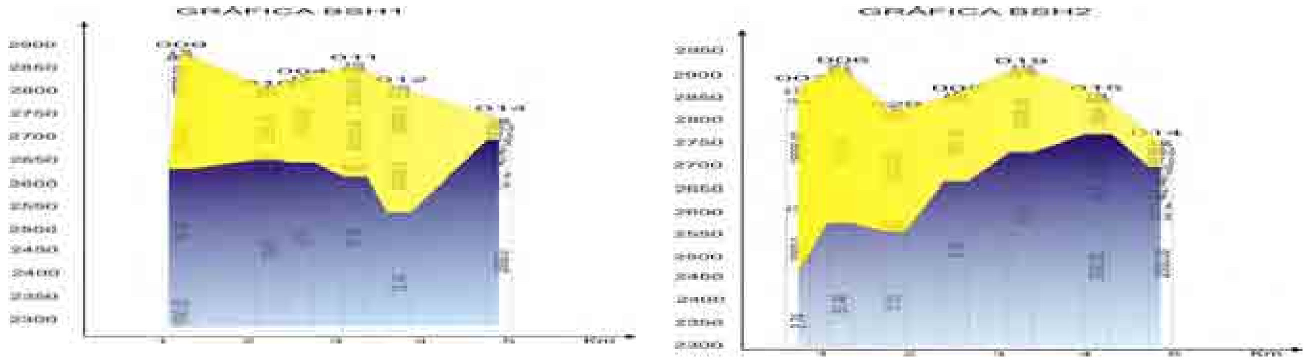
(b) Interpreted Geological Section

Source: JICA Study Team

Figure-2.3- 14 Interpretation of TEM Result (Usme area)



(a) Location Map of Geophysical Exploration (Southern Hills)



Section C-C

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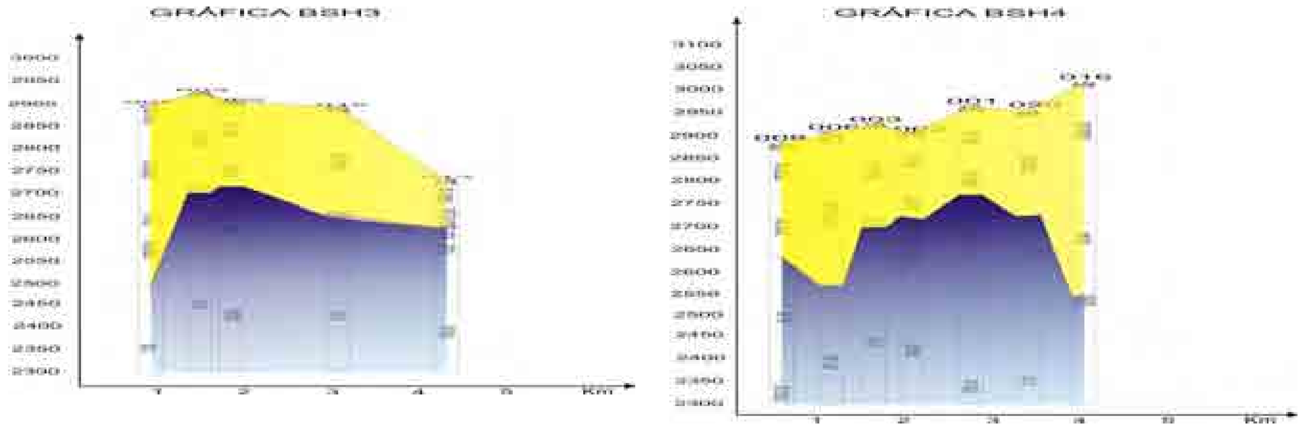


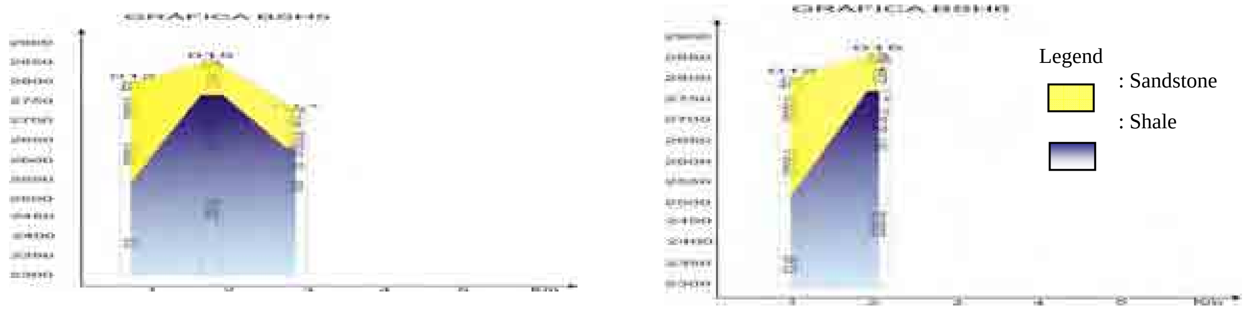
Section E-E

Section F-F

(b) Interpreted Geological Section

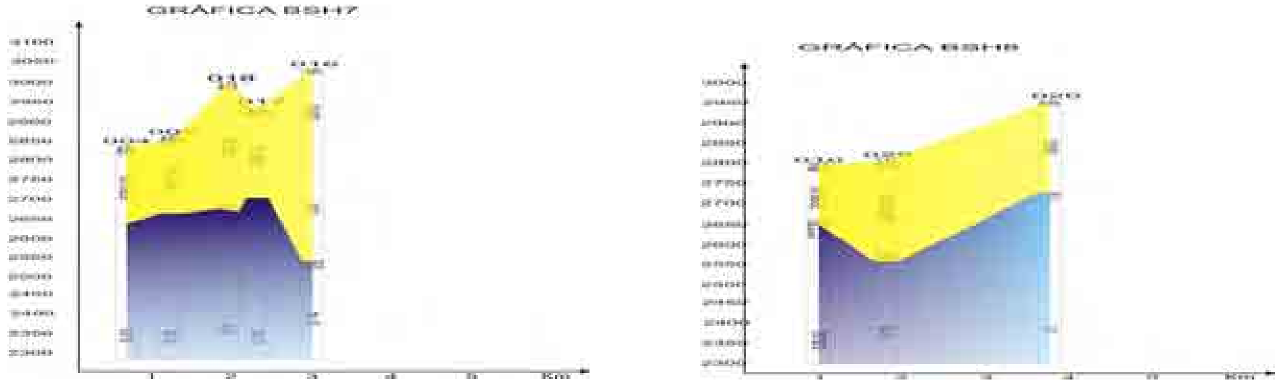
Source: JICA Study Team

Figure-2.3- 15 Interpretation of TEM Result (Southern hills) (1)



Section G-G

Section H-H



Section I-I

Section J-J

Section K-K

Section L-L

Section M-M

Section N-N

(c) Interpreted Geological Section

Source: JICA Study Team

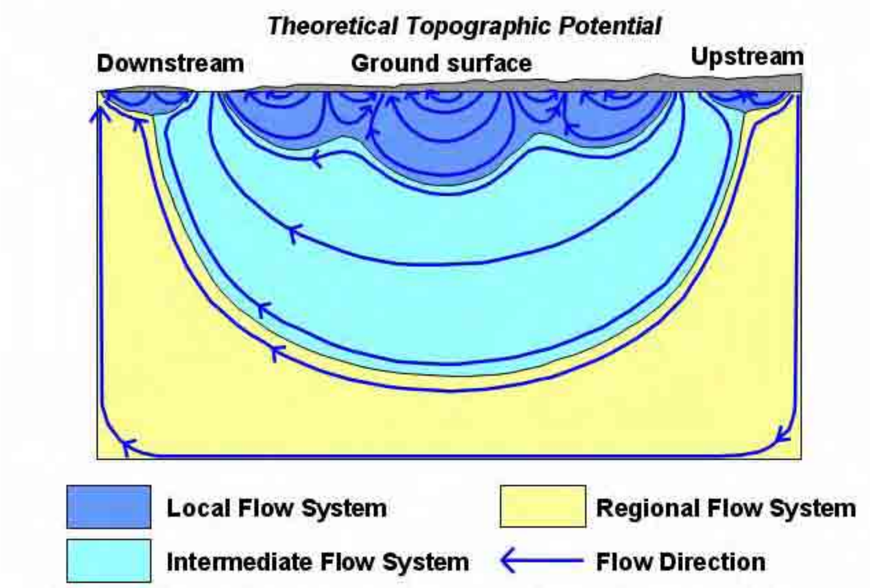
Figure-2.3-15 Interpretation of TEM Result (Southern hills)(2)

3.2.3. Groundwater Development Potential

(1) Groundwater Flow System

Since there is a discussion that Bogotá River Basin is receiving no groundwater recharge, it is necessary to clarify the basic concept of groundwater flow system before we start discussing groundwater recharge and storage amount. It is a common knowledge that water flows from a higher elevation to a lower elevation or from a point of higher head/potential to a point of lower head/potential.

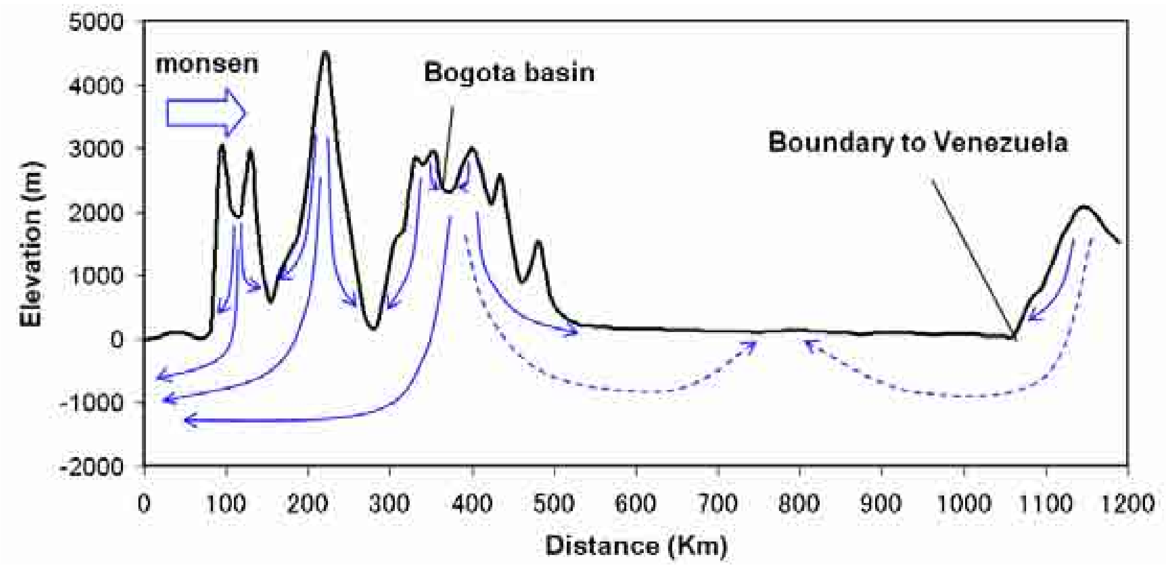
Figure-2.3-16 is a schematic image of a typical groundwater flow system that appears in many groundwater text books. In this figure, the groundwater flow components in a region (a large area covering several basins) are divided into three major systems: regional flow, intermediate flow, and local flow.



Source: Toth, 1963

Figure-2.3- 16 Basic Concept of Groundwater Flow System

Figure-2.3-17 shows a cross-section from the Pacific Ocean in the west to Venezuela in the east, crossing through Bogotá River Basin. When compared with the illustration of generalized groundwater flow systems in Figure-2.3-16, a "local flow system" is recognized to exist in Bogotá River Basin as flow components moving down from the mountain areas towards the plain in the basin, The "intermediate flow system" is recognized as flow components moving from the Andes to adjacent rivers to the west and to the huge plain to the east. Then the "regional flow system" is made up of those moving towards the Pacific from Bogotá River Basin. As long as the groundwater table elevation at Bogotá River Basin is higher than those of the surrounding area, this flow system is sustained. This, in return, indicates that the groundwater levels would keep on falling, if there were no recharge to groundwater in Bogotá River Basin. It is now clear that the issue is not about existence of groundwater recharge any more, but rather about how large the amount of recharge is.

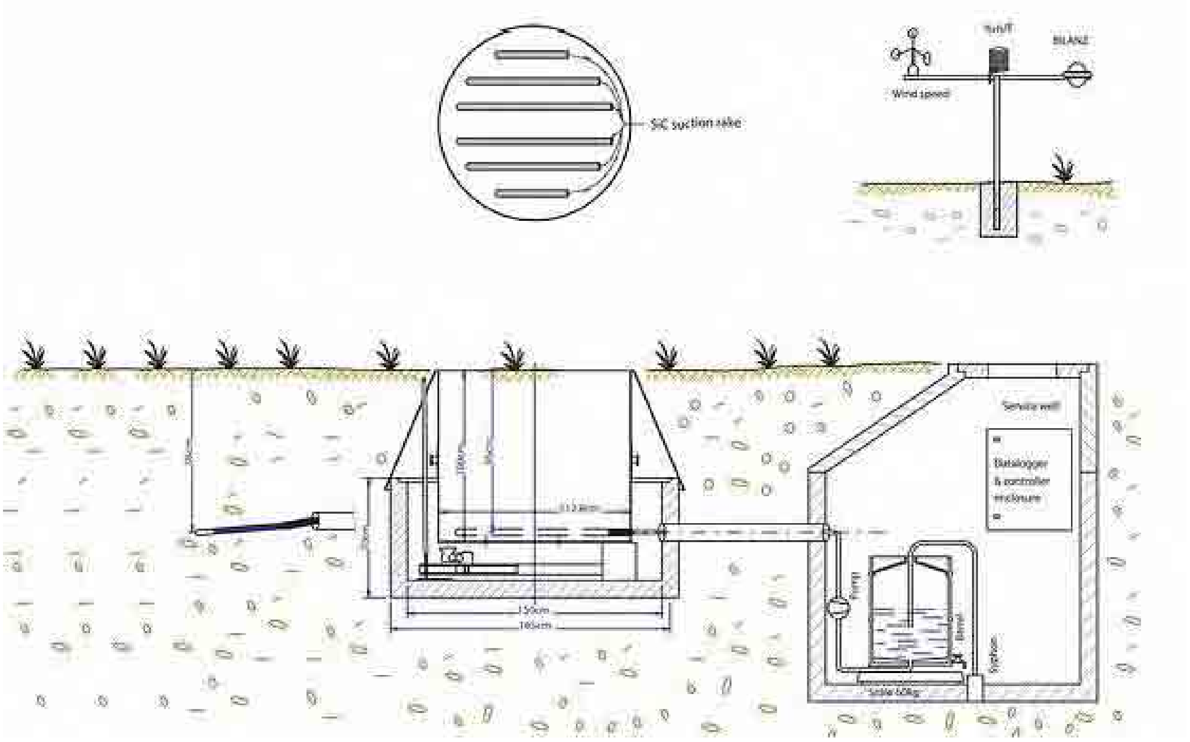


Source: JICA Study Team

Figure-2.3- 17 Groundwater Flow System in Bogotá River Basin and Surrounding Areas

(2) Measurement of Groundwater Recharge

The most reliable method to estimate groundwater recharge is the direct measurement of groundwater. There are several ways to do this, but the lysimeter is most commonly used. Results of groundwater elevation monitoring also provide invaluable data to compliment the data from this method. The tension-meter does not directly measure groundwater recharge, but it measures groundwater flow direction, which can be used for recharge estimation. Some research institutions such as Bogotá Agricultural University have started the direct measurement of recharge by precipitation into soil layers. However, the measurement activities have just started recently and it will be some time before any measurement data can be made available.



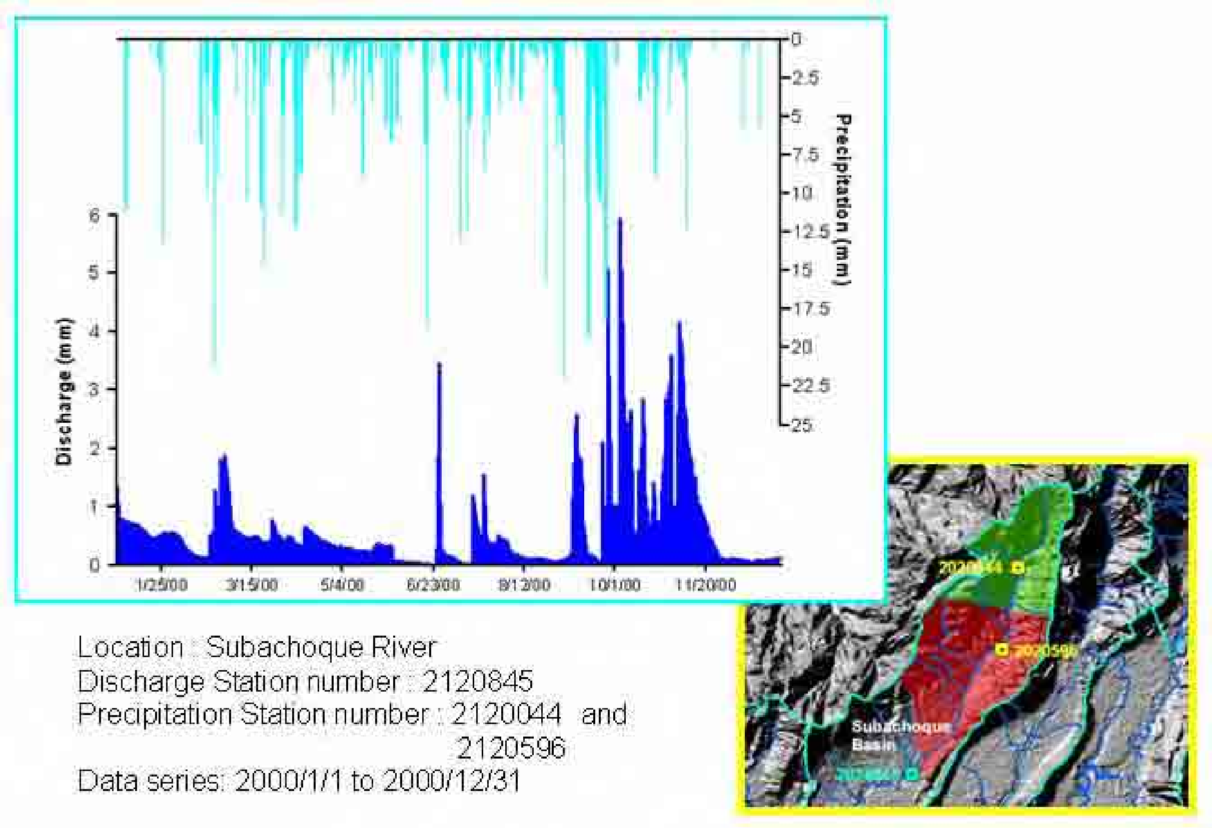
Source: JICA Study Team

Figure-2.3- 18 Schematic of Groundwater Recharge Measurement by Lysimeter

(3) Analysis by the Tank Model

The tank model, originally developed for runoff analysis of rivers, can also be used to estimate groundwater recharge amount. However, good estimation still requires groundwater level monitoring data. If groundwater monitoring data is unavailable, the reliability of estimation will inevitably go down, but still it is possible to conduct a runoff simulation to estimate the amount of direct runoff, base flow, and infiltration into deep groundwater.

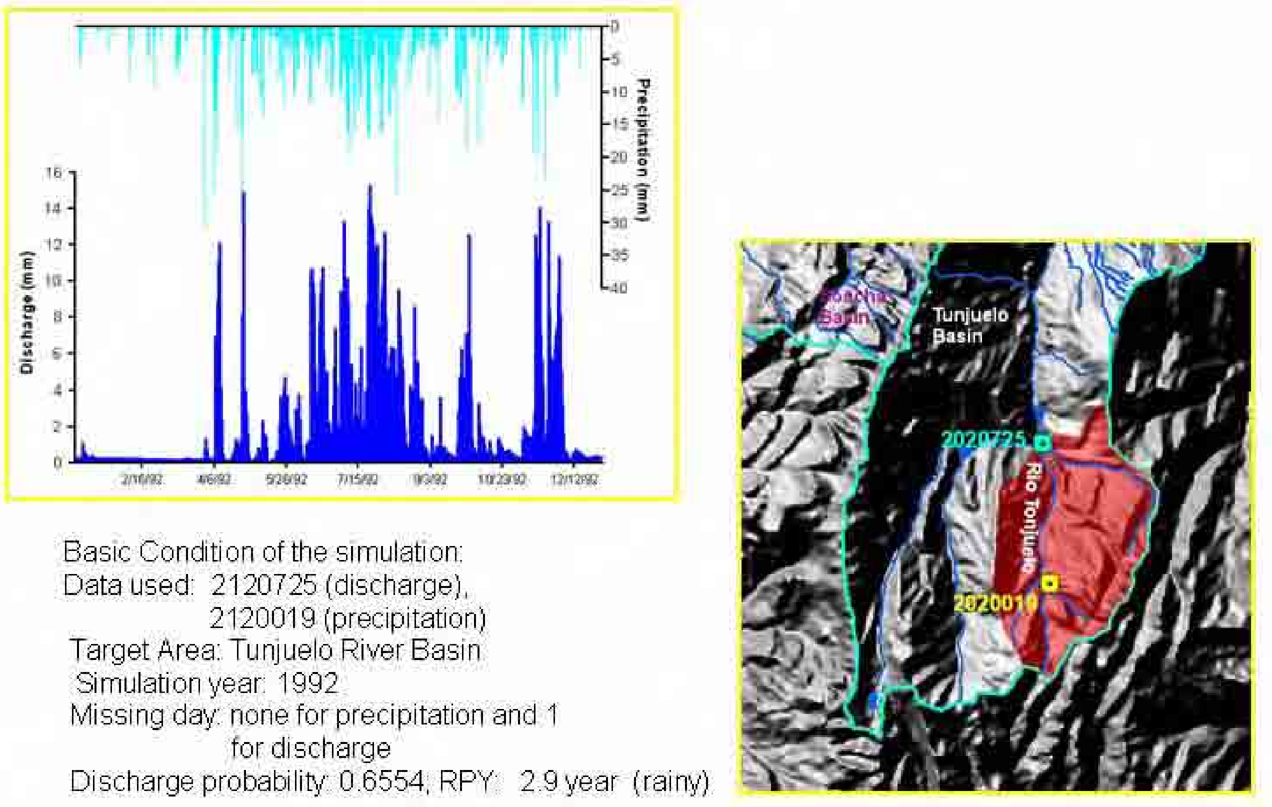
When conducting an analysis by the tank model, it is required that the precipitation and river discharge have positively correlated patterns. In the case of Figure-2.3-19, when the precipitation is large, the corresponding river discharge is small and vice versa. The tank model can not be used for such a case.



Source: JICA Study Team

Figure-2.3- 19 Example of Non-correlated Datasets of Precipitation and Discharge

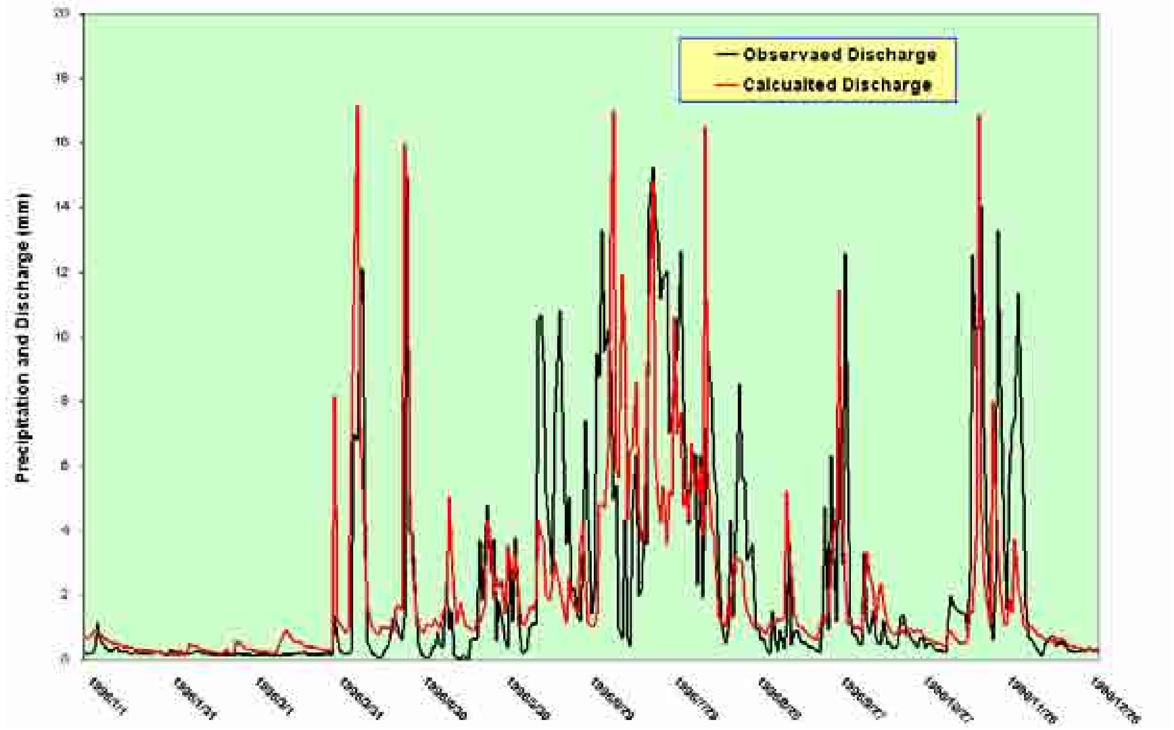
Contrary to Figure-2.3-19, Figure-2.3-20 shows good correlation of the peaks of both precipitation and river discharge. A tank model of three tanks in a series was created taking advantage of this relation, and the process of runoff generation was examined. The results of the simulation are (as also presented in Figure-2.3-21) as follows: For 1,258 mm precipitation as the input, direct runoff = 215 mm (17%), base flow = 575 mm (46%), Evapotranspiration = 330 mm (26%), Infiltration into deep groundwater =153 mm (12%).



Basic Condition of the simulation:
Data used: 2120725 (discharge),
2120019 (precipitation)
Target Area: Tunjuelo River Basin
Simulation year: 1992
Missing day: none for precipitation and 1 for discharge
Discharge probability: 0.6554, RPY: 2.9 year (rainy)

Source: JICA Study Team

Figure-2.3- 20 Example of Correlated Datasets of Precipitation and Discharge

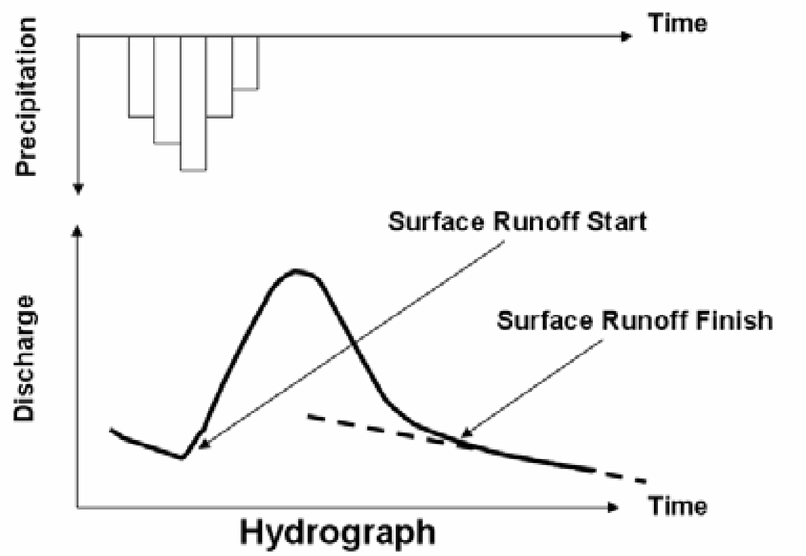


Source: JICA Study Team

Figure-2.3- 21 Result of Tank Model Simulation

(4) River Discharge Analysis

Even when there is no clear correlation is recognized between precipitation and river discharge data, direct runoff and base flow can be distinguished using the discharge analysis with a hydrograph such as the one shown in Figure-2.3-22.



Source: JICA Study Team

Figure-2.3- 22 Concept of Hydrograph Analysis

(5) Water Balance Method

While the application of the direct measurement methods or the other analysis methods to Bogotá River Basin discussed above has just started, the water balance method has been used by several institutions to analyze groundwater recharge. The principle of the water balance method is as follows: the total precipitation within a river basin is generally consumed through evapotranspiration, direct runoff, and infiltration to groundwater. Thus, if the change in storage in dams and retention ponds is small enough to be ignored, the following equation is derived.

$$P = D + E + Rd \qquad (1)$$

P : Precipitation.
D : River Discharge.
E : Evaporation or evapotranspiration.
Rd : Recharge to deep aquifer.

Transposing two terms in equation (1), the following relation is obtained.

$$Rd = P - D - E \qquad (2)$$

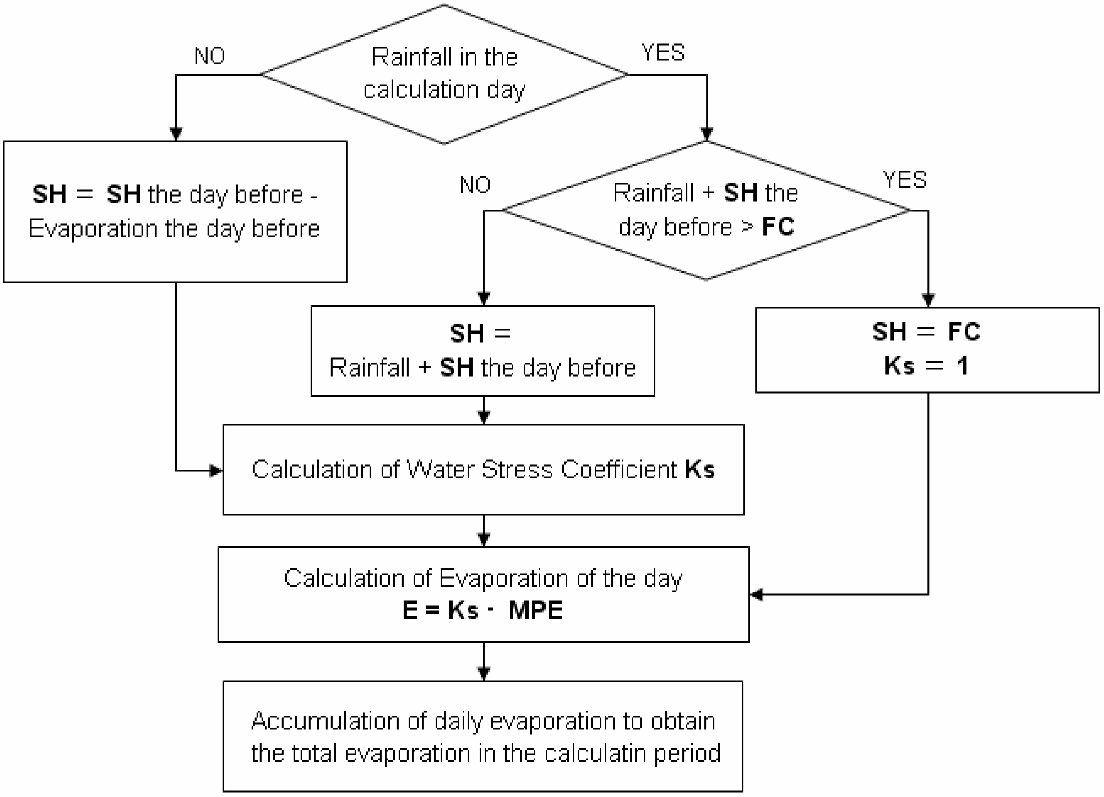
The equation tells that the recharge into the deep groundwater is calculated by subtracting river discharge and evapotranspiration from the precipitation. The river discharge (D) and precipitation (P) can be calculated through hydrologic analysis as discussed previously and thus, determining the remaining parameter value (E), evapotranspiration, will give the groundwater recharge value (Rd).

Evaluating evapotranspiration, however, is not as easy as calculating groundwater recharge by other methods. Many theoretical and empirical formula have been proposed. One of the most popular and, at the same time, accurate one is the Penman-Monteith method. This method, however, requires more than 10 meteorological parameters to be theoretically correct. Meteorological parameters are also difficult to obtain and the values are sometimes unreliable due to difficulty in measurement. So this is not usually a practical option.

In this context, FAO released a simplified version of the Penman-Monteith method designed for irrigation planning. The procedure was complied as a guidebook that contains applications to many different conditions. Since this FAO method was employed by some water resources regulatory agencies in Bogotá to calculate evapotranspiration, the same method was employed in this JICA Study as well

1) Analysis Procedure

This FAO method was originally developed for irrigation planning. It is based on the fact that the soil moisture is consumed by evapotranspiration within some days after a rainfall. The method helps to determine whether irrigation is necessary to replenish the soil moisture. The calculation procedure is presented as a flow chart in Figure-2.3-23.



Note: SH: Soil Humidity, FC: Field Capacity, Ks: Stress Coefficient, MPE: Maximum Potential Evapotranspiration
Source: WHO

Figure-2.3- 23 Procedure for FAO Method for Estimating Evapotranspiration

2) Determining Relevant Parameters

(a) Pan coefficients (Kp): This is a coefficient used to calculate Reference crop evapotranspiration (ETo) based on pan evaporation data

The FAO guidebook lists the following values for this coefficient (Kp) as shown in Table-2.3-1. In consideration of the typical weather conditions in Bogotá River Basin such as intermediate humidity (RH) and moderate wind velocity, the coefficient should be set at less than 0.7. However, in order to avoid underestimating evapotranspiration, Kp was set at 0.7.

Table-2.3- 1 Criteria for Setting Pan Coefficient

Wind speed (m s^{-1})	Windward side distance of green crop (m)	RH mean(%)		
		low < 40	medium 40 - 70	high > 70
Light	1	.55	.65	.75
< 2	10	.65	.75	.85
	100	.70	.80	.85
	1000	.75	.85	.85
Moderate	1	.50	.60	.65
2-5	10	.60	.70	.75
	100	.65	.75	.80
	1000	.70	.80	.80
Strong	1	.45	.50	.60
5-8	10	.55	.60	.65
	100	.60	.65	.70
	1000	.65	.70	.75
Very strong	1	.40	.45	.50
> 8	10	.45	.55	.60
	100	.50	.60	.65
	1000	.55	.60	.65

Source: JICA Study Team

(b) Field Capacity (FC)

Table-2.3-2 shows the FC values under various soil conditions listed in the FAO guidebook. Since the soil condition within the basin is not clear, the averaged value of 0.269 was adopted for calculation.

Table-2.3- 2 Proposed FC Values by FAO Guidebook

Soil Type	m^3/m^3	Average
Sand	0.07 - 0.17	0.12
Loamy sand	0.11 - 0.19	0.15
Sandy loam	0.18 - 0.28	0.23
Loam	0.20 - 0.30	0.25
Silt loam	0.22 - 0.36	0.29
Silt	0.28 - 0.36	0.32
Silt clay loam	0.30 - 0.37	0.34
Silty clay	0.30 - 0.42	0.36
Clay	0.32 - 0.40	0.36
Total Average	0.22 - 0.32	0.269

Source: FAO

(c) Wilting Point

Table-2.3-3 lists the values for wilting point under various soil conditions proposed by the FAO guidebook. For the same reason as FC, the averaged value of 0.1228 was adopted for calculation.

Table-2.3- 3 Proposed Values for Wilting Point by FAO Guidebook

Soil Type	m^3/m^3	Average	TAW
Sand	0.02 - 0.07	0.045	0.075
Loamy sand	0.03 - 0.10	0.065	0.085
Sandy loam	0.06 - 0.16	0.11	0.12
Loam	0.07 - 0.17	0.12	0.13
Silt loam	0.09 - 0.21	0.15	0.14
Silt	0.12 - 0.22	0.17	0.15
Silt clay loam	0.17 - 0.24	0.205	0.135
Silty clay	0.17 - 0.29	0.23	0.13
Clay	0.20 - 0.24	0.22	0.14
Total Average	0.10 - 0.19	0.146	0.1228

Source: FAO

(d) Crop coefficient (Kc)

Table-2.3-4 lists crop coefficient (Kc) values proposed in the FAO guidebook. The Kc values range greatly from 0.25 to 1.25 depending on the type of crop grown and its growth period. The estimation method for evapotranspiration explained in the previous section is strictly theoretical but its actual application is difficult in many cases. Thus, in determining this Kc values for the calculation, 0.8 was adopted to avoid underestimating evapotranspiration and also in consideration of the values used in the same method by other studies for Bogotá River Basin.

Table-2.3- 4 Proposed Values for Kc

Crop	K_{cini}^{-1}	$K_{c\ mid}$	$K_{c\ end}$
a. Small Vegetables	0.7	1.05	0.95
b. Vegetables - Solanum Family (Solanaceae)	0.6	1.15	0.80
c. Vegetables - Cucumber Family (Cucurbitaceae)	0.5	1.00	0.80
d. Roots and Tubers	0.5	1.10	0.95
e. Legumes (Leguminosae)	0.4	1.15	0.55
f. Perennial Vegetables (with winter dormancy and initially bare or mulched soil)	0.5	1.00	0.80
g. Fibre Crops	0.35	0.4-1.2	0.25-0.7
h. Oil Crops	0.35	1.15	0.35
i. Cereals	0.3	1.15	0.4
j. Forages	0.4-0.95	0.9-1.05	0.85-1.0
k. Sugar Cane	0.40	1.25	0.75
l. Tropical Fruits and Trees	0.5-0.95	0.3-1.05	0.3-1.05
m. Grapes and Berries	0.3	0.7-1.05	0.45-0.85
n. Fruit Trees	0.4-1.0	0.45-1.2	0.45-0.9
o. Wetlands - temperate climate	0.3-1.09	1.1-1.2	0.3-1.1

Source: FAO

The FAO guidebook states that Kc values fall between 0.15 and 0.2 during non-crop period of pre-sowing and post harvesting or in case the land surface is not covered with any vegetation. This implies that the actual evapotranspiration can possibly be smaller than the calculated values.

(e) Root Zone

The FAO guidebook lists the values of maximum root depth for more than a hundred plant species. The values range from 0.3 to 2.0 m and most of them are around 0.5 m. Thus, the root zone value was set at 0.5 m. The FAO guidebook states that the influence of evapotranspiration in the surface soil layer is up to 0.1 to 0.15 m in depth during non-crop period of pre-sowing and post harvesting or in case the land surface is not covered with any vegetation.

3) Calculation Result

Finally, evapotranspiration values were re-calculated using the parameters discussed above and the same pan evaporation data from the 14 observation stations as in the previous JICA study. The calculation result along with the input data set is presented in Table-2.3-5.

Table-2.3- 5 Result and Input Data for Evapotranspiration Calculation

Code	Station	Duration	E_pan_avrg	ER_avrg	STDEV	Max		Min	
2120633	Barrancas	91-98	1,124	460	35.6	531	1996	416	1998
2120540	Checua	91-98	1,369	460	55.8	562	1996	373	1997
2120630	DonaJuana	94-98	1,280	494	82.2	541	1994	461	1998
2120562	Guatavita	91-98	1,194	470	72.7	541	1994	418	1992
2120559	Guymaral	91-98	998	446	32.3	471	1996	376	1997
2120611	Balsillas	88-91	837	405	34.3	412	1991	395	1989
2120548	La Iberia	91-98	1,034	440	49.8	459	1992	411	1994,98
2120561	Muna	91-98	1,014	383	50.6	443	1996	332	1992
2120541	Neusa	91-98	867	401	69.6	433	1994,95	285	1998
2120557	Primavera	91-97	1,039	449	48	478	1993	426	1992
2120516	Ramada	91-98	998	411	52.4	439	1991	378	1995
2120548	Sisga	93-97	1,081	499	38	527	1997	476	1993
2120565	Tabio	91-98	1,023	440	75.2	457	1991	400	1995
2120631	Tisquesusa	91-98	989	412	41.5	464	1996	351	1992
2120629	Venecia	91-98	1,100	466	117.6	531	1998	419	1992

Source: JICA Study Team

4) Distribution of Evapotranspiration in Bogotá River Basin

The distribution of evapotransiration within Bogotá River Basin was estimated based on the result discussed above. The following map was created as Figure-2.3-24.

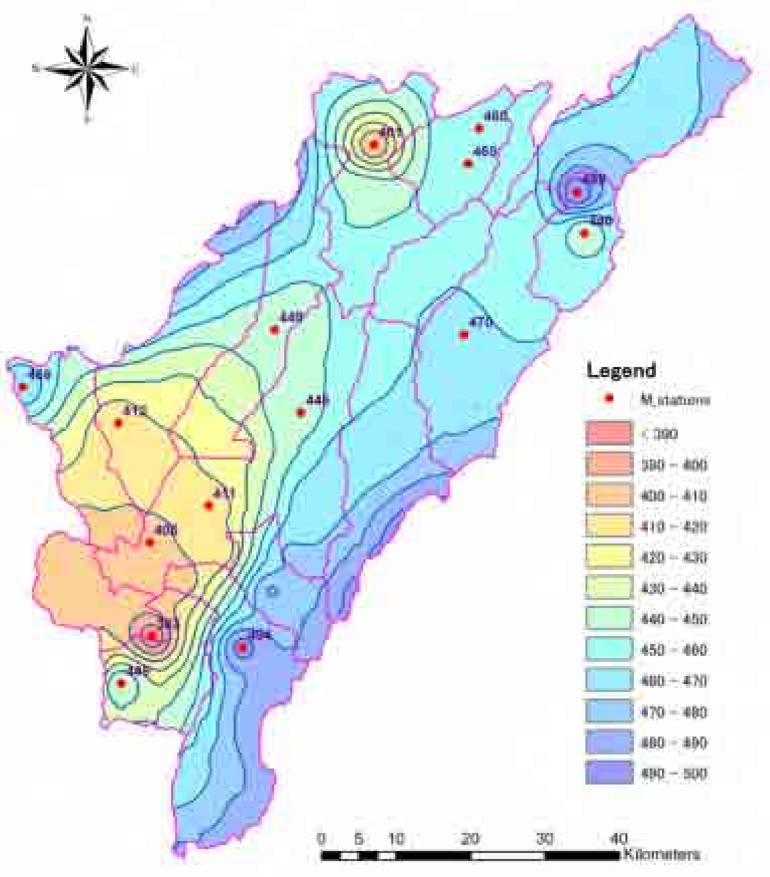
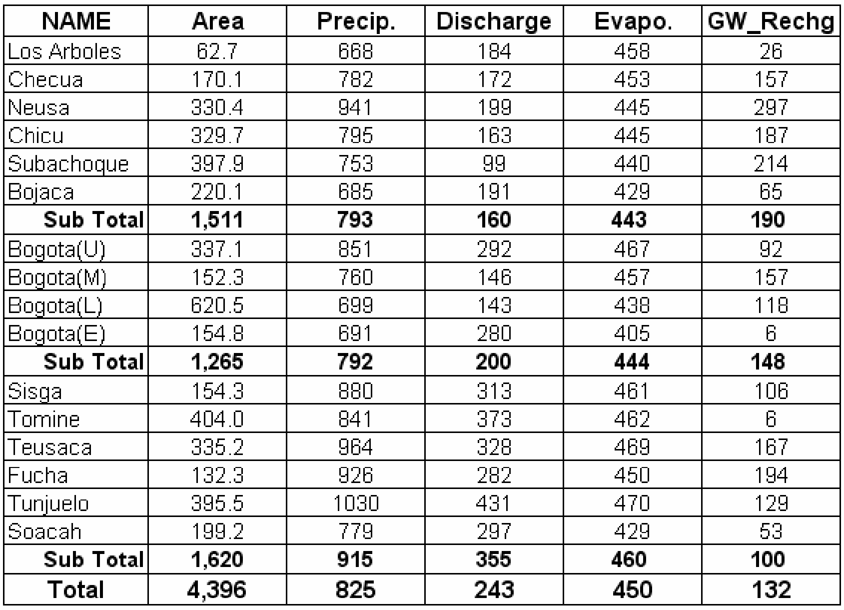


Figure-2.3- 24 Distribution of Evapotranspiration in Bogotá River Basin

5) Source: JICA Study Team Bogotá River Basin Water Balance

The results from hydrologic analysis and groundwater recharge estimation are compiled in Table-2.3-6. As shown in Table-2.3-6, groundwater recharge of Bogotá Plain is 132 mm/year in average. In formulation of groundwater development plan, evaluated value of 132 mm/year should be taken into account for designing amount of groundwater to be developed.

Table-2.3- 6 Summary of Groundwater Recharge Estimation in Bogotá River Basin



NAME	Area	Precip.	Discharge	Evapo.	GW_Rechg
Los Arboles	62.7	668	184	458	26
Checua	170.1	782	172	453	157
Neusa	330.4	941	199	445	297
Chicu	329.7	795	163	445	187
Subachoque	397.9	753	99	440	214
Bojaca	220.1	685	191	429	65
Sub Total	**1,511**	**793**	**160**	**443**	**190**
Bogota(U)	337.1	851	292	467	92
Bogota(M)	152.3	760	146	457	157
Bogota(L)	620.5	699	143	438	118
Bogota(E)	154.8	691	280	405	6
Sub Total	**1,265**	**792**	**200**	**444**	**148**
Sisga	154.3	880	313	461	106
Tomine	404.0	841	373	462	6
Teusaca	335.2	964	328	469	167
Fucha	132.3	926	282	450	194
Tunjuelo	395.5	1030	431	470	129
Soacah	199.2	779	297	429	53
Sub Total	**1,620**	**915**	**355**	**460**	**100**
Total	**4,396**	**825**	**243**	**450**	**132**

Source: JICA Study Team

3.2.4. Groundwater Simulation

1) Purpose of the Simulation

In the previous JICA study, groundwater simulation models of both regional and local scales were created to analyze the groundwater flow system in the Study Area. In this study, the groundwater flow in the Cretaceous aquifer distributed in the Eastern and Southern Hills of Bogotá River Basin was mainly investigated based on the results from the previous study. The new model followed the basic structure of the previous models and newly planned 62 deep pumping wells were put in place. The effect of pumping from these 62 deep wells on the groundwater table and hydraulic head distributions in the surrounding aquifers were evaluated. A transient simulation was conducted to examine and evaluate the “pumping time - drawdown” relation for the Cretaceous aquifer targeted for pumping, and for the Quaternary sedimentary layers that may suffer a land subsidence problem as a result of pumping.

2) Outline of the Model

(1) Conceptual Model

In preparation of simulation model, assumption below was made based on hydrogeological consideration.

Rivers

As explained in Chapter 3, the groundwater in Bogotá River Basin is recharged only by direct precipitation. Part of the precipitation normally flows off the basin as a direct river discharge. However only the precipitation component contributing to groundwater recharge is considered as an input, and no river discharge exists within Bogotá River Basin. In other words, it is not necessary to simulate river discharge from the basin in this model.

Aquifer distribution

The mountainous areas that form watersheds in the south and east of Bogotá River Basin are mostly made up of Cretaceous sedimentary rocks. These rocks develop extensive fissures and thus, the permeability is considered high enough to make it an aquifer. It was assumed that in these

Cretaceous rocks, the fissures are uniformly developed and the rocks can be treated as a normal porous media in terms of their hydraulic characteristics. Meanwhile, the Tertiary and Quaternary Formations above the Cretaceous Aquifer are assumed to have lower permeability considering the nature of their rock and sedimentary facies, and thus they are not good aquifers.

Recharge / flow direction / groundwater level

The mountain areas at higher altitudes receive more recharge by precipitation. The precipitation infiltrated into the mountain slopes slowly flows down into the groundwater basin under the Bogotá plain where Quaternary sediment is widely distributed. The Bogotá River and its tributaries flow through the Bogotá Plain and their discharge and river stages are assumed constant. The same way, the dams and retention ponds in the basin have constant water levels.

Vadose zone

It is highly possible that a thick vadose zone (unsaturated layer above water table) develops on steep mountain slopes depending on the geological conditions. However such zones were approximated and modelled as saturated zones.

Condition of groundwater discharge out of Bogotá River Basin

Outside Bogotá River Basin, the direct precipitation is applied full amount as the recharge condition. Therefore the surplus precipitation (remainder after infiltration into aquifer) has to be drained off the model area by river streams originating the watersheds of Bogotá River Basin.

(2) Structure / Parameters / Boundary condition of Model

This simulation model in principle adopted the structure and other conditions of the model created in the previous JICA Study (2000-2003). However, some alterations such as further division of vertical grids (layers) and changes in some model parameters and boundary conditions were made in order to improve stability in the model solution. MODFLOW was used as the simulation code and PMWIN was employed as the pre and post processing interface. The basic information of the model is given in Table-2.3-7.

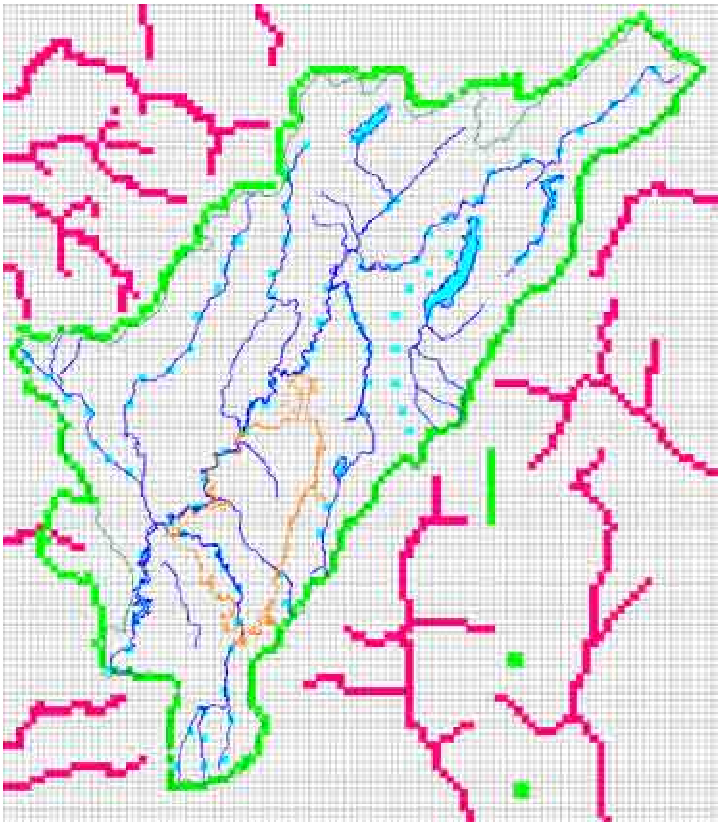
Table-2.3- 7 Outline of Groundwater Flow Simulation Model

Structure	Parameter and Boundary condition
Horizontal grid: 1000 m square x: 105, y: 120	Model Area N-S 120 km, E-W 105 km
Layer: total 12 layers	
1st layer: Quaternary	Hydraulic conductivity (K_H) : 0.001 m/day In basin: Fixed heads for rivers and dams, GHB for mountain ridges, groundwater recharge Outside basin: Drain for major rivers, full recharge
2nd layer: Tertiary	Hydraulic conductivity (K_H) : 0.005 m/day
3rd & 4th layer: Guadalupe	Hydraulic conductivity (K_H) : 0.01- 0.05 m/day 7000 existing wells, 62 newly planned wells
5th layer: Cretaceous	Hydraulic conductivity (K_H) : 0.01 m/day
6th to 12th layer: Paleozoic	Hydraulic conductivity (K_H) : 0.0001 m/day GHB for outermost perimeter cells in layer 8 and 10

Note : GHB: General Head Boundary (external head dependent), the hydraulic conductivities are initial values, $Kv = 0.1 \times K_H$

Source: JICA Study Team

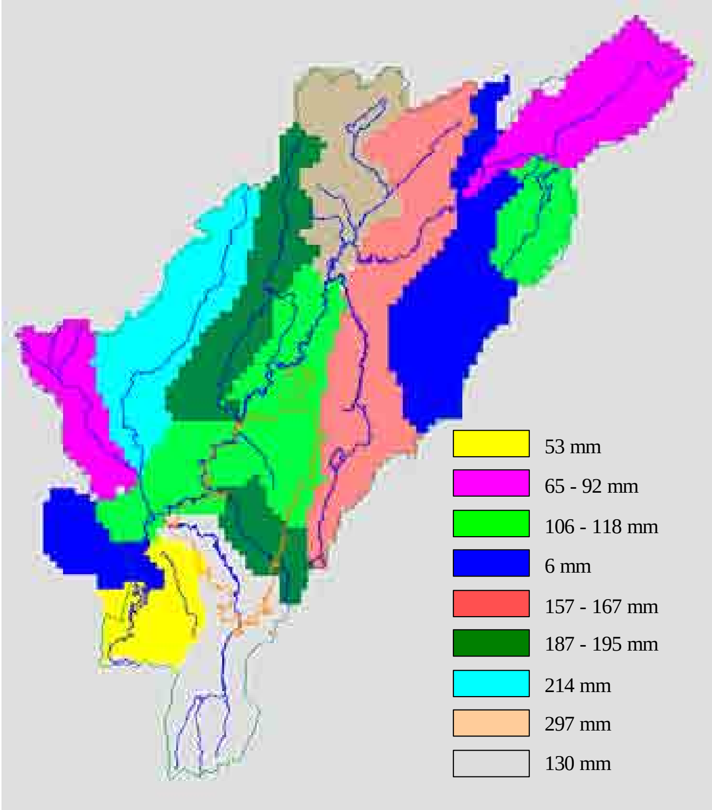
The horizontal grid and major boundary conditions in the 1st layer are shown in Figure-2.3-25. The recharge distribution is shown in Figure-2.3-26 and the location of existing pumping wells is given in Figure-2.3-27.



Note) Blue: Fixed head, Green: GHB, Red: Drain, GHB was also set for the perimeter of layer 8 and 10, The blue lines represent rivers, Orange line represents boundary of urban area.

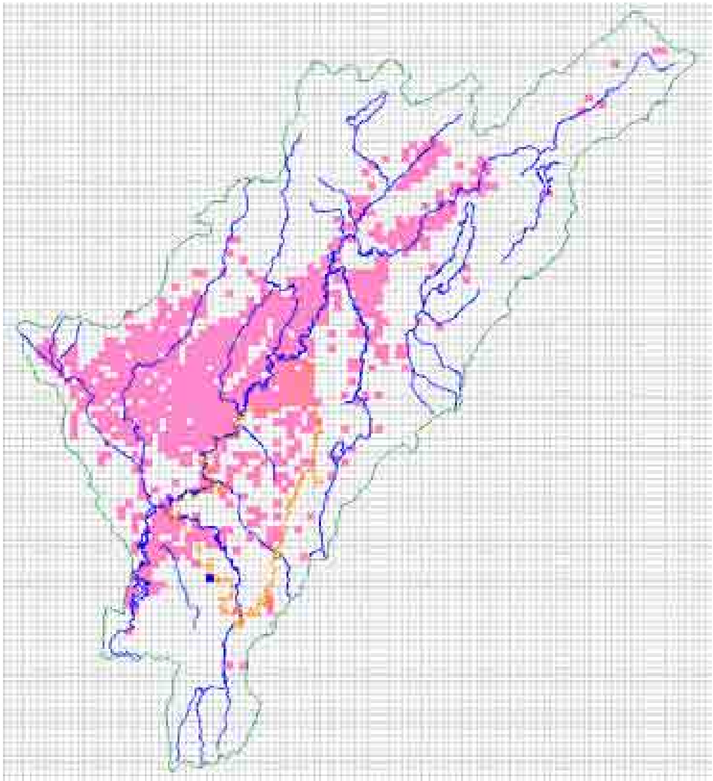
Source: JICA Study Team

Figure-2.3- 25 Model Grid and Boundary Conditions in Layer 1



Source: JICA Study Team

Figure-2.3- 26 Recharge Distribution (mm/year)

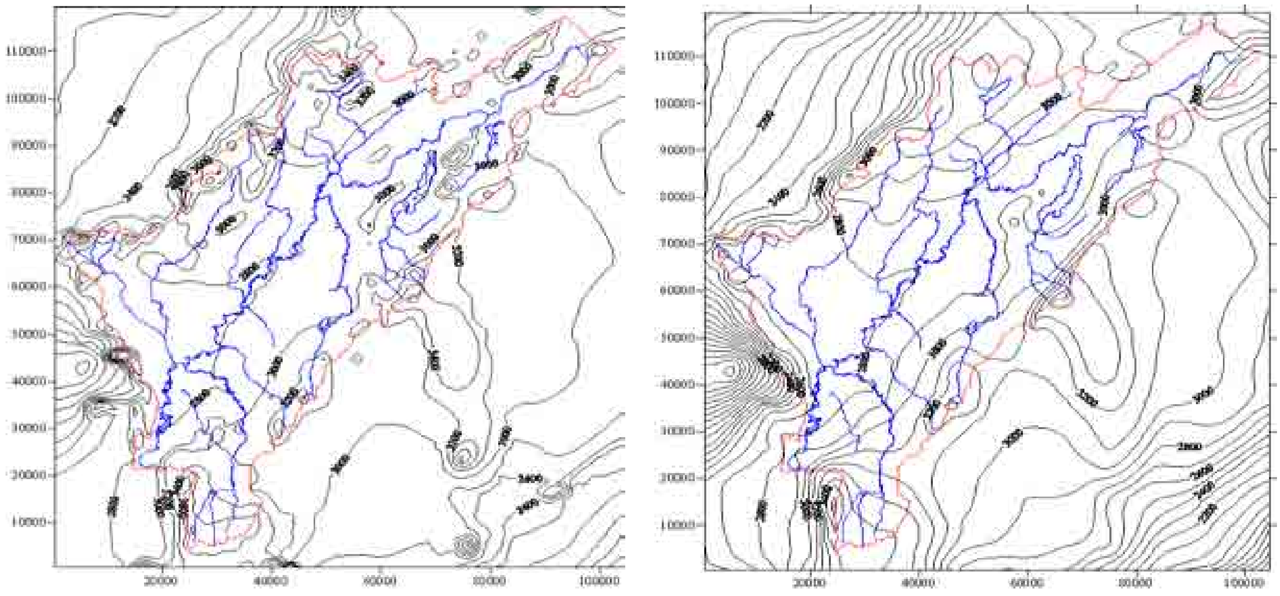


Note: The cells in pink represent those with pumping wells, total 7,000 wells are in place and total pumping rate is about320,000 m^3/day.
Source: JICA Study Team

Figure-2.3- 27 Location of Existing Wells

3) Model Calibration

The model calibration was done by adjusting the hydraulic conductivity values of each layer within a reasonable range. Due to the lack of reliable head observation data that can be used for calibration, the model was calibrated until the water table elevation in the first layer generally matches the ground elevation. The final outcome of the calibration under steady state condition is presented in Figure-2.3-28 as head distribution maps.



1st layer head distribution

4th layer head distribution

Source: JICA Study Team

Figure-2.3- 28 Head Distribution after Calibration of Steady State Model

3.2.5. Exploratory Well Drilling

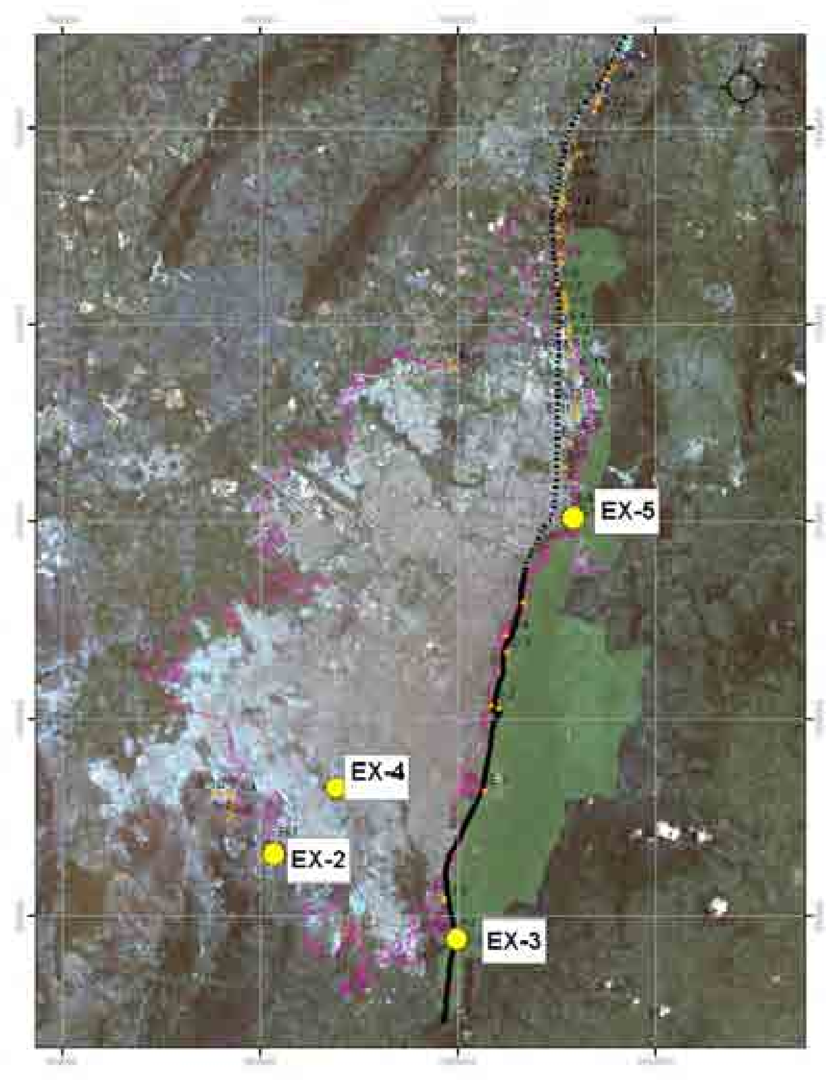
(1) Location of Well

Proposed location of the exploratory wells and observation well are shown in Table-2.3-8 and Figure-2.3-29.

Table-2.3- 8 Location of Exploratory Well

	Well No.	Area	Coordinate		Responsibility
			X	Y	
Purpose	EX-2	Ciudad Bolivar Verbenal	4° 32'14.4"N	74° 09'51.7"W	JICA
	EX-3	Usme Cerveceria Alemana	4° 29'38.1"N	74° 04'51.5"W	JICA
	EX-5	La Aguadora	4° 38'04.4"N	74° 03'20.7"W	Acueducto
Observation well	EX-4	Embalse Seco No.1	4° 33'48.84"N	74° 08'18.696"W	JICA

Source: JICA Study Team



Source: JICA Study Team

Figure-2.3- 29 Location of Exploratory Wells

Site of exploratory wells was decided taking into account of view points listed below:

<Hydrogeology>

- Sites for the exploratory wells were located where Cretaceous sandstone is distributed near Bogotá Fault and other eminent geological structure such as main faults and folding axes, which reads to high possibility of groundwater development.

- Groundwater level may be deep in area with high altitude of the hills. Therefore, exploratory wells should be located at the foot of the hills or on the middle of the hill slope, where the groundwater level is expected to be shallow.

<Environmental Regulation>

- Any activity is prohibited in the forest protection area in the Eastern Hills. Therefore, the exploratory wells were located in the area out of the forest protection area. On the other hand, there is not forest protection area in the Southern Hills.

<Facilities construction>

- Considering future use of the exploratory wells for production wells, the sites for exploratory wells were selected near the existing water supply facilities, which will make easy connection between the wells and the existing facilities in the future.
- Sites for exploratory wells were located where there is enough space for drilling work and other construction works, near the road with easy access for drilling rigs and construction machineries.

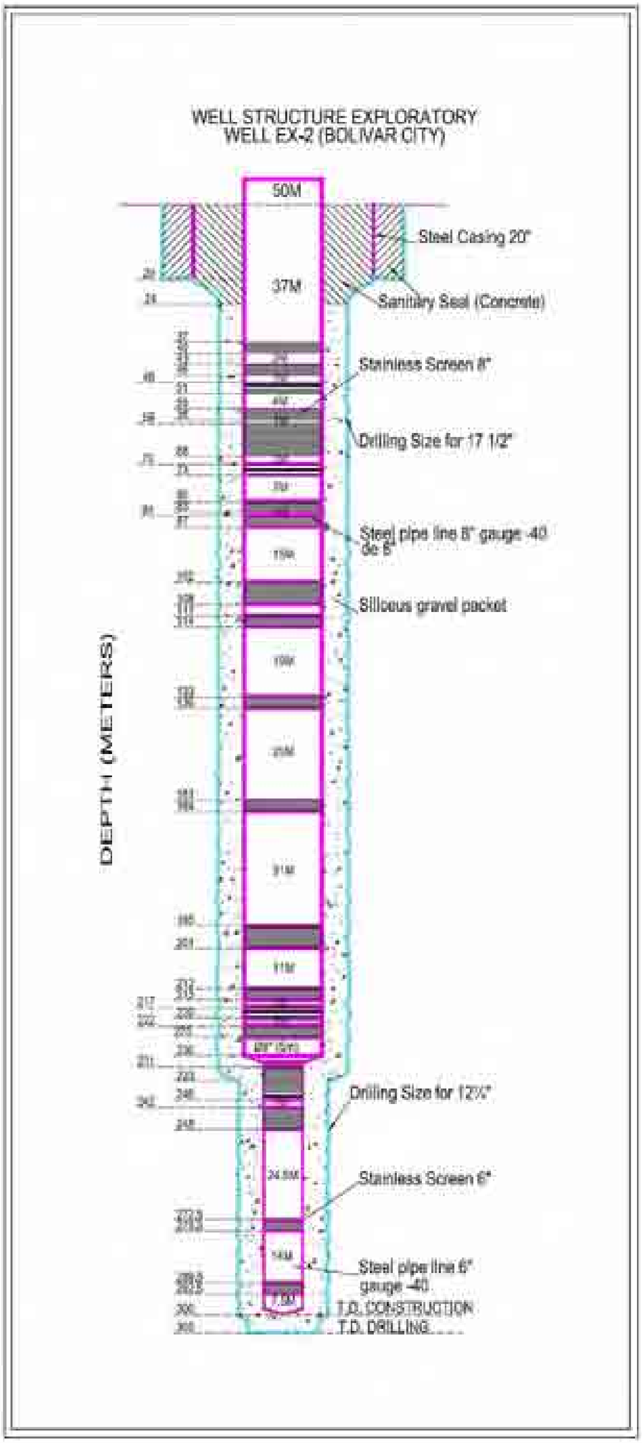
(2) Result of Exploratory Drilling

Well Structure

Structure of the exploratory wells (EX-2, EX-3) and observation well (EX-4) were designed as shown in Figure-2.3-30~35.

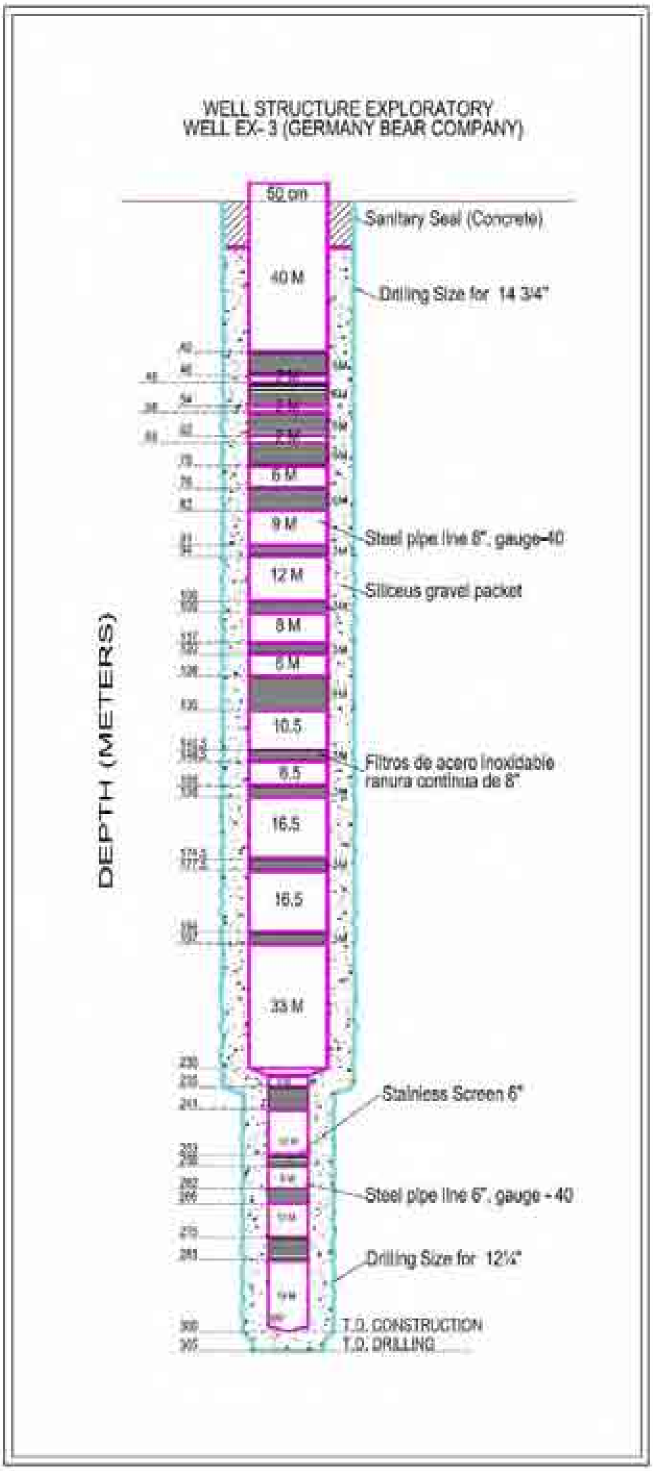
Drilling Result

Result of exploratory drilling (EX-2, EX-3,EX-5) and observation well (EX-4) are summarized in Table-2.3-9 and Table-2.3-10. Geological columnar of the wells are shown in Figure-2.3-30~35. Pumping test was carried out after completion of the wells. Continuous pumping test was conducted for 48 hours. Following it, recovery test was conducted. Then, step draw down test was conducted.2.3-35



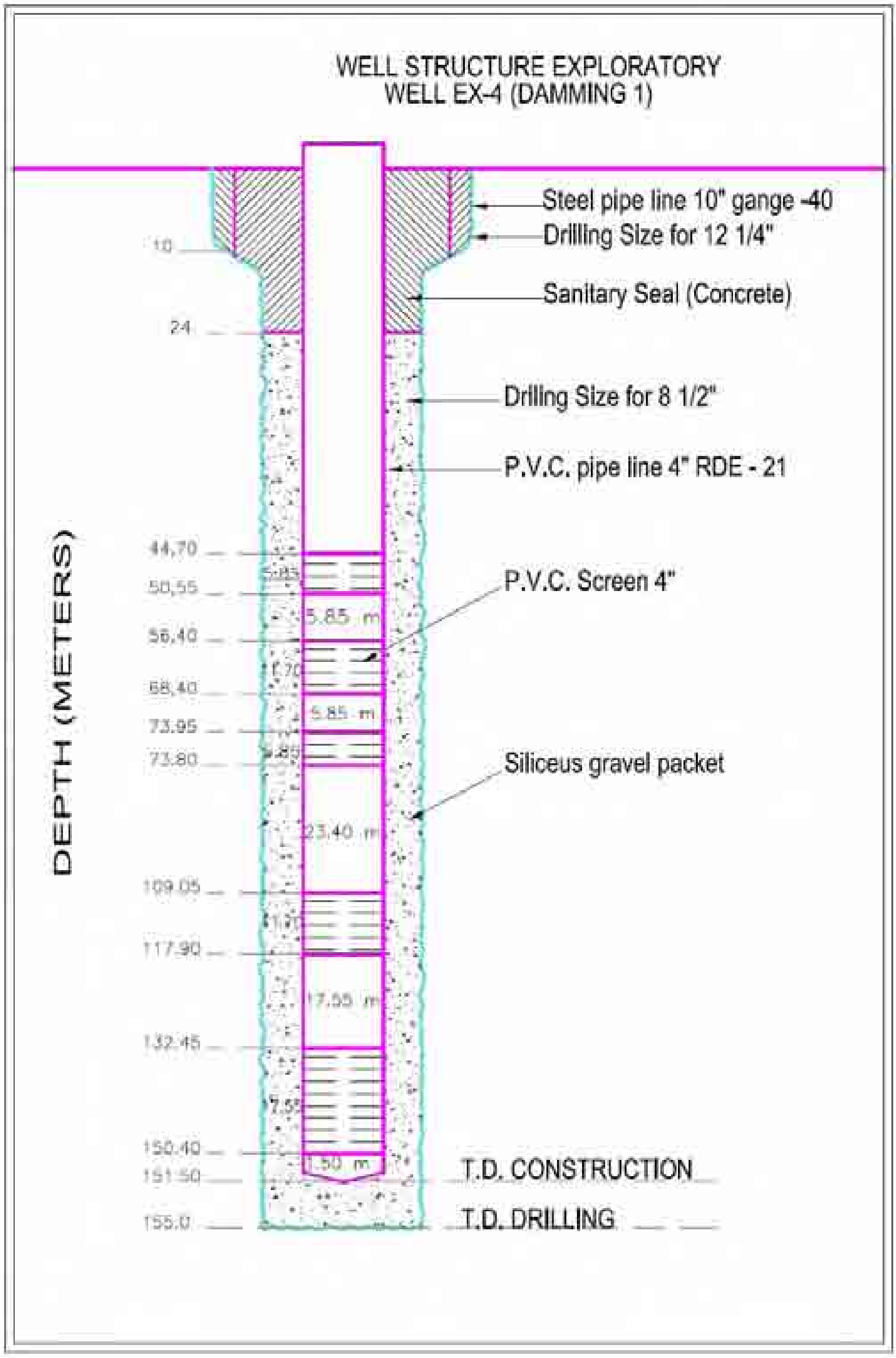
Source: JICA Study Team

Figure-2.3- 30 Well Structure EX-2 (a)



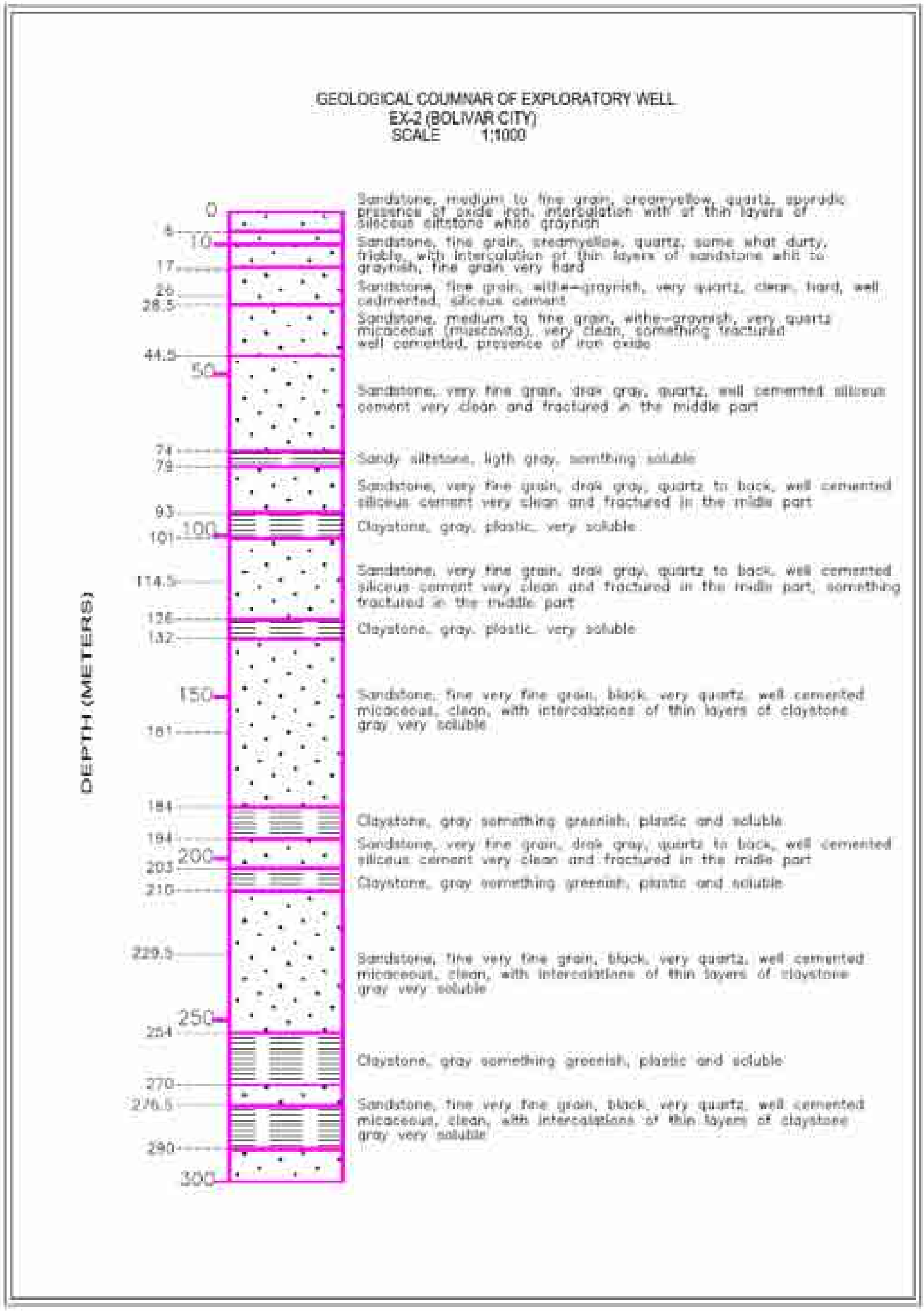
Source: JICA Study Team

Figure-2.3- 31 Well Structure EX-3(b)



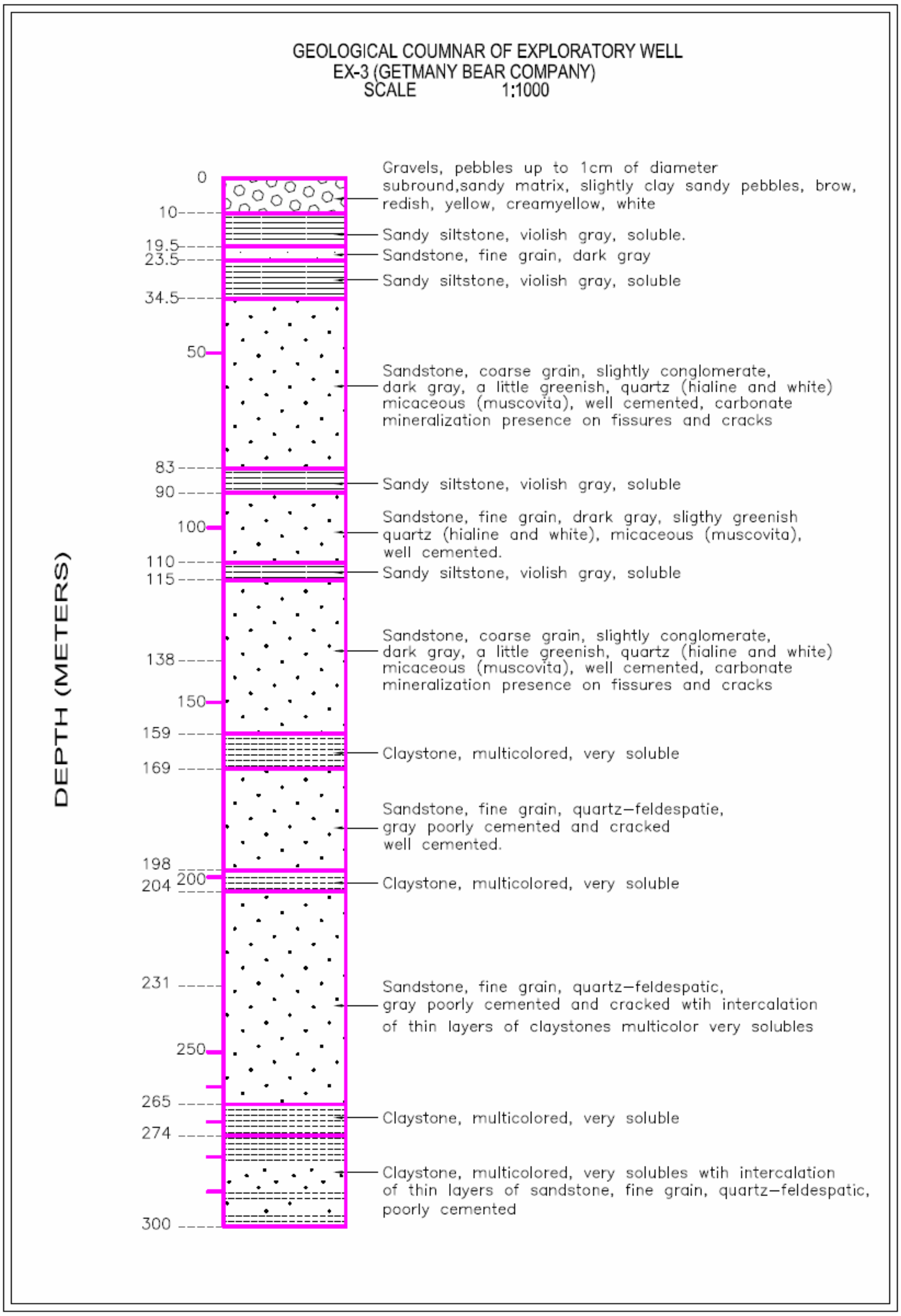
Source: JICA Study Team

Figure-2.3- 32 Well Structure EX-4(c)



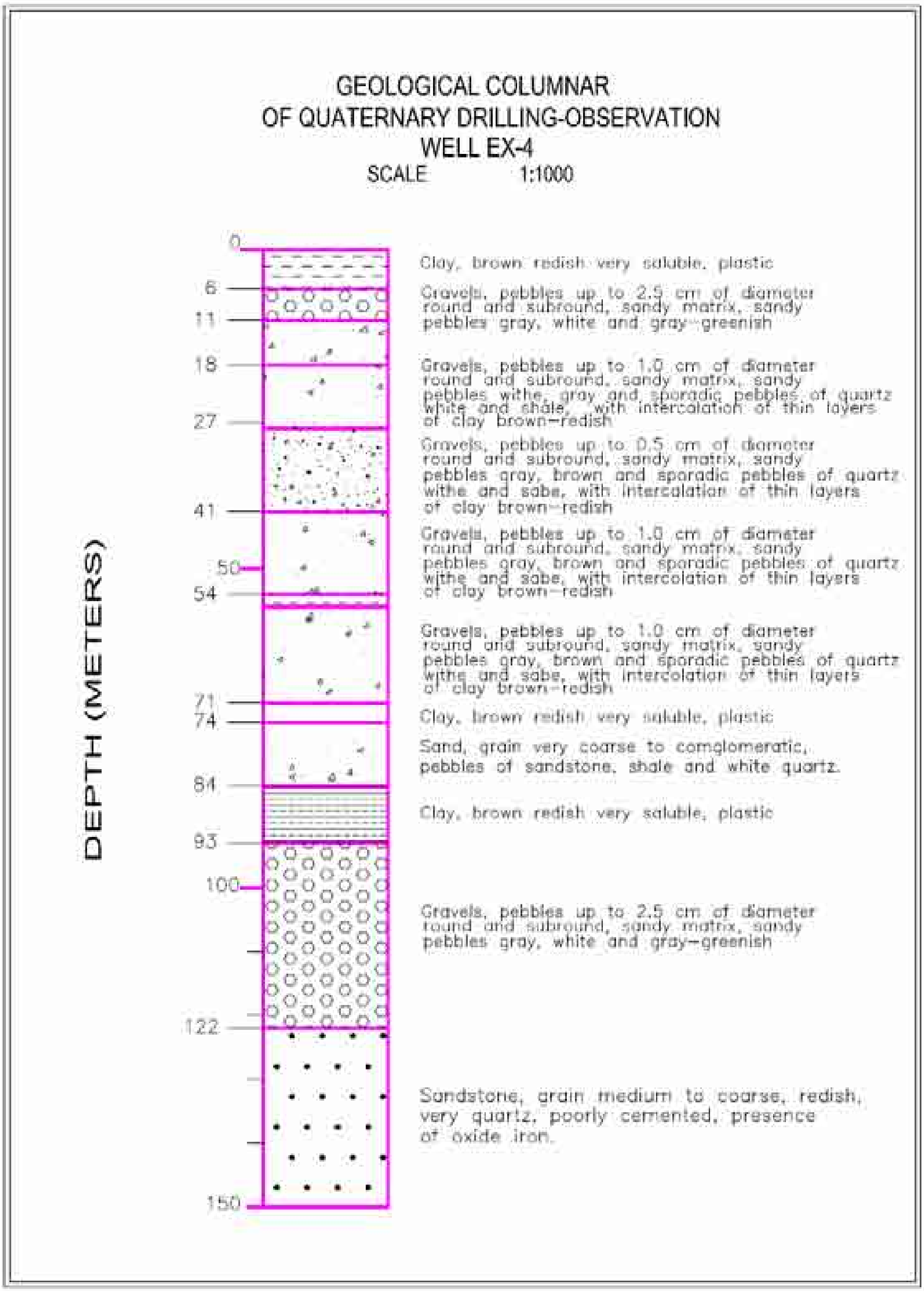
Source: JICA Study Team

Figure-2.3- 33 Geological Columnar of Exploratory Well EX-2 (a)



Source: JICA Study Team

Figure-2.3- 34 Geological Columnar of Exploratory Well EX-3 (b)



Source: JICA Study Team

Figure-2.3- 35 Geological Columnar of Exploratory Well EX-3 (c)

Table-2.3- 9 Result of Exploratory Drilling

Well No. （Site）	EX-3 (Usme)		Ex-2 (Ciudad Bolivar)		EX-5 (La Aguadora)		EX-4 (Embalse Seco No.1)
Well depth (m)	300m		300m		300m		150m
Screen depth (GL-m)	37 - 40, 43 - 46, 48 -51, 55 - 58, 59 - 68, 70 - 73, 80 - 83, 84 - 87, 102 - 108, 111 - 114, 133 - 136, 161 - 164, 195 - 201, 212 - 215, 217 - 220, 222 - 225, 233 - 240, 242 - 248, 273 - 275, 289 - 292 (Total 80m)		40 - 46, 48 - 54, 56 - 62, 64 - 70, 76 - 82, 91 - 94, 106 - 109, 117 - 120,126 - 135, 145 - 148, 155 - 158, 174 - 177,194 - 197, 235 - 241, 253 - 256, 262 - 265, 275 - 281 (Total 80m)		109～118, 120～129, 131～140, 148～154,155～164, 165～174, 175～181, 194～197, 201～207, 216～222, 223～232, 233～242, 243～246, 256～262, 286～289, 290～299。 (Total 111m)		44- - 51, 56 - 68, 74 - 78, 110 -115, 132 – 150 (Total 50m)
Casing Diameter	8 inch		8 inch		10 inch		4 inch
Aquifer	Sandstone		Sandstone		Sandstone		Sand and Gravel
Continuous pumping test							
S.W.L [1)] (GL-m)	20.70		18.20		37.6		25.2
Yield (m3/day)	95		864 - 1,223		864		145
Drawdown	69.29		52.70		71.4		7.1
D.W.L[2)] (GL-m)	89.99		70.90		109		32.3
Specific Capacity (m^3/day/m)	1. 37		23.2		12.1		20.4
Transmissivity (m^2/day)	1.9		14.7		13.6		27.8
Conductivity (m/day)	0.023		0.18		0.17		0.56
Storativity	$6.9x10^{-4}$		$2.2x10^{-2}$		$2.06x10^{-2}$		$4.2x10^{-3}$
Step draw-down test							
Step	Yeild (m^3/day)	Draw down (m)	Yeild (m^3/day)	Draw- down (m)	Yeild (m^3/day)	Draw down (m)	-
1 step	41	43.4	966	11.1	290	15.4	-
2 step	82	47.9	1,240	17.1	360	22.3	-
3 step	121	57.3	1,446	20.9	470	33.6	-

Note Conductivity and storativity were analyzed by Jacob method and recovery method
Source: JICA Study Team

Table-2.3- 10 Geological Condition of Exploratory Well

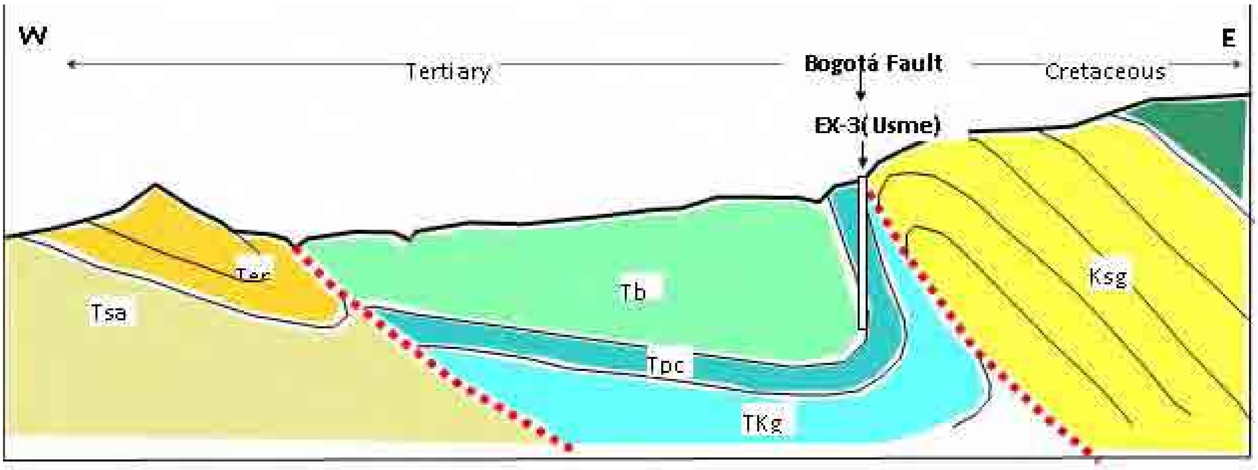
Well No.	Geology		Depth (G.L.-m)	Rock Face
	Age	Formation		
EX-2 Exploratory well	Cretaceous	Planers Formation	0- 17	Sandstone, sandy siltstone
		Dura Formation	17-300	Fine sandstone.
EX-3 Exploratory well	Quaternary	Colluvial	0- 10	Sand and Gravel.
	Cretaceous-Tertiary	Cacho Formation	10- 35	Clay stone.
			35- 90	Coarse sandstone with intermediate thin clay stone layer.
			90-115	Fine sand with intermediate thin clay stone layer.
			115-159	Coarse sandstone.
	Tertiary	Bogotá Formation	159-265	Fine sand with intermediate thin clay stone layer.
			265-300	Clay stone.
EX-5 Exploratory well	Quaternary	Colluvial	1-5	Soil and weathered rock
	Cretaceous	Labor y Tierna Formation	5-300	Sandstone and clay stone
EX-4 Observation well	Quaternary	Alluvium - Diluvium	0- 6	Soft clay of brown color.
			6- 71	Sand and gravel. Pebble of ϕ 0.5-1.0cm
			71- 74	Clay.
			74- 84	Sand.
			93-122	Sand and gravel. Pebble with ϕ2.5cm.
	Tertiary	Regadera Formation	122-150	Sandstone

Source: JICA Study Team

Characteristics of Cretaceous aquifer

It is well known that Bogotá fault lies between Cretaceous group and Tertiary group in the eastern hill. Exploratory well of EX-3 (Usme) is located on just above Bogotá Fault. It was expected that there would be enough groundwater in Cretaceous sandstone with many fissures developed along Bogotá Faults. However, it was made clear by the exploratory drilling of EX-3 that geological structure of the site is complicated as shown in Figure-2.3-36. Under the Cretaceous sandstone, Tertiary rocks are distributed by effect of reverse fault (= Bogotá fault). Tertiary rocks consist mainly of claystone, which has low permeability with the result of low groundwater productivity. From the result of exploratory drilling of EX-3, important hydrogelogical condition below was concluded.

- Cretaceous sandstone, which is distributed in the east of Bogotá fault, is excellent aquifer in the eastern hill.
- Bogotá fault is definitely reverse fault. The reverse fault will cause drilling to encounter Cretaceous rock in shallow but encounter Tertiary rock in deep. It means that older stratum overlays younger stratum.
- It is desirable to locate drilling point as far as possible at the east of Bogotá faults. According to the example in exploratory drilling in Vitelma site, drilling point more than 200m east of Bogotá fault can escape from effect of the reverse fault (seeFigure-2.3-37).



Source: Llanopozos, JICA Study Team

Figure-2.3- 36 Geological Structure of EX-3 Site

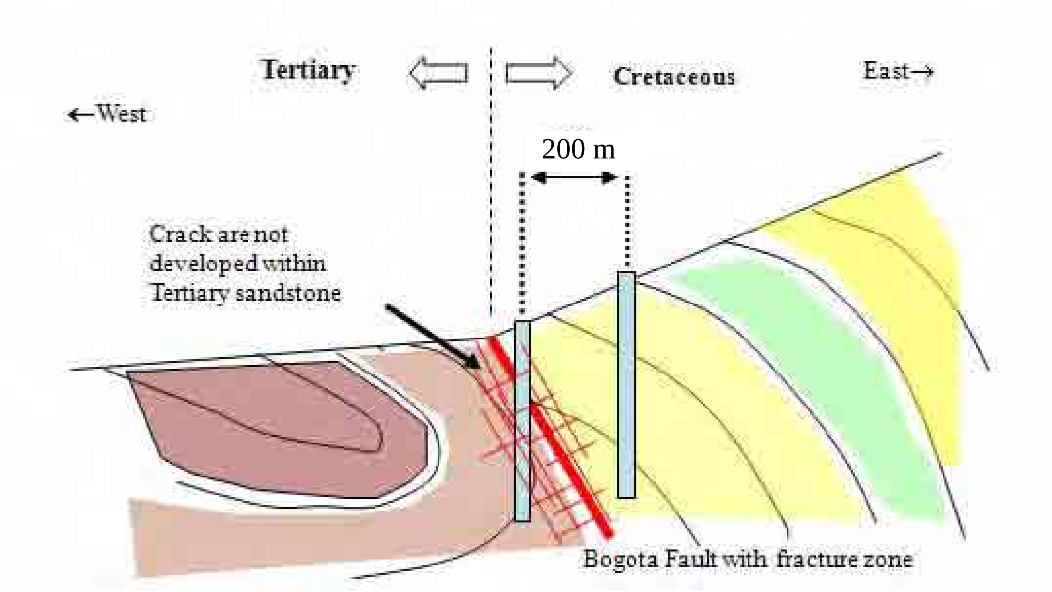


Figure-2.3- 37 Recommended Optimum Well Location

(3) The Result of Water Quality Tests

Table-2.3-11 and Table-2.3-12 show the results of water quality tests in the JICA Exploratory Wells as EX-6 Ciudad Bolivar and EX-3 Usme Cerveceria Alemana which were completed during the JICA's Study.

Table-2.3- 11 Results of Water Quality of EX-6 Ciudad Bolivar Well

Items	unit	The results	Colombian Norm Decreto1575/2007 and 2115/2007
Alkalinity	mg/ℓ	137	200
Ca	mg/ℓ	13.394	60
Cl	mg/ℓ	1.00	250
Color	UPC	38	15
Conductivity	µS/cm	270	1000
Hardness	mg/ℓ	19	300
Fe	mg/ℓ	2.002	0.3
Mg	mg/ℓ	1.438	36
Mn Total	mg/ℓ	0.041	0.1
PH	—	7.04	6.5 – 9.0
TDS	mg/ℓ	206	-
SO_4	mg/ℓ	ND	250
Turbidity	UNT	9.2	5

Table-2.3- 12 Results of Water Quality of EX-3 Usme Cerveceria Alemana

Items	unit	The results	Colombian Norm Decreto1575/2007 and 2115/2007
Alkalinity	mg/ℓ	60	200
Ca	mg/ℓ	15.82	60
Cl	mg/ℓ	2.60	250
Color	UPC	47	15
Conductivity	µS/cm	138	1000
Hardness	mg/ℓ	33	300
Fe	mg/ℓ	5.355	0.3
Mg	mg/ℓ	1.869	36
Mn Total	mg/ℓ	0.137	0.1
PH	—	8.02	6.5 – 9.0
TDS	mg/ℓ	103	-
SO_4	mg/ℓ	1	250
Turbidity	UNT	48	5

Font : JICA Study Team：Outsource to the ACUEDUCTO laboratory in May, 2008

The results exceeding the water quality standard are as follows.

1) Cloration

In addition to odor and taste, coloration has an impact on the perception of water quality. A high degree of coloration effectively limits the degree to which water can be used. Water source standard (assuming antiseptic chlorination) is 20 TCU, according to the Acueducto laboratory.

2) Fe and Mn

Detected iron and Manganese concentrations exceed the water quality standard. It is clear that both iron and manganese are affected by geological features. These results indicate same as the ex- JICA study. However it is not a special case of well water quality. Detected concentrations showed a range of values with tendency as well to exceed the accepted criterion. Methods for treating this are Oxidation, Oxidation-reduction, or Absorption. Treatment detail methods in this regard are to be designed at the feasibility study stage.

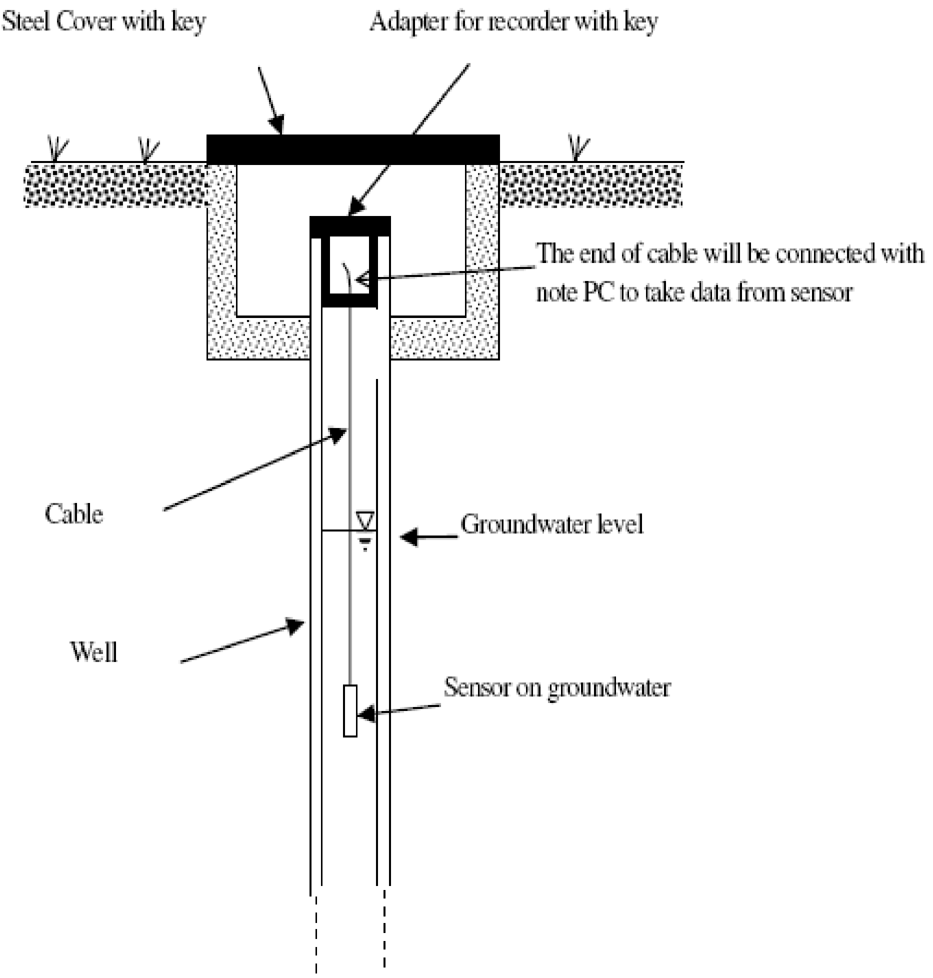
Even if exhibits a high concentration of Fe and Mn, overall, water quality of these exploratory wells is good.

(4) Installation of Automatic Groundwater Level Recorder

Automatic groundwater level recorders were installed into 2 exploratory wells and 1 observation well. Groundwater level of three wells will be continuously observed by the automatic recorders.

Structure of well with groundwater level automatic recorder is as shown in Figure-2.3-38.

- Acueducto will continue maintenance and monitoring of the recorders.



Source: JICA Study Team

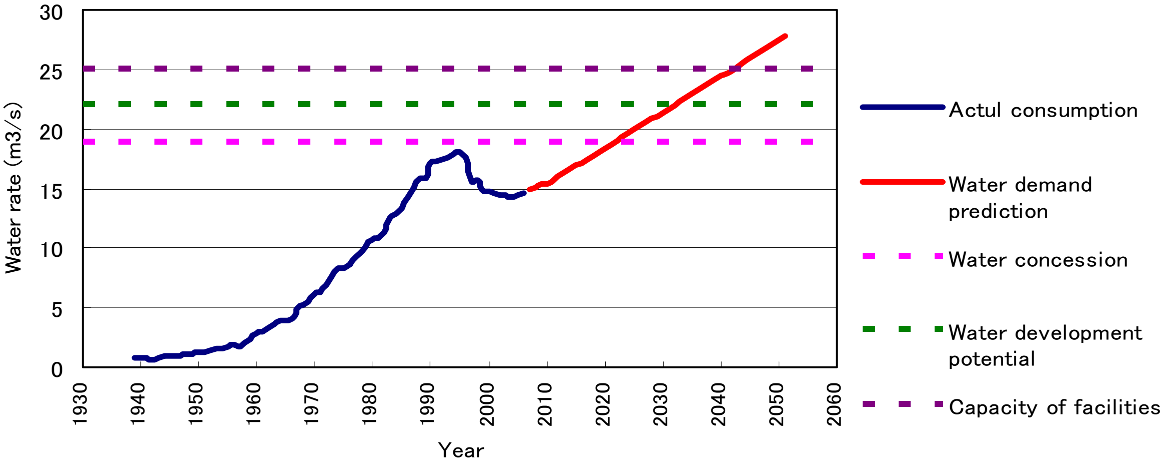
Figure-2.3- 38 Structure of Observation Well

CHAPTER 4 ISSUES IN EXISTING MASTER PLAN OF WATER SUPPLY

4.1. Existing Master Plan

(1) Water Demand Projection

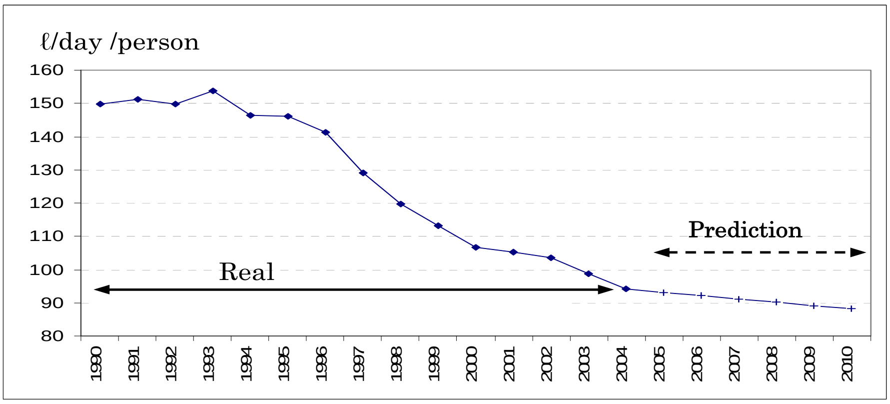
Actual water consumption in the past and predicted water demand for the future is shown in Figure-2.4-1. Actual unit water consumption for domestic use is shown in Figure-2.4-2.



Source: Acueducto, Plan de Expansión de Abastecimiento de Agua, 2005

Figure-2.4- 1 Actual Water Consumption and Predicted Water Demand

Water from Chingaza System was interrupted for nine months in 1997 because of collapse of the water conveyance tunnel from Chuza Reservoir. It is called "Crisis of Chingaza". Water consumption was dramatically reduced in that time. After the crisis, Acueducto reduced pressure of water supply, raised water tariff and performed campaign for saving water. As a result, the water consumption has been reduced to 89 ℓ/day/person in 2006, which is 60% of that in early 1990s of 150 ℓ/day/person. Water consumption is still being kept low in Bogotá after "Crisis of Chingaza".



Source: Acueducto, Estudio, Revisión y Ajuste del Modelo de Proyección de Demanda de Agua para la Ciudad de Bogotá, y los Municipios vecinos.

Figure-2.4- 2 Unit Water Consumption for Domestic Use and Prediction

Population of Bogotá is steadily growing during 1996 and 2006 with annual population growth rate of 2.9%. In contrast to population growth rate, the water consumption is steadily decreasing. As a result, total water consumption is still decreasing until now as shown in Figure-2.4-1. On the other hand, decreasing rate in unit consumption is predicted to be smaller or almost constant after 2006 as shown in Figure-2.4-2. As a result, total consumption is expected to increase after 2007, because effect of growing population will be more dominant than effect of decreasing unit consumption rate.

(2) M/P (1995 version)

Acueducto formulated the Expansion of Water Supply System (M/P) in 1995. Water production capacity of Acueducto is 25 m^3/s at that time. On the other hand, water demand was 18 m^3/s. It was predicted that water demand would exceed water production capacity in 2005. Therefore, development of new water resources was considered to be necessary from 2005. Based on this prediction, projects for water resources development were proposed as shown in Figure-2.4-1. However, predicted water demand was much higher than real water consumption because of “Crisis of Chingaza” in 1997. After the crisis, water consumption has been controlled by Acueducto.

Table-2.4- 1 Water Resources Development Projects in M/P in 1995

Project		**Water to be developed**	**Investment (Million US$)**
Chingaza expansion		5.0 m^3/s	250
Regadera II		1.2 m^3/s	100
Sumapaz	Upper-stream Sumapaz	10 m^3/s	500
	Down-stream Sumapaz	17 m^3/s	800

Source: Acueducto, Plan Maestro de Abastecimiento de Agua para Santa Fe de Bogotá, 1995

(3) Revised M/P (2005)

Acueducto revised the M/P (1995 version) in 2005. Water consumption of Bogotá D.C. was extremely reduced after “Crisis of Chingaza”. Then, water demand control followed by “Crisis of Chingaza” by Acueducto kept water consumption in lower level afterward. Revised M/P in 2005 succeeded projects proposed by the old M/P. However, beginning of projects proposed by the old M/P was put afterward to year of 2028, because real water demand was lower than the predicted demand. Projects proposed by revised M/P are classified into three categories as shown in Table-2.4-2.

Table-2.4- 2 Projects Proposed in Revised M/P (2005)

Period		Project	2010 2015 2020 2025 2030 2035 2040 2045 2050									
1st	2005-2020	1) Basic Study and Design	━	━	━							
2nd	2021-2028	2) Optimization of Water Supply System				━	━					
3rd	2029-2050	3) Expansion of Water Supply System						━	━	━	━	

Source: Acueducto, Plan de Expansión de Abastecimiento de Agua, 2005

Proposed project in the M/P is explained below:

<u>1st Period (2005-2020): Basic Study and Design</u>

Content of Basic Study and Design during 2005-2020 is shown in Table-2.4-3. These projects consist of various kinds of works such as field survey, design and construction work to prepare for the next stage: Optimization of Water Supply System (2021-2028), Expansion of Water Supply System (2029-2050). Groundwater development is included in this period. Importance of groundwater development proposed in M/P is summarized as shown below:

- Groundwater development in Bogotá city has a role of supplemental water supply to mitigate vulnerability of the current water supply system that depends on surface water sources of distant places.
- Groundwater is expected for water sources for emergency in case of water shortage due to vulnerability of the current water supply system.
- Water supply by use of groundwater should be planned, independent of the current water supply by use of surface water. It is because water supply by groundwater can compensate vulnerability of water supply by surface water.

Table-2.4- 3 Basic Study and Design during 2005-2020

Activity	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
a) Water Supply System																
– Review of the Master Plan of Supply						■					■					■
– Operation of Facilities		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
– Measurement of capacity of reservoir				■					■					■		
b) Rehabilitation and Vulnerability of the Current System																
– Use of overflow from Chuza dam					■											
– Design of conveyance pipe among La Regadera and El Dorado		■														
– Construction of conveyance pipe among La Regadera and El Dorado				■	■											
c) Optimization of Current Water Supply System																
– System of the Tunjuelo and San-Cristóbal River																
– Design of conveyance among La Laguna and Vitelma		■														
– Design for use of San-Cristóbal river				■												
d) Chingaza System																
– Reinforcement of water conveyance tunnel		■	■	■	■	■	■									
– Study on water quality of Blanco river				■												
– Study on capacity of intake of Blanco river		■														
e) Network of main distribution pipeline																
– Interconnection of the pipeline systems				■												
f) Expansion of Current Water Supply System																
– Expansion of Chingaza																
– Geological and topographical survey									■	■						
– Expansion of Wiesner Plant		■	■	■	■	■										
g) Groundwater development	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■

Source: Acueducto, Plan de Expansión de Abastecimiento de Agua, 2005.

2nd period (2021-2028): Optimization of Water Supply System

Projects proposed in optimization of Water Supply System are as shown in Table-2.4-4. In those projects, water resources will not be newly developed, but the existing water supply facilities will be improved for optimum use. Total amount of water of 2.73 m^3/s will be newly produced by improvement of the existing facilities.

Table-2.4- 4 Optimization of Water Supply System

Project Name	Construction period (year)	Cost (2004/Aug.)	Produced flow (m^3/s)	Volume (m^3)	Project life (year)
Expansion of pipeline from Regadera to La Laguna Plant, Vitelma Plant, Regadera dam, La Laguna Plant	2	7, 168, 000, 000	0.95	1,497,960,000	50
Full usage of Tominé Reservoir	2	63,409,000,000	1.48	2,333,664,000	50
Recycle of washing water in purification plant	2	23,100,000,000	0.30	520,344,000	50

Source: Acueducto, Plan de Expansión de Abastecimiento de Agua, 2005.

3rd period (2029-2050): Expansion of Water Supply System

Projects proposed in Expansion of Water Supply System are listed in Table-2.4-5. In these projects, water resources will be newly developed. Total amount of 17.82 m^3/s will be produced for water supply by projects below. As shown in Table-2.4-5, projects for expansion of water resources in Chingaza System are given high priority.

Table-2.4- 5 Expansion of Water Supply System

Priority	Water supply system	Project	Investment (Mill. US$)	Flow to be secured (m^3/s)	Unit price of water (US$/$m^3$)	Expected flow with concession (m^3/s)	Potential flow (m^3/s)
Current supply			-	-	-	17.84	21.04
1	Chingaza System	Over flow of Chuza dam	5.30	0.10	0.053	17.94	21.14
2		Chuza north water channel, stage-2	96.46	2.33	0.098	20.27	23.47
3		Chuza north water channel, stage-3	61.77	1.57	0.137	21.84	25.04
4		Playa dam	59.11	1.05	0.121	22.89	26.09
5		Southeast Chingaza water channel	65.19	1.08	0.122	23.97	27.17
6	Southern System	Regadera Dam II	123.60	0.70	0.248	24.67	27.87
7	-	Sumapaz upper-stream water channel	756.45	7.58	0.261	32.25	35.45
8		Sumapaz middle-stream water channel	1,109.26	17.82	0.680	42.49	45.69

Source: Acueducto, Plan de Expansión de Abastecimiento de Agua, 2005.

(4) Long term Water Demand Prediction

Long-term water demand of Bogotá D.C. is shown in Figure-2.4-1. On the other hand, the current capacity of facilities for water supply by Acueducto is shown in Table-2.4-6.

Table-2.4- 6 Water Right and Capacity of Water Production by Acueducto (2007)

Water Supply System	Factor to affect Water Use				Current production (m^3/s)	Potential increase in water production (m^3/s)
	Hydrological potential (m^3/s)	Capacity of purification[1] (m^3/s)	Water concession (m^3/s)	Minimum of (a), (b), (c)		
	(a)	(b)	(c)	(d)	(e)	(d)-(e)
(1) Chingaza	14.1	17.6	13.2	13.2	10.0	3.2
(2) Tibitóc	7.0	10.5	4.8	4.8	4.0	0.8
(3) Southern	0.9	2.1	1.0	0.9	0.5	0.4
Total	22.0	30.2	19.0	18.9	14.5	4.4

Source: Acueducto.

Note-1) Water purification capacity of Vitelma and San Diego plants is not included

As shown in Table-2.4-6, relationship among hydrological potential, capacity of facilities and water right is as below:

Water concession	<	Hydrological potential	<	Capacity of purification
(19.0 m^3/s)		(22.0 m^3/s)		(30.2 m^3/s)

As shown in above, amount of water concession is smallest of 3 factors. Water demand is predicted to exceed water right (18.8 m^3/s) in 2022, water potential (22.12 m^3/s) in 2033 and capacity of purification (25 m^3/s) in 2042, respectively.

As shown in Table-2.4-6, development of new water resources (construction of water intake facilities) and additional water right is necessary to use full capacity of the current facilities

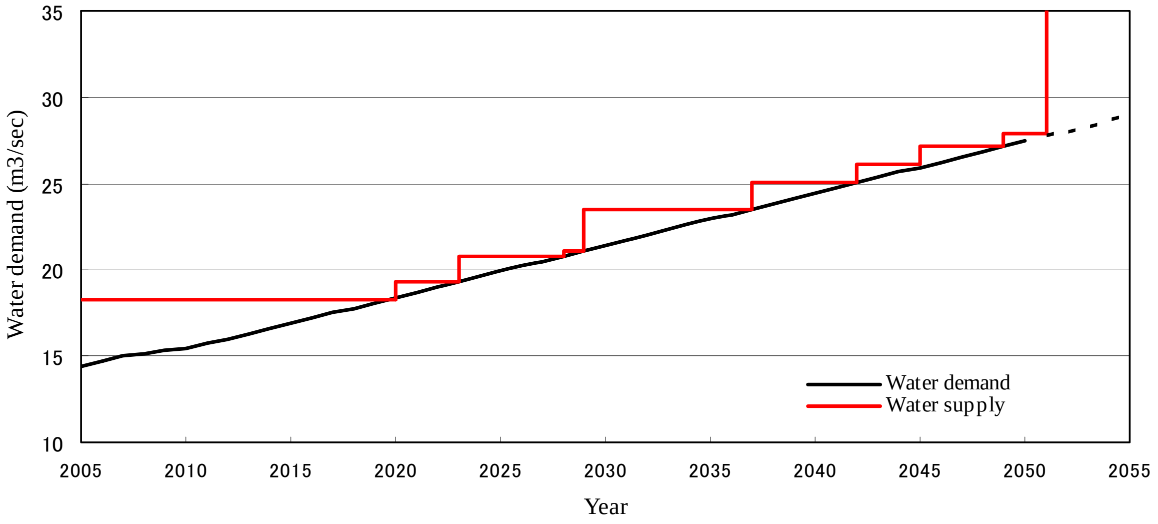
4.2. Review of Existing Master Plan

(1) Water Demand and Development of Water Resources

Acueducto has Master Plans of the optimization of water supply and expansion of water supply system. Relation between water demand and water supply by above project is shown in Figure-2.4-3.

(2) Quantity and Cost of Water Development

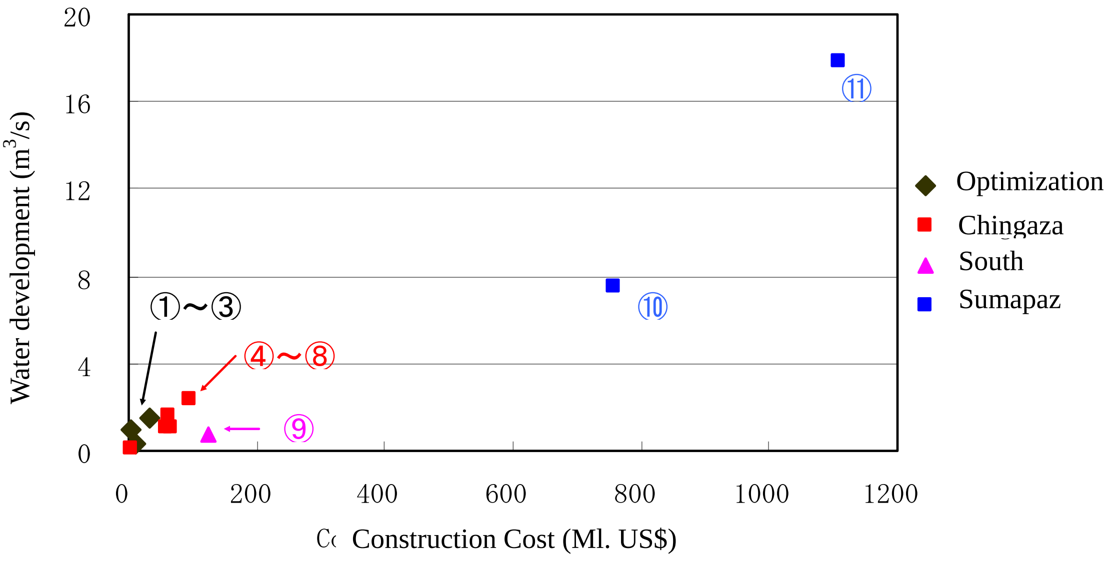
Relation between quantity and cost of water resources development of proposed projects is shown in Figure-2.4-4 and Figure-2.4-5.



	No.		Project		No.		Project
Optimization	①		Expansion of pipeline from Regadera to La Laguna Plant, Vitelma Plant, Regadera dam, La Laguna Plant	Expansion	⑥	Chingaza	Chuza north water channel, stage-3
	②		Full usage of Tominé Reservoir		⑦		Playa dam
	③		Recycle of washing water in purification plant		⑧		Southeast Chingaza water channel
					⑨	Southern	Regadera Dam II
	④	Chingaza	Over flow of Chuza dam		⑩	Sumapaz upper-stream water channel	Sumapaz upper-stream water channel
	⑤		Chuza north water channel, stage1-2		⑪		Sumapaz middle-stream water channel

Source: JICA Study Team analyzed based on M/P of Acueducto (2005)

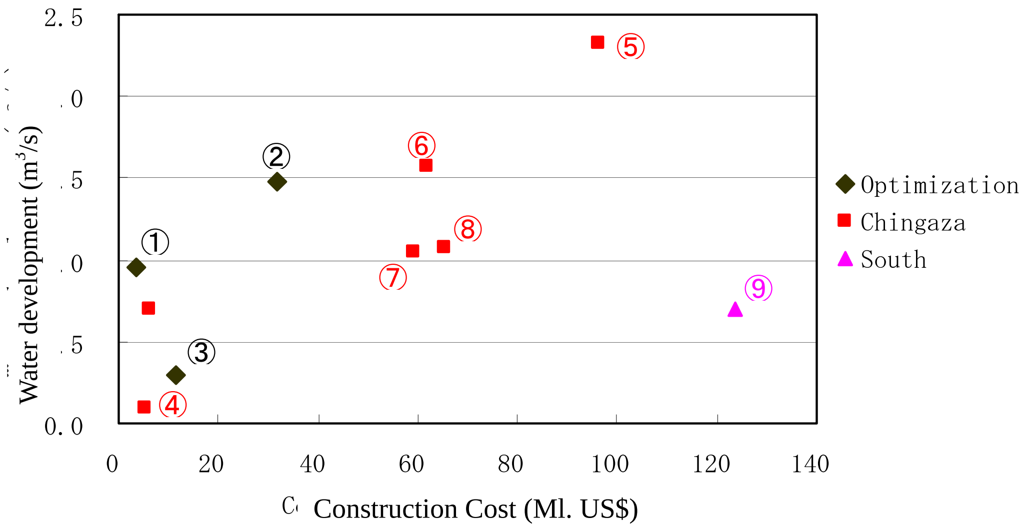
Figure-2.4- 3 Water Demand and Water Supply



Note: Number of project 1-11 is same as number in Figure-2.4-3 Source:

Source: JICA Study Team analyzed based on M/P of Acueducto (2005)

Figure-2.4- 4 Quantity and Cost of Projects (All)



Note: Number of project 1-11 is same as number in Figure-2.4-3.

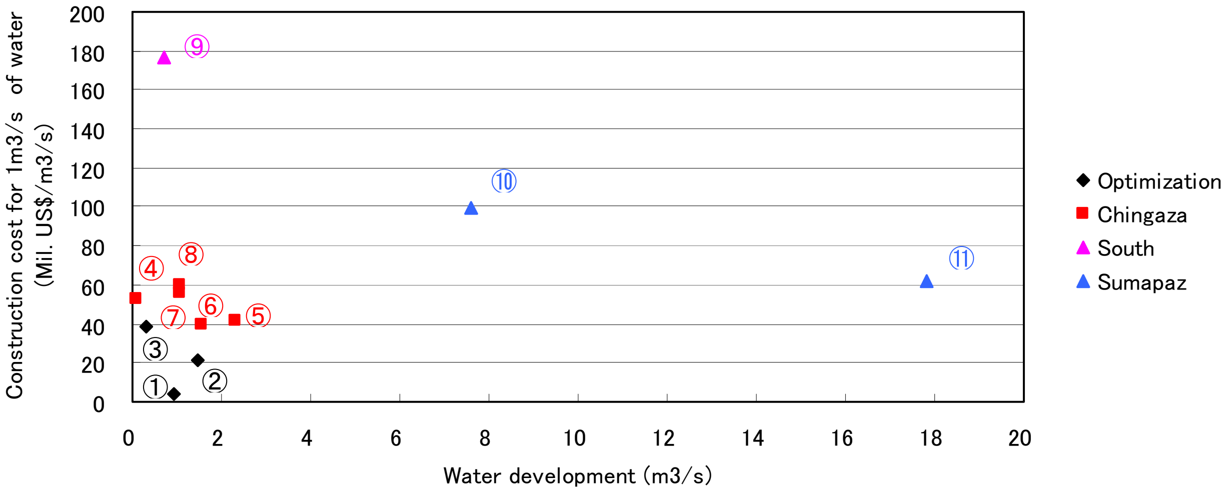
Source: JICA Study Team analyzed based on M/P of Acueducto (2005)

Figure-2.4- 5 Quantity and Cost of Water Development (Optimization and Expansion)

As shown in Figure-2.4-4, Sumapaz projects extremely lager than the other projects in quantity and cost. To the contrary, as shown in Figure-2.4-5, the optimization projects are smaller than the others. Chingaza expansion project is between them.

(3) Cost Efficiency of Projects

Cost of water development per 1m^3/s is shown by project in Figure-2.4-6.



Source: JICA Study Team analyzed based on M/P of Acueducto (2005)

Figure-2.4- 6 Cost Efficiency of Projects

It is said that there is a scale merit in water resources development projects. Generally, water development cost per 1 m^3/s will decrease as scale of water development increases. However, scale merit is not clear in proposed projects as shown in Figure-2.4-6.

- Chingaza expansion project is lower in development scale but higher in cost efficiency than Sumapaz development project. Both projects need construction of new facilities. However, existing water conveyance tunnel (40 km length) can be used for Chingaza expansion projects. This why Chingaza project has such a high cost efficiency.
- Chingaza expansion project consists of 5 independent projects. Each project can be implemented step by step closely following increase of water demand. It will make unused facilities minimum and realize higher cost efficiency.

- Optimization project has highest efficiency because new construction is not necessary for this project. However, amount of developed water is small.

Southern development (new Regadera dam) project has the lowest efficiency. There are already 3 existing dams (Regadera, Tunjuelo、Los Tunjos) in the Tunjuelo river. It is why efficiency of additional dam construction is lower in Tunjuelo River

(4) Implementation Schedule of Expansión of Water Resources

Implementation schedule of 11 projects for water resources expansion, which was proposed in the existing Acueducto M/P, is closely keeping pace with growing water demand. In principle, projects with higher efficiency and lower cost are scheduled to begin earlier. On the other hand, projects with lower efficiency and large cost are scheduled to begin later. Such an arrangement will achieve high financial efficiency.

4.3. Water Resources Management

The existing M/P was reviewed in this Study from 4 view points: i) quantity management, ii) quality management, iii) water distribution management and vi) risk management. The result of the review is described below.

(1) Quantity Management

Control of water supply rate

Access rate to water supply in Bogotá D.C. is more than 90%. Average unit water consumption is 89 ℓ/capita/day for domestic use. There was serious water shortage in 1997 called “Crisis of Chingaza”. After it, Acueducto has controlled water consumption by high water tariff, reduced pressure of water tap and campaign for saving water. As a result, water consumption was reduced from 150 ℓ/capita/day in 1992 to 89 ℓ/day/person in 2006 in average. This consumption rate is much lower than that in capital cities of the other South American countries. For more efficient water supply, Acueducto has implemented measures explained below:

Measure to uncounted for water

The current uncounted for water of Acueducto is said 38%. Acueducto is performing detection of water leakage. Then, Acueducto will replace old pipes with new ones. According to Acueducto, water leakage rate is 12%, which is much lower than that of other capital cities in other southern American countries. It is expected that leakage rate will be kept low level in the future by continuous effort by Acueducto.

(2) Quality Management

(a) Surface Water Quality

Water supply of Bogotá Metropolitan Area depends on surface water. There are three water supply systems, which take water from the rivers and treat it in the purification plants. Treated water quality meets water quality standard of Colombia. The current situation of water quality control in the 3 water supply system is shown in Table-2.4-7.

Table-2.4- 7 Current Situation of Water Quality Control

Supply system	River for water sources	Control of water quality
a) Chingaza	-Chuza -Guatiquía -Blanco	Rivers are located inside the national park. Any activity to give impact to the water quality of the rivers is prohibited, which keeps clean river water. Acueducto is implementing projects to conserve water quality in the area
b) Tibitóc	-Bogotá	CAR is in charge of control of water quality of Bogotá River out of Bogotá D.C., including water intake point of Acueducto in Tibitóc Plant. Deterioration of water quality of Bogotá River is more serious than the other water sources.
c) Southern	-Tunjuelito	There is no activity to give impact to water quality in upper reaches of Tunjuelito River, where Acueducto takes river water for water supply. Acueducto is implementing projects in the area to keep river water clean.

Source: JICA Study Team

Water use is very active along Bogotá River, where there are many points for water intake and drainages. Water quality of Bogotá River is more deteriorated than other water sources. In the area of upper reaches of Tibitóc Plant, water quality of Bogotá River is under control of CAR. CAR is currently operating water sewerage treatment plants in 24 sites in upper reaches of Bogotá River, where degree of contamination is currently within the limits stipulated in water quality standard. However, polluted load will be increased in the near future so that it is expected that current water treatment plants will not be able to treat it any more. It depends on CAR whether water quality of Bogotá River is improved or worsens in the future.

(b) Groundwater Quality

Management of groundwater quality of the Study Area is as follows:

Groundwater quality of the Quaternary Aquifer

There is high concentration of organic materials in groundwater in the Quaternary Aquifer, which needs full-scale water purification for drinking. Therefore, groundwater of the Quaternary Aquifer is mainly for agricultural use. The organic materials are originated from geology and not by artificial pollution. Large amount of groundwater is currently being withdrawn from the Quaternary Aquifer, but no measure is performed in order to conserve groundwater quality.

In recent years, non-operating wells within Bogotá urban area were closed by SDA. It is for protection of groundwater to be contaminated though the non-operating wells. This can be called as an activity for water quality management.

Groundwater in the Cretaceous Aquifer

Water quality of the Cretaceous Aquifer is good, which is suitable for drinking. However, currently groundwater is not being withdrawn from the Cretaceous Aquifer of the Eastern and Southern Hills. So far there is no information on pollution of the groundwater of the Cretaceous Aquifer in the area. Every activity for new development is prohibited in the forest protection area of the Eastern Hills by regulation since 2004. This regulation will contribute to conservation of the groundwater resources of the Cretaceous Aquifer, which is mainly recharged by rainfall in the Eastern Hills. This can be called as an activity for water quality management.

(3) Water Distribution

(a) Water concession of surface water

Water concession for Acueducto is divided into two categories: Bogotá River Basin and the other River Basin.

Water concession of Bogotá River Basin

Water production of Tibitóc Plant occupies 30% of the total water supply by Acueducto. Water of Bogotá River is used not only for water supply but also for agricultural and industrial use. Water concession for agricultural use is recently increasing. Taking into account of current tendency above, it is not practical for Acueducto to expect increase of water concession of Bogotá River in the future. Water concession for intake at Tibitóc Plant is under pending in court between CAR and Acueducto since 2002.

Water concession out of Bogotá River Basin

Acueducto is planning to develop water resources out of Bogotá River Basin, such as in Chingaza and Sumapaz River Basin. Water concession of those rivers basin is controlled by UAESPNN, CORPOGUAVIO and CORPOORINOQUIA. Acueducto has water concession from these organizations for current water use. Considering relationship between Acueducto and above three organizations, there is high possibility that Acueducto will get new water concession from these organizations in the future.

Price of water concession

In the past, Acueducto paid Col$ 120-150 /m^3 to CAR for water concession for intake of river water for water supply. However, price of concession sharply decreased to Col$ 0.56 /m^3 in 2006. It will be again raised gradually every year for coming 10 years stating from minimum concession price of Col$ 0.56 /m^3. The price will be decided based on negotiation between environmental organizations (CAR and SDA) and water users (such as Acueducto).

(b) Water concession of Groundwater

Groundwater in the Eastern and Southern Hills of Bogotá is promising for new water sources of water supply. CAR and SDA has authority to give concession of groundwater of the above mentioned area. Whether concession will be given or not depends on estimated groundwater development potential. Concession will be given to users if CAR and SDA judge that groundwater development potential of the area is large enough for development. On the other hand, any activity including water resources development is prohibited in the forest protected area (almost above 2,700 m) of the Eastern Hills. Therefore, groundwater development should be performed out of the protected area. To the contrary, there is no forest protection area in the Southern Hills, where groundwater development is prohibited.

(4) Risk Management

According to M/P by Acueducto (2005), water resources development in Chingaza Area is proposed as high priority projects to meet the future water demands. Excellent water quality of the area contributes to lower operation cost for water purification than those of the other supply systems. Moreover, there is large amount of water resources in the area. As a result, Chingaza System occupies 70% of the total water supply by Acueducto, with the lowest cost of the entire supply system. There is still enough surplus capacity of water conveyance in Chingaza System, which will be able to cover future expansion. It is sure that Chingaza System will become more important in future water supply.

On the other hand, water is conveyed though mountain tunnel of 40 km length in Chingaza System, which is vulnerable to natural disaster such as earthquake. It is likely to happen that water conveyance tunnel will collapse, and water supply will be interrupted again, the same as case of “Chingaza Crisis” in 1997. It is clear that expansion of Chingaza System will increase vulnerability of water supply. To mitigate its vulnerability, measures shown in Table-2.4-8 are proposed.

Table-2.4- 8 Measures for Emergency Water Supply

Measures		Content
Measures in hardware	Improvement for anti-seismic structure	• Design and reinforcement for anti-seismic structure of water supply facilities such as dams, pipelines, tanks and so on.
	Alternative water sources for emergency	• Re-operation of closed water purification plants • Temporal increase of water production of existing plants • Development of new water sources such as Groundwater.
Measures in software	Establishment of emergency water supply system	• Preparation of manual for emergency water supply • Establishment of centralized control system of water supply facilities for emergency response

Source: JICA Study Team

It is concluded by the previous studies that damage by earthquake will be more serious than the other natural disasters in the Study Area. Damage to water supply facilities by occurrence of large earthquake has been analyzed in the past studies. Acueducto is preparing for emergency response in hardware and software aspects as explained below:

According to the Study of Acueducto (2006), various types of measures have been proposed, which is mainly anti-seismic design and reinforcement for water supply facilities. However, it is also important to develop alternative water sources near Bogotá Metropolitan area and to establish emergency water supply system by use of the alternative sources. Continuous maintenance works for seismic reinforcement is also important. Incorporation of every measure will make great efficiency for emergency water supply.

4.4. Proposal to M/P of Acueducto

1) Projects proposed in M/P are scheduled to start after year of 2029. High priority is given to

projects of expansion of water sources in Chingaza System. There are enough surpluses in capacity of water conveyance of the system. Therefore, construction of new water conveyance system is not necessary for Chingaza System. Water sources in Chingaza System are located in high elevation area, which allows the water to be conveyed and transmitted by gravity only with low cost. Moreover, excellent water quality of the water sources contributes to low cost for water treatment. Taking into account of favorable condition above, it is evident that expansion of Chingaza System has a clear advantage over projects in the other area, from every view points. Water sources should be expanded following above mentioned context.

2) On the other hand, water is conveyed to Bogotá Metropolitan area though single mountain tunnel of 40 km length in Chingaza System. There is high risk of interruption of water conveyance due to tunnel collapsing, as “Crisis of Chingaza (1997)” proved it. Thus, Tibitóc and Southern System is less vulnerable than Chingaza System, in view point of maintenance of water transmission and distribution.

3) Water supply by Chingaza System occupies 70% of total water supply of Bogotá Metropolitan area in quantity. According to M/P of Acueducto, water supply by Chingaza System will be expanded in the future. Therefore, risk in interruption of water conveyance from Chingaza area will be increased in the near future. As measures for it, projects for emergency water supply should be prepared as shown below:

    a) Continuous operation of Tibitóc plant, and increase of water production of the plant in case of emergency.

    b) Preparation for re-operation of closed plants.

    c) Development of groundwater in suburb of Bogotá Metropolitan area for alternative water sources for emergency.

4) M/P of Acueducto will be reviewed in 2008. It should be carefully re-examined when projects proposed in M/P will begin. Moreover, plan for development of alternative water sources for emergency water supply should be included in the M/P.