2.2 Groundwater Recharge

2.2.1 Basic Equation of Water Balance Analysis

Groundwater is recharged from rainfall in mountains and hills, plains and rivers in the Study Area, then recharge groundwater gradually infiltrates into deep aquifers. The purpose of water balance analysis is to estimate groundwater recharge. Water balance equation used for this analysis is shown below.

$$P - ETR + (D_1 - D_2) + (G_1 - G_2) - U = \Delta Ss + \Delta Sw + \Delta Hs \quad (1)$$

P------ Precipitation (mm)
ETR-- Real evapo-transpiration (mm)
G1---- Direct runoff into basin (mm)
G2---- Direct runoff from basin (mm)
D1----Groundwater flow into basin (mm)
D2----Groundwater flow from basin (mm)
U----- Consumed water within basin (mm)
ΔSs---Increase of surface water storage in basin (mm)
ΔSw—Increase of groundwater storage in basin (mm)
ΔHs---Increase of soil moisture in basin (mm)

Rainfall which reaches the ground surface infiltrates into soil. Infiltrating water recovers soil moisture deficit, then it becomes partly direct runoff and partly becomes groundwater recharge. Under this assumption, groundwater recharge was calculated by the use of equation above. This equation is almost the same as that used by INGEOMINAS and CAR. This equation was applied for selected ten river basins, Tunjuelito, Teusaca, Tomine, Sisga, Choconta, Neusa, Frio, Chicu, Subachoque, Bojaca to estimate groundwater recharge.

Equation (1) is simplified by assumption below.

- D_1 (direct runoff into basin) and G_1 (Groundwater flow into basin) are neglected because water balance analysis deals entire basin.
- U(water consumption in basin) and ΔSs (Increase of surface water storage) is neglected because these element is negligible compared with the other elements.

Under assumption above, equation (1) is simplified as below:

$$P - D_2 - ETR - G_2 = \Delta Sw + \Delta Hs$$

Moreover, equation (1) is modified as below:

$$P - D_2 - ETR - \Delta Hs = G_2 + \Delta Sw \quad (2)$$

P----- Precipitation into basin (mm)
ETR—Real evapo-transpiration from basin (mm)
D_2 ----direct runoff from basin (mm)
ΔHs—Increase of soil moisture in basin (mm)
G_2 ---Groundwater flow from basin (mm)
ΔSw---Increase of groundwater storage in basin (mm)

The right terms of equation (2) means groundwater recharge. Therefore, calculation of the left terms of equation (2) gives groundwater recharge. Groundwater flow from basin (G_2) consists of baseflow ($G_{2\text{-baseflow}}$) and groundwater infiltration to deep aquifer ($G_{2\text{-aquifer}}$).

$$G_2 = G_{2\text{-baseflow}} + G_{2\text{-aquifer}}$$

G_2 : Groundwater flow
$G_{2\text{-baseflow}}$: Baseflow of river
$G_{2\text{-aquifer}}$: Groundwater infiltration into deep aquifer

Therefore, equation (2) is modified as shown below:

$$P - D_2 - ETR - \Delta Hs = G_{2\text{-baseflow}} + G_{2\text{-aquifer}} + \Delta Sw$$

Equation above is modified again as shown below:

$$P\text{-}ETR\text{-} (D_2 + G_{2\text{-baseflow}}) + \Delta Hs = G_{2\text{-aquifer}} + \Delta Sw \quad (3)$$

Observed river discharge is (D_2+ $G_{2\text{-baseflow}}$), then left terms of equation (3) were calculated in this analysis. Therefore, value of the right terms of equation (3) is "total groundwater infiltration into aquifer minus baseflow". ΔHs and ΔSw in equation (3) is approximated ΔHs÷ 0 and ΔSw ÷0 if added up for one year. Therefore, annual groundwater annual recharge can be calculated by equation below:

$$\text{Annual groundwater recharge} = P\text{-}ETR\text{-} (D_2 + G_{2\text{-baseflow}}) \quad (4)$$

P : Precipitation into basin (mm/year)
ETR :Real evapo-transpiration from basin (mm/year)
(D_2 +$G_{2\text{-baseflow}}$) :Runoff from basin (mm/year)

Basins for Water Balance Analysis and Period for Water Balance Analysis

Water balance analysis was carried out for all the basins of the Study Area. Hydrological and meteorological data used for this analysis are mainly from CAR that has accumulated long-term observation data for 5 to 30 years. Groundwater recharge was analyzed using long-term annual average data.

Precipitation of Basins (P)

Average annual precipitation of the Study Area is shown in Figure-2.3. Average annual precipitation of the Study area is 802mm.

River Discharge of Basins（D_2 +$G_{2\text{-baseflow}}$）

River discharge of the Study Area was analyzed and its result is shown in "2-1 Water Balance".

Potential Evapo-transpiration (Etp)

Potential evapo-transpiration is necessary for analysis of real evapo-transpiration. Real evapo-transpiration is function of precipitation, river discharge, potential evapo-transpiration and soil moisture. Therefore, potential evapo-transpiratoin is most important factor for estimation of real evapo-transpiration. However, it is extremely difficult to directly measure potential evapo-transpiration. Accordingly, potential evapo-transpiration is usually evaluated by experimental methods. Three methods listed below were frequently used for evaluation of potential evapo-transpiration in the Study Area. Thornthwait method, which is commonly used in Japan, has seldom been used in the Study Area because this method gives too high evapo-transpiration in the Study Area.

Table-2.7 Methods Commonly used in the Study Area for Evaluation of Potential Evapo-transpiration and Meteorological Data Necessary for Calculation

Parameters	Penmma –Monteith[1)]	Hargreaves	Turc
Average temperature	○	○	○
Average humidity	○	-	○
Average wind speed	○	-	-
Average sun shine hours	○	○	-
Average maximum sunshine hours	-	○	-
Average solar radiation	-	○	○

Note) Penmman-Monteith method needs more parameters than shown in Table-2.9, of which values were selected following FAOs standard values.

Three methods above use different meteorological data to evaluate potential evapo-transpiration and usually give different results. There is no conclusion so far on which method is most suitable for the Study Area. Then, comparison of these three methods was carried out in this analysis. For this purpose, results of above three methods were compared with observed pan-evaporation. Six meteorological stations, where necessary data for calculation of three methods and pan-evaporation data are accumulated, were selected in the Study Area. These six stations are listed below:

- Dona Juana
- Muna
- Neusa
- Checua
- Guatavita
- Guaymaral
- Tabio

Monthly potential evapo-transpiration was calculated for six stations by use of monthly data available, and these calculated results were compared with pan-evaporation data. Result of this comparison is summarized below:

- Penmman –Monteith Method gives potential evaporation of 100%～160% of pan-evaporation.
- Hargreaves Method gives potential evapo-transpiration of 85%-120% of pan-evaporation.
- Turc Method gives potential evapo-transpiration of 75%-100% of pan-evaporation
- Result of Turc Method has the highest correlation with pan-evaporation, Hargreaves Method has medium correlation, and Penmma –Monteith Method has lowest correlation.

As mentioned above, Turc Method seems most suitable for the Study Area if compared with pan-evaporation. However, reliability of three methods have not been concluded so far in the Study area. Therefore, the Study team used pan-evaporation for evaluation of potential evapo-transpiration. Pan-evaporation is easily converted to potential evapo-transpiration and is widely used for evaluation of potential evapo-transpiration. Accordingly, it seems that evaluation of potential evapo-transpiration from pan-evaporation is most reliable in the Study Area. In the Study Area, Class-A-Pan evaporimeters are used. It is commonly said that potential evapo-transpiration is approximated by 70% of pan-evaporation value measured by Class- A- Pan evaporimeter. Pan-evaporation of each basin was calculated by Thiessen method (see Figure-2.12), and potential evapo-transpiration of each basin was calculated as 70% of the pan-evaporation of reach basin. The calculated potential evapo-transpiration is shown in Figure-2.12.

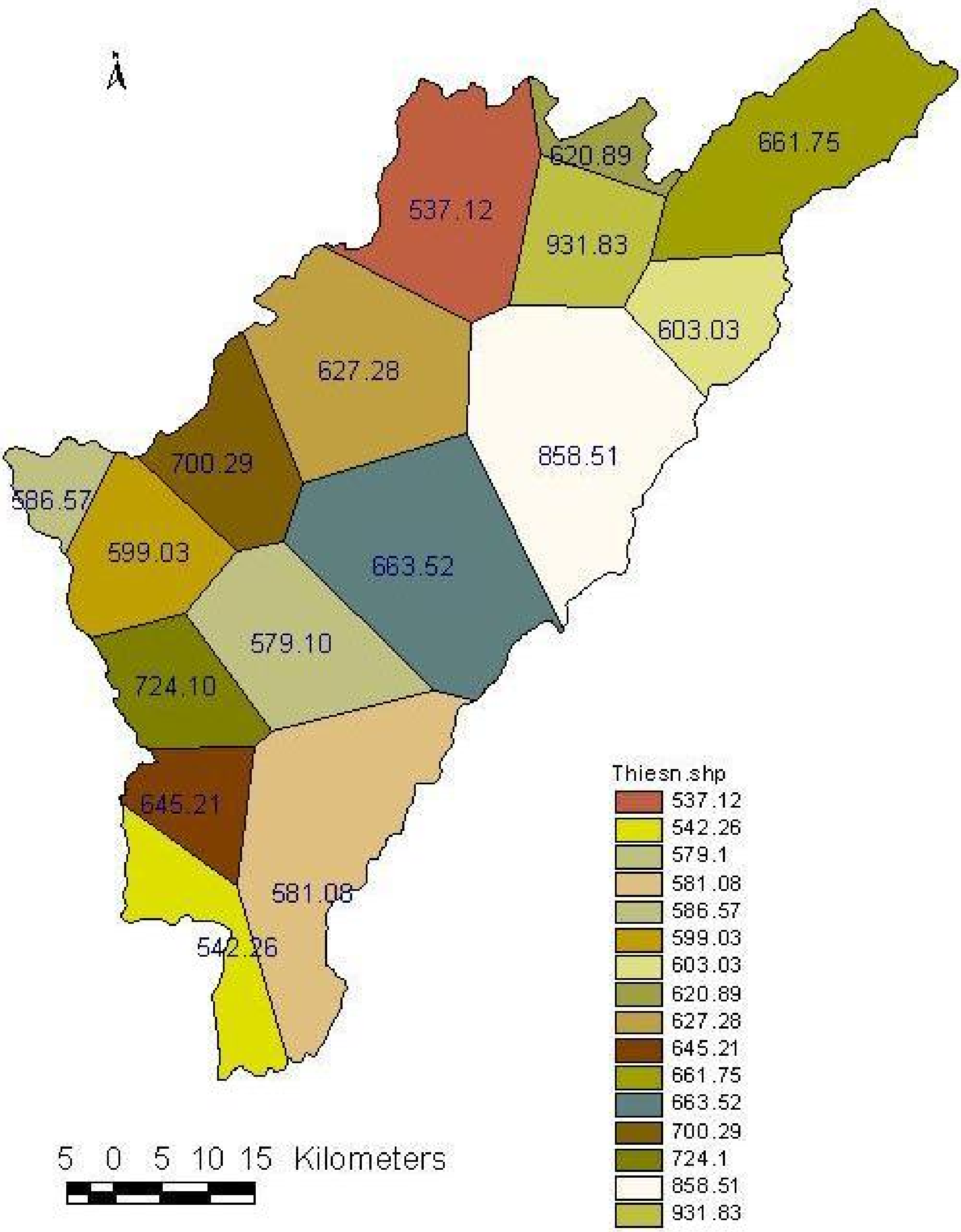

Figure-2.12 Annual ETP (mm/year)

Real Evapo-transpiration

Real evapo-transpiration (ETR) is function of precipitation, potential evapo-transpiration (ETP) and soil moisture. Especially, evapo-transpiration ratio (= ETR/ETP) is said to have strong relationship with of precipitation, potential evapo-transpiration and soil moisture. Therefore, firstly special model was made for calculation of evapo-transpiration ratio (= ETR/ETP). Using this model, evapo-transpiration ratio was expressed by function of precipitation, potential evapo-transpiration (ETP) and soil moisture. Secondly real evapo-transpiration was calculated by applying this function to the Study Area.

Date for Model Analysis

Daily precipitation data and daily pan-evaporation data were used for the model analysis as shown in Table-2.8. Most of data are during 1991 to 1998, for 8 years.

Table-2.8 Observation Station of CAR

CAR Station	Observation period
Checua	1991-1997
Guatavita	1991-1997
Guymaral	1991-1998
Iberia	1991-1998
Muna	1991-1998
Neusa	1991-1998
Primavara	1991-1998
Ramada	1991-1998
Tabio	1991-1996
Venecia	1991-1997
Dona Juana	1991-1992,1994-1998
Barrancas	1991-1997
Sisga	1993-1997
Tisquesusa	1991-1998

(1) Total Available Moisture in the Soil by Soil Type

To estimate evapo-transpiration ratio by model calculation, Total Available Moisture in the Soil must be given to the Model. Total Available Moisture in the Soil was set for typical three type of soils based on FAO data.

Table-2.9 Total Available Moisture in the Soil

Soil Type	Field capacity－Wilting Point	Soil Thickness	Total Available Moisture in the Soil
Clayey Soil	180mm/m	× 0.5m	= 90mm
Medium Soil	140mm/m	× 0.5m	= 70mm
Sandy Soil	100mm/m	× 0.5m	= 50m

(2) Model Calculation Method

Daily soil water balance was analyzed in Model soil with daily precipitation and daily potential evapo-transpiration.

- When soil water exceeds Total Available Moisture in the soil, surface water and groundwater discharge occur.
- Daily potential evapo-transpiration (ETR) = Daily pan evaporation ×0.7
- Actual maximum Potential Evapo-transpiration (ETP_R) = kc ×ETR. Where, kc is Crop

Coefficient. Crop coefficient is set 0.8 considering vegetation of the Study Area and referring FAO data.

- Real evapo-transpiration occurs following relation below:

Soil moisture > Total Available Moisture in the soil	ETR of the day = Actual maximum Potential Evapo-transpiration (ETP_R)
Soil moisture > Total Available Moisture in the soil	ETR of the day = ETP_R ×Soil water of the day /Total Available Moisture in the soil

14 observation stations have almost 100% of daily precipitation data. On the other hand, many daily pan-evaporation data are missing in 14 stations. Missing pan-evaporation were assumed by two methods, 1) interpolation, 2) use of average values of all the recorded data for missing data Both method gave almost the same result on evapo-transpiration ratio (ETR/ETP).

(3) Result of Analysis

Water soil balance was analyzed using daily precipitation and daily pan-evaporation of 8 years. The analysis were carried out for 3 types of soil, and evapo-transpiration ration (ETR/ETP) were obtained for each soil type for 8 years. The result is shown in Table-2.10, 2.11, 2.12. Though calculated evapo-transpiration ratio of 14 stations shows difference each year, average of 8 years show clear tendency.

Table-2.10 Average evapo-transpiration ration of 8 years (Total Available Moisture in soil = 50mm)

Station	Period	Precipitation (mm/year)	Pan evaporation (mm/year)	ETP (mm/year)	ETR (mm/year)	Precipitation / ETP	(ETR/ETP)
Checua	1991-1997	576	1376	963	463	0.60	0.48
Guatavita	1991-1997	699	1167	817	486	0.86	0.59
Guymaral	1991-1998	791	1006	704	463	1.12	0.66
Iberia	1991-1998	774	1053	737	446	1.05	0.61
Muna	1991-1998	554	1008	706	379	0.79	0.54
Neusa	1991-1998	833	874	612	417	1.36	0.68
Primavara	1991-1998	750	1040	728	457	1.03	0.63
Ramada	1991-1998	720	999	699	421	1.03	0.60
Tabio	1991-1996	734	1159	811	465	0.90	0.57
Venecia	1991-1997	854	1070	749	471	1.14	0.63
Dona Juana	1991-1992 1994-1998	656	1279	895	494	0.73	0.55
Barrancas	1991-1997	656	1124	787	462	0.83	0.59
Sisga	1993-1997	1042	1071	749	505	1.39	0.67
Tisquesusa	1991-1998	643	991	694	422	0.93	0.61

Note) Potential evapo-transpiration (ETP) = 0.7×Pan evaporation

(4) Approximation Function for Evapo-transpiration Ratio

Analyzed results in Table-2.10, 11, 12 show that Evapo-transpiration ratio (ETR/ETP) has strong relationship with (Annual precipitation÷Annual ETP) and soil moisture as shown in Figure-2.14. Therefore, evapo-transpiration ratio (ETR/ETP) can be approximated by a function with three parameters (annual precipitation, annual ETP and available soil water). Function is proposed as shown below:

Table-2.11 Average evapo-transpiration ration of 8 years (Total Available Moisture in soil = 70mm)

Station	Period	Precipitation (mm/year)	Pan evaporation (mm/year)	ETP (mm/year)	ETR (mm/year)	Precipitation / ETP	(ETR/ETP)
Checua	1991-1997	576	1376	963	484	0.60	0.50
Guatavita	1991-1997	709	1192	835	511	0.85	0.61
Guymaral	1991-1998	791	1006	704	475	1.12	0.67
Iberia	1991-1998	774	1053	737	457	1.05	0.62
Muna	1991-1998	554	1008	706	395	0.79	0.56
Neusa	1991-1998	833	874	612	427	1.36	0.70
Primavara	1991-1998	750	1040	728	474	1.03	0.65
Ramada	1991-1998	720	999	699	437	1.03	0.62
Tabio	1991-1996	754	1016	711	457	1.06	0.64
Venecia	1991-1997	854	1070	749	489	1.14	0.65
Dona Juana	1991-1992, 1994-1998	656	1279	895	512	0.73	0.57
Barrancas	1991-1997	656	1124	787	480	0.83	0.61
Sisga	1993-1997	1042	1071	749	514	1.39	0.69
Tisquesusa	1991-1998	643	991	694	431	0.93	0.62

Note) Potential evapo-transpiration (ETP) = 0.7×Pan evaporation

Table-2.12 Average evapo-transpiration ration of 8 years (Total Available Moisture in soil = 90mm)

Station	Period	Precipitation (mm/year)	Pan evaporation (mm/year)	ETP (mm/year)	ETR (mm/year)	Precipitation / ETP	(ETR/ETP)
Checua	1991-1997	576	1376	963	497	0.60	0.52
Guatavita	1991-1997	699	1167	817	513	0.86	0.63
Guymaral	1991-1998	791	1006	704	475	1.12	0.67
Iberia	1991-1998	774	1053	737	467	1.05	0.63
Muna	1991-1998	554	1008	706	399	0.79	0.57
Neusa	1991-1998	833	874	612	433	1.36	0.71
Primavara	1991-1998	750	1040	728	484	1.03	0.67
Ramada	1991-1998	720	999	699	447	1.03	0.64
Tabio	1991-1996	754	1016	711	466	1.06	0.65
Venecia	1991-1997	854	1070	749	500	1.14	0.67
Dona Juana	1991-1992, 1994-1998	656	1279	895	524	0.73	0.59
Barrancas	1991-1997	656	1124	787	493	0.83	0.63
Sisga	1993-1997	1042	1071	749	519	1.39	0.69
Tisquesusa	1991-1998	643	991	694	439	0.93	0.63

Note) Potential evapo-transpiration (ETP) = 0.7×Pan evaporation

Evapo-transpiration ratio(ETR/ETP)=LN($a \times P^b \times W^c$)

P ：（Annul precipitation ÷ Annual ETP）
W： Maximum Available water of soil (mm)
a、b、c ：Constant
LN( )：Natural log

Constants (a, b, c) are assumed by the least square method. This result is: a=1.49, b=0.216, c=0.0545. The function is finally decided as shown below:

Annual Evapo-transpiration Ratio (ETR/ETP) = LN($1.49 \times P^{0.216} \times W^{0.0545}$)

Accuracy of the function is shown in Figure-2.13. Figure-2.13 shows high accuracy of the function. By this function, real evapo-transpiration (ETR) of the Study Area can be estimated considering precipitation, potential evapo-transpiration (ETP) and soil types.

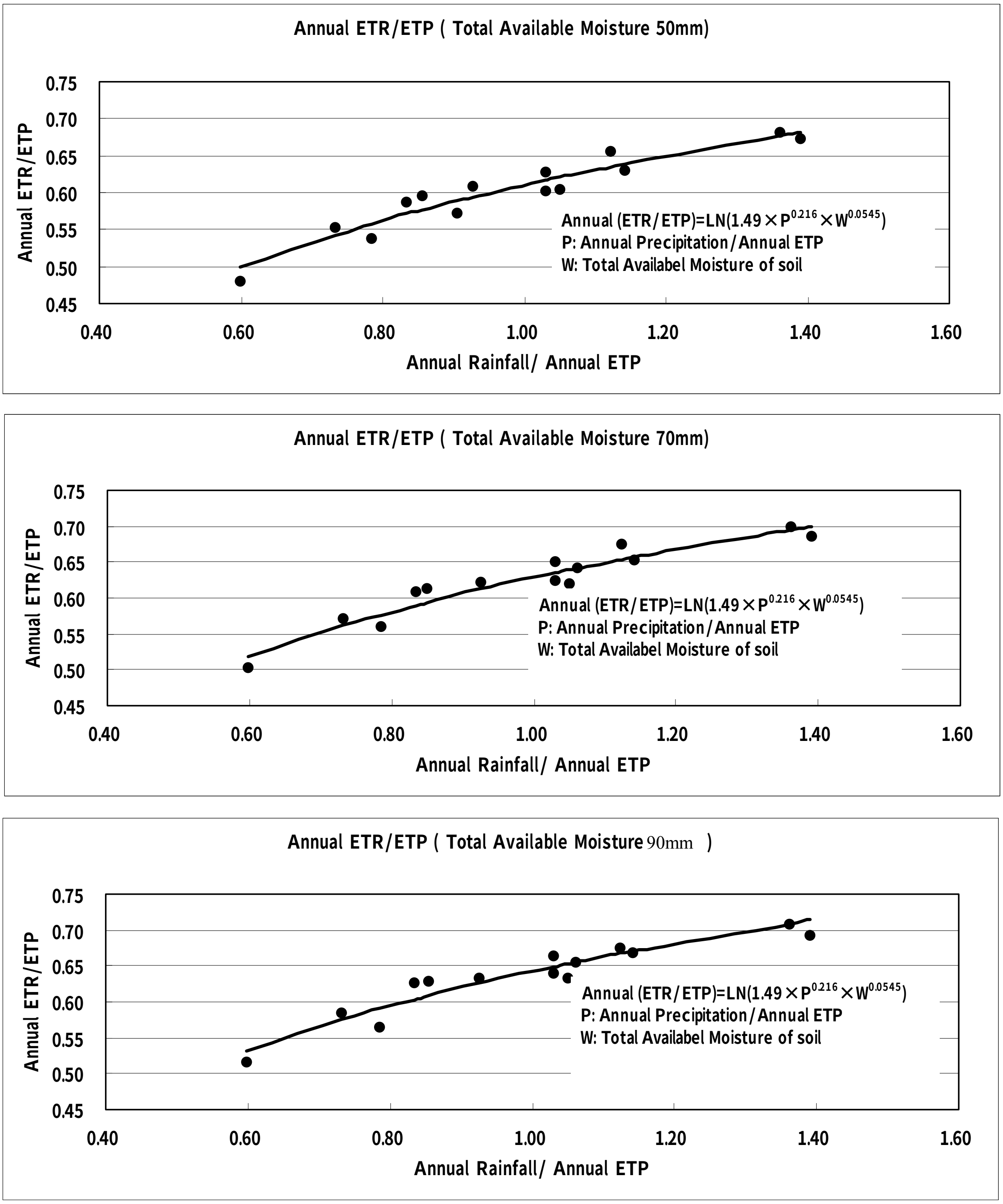

Figure-2.13 Analyzed Result of 14 Stations (by Soil Types) and Approximation by Function

Real Evapo-transpiration of the Study Area

Real evapo-transpiration of the Study Area was analyzed using the function that was obtained in the previous section. For calculation of ETR, "Annual Precipitation Map", "Annual ETR Map" and "Total Available Moisture Map" were overlapped and the function was applied. Resultant calculated ETR is shown in Figure-2.15. By the way, "Total Available Moisture Map" was made from "Land use Map" by the Study Team. How to make this map is outlined in Table-2.13.

Table-2.13 Outline of Total Available Moisture Map

Category of Land Use	①Forest, ②Grass land and crop land, ③Bare land, ④Water, ⑤City area
Total Available Moisture in the soil	(Field Capacity (mm/m)－Wilting Point (mm/m)) x Thickness of soil (m) Where, (Field Capacity－Wilting Point) was estimated as below referring FAO data. Clayey Soil :180(mm/m) Medium Soil :140(mm/m) Sandy Soil :100(mm/m) In "Water", ETR=ETP.
Thicknessof Soil	Thickness of soil was set considering topographical classification. Soil thickness is 0.4m in low plain (E.L.<2600m) and high plain (E.L.>2600m) Soil thickness is 0.2m in mountains and hills.

(5) Groundwater recharge

Groundwater recharge was calculated from equation (4) that was previously explained. Equation (4) is again shown below:

Annual groundwater recharge = P-ETR- (D_2+ $G_{2\text{-baseflow}}$) (4)

P----- Precipitation of basins (mm/yesr)
ETR—Real evapo-transpiration from basin (mm/year)
(D_2 +G_2-baseflow) ---River discharge from basin (mm/year)

For calculation of annual groundwater recharge, "Precipitation Map", "ETR Map", "River Discharge Map" was overlapped. Calculated groundwater recharge is shown in Figure-2.16.

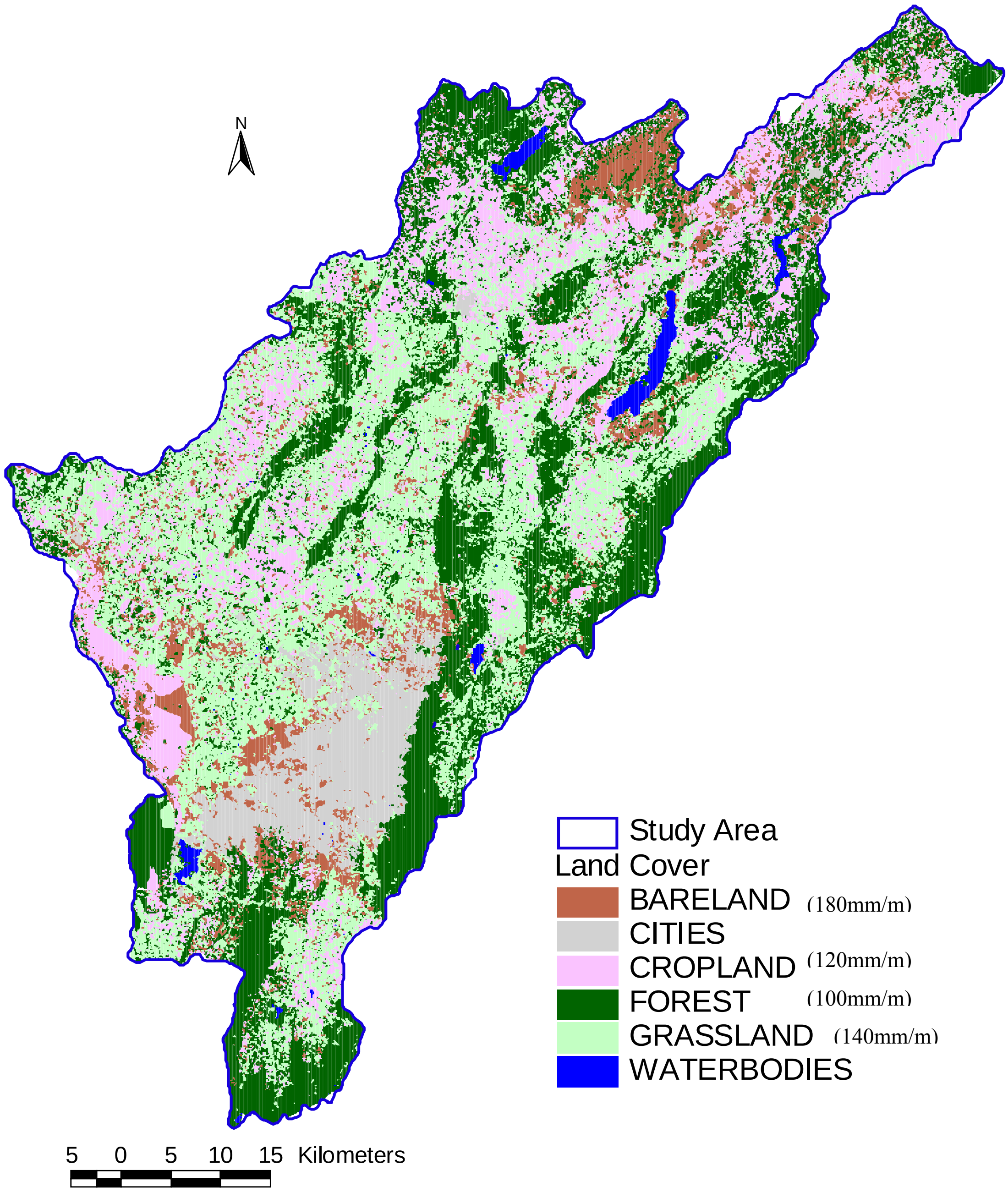

Figure-2.14 Classification of Total Available Moisture in Soil

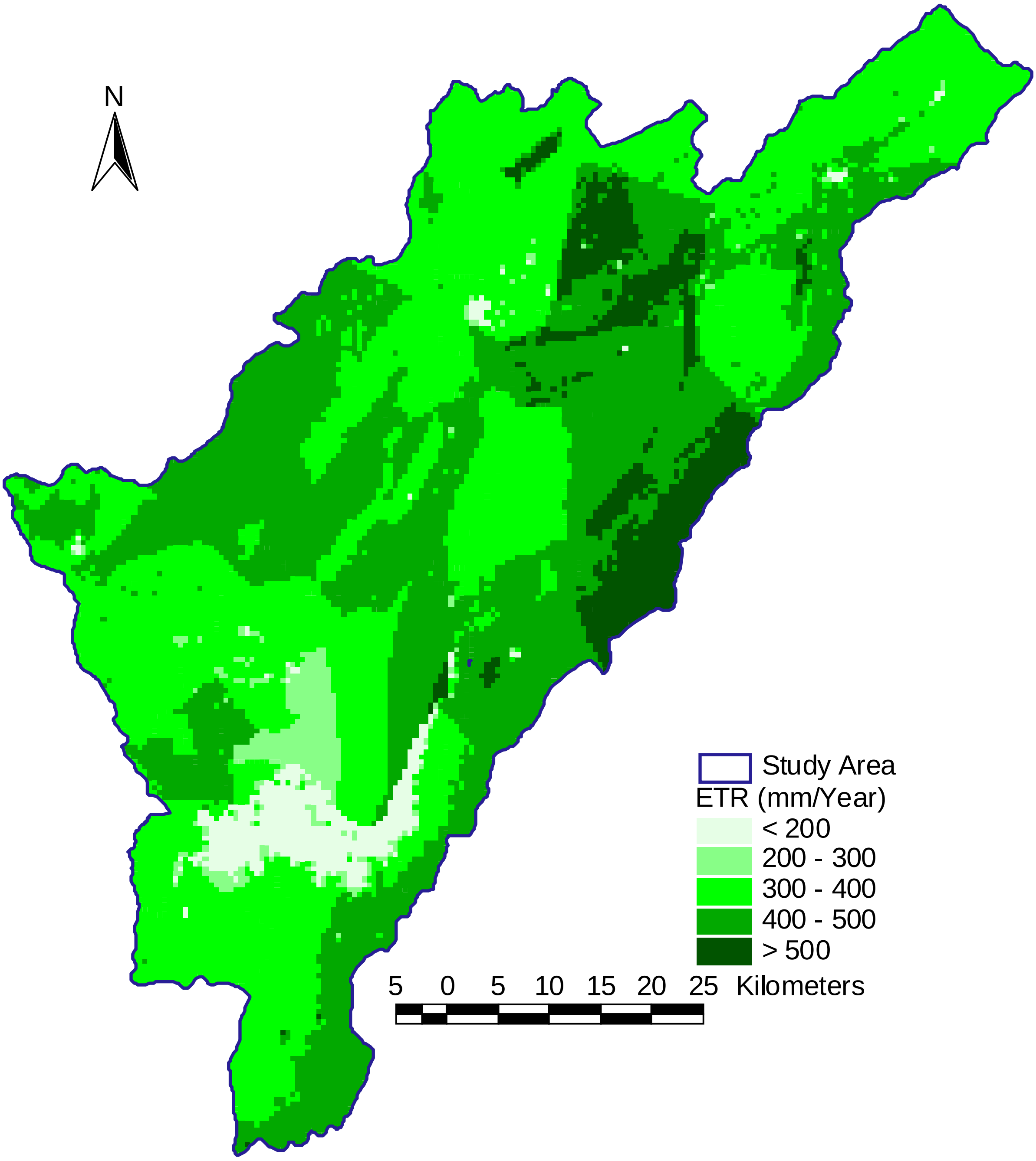

Figure-2.15 Annual ETR

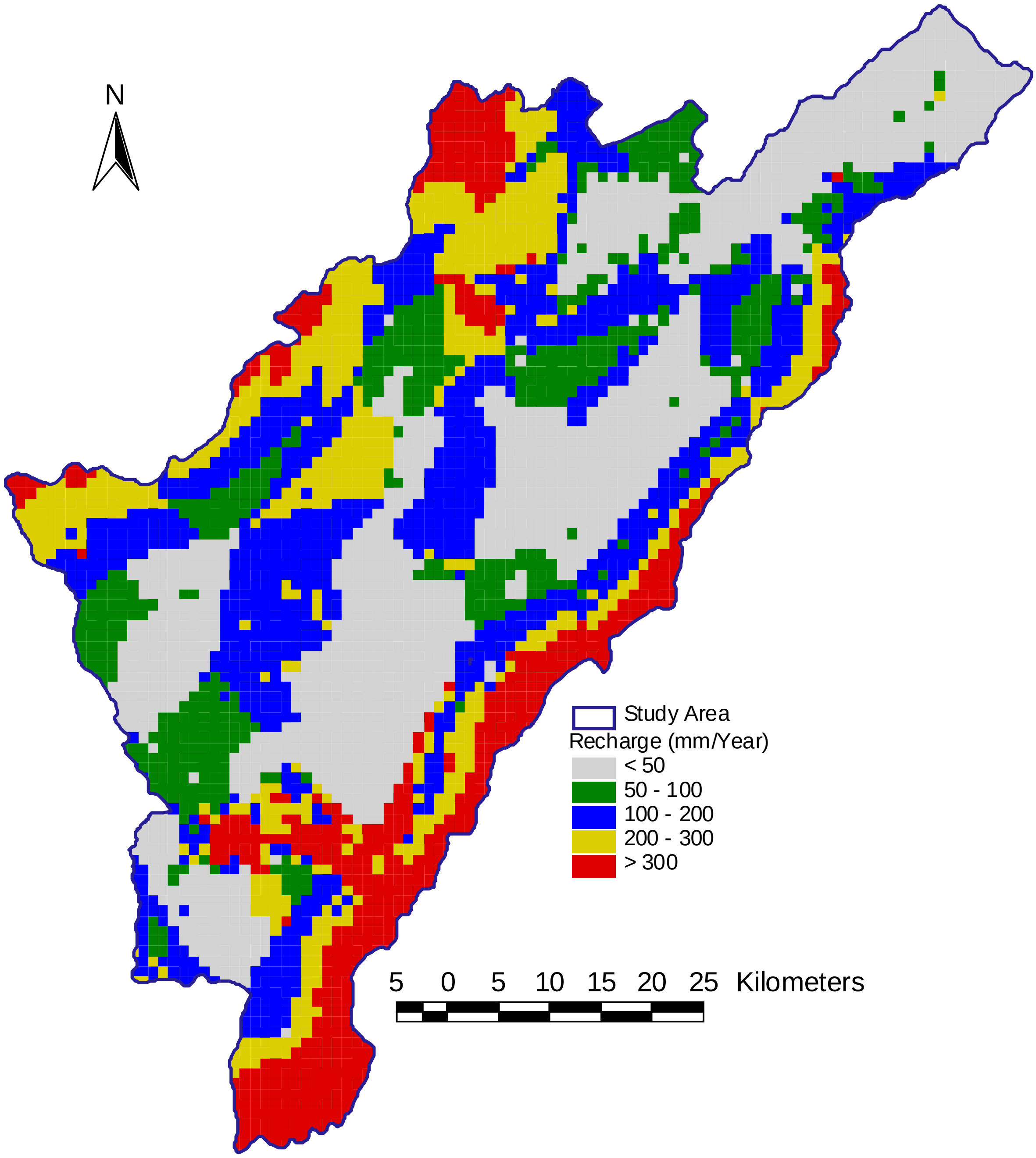

Figure-2.16 Annual Groundwater Recharge

Table-2.14 Result of Groundwater Recharge Analysis

Basin	Catchment Area (km^2)	Annual precipitation (mm)	Annual Runoff (mm)	Annual ETR (mm)	Annual Groundwater Recharge	
					($\times 10^6 m^3$)	(mm)
Bogotá 1-Bogota 3	36	707	270	333	71.0	105
Bogotá 4-Bogota 6	111	727	186	391	34.7	149
Bogotá 7 Bogotá 9	103	724	244	418	34.5	62
Bojaca	219	755	248	378	28.2	129
Chicu	134	751	150	414	25.1	187
Frio	194	838	353	385	19.4	100
Neusa	432	850	257	406	80.9	187
Sisga	152	913	365	405	21.7	143
Muna	128	727	330	339	7.49	58
Subachoque 1	32	600	120	409	2.23	71
Subachoque 2	386	833	268	415	57.9	150
Teusaca	353	896	307	423	58.7	166
Tomine	368	873	297	467	40.2	109
Tunjuelito	404	942	289	323	133	330
Total	4268	805	271	391	615	144

It is impossible to calculate groundwater recharge in river basin "Bogota(3)E" by the same method which was applied to the other basins, because "Bogota (3)E" basin is highly developed area where ground surface is covered with artificial materials and rainfall can not infiltrate into the ground. On the other hand, leakage from water supply of EAAB is estimated around 100mm/year and this leakage may become groundwater recharge in Bogota City Area. Therefore, water balance and groundwater recharge in Bogota City Area of "Boogta (3)E basin" was calculated based on the relation shown below:

- Precipitation = River discharge + ETR
- Groundwater recharge = Leakage from water supply of EAAB

Average groundwater recharge of all study area was calculated 144mm/year (615 million m^3/year, or 19.5m^3/s).

Table-2.15 Total Groundwater Recharge of the Study Area

Area	Catchment Area (km^2)	Groundwater Recharge	
		mm/year	m^3/s
All the Study Area including Bogotá Plain	4,268	144	19.5

(6) Sensitive Analysis of groundwater Recharge

Soil moisture has great influence in estimation of Groundwater recharge. However, to decide soil moisture exactly is difficult. In order to evaluate change of groundwater recharge when soil moisture value is changed, calibration of groundwater recharge was conducted by changing Total Available Moisture in soil (TAM). The result of this calibration is shown in Figure-2.16. As shown in Figure-2.16, there is small change in groundwater recharge even though TAM widely changed.

(7) Water Balance of Study Area

Part of river water is taken for irrigation use and other purposes. This water finally will be lost by evapo-transpiration. Considering this situation, water balance of the Study Area was summarized as shown in Table-2.16. This balance includes groundwater water balance that was calculated by groundwater simulation mentioned later in this Chapter.

Table-2.16 Water Balance of Study Area

Item	mm/year	m^3/year	Total %	% of groundwater balance
・Annual Rainfall	802	108.5	100.0	-
・annual Evapo-transpiration	430	58.0	53.6	-
・Annual surface runoff	228	31.0	28.4	-
・Annual groundwater recharge	144	19.5	18.0	100.0
-Annual Groundwater use	27	3.7	3.4	18.8
-Annual Groundwater inflow to Study Area	8	1.1	1.0	5.6
-Annual Groundwater outflow from Study Area	125	16.9	15.6	86.8

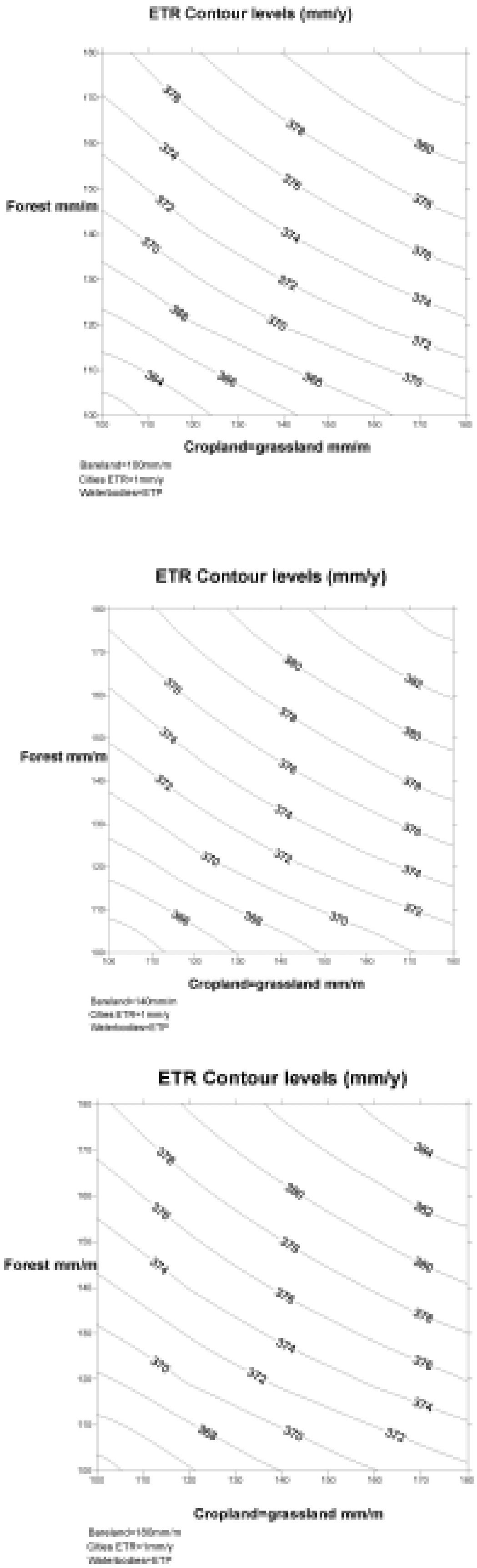

Figure-2.17 Calibration Result

(8) Existing water Balance Analysis

INGEOMNAS carried out water balance analysis for the Study Area during 1987 to 1994. River basin division of this analysis is almost the same as that of the Study Team, and water balance was analyzed for each river basin. This analysis dealt eleven tributary river basins of the Study Area, which is 70% of total Study Area, and main Bogotá River was excluded from this analysis.

Basic equation of water balance used for this analysis is same as that used by the Study Team. According to analyzed result, groundwater recharge of eleven river basins (total area of 2,809km^2) is 31mm/year(= 87 million m^3/year, 2.8m^3/s). If estimated recharge rate of 31mm/year is simply applied to entire Study Area (4,200km^2), total groundwater recharge of 130 million m^3/year (=4.1m^3/s) is obtained for entire Study Area.

Table-2.17 Groundwater Recharge by INGEOMINAS

River Basin	Catchment Area by INGEOMINAS (km^2)	Annual Groundwater Recharge
Tunjuelito	286	119mm
Muna	107	7mm
Bojaca	225	20mm
Chicu	141	63mm
Teusaca	362	2mm
Frio	182	21mm
Neusa	282	24mm
Choconta	278	15mm
Sisga	157	17mm
Subachoque	377	30mm
Tomine	412	23mm
Total	2,809	31mm

1) Characteristics of Method of Water Balance Analysis by INGEOMONAS

Method of water balance analysis by INGEOMINAS has characteristics listed below.

- Water balance was analyzed for each soil type that was classified for each river basin.
- Water balance was carried out monthly.
- River discharge was estimated by the use of experimental equation, which gives river discharge from altitude and precipitation.
- Base flow was estimated, then direct flow was calculated from the total river discharge and the base flow.
- Turc method was used for estimation of potential evapo-transpiration.
- Original program was used for calculation of soil water balance.

2) Characteristics of Result of Water Balance Analysis by INGEOMINAS

The Study Area consists of plains and mountains. Ground surface of the plains consists of usual soil, and ground surface of mountains consists of sandy and gravely soils. According to the result of water balance analysis by INGEOMINAS, soil with high field capacity can store more water, then produces less groundwater recharge. For example, soil on hills and mountains of Guadalupe Group has smaller field capacity, then produces more groundwater recharge. On the contrary, soil on plain has higher field capacity, then produces less groundwater recharge. This is general trend of result of water balance analysis by INGEOMINAS.

3) Water Balance Analysis by CAR

CAR implemented water balance analysis for all the Cundinamarca Department. Though method of this water balance analysis is almost the same as that of INGEOMNAS, CAR uses observed river discharge and the latest meteorological date. Moreover, by the use of GIS, precipitation, river discharge, soil type, evapo-transpiration are effectively combined to make accuracy of the analyzed result higher. Groundwater recharge by this analysis is 11mm/year in average of All the Study Area.

CHAPTER 3 Groundwater Simulation

By groundwater simulation, Groundwater potential was evaluated and possibility of groundwater development was examined. Groundwater simulation was carried out by step shown below:

- Analysis of the existing groundwater simulation Result.
- Implementation of large area groundwater simulation which analyzes majority of Cundinamarca Department including the Study Area.
- Implementation of groundwater simulation for the Study Area

In this Study, the exiting groundwater simulation model was expanded to all the Study Area to evaluate groundwater potential. The result of analysis is explained below.

3.1 Result of Existing Groundwater Simulation

Groundwater simulation was carried out for the Study Area in the past (Hydrogeology of Bogotá City, 1999, EAAB and DAMA). The Study Team analyzed the result of this simulation before implementation of groundwater simulation. The existing simulation was carried out with Visual Modflow. The result of the simulation is explained below.

(a) Purpose of the Existing Groundwater Simulation

The purpose of the existing groundwater simulation was to know future groundwater level under current groundwater use. Analyzed area by the simulation was the south part of the Study area, and its area is 1,138km^2, which corresponds one forth of the Study Area.

(b) Groundwater Recharge and Current Pumping Used by Simulation

Groundwater recharge of 73,555 m^3/day (23mm/year) from precipitation and total yield of 95,685m^3/day (31mm/year) from the current wells were given to simulation model.

(c) Result of the Simulation

According to the simulation, if the current pumping (95,685 m^3/day) continues, groundwater level of analyzed area will continuously decrease, because groundwater of 57,901 (m^3/day)=19.3mm/year will be consumed from aquifer of Bogotá Plain by pumping.

(d) Condition of the simulation

The simulation was strongly affected by an important condition of the model, which will be explained below.

- Most of the boundary of the simulation model was set as '"Groundwater flow =0".
- By the condition above, groundwater flow system, groundwater recharge-> pumping -> evapo-transpiration –> groundwater flow, was limited within the analyzed area (1,138km^2).
- Therefore, groundwater flow system outside of analyzed area has no influence on

groundwater flow system of the analyzed area. This means that the analyzed area has no connection with surrounding areas of the Bogotá Plain in hydrogeological viewpoints.

(e) Problem in the Existing Simulation

The existing simulation limited the analysis area and groundwater flow system within a part of Bogotá Plain (1,138km^2). However, if all the Study area (4,268km^2) is included in the simulation model and groundwater can flow in all the Study Area, simulation result may be different.

3.2 Large Area Groundwater Simulation

(1) Area for Implementation of Large Area Groundwater Simulation

The Study Team made large area simulation model covering Magdalena River to the west, Orinoco River to the east including the Study area. The area of large simulation is 32,200 km^2, and this area covers most of Cundinamarca Province (see Figure-3.1).

(2) Purpose of Large Area Simulation

The existing simulation limited groundwater flow system, groundwater recharge and pumping, within part of the Study Area. Moreover, there was assumption that no groundwater flows into the study area and no groundwater flows out from the Study area. If groundwater of the Study area has connection with groundwater out of the Study Area, this effect must be evaluated. Large area groundwater simulation was carried out to estimate this effect.

(3) Large Area Groundwater Simulation Model

Outline of the large area groundwater simulation model is explained below. Visual Modflow was used for the simulation.

<u>Size of Model</u>

Mesh distance of the model is 1,500 m and total number of cells is 57,600 (240×240) covering 32,000 km^2.

<u>Modeled Area and boundary condition</u>

In the decision of modeling area, the matters below were taken into account.

- Model boundary needs boundary condition. Therefore, boundary of model must be set far from the Study Area in order that boundary condition does not influence on groundwater flow of the Study Area.
- To examine groundwater flow of the Study area, groundwater flow to Magdalena River and to Orinoco River Plain must be analyzed in the model. Therefore these two regions must be included in the model.
- Model border must correspond to Magdalena River, Orinoco River Plain, the other main rivers and main water sheds (see Figure-3.2).

Based on principles above, boundary condition of the model was set as explained below (see Figure-3.2).

- Constant head boundary was set for Magudalena River.
- Constant head boundary was set for Orinoco Plain.
- For the other border of the model, ”Boundary of Groundwater flow = 0 “ was set for where boundary correspond to watershed, and “Constant head boundary ” was set for where boundary correspond to rivers.
- Boundary condition was set not only along the limits of the model but also in the inside

area. The condition ser is "Drain boundary", which is similar to constant head boundary. This boundary condition fixes groundwater level to riverbed altitude where groundwater table crosses the river (see Figure-3.2). When groundwater level exceeds river altitude, groundwater springs into the river and groundwater level is fixed at this altitude. This boundary condition is necessary for reasonable simulation results.

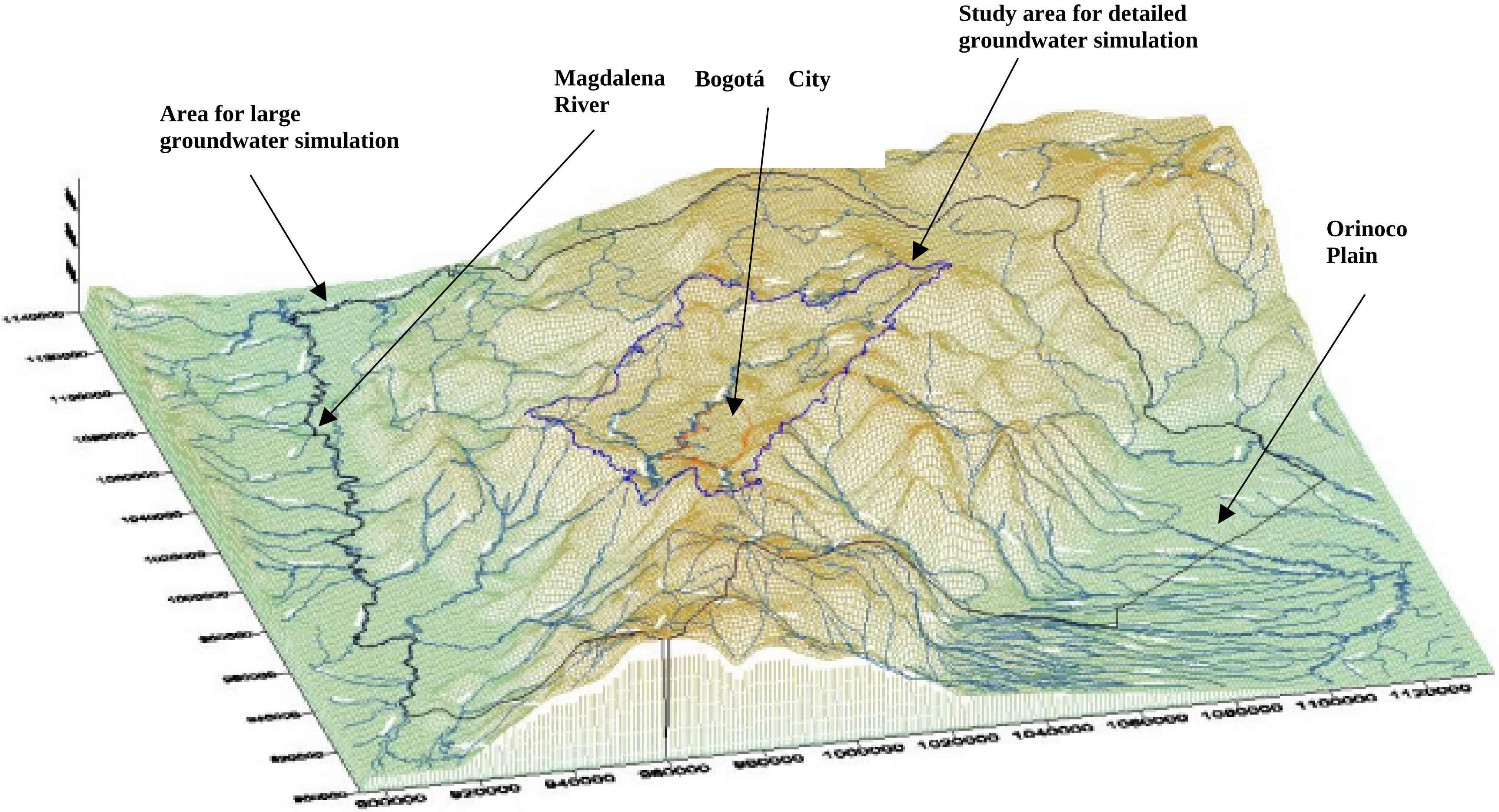

Figure-3.1 Area for Groundwater Simulation

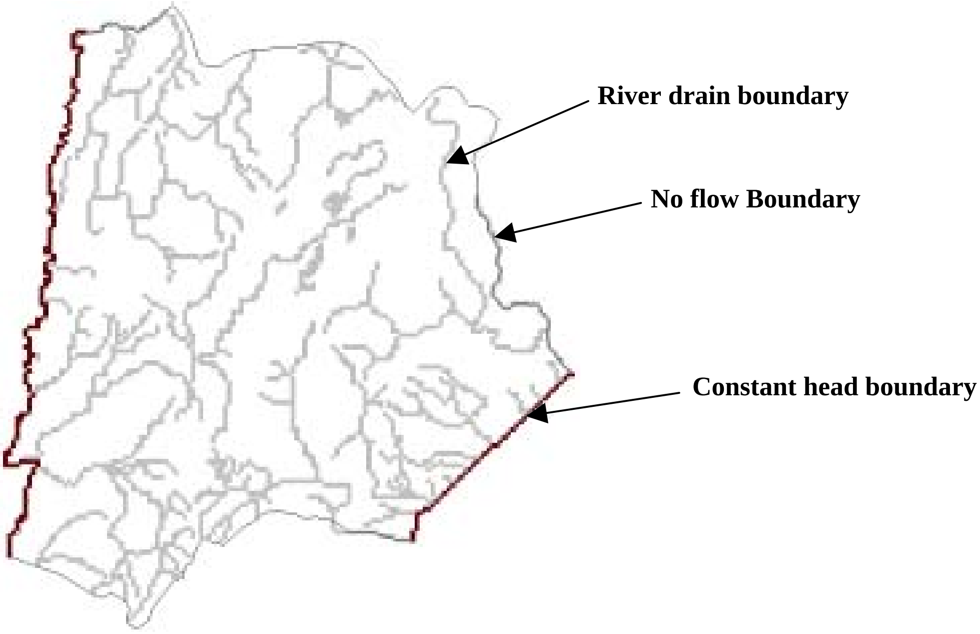

Figure-3.2 Boundary Condition of the Model

Aquifer Structure

In Aquifer model formulation, geological sections were made by the Study Team based on "ATLAS GEOLOGICO DIGITAL DE COLOMBIA (INGEOMINAS, 1997)". Then, three-dimensional geological model was made based on these geological sections. This simulation model has eight aquifers following classification of INGEOMONAS Map. Example of model geological section is shown in Figure-3.3.

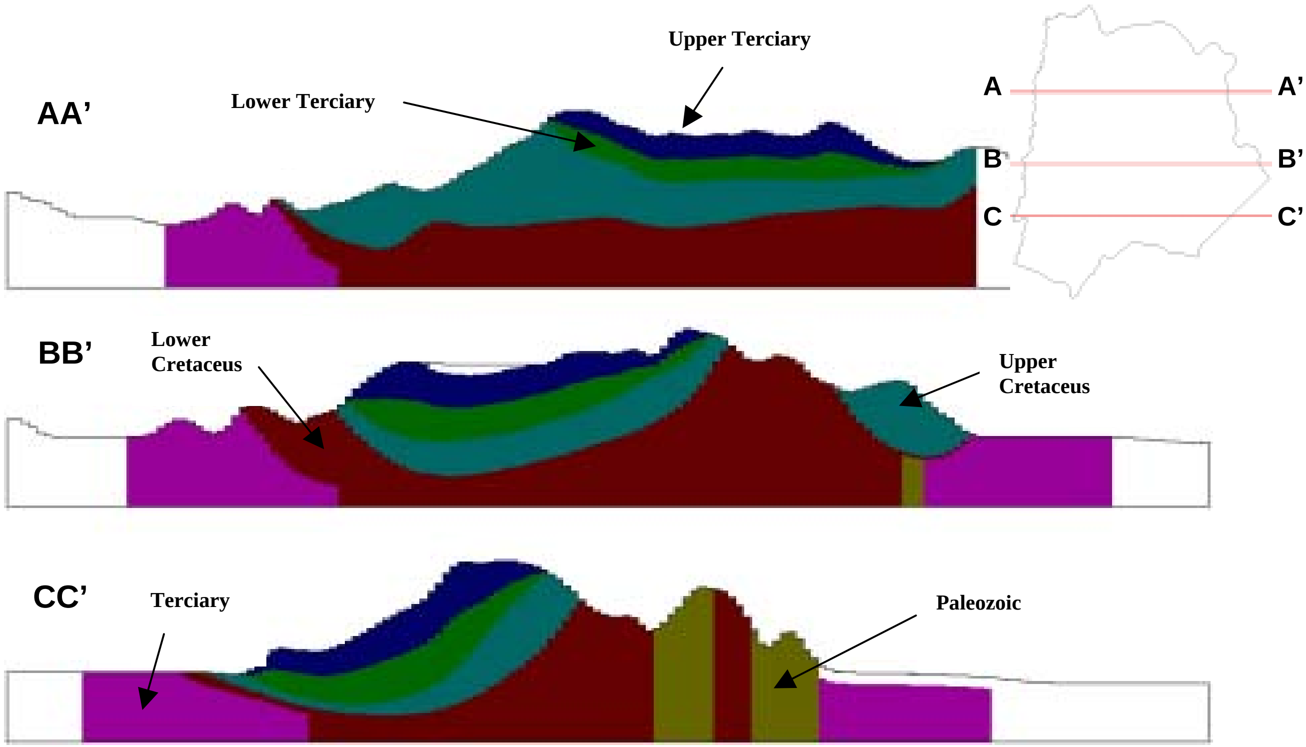

Figure-3.3 Example of Aquifer Structure of the Model

Aquifer Parameters

In setting up of aquifer parameter, initial aquifer parameters were set based on statistical values of aquifer parameters that were analyzed in Section 3.5.2. In the course of implementation of the ground water simulation, initial parameters were modified again and again to reach the reasonable simulation result. The final aquifer parameters used for the final model are shown in Table-3.1.

Table-3.1 Aquifer Classification and Aquifer Parameters for Groundwater Simulation

No.	Aquifer	Permeability Coefficient (cm/s)	
		Horizontal	Vertical
1	Quaternary	6×10^{-5}	3×10^{-6}
2	Upper Tertiary	3×10^{-4}	3×10^{-5}
3	Lower Tertiary	3×10^{-4}	3×10^{-5}
4	Upper Guadalupe Group	1.2×10^{-4}	1.2×10^{-5}
5	Lower Guadalupe Group	6×10^{-5}	6×10^{-6}
6	Middle Cretaceous	3×10^{-5}	3×10^{-6}
7	Lower Cretaceous	1.5×10^{-5}	1.5×10^{-6}
8	Paleozoic	6×10^{-5}	3×10^{-6}

Groundwater Recharge

There is no information for estimation of groundwater recharge of modeled area. Purpose of this simulation is to know large area concept of groundwater flow. Groundwater recharge was set based on the assumptions explained below.

- Groundwater recharge was estimated based on annual rainfall maps by IDEAM and CAR covering entire Cundinamarca Province.
- The percentage of precipitation which becomes groundwater was assumed for every geological type.
- For the estimation above, maps by INGEOMINAS showing relation between geology and recharge condition were examined.
- Based on Maps above, annual precipitation and assumed groundwater recharge rate (%) was combined and groundwater recharge was estimated for each geology type. This groundwater recharge was used as initial value for simulation.
- In the course of implementation of groundwater simulation, initial groundwater recharge was modified again and again within allowable range to reach reasonable simulation result. The final groundwater recharge used for the final model is shown in Table-3.2.

Table-3.2 Groundwater Recharge by Geology used for Large Area Groundwater Simulation

No.	Aquifer	Groundwater recharge rate (%) to annual precipitation
1	Quaternary	5%
2	Upper Tertiary	15%
3	Lower Tertiary	3%
4	Upper Guadalupe Group	10%
5	Lower Guadalupe Group	10%
6	Middle Cretaceous	3%
7	Lower Cretaceous	3%
8	Paleozoic	3%

Pumping Well

To examine influence on groundwater flow system by pumping wells of the Study area, simplified wells were set in the Study Area of the model (see Figure-3.4). Total yield from modeled wells was set to five patterns as shown below.

- Pattern-1: Total yield is 0% of total groundwater recharge of the Study Area.
- Pattern-2: Total yield is 10% of total groundwater recharge of the Study Area.
- Pattern-3: Total yield is 20% of total groundwater recharge of the Study Area.
- Pattern-4: Total yield is 30% of total groundwater recharge of the Study Area.
- Pattern-5: Total yield is 40% of total groundwater recharge of the Study Area.

As explained above, total yield from wells was changed from 0% to 40% of total groundwater recharge to the Study area. Therefore, the variation of groundwater flow system by the change of well yield was examined.

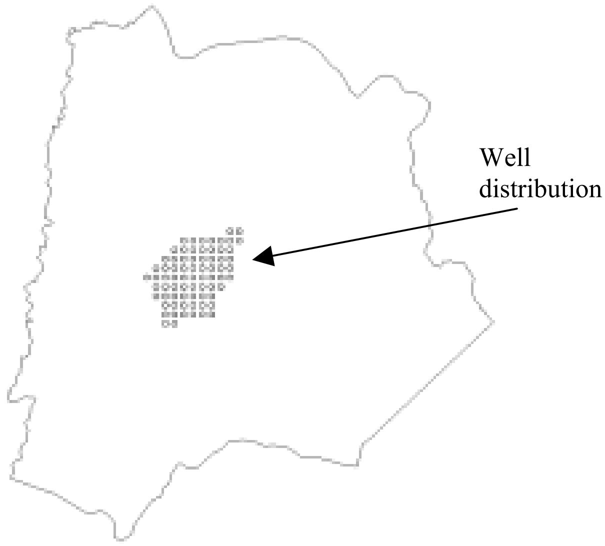

Figure-3.4 Distribution of Well

(4) Result of Large Area Groundwater Simulation

<u>Groundwater Flow System</u>

Calculated groundwater flow situation without pumping is shown in Figure-3.5, and calculated groundwater flow situation with different pumping rates are shown in Figure-3.6 to Figure-3.7.

According to Figure-3.5, groundwater flow system is classified into two types.

- Groundwater flow system flowing to Magdalena River.
- Groundwater flow system flowing to Orinoco Plain.

The Study Area belongs to groundwater flow system flowing to Magdalena River. East border of the Study Area is located near the boundary between groundwater flow system flowing to Magdalena River and groundwater flow system flowing to Orinoco Plain.

Groundwater flow system around the Study area is finally classified into three types.

- Groundwater flow system flowing toward the south –west direction to Magdalena River.
- Groundwater flow system flowing toward the west direction to Magdalena River.
- Groundwater flow system flowing toward the east direction to Orinoco Plain

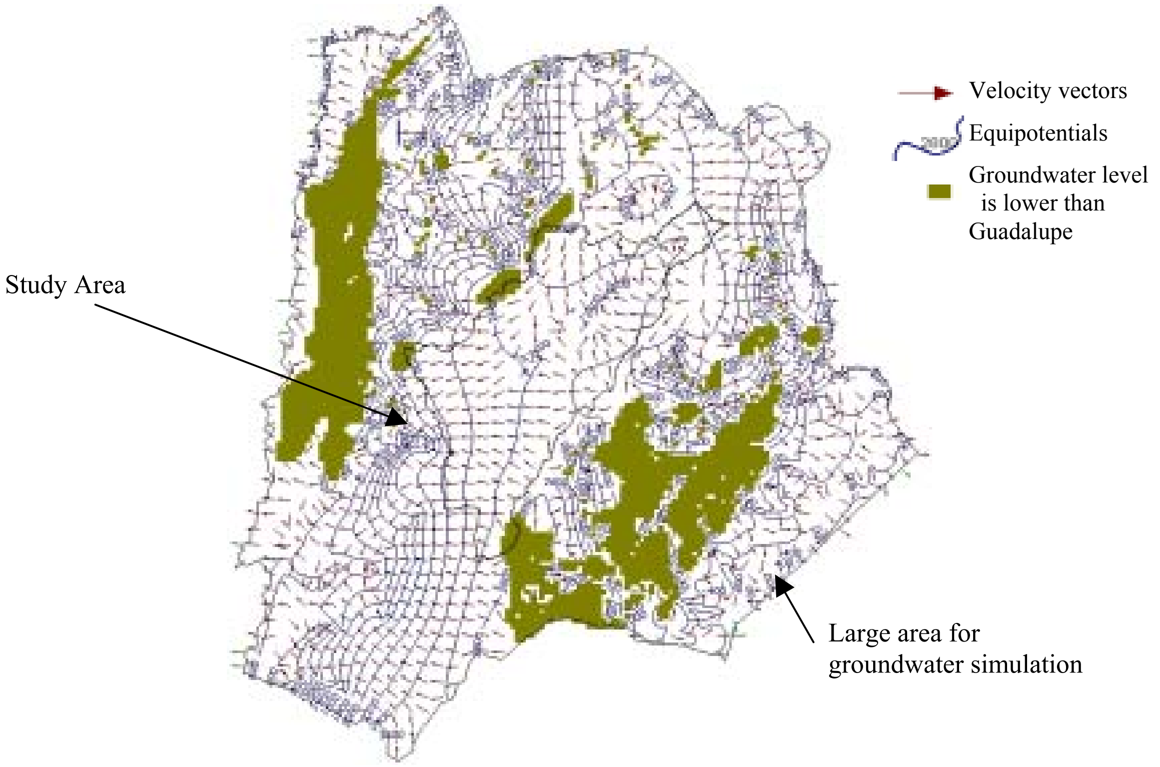

Figure-3.5 Results of Large Area Groundwater Simulation (Yield = 0% of Recharge)

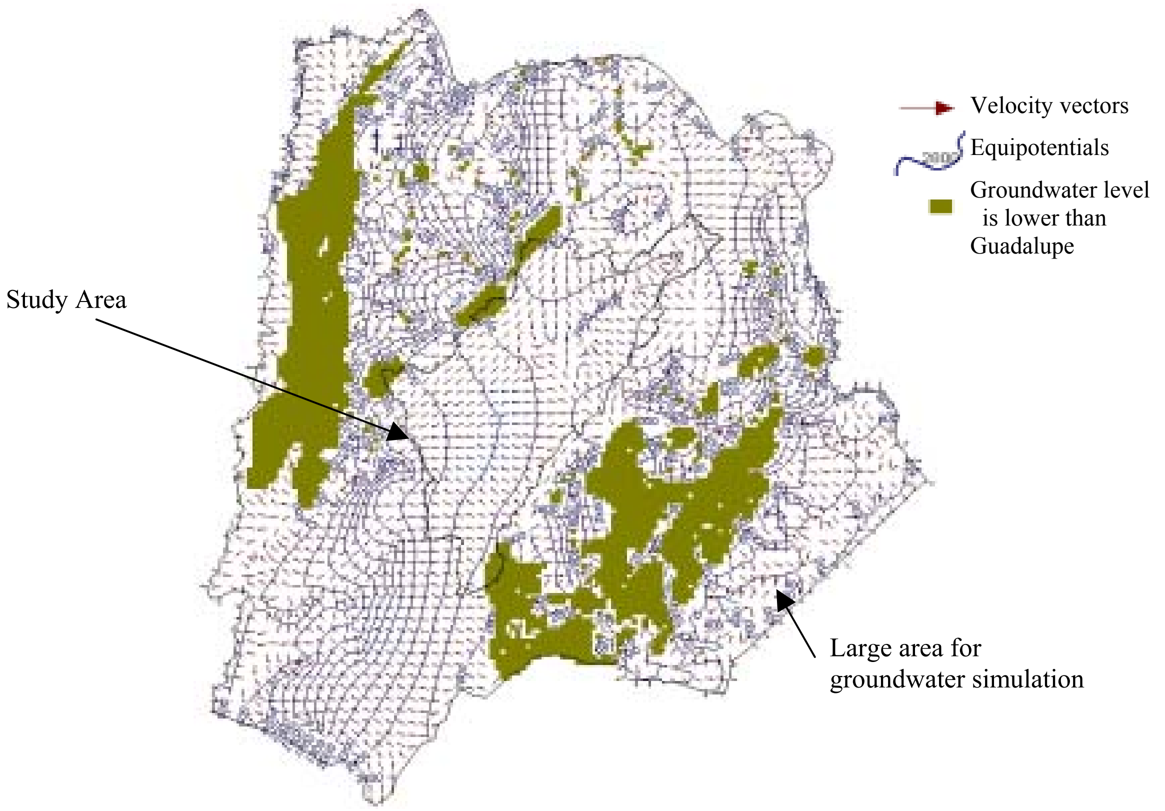

Figure-3.6 Results of Large Area Groundwater Simulation (Yield = 20% of Recharge)

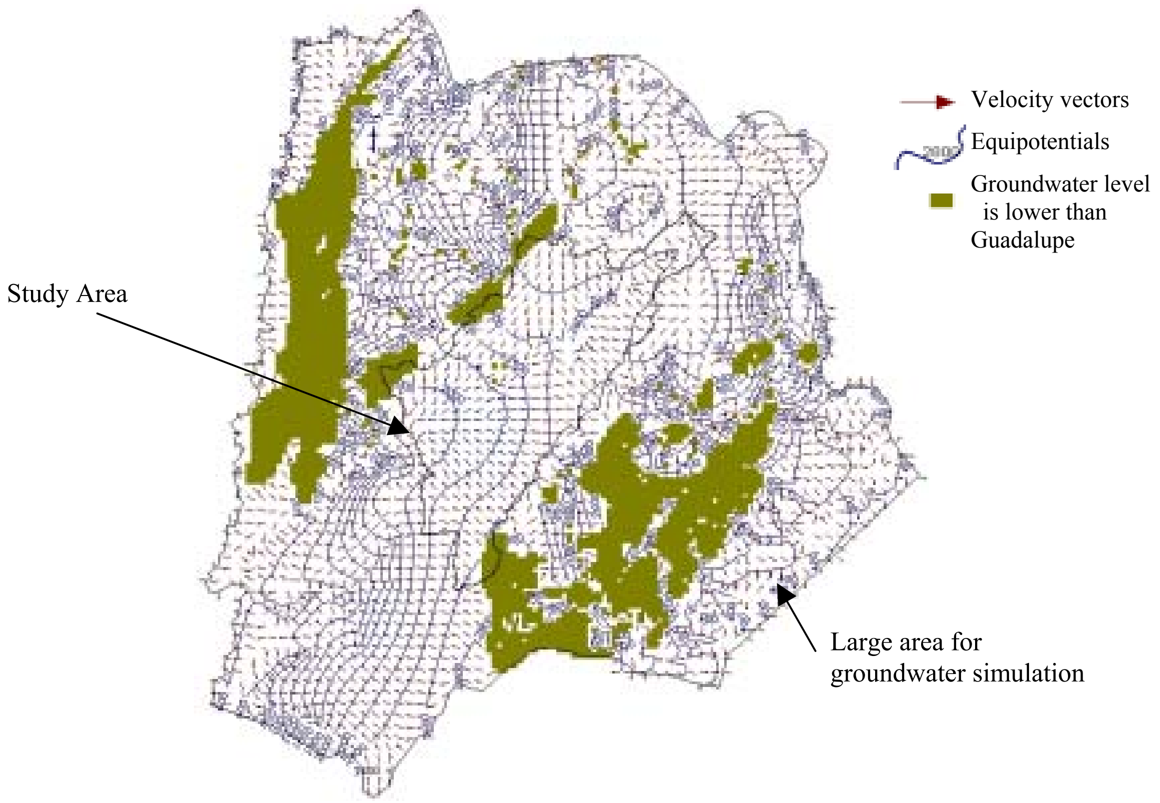

Figure-3.7 Results of Large Area Groundwater Simulation (Yield = 40% of Recharge)

The three groundwater systems above are divided by groundwater shed. Most of the Study Area is included in a) Groundwater flow system flowing toward south-west direction to Magdalena River. It should be noticed that the boundary between the three groundwater flow systems corresponds to the limits of the Study area in the east-north-west. On the other hand, groundwater is flowing crossing the south border of the Study Area. Those groundwater flow belong to groundwater flow system flowing to toward the south –west direction to Magdalena River (see Figure-3.5).

<u>Influence on groundwater flow system by pumping of the Study Area</u>

According to Figure-3.8, influence on groundwater flow system by pumping by the Study Area is as follows.

- As yield from pumping increases, groundwater flow to wells is accelerated, and at the same time groundwater level is lowered around wells.
- As shown in Figure-3.8, the boundaries of three groundwater flow systems are expanded from the Study Area toward surrounding regions by increase of pumping. Increase of pumping enlarges the area influenced by pumping, then groundwater outside of the Study area is finally drawn into the Study area.

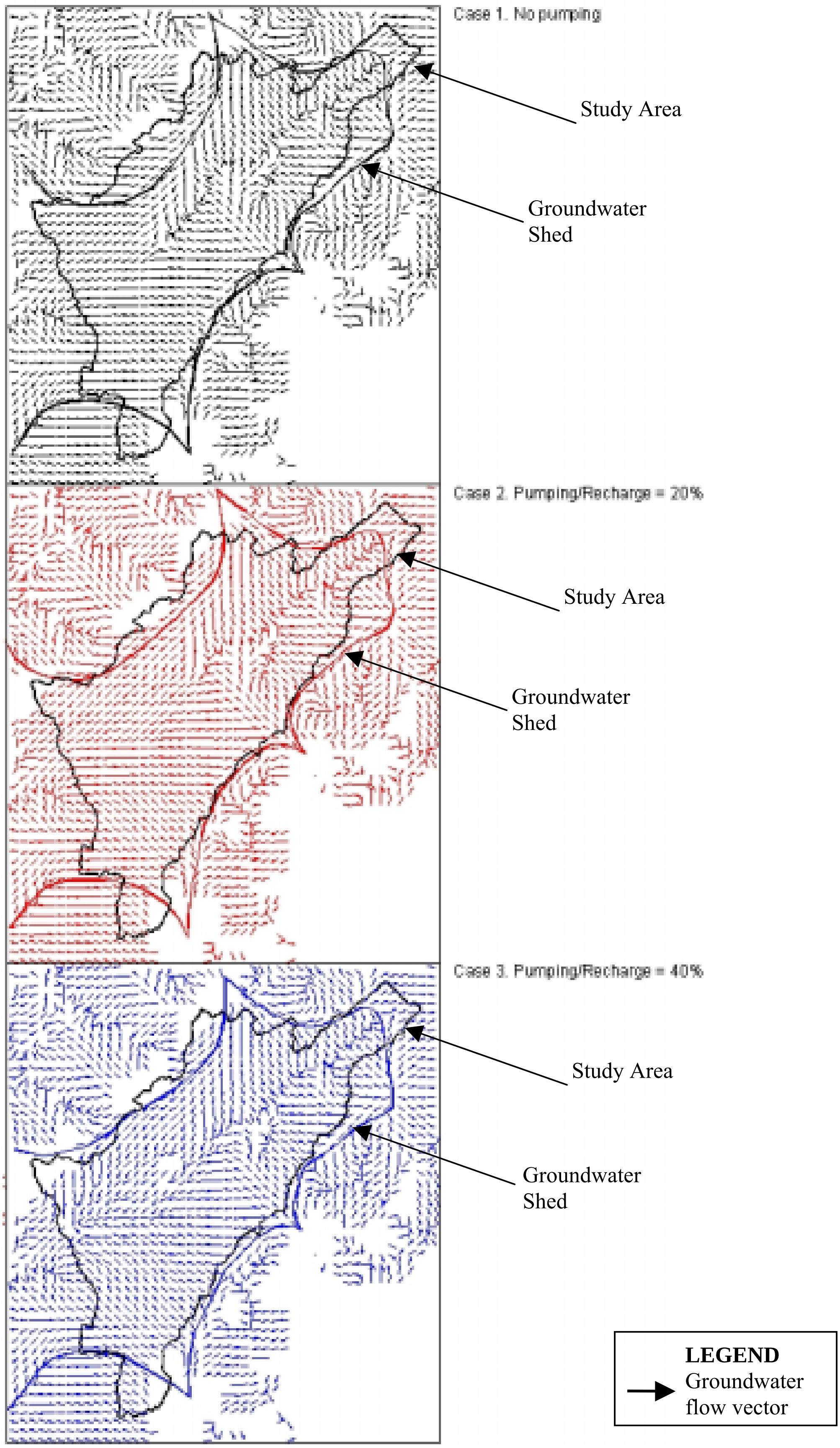

Figure-3.8 Change of Groundwater-shed by Pumping Rate of the Study Area

(5) Conclusion of Simulation Results

From the result of large area groundwater simulation, matters below are concluded.

- Before the current groundwater development of the Study area, groundwater is flowing toward the southwest direction to Magdalena River following general land gradient in the Study Area.
- After commencement of groundwater development, groundwater flow toward current wells was accelerated, and at the same time groundwater level was lowered in the Study Area.
- Groundwater shed of groundwater flow system, which the Study Area belongs to, has expanded toward outside of the Study area as groundwater development increased.
- Conclusion above means that groundwater flow is not limited within the Study area. As pumping increases, influenced area is enlarged toward outside of the Study area.
- Groundwater level of the Study area may be continuously lowered as pumping increases if groundwater flow is limited within the Study Area. However, as increase of developed groundwater, influenced area is enlarged toward out side of the Study Area from where groundwater is drawn. Lowering of groundwater level finally stops when pumping and groundwater inflow is balanced.

3.3 Groundwater Simulation of the Study Area

(1) Area for Simulation

The Study Team made detailed simulation model for the Study Area. The current groundwater flow will be reproduced in this model, and possibility of future groundwater development and change of groundwater environment of the Study area will be analyzed by this model.

(2) Purpose of Simulation

This simulation examines appropriateness of groundwater recharge of 144mm/year that was estimated in water balance analysis. Estimated groundwater recharge of 144mm/year is installed into the simulation model and this simulation model reproduces current groundwater flow. In the course of implementation of this simulation, appropriateness of estimated groundwater recharge was examined.

(3) Important Points in Simulation Model Formulation

In formulation of the simulation model, result of large area simulation was refereed. Specially, boundary condition of the model was carefully examined, which controls groundwater connection between the Study Area and outside of it. In implementation of the simulation, current groundwater flow of the Study Area was reproduced in the model to evaluate current groundwater potential.

(4) Outline of Simulation Model

Outline of simulation model for Study area is explained below. Visual Modflow was used for this simulation.

<u>Size of Model</u>

Mesh distance of the model is 1,000 m and total number of cells is 105x120=52,500.

Modeled Area and boundary condition

Area of 105km x 120km including all the Study Area was modeled for simulation of the Study Area. In setting up of boundary condition, result of large area simulation was referred. Principles of boundary condition are explained below (see Figure-3.9).

<Boundary condition inside the Study Area>

Only few "River Drain Condition" was given to the model inside of the Study Area. Groundwater recharge given to the model does not include base flow into rivers, which is explained in "Groundwater Recharge" of this Report. Therefore, "River Drain Condition" is not necessary to the model under the assumption that recharged water does not flow into rivers. However, "River Drain Condition" was set to a little parts of the model in order to avoid inadequate result.

<Boundary condition out of the Study Area>

According to the result of large Area groundwater simulation, groundwater is flowing to Magdalena River and Orinoco River Basins. Therefore, river system outside of the Study Area was installed to the Model as "River Drain Condition".

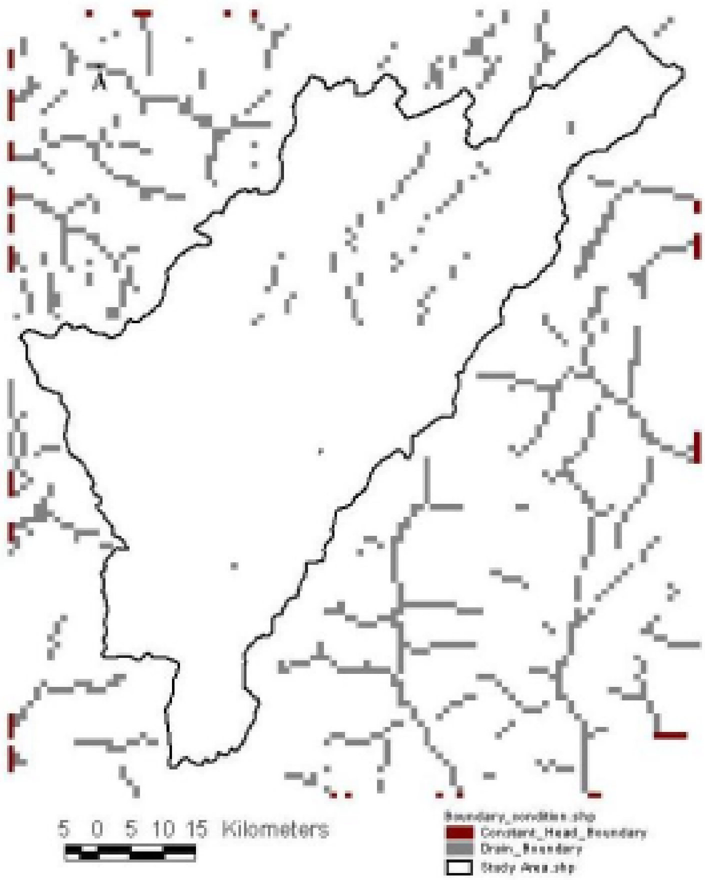

Figure-3.9 Boundary Condition of the Model

Aquifer Structure

In Aquifer model formulation, the Study Team made geological sections based on existing geological map of 1/100,000 by INGEOMINAS. Then, three-dimensional geological model was made based on these geological sections. This simulation model has five aquifers following classification of INGEOMINAS map as shown in Table-1.1. Example of model geological section is shown in Figuer-3.10.

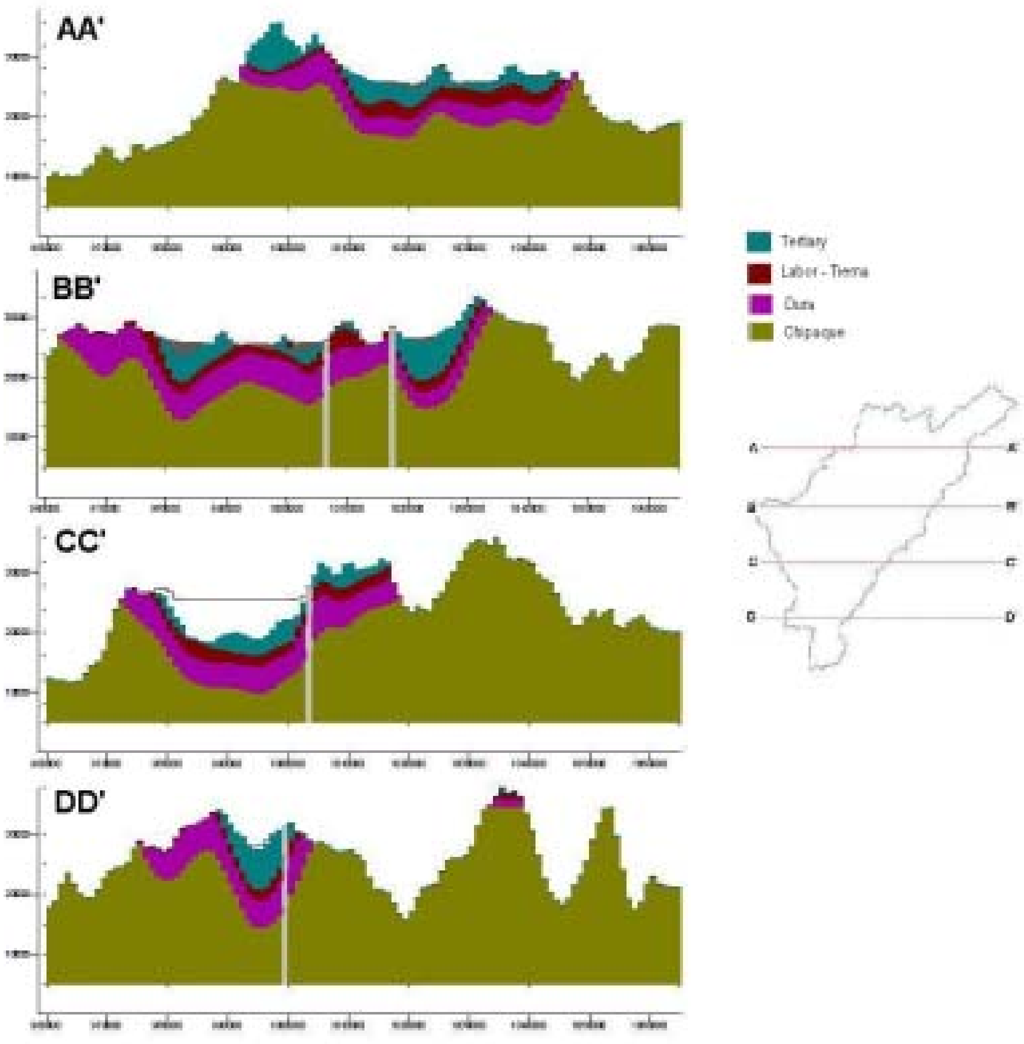

Figure-3.10 Example of Aquifer Structure of the Model

Aquifer Parameters

In the setting of aquifer parameters, initial aquifer parameters were set based on statistical values of aquifer parameters that were analyzed in "Hydrogeologic Analysis" of this Report. Ratio of (vertical permeability) / (horizontal permeability) is set (1/15). In the course of implementation of the ground water simulation, initial parameters were modified again and again to reach the reasonable simulation result. The final aquifer parameters are shown in Table-3.3. The coefficients of permeability in Table-3.3 are correspondent with existing data.

Table-3.3 Aquifer Classification and Aquifer Parameters for Groundwater Simulation

No.	Aquifer	Permeability Coefficient (m/day)	
		Horizontal	Vertical
1	Quaternary	0.6	0.04
2	Tertiary	0.06	0.004
3	Labor Tierna	1.0	0.067
4	Plaeners	0.5	0.033
5	Chipaque	0.12	0.008
6	Bogota Fault	10.0	10

Groundwater Recharge

Groundwater recharge, which was calculated by water balance analysis, was given to the model (see “Groundwater Recharge”). Groundwater recharge given to the Model is shown in Fugure-3.11. On the other hand, groundwater recharge outside of the Study Area is not examined in detail. Therefore, groundwater recharge outside of the Study Area was given to the Model referring that of large area simulation model.

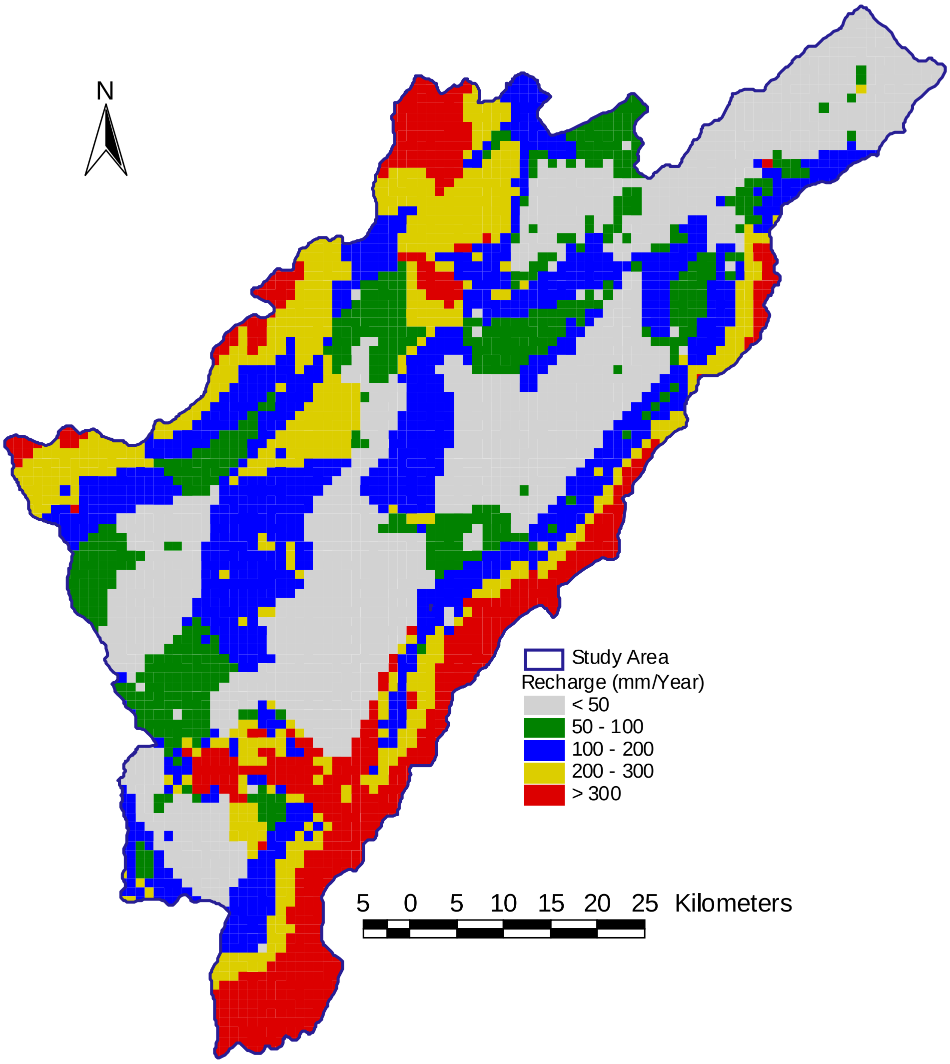

Figure-3.11 Groundwater Recharge of Simulation Model

Current Pumping

The current pumping wells of the Study Area were given to the model. For this, information of well inventory result was used. Yield of almost all the wells in the Study Area (around 7,000 wells) were given to the model. The total amount of yield is about 320,000m^3/day. This total yield is explained in “PART 11 WELL INVENTORY”. In the installation of yield to the Model, matters below were considered.

- Well location is set up exactly into the model, based on the coordinates recorded in well data-base.
- Aquifer of well is set up exactly into the model, based on the information recorded in

well data-base.

- Yield of well is exactly set up into the model, based on the information recorded in well data-base.
- Wells with unreasonable information or without enough information for modeling are adequately set up into the model after careful data modification.

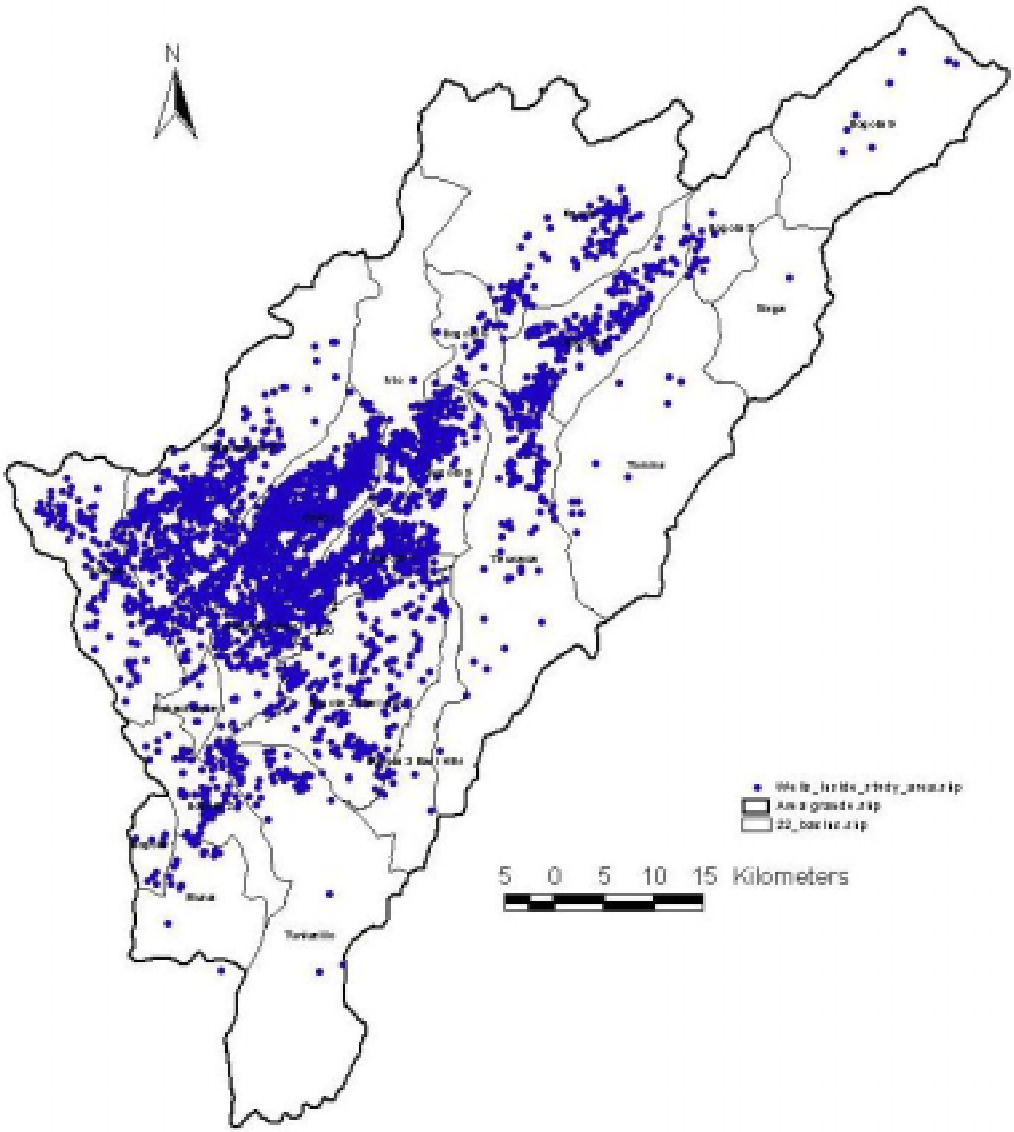

Figure-3.12 Wells in Simulation Model

(5) Result of Groundwater Simulation of the Study Area

The groundwater simulation was carried out under the condition explained above. The simulation was carried out by steady state condition. The result of the simulation is shown in Figure-3.13. The result of the simulation is explained below.

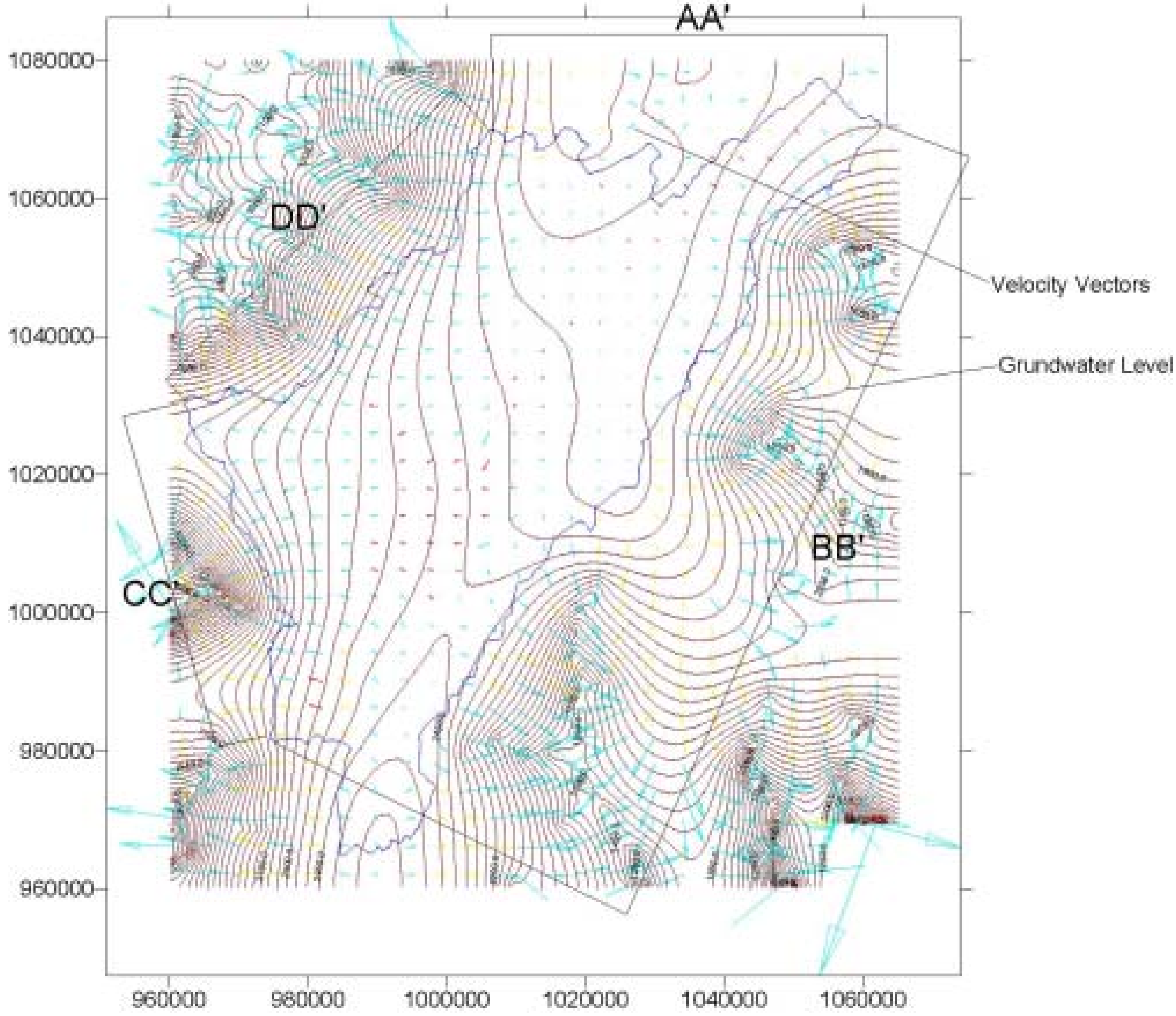

Figure-3.13 Calculated Groundwater Level of Quaternary by Simulation

<u>Reliability of the simulation result</u>

The calculated groundwater level is shown in Figuer-3.13 for Cretaceous. Calculated groundwater level has the same tendency with observed groundwater level but flatter and smoother than observed one. Groundwater level observed in wells is apparent groundwater level that is strongly affected by topography. Perched groundwater of unsaturated zone usually makes apparent groundwater table in mountains and plains. This groundwater makes local groundwater movement that flows toward nearby river. On the other hand, groundwater level that was calculated by this simulation shows regional groundwater flow.

<u>Groundwater balance by the simulation</u>

The calculated water balance in the simulation is shown in Table-3.4. Of groundwater recharge given to the Model, which is 144 mm/year, 19 % is pumped up by the wells and 81 % flows away from the Study Area.

Table-3.4 Calculated Groundwater Balance by the Groundwater Simulation

Groundwater balance	Items	Result			
Groundwater in	Groundwater recharge	1,690,000m^3/day	144mm/year	19.6m^3/s	100%
Groundwater out	Pumping from wells	321,000m^3/day	27mm/year	3.7m^3/s	19%
	Groundwater flowing out from the Model	1,368,900m^3/day	117mm/year	15.9m^3/s	81%

Groundwater out from the Study Area is broke down as shown in Table-3.5.

Table-3.5 Groundwater out from the Study Area

Total out	Flow in and out		
	Boundary	In and out	%
1,368,900(m^3/day)	North (A-A’)	94,640 (m^3/day) flow in	7%
	East (B-B’)	621,920(m^3/day) flow out	45%
	South (C-C’)	341,380(m^3/day) flow out	25%
	West (D-D’)	500,240(m^3/day) flow out	37%

CHAPTER 4 Evaluation of Groundwater Potential

Groundwater potential was analyzed following the steps as shown below.

a) Groundwater recharge was estimated by water balance analysis
b) Appropriateness of the estimated groundwater recharge was examined by groundwater simulation.

According to the result of above two analyses, groundwater recharge of the Study Area was estimated as 144mm/year in average. From this result, conclusion below can be obtained.

1) Based on the result of the existing study about groundwater age, it has been said that groundwater of the Study Area is not moving. However, result of this Study shows that groundwater of the Study Area is moving. Therefore, groundwater resource of the Study Area is considered renewable water resource that receives recharge and is involved into large groundwater flow system. Groundwater recharge is estimated 144mm/year by this Study and the same amount of groundwater is flowing in aquifers
2) If amount of groundwater development exceeds amount of groundwater recharge,

groundwater level will continue to go down because water balance is never satisfied. On the other hand, if amount of groundwater development is less than amount of groundwater recharge, lowering of groundwater level will finally stop. However, even in this case, groundwater lowering will always occur. Magnitude of groundwater lowering depends on amount of groundwater development and area of development. Therefore, for the sustainable groundwater development, groundwater lowering by new groundwater development must be predicted under the assumption of 144mm/year of groundwater recharge. Whether this groundwater lowering is approval or not is important point for planning of the new groundwater development.

(1) Safe Yield by Basin

Current yield from wells and groundwater recharge

The current rate of groundwater use (well yield ÷ groundwater recharge) is shown in Table-4.1 by basin. Total groundwater use of the Study Area is only 19% of total groundwater recharge. However, there is big difference in the current groundwater use by basin, 1% to 65%. It is clear that the current yield is much less than groundwater recharge in every basin. Therefore, pumping and groundwater recharge has been already balanced and lowering of groundwater level also has already stopped in every basins.

Table-4.1 Current Yield from Well and Groundwater Recharge by Basin

Basin	Catchment Area (km2)	Number of wells	Yield (mm/year)	Groundwater Recharge (mm/year)	Rate of groundwater use
Bogotá 1-3	678	1,559	42	105	40%
Bogotá 4-6	232	1,141	72	149	48%
Bogotá 7-9	557	429	18	62	29%
Bojaca	219	311	36	129	28%
Chicu	134	1,620	122	187	65%
Frio	194	320	23	100	24%
Neusa	432	185	7	187	4%
Sisga	152	1	0	143	1%
Muna	128	40	4	58	6%
Subachoque 1	32	18	3	71	5%
Subachoque 2	386	1,078	52	150	35%
Teusaca	353	256	15	166	9%
Tomine	368	21	1	109	1%
Tunjuelito	404	103	10	330	3%
Total	4,268	7,081	27	144	19%

Rate of groundwater use Yield ÷Groundwater recharge

Safe Yield

Theoretically, 100% of groundwater recharge can be used for groundwater development. However, it will cause considerable lowering of groundwater level and will give bad impact to existing wells. As shown in Table-1, the highest rate of groundwater use in the Study Area is 65% in Chicu Basin. Groundwater development will always cause lowering of groundwater level and the current lowering of groundwater level of the Study Area seems to be allowable. Therefore, it is recommended that safe yield should be less than 60% of groundwater recharge, which corresponds to highest rate of current groundwater use in the Study Area. Safe yield by basin is proposed as shown in Table-4.2.

For small-scale groundwater development (Quaternary and Tertiary aquifers), production wells should be planed based on safe yield by basin. On the other hand, for large-scale groundwater development of Cretaceous aquifer, amount of new development should be planed based on total amount of safe yields of several basins that will be affected by this development, because Cretaceous aquifer extends over several basins. Moreover, groundwater simulation should be implemented to estimate influence by development before hand.

Table-4.2 Safe Yield by Basin

Basin	Catchments Area (km^2)	Safe Yield (mm/year)	Basin	Catchments Area (km^2)	Safe Yield (mm/year)
Bogotá 1-3	678	63	Sisga	152	86
Bogotá 4-6	232	90	Muna	128	35
Bogotá 7-9	557	37	Subachoque 1	32	43
Bojaca	219	77	Subachoque 2	386	90
Chicu	134	112	Teusaca	353	100
Frio	194	60	Tomine	368	66
Neusa	432	112	Tunjuelito	404	198
Total	86 mm/year				

Note) Safe Yield = Groundwater recharge×60%

Influence from over pumping

Environmental hazard caused by over pumping is that groundwater resource is dried up and land-subsidence takes place. Groundwater resource will not be dried up if pumping amount is less than groundwater recharge.

Land subsidence that is easily observed is usually caused by i) depression of soil with change of dry-wet condition, ii) local land subsidence by construction work. On the other hand, land subsidence that is caused by lowering of groundwater is called regional land subsidence, which is gradually taking place equally over large area during long period. It is difficult to observe this land subsidence by eyes and only long-term leveling of ground elevation can show this subsidence. In the Study Area, such leveling was not carried out so far and there is no evidence of regional land subsidence. Land-subsidence takes place depending on lowering of groundwater level and mechanical strength of ground. In the Study Area, geological formation that will be affected by lowering of groundwater level exists deeper than G.L.-100m. Such formation has strong resistance against land-subsidence. Therefore, land-subsidence by lowering of groundwater is negligible. Especially in western part of Bogotá Plain, there is almost no influence by land-subsidence because there is not high building with deep pile foundation that will be damaged by land-subsidence.