CHAPTER 4 GROUNDWATER POTENTIAL STUDY

4.1 Hydrogeology Analysis

(1) Aquifer Classification and Characteristics

(a) Aquifer Classification

In the Study, aquifers are classified according to the following geological classification. This Study follows the existing aquifer classification. Aquifer classification and aquifer characteristics are summarized in Table-4.1

Table-4.1 Aquifer Classification of the Study Area

Age		Stratigraphy	Rock Faces	General Permeability
Quaternary	Holocene	Alluvium	Clay, silt, sand, gravel	High-Low
	Pleistocene	Terraza Formation	Clay, sandy clay, sand	Middle-Low
		Sabana Formation	Clay, sandy clay, sand	Middle-low
		Tilata Formation	Sand and gravel, silt, clay (consolidated)	High
Tertiary	Oligocene	Usme Formation	Claystone	Low
	Eocene	Regadera Formation	Sandstone, conglomerate, claystone	Low
		Bogotá Formation	Claystone, siltstone, sandstone	Middle-Low
	Paleocene	Cacho Formation	Sandstone, conglomerate	High
		Guaduas Formation	Claystone, shale	Middle-Low
Cretaceous		Guadalupe Group	Sandstone, siltstone, shale	High-low
		Chipaque Formation	Shale, sandstone	Low

(b) Characteristics of Aquifer

Aquifers in the Study Area are classified into 3 types as shown below;

i) Quaternary aquifer
ii) Tertiary aquifer
iii) Cretaceous aquifer

The formations above consist of alternation of permeable and impermeable ones. Therefore, aquifers are limited to permeable formations of them. Each aquifer has outcropping part where groundwater is recharged, hence each aquifer has characteristics of both unconfined and confined condition.

Quaternary aquifer

Groundwater currently pumped up through wells in the Study Area is stored in sand and gravel layers of Sabana Formation. Quaternary aquifer consists of sand and gravel layers, which distribute irregularly in different depth with poor continuity. Each sand and gravel layers has different groundwater levels. Therefore, groundwater levels observed in wells are combined groundwater levels of different groundwater level of each sand and gravel layers.

Tertiary aquifer

In the Study Area, Tertiary mainly consists of clayey sediments. Only small sand and gravel strata locally included in clayey strata form aquifers. Tertiary aquifers are difficult for large scale groundwater development because the scales are too small.

Cretaceous aquifer

Cretaceous system consists of Guadalupe Group and Chipaque Group in the Study Area.

Guadalupe Group forms excellent aquifer including sand formation. On the other hand, Chipaque Formation mainly consists of shale. Guadalupe Group consists of three formations as shown below.

a) Labor Tierna Formation

b) Plaeners Formation

c) Arenisca Dura Formation

Labor Tierna Formation, the upper-most formation of Guadalupe Group, is excellent aquifer consisting of permeable sandstone. Plaeners Formation, the middle of Guadalupe Group, is low permeable formation consisting of shale. Arenisca Dura Formation, the lowest formation of Guadalupe Group, consists of alternation of sand and shale with lower permeability than that of Labor Tierna Formation. Therefore, Labor Tierna Formation, the upper-most formation of the Guadalupe Group, is most promising for groundwater development. Additionally, Arenisca Dura Formation is also promising.

(c) Hydrogeological Structure

Hydrogeological structure of the Study Area is strongly dominated by complicated geological structure, and distribution and continuity of aquifers are influenced by faults and folding. It seems that Quaternary, Tertiary and Cretaceous aquifers form confined aquifers. Superficial aquifers of the Quaternary seem to form small-unconfined aquifers. Groundwater is confined in Savanna Formation and Tilata Formation that form main aquifer of Quaternary because these strata are overlaid by impermeable strata. The static groundwater level of Quaternary, Tertiary and Cretaceous is between GL-20m to GL-50m. Though the depth distribution of these aquifers is different, static groundwater levels of these aquifers are similar. This suggests that there is hydrogeological connection among three aquifers.

(d) Groundwater recharge mechanism

Ground water recharge mechanism of Quaternary and Tertiary

There is high possibility that Quaternary and Tertiary aquifer is recharged from river channels and sediments at the foot of mountains. It is assumed that rainfall, which reaches the surface, infiltrates into deep aquifers though soil and impermeable layers.

Ground water recharge mechanism of Cretaceous

Cretaceous Group forms mountains surrounding Bogotá Plain. Cretaceous Group distributes in the deep part of the ground in the center of Bogotá Plain by folding and fault movement. Therefore, it is assumed that Cretaceous aquifers are recharged in the mountains surrounding Bogotá Plain. It is assumed that groundwater is flowing from mountain areas toward deeper parts of the Cretaceous aquifers.

(e) Aquifer Parameter

Aquifer parameters were analyzed from the result of pumping tests, which were carried out in the Study Area. Reliable results of the pumping test were carefully selected and used for this analysis.

Table-4.2 Hydraulic Parameters of Quaternary and Guadalupe Aquifers

Quaternary Aquifer		
Parameter	**Range**	**Representative Values**
Yield(m^3/day)	30—1,500	150—250
Specific Capacity(m^3/day/m)	1—500	4—30
Transmissivity(m^2/day)	1.5—250	4—15
Permeability coefficient(m/day)	0.01—10.0	0.15—1.0
Storativity coefficient(-)	10^{-7}—10^{-1}	10^{-5}—10^{-3}
Guadalupe Aquifers		
Parameter	**Range**	**Representative Values**
Yield(m^3/day)	50—7000	150—1000
Specific Capacity(m^3/day/m)	1—1000	10—120
Transmissivity(m^2/day)	1—1000	15—150
Permeability coefficient(m/day)	0.05—10.0	0.5—1.0
Storativity coefficient(-)	10^{-9}—10^{-1}	10^{-7}—10^{-3}

(2) Hydrogeological Map

The Study Team compiled hydrogeological map using GIS by putting together all the Study results. Items stored by GIS are: aquifer distribution, groundwater level, groundwater recharge by aquifer, distribution of wells, distribution of aquifer parameters (permeability coefficient and storativity coefficient), distribution of groundwater quality, groundwater development potential by aquifer and so on.

4.2 Water Balance and Groundwater Recharge

The purpose of water balance analysis is to estimate groundwater recharge of Study Area. Before water balance analysis by the Study Team, the existing result of water balance analysis was examined. Hydrological and meteorological data of CAR and EAAB was employed for the water balance analysis. Groundwater recharge is the output of water balance analysis and is used for the input parameter for groundwater simulation. Method and result of the water balance analysis is described below.

4.2.1 Water Balance Analysis

(1) Method of Analysis

Calculation process of runoff and precipitation of the basin is shown in Figure-4.1 Water balance analysis is explained below.

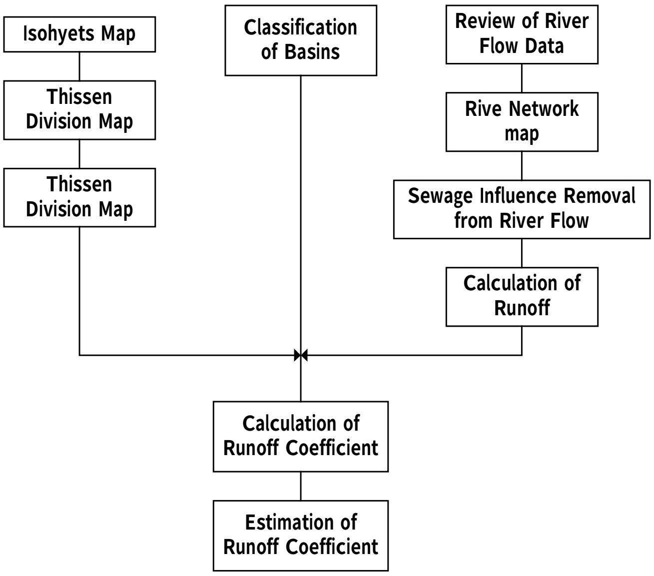

Figure-4.1 Calculation Process of Hydrological Analysis

(2) Classification of Basins

Based on the assumption that runoff into the rivers basically occurs in mountains, it is estimated that topographical characteristic (area ratio between mountains and plan) and runoff coefficient of the basin must have closer correlation. On the basis of this estimation, all 20 basins were divided into 3 groups according to their area ratios. Regarding the basins without any river flow data available for runoff coefficient calculation, the runoff coefficient of the other basins that belong to the same group is applied.

Table-4.3 Classification of Basins

Group 1	High area proportion of mountains. Mainly tributary river basins. A little human-activity influence on river flow data.
Group 2	Area ratio of about 50%. Tributary river basins in agriculture area. Significant water intake influence on river flow data.
Group 3	Low area portion of the plain. Rio Bogotá mainstream. Significant influences on river flow data, i.e. sewage outflow and water intake for domestic use and irrigation use.

(3) Calculation of Precipitation

Based on long-term precipitation data, an annual precipitation map was made as shown in Figure-4.4. Annual precipitation by basin was calculated from this map.

(4) River Network

After a river network map was drawn, a flow diagram of Rio Bogotá was plotted from the upstream to Alicachin station located at the downstream according to flow data observed during 1973-1999 and data of water uses. Refer to Figure-4.2. This diagram clearly shows that the water intake at Tibitoc purification plant and the sewage outflow from the center of Bogotá city affect the volume of Rio Bogotá in a great degree.

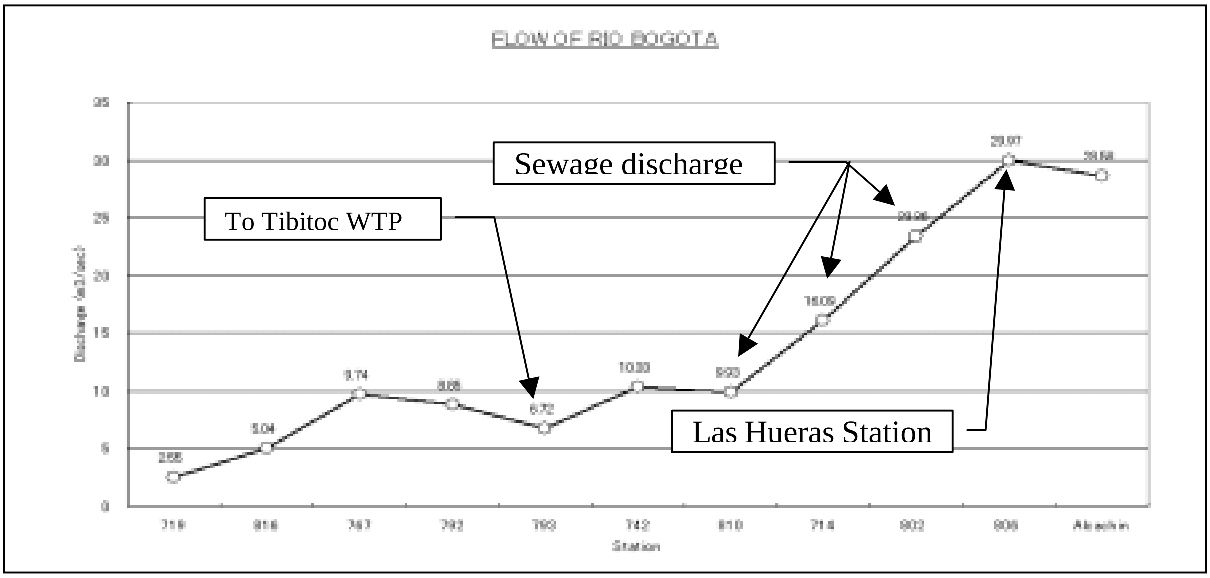

Figure-4.2 Flow curve of Bogota River

(5) Sewage Outflow Infuence

Sewage outflow must be taken off from the runoff obtained from the flow data. For the Bogotá (3) basin that has much of the sewage outflow, actual runoff without sewage outflow was estimated from flow data and the amount of water supply.

(6) Calculation of Runoff

Runoff coefficients were calculated from flow data by basin. These coefficients were applied for estimation of runoff coefficient of the other basins that do not have enough flow data for the caluculation. Finally obtained discharge of basins is shown in Table-4.4.

Table-4.4 Runoff of the Study Area

Bain	Annual Precipitation (mm)	Runoff Coefficient (%)	Runoff (m^3/sec)	Bain	Annual Precipitation (mm)	Runoff Coefficient (%)	Runoff (m^3/sec)
SISGA	913	40.0%	1.77	BOGOTÁ (8)	725	40.0%	0.95
TOMINE	873	34.0%	3.47	BOGOTÁ (7)	730	20.0%	0.80
TEUSACA	896	34.2%	3.42	BOGOTÁ (6)	772	20.0%	0.32
TUNJUELITO	941	30.7%	3.71	BOGOTÁ (5)	705	20.0%	0.47
NEUSA	850	30.2%	3.52	BOGOTÁ (4)	713	41.0%	0.58
FRIO	838	42.1%	2.18	BOGOTÁ (3)-E	770	48.5%	4.36
CHICU	752	20.0%	0.63	BOGOTÁ (3)-W	624	20.0%	0.65
BOJACA	755	32.9%	1.72	BOGOTÁ (2)	618	20.0%	0.44
SUBACHOQUE (2)	833	32.2%	3.28	BOGOTÁ (1)	722	50.1%	0.41
SUBACHOQUE (1)	600	20.0%	0.12	MUNA	727	45.4%	1.35
BOGOTÁ (9)	719	39.9%	2.54	-	-	-	-
Total	Annual Precipitation=802mm, Runoff Coefficient=33.7%, Runoff=36.69m^3/s. Taking account of water taken and put back, the discharge at the outlet of the Bogotá plain can be calculated at 30.73m^3/s. Total runoff occurred in the Study Area is 24.57m^3/s after sewage volume is deducted whose water supply come form the other basin. <Water taken: 16.20m^3/s - for irrigation; 11.10m^3/s, for domestic or other use; 5.10m^3/s> <Sewage: 10.24m^3/s – source within the Area; 4.08m^3/s, source outside the Area; 11.10m^3/s>						

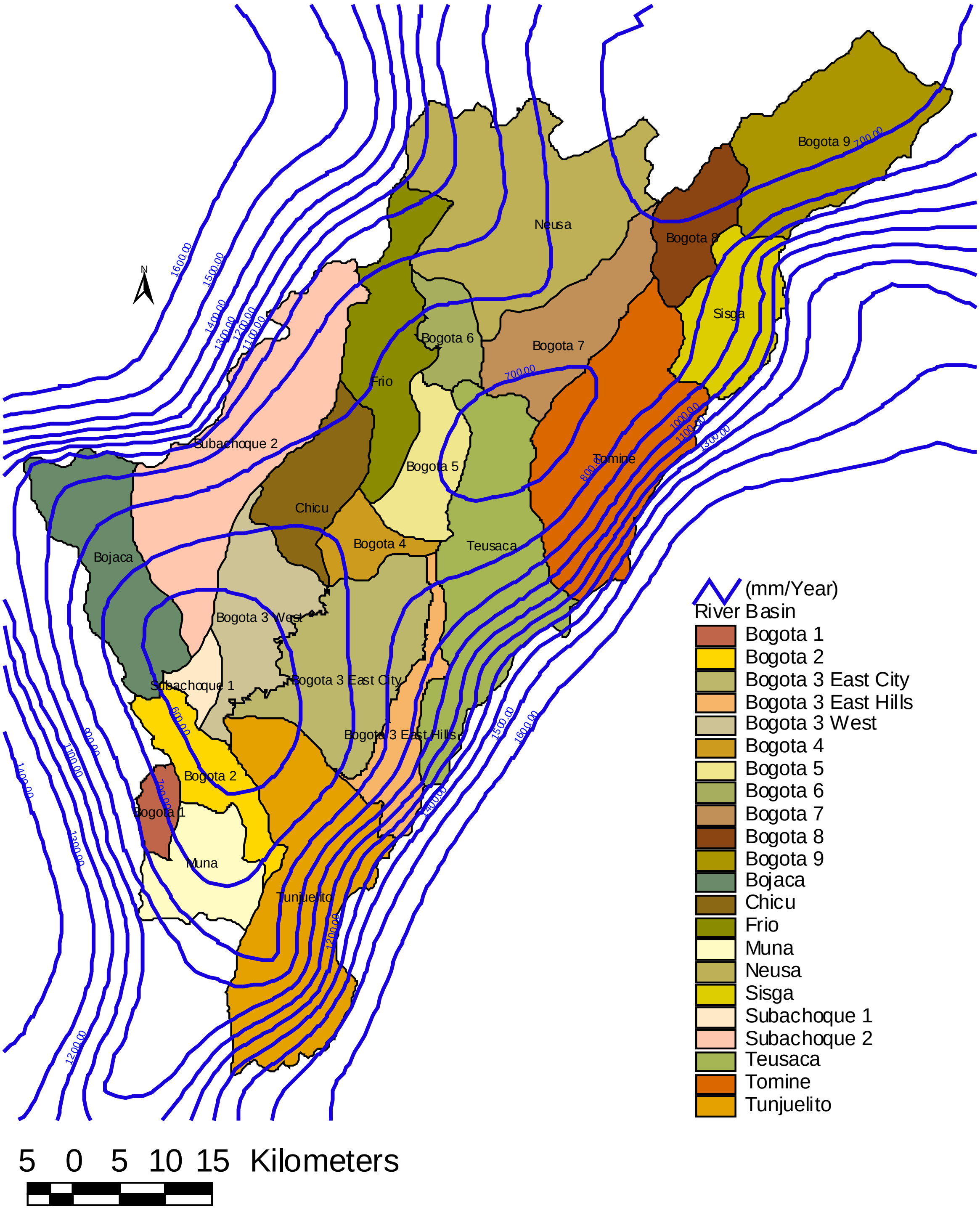

Figure-4.3 Equi-Precipitation Map

4.2.2 Groundwater Recharge

(1) Basic Equation of Water Balance Analysis

Groundwater is recharged from rainfall in mountains and hills, plains and rivers in the Study Area, then recharged groundwater gradually infiltrates into deep aquifers. In this Study, groundwater recharge was evaluated by water balance analysis. Water balance equation used for this analysis is shown below.

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

where,

P	: Precipitation into basin (mm/year)
ETR	:Real evapo-transpiration from basin (mm/year)
D_2	:Direct runoff from basin (mm)
G_2-$_{\text{baseflow}}$	:Base flow(mm)
(D_2 +G_2-$_{\text{baseflow}}$)	:Runoff from basin (mm/year)

(2) 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.

(3) Precipitation of Basins (P)

Average annual precipitation of the Study Area is shown in Figure-4.3. Average annual precipitation of the Study area is 802mm.

(4) River Discharge of Basins （D_2 +G_2-$_{\text{baseflow}}$）

River discharge of the Study Area was analyzed and the results of water balance analysis by basin were applied.

(5) Potential Evapo-transpiration (ETP)

The Study Team used pan-evaporation for evaluation of potential evapo-transpiration. In the Study Area, Class-A-Pan evaporimeters are used and potential evapo-transpiration is approximated 70% of pan-evaporation by Class A-Pan. Pan-evaporation of basins was calculated by Thiessen method, and potential evapo-transpiration of basins was calculated.

(6) 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. In this Study, evapo-transpiration ratio was expressed by function of precipitation, potential evapo-transpiration (ETP) and soil moisture by calculation of soil model. Real evapo-transpiration was calculated by applying this function to the Study Area.

<u>Date for Soil Model Analysis</u>

Daily precipitation data and daily pan-evaporation data at observation stations shown in Table-4.5 were used for the model analysis. Most of data are during 1991 to 1998, for 8 years. Three types of Total Available Moisture in the soil were set for the model based on FAO data.

Table-4.5 Observation Station for Soil

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

Result of Model Analysis

Soil water balance was analyzed using daily precipitation and daily pan-evaporation of about 8 years. The soil moisture balance was analyzed for 3 types of soil for 8 years. Evapo-transpiration ratio (ETR/ETP) were obtained for each soil type. Analyzed result shows that Annual evapo-transpiration ratio (ETR/ETP) has strong relationship with (Annual precipitation ÷ Annual ETP) and soil moisture. Therefore, annual evapo-transpiration ratio (ETR/ETP) can be approximated by a function of three parameters (annual precipitation, annual ETP and available soil water). Function is proposed as shown below:

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

Where
P : (Annul precipitation ÷ Annual ETP)
W : Maximum available water of soil (mm)
LN( ) : Natural logarithm

High accuracy of the function is shown in Figure-4.1. By this function, real evapo-transpiration (ETR) of the Study Area can be estimated considering precipitation, potential evapo-transpiration (ETP) and soil types.

(7) Real Evapo-transpiration of the Study Area

Real evapo-transpiration of the Study Area was analyzed using the function. For calculation of ETR, “Annual Precipitation Map” (Figure-4.3), “Annual ETR Map” and “Total Available Moisture in Soil Map” were overlapped and the function was applied. Calculated ETR is shown in Figure4.4.. “Maximum Available Moisture Map” was made from “Land use Map” by the Study Team.

(8) Groundwater Recharge

For calculation of annual groundwater recharge, “Precipitation Map”, ”ETR Map” and ”River Discharge Map” were overlapped. Calculated groundwater recharge is shown in Fifure-4.5. Annual groundwater recharge by basin is shown in Table-4.6.

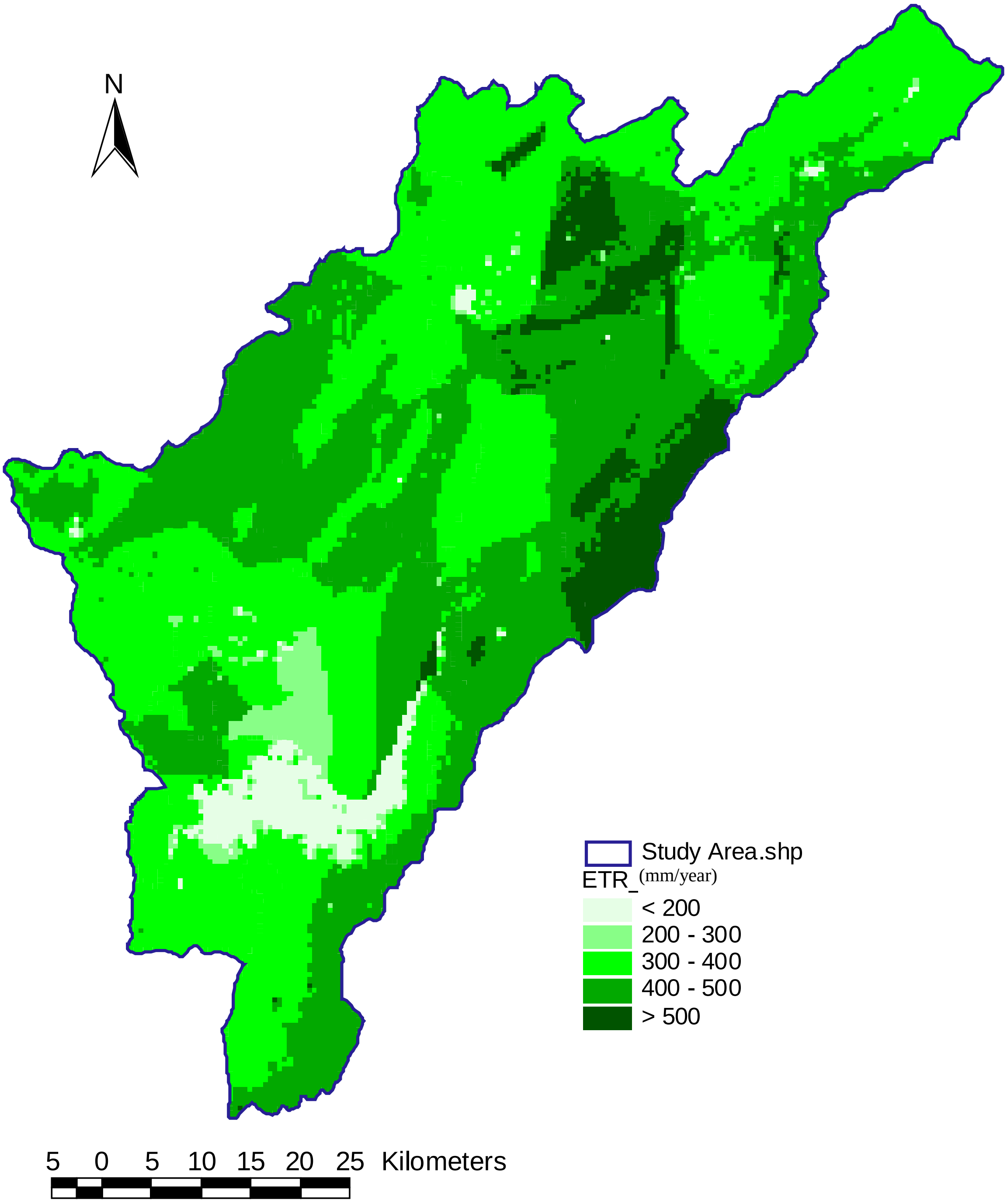

Figure-4.4 Annual ETR

Table-4.6 Result of Groundwater Recharge Analysis

Basin Name	Catchment Area (km^2)	Annual Rainfall (mm/year)	Annual Discharge (mm/year)	Annual Soil Infiltration (mm/year)	Annual Potential Evapo-transpiration (mm/year)	Annual Real Evapo-Transpiration (mm/year)	E.T.R./ E.T.P.	Groundwater Recharge	
								mm/year	m^3/year
Tunjuelito	411	946	315	630	582	460	79%	173	71,185,200
Bojaca	233	576	201	375	627	369	59%	8	1,817,400
Choconta	281	772	271	500	662	443	67%	56	15,764,100
Chicu	154	789	346	443	655	404	62%	38	5,852,000
Frio	193	787	300	487	601	440	73%	47	9,148,200
Neusa	429	840	186	654	649	476	73%	180	77,177,100
Sisga	154	808	345	464	615	417	68%	43	6,668,200
Subachoque	409	804	206	598	647	470	73%	128	52,270,200
Teusaca	366	801	267	534	709	492	69%	41	15,006,000
Tomine	372	691	170	521	834	516	62%	8	2,901,600
Total of 10 Basin	3,002	792	247	521	665	459	69%	86	257,790,000

Average groundwater recharge all the Study Area was calculated 144mm/year (615 million m^3/year, or 19.5m^3/s).

(9) Water Balance of Study Area

Some 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-4.7. This balance includes groundwater water balance that was calculated by groundwater simulation mentioned later in this Chapter.

Table-4.7 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

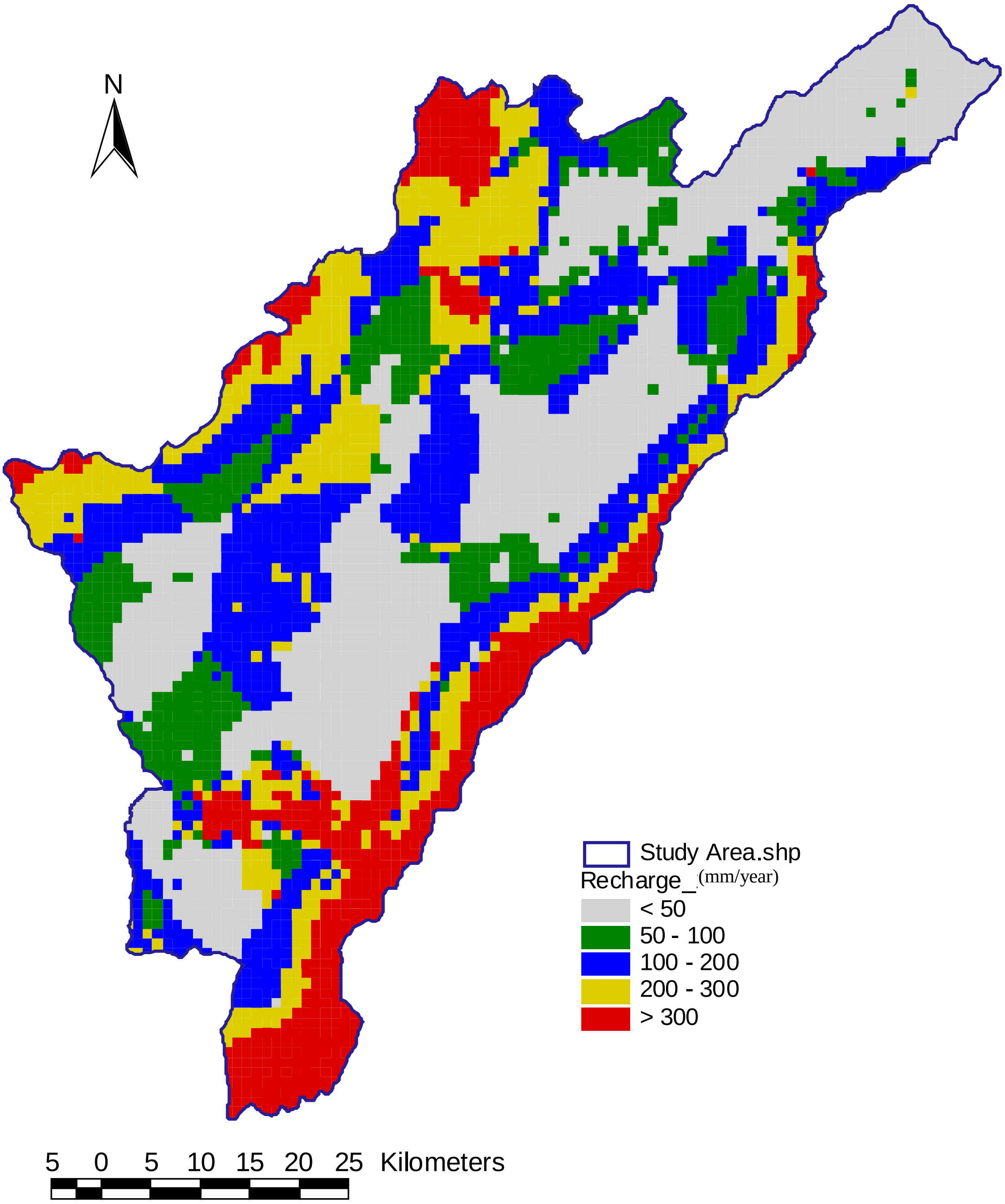

Figure-4.5 Annual Groundwater Recharge

4.3 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.

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

4.3.1 Large Area Groundwater Simulation

(1) Purpose and Area for Large Area Groundwater Simulation

Large area groundwater simulation was carried out to analyze groundwater flow system of the large area including the Study and to find suitable boundary conditions of the Study Area. The area of large simulation is 32,200 km^2, and this area covers most of Cundinamarca Department (Refer to Figure-4.6)

(2) Large Area Groundwater Simulation Model

<u>Size of Model and boundary condition</u>

Mesh distance of the model is 1,500 m and total number of cells is 57,600 (240×240). Boundary conditions of the model were set as explained below.

- Constant head boundary was set for Magdalena River.
- Constant head boundary was set for Orinoco Plain.
- For other borders of the model, ”Boundary of Groundwater flow = 0 “ was set for where the boundary corresponds to watershed, and “Constant head boundary ” was set for where the boundary corresponds to rivers.
- Inside the model, “Drain boundaries” were set to main rivers in the mode.

<u>Aquifer Structure</u>

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.

<u>Aquifer Parameters</u>

Aquifer parameters were set based on statistical values of aquifer parameters that were analyzed in Hydrogeological Analysis

<u>Groundwater Recharge</u>

There is no reliable information for estimation of groundwater recharge of modeled area. Accordingly, groundwater recharge was estimated based on annual rainfall maps by IDEAM and CAR covering entire Cundinamarca Department. In the processes of groundwater simulation, initial groundwater recharge was modified over times within allowable range to reach reasonable simulation results.

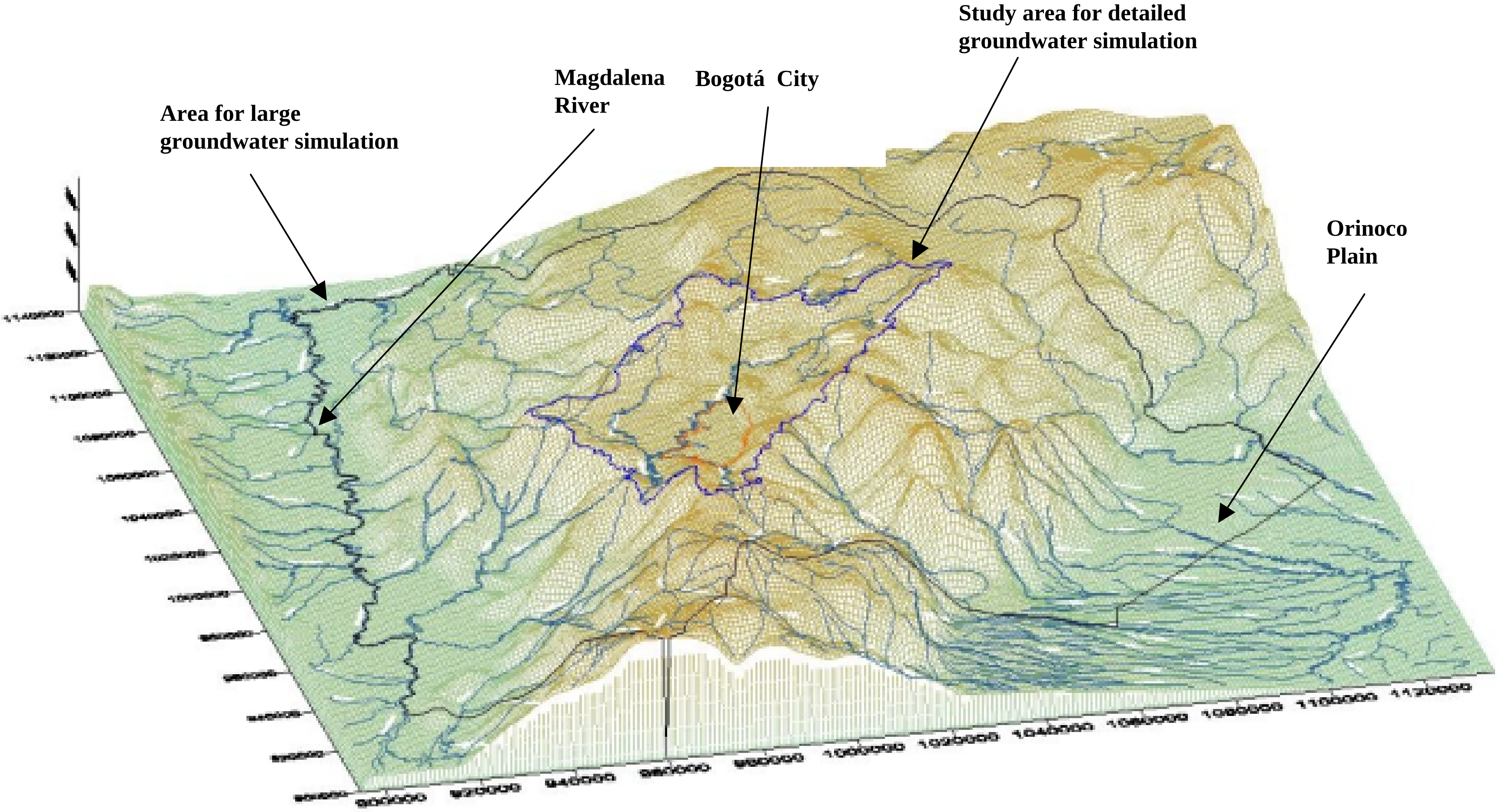

Figure-4.6 Area for Groundwater Simulation

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. Total yield from wells was changed from 0%, 20%, 30% and 40% of the total groundwater recharge to the Study Area. Therefore, the change of groundwater flow by the change of well yield was examined.

(3) Result of Large Area Groundwater Simulation

Groundwater Flow System

Calculated groundwater flow with pumping rate of 40% of groundwater recharge is shown in Figure-4.7. According to Figure-4.7, groundwater flow system is classified into two types.

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

Most of the Study Area is included in Groundwater flow system flowing toward the south-west direction to Magdalena River.

Influence on groundwater flow system by pumping of the Study Area

According to result of simulation, the influence of pumping on groundwater flow is as follows.

- As yield from pumping increases, the groundwater flow to wells is accelerated. Meanwhile, groundwater level is lowered near wells.
- The groundwater shed expands from the Study Area toward surrounding regions by increase of pumping. Increase of pumping enlarges the area influenced by pumping. Ultimately, groundwater outside of the Study area is drawn into the Study area.

(4) 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 south-west 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 flow is not limited within the Study area. As pumping increases, influenced area is enlarged toward outside of the Study area.

4.3.2 Groundwater Simulation of the Study Area

(1) Purpose of Simulation

This simulation examines appropriateness of groundwater recharge of 144mm/year that was estimated in water balance analysis.

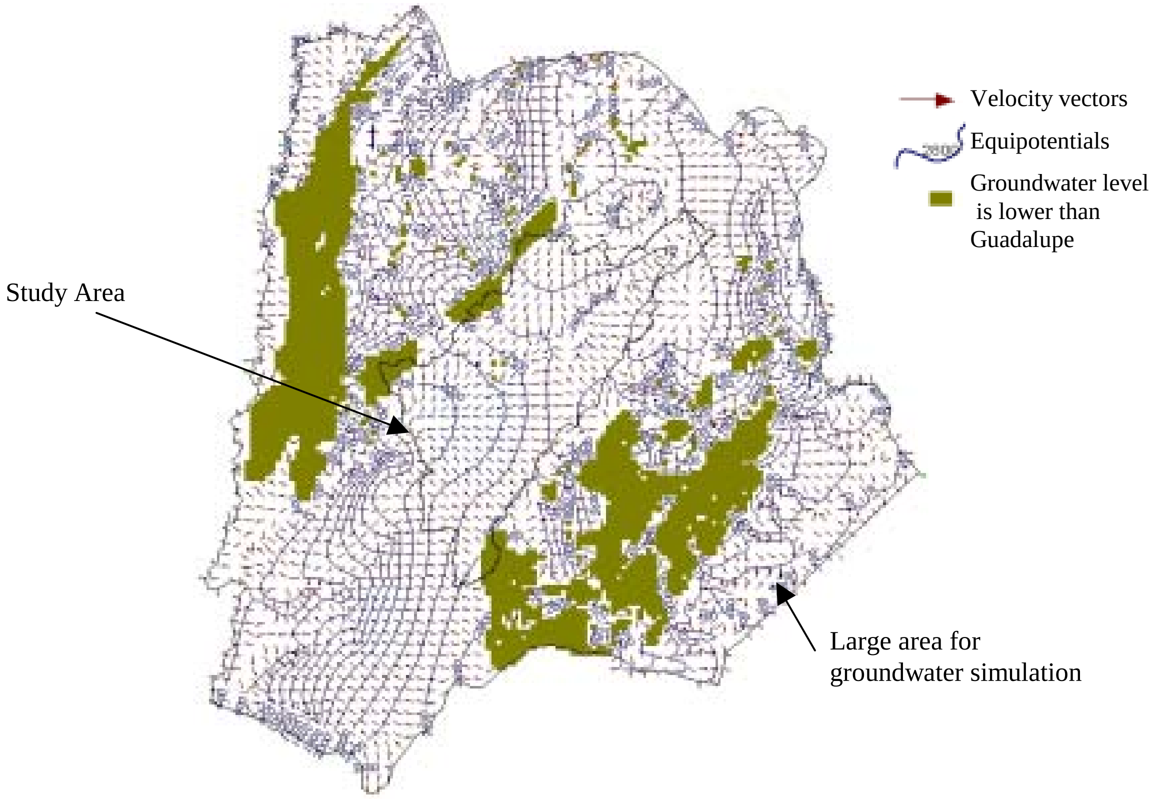

Figure-4.7 Results of Large Area Groundwater Simulation (Yield = 40% of Recharge)

(2) Simulation Model

Size of Model, modeled area and boundary condition

Mesh distance of the model is 1,000 m and total number of cells is 12,600 (105x120). Area of 105km x 120km including all the Study Area was modeled for simulation.

Boundary condition

According to the result of the large Area groundwater simulation, groundwater is flowing to Magdalena River and Orinoco River Basins. Therefore, river systems outside of the Study Area were installed to the Model as “River Drain Condition”. Moreover, “River Drain Conditions” were set to a little parts of the model in order to obtain reasonable result.

Aquifer Structure

In Aquifer model formulation, the Study Team made geological sections based on existing geological map of 1/100,000 by INGEOMINAS. Then, a three-dimensional geological model was made. This simulation model has five aquifers following classification of INGEOMINAS map as shown in Figure-4.8.

Aquifer Parameters

The initial aquifer parameters were set based on statistical values of aquifer parameters that were analyzed in Hydrogeology Analysis.

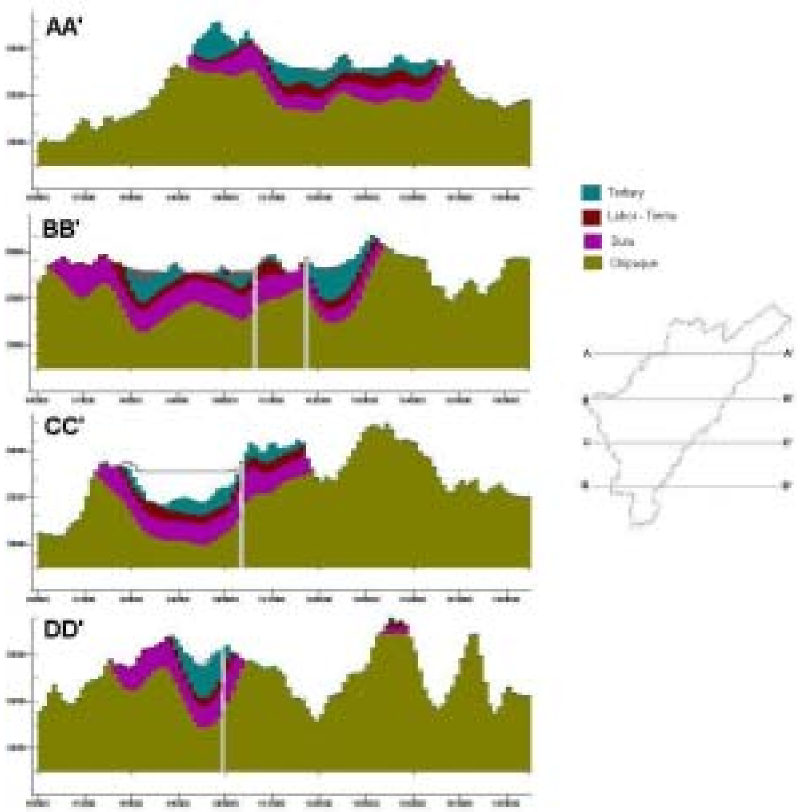

Figure-4.8 Example of Aquifer Structure of the Model

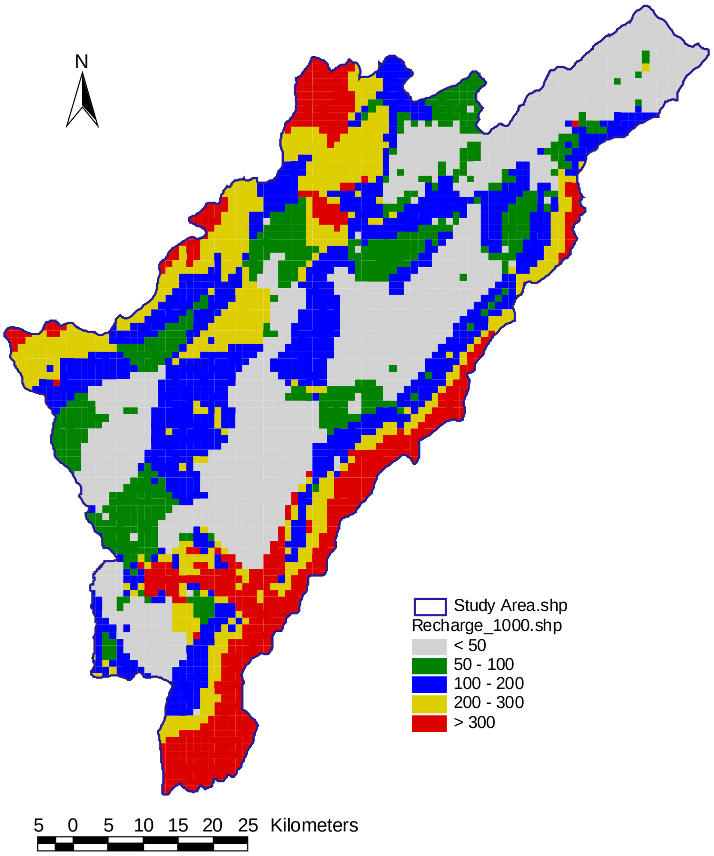

Figure-4.9 Groundwater Recharge of Simulation Model

Groundwater Recharge

Groundwater recharge, which was calculated by water balance analysis, was given to the model (refer to Figure-4.9). Average groundwater recharge is 144mm/year. On the other hand, there is not detailed information on groundwater recharge outside the Study Area. Therefore, groundwater recharge outside the Study Area was given to the Model based on the result of the large area simulation model.

Current Pumping

The current pumping wells of the Study Area (around seven thousand wells) were given to the model based on the result of Well Inventory. The total amount of yield is about 320,000m^3/day.

(3) Result of Groundwater Simulation of the Study Area

Calculated groundwater level

The calculated groundwater levels are shown in Figure-4.10 for Cretaceous aquifers. Calculated groundwater levels have the same tendency with observed groundwater levels but flatter and smoother than observed ones. Groundwater levels observed in wells are apparent groundwater levels that are strongly affected by topography. Perched groundwater of unsaturated zone usually makes apparent groundwater tables in mountains and plains. This groundwater makes local groundwater movements that flow toward nearby rivers. Besides, groundwater levels that were calculated by this simulation show regional groundwater flow.

Groundwater balance by the simulation

The calculated water balance in the simulation is shown in Table-4.8.

Table-4.8 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-4.9.

Table-4.9 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%

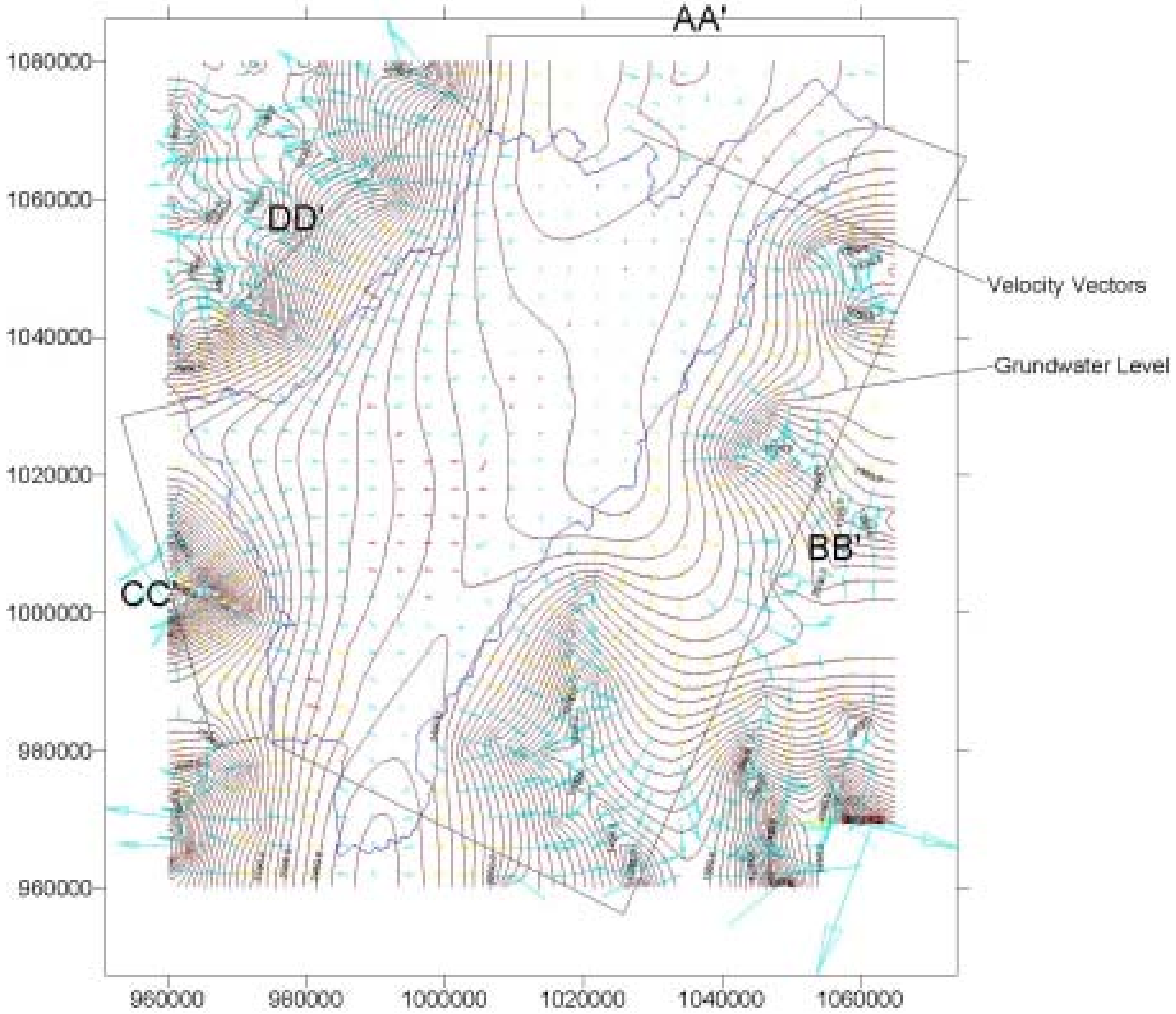

Figure-4.10 Calculated Groundwater Level of Cretaceous by Simulation

4.4 Evaluation of Groundwater Potential

Groundwater potential was analyzed by 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 results of above two analyses, groundwater recharge of the Study Area was estimated as 144mm/year on average. From this result, conclusion below can be obtained.

1) From the result of the past studies about groundwater age, it was said that groundwater of the Study Area is not moving. However, the 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.

2) 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 acceptable or not is the

important point for planning of the new groundwater development.

(1) Safe Yield by Basin

Current yield from wells and groundwater recharge

The current ratio of groundwater use (well yield ÷ groundwater recharge) is shown in Table-4.10 by basin. Total groundwater use in the Study Area account for just 19% of the total groundwater recharge. However, there is a large 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 all basins. Therefore, pumping and groundwater recharge has already been balanced and lowering of groundwater levels also has already stopped in every basins.

Table-4.10 Current yield from well and groundwater Recharge by Basin

Basin	Catchment Area (km^2)	Number of wells	Yield (mm/year)	Groundwater Recharge (mm/year)	Ratio 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%**

Ratio of groundwater use Yield ÷Groundwater recharge

Safe Yield

Theoretically, 100% of groundwater recharge can be used for groundwater development. However, it will cause considerable decline of groundwater level and will give negative impacts on existing wells. As shown in Table-4.10, 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-4.11.

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

Table-4.11 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%

(2) Pumping and Land-subsidence

Environmental hazards caused by over pumping are drought of groundwater resource and land-subsidence. Groundwater resource will not be dried up in case the pumping amount is less than groundwater recharge.

Land subsidence, which is easily observed, is usually caused by i) depression of soil with change of dry-wet condition, ii) local land subsidence by construction work, at one hand. On the other hand, land subsidence that is caused by lowering of groundwater levels is called regional land subsidence, which is gradually taking place equally over a large area during long period. It is difficult to observe this type of land subsidence by eyes and only long-term leveling of ground elevation can show this subsidence. In the Study Area, such leveling has not been carried out so far and there is no evidence of regional land subsidence. Land-subsidence takes place depending on lowering of groundwater levels and mechanical strength of the ground. In the Study Area, geological formation that will be affected by lowering of groundwater levels 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.