5.3 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

The result of analysis is explained below.

5.3.1 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-5.14).

(a) Purpose of Large Area Simulation

Large area groundwater simulation was carried out to analyze groundwater flow system of the large area including the Study Area.

(b) Large Area Groundwater Simulation Model

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

Size of Model

Mesh distance of the model is 1,500 m and total number of cells is 42,000.

Modeled Area and boundary condition

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-5.15).

Based on principles above, boundary condition of the model was set as explained below (Figure-5.15).

- 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.
- Inside the model, “Drain boundary” was set to main rivers in the mode.

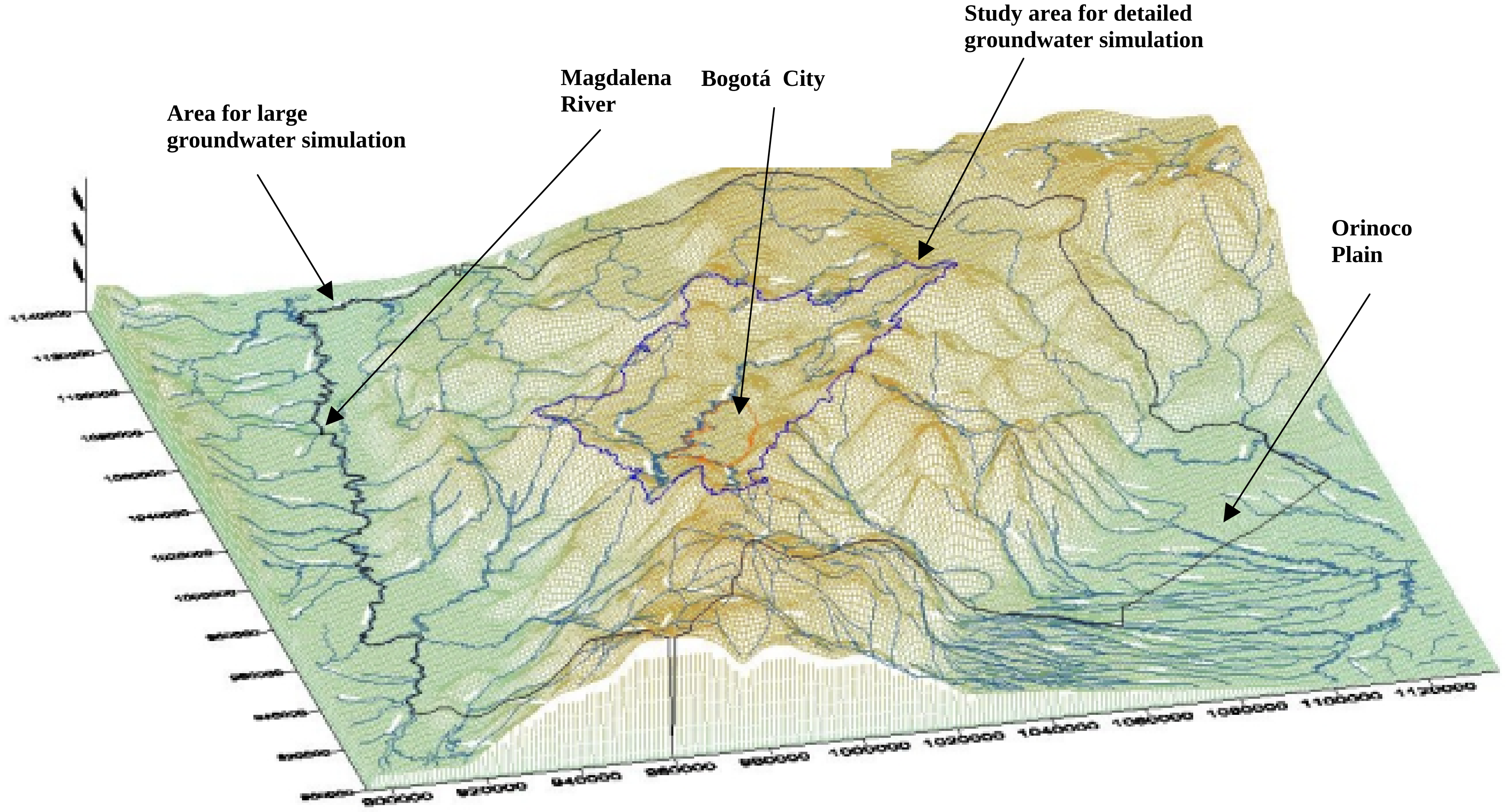

Figure-5.14 Area for Groundwater Simulation

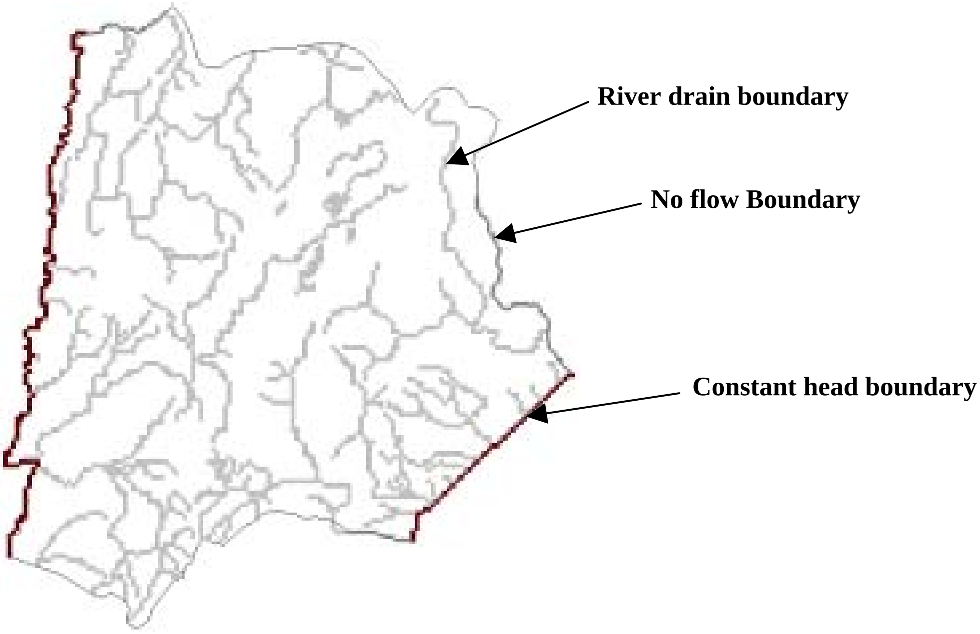

Figure-5.15 Boundary Condition of the Model

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. An example of model geological section is shown in Figure-5.16.

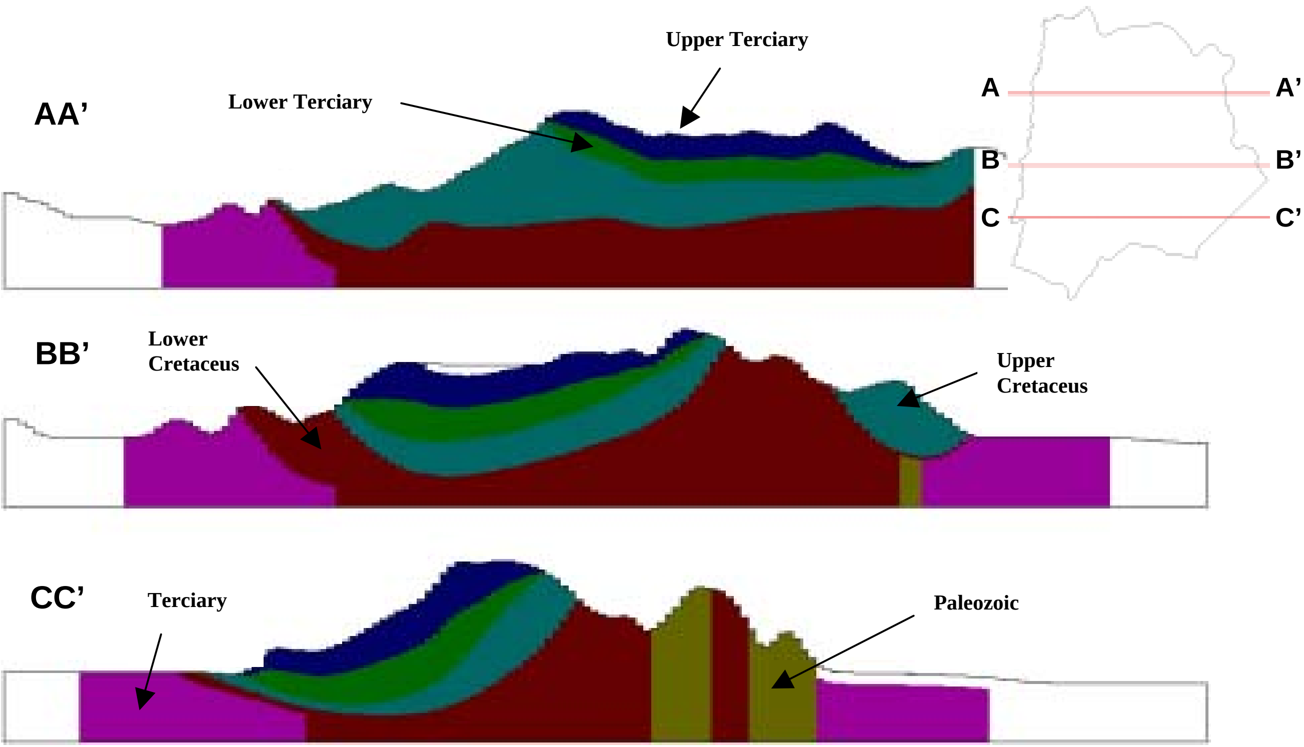

Figure-5.16 Example of Aquifer Structure of the Model

Aquifer Parameters

Aquifer parameters were set based on statistical values of aquifer parameters that were analyzed in Hydrogeological Analysis The final aquifer parameters used for the final model are shown in Table-5.14.

Table-5.14 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 reliable information for estimation of groundwater recharge of modeled area. Accordingly, 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 that becomes groundwater was assumed for every geological type by recharge Map by INGEOMINAS.
- 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-5.15.

Table-5.15 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-5.17). Total yield from wells was changed from 0%, 20%, 30%, 40% of total groundwater recharge to the Study Area. Therefore, the change of groundwater flow by the change of well yield was examined.

Figure-5.17 Distribution of Well

(2) Result of Large Area Groundwater Simulation

Groundwater Flow System

Calculated groundwater flows without pumping and with pumping 40% of recharge are shown in Figure-5.18 and Figure-5.19, respectively. According to Figure-5.18 and Figure-5.19, groundwater flow is classified into two types.

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

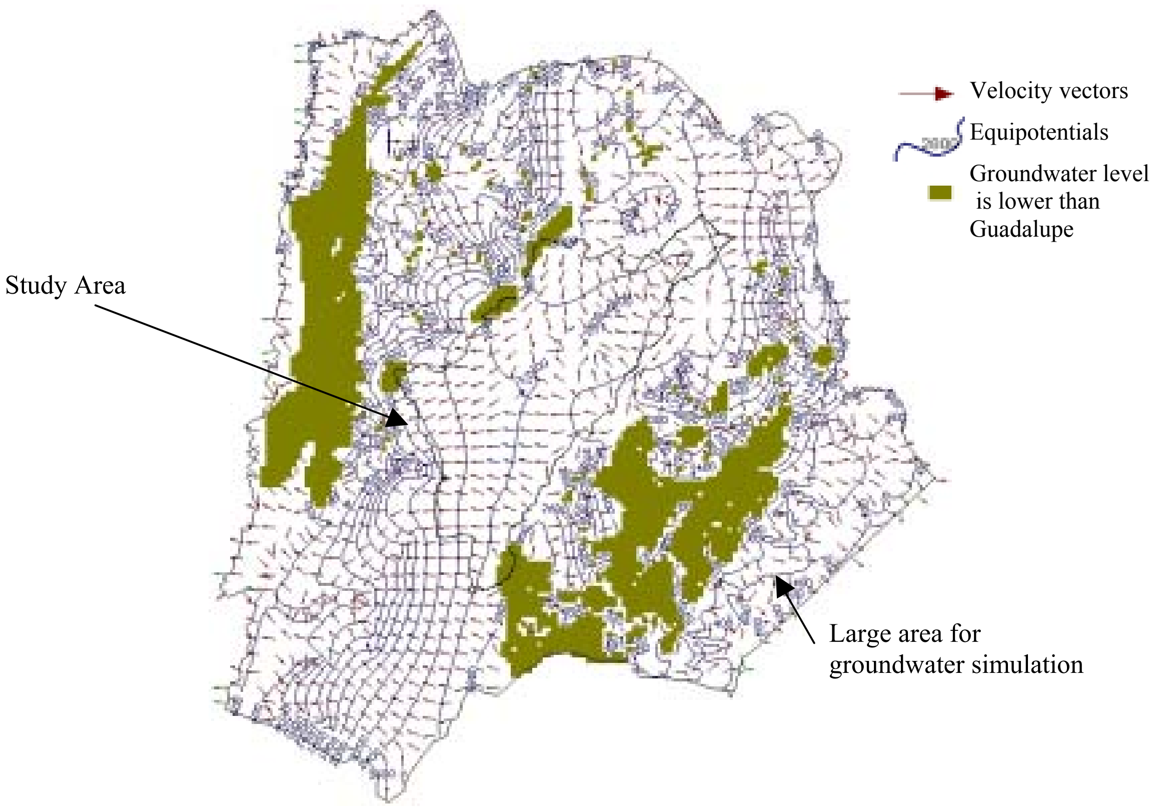

Figure-5.18 Results of Large Area Groundwater Simulation (Yield = 0% of Recharge)

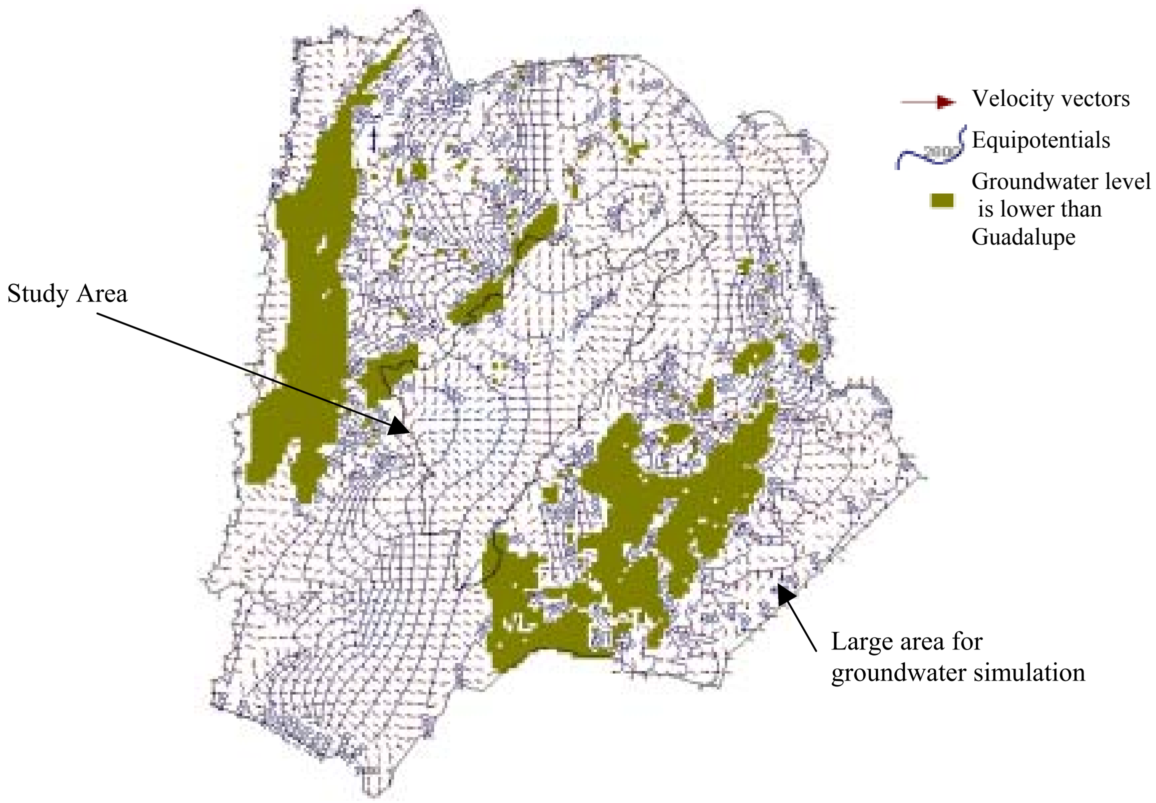

Figure-5.19 Results of Large Area Groundwater Simulation (Yield = 40% of Recharge)

Most of the Study Area is included in Groundwater flow system flowing toward the south-west direction to Magdalena River. (see Figure-5.18 and Figure-5.19).

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

According to Figure-5.20, 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-5.20, the groundwater shed expands 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.

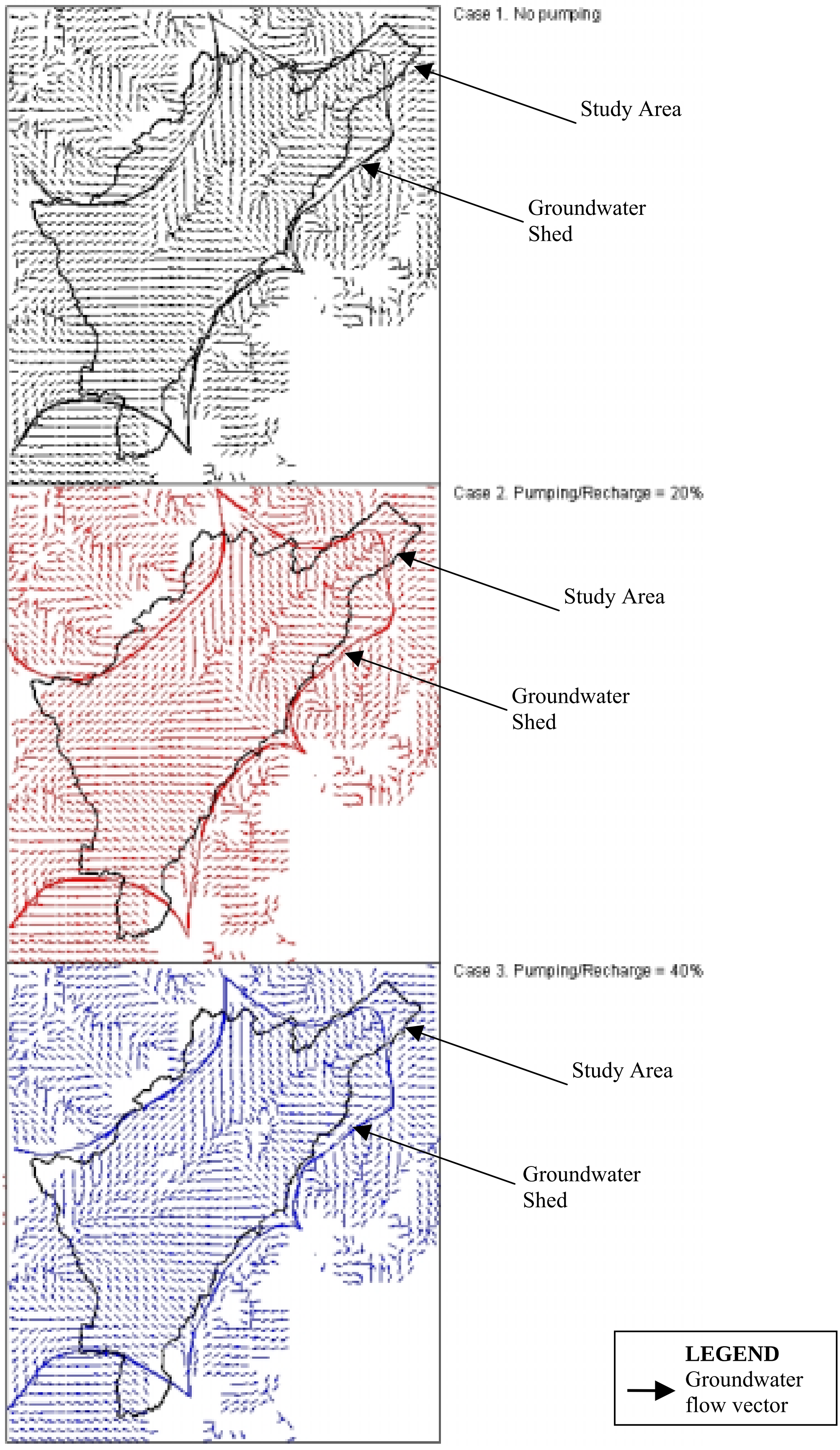

Figure-5.20 Change of Groundwater-shed by Pumping Rate of the Study Area

(3) 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 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.

5.3.2 Groundwater Simulation of the Study Area

(a) Purpose of Simulation

Detailed simulation model of the Study Area was made to examine appropriateness of groundwater recharge of 144mm/year that was estimated in water balance analysis.

(b) Simulation Model

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 1000 m and total number of cells is 105x120=52,500.

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

Area of 105km x 120km including all the Study Area was modeled for this simulation. In setting up boundary condition, result of large area simulation was referred.

<Boundary condition inside the Study Area>

Only few “River Drain Condition” was given to the model inside the Study Area. Groundwater recharge given to the model does not include base flow into rivers, which is explained in SECTION-2 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”.

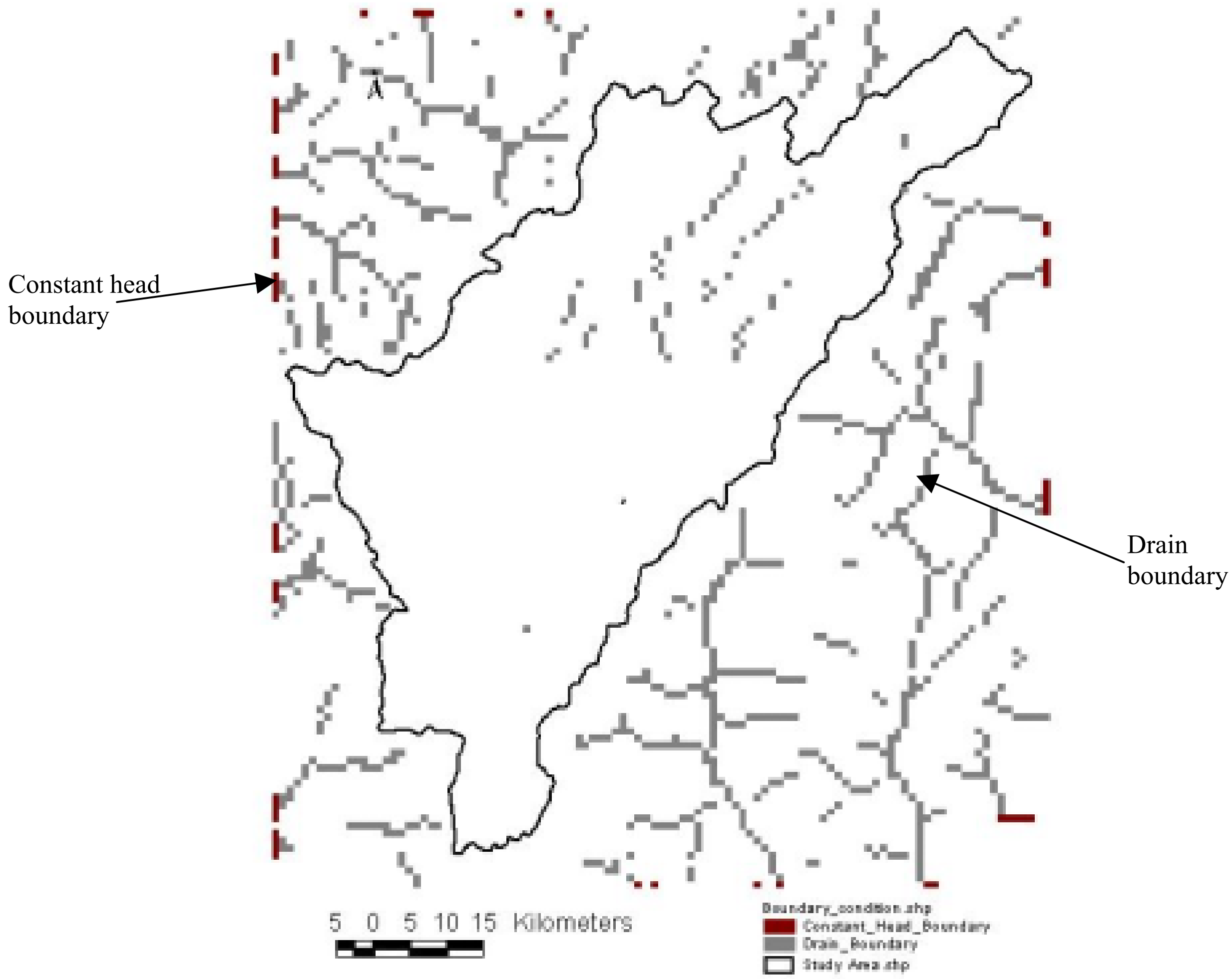

Figure-5.21 Boundary Condition of the Model

<u>Aquifer Structure</u>

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-5.16. An example of model geological section is shown in Figure-5.22.

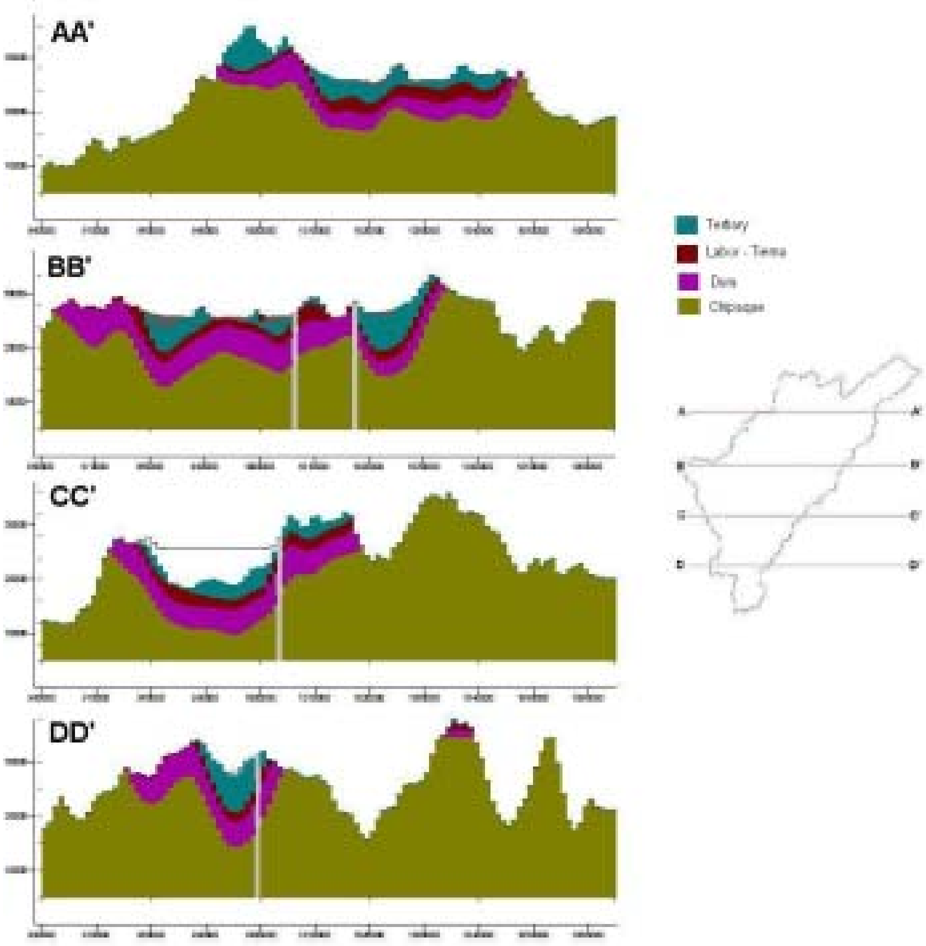

Figure-5.22 Example of Aquifer Structure of the Model

Aquifer Parameters

The initial aquifer parameters were set based on statistical values of aquifer parameters that were analyzed in Hydrogeology Analysis of this Report. Ratio of (vertical permeability) / (horizontal permeability) is set (1/15). The final aquifer parameters are shown in Table-5.16.

Table-5.16 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	0.13	0.009
6	Bogotá Fault	10	10

Groundwater Recharge

Groundwater recharge, which was calculated by water balance analysis, was given to the model. Groundwater recharge given to the Model is shown in Figure-5.23. On the other hand, there is not detailed information on groundwater recharge outside of the Study Area. Therefore, groundwater recharge outside of the Study Area was given to the Model based on result of large area simulation model.

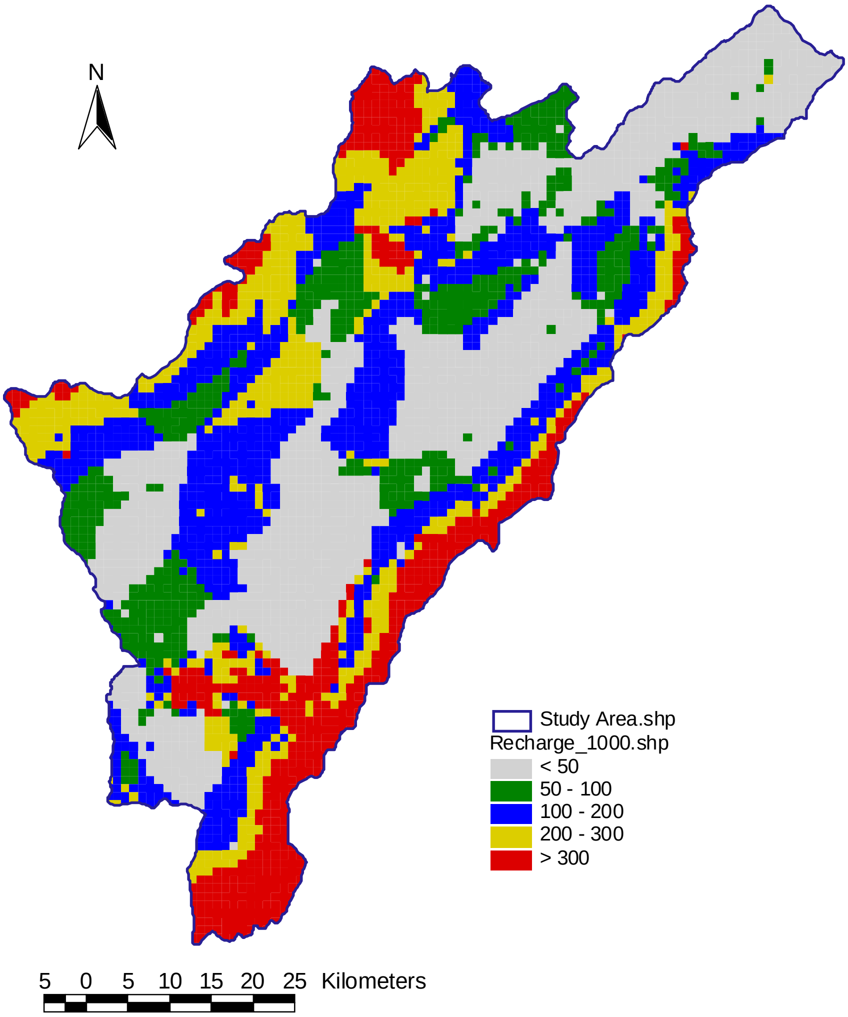

Figure-5.23 Groundwater Recharge of Simulation Model

Current Pumping

The current pumping wells of the Study Area were given to the model based on result of Well Inventory. Yield of 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.

- Well location was set up exactly into the model, based on the coordinates of well data-base.
- Aquifer of well was identified exactly into the model, based on the information of well data-base.
- Yield of well was exactly given to the model, based on the information of well data-base.
- Wells with unreasonable information or without enough information are adequately modified and given to the model.

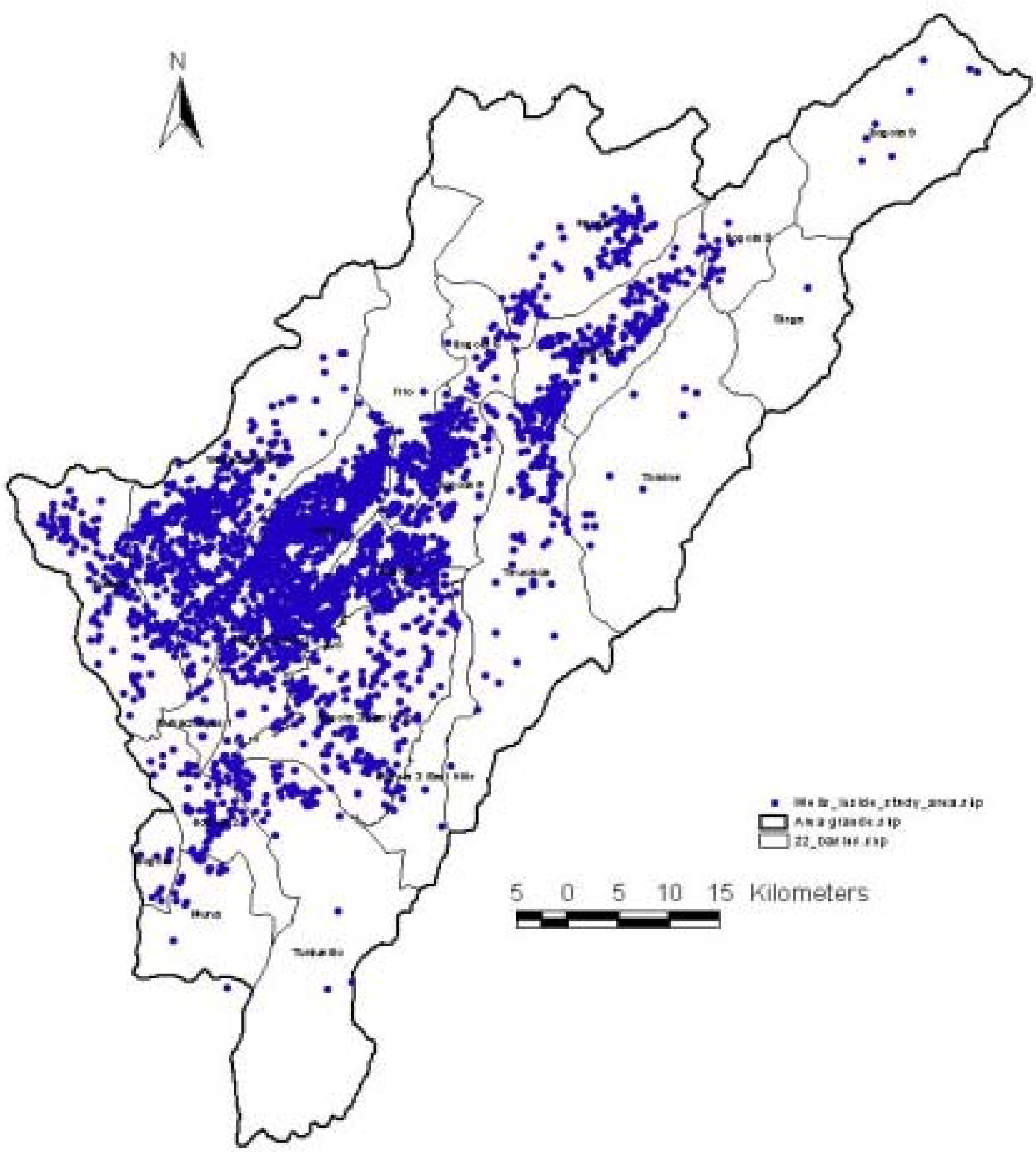

Figure-5.24 Wells in Simulation Model

(3) Result of Groundwater Simulation of the Study Area

The groundwater simulation was carried out under the condition explained above. This simulation was by steady state condition. The result of the simulation is explained below.

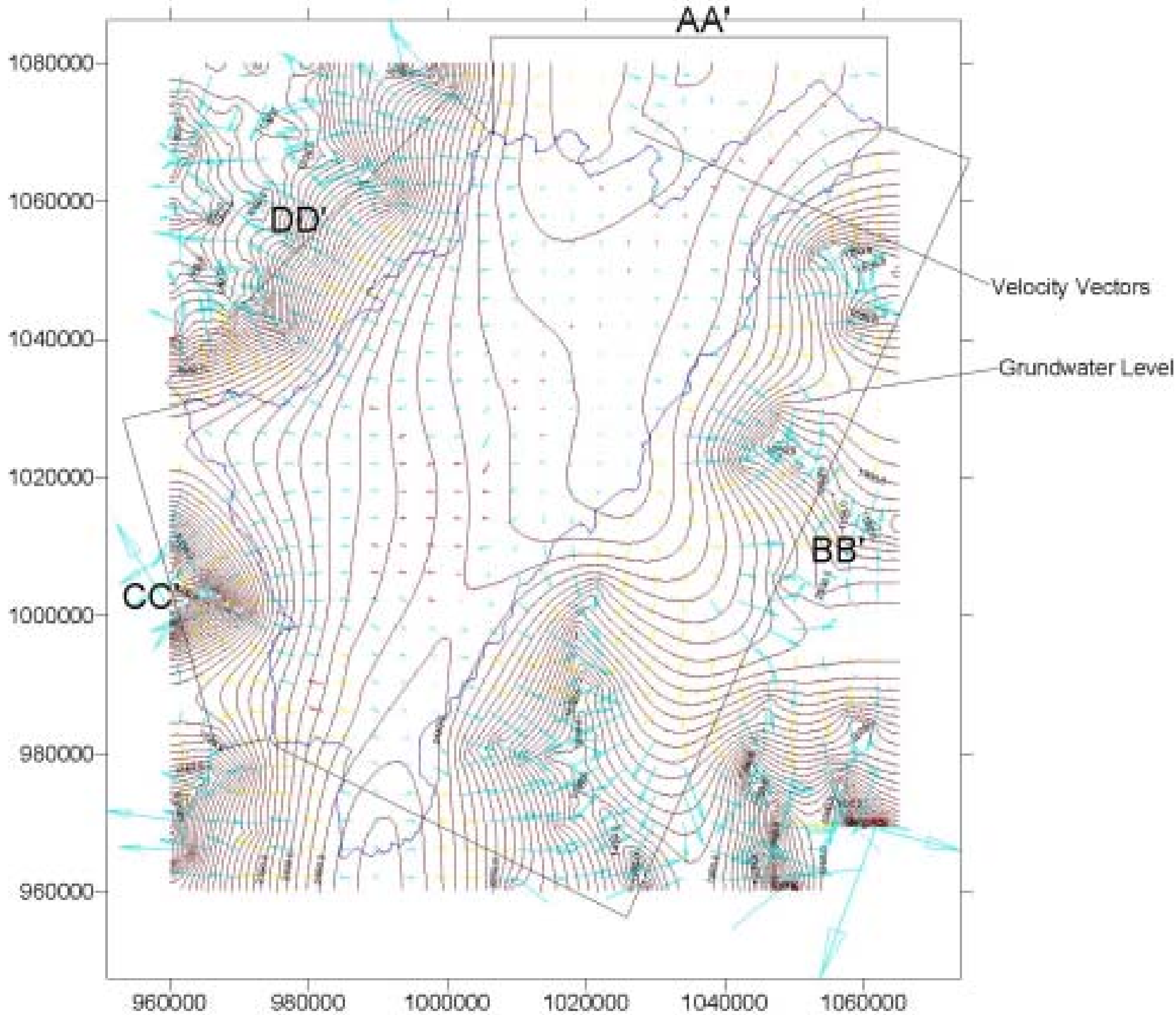

Figure-5.25 Calculated Groundwater Level of Cretaceous by Simulation

Calculated groundwater level

The calculated groundwater level for Cretaceous is shown in Figure-5.25. Calculated groundwater level has the same tendency as 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.

Groundwater balance by the simulation

The calculated water balance in the simulation is shown in Table-5.17. Of groundwater recharge given to the Model that is 144 mm/year, 19 % is pumped up by the wells and 81 % flows away from the Study Area.

Table-5.17 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-5.18.

Table-5.18 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%

5.4 Evaluation of Groundwater Potential

(1) 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 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 150mm/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.

(2) Groundwater Development Potential by Basin

<u>Current yield from wells and groundwater recharge</u>

The current rate of groundwater use (well yield ÷ groundwater recharge) is shown in Table-5.19 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-5.19 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

<u>Safe Yield</u>

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-5.19, 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-5.20.

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-5.20 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%

Pumping and land-subsidence

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 phenomena of ground surface 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.