CHAPTER 5 GROUNDWATER POTENTIAL STUDY

5.1 Hydrogeology Analysis

(1) Aquifer Classification and Characteristics

(a) Aquifer Classification

In the Study, aquifer classification was done following geological classification. This Study follows the existing aquifer classification. Aquifer classification and aquifer characteristics are summarized in Table-5.1.

Table-5.1 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
ii) Cretaceous aquifer

Aquifers above consist of alternation of permeable and impermeable formations. 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 conditions.

<u>Quaternary aquifer</u>

Groundwater currently pumped up by 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 level. Therefore, groundwater level observed in wells is combined groundwater level of different groundwater level of each sand and gravel layers.

<u>Tertiary aquifer</u>

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

<u>Cretaceous aquifer</u>

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 aquifer form confined aquifers. Superficial aquifer of the Quaternary seems to form small-unconfined aquifer. Groundwater is confined in Savanna Formation and Tilata Formation that form main aquifer of Quaternary, because these strata are overlaid by impermeable strata. Groundwater is also confined in Tertiary and Cretaceous aquifers by overlying thick impermeable formations. The static groundwater level of Quaternary, Tertiary and Cretaceous is between GL-20m to GL-50m. Though distribution depth of these aquifers is different, static groundwater levels of these aquifers are similar. This suggests that there is hydrogeological connection among three aquifers.

Groundwater 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 ground surface, infiltrates into deep aquifer 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 aquifer is recharged in the mountains surrounding Bogotá Plain. It is assumed that groundwater is flowing from mountains area toward deeper parts of the Cretaceous aquifer. It is natural to think that even in some area of Quaternary and Tertiary the groundwater infiltrates into the deep Cretaceous aquifer through Quaternary and Tertiary.

(d) Aquifer Parameter

Aquifer parameters were analyzed form 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.

Aquifer parameter of Quaternary

Yield, specific capacity, transmissivity, permeability coefficient and storativity coefficient of Quaternary aquifer have values of wide range, and these distributions are approximated by log normal distribution. Specific capacity has strong relation with transmissivity, and it is possible to estimate transmissivity roughly from this relation. Result of pumping test is summarized in Table-5.2.

Table-5.2 Hydraulic Parameters of 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}

<u>Hydraulic parameters of Guadalupe Group</u>

Yield, specific capacity, transmissivity, permeability coefficient and storativity coefficient of Guadalupe Group have values of wide range, and these distributions are approximated by log normal distribution. Result of pumping test is summarized in Table-5.3.

Table-5.3 Hydraulic Parameters of Guadalupe Aquifer

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.

5.2 Water Balance and Groundwater Recharge

The purpose of water balance analysis is to estimate groundwater recharge of Study Area. Hydrological and meteorological data of CAR and EAAB was used for the water balance analysis. Groundwater recharge is output of water balance analysis and was used for input parameter for groundwater simulation. Method and result of the water balance analysis is explained below.

5.2.1 Water Balance Analysis

(1) Method of Analysis

Calculation process of runoff and precipitation in the basin is shown in Figure-5.1. Water balance analysis is explained below.

(2) Classification of Basins

Based on the assumption that runoff into the river 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 the 20 basins was divided into 3 groups according to their area ratios. For the basins without any river flow data available for runoff coefficient calculation, the runoff coefficient of the other basins that belongs to the same group is applied.

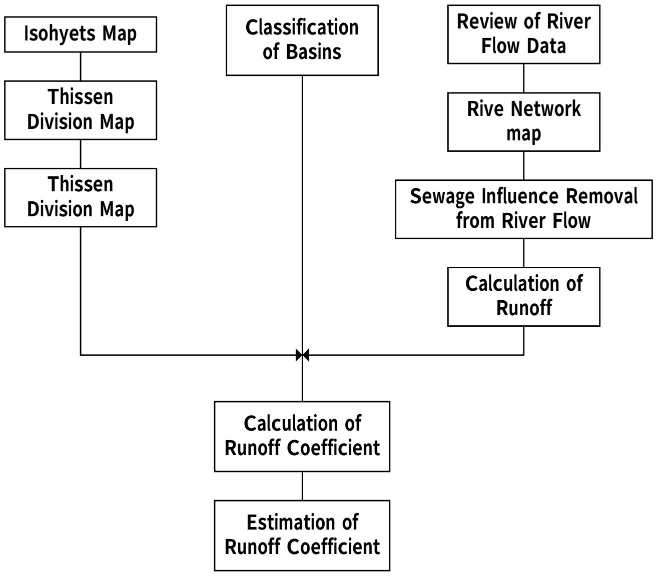


Figure-5.1 Calcualtion Process of Hdrological Analysis

Table-5.4 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 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, annual precipitation map was made as shown in figure-3.7. Annual precipitation by basin was calculated from this map. The figure shows that rainfall intensity is high in the tributary areas of Group-1 and low in the southwest plain; annual average precipitation is 941mm in Rio Tunjuelito basin at maximum and 600mm in Subachoque (1) basin at minimum.

(4) River Network

A river network map was drawn by plotting flow data. Accordingly, a flow diagram of Rio Bogotá (Figure-5.3) was made by plotting the observation flows from the upstream to Alcachin station located at the downstream. This diagram clearly shows that the water intake to Tibitic purification plant and the sewage outflow in the center of Bogotá city affect the amount of river flow of Rio Bogotá to a great degree.

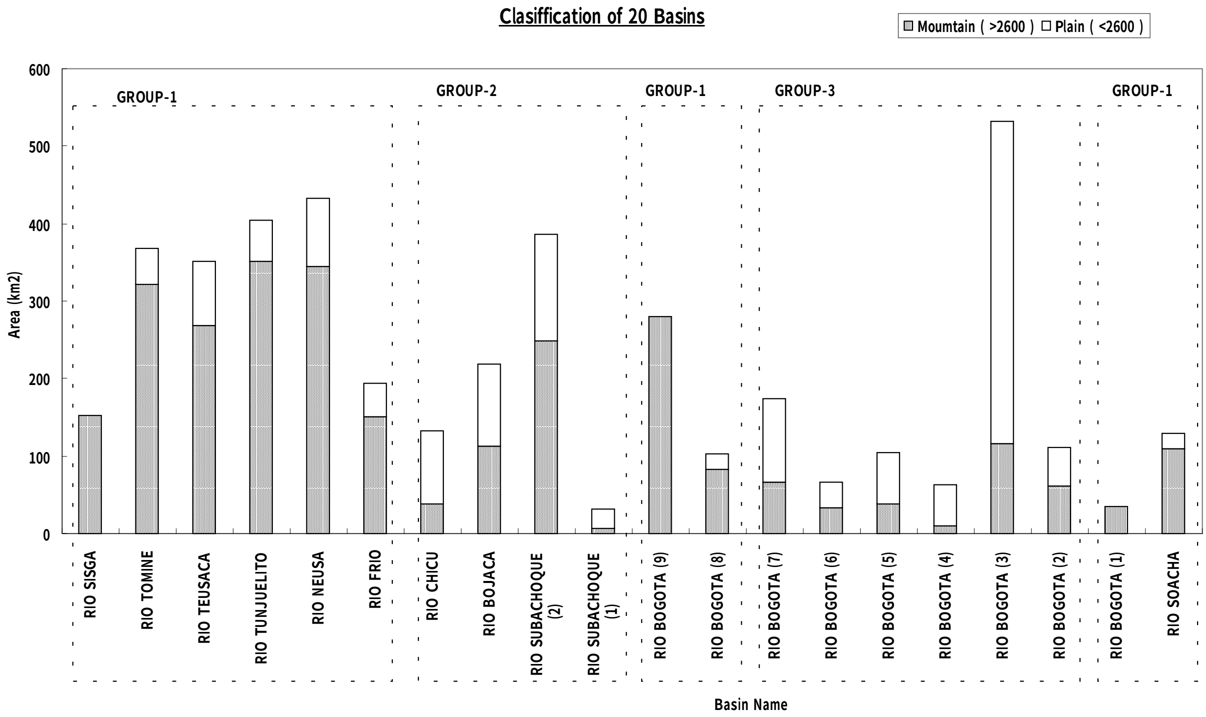


Figure-5.2 Classification of Basins

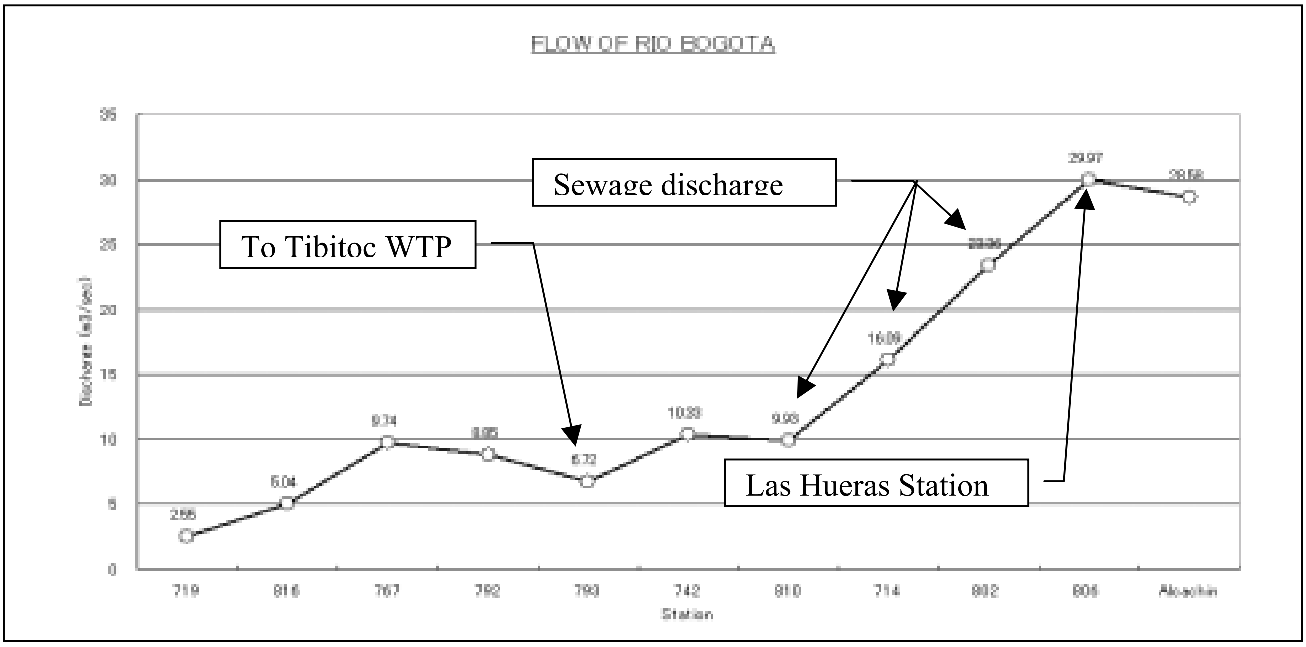


Figure-5.3 Flow curve of Bogotá River

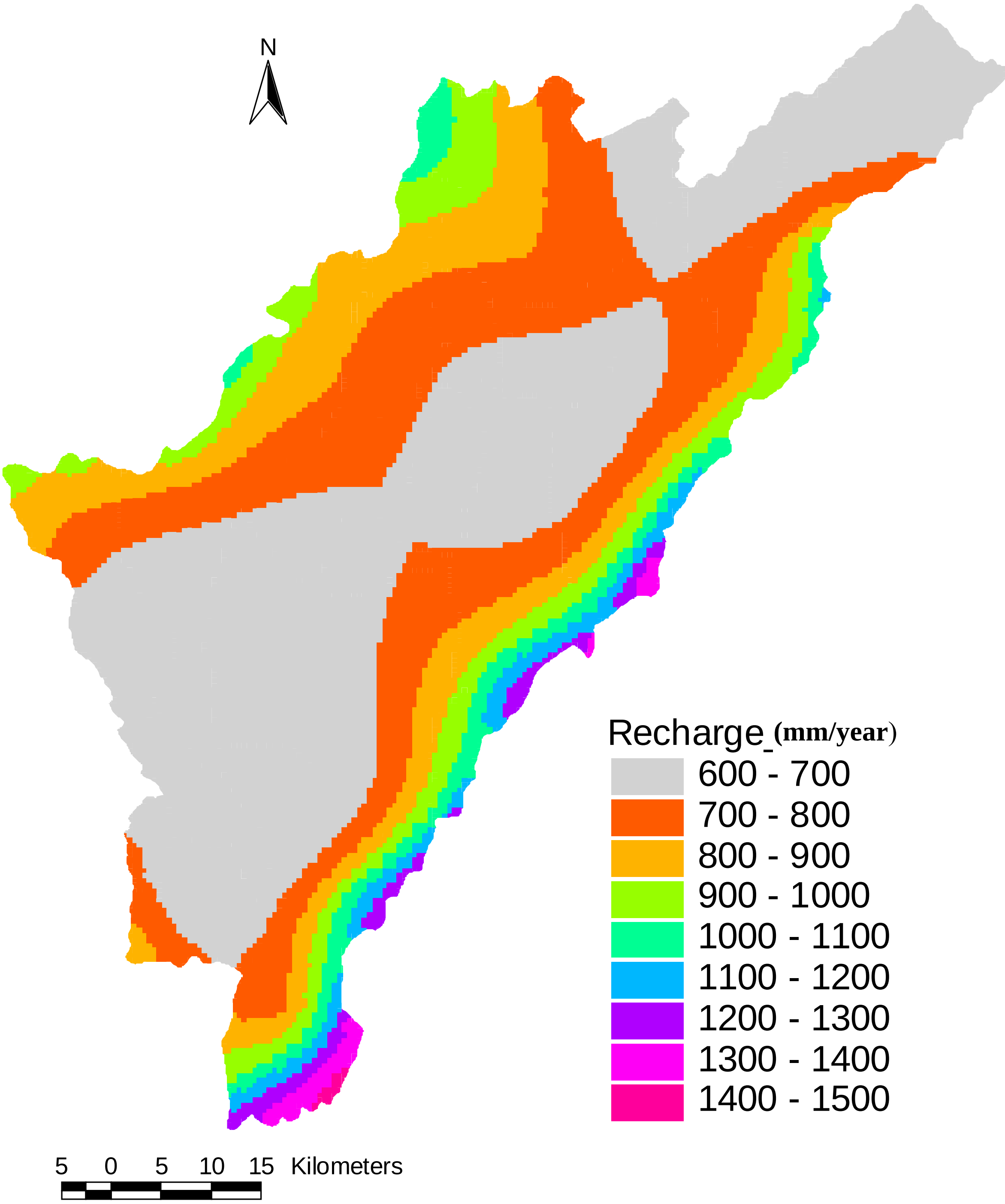


Figure-5.4 Equi-Precipitation Map

(5) Sewage Outflow Infuence

Since sewage outflow has a significant impact on Rio Bogotá, i.e. the Bogotá(3) and Bogotá(4) basins, and Rio Tujenlito. In these rivers, sewage outflow must be taken from the runoff obtained from the flow data. A generated sewage has been assumed as 80% of the water supply volume, of which the sewage from the Bogotá(3) basin makes up 79%, from the Bogotá(4) basin does 9% and from the Tujenrito basin does 12% in proportion to their areas. In this assumption, water supply per unit area of the Tujenlito basin is estimated half as much as those of other basins. For the Bogotá (3) basin that makes up much of the sewage outflow, a net runoff shown in Figure-5.8 has been estimated by plotting the flow data at the inlet and outlet of the basin as well as the amount of water supply. The river flow data from 1973 to 1999 is applied for the calculation. From the calculation the following values were obtained.

Table-5.5 Sewage Outflow

Applied period of river flow data： 1973-1999		
Average water supply： 12.8 m3/sec		
Total sewage outflow	Total	10.24 m^3/sec
	Bogotá (3)	8.09 m^3/sec
	Tunjuelito	1.23 m^3/sec
	Bogotá (4)	0.93 m^3/sec
Gross runoff	Bogotá (3)	13,15 m^3/.sec
	Tunjuelito	4.94 m^3/sec
Net runoff	Bogotá (3)	5.06 m^3/sec
	Tunjuelito	3.71 m^3/sec

(6) Calculation of Runoff Coefficient

Runoff coefficients have been calculated from their calculated runoffs. As for Group-2 and Group-3, only few basins have obtained their runoff coefficients due to a lack of the appplicable river flow. Data. In the cases of Rio Tunjuelito and Rio Bogotá(3) basins, gross runoff coefficients are put down with net ones where sewage outflow influences are eliminated.

Table-5.6 Runoff Coefficients Calculated from Flow Data

	Basin Name	Runoff Coefficinet
Group-1	RIO SISGA	40.0%
	RIO TOMINE	34.0%
	RIO TUNJUELITO	30.7% (40.9%)
	RIO NEUSA	21.5%
	RIO BOGOTÁ (9)	39.9%
Group-3	RIO BOGOTÁ (5)	20.0%
	RIO BOGOTÁ (3)	41.0% (107.6%)

Note) figure in parenthesis shows gross runoff coefficient.

(7) Estimation of Runoff Coeficient

A calculated runoff coefficients have been applied to estimate those of other basins that does not have flow data base on similarity of basin condition.

< Group-1 >

The runoff coefficients of the stations in Group-1 are plotted in Figure-5.5. Runoff coefficients vary widely where basin area is small, but they seem to converge as basin area becomes larger. Based on Figure-5.5, an approximate formulla to calculate a runoff coefficient from a basin area was obtained. Linealization is applied for approximate formula. Figure-5.6 shows the approximate curve.

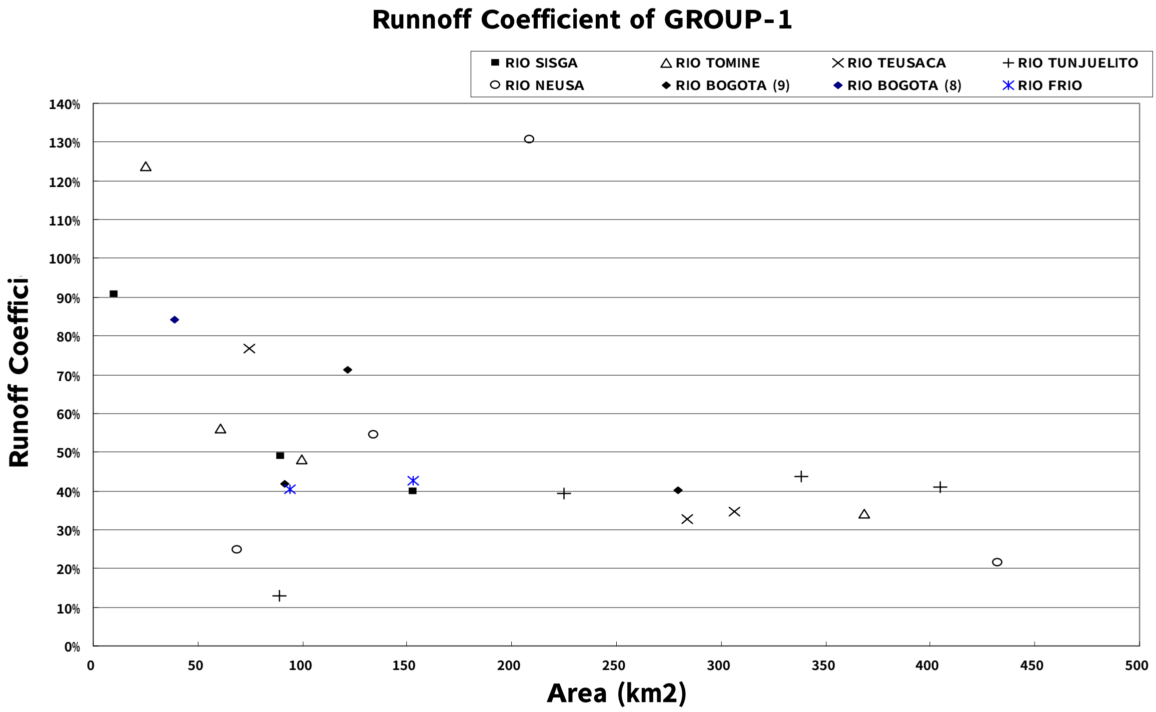


Figure-5.5 Runoff Coefficient in Group-1

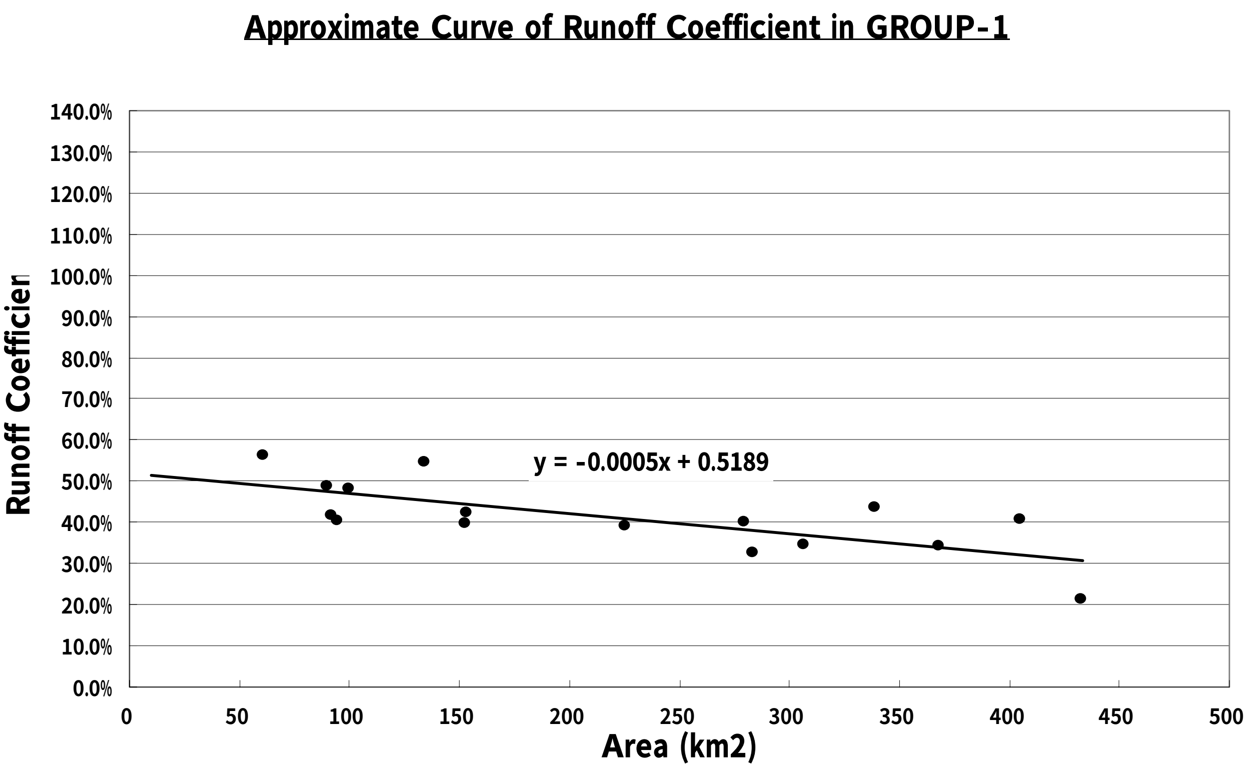


Figure-5.6 Approximate Curve of Runoff

Table-5.7 Runoff Coefficient of Group-1

Basin	Runoff Coeficient		
	Station Data	Approximate Formula Y=-0.0005x+0.5183	Applied Valie
Sisga	39.8%	44.2%	39.8%
Tomine	34.2%	33.4%	34.2%
Teusaca	-	34.2%	34.2%
Tunjuelito	30.7%(40.9%)	31.6%	30.7%
Neusa	21.5%	30.2%	30.2%
Frio	-	42.1%	42.1%
Bogotá(9)	40.0%	37.9%	40.0%
Bogotá(8)	-	46.7%	40.0%
Bogotá(1)	-	50.1%	50.1%
Muna	-	45.4%	45.4%

< Group-2, 3 >

In Group-2 and 3, area ratio of plain is high. It is considered that the runoff coefficient of the plain is low and varies little inspite of basin area beacause runoff causes mainly in mountains. Therefore, runoff coefficients that belong to these groups were calculated on the assumption that runoff coefficient of plain is almost constant Method of caluculation is explained below.

- Basins with calculated runoff coefficients from the observation data are only Bogotá(3) and Bogotá(4) basins. Runoff coefficients of these two basins were appliyed to baisns without flow data based on similarity of basin condition.
- Bogotá(3) basin has been divided into two sub-baisns along Rio Bogotá. Bogotá(3)-E is east side and Bogotá(3)-W is west side of Bogotá River. Bogotá(3) basin has large area and has completely different aspects in both sides. Then, runoff coefficients were estimated for both.
- Bojica and Subachoque basins have been divided into two areas, plain and mountain. Then, the respective runoff coefficients were estimated by applying the approximate curve to the mountain and by using the runoff coefficient of 20% to plain.

Runoff coneffients of the basins in Group-2 and 3 are summarized in Table-5.8. In addition, the calculation of the runoff coefficients of Bogotá(3)-E, Bogotá(3)-W, Bojaca and Subachoque basin is shown in Figure-5.7.

Table-5.8 Runoff Coefficient of Basins in Group-2, 3

	Basin Name	Runoff Coefficient	Basis
Group-2	RIO CHICU	20.0%	Value of Bogotá(5)
	RIO BOJACA	32.9%	See the calculation of next page
	RIO SUBACHOQUE (2)	32.2%	See the calculation of next page
	RIO SUBACHOQUE (1)	20.0%	Value of Bogotá(5)
Group-3	RIO BOGOTÁ (7)	20.0%	Value of Bogotá(5)
	RIO BOGOTÁ (6)	20.0%	Value of Bogotá(5)
	RIO BOGOTÁ (5)	20.0%	From observation flow data
	RIO BOGOTÁ (4)	41.0%	Value of Bogotá(3)
	RIO BOGOTÁ (3)-E	48.5%	See the calculation of next page
	RIO BOGOTÁ (3)-W	20.0%	Value of Bogotá(5)
	RIO BOGOTÁ (2)	20.0%	Value of Bogotá(5)

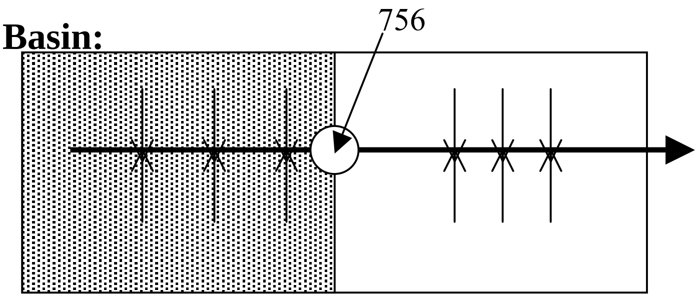
Runoff that was finally obntained for all the basin is shown in Figure-5.9.

Table-5.9 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>						

Runoff Coefficient Estimation
in Bojaca, Subachoque(2), Bogotá(3) basins

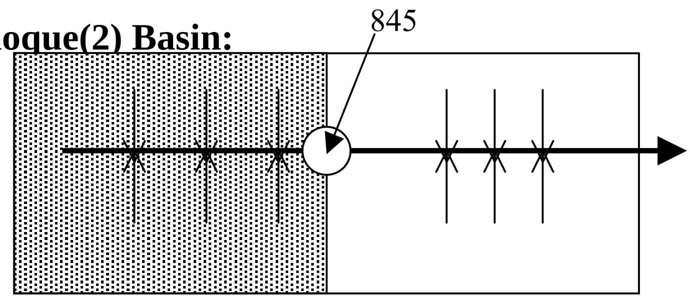
Rio Bojica Basin:



Runoff coefficient 47% (mountain) 20% (plain)

<u>32.9%(total)</u>

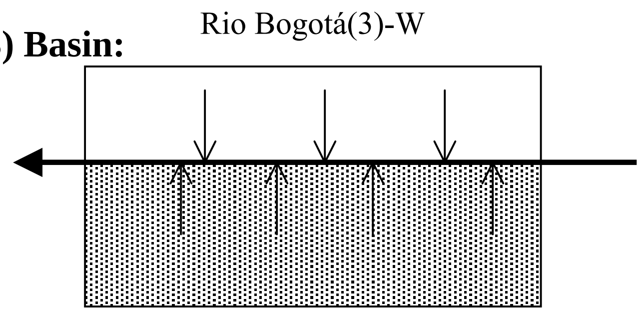
Rio Subachoque(2) Basin:



Runoff coefficient 41% (mountain) 20% (plain)

<u>32.2%(total)</u>

Rio Bogotá(3) Basin:



Runoff coefficient	Rio Bogotá(3)-W	20% (plain)
	Rio Bogotá(3)-E	**<u>48.5%</u>**
	Rio Bogotá(3) Total	41.4%

Figure-5.7 Runoff Coefficient of Bojaca, Subachoque(2), Bogotá(3) Basin

5.2.2 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 recharge 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.

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

P------ Precipitation (mm)
ETR-- Real evapo-transpiration (mm)
D_1---- Direct runoff into basin (mm)
D_2---- Direct runoff from basin (mm)
G_1---- Groundwater flow into basin (mm)
G_2---- 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. Equation (1) is simplified by some assumptions. Finally annual groundwater recharge is calculated by equation below:

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

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)

In this Study, annual groundwater recharge was calculated based on equation (2).

(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-5.8. 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 its result is shown in water balance analysis.

(5) Potential Evapo-transpiration (ETP)

It is extremely difficult to directly measure potential evapo-transpiration. Accordingly, potential evapo-transpiration is usually evaluated by experimental methods. Three methods, Penmman – Monteith, Hargreaves and Turc method were frequently used for evaluation of potential evapo-transpiration in the Study Area. In this Study, results of above three methods were compared with observed pan-evaporation of the seven meteorological stations. From the result of this comparison, Turc Method has highest relation with observed pan-evaporation. However, reliability of three methods has not yet been concluded so far in the Study area. Therefore, the Study Team used pan-evaporation for evaluation of potential evapo-transpiration. This method is widely used. In the Study Area, Class-A-Pan evaporimeters are used and potential evapo-transpiration is approximated by 70% of pan-evaporation by Class A-Pan.

Pan-evaporation of basins was calculated by Thiessen method, and potential evapo-transpiration of basins were calculated as 70% of the pan-evaporation. The calculated potential evapo-transpiration by basin is shown in Figure-5.8.

(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, soil model was made for calculation of evapo-transpiration ratio (= ETR/ETP). Then, using this model, evapo-transpiration ratio was expressed by function of precipitation, potential evapo-transpiration (ETP) and soil moisture. 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-5.10. Most of data are during 1991 to 1998, for 8 years.

Table-5.10 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	Primavara	1991-1998	Barrancas	1991-1997
Guymaral	1991-1998	Ramada	1991-1998	Sisga	1993-1997
Iberia	1991-1998	Tabio	1991-1996	Tisquesusa	1991-1998
Muna	1991-1998	Venecia	1991-1997	-	-

Total Available Moisture in the Soil by Soil Type

Three types of Total Available Moisture in the soil were set for the model based on FAO data.

Table-5.11 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

Model Calculation Method

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

- Soil water balance was calculated daily.
- When soil water exceeds Total Available Moisture in the soil, surface water and groundwater discharge occur.
- Daily potential evapo-transpiration (ETR) is calculated by Daily pan evaporation ×0.7
- Actual maximum Potential Evapo-transpiration (ETP_R) is calculated by 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

<u>Result of Model Analysis</u>

Water soil 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 as shown in Figure-5.9. 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 log

High accuracy of the function is shown in Figure-5.9. By this function, real evapo-transpiration (ETR) of the Study Area can be estimated considering precipitation, potential evapo-transpiration (ETP) and soil types.

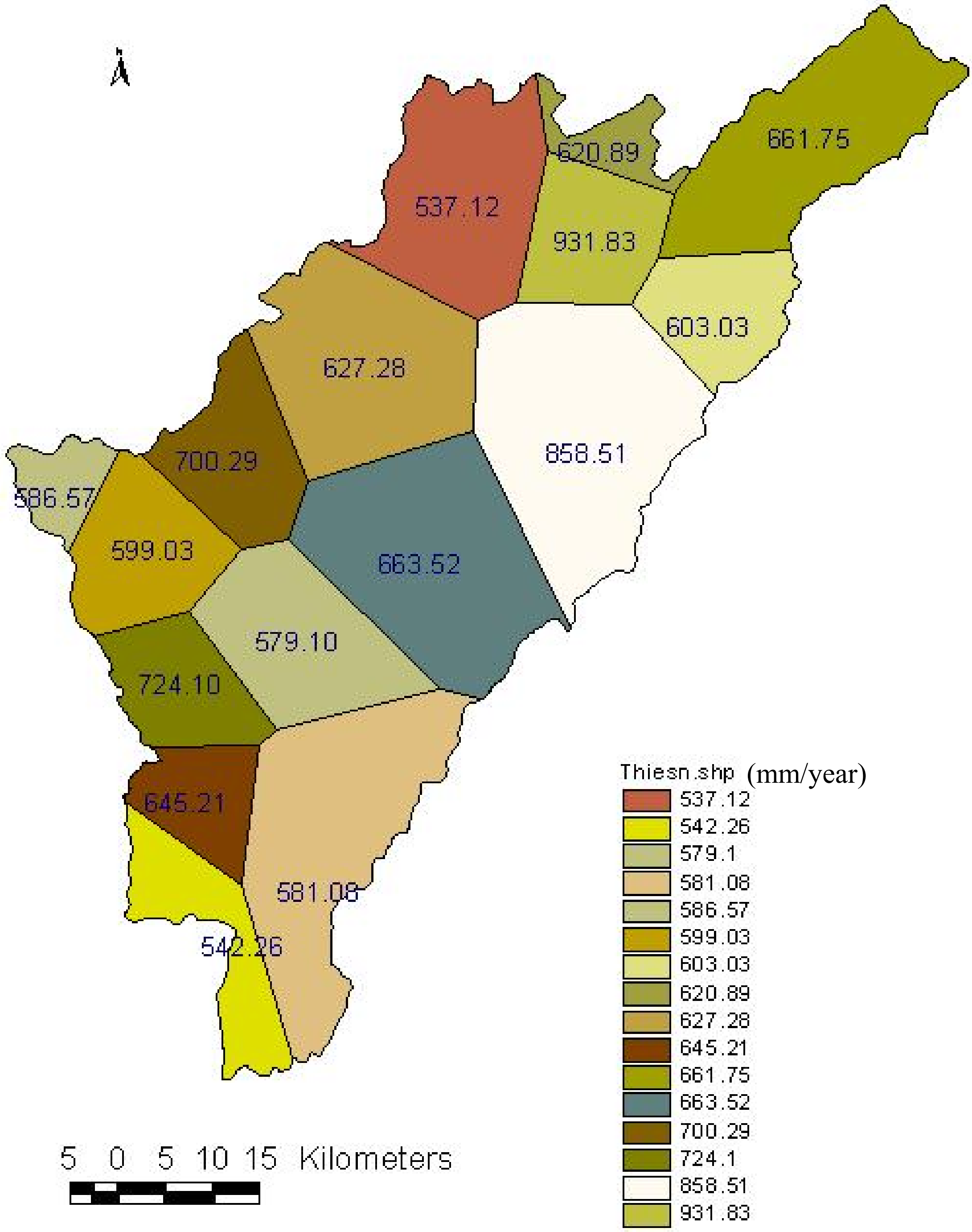
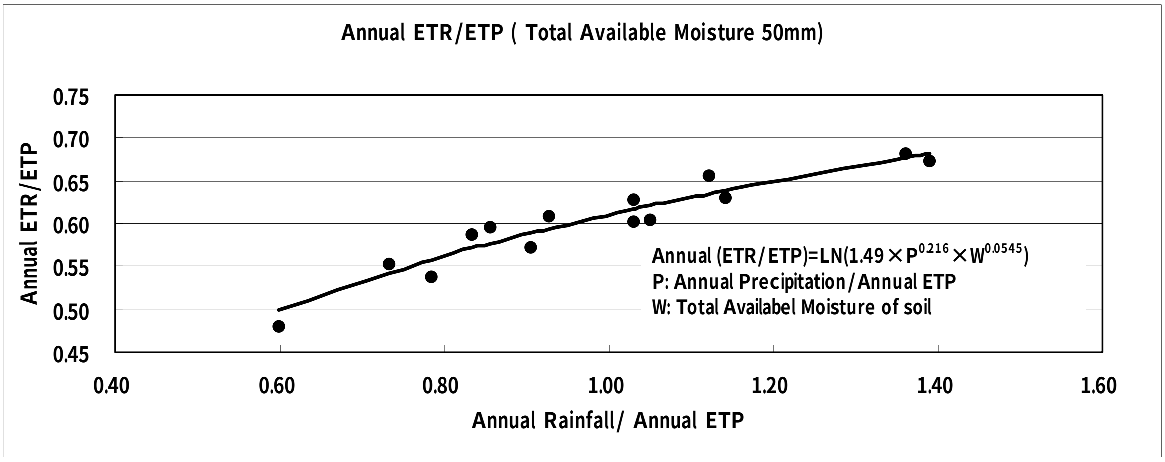
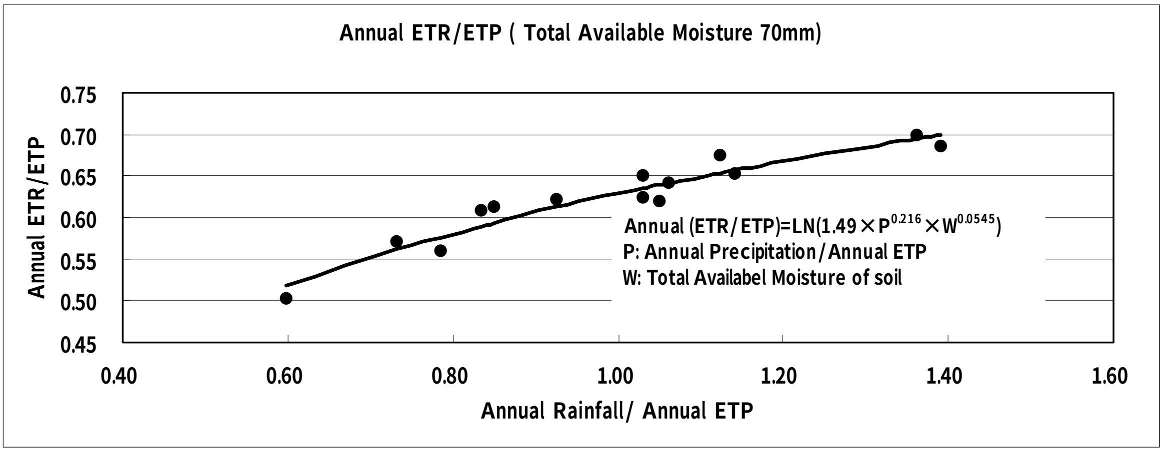


Figure-5.8 Annual ETP





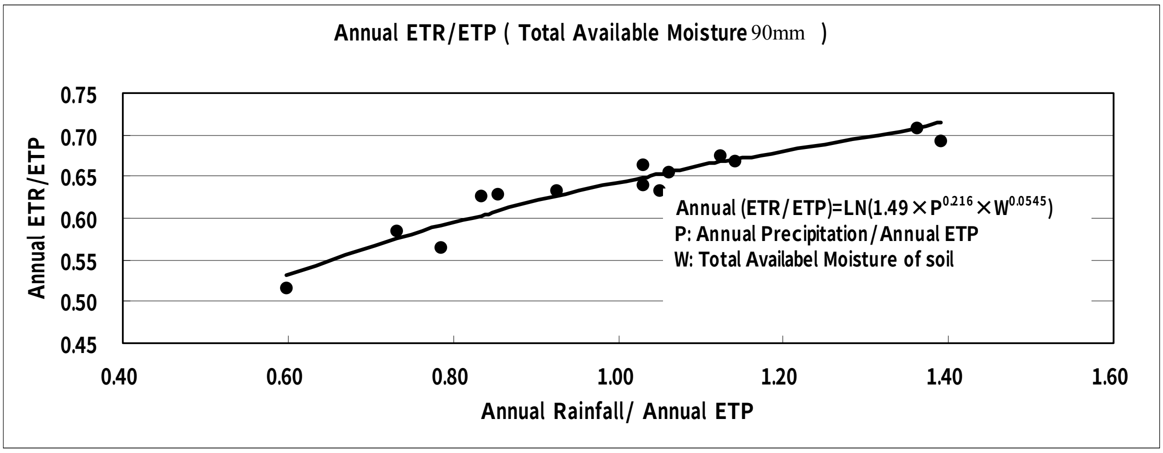


Figure-5.9 Analyzed Result of 14 Stations (by Soil Types) and Approximation by Function

(7) 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 in Soil Map" were overlapped and the function was applied. Resultant calculated ETR is shown in Figure-5.11. 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-5.12.

Table-5.12 Outline of Total Available Moisture Map

Item	Method for estimation
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.
Thickness of 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.

(8) Groundwater Recharge

Groundwater recharge was calculated from equation (2) below.

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

P	Precipitation of basins (mm/year)
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" were overlapped. Calculated groundwater recharge is shown in Figure-5.12.

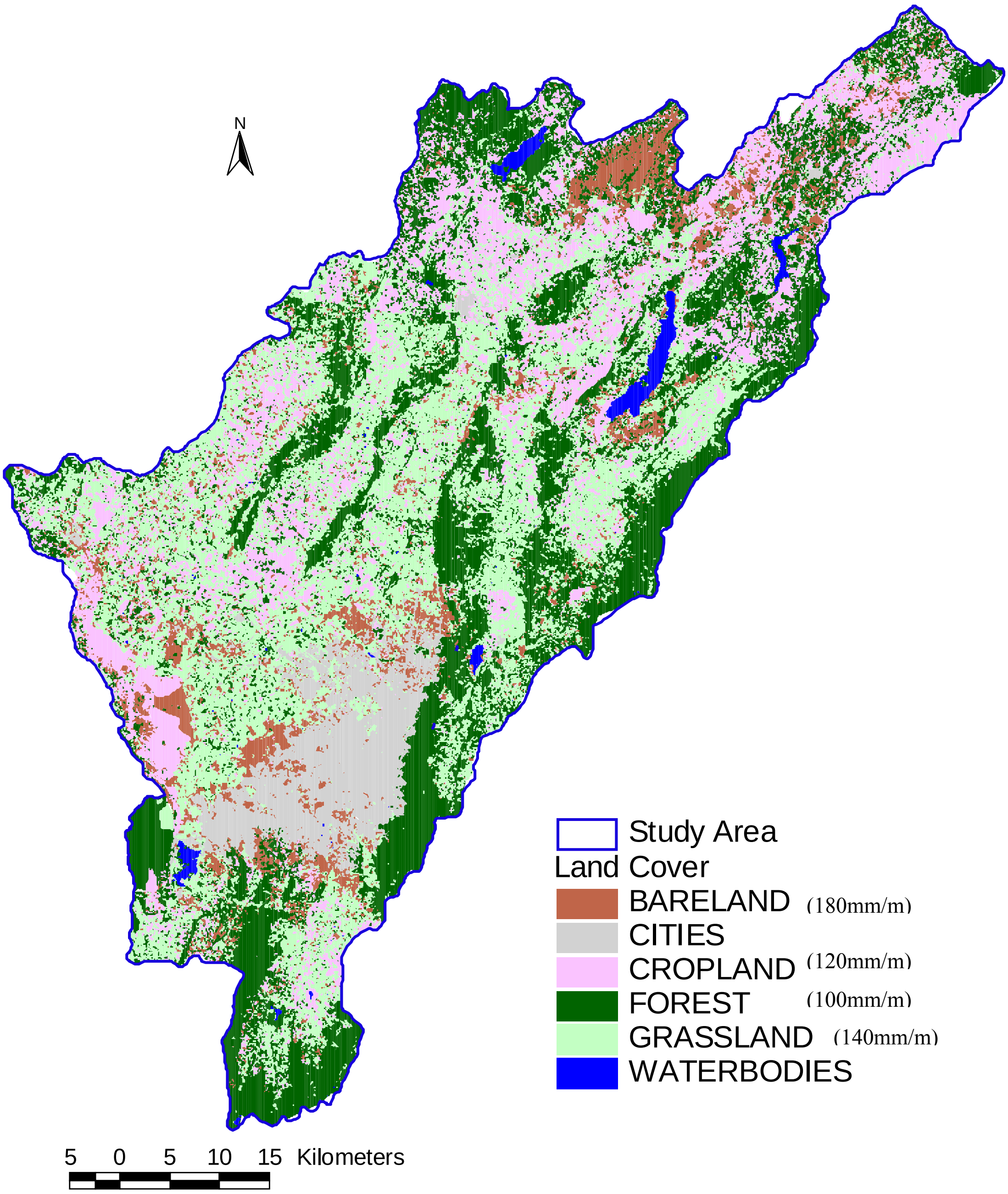


Figure-5.10 Classification of Total Available Moisture in Soil

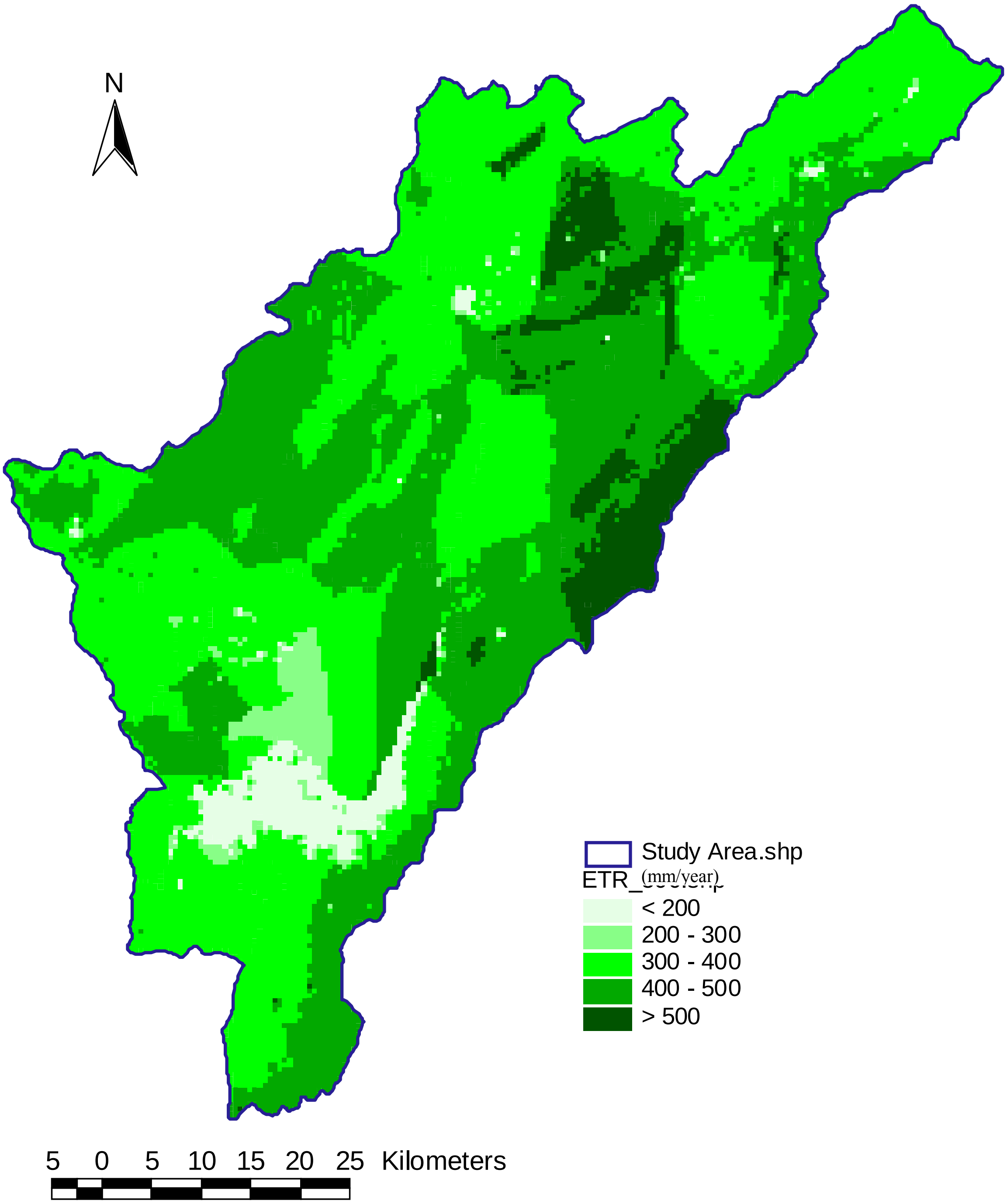


Figure-5.11 Annual ETR

Table-5.13 Result of Groundwater Recharge Analysis

Basin	Catchment Area (km^2)	Annual precipitation (mm)	Annual Runoff (mm)	Annual ETR (mm)	Annual Groundwater Recharge	
					(×10^6m^3)	(mm)
Bogotá 1-Bogotá 3	36	707	270	333	71.0	105
Bogotá 4-Bogotá 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 "Bogotá (3)E" by the same method which was applied to the other basins, because "Bogotá (3)E" basin is highly developed where ground surface is covered with artificial materials and rainfall can not infiltrate into the ground. Therefore, water balance and groundwater recharge in Bogotá City Area of "Bogotá (3)E basin" was calculated based on the relation shown below:

- Precipitation = River discharge + ETR
- Groundwater recharge = 0 mm/year

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

<Total Groundwater Recharge of the Study Area>

Area	Catchment Area (km^2)	Groundwater Recharge	
		mm/year	m^3/year
All the Study Area including Bogotá Plain	4,260	144	615,200,000

(9) Calibration for Result of Groundwater Recharge by Soil Characteristics

Soil moisture has great influence in estimation of Groundwater recharge. However, to decide soil moisture exactly is difficult. In order to evaluate change of calculated groundwater recharge with change of soil moisture value, calibration was conducted by changing Total Available Moisture in soil (TAM). The result of this calibration is shown in Figure-5.13. As shown in Figure-5.13, there is small change in groundwater recharge even though TAM is widely changed.

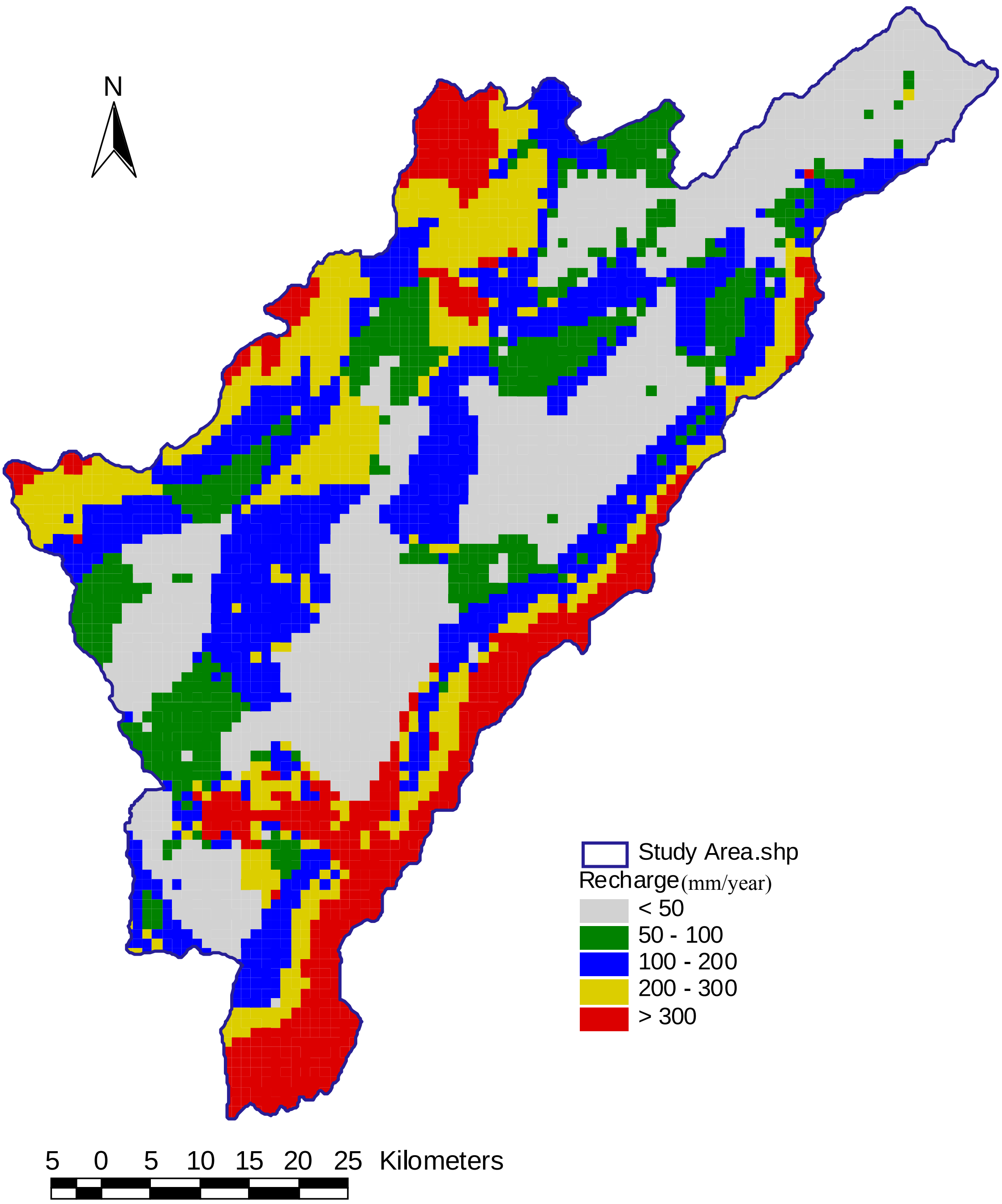


Figure-5.12 Annual Groundwater Recharge

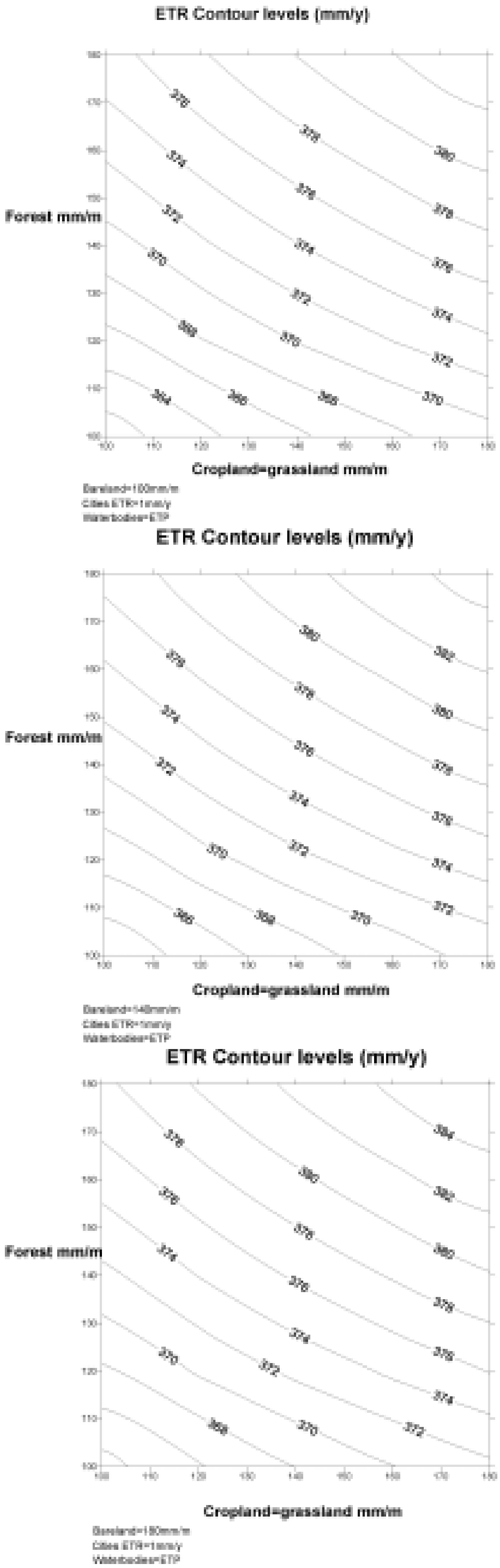


Figure-5.13 Calibration Result