THE STUDY
ON SUSTAINABLE GROUNDWATER DEVELOPMENT
FOR BOGOTA PLAIN
IN THE REPUBLIC OF COLOMBIA

FINAL REPORT
SUPPORTING REPORT

PART 13

GROUNDWATER POTENTIAL STUDY

Final Report
(Supporting Report)

Part 13 Groundwater Potential Study

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PART - 13 GROUNDWATER POTENTIAL STUDY

CHAPTER 1 Hydrogeologic Analysis

1.1 Aquifer Classification and Characteristics

(1) 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-1.1.

Table-1.1 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

(2) 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 condition.

Quaternary aquifer

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.

Tertiary aquifer

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 groundwater development because the scale of aquifer is 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 consists of impermeable shale. Therefore, Chipaque Formation becomes impermeable basement of Guadalupe aquifer from hydrogeological viewpoint. 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 consiting of shale. Arenisca Dura Formation, the lowest formation of Guadalupe Group, consists of alternation of sand and shale with low permeability, and groundwater is stored only in fractures. Therefore, only Labor Tierna Formation, the upper-most formation of the Guadalupe Group, is promising for groundwater development.

(3) 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.

<u>Groundwater recharge mechanism of Quaternary</u>

There is high possibility that Quaternary aquifer is recharged from river channels and sediments at the foot of mountains. There are many unknown points in the mechanism that rainfall reaching ground surface infiltrates into deep aquifer though soil and impermeable strata. However, in current situation, it seems best to estimate groundwater recharge based on the mechanism explained above. Therefore, in this Study, groundwater recharge is estimated based on the mechanism explained above (see 3.5.3). The existing estimation of groundwater recharge by INGEOMINAS and on going analysis by CAR used the same recharge mechanism. Groundwater recharge mechanism of Tertiary is considered the same as Quaternary.

<u>Ground water recharge mechanism of Cretaceous</u>

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. Groundwater recharged in mountains may be flowing toward deeper parts of the aquifer. The Cretaceous formation is divided by many faults. However, role of faults in groundwater flow are unknown so far. Groundwater of Cretaceous aquifer is strongly confined, which sometimes results in groundwater flow toward Tertiary and Quaternary overlying on Cretaceous. However, there is not data that proves this situation. It is more natural to think that groundwater is recharged in the ground surface and it infiltrates into the deep Cretaceous through Quaternary and Tertiary. Exceptionally there is possibility that groundwater flows upward near pumping well.

1.2 Aquifer Parameter

Permeability and storativity dominate physical characteristics of aquifer, which are expressed by permeability coefficient and storativity coefficient. These values are obtained by pumping test. Aquifer parameters were analyzed form result of pumping tests which were carried out in the Study Area. For this analysis, only reliable results of the pumping test were used. The result of this analysis is shown in Figure-1.1 and Figure-1.2.

Aquifer parameter of Quaternary

As shown in Figure-1.1, yield, specific capacity, transmissivity, permeability coefficient and storativity coefficient 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-1.2. Representative value in Table-1.2 means value of near the center of log normal distribution.

Table-1.2 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}

Hydraulic parameters of Guadalupe

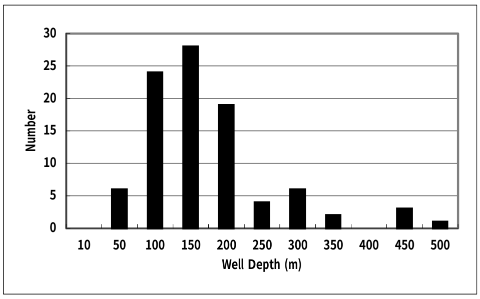
As shown in Figure-1.2, yield, specific capacity, transmissivity, permeability coefficient and storativity coefficient have values of wide range, and these distributions are approximated by log normal distribution. Relation between transmissivity and specific capacity is not strong. Result of pumping test is summarized in Table-1.3. Representative value in Table-1.3 means value of near the center of log normal distribution.

Table-1.3 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}

1.3 Hydologeological 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.



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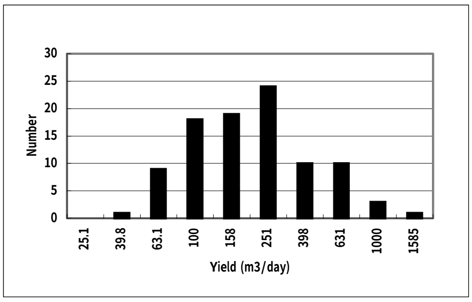

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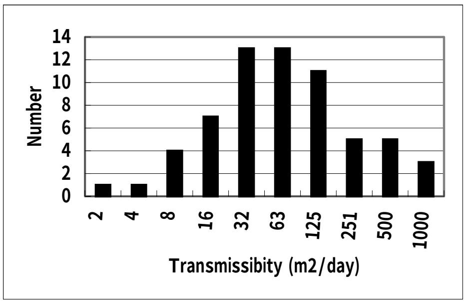

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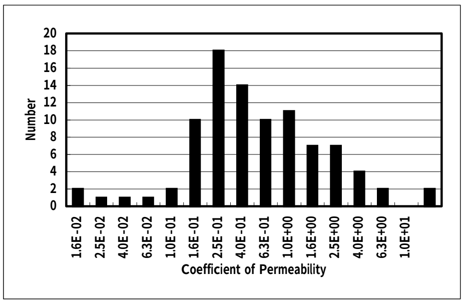

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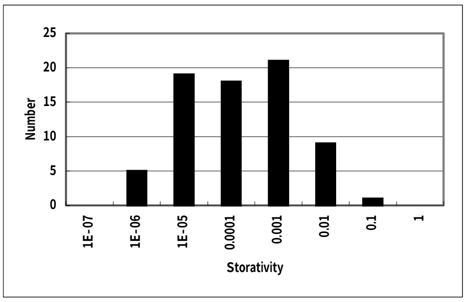

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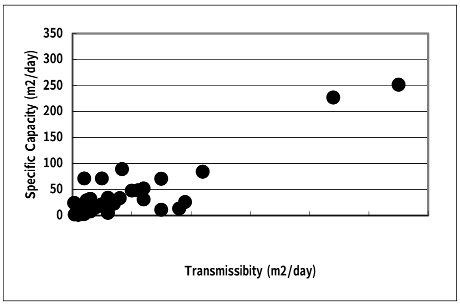

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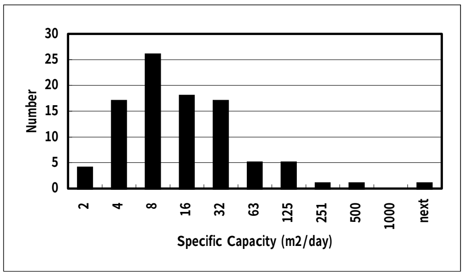

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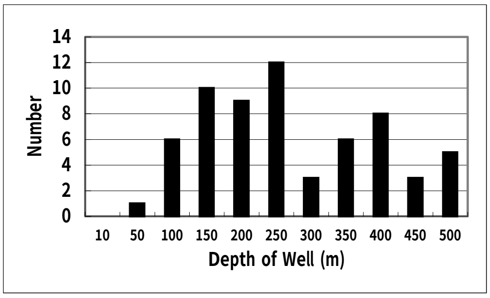
Figure-1.1 Hydraulic Parameters of Quaternary Aquifer



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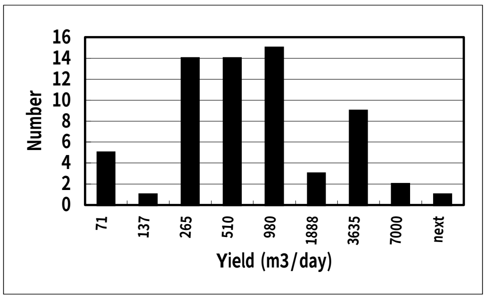

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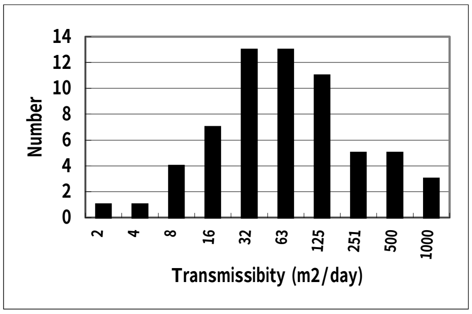

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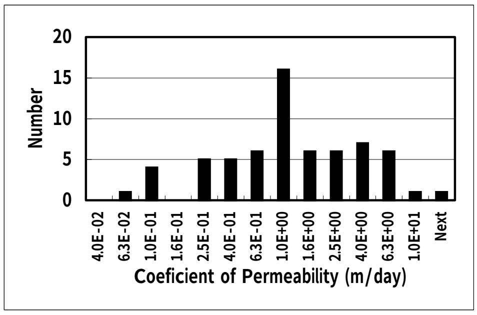

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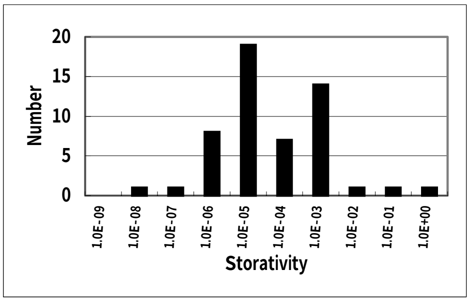

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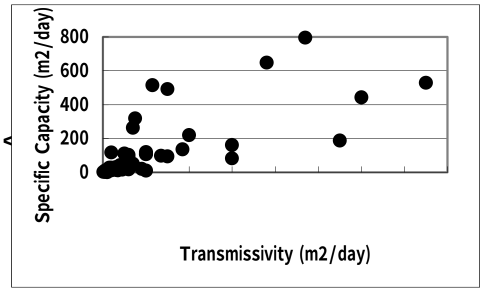

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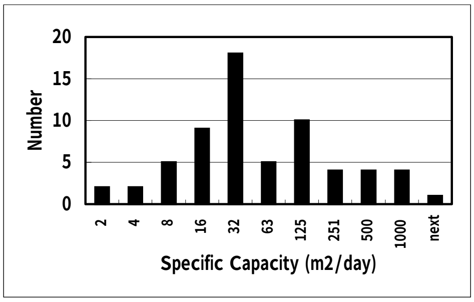

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Figure-1.2 Hydraulic Parameters of Cretaceous Aquifer

CHAPTER 2 Water balance and Groundwater Recharge

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

2.1 Water Balance

(1) Method of Analysis

Calculation process of runoff and precipitation of the basin is shown in Figure-2.1. Water balance analysis is explained below.

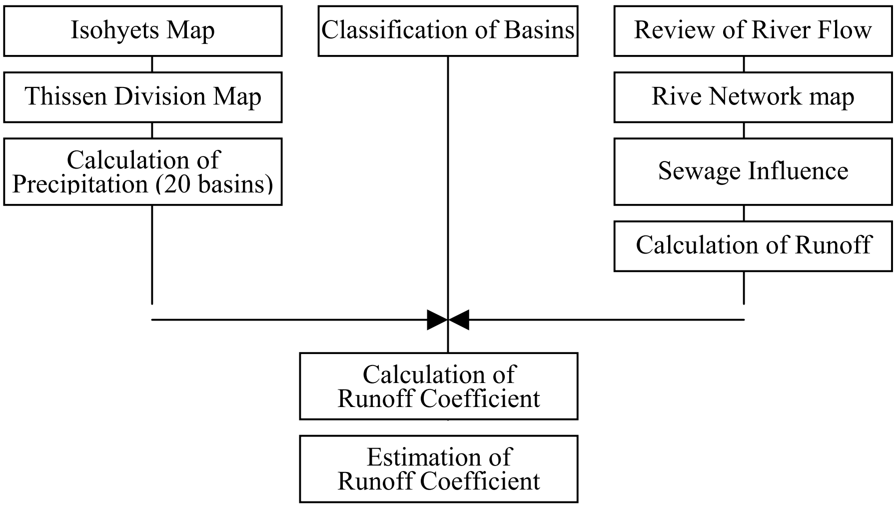


Figure-2.1 Calcualtion Process of Hydrological Analysis

(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 were 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.

Table-2.1 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-2.3. 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 Tujenlito basin at maximum and 600mm in Subachoque (2) basin at minimum.

In order to demonstrate the error of real precipitation of the whole Study that is caused by distribution of point rainfall at each observation station, a comparison was carried out. Simple average of point precipitations and calculated real precipitation by basin is shown in Figure-2.5.

According to this figure, it is estimated that regional difference of point precipitation gives around 10% error at the maximum in areal precipitation of the Study area.

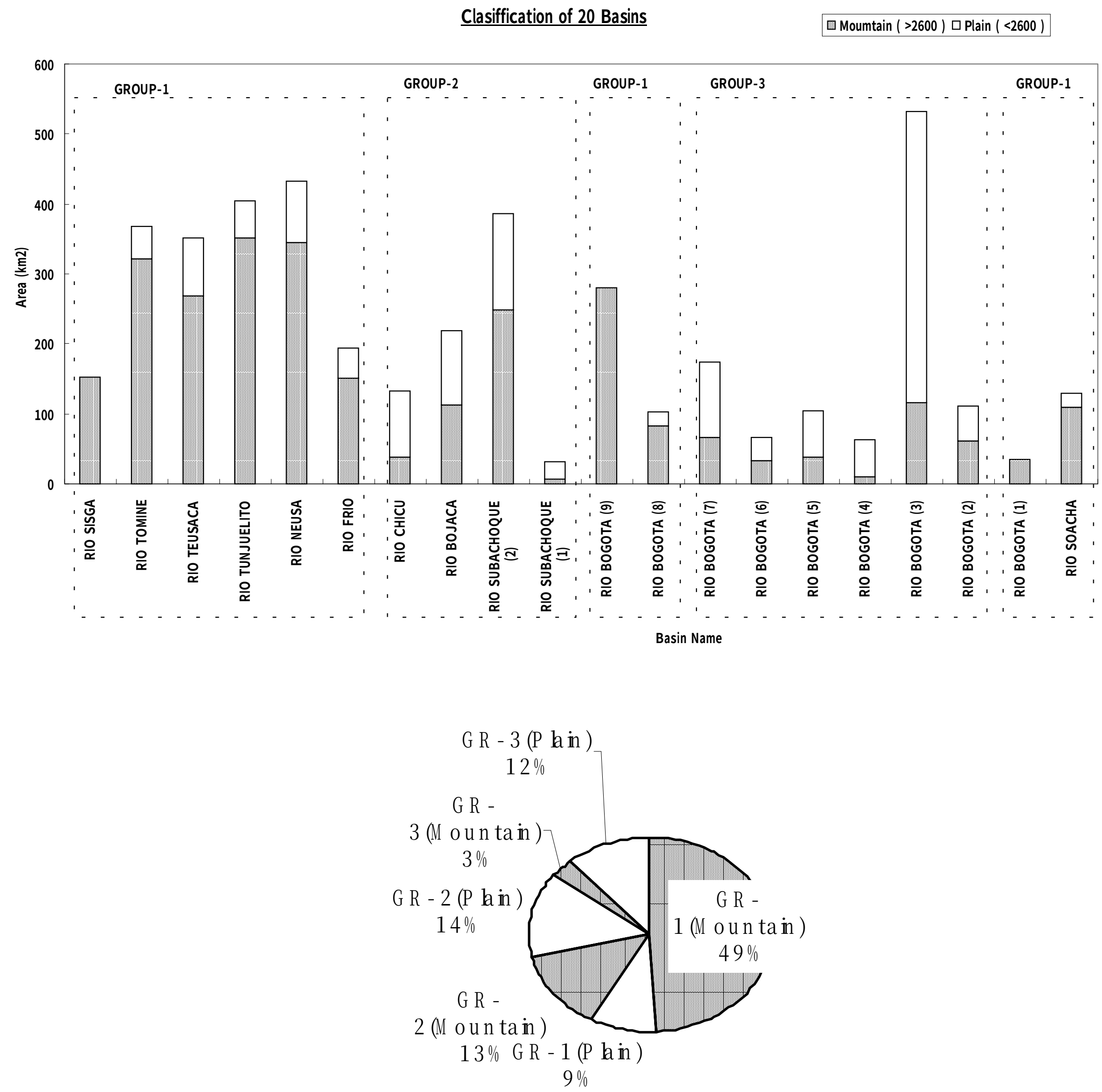


Figure-2.2 Basin Characteristics

(4) Runoff Calculation

<u>Review of River Flow Data</u>

River flow data for runoff calculation seems to be not so much precise due to measuring error and luck of device calibration as well as influence of human activities. For precision criteria of river flow data, the correlation among the data of continuous observation stations located at the same river was analyzed. Figure-2.6 shows its examples.

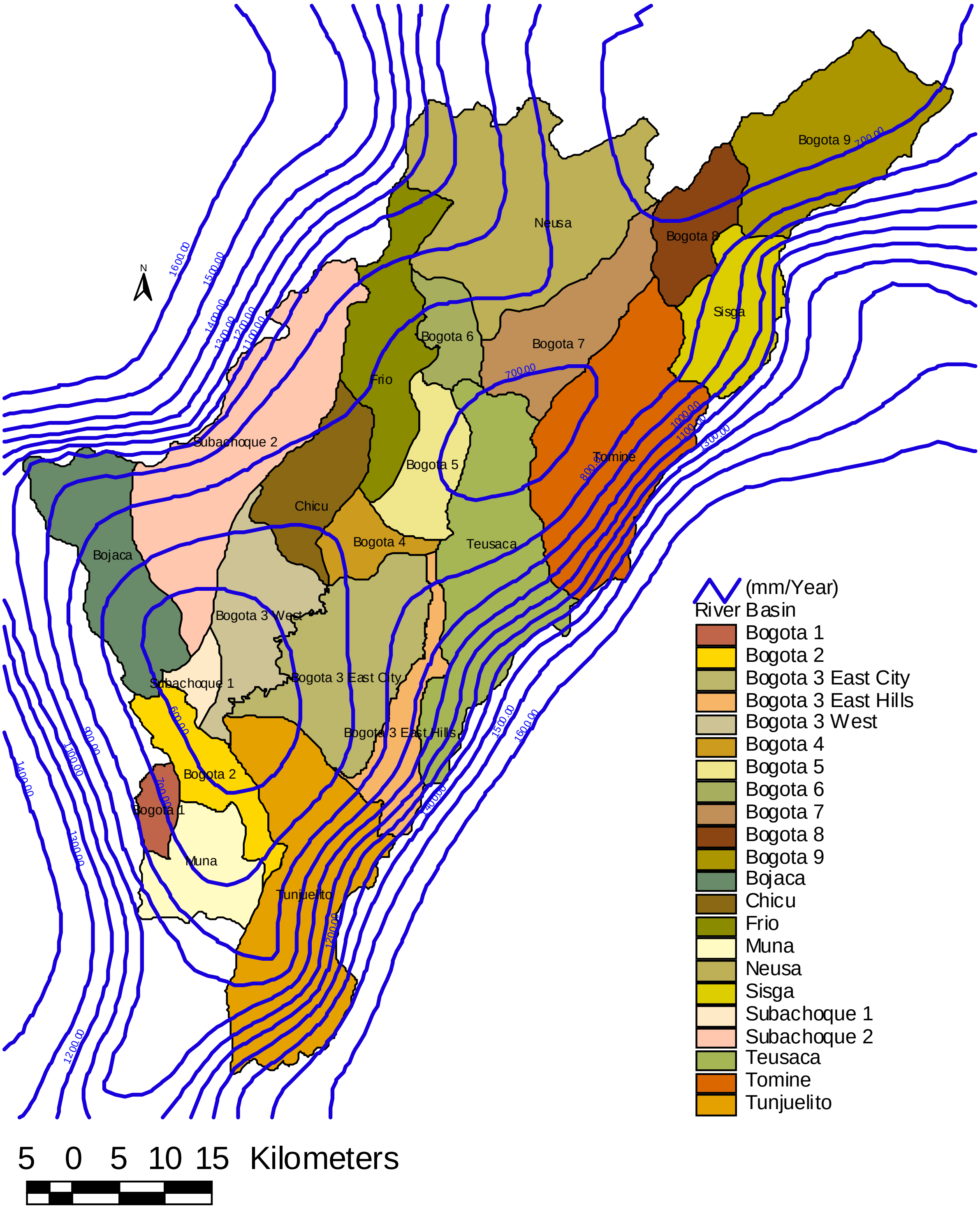


Figure-2.3 Precipitation Map

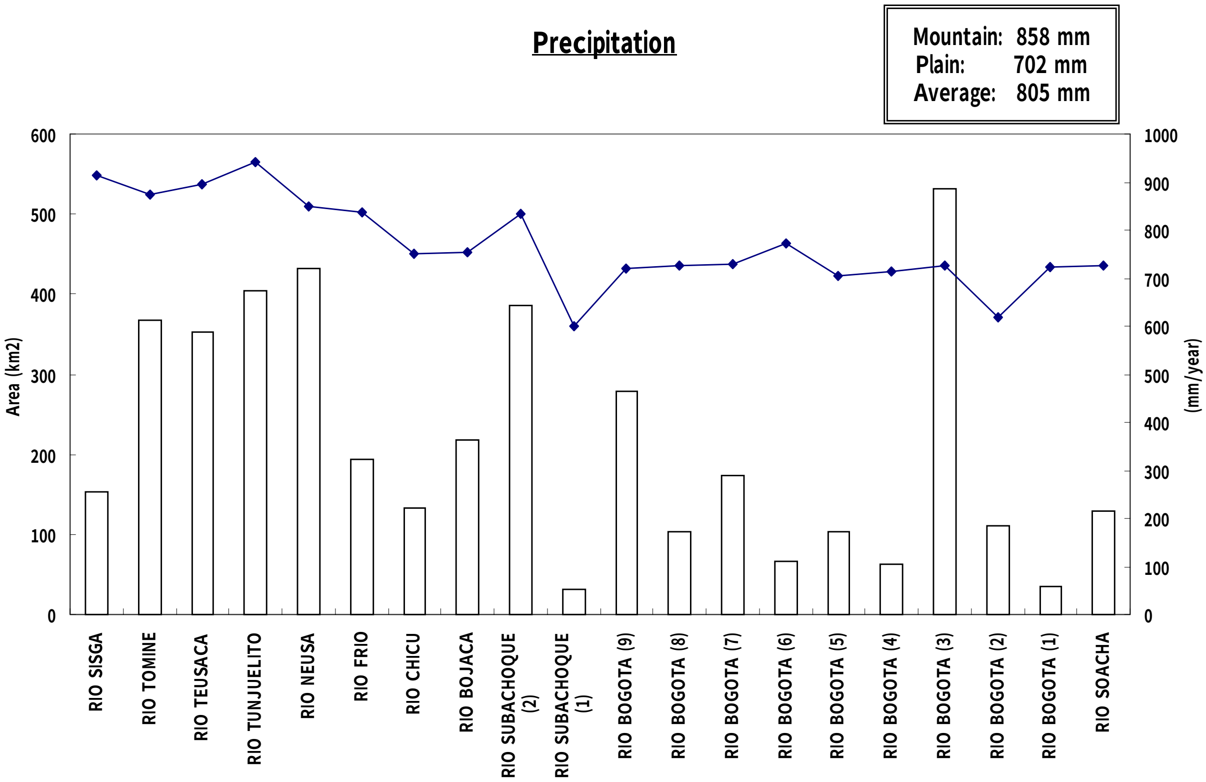


Figure-2.4 Precipitation

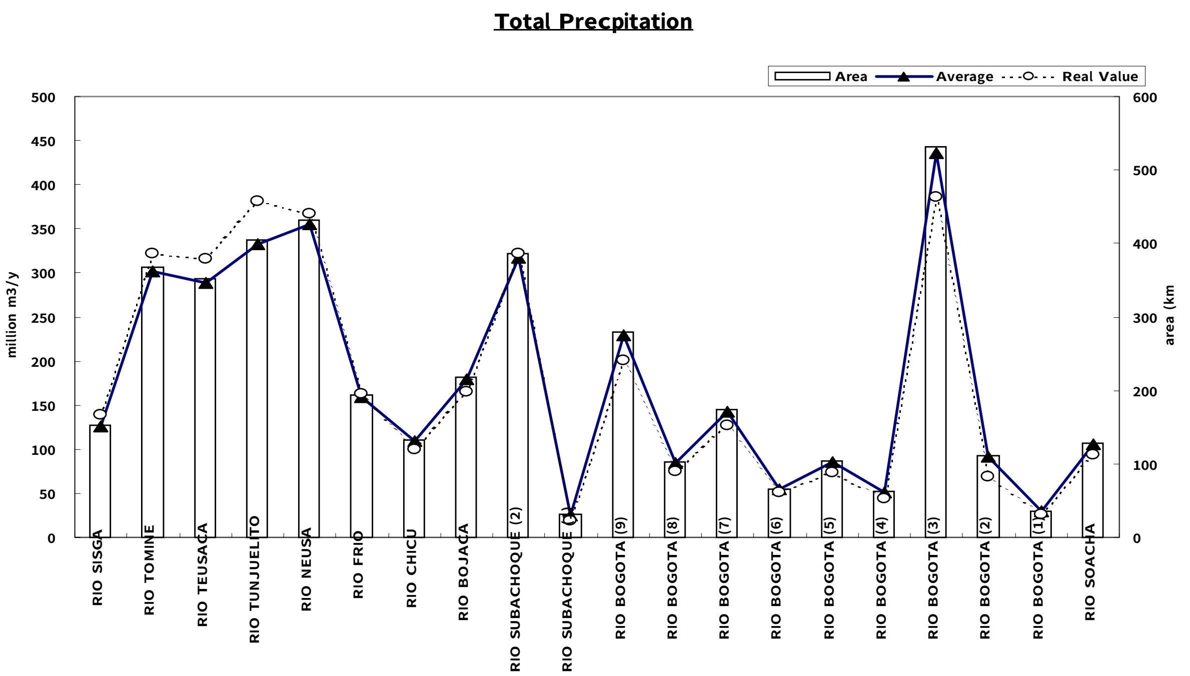
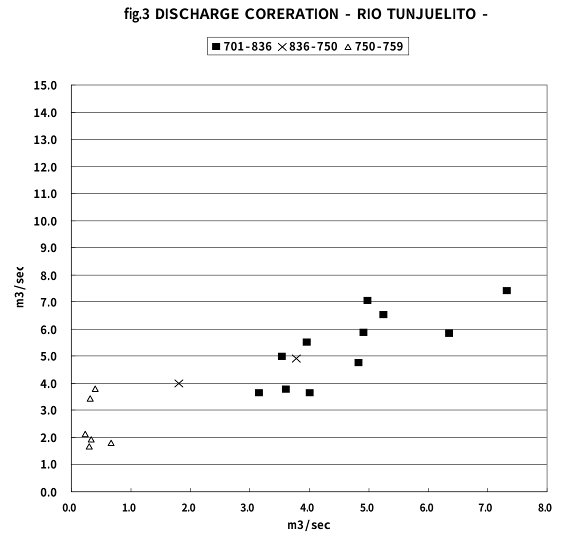


Figure-2.5 Total Precipitation



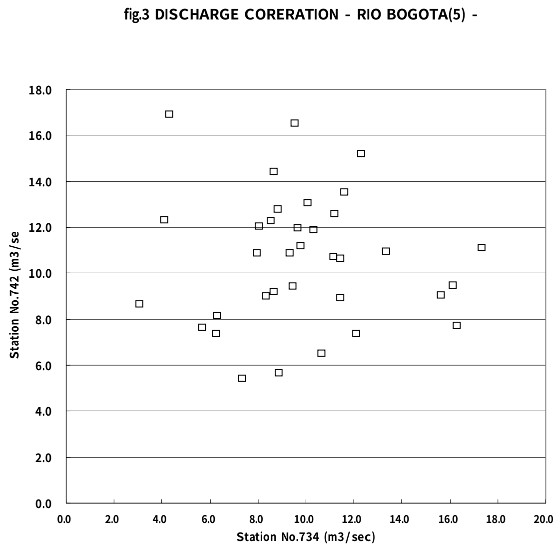


Figure-2.6 Correlation among River Flow Data

In above figures, the left one shows the correlation among the river flow data of the observation stations in Tunjuelito basin, and the right one shows that of Bogotá (5) basin. In the first case, good correlation can be recognized. However, in the other case, it seems to have low correlation from the figure.

River Network Drawing

A river network map was drawn by plotting flow data. Accordingly, a flow diagram of Rio Bogata (Figure-2.7) was made by plotting the observation flows from the up-stream area to Alicachin station located at the downstream. This diagram clearly shows that the water intake of Tibitoc purification plant and the sewage outflow from the center of Bogota city affect discharge of Bogotá River to a great degree.

Sewage Outflow Infuence

Since sewage outflow has a significant impact on Rio Bogotá in discharge, i.e. the Bogotá (3) and Bogotá (4) basins, and Rio Tunjuelito, for these rivers, sewage outflow must be subtracted from the discharge obtained from the flow data. A generated sewage was 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 Tunjuelito basin does 12% in proportion to their areas. In this assumption, water supply per unit area of the Tunjuelito basin was estimated half as much as those of other basins. As amount of water supply is increasing year-by-year, simple average method is not available for the sewage outflow estimation. For the Bogotá (3) basin that makes up much of the sewage outflow, a net runoff, shown in Figure-2.8, has been estimated by plotting the flow data at the inlet and outlet as well as the amount of water supply. The river flow data from 1973 to 1999 was applied for the calculation. From the calculation, the following values have been obtained.

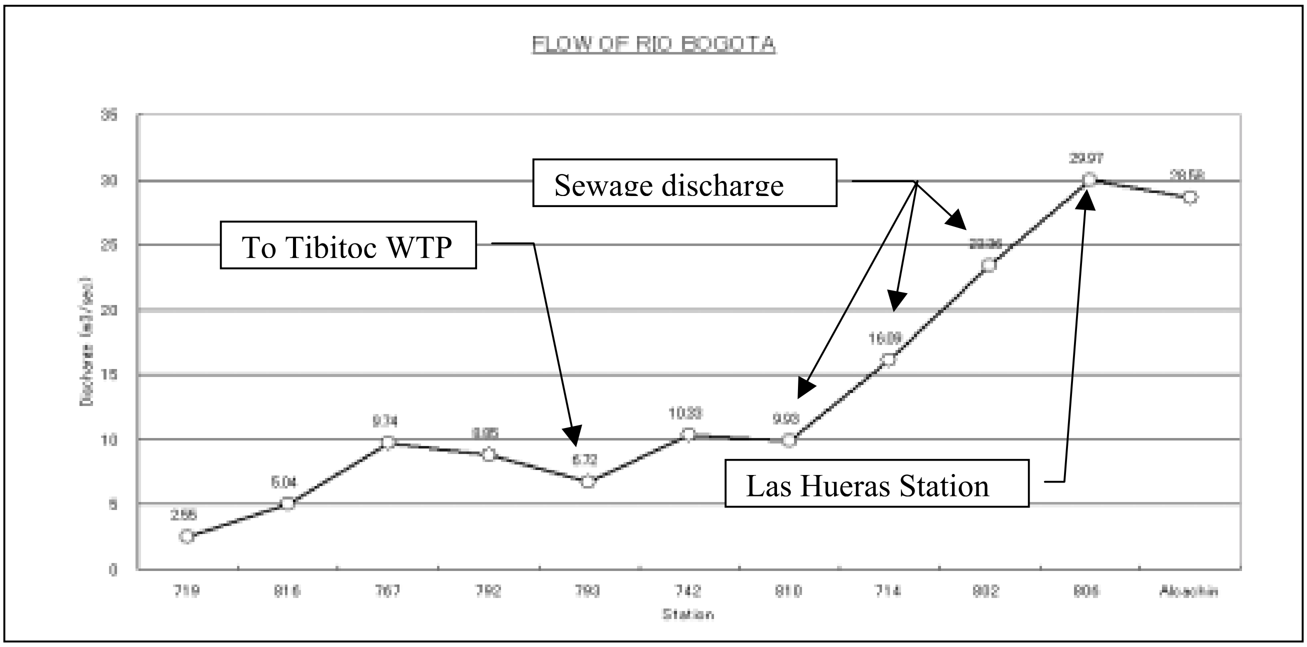


Figure-2.7 Flow Curve of Bogota River

<u>Sewage Outflow Infuence</u>

Since sewage outflow has a significant impact on Rio Bogotá in discharge, i.e. the Bogotá (3) and Bogotá (4) basins, and Rio Tunjuelito, for these rivers, sewage outflow must be subtracted from the discharge obtained from the flow data. A generated sewage was assumed as 80% of the water supply volume, of which the sewage from the Bogotá (3) basin makes up 79%, from the Bogota (4) basin does 9% and from the Tunjuelito basin does 12% in proportion to their areas. In this assumption, water supply per unit area of the Tunjuelito basin was estimated half as much as those of other basins. As amount of water supply is increasing year-by-year, simple average method is not available for the sewage outflow estimation. For the Bogota (3) basin that makes up much of the sewage outflow, a net runoff, shown in Figure-2.8, was estimated by plotting the flow data at the inlet and outlet as well as the amount of water supply. The river flow data from 1973 to 1999 was applied for the calculation. From the calculation, the following values have been obtained.

Table-2.2 Sewage Outflow

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

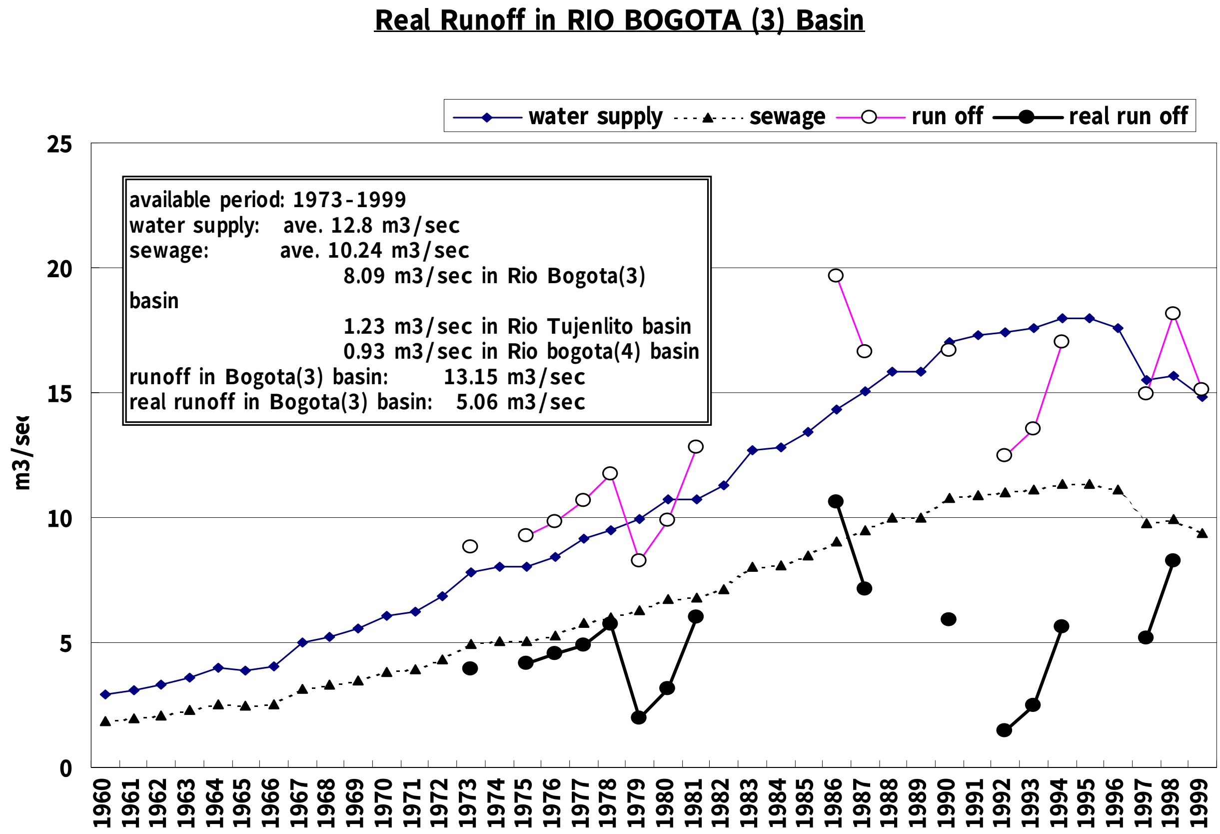


Figure-2.8 Removal of Sewage Discharge

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

Table-2.3 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 BOGOTA (9)	39.9%
Group-3	RIO BOGOTA (5)	20.0%
	RIO BOGOTA (3)	41.0% (107.6%)

Note) Figure in parenthesis shows net runoff coefficient.

(4) Estimation of Runoff Coeficient

A calculated runoff coefficinet was applied to estimate those of other basins. For this purpose, it is important to apply as much data as possible. Therefore, available data of stations located in a basin was applied for the estimation.

Group-1

The runoff coefficients of the stations in Group-1 are plotted in figure-9. Runoff coefficients vary widely where basin area is small, but they seem to converge as basin area becomes larger.

The ruoff coefficient of Tunjuelito basin looks high because of using gross value. By contrast, that of Neusa basin's outlet at the far right of the figure looks low compared with other points.

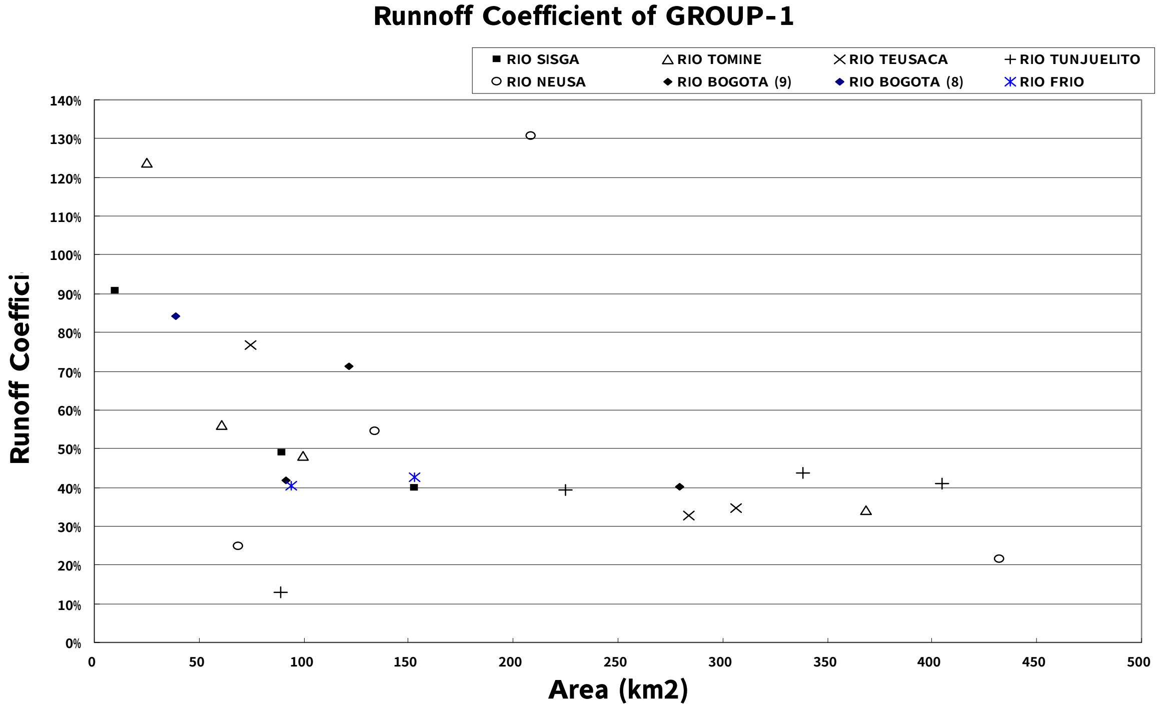


Figure-2.9 Runoff Coefficient in Group-1

The above chart leads an approximate formulla, using this formula runoff coefficient can be calculated from a basin area. Approximate formulla is usually expressed by exponetial curve. However, runoff coefficient is inclined to be high and not to corespond to reality in case of small basin area because of its mathematical charcteristics. Since both exponetial-curve and linear-line show almost same aspects over some extent of basin area, linealization is applied to approximate formulla. Figure-2.10 is the approximate curve of linealization obatained from the above chart by plotting available points.

Runoff coefficients in Group –1 were identified as shown in Table-2.4 by applying the approximate curve to the basins where runoff coefficients are unknown. On the other hand, the value of Bogota (9) basin was appled to that of Bogota (8) basin in assumption that the value of Bogota (8) is supposed to be almost same as that of Bogota (9) because both basins are contermious. Fundamentally, runoff coefficients obatained from flow data were applied. However, since the value of Neusa basin is lower than those of other basins, the value obtained from approximate curve was applied on the assumption that it resulted from the water intake, especailly waster supply.

Table-2.4 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%
Bogota(9)	40.0%	37.9%	40.0%
Bogota(8)	-	46.7%	40.0%
Bogota(1)	-	50.1%	50.1%
Muna	-	45.4%	45.4%

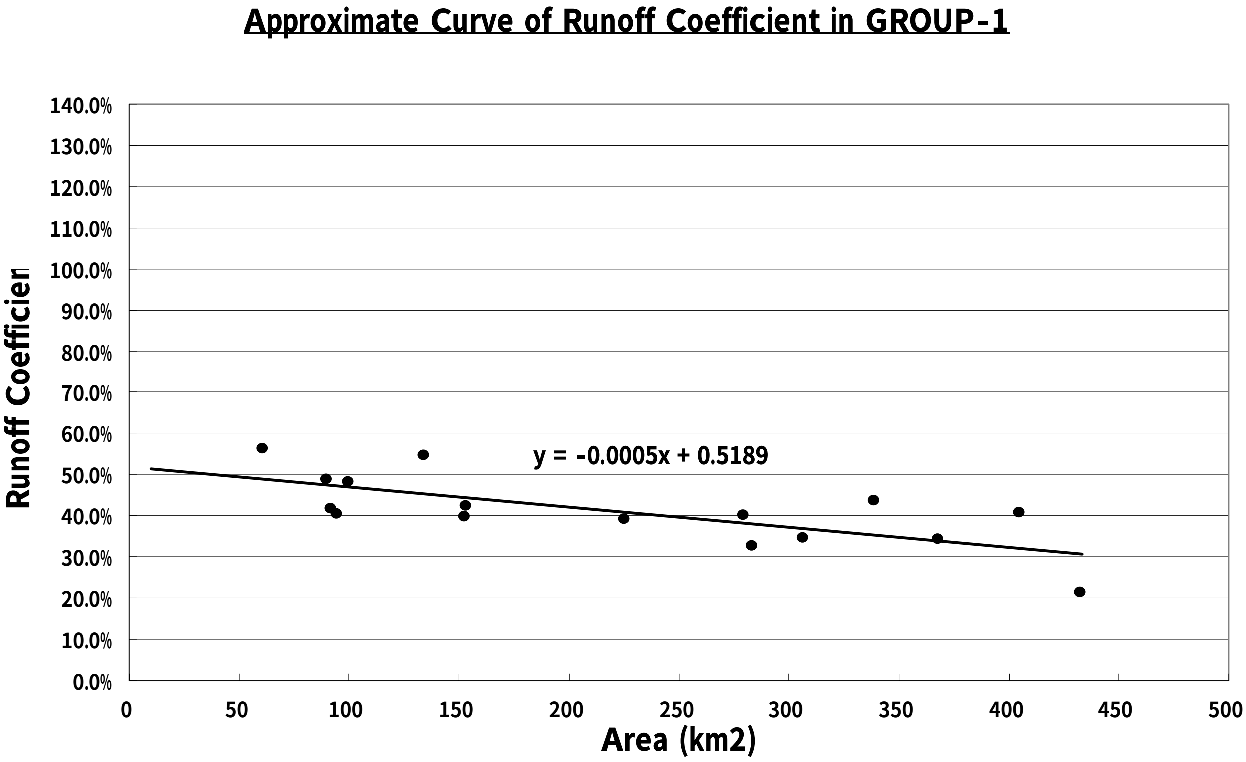


Figure-2.10 Approximate Curve of Runoff Coefficient in Group-1

<u>**Group-2 and 3**</u>

In Group-2 and 3, area ratio of plain is high. Runoff coefficients that belong to these groups were calculated on the assumption that the runoff coefficient of the plain does not vary relative to the basin area, and is almost constant beacause runoff causes mainly in mountains. Basins with calculated runoff coefficients from the observation data are Bogota (3) and Bogota (4) basins. Among them, Bogota (3) basin is a urbanized region at the core of Bogota City, and its runoff coefficient can not be used for other areas where agriculture is dominant. Therefore, only the value of Bogota (5) basin can be applied to estimate the values of other basins. Within the basins in Group-2 and 3, the runoff coefficient of 20% of Bogota (5) has been directly applied to Chicu and Subachoque (2) basins. Only for Bogota (4) basin located in the north of Bogota City, the value of Bogota (3) was applied beacause landuse of this area is same as Bogota (3) basin. Also, Bogota (3) basin has been divided into two sub-baisns by

Rio Bogota, Bogota (3)-E as east side and Bogota (3)-W as west side, because Bogota (3) basin has large area and has completely different aspects in both sides. Then, runoff coefficients have been estimated for both sub-basins. Also, Bojacá 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 the runoff coefficient of 20% of Bogota (5) basin to plain. Runoff coneffients of the basins in Group-2 and 3 are summarized in Table-2.5. In addition, the calculation of the runoff coefficients of Bogota (3)-E, Bogota (3)-W, Bojaca and Subachoque basin are shown in Figure-2.11.

Table-2.5 Runoff Coefficient of Basins in Group-2 and 3

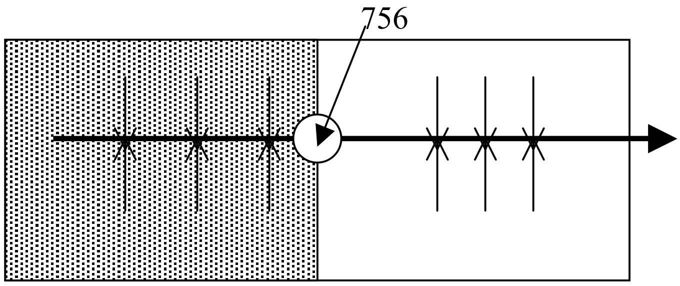
	Basin Name	Runoff Coefficient	Basin
Group-2	RIO CHICU	20.0%	Value of Bogota(5)
	RIO BOJACA	32.9%	See the calculation of next page
	RIO SUBACHOQUE (2)	32.2%	See the calculation of next page
	RIO SUBACHOQUE (1)	20.0%	Value of Bogota(5)
Group-3	RIO BOGOTA (7)	20.0%	Value of Bogota(5)
	RIO BOGOTA (6)	20.0%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

Runoff that was finally obntained for all the basin is shown in Table-2.6.

Table-2.6 Runoff of the Study Area

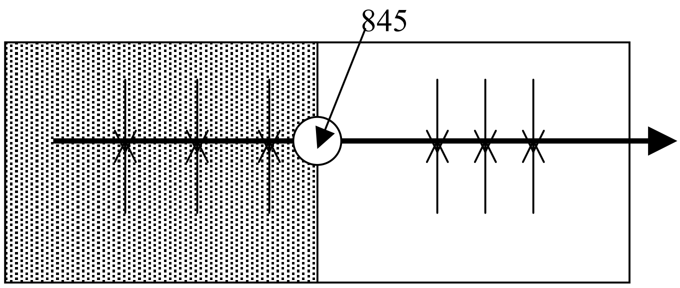
Basin	Annual Precipitation (mm)	Runoff Coefficient (%)	Runoff (m3/sec)	Basin	Annual Precipitation (mm)	Runoff Coefficient (%)	Runoff (m3/sec)
SISGA	913	40.0%	1.77	BOGOTÁ (8)	725	40.0%	0.95
TOMINE	873	34.0%	3.47	BOGOTÁ (7)	730	20.0%	0.80
TEUSACA	896	34.2%	3.42	BOGOTÁ (6)	772	20.0%	0.32
TUNJUELITO	941	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=36.68(m3/sec)						

Rio Bojaca Basin:



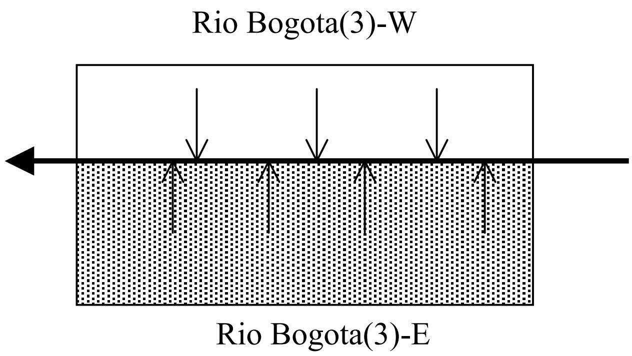
Runoff coefficient

Rio Subachoque (2) Basin:



Runoff coefficient

Rio Bogota (3) Basin:



Runoff coefficient	Rio Bogota(3)-W	20% (plain)
	Rio Bogota(3)-E	**48.5%**
	Rio Bogota(3) Total	41.4%

Figure-2.11 Runoff Coefficient Estimation in Bojica, Subachoque (2), Bogota (3) basins