MONITORING AND ANALYSIS OF HYDROLOGICAL CYCLE OF THE CHEONGGYECHEON WATERSHED IN SEOUL, KOREA

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ABSTRACT

In order to analyze the hydrological cycle of the Cheonggyecheon watershed in Seoul, Korea, we reviewed the current hydrological monitoring system, analyzed compiled hydrometeorological data and measured the region's streamflow on a regular basis to gather information on the inflow from the upper watershed in the dry season.

The annual water balance of the region was calculated using observed data including precipitation, runoff, water supply and sewage, changes in groundwater level. SWAT and WEP, distributed hydrological models, were also used to increase the accuracy of calculations. The results from HRU and grid based distributed model provide more detail information of the watershed. The spatial distributions of evapotranspiration and runoff can be analyzed from the model and utilized for normalization plan of urban water cycle.

1 INTRODUCTION

The Seoul Metropolitan Government decided to restore the old Cheonggyecheon (CHEON-gay-cheon) Stream, which flows through downtown Seoul. The city government began restoration work on July 1, 2003, with the goal of completing the project by September 2005. The stream had been covered and used by roadway and elevated expressway from 1971. The completed stream will be 30-80m wide and 30cm deep. In order to achieve this, 98,000 m^3 of water will be supplied every day from the Jayang Intake Facility, which collects water from the Han River through pipes used solely for this purpose, and 22,000 m^3 of groundwater will also be supplied from subway stations. A total of 120,000 m^3 of water will flow into the Cheonggyecheon main stream every day (Seoul metropolitan government, 2004; Lee, 2004).

Urban areas are faced with problems of flood damage, declining water supply safety during the dry season, declining streamflow, worsening water quality of the public water supply and contamination of groundwater, etc. (Kim et al., 2004).

Seoul also faces the same problems. Therefore, we need to search for ways to normalize the hydrological cycle in urban areas, which has been neglected, while carrying out the Cheonggyecheon Restoration Project. The Cheonggyecheon watershed's runoff characteristics and the declining groundwater levels due to urbanization will have unfavorable effects on the stream's ecosystem, including streamflow and water quality (Kim et al., 2004).

This research will provide the results of monitoring of changes in the patterns of the hydrological cycle, the weather, water quality, the ecosystem, groundwater. due to the Cheonggyecheon Restoration Project. It will also provide the results of analysis of past observation data and the future real-time monitoring plan after completion of the work. This research will also present an analysis of the hydrological cycle of the Cheonggyecheon watershed using monitoring results, and methods for correcting a distorted hydrological cycle.

The hydrological analysis, based on the hydrological monitoring system of the watershed and accumulated data, will regularly measure low flow from the upper watershed for use as data. The approximate annual water balance was calculated by using such observation data as precipitation, runoff, water supply and sewage, and changes in groundwater levels. Hourly and daily hydrological analyses were conducted in order to calculate water balance more accurately with SWAT and WEP, HRU and grid-based distributed hydrological models.

2 OVERVIEW AND CHARACTERISTICS OF THE CHEONGGYECHEON WATERSHED

The Cheonggyecheon is the first tributary of the Jungrangcheon Stream. It originates from the foot of Inwangsan Mountain and of Bukhansan Mountain northwest of its watershed and flows southwest. As an urban stream, it flows through the downtown core north of the Han River, to the left banks of Seongbukcheon Stream and Jeongneungcheon Stream, and finally into the right bank of the Jungrangcheon Stream. The Cheonggyecheon watershed is 50.96km^2 in size and 13.75km in length, and is located in the downtown of Seoul City. Its bed slope is between 1/310 and 1/510 (Seoul Metropolitan Government, 2004).

Figure 1: Aerial photograph of the Cheonggyecheon watershed

2.1 Topography and geology

The average elevation and slope of the Cheonggyecheon watershed are 70.1m and 0.07, respectively. Figure 2 shows the topographic characteristics of the region, including DEM (digital elevation model) data.

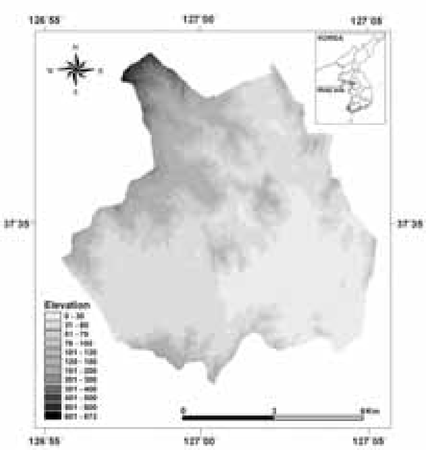
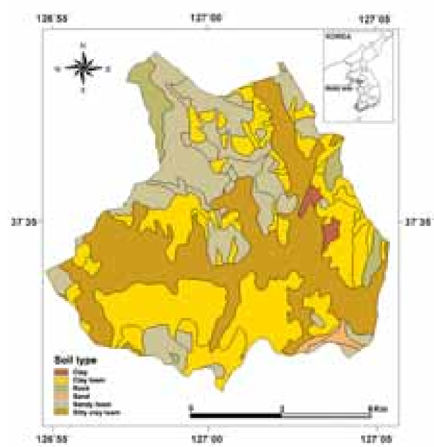


Figure 2: Topographic characteristics of the Cheonggyecheon watershed (DEM)

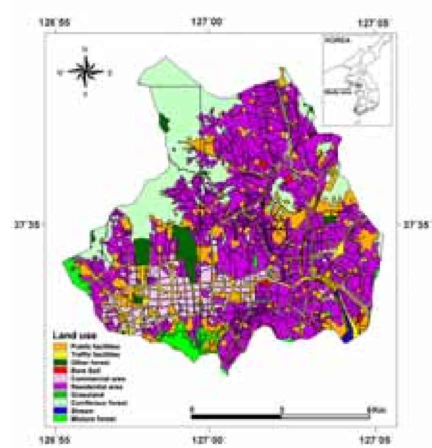
2.2 Soil and land use

The soils of the Cheonggyecheon watershed consist primarily of loam, including sandy soil (1.0%), rock (4.0%), silty loam (25.3%), silty clay loam (33.0%), clay loam (35.9%) and clay soil (0.9%). The portion of the Cheonggyecheon watershed where restoration work is to be conducted and most of the neighboring streams consist of clay loam, and mountainous areas like Bukhansan Mountain and some parts of Namsan Mountain are sandy loam.

The land use is composed of forested areas (23.2%: coniferous trees 17.7%; mixed trees 2.7%; and other forested areas 2.8%), urban areas (75.9%: residential areas 42.6%; commercial areas 9.4%; traffic facilities 12.3% and public facilities 11.6%), vacant housing sites (0.5%), streams (0.5%) and grassland.



a) Soil type



b) Land use

Figure 3: Soil type and land use in the Cheonggyecheon watershed

3 HYDROLOGICAL MONITORING

In order to conduct hydrological monitoring, precipitation and water level data were analyzed, in-situ streamflow measurements were taken, and a hydrological analysis was carried out. Weather observatory facilities in the Cheonggyecheon watershed include the Seoul Weather Station, six automatic weather systems under the Korea Meteorological Administration (KMA), and 12 rainfall stations. There are two stream gauging stations in the watershed, one at the Majanggyo (bridge) at lower Cheonggyecheon watershed and another at Yongdoogyo (bridge) at lower Jeongneungcheon Stream.

In order to investigate streamflow during the dry season, which is required for conducting a hydrological analysis of the Cheonggyecheon watershed, in-situ streamflow measurements have been taken at eight locations on a regular basis since September 2003.

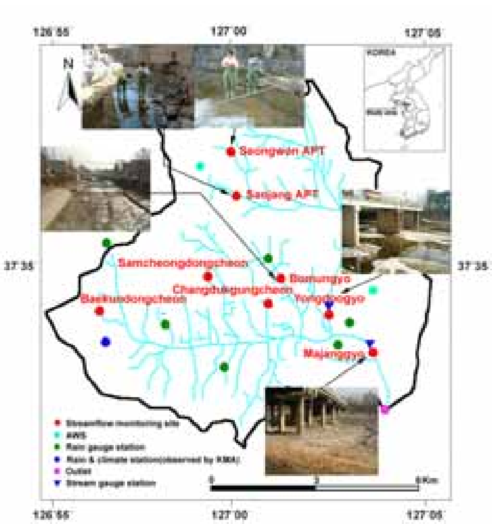


Figure 4: Location map of rainfall and stream gauge stations in the Cheonggyecheon watershed

3.1 Precipitation analysis

According to 30-year data (1971-2000) compiled by the Seoul Weather Station under the KMA, Seoul's annual average precipitation is 1,344mm, and 660mm falling in July and August.

From the accumulated precipitation and frequency based on daily rainfall intensity for a 10-year period (1993-2002), there are 261 days on average in a year without precipitation and 57 days with less than 5mm of precipitation. More than 50mm of precipitation falls 7.3 days on average each year.

Figure 5 shows that the gap between daily precipitation measured by regional observatories is as large as 70mm from August 3 to 6, 2002, which enables us to qualitatively assess regional differences.

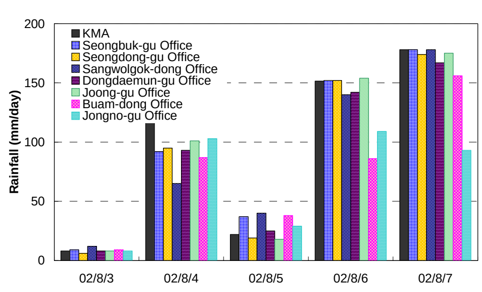
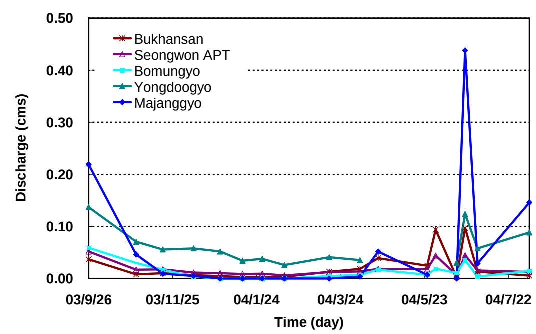


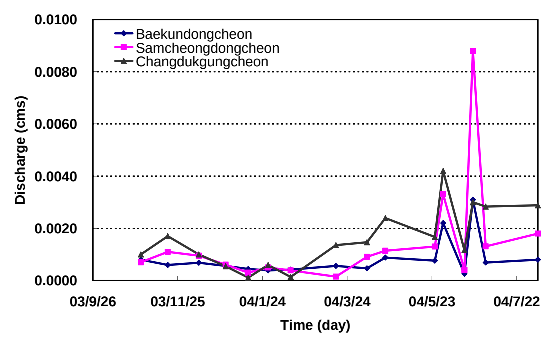
Figure 5: Comparison of daily rainfall of each rainfall gauge station (5 days)

3.2 In-situ streamflow measurement

Since September 2003, streamflow has been measured regularly at the water level stations and at major tributaries of the Cheonggyecheon Watershed such as upper Jeonggeungcheon Stream and middle Seongbukcheon Stream and minor tributaries such as Cheongundongcheon Stream, Baekundongcheon Stream and Changdeokgukcheon Stream. Figure 6 (a) shows that the streamflow measured at the Majanggyo and the Second Bomungyo (bridge) began to decrease rapidly as of September 2003 to almost zero after December 2003, and that the streamflow at Yongdoogyo was almost constant for more than three months after the decrease in September 2003, because groundwater is constantly supplied from subway station. Figure 6 (b) reveals that the upper tributaries of the Cheonggyecheon watershed maintain a constant streamflow even in dry season, although the amount is small.



a) main stream



b) tributaries

Figure 6: Temporal variations of measured streamflow

4 ANALYSIS OF HYDROLOGICAL CYCLE

In order to analyze the hydrological cycle of the Cheonggyecheon watershed, annual water balance was calculated by using observed data. SWAT and WEP, distributed hydrological models, were also used to increase the accuracy of calculations.

4.1 Calculation of water balance of the Cheonggyecheon watershed based on observed data

Generally, precipitation, water supply and ground water are used as inflow data, and runoff, sewage, evapotranspiration and the watershed's undercurrent due to changes in groundwater levels are used as runoff data to calculate the water balance of urban river watersheds. A simple equation (1) was used to calculate the water balance of the Cheonggyecheon watershed.

$$P_{pre} + Q_{sup\ ply} + Q_{gws} = Q_{stream} + Q_{sewage} + E_{evt} + \Delta S \quad (1)$$

where P_{pre} is the precipitation (mm), $Q_{sup\ ply}$ is the municipal water supply (mm), Q_{gws} is the groundwater supply (mm), Q_{stream} is the runoff (mm) from gauging station, Q_{sewage} is the inflow (mm) into sewage treatment plant, E_{evt} is the evapotranspiration (mm) which is assumed from daily rainfall less than 10 mm, and ΔS is the groundwater storage change which is calculated from groundwater level change of watershed and effective porosity.

As shown in Table 1, the detailed calculation results showed that the runoff of the watershed was smaller than the inflow. Considering the uncertainty of hydrological factors and limits and restrictions on data including water supply, sewage, evapotranspiration and groundwater storage, this seems to have produced quantitative values.

In fact, artificial inflows and outflows have a greater effect on urban river watersheds than natural inflows and runoff. Therefore, an effort to reduce uncertainties through close examination of hydrological factors would help allow the hydrological cycle of the watershed to be more accurately analyzed.

Table 1: Annual water balance of the Cheonggyecheon watershed

Factor		**flow depth** (mm)
Inflow	Total	5,058
	Rainfall	1,388
	Water supply	3,575
	Ground water use	95
Outflow	Total	4,870
	River	606
	Wastewater	4,192
	Ground water stage change	(-)159
	Evapotranspiration	231

4.2 Water balance calculation using SWAT

SWAT, developed by the ARS (Agricultural Research Service) of the USDA (U.S. Department of Agriculture), is a watershed model for forecasting the long-term effects of land management methods on the behavior of water, sediment and agricultural chemicals according to the soil type, land use and land management status of large and complex watersheds.

Daily surface runoff is calculated using the SCS method, the kinematic storage model is used to calculate lateral runoff, and the ground is divided into as many as ten layers in the linear reservoir model to calculate infiltraion. Groundwater is divided into two aquifers in SWAT, one being the shallow, unconfined aquifer that supplies water returning to the watershed's rivers and the other being the deep, confined aquifer that contributes water returning to rivers outside the watershed. (Neitsch et al., 2001)

4.2.1 Building input data for SWAT

SWAT (Soil and Water Assessment Tool) uses the SCS runoff curve number method or the Green & Ampt method to calculate urban runoff.

Urban areas have a different proportion of impermeable zones than rural areas. The construction of buildings, parking lots and paved roads increases impermeable zones and decreases infiltration of the ground. Industrial development changes the runoff flow pattern and runoff ratio increases due to artificial water channels, curbing and stormwater systems. These changes increase runoff volume and velocity, and cause large-scale peak floods.

SWAT divides urban areas into two groups to calculate surface runoff in urban areas: impermeable zones directly connected to the drainage system and permeable/impermeable zones not directly connected to the drainage system. The runoff curve number is always 98 for impermeable zones while it varies among other zones.

Input data for SWAT are divided into three groups: topographical data; data linked to the attributes of topographical data; and data on weather and watershed management. Watershed boundaries in the water resource unit map, land use maps, DEM, soil maps, etc. were used as topographical data. DEM, a basic map that provides a framework for spatial information, was constructed from data collected by the Ministry of Environment. the land use map (scale = 1: 25,000) composed of aerial photographs (scale = 1:37,500) and digital topographic maps (scale = 1:5,000). The aerial photographs and digital topographic maps are used for creating digital topographic maps (scale = 1:25,000) that are a component of NGIS (National Geographic Information System) theme mapping by the Korea Institute of Construction Technology. A reconnaissance soil map (scale = 1:50,000) compiled by the Rural Development Agency was used as a soil map.

The Seoul Weather Station's temperature, wind speed, humidity and solar radiation data from January 1, 1993 to December 31, 2002 were used for potential evapotranspiration caluculation using Penman-Monteith equation in SWAT.

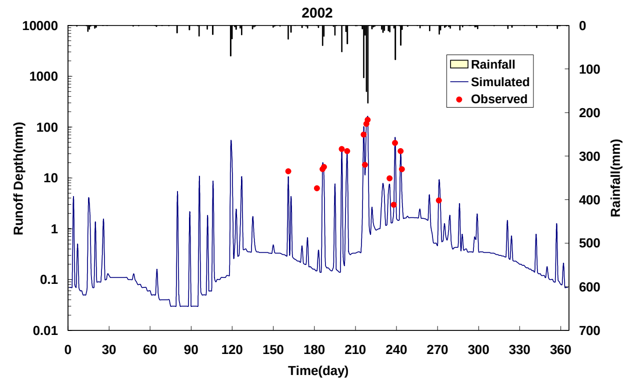
4.2.2 SWAT simulation results

The characteristics of the long-term runoff at the lowest end of the Cheonggyechon were simulated and compared with field data after calibrating parameters. The Cheonggyecheon watershed was divided into eight sub-watersheds by generating a digitized Cheonggyecheon watershed river network and designating confluences of each tributary of the Cheonggycheon Stream as the outlets of the sub-watersheds. These sub-watersheds were again divided into 138 HRUs according to soil type and land use.

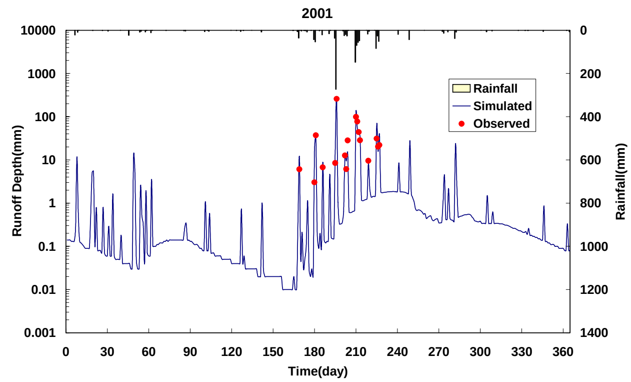
The 2002 data were used to calibrate SWAT. Only the field data from 2000 to 2002 regarding floods were available due to the lack of observed low flow data. Furthermore, these data were measured on an hourly basis only during flood season, which means they are of limited use as reference data in simulating the long-term characteristics of runoff because constantly observed data during dry season is insufficient.

A comparison of observed and simulated flows revealed that SWAT estimates of daily runoff were comparable to field data in both calibration and testing years. SWAT is thought to be helpful in planning to develop technology to normalize the hydrological cycle through analyses of the relationship between rainfall, surface runoff, soil water, groundwater, river water, etc. – the compositional elements of the watershed's hydrological cycle – taking into account changes in the hydrological cycle of the watershed. Figure 7 and 8 show the calibration and validation results.

Due to the unavailability of low water level data, some data gathered during flood season were used to calibrate and validate the SWAT results. The analysis results showed that the total and direct runoff were 925mm and 799mm respectively for 1,388mm of precipitation in 2002; 788mm and 666 for 1,187mm of precipitation of in 2000; and 1,012 and 890mm for 1,386mm of precipitation in 2001. This means that the expanded impermeable zones have contributed to the direct runoff of rainfall that does not permeate the ground.



(a) calibration (2002)



(b) validation (2001)

Figure 7: Comparison of daily hydrograph for calibration and validation results at the outlet of the Cheonggyecheon watershed

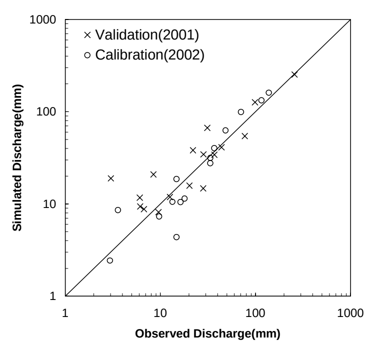


Figure 8: Comparison of daily streamflow for calibration and validation results at the outlet of the Cheonggyecheon watershed

Table 2: Summary of SWAT results

Year	**Rainfall** (mm)	**Surface Q** (mm)	**Lateral Q** (mm)	**Groundwater Q** (mm)	**Percolate Q** (mm)	**Evapotranspiration** (mm)	**Runoff depth** (mm)	**Runoff ratio** (%)
2000	1187	666	8	115	157	357	789	66.4
2001	1386	890	8	114	170	322	1012	73.0
2002	1388	799	9	118	176	404	926	66.6

4.3 Water balance calculation using WEP

WEP (Water and Energy transfer Process model), jointly developed by Doctor Jia, the Public Works Research Institute in Japan and the Japan Science and Technology Agency, is a physically-based and spatially-distributed model for quantifying the hydrological cycle of urban river watersheds with complex land uses. After a basic version of the model was developed, it was modified with additional functions like the calculation of groundwater flow, ground-surface flow interaction, and the effects of flooding facilities, flood retention reservoirs and agricultural land (Public Works Research Institute in Japan, 2002).

The WEP can predict streamflow very precisely without past streamflow data and validation, as it directly interprets the physical features of various hydrological cycle processes. It can also simulate spatial and chronological distributions of infiltration, evapotranspiration, surface runoff into rivers, groundwater runoff, groundwater flow, etc. on a watershed scale. In addition, it reflects the heterogeneity of land use within the mesh using a mosaic method, etc. and identifies artificial water flow due to human activities in terms of time and space (Jia et al., 2001).

4.3.1 Building input data for WEP

Fig. 9 shows the eight sub-watersheds and the locations of river channels. Land use data with grid size 25 were input into WEP. There are 64 detailed data regarding land use within a single square of the grid.

Table 3 shows the classification of input data according to their characteristics for WEP analysis. The Cheonggyecheon watershed was divided into grids of size 200m (54x54) and divided again into eight sub-watersheds by inputting the accumulated data into the GIS program after which the ground surface elevation, slope, flow direction, etc. of those grids were determined. Data such as types of surface soils, locations of river channels, land use, etc. were obtained from the GIS data.

Weather data measured at the Seoul Weather Station were used for the evapotranspiration using Penman-Monteith equation. And aquifer data including thickness, hydraulic conductivity were applied from the preliminary investigation report of the Cheonggyechon restoration project.

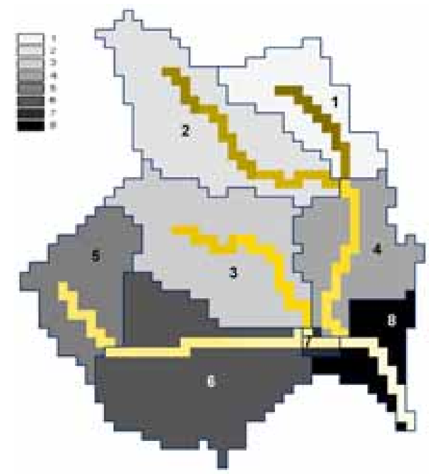


Figure 9: Sub-watershed and stream grid formulation of the Cheonggyecheon watershed

Table 3: Input data of WEP model

Classification	Input data
Objective watershed	Objective area, watershed partition, population distribution
Weather condition	Location and elevation of weather observation station, representative area of weather observation station, weather data
Surface condition	Surface elevation, slop, flow direction, accumulative number of incoming mesh, calculation order, mesh matching for calculation order, land use, impermeable range
Surface layer soil	Type, soil factor, vegetation factor
River	Location, shape, river bed material and thickness, etc.
Ground water layer	Aquifer thickness, saturated hydraulic conductivity, storage conductivity
Artificial water use	Domestic water use rate, diurnal variation pattern of sewerage, leakage rate, water supply from office of waterworks, irrigation quote, control domain of diversion site, daily averaged flow of diversion site, extra water supply code, etc.
Artificial heat balance	Artificial heat pattern, artificial heat quote
Initial and boundary condition	Initial moisture content of surface layer soil, initial groundwater table of 1st and 2nd aquifer, stage of each observation site as boundary, representative domain of each observation site

4.3.2 WEP simulation results

In order to mitigate the effects of initial conditions such as the initial moisture level of the surface soil and the initial groundwater level, we simulated the 1998-2000 period and used the conditions at 24:00 on December 31, 2000 as the initial conditions. The simulated period was the two-year period from 01:00 on January 1, 2001 to 24:00 on December 31, 2002. 2001 data were used to calibrate the WEP and 2002 data were used to verify the WEP. The simulation interval was set at one hour. It took 30 minutes for a Pentium 4 computer with a 2.8 GHz CPU and 512M of RAM to simulate the two years.

Figure 10 shows the WEP simulation results for the annual water balance of the Cheonggyecheon watershed for 2002. According to the results, the amount of direct runoff, infiltration and evapotranspiration were 832mm, 385mm and 398mm (146mm into the impermeable layer, 26.9mm into the permeable layer 225mm into the surface soil) respectively for an annual precipitation of 1,388mm. The runoff to rivers was 1,205mm (the proportion of direct runoff, intermediate runoff and groundwater runoff were 69%, 12.5% and 18.3% respectively).

Table 4 shows water balance according to sub-watershed. The table shows that the predicted hydrological cycles of the sub-watersheds have different patterns. The proportion of impermeable zones varies from 0.406 to 0.936 according to urbanization level, which affects the amount of evapotranspiration and direct runoff. Figure 11 shows the cumulative and direct runoff by grid square for 2002. there is more direct runoff in grid squares containing urban areas than in those grid squares with lower impermeability rates due to the relatively abundant forests and green zones. Figure 12 shows the river channel routing simulation results in WEP compared with those from the Majanggyo. The simulation interval was set at one hour. The simulation results are similar to the change pattern and scale of the field data. The compared field data were used after calibrating the hourly average data from each stream gauging station.

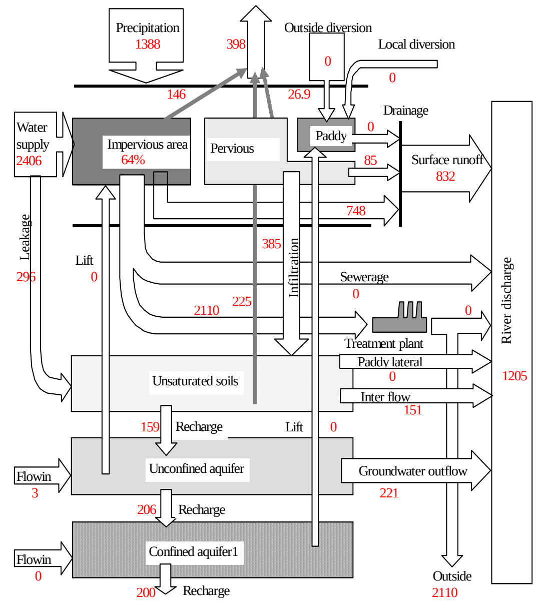


Figure 10: Water balance of the Cheonggyecheon watershed (2002)

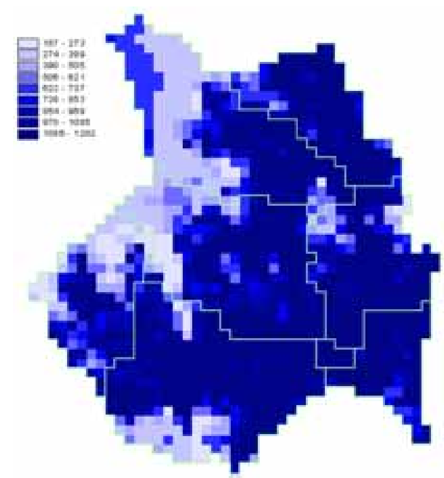


Figure 11: Spatial distribution of annual direct runoff (2002)

Table 4: Water balance of each sub-watershed (2002)

Watershed number	**total**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Area (km^2)	50.8	4.2	9.6	9.6	6.0	5.6	10.2	0.4	3.2
Impervious ratio	0.642	0.825	0.406	0.650	0.749	0.481	0.719	0.939	0.841
Rainfall (mm)	1388.0	1388.0	1388.0	1388.0	1388.0	1388.0	1388.0	1388.0	1388.0
Evapotranspiration (mm)	397.7	301.9	519.6	309.4	355.6	468.5	360.7	250.9	328.1
Direct runoff (mm)	832.7	998.8	640.0	822.6	950.0	645.9	891.4	1096.8	1038.3
Infiltration (mm)	384.6	193.6	616.4	395.6	243.1	598.2	313.8	77.3	145.1
Interflow (mm)	151.0	80.6	98.3	183.5	232.2	185.9	131.7	0.0	197.1
Groundwater flow (mm)	221.4	133.6	202.6	83.0	999.2	103.6	40.8	444.8	172.2
River discharge (mm)	1205.1	1212.9	940.9	1089.1	2181.4	935.3	1063.9	1541.5	1407.7
Water supply (mm)	2406.2	2482.5	2765.7	2187.8	3536.0	1215.8	1881.7	3505.0	3420.6
Leakage (mm)	296.0	305.4	340.2	269.1	434.9	149.5	231.4	431.4	420.7

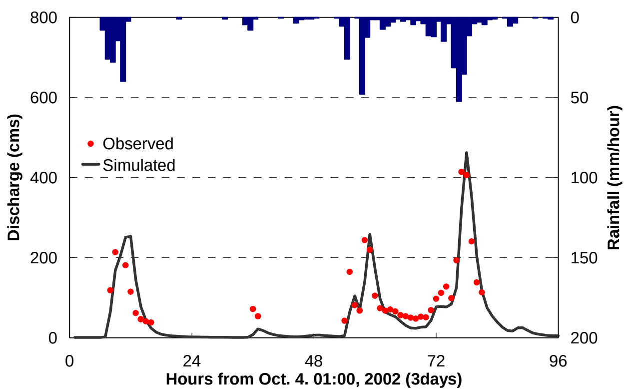


Figure 12: Comparison of observed and simulated hydrograph at Majanggyo gauging station

5 CONCLUSION

In order to analyze the hydrological cycle of the Cheonggyecheon Watershed, we reviewed the current hydrological monitoring system, analyzed hydrometeorological data and measured the region's streamflow on a regular basis to gather information on the flow into the upper watershed in the dry season.

The annual water balance in the region was calculated using observed data such as precipitation, runoff, water supply and sewage, changes in groundwater storage. SWAT and WEP, distributed hydrological models, were also used to increase the accuracy of calculations. The calculations showed that the Cheonggyecheon watershed's characteristics are typical of an urban area: a large amount of direct runoff during rainfall; quick response of runoff to rainfall; less evapotranspiration than in forested areas.

The results from HRU and grid based distributed model provide more detail information of the watershed. The spatial distributions of evapotranspiration and runoff can be analyzed from the model and utilized for normalization plan of urban water cycle.

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