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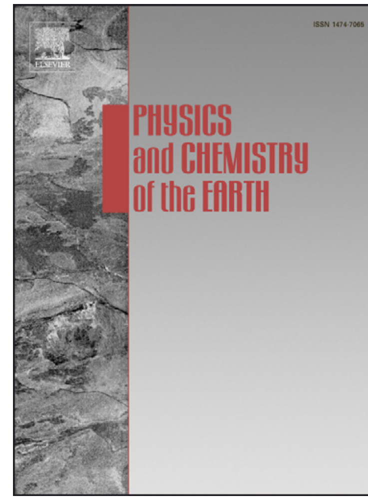

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Integrated watershed management for mitigating streamflow depletion in an urbanized watershed in Korea

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Abstract

A systematic, seven-step approach to integrated watershed planning and management is applied to an urbanized watershed, the Anyangcheon (AY) watershed in Korea which consists of 1) understanding watershed components and processes, 2) identifying and ranking problems to be solved, 3) setting clear and specific goals, 4) developing a list of management options, 5) eliminating infeasible options 6) testing the effectiveness of remaining feasible options, and 7) developing the final options. Watershed characteristics, water quantity and quality simulations with SWAT and PLOAD models, and the developed problem indices of PFD (Potential Flood Damage), PSD (Potential Streamflow Depletion), and PWQD (Potential Water Quality Deterioration) identify that streamflow depletion is more serious than flood risk and water pollution in the study watershed (Steps 1&2). Instreamflow requirements, which are the maximum value of the average low flow and the fish flow, are estimated using regional regression and the software PHABSIM (Step 3). Feasible solutions that improve the depleted streams are listed and screened qualitatively against technical, economical, and environmental criteria (Steps 4&5). Effectiveness of the remaining 14 feasible alternatives are then analyzed using SWAT (Step 6) and their priority ranks are determined against an evaluation criterion that uses the concept of pressure, state, and response (Step 7).

1. Introduction

Streamflow depletion is the process of running down or reducing the total water resources available (http://en.wikipedia.org/wiki/Sustainability_Depletion). Streamflow depletion not only results in water shortages but often adversely affects water quality and the aquatic environment. Numerous studies report incidents of streamflow decrease and depletion across the world, for example, in central Asia (Malik et al., 2000), Canada (Zhang et al., 2001), Spain, the Eastern Europe, and UK (Hisdal et al., 2001), Corolado, Nebraska, and Kansas, USA (Szilagyi, 1999), Massachusetts, USA (DeSimone, 2004). Korea is no exception. Shim (2003) recently warned that 543 of 3,773 (14.4%) second-graded streams in Korea were at risk for depletion.

In nature, many streams are repeatedly dried and replenished. More than 50 years ago, Blaney (1951) considered streamflow depletion a natural phenomenon and defined it as "the amount of water that flows into a valley, or onto a particular land area, minus the water that flows out the valley or off from the particular land area". In this paper, however, we focus mainly on the anthropogenic causes of streamflow depletion, which may chronically distort a hydrologic cycle. Examples of such causes include rapid increases of impervious area due to urban development, excessive groundwater pumping, and stormwater loss via combined sewer systems. Causes specific to the study watershed are discussed in the following sections.

Various management measures have been implemented to mitigate streamflow depletion. Most of the past projects, however, focused on a single sectoral interest and objective with limited participation. For instance, historic projects in Korea that were determined to be successful in mitigating streamflow depletion have often worsened flood damage and water quality problems (Lee et al., 2006). The approach proposed in this paper is rather integrated, multi-purpose, and collaborated. This study uses a recent, prominent framework of the Integrated Watershed Management (IWM) to simultaneously pursue solutions for both the primary objective (i.e. streamflow depletion) and other secondary objectives of water resources management (i.e. flood mitigation and water quality improvement). Heathcote (1998) similarly emphasized that IWM should satisfy the following four conditions to be successful: 1) allow an adequate supply of water that is sustainable over many years, 2) maintain water quality at levels that meet government standards and other social water quality objectives, 3) minimize flood damage, and 4) allow sustainable economic development over the short and long term.

A variety of terms are interchangeably used with IWM. Heathcote (1998) defined IWM 'Watershed management to integrate water quantity and quality, and natural (environmental impact) and human (social impact) systems simultaneously and even consider costing and legal, institutional and administrative concerns'. Other common terminology for IWM includes 'integrated water resources management' and 'comprehensive river basin management', but these terms are usually restricted solely to issues of water quantity (World Bank, 2003; IUCN, 2003). Therefore, this study adopts the term IWM because it is more commonly used to identify hydrologic, environmental, and ecological connections between water (both quantity and quality), land, and other resources.

Integration in IWM should not be restricted to only water quantity and quality. IWM should integrate multiple subjects (e.g. quantity and quality; water and land; green water and blue water), time (e.g. short and long term strategies), space (e.g. surface and subsurface resources; upstream and downstream basins), and participation (e.g. stakeholders and decision makers) as the Global Water Partnership (2000) categorized. This study considers most of these IWM categories to achieve the primary objective of mitigating streamflow depletion.

Heathcote (1998) identified a systematic, seven-step process to organize an integrated approach to watershed planning and management: 1) understand watershed components and processes, 2) identify and ranking problems to be solved, 3) set clear and specific goals, 4) develop a list of management options, 5) eliminate infeasible options 6) test the effectiveness of remaining feasible options, and 7) develop final options. The following seven sections detail the theory and methodology of each step and present the results of the application of this integrated approach for the watershed examined in this study.

The proposed IWM methodology is applied to the Anyangcheon (AY) watershed in Korea, which has been suffering from streamflow depletion (Fig. 1), as a typical urbanized watershed. The AY stream is the first tributary of the Han River in Korea, flowing 17.91 km and draining 287 km^2 (Fig. 2). The watershed where approximately 3.8 million people reside in 2003 consists of 14 administrative districts that have various interests in managing their watersheds. Based on the digital elevation map and the streamflow and storm sewer network, the entire AY watershed is divided into 23 sub-watersheds. This study chose the midstream & upstream watersheds (approximately 127 km^2 large) as a study site,which is depicted with a red boundary in Fig. 2. The study watershed consists of 8 sub-watersheds named Wanggok (WG), Ojeon (OJ), Dangjeong (DJ), Sanbon (SB), Hakui (HU), Suam (SA), Samseong (SS), and Sanbon (SB1) and their watershed characteristics are summarized in Table 1.

Fig. 1. Examples of streamflow depletion: the WG and SA streams of the Anyangcheon watershed.

Fig. 2. Location of the Anyangcheon stream and its sub-watersheds

Table 1. Watershed characteristics of the 8 study sub-watersheds

2. Understanding Watershed Components and Processes

2.1 Watershed components

Water is the lifeblood of a watershed system. Water movement in a system is affected by many physical, chemical, and biological components (or features) and processes. An understanding of these components and processes is an essential first step in the assessments of the condition of a watershed system and the impacts of management actions on a system (Heathcote, 1998). This step generally requires data on geology, climate, surface and groundwater hydrology, water quality, ecology, and socioeconomics, as listed in the first column of Table 2.

This project also started with the collection of relevant data for understanding the components of the AY watershed. At the early first stage of the project, approximately about 50 literatures were collected and reviewed, about 20 field trips were made, and about 500 photos were taken. Table 1 summarizes the components of the AY watershed, which are used as the core information throughout the IWM procedure. Especially, many of these components are used to calibrate parameters and as values of input variables that are necessary to develop hydrologic models for the watershed process simulation.

Table 2. Components necessary for understanding the Anyangcheon watershed

Among the components listed in Table 1, the land use images (Fig. 3) can be used as an indicator to assess how rapidly the urbanization has progressed during the last decades. Fig. 3 shows the increase of the urban area from 7.8 % in 1975 to 38.3 % in 2000. Therefore, the urbanization and its potential impact seem very evident in the AY watershed. For example, it is not unusual that many streams in this watershed are covered by impervious areas such as roads and used for sewers, and thus, most of streamflow during the dry season is flowed through the sewage into wastewater treatment plants.

Fig. 3. Land use changes between 1975 and 2000

2.2 Watershed processes

The water and its pollutant cycle can be quantified and thus in part understood with process simulation models. In this study, the water quantity and quality for the study watershed are simulated with the SWAT (Soil and Water Assessment Tool; Arnold et al., 2002) and the PLOAD (Pollutant LOADings; Edwards and Millar, 2001) models, respectively.

2.2.1 Water quantity simulation

SWAT was originally developed to predict the impact of land management practices on water, sediment, and agricultural chemical yields in large and complex watersheds with varying soils and land use and management conditions over long periods of time. Since its birth, SWAT has been widely applied and validated for several watersheds (e.g. Arnold et al., 1999; Santhi et al., 2001, Kim et al., 2003), especially for rural watersheds. Major model components of SWAT include climate cycles, hydrology, soil temperatures, plant growth rates, nutrients, pesticides, land management practices, and flow routing (Eckhardt and Arnold, 2001). SWAT classifies sub-watersheds further into smaller spatial modeling units known as hydrologic response units according to the heterogeneity of land uses and soil types within each sub-watershed. At the scale of a hydrologic response unit, watershed variables such as topographical and hydrometeorological features are assumed homogeneous (Arnold and Fohrer, 2005).

The topographical input data used in this study include a 1:25,000 scaled digital elevation map, a land use map, and a soil map for the years of 1975, 1980, 1985, 1990, 1995, and 2000. The resolution of the digital elevation map is a very important factor for accurately simulating streamflow with distributed hydrological models as Chaubey et al. (2005) showed that it affects the watershed delineation, stream network, and sub-basin classification in SWAT. This study employs 30 m since Cho et al. (2003) suggested that a suitable pixel size for analysis ranges from 25 m to 50 m.

This study also used the hydrometeorological input data such as historical records of daily data (1973-2004) of precipitation, maximum & minimum temperature, average wind speed, average humidity, and average solar radiation, which are available from the Korea Meteorological Administration, streamflow stage (2005-2006) at Giadaegyo, which is the outlet of the study watershed, and groundwater withdrawal (1995-2004), which are available from the Korea Water Resources Cooperation (KOWACO, 1995-2004).

Like other hydrologic models, SWAT needs to estimate 2 physical and 26 hydrological parameters to be estimated. Distributed models such as SWAT are effectively calibrated by first, developing a proper mechanism for reducing the number of parameters to be estimated. Therefore, this study tested the sensitivity of the model output such as total runoff and the peakflow to changes in each parameter and then selected the parameter whose sensitivity was greater than 1%. The selected parameters were SOL_AWC, GW_DELAY, and CN2, which represented, respectively, the available water capacity of the soil layer (mm/mm), the groundwater delay time (i.e. the lag between the times that water exits the soil profile and enters the shallow aquifer), and the initial Soil Conservation Service runoff curve number for moisture condition II.

By a trial-error procedure, these three sensitive parameters are calibrated to maximize the efficiency of a model defined by Nash and Sutcliffe (1970) as

$$R^2 = \frac{F_0^2 - F^2}{F_0^2} = \frac{\sum_{i=1}^{n}\left(M_{obs,i} - Q_{obs,i}\right)^2 - \sum_{i=1}^{n}\left(Q_{sim,i} - Q_{obs,i}\right)^2}{\sum_{i=1}^{n}\left(M_{obs,i} - Q_{obs,i}\right)^2} \qquad (1)$$

where n is the number of samples, $Q_{obs,i}$ is the observed value of i th day, $M_{obs,I}$ is the average of the observed values, and $Q_{sim,i}$ is the simulated value of i th day. The model becomes more efficient as R^2 approaches 1.

Using the calibrated parameters of SWAT, the hydrologic cycle for some AY sub-watersheds were simulated for dry seasons (from October to the following May) in two representative years, 1975 and 2000. Fig. 4 compares the water balances between the two years for 5 sub-wathersheds and the entire study watershed. Overall, the baseflow and the total runoff were decreased by 3.4 % and 11.6%, respectively, from 1975 to 2000. This hydrologic distortion would results mainly from the rapid urbanization, which has increased the impervious area, decreased the infiltration, and consequently reduced the baseflow runoff during the dry season as well as increased the overland runoff during the flood season. Note that the total flows from HU and SS are considerably greater than those of the other three watersheds (WG, OJ, SB1) in Fig. 4 because some management alternatives have been already applied to the HU and SS streams, such as reuse of wastewater, return of groundwater leakage from subway stations, and revision of reservoir operation objectives.

Fig. 4. Hydrological simulation results for 5 AY sub-watersheds and entire study watershed (Giadagyo)

2.2.2 Water quality

PLOAD is a GIS-based model used to calculate pollutant loads for watersheds. PLOAD estimates non-point sources (NPS) of pollution on an annual average basis for any user-specified pollutant. The user may calculate the non-point source loads using either the export coefficient or the EPA's simple method approach. Best management practices, which can reduce non-point and point source loads, may be optionally included in computing total watershed loads. Several output alternatives may be specified to show the NPS pollution results as maps and tabular lists, and to compare between multiple sessions.

PLOAD requires two kinds of input data, such as land use maps and all unit loads of land use (urban, agricultural, forest, and pasture). Since the non-point source pollution from urban areas occupies a major part of the total, its unit load plays a critical role in this process. Therefore, the unit loads of urban areas (Chung and Lee, 2006) were carefully estimated, with many data measured 4 times at the outlet of the study watershed.

Fig. 5 shows the calculated loads of BOD, COD, SS, TN, and TP per unit area for the 5 study sub-watersheds and the entire study watershed (Giadagyo). The urbanized watershed such as DJ, SB, HU, SA, and SB1 emit higher pollutant loads to their streams than the others, which suggests that these sub-watersheds require the best management practices to improve their water quality.

Fig. 5. Pollutant loads per unit area for the 8 AY sub-watersheds and the entire study watershed (Giadagyo)

3. Identifying and ranking problems

To diagnose the study watershed, this study introduces three indices such as Potential Flood Damage (PFD), Potential Streamflow Depletion (PSD), and Potential Water Quality Deterioration (PWQD) that quantify the problems of flood, depletion, and pollution, respectively, as their names indicate. Each index consists of several basic indicators that are listed in the following sub-sections. The basic indicators can be grouped into damage object, damage possibility, and defense vulnerability, which are based on the framework of sustainable development such as pressure, state, and response (OECD, 1993). As suggested by Hartmann et al.(1987), each sub-watershed is classified into a sound state (0~0.3), acceptable state (0.3~0.6), or poor state (0.6~1) according to the value of each index.

In this step, composite programming is employed to objectively estimate values of PFD, PSD, and PWQD, which are shown in equations (2), (3), and (4), respectively. Composite programming, which is a multi-level multi-objective programming method, was originally introduced by Bardossy and Bogardi (1983) as an empirical technique used to resolve geological exploration problems. A general problem with multiple objectives is transformed to a single objective problem such as those of Hagemeister et al.

(1995), Lee et al. (1991), and Lee et al. (1992). This transformation is accomplished via a step-by-step regrouping of a set of objectives into a single objective.

Composite programming employs a double weighting mechanism. One weighting is for indicators, which articulates the decision-maker's preferences with respect to the relative importance of each indicator. The other weighting addresses the "balancing factors" assigned to each group, in which a number of indicators are involved. Unlike weighting, these balancing factors are associated with the groups rather than each indicator. While the choice of weights emphasizes the relative importance among the indicators, the selection of the balancing factors refers to the significance of larger deviations in the indicators. The purpose of high balancing factors is to give more emphasis to indicators that have large negative values (Goicoechea et al., 1982; Torno et al., 1988).

3.1 Potential Flood Damage Index

PFD, proposed by KICT (2001) and modified by Kim (2004), measures the vulnerability of a watershed to flood using socioeconomic as well as hydrologic data. In this study, PFD is modified for use of composite programming as follows,

$$\begin{aligned} PFD = \{ & (\beta_{1,1} s_{PD}^{b_1} + \beta_{1,2} s_{PV}^{b_1} + \beta_{1,3} s_{NI}^{b_1} + \beta_{1,4} s_{NNC}^{b_1}) + (\beta_{1,5} s_{RI}^{b_1} + \beta_{1,6} s_{UR}^{b_1} \\ & + \beta_{1,7} s_{SW}^{b_1} + \beta_{1,8} s_{FD}^{b_1}) + (\beta_{1,9} s_{SL}^{b_1} + \beta_{1,10} s_{NR}^{b_1} + \beta_{1,11} s_{NP}^{b_1}) \}^{1/b_1} \end{aligned} \tag{2}$$

where β ($\beta_{1,1} + \beta_{1,2} + \beta_{1,3} + \beta_{1,4} = 1$, $\beta_{1,1} + \beta_{1,2} + \beta_{1,3} + \beta_{1,4} = 1$, $\beta_{1,5} + \beta_{1,6} + \beta_{1,7} + \beta_{1,8} = 1$, $\beta_{1,9} + \beta_{1,10} + \beta_{1,11} = 1$) are the weighting factors, b_1 (=1) is the balancing factor, and *s* are the basic indicators for PFD, which include

- Damage object: population density (s_{PD}), property value (s_{PV}), the number of infrastructure (s_{NI}) and the number of natural and cultural resources (s_{NNC})
- Damage possibility: rainfall intensity (s_{RI}), urban area ratio (s_{UR}), slope of watershed, and amount of flood damage (s_{FD})
- Indefensibility: stability of levee inundation (s_{SL}), the number of reservoirs (s_{NR}), and the number of pumping stations (s_{NP})

By the ideal approach method, each indicator becomes dimensionless, ranging from 0 and 1. Therefore, the resulting PFD has the same range and so do PSD and PWQD, as provided in the next sections. The closer to 1 PFD is, the more vulnerable the watershed is to flood.

This study uses the weighting factors that have been suggested by Kim (2004), as shown in Table 3, but these estimates should be further studied in the future. The socioeconomic data used in the damage object were obtained from the Korea National Statistical Office (KNSO) and the urban area ratio and the geographical characteristics were obtained using GIS software Arcview 3.2. The status of flood mitigation measures such as levees, reservoirs, and pumping stations were investigated by Hyundai Engineering Corporation (2003).

Table 4 reports the calculated PFD values for the 8 AY sub-watersheds and compares them with the average value of the entire AY watershed. Since these 8 study sub-watersheds are located in the upper part of the AY watershed, their flood risk seems less serious than those in the other part of the watershed. However, some urbanized watersheds such as DJ, SB, SA, and SB1 show moderately high flood potential. Fig. 6(a) also shows the spatial variation of PFD for the study watersheds.

Table 3. Weighting values ($\beta_{i,j}$) of PFD, PSD, and PWQD indices for the AY watershed

Table 4. Results of PFD, PSD, and PWQD for the 8 AY sub-watersheds

Fig. 6. Spatial variation of PFD, PSD, and PWQD for the 8 AY sub-watersheds

3.2 Potential Streamflow Depletion Index

PSD, proposed by Shim (2003) and modified by Lee et al. (2006), quantifies streamflow depletion by also using socioeconomic as well as hydrologic data. PSD is calculated as

$$\begin{aligned} PSD = \{ & (\beta_{2,1} s_{PD}^{b_2}) + (\beta_{2,2} s_{SS}^{b_2} + \beta_{2,3} s_{UR}^{b_2} + \beta_{2,4} s_{GW}^{b_2} + \beta_{2,5} s_{SW}^{b_2}) \\ & + (\beta_{2,6} s_{RT}^{b_2} + \beta_{2,7} s_{NR}^{b_2} + \beta_{2,8} s_{IT}^{b_2} + \beta_{2,9} s_{UR}^{b_2}) \}^{1/b_2} \end{aligned} \tag{3}$$

where $\beta_{2,1} = \beta_{2,2} + \beta_{2,3} + \beta_{2,4} + \beta_{2,5} = 1$, $\beta_{2,6} + \beta_{2,7} + \beta_{2,8} + \beta_{2,9} = 1$, b_2 (=1) is the balancing factor, and s are the basic indicators for PSD, which include

- Damage object: population density (s_{PD})
- Damage possibility: streamflow seepag (s_{SS}), urban area ratio (s_{UR}), groundwater withdrawal (s_{GW}), and slope of watershed (s_{SW})
- Defense vulnerability: reuse of treated wastewater (s_{RT}), the number of reservoirs (s_{NR}), interbasin transfer (s_{TR}), use of groundwater collected by subway stations (s_{UG})

The PSD weighting factors were estimated as suggested by Lee et al. (2006) and are presented in Table 3. The population density data were obtained from KNSO, the slope of watershed and the urban area ratio from Arcview, the groundwater data from KOWACO (2001), and the other data from several field surveys. The calculated PSD values for the study watersheds are shown in Table 4 and Fig. 6(b). Contrary to PFD, the PSD for the study watersheds is higher than the average of the entire watershed, which indicates that the streamflow depletion problem seems more important than the flood risk in the upper AY watershed. Note that the SA sub-watershed shows the most severe depletion problem (PSD = 0.73) but simultaneously shows the high flood risk (PFD = 0.61).

3.3 Potential Water Quality Deterioration Index

As an improved version of Schuler's impervious area ratio method (1994), PWQD quantifies the possibility of water quality deterioration. PWQD is calculated as

$$PWQD = \{(\beta_{3,1}s_P^{b_3}) + (\beta_{3,2}s_{LB}^{b_3} + \beta_{3,3}s_{LC}^{b_3} + \beta_{3,4}s_{LS}^{b_3} + \beta_{3,5}s_{LP}^{b_3} + \beta_{3,6}s_{LN}^{b_3} + \beta_{3,7}s_{WI}^{b_3} + \beta_{3,8}s_{PD}^{b_3} + \beta_{3,9}s_{CS}^{b_3}) + (\beta_{3,10}s_{ST}^{b_3} + \beta_{3,11}s_{RS}^{b_3})\}^{1/b_3} = 1 \quad (4)$$

where $\beta_{3,1} = \beta_{3,2} + \beta_{3,3} + \beta_{3,4} + \beta_{3,5} + \beta_{3,6} + \beta_{3,7} + \beta_{3,8} + \beta_{3,9} = \beta_{3,10} + \beta_{3,11} = 1$, b_3 (=1) is the balancing factor, and s are the basic indicators for PWQD which include

- Damage object: population (s_P)
- Damage possibility: Loads of BOD (s_{LB}), COD (s_{LC}), SS (s_{LS}), TP (s_{LP}), and TN (s_{LN}), untreated wastewater intrusion (s_{WI}), population density (s_{PD}), and covered stream (s_{CS})
- Defense vulnerability: streamflow treatment facility (s_{ST}), riverside and street sweeping (s_{RS})

The PWQD weighting factors were estimated as suggested by Lee et al. (2006) and are presented in Table 3. All loads were obtained from PLOAD's results (shown in Fig. 5) in Step 1, the population and its density data from KNSO, the covered stream from Arcview, and the other data from several field surveys. The PWQD values shown in Table 4 and Fig. 6(c) are not high except those of DJ and SB, so the overall water quality in the upper AY watershed has not deteriorated yet. Note that the DJ sub-watershed shows the worst water quality (PWQD = 0.58) as well as the highest flood risk (PFD = 0.66) but simultaneously shows the severe streamflow depletion problem (PSD = 0.57).

4. Setting clear and specific goals

The previous step identified that streamflow depletion is the most serious problem in the study watershed. Therefore, the ultimate goal of this study is to devise feasible management alternatives that can recover the distorted hydrological cycle and consequently, the depleted streams of the watershed to a certain target, which is often called the instreamflow requirement. This section addresses how the instreamflow requirement can be calculated.

Instreamflow requirement is typically defined as the value of minimum flow which must remain in the stream. It should be not only guaranteed hydrologically but also satisfied environmentally. Therefore, instreamflow requirement is generally a maximum value between the hydrological low flow and the environmental flow. The environmental flow is derived from factors such as water quality, ecosystem, recreation, scenery, and other environmental aspects. In this study, only the flow for fish habitats (called the fish flow) is considered and compared with the hydrological low flow.

4.1 Hydrological low flow

The numerical definition of hydrological low flow varies by country. In Korea, the term, "the average low", is often used as the low index. The average low flow is defined as the mean value of annual daily flows that exceed 355 days of a year. However, historical flow records that are sufficiently long for such a reliable statistical analysis are seldom available in Korea and the AY watershed is not an exception. Therefore, this study reviewed the low flow estimation methods for ungauged basins.

As reviewed by Smakhtin (2001), many low flow estimation methods for ungauged basins are available in the hydrology literatures, but the most popular choices include the drainage-area method (Riggs, 1972), the regional regression method (Vogel and Kroll, 1992), and the baseflow correlation method (Stedinger and Thomas, 1985). After applying the three methods to the study watershed, this study concluded that the regional regression method, which estimates the average low flow as a function of the basin characteristics, is the most appropriate. To identify regression equation and calibrate their parameters, this study used the observed flow data at six dam basins (Soyanggang Dam, Goesan Dam, Daechung Dam, Andong Dam, Imha Dam, and Hapcheon Dam) and nine gauging stations (Emokjeong, Baekokpo, Youngyang, Cheongsong, Donggok, Goro, the Epyoung bridge, the Tanbu bridge, and the Gidae bridge). Testing the candidate models, this study found that the model only with the basin area was the best, which is written as,

$$Q = 0.0357A^{0.55} \quad (3)$$

where Q is the average low flow (m^3/sec), A is the basin area (km^2). The second column of Table 5 presents the average low flow for the 8 study sub-watersheds with regional regression.

Table 5. The average low flow, the fish flow, and the resulting instreamflow requirement for the 8 AY sub-watersheds

4.2 Fish flow

To calculate the fish flow for the study watershed, this study used a software, PHABSIM (Physical HABitat SIMulation system) that was developed by USGS (2001). PHABSIM is composed of two major components, the stream hydraulic modeling and the life stage-specific habitat modeling (Stalnaker et al., 1995).

The stream hydraulic modeling simulates water depths and velocities as a function of discharge. PHABSIM uses the HEC-RAS model for the water depth simulation and the VELSIM model, which basically uses the Manning's equation for the velocities simulation. The cross sections and roughness data of the AY basin for the HEC-RAS model were provided by Hyundai Engineering Corporation (2003).

On the other hand, the habitat modeling derives a relation between weighted usable area and discharge by combining the hydraulic modeling result with the habitat suitability criteria of target species. To determine the target species, this study cited Gyeonggi Research Institute (2003), who investigated the dominant species for the entire AY watershed, and thus selected Carassius auratus (Goldfish) for the Gia bridge, Zacco platypus for the HU sub-watershed, Rhynchocypris oxycephalus for the DJ, SB, SS, and

SB1 sub-watersheds as the dominant species. Fig. 7 shows these species. This study also used information from former studies, such as those by Korea Institute of Construction Technology (1995) and Kim (1999), to derive the habitat suitability criteria of the target species. Table 6 reports the habitat suitability criteria used in this study.

Fig. 7. Target species for the AY watershed

Table 6. Habitat suitability criteria of the target species

Increasing the discharge gradually, PHABSIM searches the discharge that maximizes the weighted usable area as the fish flow. Table 5 presents the fish flow calculated with PHABSIM for the 8 study sub-watersheds. Note that the fish flows are available only for the spawning season from Aril to October.

4.3 Instreamflow requirement

The calculated average low flow and the fish flow for each study sub-watershed are compared and their maximum values are determined as the instreamflow requirements. As shown in Table 5, the fish flows for the spawning season are always greater than the average low flow in all the study sub-watersheds, the fish flow from April to October and the average low flow from November to March were selected as the instreamflow requirements.

5. Developing list of management options

Once the problems and specific goals have been identified, a list of all possible alternatives should be created. The challenge for the decision-making process is to overcome preconceptions about workable options and create a broad and imaginative range of solutions for further investigation. Broad creativity is absolutely necessary in this step (Heathcote, 1998).

Management options may include measures that use structures or technology to change existing conditions (structural), or those that rely on changes in human behavior or management practices (nonstructural). In every management planning opportunity, one management strategy is to keep doing what is currently underway, in other words, to maintain the status quo. Various creative management options appropriate for the study watershed were developed. These include

- Do nothing (i.e. the status quo)
- Construction of retention pond (structural)
- Restoration of covered stream (structural)
- Inter-basin transfer (reuse of WWTP effluent) (structural)
- Use of groundwater collected by subway stations (structural)

To constrain the development of impractical alternatives, none of the proposed options should increase flood damage or deteriorate water quality from the IWM standpoint. All feasible alternatives are shown in Table 7 with their descriptions. Though all possible combinations of these options should be listed, this was not attempted in this analysis. Future studies should attempt a comprehensive listing of options, though the number of options may be large.

Table 7. Feasible management alternatives and their descriptions for the 8 AY sub-watersheds

6. Eliminating infeasible options

Several approaches for eliminating infeasible options are possible but the elimination (or screening) procedure generally has the following two goals (Walesh, 1989):

(1) To determine which of the available alternatives is feasible – that is, meets the technical, economic, and environmental constraints

(2) To determine which of the remaining alternatives performs best in terms of specified evaluation criteria

We call the first and the second goals the pre-feasibility and the feasibility studies, respectively. The pre-feasibility study that is addressed in this section can inexpensively provide rapid insight into the probable effectiveness of different management strategies. It often provides a base result for the kind of detailed and quantitative results (from a feasibility study that is addressed in the next section) necessary to justify fiscal commitment or definitively sway public or political opinions (Heathcote, 1998).

This study evaluated qualitatively the management alternative listed in Table 7 by three criteria: technical, economical, and environmental feasibilities. Table 8 reports the answers from the pre-feasibility analysis and Fig. 8 shows the resulting master plan for the 8 AY sub-watersheds.

Table 8. Screening results from the pre-feasibility analysis for the 8 AY sub-watersheds

Fig. 8. A master plan from the pre-feasibility analysis for the 8 AY sub-watersheds

7. Testing the effectiveness of the remaining feasible options

This step (called the feasibility study in the previous section) tests quantitatively the effectiveness of the feasible management options that were screened from the pre-feasibility study. In general, massive amount of information and computation are required in the feasibility study, and thus, computer simulation models that have been validated are often employed to make this step efficient. With such models, various detail scenarios that could not be considered in the previous steps can be tested. On the contrary, some feasible options may be proved ineffective after the detail simulation.

This study uses the SWAT model again, which has been previously calibrated in the early step of this

IWM project. Using SWAT, the 14 pre-screened, management alternatives for the study watershed were tested, and the increase of the target flow for each case was calculated as an effectiveness criterion. The results from the effectiveness analysis of each alternative are presented in Table 9, where the target flow is represented as the 355th and 275th daily flows in a flow duration curve and the effectiveness criterion is expressed as the 355th or 275th flow increase divided by the instreamflow. Overall, the alternatives of 'I', which are the water reuse from wastewater treatment plants through the inter-basin transfer, secure the largest amount of instreamflow.

Table 9. Effectiveness and ranks of the remaining feasible alternatives for the 8 AY watersheds

8. Developing the final options

In the many cases of various projects, budget and resource are generally limited and thus all the feasible alternatives are seldom accepted simultaneously. Therefore, we should find a set of alternatives that maximizes our objective (i.e. the security of the instreamflow requirement in this study) and at the same time, satisfies the constraints such as limited budget and resource. This is a category of optimization problems.

However, especially when the constraints are uncertain, ranking the feasible alternatives could be preferred to finding an optimal solution, and decision makers can execute an IWM project according to the ranks whenever the budget and resource are available. In this last step, this study formulates an evaluation index and then ranks the 14 alternatives. The evaluation index used in this study can be written as

$$f(a_i) = \alpha\ PO(a_i) + \beta\ PSD(a_i) + \gamma\{0.5d(a_i) + 0.5h(a_i)\} \tag{5}$$

where $PO(a_i)$ is the population of a sub-watershed where the alternative a_i is applied, $d(a_i)$ and $h(a_i)$ are efficiencies against the drought and low flow, respectively, and α, β, and γ are the weighting factors ($\alpha + \beta + \gamma = 1$).

The above equation is based on the concept of the pressure, state, and response but various formats are now being tested as an ongoing research to find the most appropriate index. Currently, the weighting factors α, β, and γ of the pressure, state, and response are estimated as the equi-weighted value, 1/3, which is also a topic of a future research. The last column of Table 9 shows the ranks of the 14 feasible alternatives for the study watershed.

9. Conclusions

Many watersheds in the world have problems caused by human activities. In particular, urbanization distorts the hydrologic cycle of watersheds and, in extreme cases, threatens the sustainability of watersheds. Comprehensive, integrated water resource planning for watershed management is therefore necessary for sustainable development within a watershed. This study provides a procedure and an applied example of integrated watershed planning and management in the decision-making process for the sustainable development of a watershed.

The project started with the collection and analysis of watershed characteristics such as climate, soils, groundwater, water quality, land-use, and other relevant data. The water quantity and quality cycle for the study watershed were then simulated with the SWAT and the PLOAD models, respectively (Step 1). To diagnose the study watershed, this study introduced three indices such as PFD, PSD, and PWQD that quantify the problems of flood, depletion, and pollution, respectively. Composite programming was introduced to objectively estimate the index parameters (Step 2). As a result, the primary objective identified in this process was set to secure instreamflow during dry seasons, and the ultimate goal of this study was to develop feasible management alternatives that could recover the distorted hydrological cycle and consequently, the depleted streams of the watershed to the target instreamflow requirement (Step 3). In order to secure the instreamflow, various creative alternatives were investigated (Step 4) and feasible management options were selected based on technical, economical, and environmental criteria (Step 5). These feasible alternatives included reservoir redevelopment (OG, HU, SS), a new retention pond (WG, SS), restoration of the covered stream (DJ, SB, SA), inter-basin transfer (reuse of wastewater treatment plants effluent; HU, SS1, SS2, SA, SB1), and use of groundwater collected by subway stations (U1). Using SWAT, the pre-screened management alternatives were tested, and quantified the increase of the target flow for each case (Step 6). Finally, the priority ranking of feasible alternatives was derived by using the proposed evaluation index equation, which uses the concept of the pressure, state, and response (Step 7). This study served as a guideline for constructing decision support systems for integrated watershed management.

Opportunities for future studies exist. For example, the determination of weighting factors should be determined more precisely since the indices of PFD, PSW, and PWQD are very sensitive to weighting values. The weighting factors need to consider the socio-economic component. The effectiveness of water quality enhancement should be also evaluated, as S1, S2, and S3 appear to be more effective for water quality than water quantity. Further, other creative and feasible options should be considered in the alternatives. Finally, the determination of appropriate target quantity of instreamflow should be carefully studied as this quantity has great influence on the feasibility of alternatives and the overall efficiency of management opportunities.

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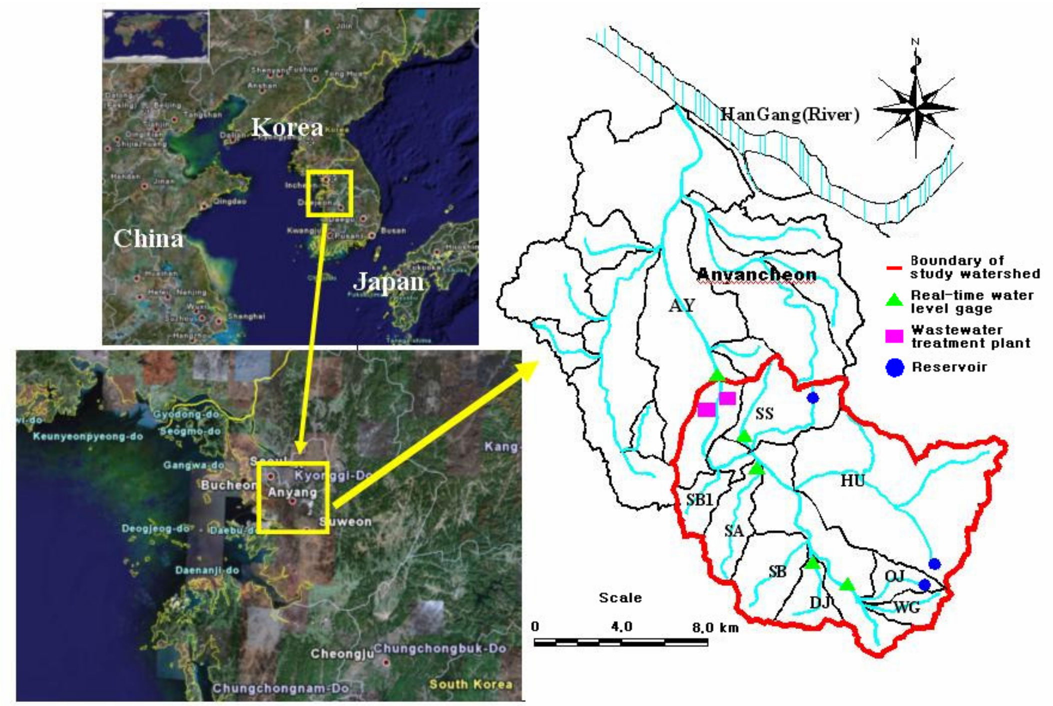
(a) Wanggok (WG) (b) Suam (SA)

Fig. 1. Examples of streamflow depletion: the WG and SA streams of the Anyangcheon watershed.


Korea
China
Japan
Anyang
Suweon
HanGang(River)
Anyancheon
AY
SS
SB1
SA
HU
SB
DJ
OJ
WG
Boundary of study watershed
Real-time water level gage
Wastewater treatment plant
Reservoir
Scale
0
4.0
8.0 km

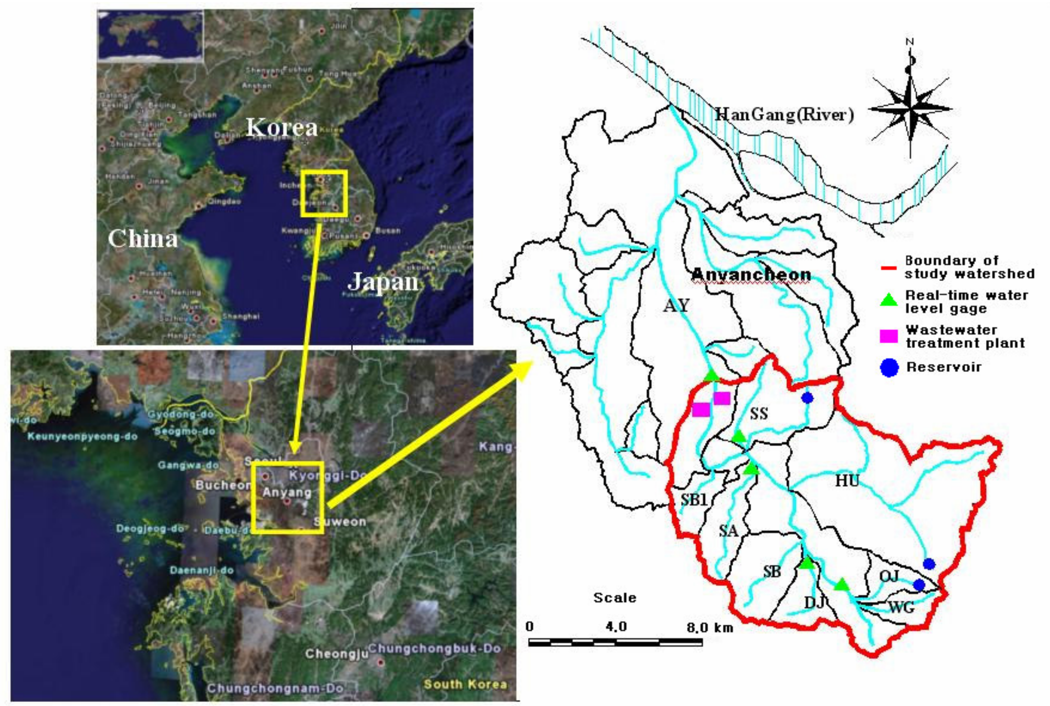
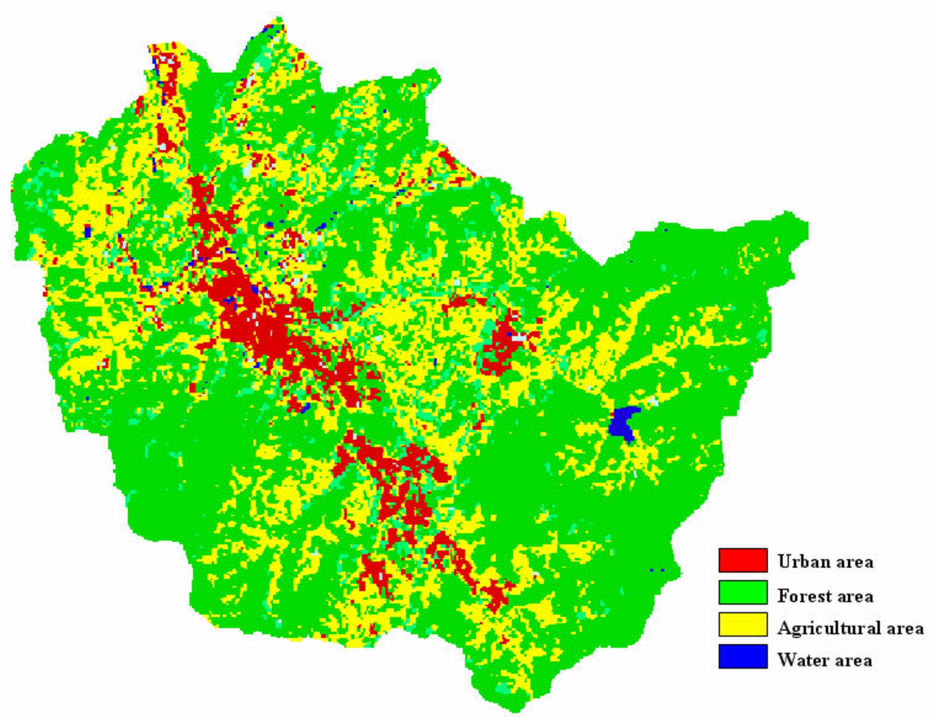
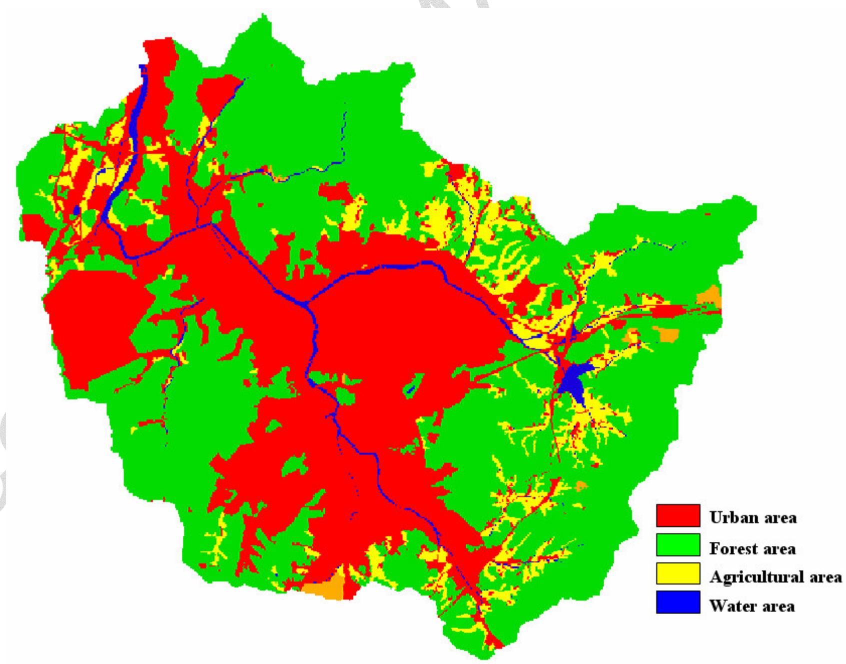


Fig. 2. Location of the Anyangcheon stream and its sub-watersheds

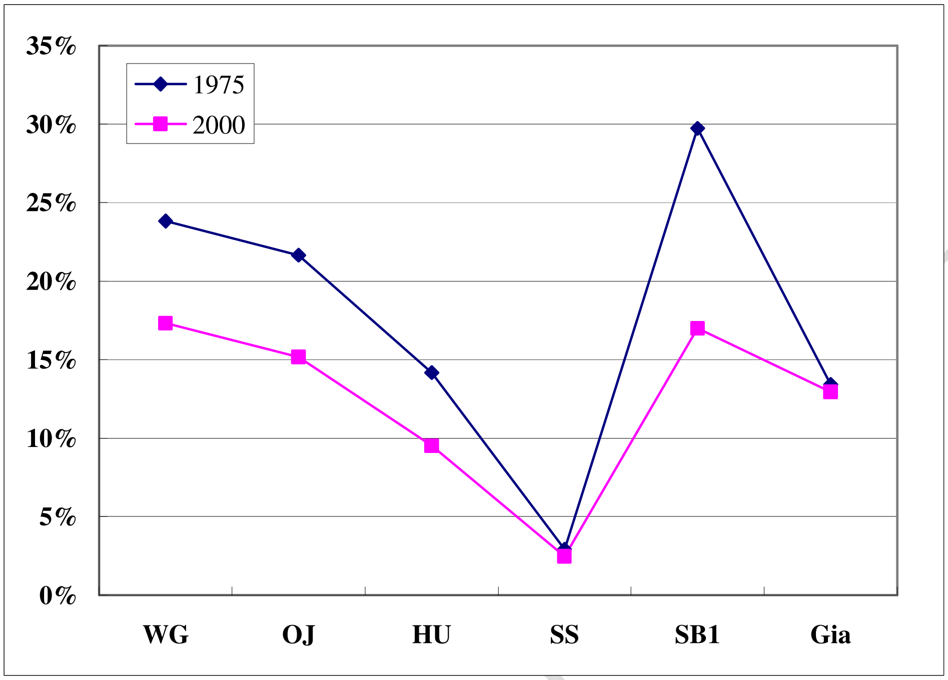


(a) 1975

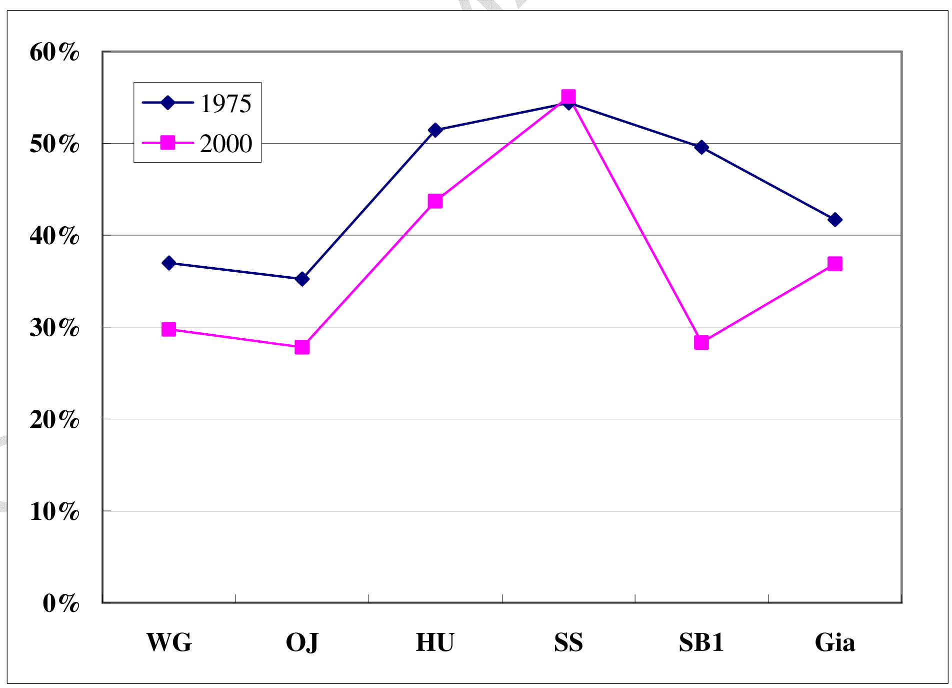


(b) 2000

Fig. 3. Land use changes between 1975 and 2000

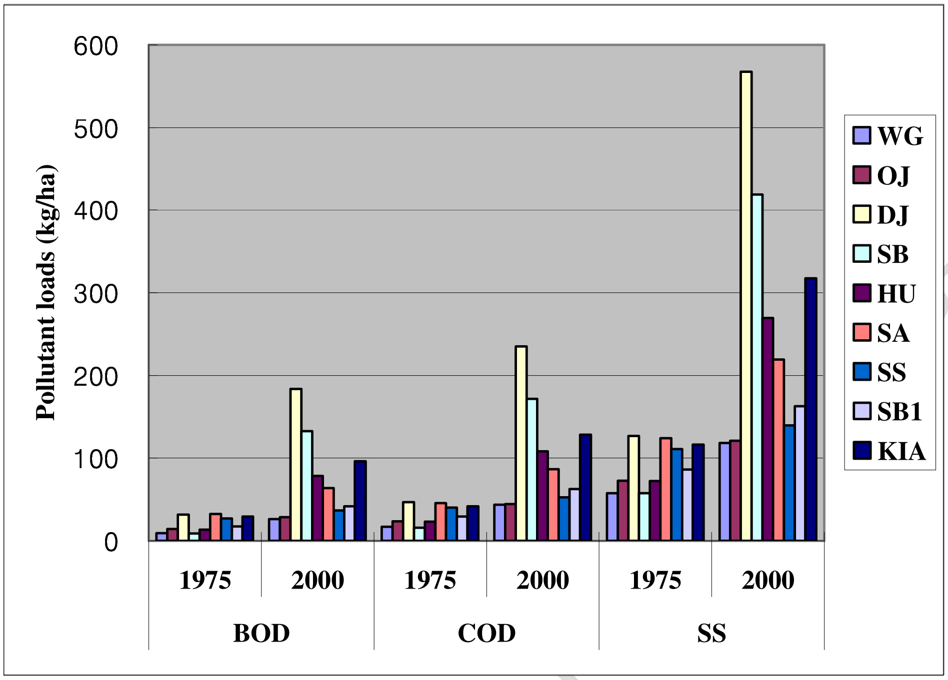


(a) Baseflow



(b) Total flow

Fig. Fig. 4. Hydrological simulation results for 5 AY sub-watersheds and entire study watershed (Giadagyo)



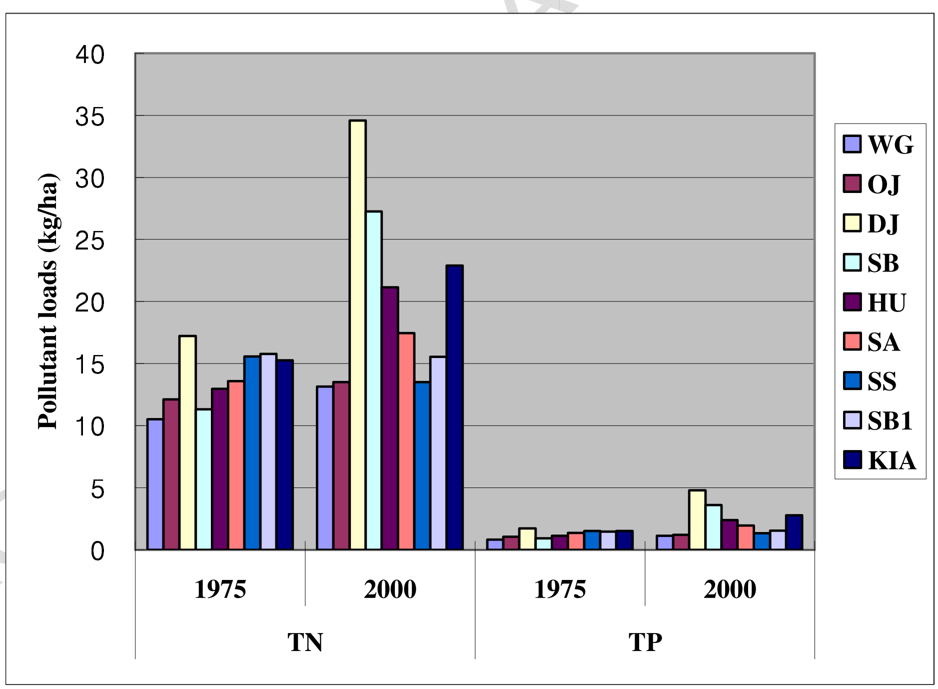
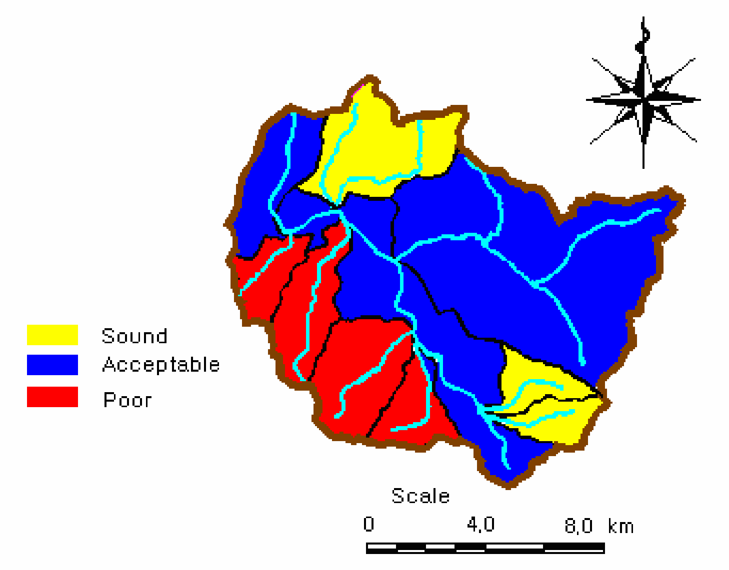
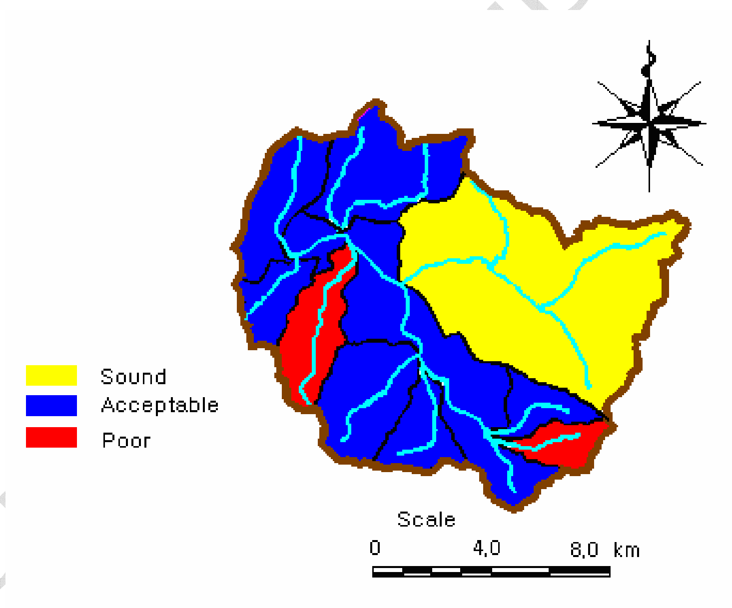


Fig. 5. Pollutant loads per unit area for the 8 AY sub-watersheds and the entire study watershed (Gia)


Sound
Acceptable
Poor
Scale
0
4,0
8,0 km

(a) PFD


Sound
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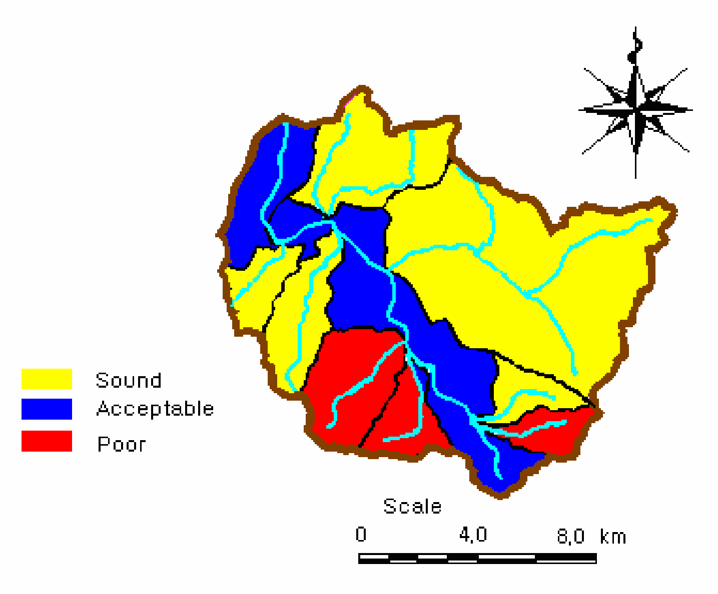
(b) PSD



(c) PWQD

Fig. 6. Spatial variation of PFD, PSD, and PWQD for the 8 AY sub-watersheds

(a) Carassius auratus

(b) Zacco platypus

(c) Rhynchocypris oxycephalus

Fig. 7. Target species for the AY watershed

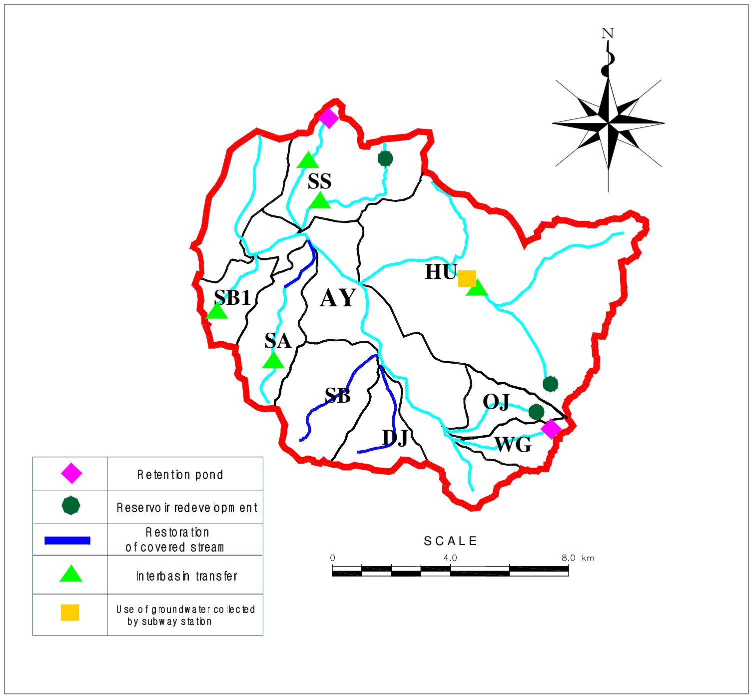


Fig. 8. A master plan from the pre-feasibility analysis for the 8 AY sub-watersheds

Table 1. Watershed characteristics of the 8 study sub-watersheds

Name of sub-atershed	Water-shed area (km^2)	Length of stream (km)	Slope	Elevation (EL. m)	Landuse (2000) (%)			Soil constituent (2000) (%)			Ground-water withdrawal (2000) (mm/year)
					Urban	Forest	Agri-cultural	Clay	Silt	Sand	
Study watershed	127.13	17.91	1/250	120	38.3	51.6	7.5	18.6	33.4	48.0	31.4
WG	3.78	3.82	1/50 ~ 1/60	180	6.96	81.51	9.43	16.8	25.2	58.0	84.5
OJ	4.26	2.85	1/30 ~ 1/60	163	7.65	77.48	11.38	16.0	25.6	58.4	70.1
DJ	5.35	4.02	1/270 1/140 ~ 1/180	70	57.09	27.73	11.21	18.0	32.4	49.6	16.2
SB	10.29	4.32	1/160	135	40.34	48.49	9.15	17.6	32.1	50.3	2.8
HU	44.58	9.26	1/410 1/140 ~ 1/160	127	22.82	57.47	15.7	16.5	32.9	50.6	44.8
SA	8.07	6.49	1/90 ~ 1/40	169	18.90	72.61	5.12	18.8	46.2	35.0	1.9
SS	13.17	5.74	1/120 1/20 ~ 1/50	203	7.88	83.21	8.16	11.8	34.2	54.0	4.4
SB1	4.59	2.76	1/60 ~ 1/100	97	11.52	68.91	11.48	18.7	37.1	44.2	18

Table 2. Components necessary for understanding the Anyangcheon watershedComponents	Descriptions
Physical features: bedrock geology, surficial geology and landforms	Physical features were obtained by ARCVIEW (v.3.2) using digital elevation maps of National Geographic Information Institute (NGII) of Ministry of Construction and Transportation of Korea.
Climate: temperature, evaporation, precipitation, wind, humidity	Climate data were obtained from the Suwon station of Korea Metrological Association. The distance between the Suwon and the study watershed is less than 10 km. Like other Korean watersheds, AY is dominated by the Asian Monsoon climate cycle, and thus shows strong seasonality: 69.1% of the total annual precipitation occurs during the flood season (June, July, August, and September) and 13.2% during the farming season (April and May). Only 17.7% occurs during the remaining 6 months of the year.
Soils and infiltration	A 1:25,000 soil map was obtained from National Institution of Agricultural Science of Ministry of Agriculture of KoreaKorea. Soil consist of 48.0 % sand, 33.4% silt, and 18.6% clay.
Streamflow: water level	Daily streamflow volumes were obtained from three real-time water-level stations where their rating curve developed previously are available.
Groundwater: groundwater level,	Groundwater withdrawal data were obtained from the Korea Water Resources Cooperation (1995-2004). Groundwater withdrawalsof WG, OJ,

groundwater withdrawal	and HU in2000 are 84.5, 70.1, and 44.8 (mm/year) which are 6.4%, 5.3%, and 3.4% of annual precipitation, respectively.
Water quality: BOD, COD, DO, TN, TP	Water quality data were gathered from Ministry of Environment of Korea as well as many field measurements. The water quality data in2005 are as follows: temperature 17 ℃, BOD 9.2 mg/L, DO 8.1 mg/L, COD 11.1 mg/L, SS 8.4 mg/L, TN 1.8 mg/L, TP 1.2 mg/L. Though the stream quality has been improved remarkably due to an remitting effort of government and citizens, compared with those of 1993 (temperature 19 ℃, BOD 30.2 mg/L, DO 4.2 mg/L, COD 30.2 mg/L, SS 27.5 mg/L, TN 10.5 mg/L, TP 1.1 mg/L), it is still far from the target for swimming of BOD(3 ppm of BOD).
Landuse: past and present status	Land use maps were obtained from NGII using ARCVIEW (v.3.2). The landuses of 1975 and 2000 were shown in Fig. 2. The urban area ratio has been increased by 30.5% from 1975 to 2000.
Plant and animal communities: species number and population	Lee et al. (2006) investigated what species of plant, fowl, fish, invertebrate animal are distributed and how many populations are in the study watershed.
Social and economic systems: population, flood damage	There have been 0.98 million residents in the study watershed.There was 39.1 billions dollars of flood damage in 1987 which is the largest during the last 20 years. The total damage of the last 20 years is 115.4 billions. The damages in the downstream watershed were the most serious and the total amounts were to 31 and 26 billions.
Valued features and activities	There have been some non-government organizationsand the interests of residents in the stream environment are very high. The committee consisting of the representatives from13 local governments was established in 1999 for the improvement of stream environment.

3 Weighting values ($\beta_{i,j}$) of PFD, PSD, and PWQD indices for the AY watershed

i \ *j*	1	2	3	4	5	6	7	8	9	10	11
1	0.4	0.3	0.2	0.1	0.1	0.4	0.1	0.4	0.6	0.2	0.2
2	1.0	0.1	0.4	0.3	0.2	0.2	0.4	0.2	0.2	-	-
3	1.0	0.15	0.15	0.1	0.05	0.05	0.2	0.1	0.2	0.8	0.2

* *i* = 1 for PFD, *i* = 2 for PSD, and *i* = 3 for PWQD

Table 4. Results of PFD, PSD, and PWQD for the 8 AY sun-watersheds

Name of sub-watershed	PFD	PSD	PWQD
WG	0.25	0.71	0.03
OJ	0.07	0.60	0.05
DJ	0.66	0.57	0.58
SB	0.64	0.55	0.45
HU	0.34	0.25	0.19
SA	0.61	0.73	0.13
SS	0.30	0.56	0.05
SB1	0.61	0.58	0.08
Study watershed	0.44	0.58	0.19
AY watershed	0.49	0.53	0.36

Table 5. The average low flow, the fish flow, and the resulting instreamflow requirement for the 8 AY sub-watersheds

Unit: cms

Name of sub-watershed	Average low flow	Fish flow						
		Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.
WG	0.074	0.6	0.6	0.9	0.9	0.9	0.9	0.9
OJ	0.079	0.5	0.5	0.9	0.9	0.9	1.2	1.2
DJ	0.090	0.5	0.5	0.9	0.9	0.9	1.2	1.2
SB	0.128	1.6	1.6	2.2	2.2	2.2	2.2	2.2
HU	0.288	1.2	1.2	1.8	1.8	1.8	1.8	1.8
SS	0.147	1.6	1.6	2.2	2.2	2.2	2.2	2.2
SA	0.112	1.6	1.6	2.2	2.2	2.2	2.2	2.2
SB1	0.082	0.6	0.6	0.9	0.9	0.9	0.9	0.9
Study watershed	0.511	3.0	-	-	1.0	1.0	3.0	3.0

Table 6. Habitat suitability criteria of target species

Species	Water depth (cm)			Velocity (cm/sec)		
	Spawning	Fry	Adult	Spawning	Fry	Adult
Carassius auratus	20 ~ 50 (May, Jun.)	10 ~ 40 (summer ~ autumn)	30 ~ 200 (spring ~ autumn)	5 ~ 10	10 ~ 20	20 ~ 30
Rhynchocypris oxycephalus	10 ~ 20 (Apr., May)	20 ~ 30 (summer ~ autumn)	30 ~ 50 (spring ~ autumn)	10 ~ 30	20 ~ 40	30 ~ 120
Zacco platypus	10 ~ 30 (Apr., May)	10 ~ 40 (summer ~ autumn)	10 ~ 70 (spring ~ autumn)	10 ~ 30	10 ~ 40	20 ~ 60

Table 7. Feasible management alternatives and their descriptions for the 8 AY sub-watersheds

Alternatives	Sub-watershed	Description	Name
Reservoir redevelopment	OJ	- Construction of sluice gate - Proper operation (discharge: 0.01 CMS from Oct. to May)	R1
	HU	- Proper operation (discharge: 0.1 CMS from Oct. to May)	R2
	SS	- Proper operation (discharge: 0.01 CMS from Oct. to May)	R3
New retention pond	DJ	- Capacity: 60,000 m^3 - Discharge: 0.01 CMS from Oct. to May	N1
	SB		N2
	WG		N3
	SS		N4
	SA		N5
	SB1		N6
Restoration of covered stream	DJ	- To remove roads and restore the stream - Covered length: 1.59 km - Construction of sewers	S1
	SB	- To remove roads and restore the stream - Covered length: 2.74 km - Construction of sewers	S2
	SA	- To remove roads and restore the stream - Covered length: 0.645 km - Construction of sewers	S3
Inter-basin transfer (reuse of WWTP effluent)	WG	- To transfer highly-treated wastewater of WWTP - Maximum quantity is 21,000 m^3/day but used quantity is dependent upon the actual operation result of WWTP	I1
	OJ		I2
	DJ		I3
	SB		I4
	HU		I5
	SS(1)		I6
	SS(2)		I7
	SA		I8
	SB1		I9
Use of groundwater collected by subway stations	HU	- To transfer groundwater collected by subway station into the stream - Average quantity: 3,720 m^3/day	U1

Table 8. Screening results from the pre-feasibility analysis for the 8 AY sub-watersheds

Name of Alternatives	Technical Feasibility	Economic Feasibility	Environmental Feasibility	Selection
R1	Yes	Yes	Yes	**Yes**
R2	Yes	Yes	Yes	**Yes**
R3	Yes	Yes	Yes	**Yes**
N1	No	Yes	Yes	No
N2	No	Yes	Yes	No
N3	Yes	Yes	Yes	**Yes**
N4	No	Yes	Yes	No
N5	Yes	Yes	Yes	**Yes**
N6	No	Yes	Yes	No
S1	Yes	Yes	Yes	**Yes**
S2	Yes	Yes	Yes	**Yes**
S3	Yes	Yes	Yes	**Yes**
I1	Yes	No	Yes	No
I2	Yes	No	Yes	No
I3	Yes	No	Yes	No
I4	Yes	No	Yes	No
I5	Yes	Yes	Yes	**Yes**
I6	Yes	Yes	Yes	**Yes**
I7	Yes	Yes	Yes	**Yes**
I8	Yes	Yes	Yes	**Yes**
I9	Yes	Yes	Yes	**Yes**
U1	Yes	Yes	Yes	**Yes**

Table 9. Effectiveness and ranks of the remaining feasible alternatives for the 8 AY watersheds

Name	Pressure	State	Response								Evaluation Index	Rank
	Population	PSD	Target Instream Flow (cms)	Drought Flow			Low Flow			Average Efficiency		
				Before (cms)	After (cms)	Efficiency	Before (cms)	After (cms)	Efficiency			
R1	0.179	0.60	0.009	0.010	0.011	1.3%	0.004	0.015	13.9%	7.6%	0.614	12
R2	0.203	0.25	0.196	0.060	0.157	33.7%	0.105	0.205	34.7%	34.2%	0.582	5
R3	0.096	0.56	0.090	0.000	0.007	4.8%	0.003	0.012	6.1%	5.4%	0.675	14
N3	0.052	0.71	0.009	0.001	0.011	13.5%	0.004	0.014	13.5%	13.5%	0.565	8
N5	0.179	0.73	0.090	0.000	0.006	5.4%	0.002	0.012	8.9%	7.1%	0.585	11
S1	0.471	0.57	0.013	0.000	0.000	0.0%	0.000	0.002	2.2%	1.1%	0.575	6
S2	0.379	0.55	0.026	0.000	0.001	0.8%	0.000	0.008	6.3%	3.5%	0.598	10
S3	0.179	0.73	0.018	0.000	0.002	1.8%	0.000	0.014	12.5%	7.1%	0.558	7
I5	0.203	0.25	0.196	0.060	0.139	27.4%	0.105	0.184	27.4%	27.4%	0.629	9
I6	0.096	0.56	0.090	0.000	0.040	27.2%	0.002	0.068	44.9%	36.1%	0.463	3
I7	0.096	0.56	0.090	0.000	0.029	19.7%	0.002	0.063	41.5%	30.6%	0.501	4
I8	0.179	0.73	0.018	0.002	0.046	39.3%	0.014	0.078	57.1%	48.2%	0.274	1
I9	0.148	0.58	0.010	0.009	0.026	20.7%	0.017	0.068	62.2%	41.5%	0.399	2
U1	0.203	0.25	0.196	0.060	0.123	21.9%	0.105	0.168	21.9%	21.9%	0.667	13