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Assessment of Integrated Watershed Health based on Natural Environment, Hydrology, Water Quality, and Aquatic Ecology

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Abstract

Watershed health, including the natural environment, hydrology, water quality, and aquatic ecology, was assessed for the Han River basin (34,148 km²) in South Korea using the Soil and Water Assessment Tool (SWAT). The evaluation procedures followed those of the Healthy Watersheds Assessment by the U.S. Environmental Protection Agency (EPA). To evaluate watershed health (basin natural capacity), 6 components of the watershed landscape were examined: stream geomorphology, hydrology, water quality, aquatic habitat condition, and biological condition. In particular, for the hydrology and water quality components, the SWAT was applied for the study basin with 237 sub-watersheds (within a standard watershed on the Korea Hydrologic Unit Map) and including three multipurpose dams, one hydroelectric dam, and three multifunction weirs. The SWAT was calibrated (2005–2009) and validated (2010–2014) using each dam and weir operation, the flux tower evapotranspiration, TDR soil moisture, and groundwater level data for the hydrology assessment and using sediment, total phosphorus, and total nitrogen data for the water quality assessment. The water balance considering the surface–groundwater interactions and the variation in stream water quality were quantified according to the sub-watershed-scale relationship between the watershed hydrologic cycle and stream water quality. We assessed the integrated watershed health according to the U.S. EPA evaluation process based on the vulnerability levels of the natural environment, water resources, water quality, and ecosystem components. The results suggest that approaches aimed at simultaneously improving the water quality, hydrology, and aquatic ecology conditions may be necessary to improve integrated watershed health.

Keywords: Watershed health assessment; SWAT; Watershed hydrology; Water quality; Aquatic ecology

1. Introduction

Watershed management can be defined as the integrated and iterative decision process applied to maintain the sustainability of resources through the balanced use and conservation of water quantity, land, vegetation, and other natural resources within the watershed. The river is a constituent element of the watershed ecosystem that is of primary concern for watershed management; the river discharge and water quality are key components of the watershed ecosystem, and their interactions can be affected by land use and vegetation cover. The Han River basin in South Korea, with its large-scale water supply dams and weirs, is a rare case worldwide. Twenty-six years ago, the government initiated programs designed to restore the environmental and human health-related quality of the Han River basin. However, an integrated approach considering water supply, water quality improvement, and natural ecosystem maintenance and their interactions within the watershed was lacking. It has become clear that a broader view of watershed ecosystems is essential if we are to truly protect the chemical, physical, and biological integrity of our watersheds (U.S. EPA, 2012).

One of the key components of watershed management strategies is to increase the protection of healthy waters, including healthy watersheds. A key component of watershed health is its ability to withstand, recover from, or adapt to disturbances, such as floods and droughts. A more complete understanding of the watershed ecosystem components affecting watershed health is important for identifying management actions to protect healthy watersheds. Without an integrated watershed health assessment system, the successes in restoring impaired waters will be limited and the many socioeconomic benefits of healthy watershed systems will be lost.

In general, the assessment of the major components of watershed health must incorporate evaluations of the natural environment, hydrology, water quality and aquatic ecology. A number of studies have recently assessed the potential for effective watershed management through an analysis of a variety of health indicators. Sanchez et al. (2015) characterized the relationships between in-stream health indicators (flow, sediment, and nutrient loads) using the Soil and Water Assessment Tool (SWAT) model and socioeconomic measures of communities using spatial clustering techniques and confirmatory factor analysis in the Saginaw River watershed in Michigan. Cook et al. (2015) explored the effects of both water quality and habitat on benthic macroinvertebrates using the data from a three-year field study and Virginia Stream Condition Index (VSCI) scores to evaluate site-specific environmental variables (land use, habitat metrics, water quality parameters), examining these relationships in five watersheds along the Virginia–Kentucky border. Tango and Batiuk (2016) analyzed interactions affecting the watershed and bay water quality recovery responses to management actions and a range of health conditions and impairments by measuring the physical, chemical and biological parameters in Chesapeake Bay.

The U.S. EPA has made considerable efforts to move towards integrated evaluations of watershed health. For example, The Virginia Watershed Integrity Model uses an integrated approach to evaluate the landscape condition and terrestrial habitat to identify ecologically important catchments across the landscape (Virginia Department of Conservation and Recreation, 2008). Minnesota's Watershed Assessment Tool used hydrology, geomorphology, biology, connectivity, and water quality data in an integrated context to evaluate the health of Minnesota's watersheds (Minnesota Department of Natural Resources, 2011). The Oregon Watershed Assessment addressed landscape, habitat, biology, water quality, hydrology, and geomorphology through field assessments and follow-up analyses based on a classification and condition assessment of channel habitat types (Watershed Professionals Network, 1999). The California Watershed Assessment Manual evaluated the six essential ecological attributes of landscape status: hydrology/geomorphology, biotic condition, chemical/physical condition, natural disturbance regimes, and ecological condition (Shilling, 2007).

Regional water quantity and quality can be assessed by systematic modeling using the hydrologic model SWAT (Arnold et al., 1998) because of its robust approach based on the soil water balance at the watershed scale. The SWAT model has been successfully applied to a number of river basins and is widely used to study the long-term impacts of hydrological (e.g., Sun and Cornish 2005; Wan et al., 2013; Ahn et al., 2016; Karlsson et al., 2016; Sellami et al., 2016; Chung et al., 2017) and environmental changes (e.g., Eckhardt and Ulbrich, 2003; Rosenberg et al., 2003; Bouraoui et al., 2004; Chaplot, 2007; Mehdi et al., 2015; Zhou and Li, 2015). Thus, the use of this qualified watershed model is highly useful for assessments of continuous time-series changes and spatial distributions changes in watershed information.

However, most previous studies have employed a fragmentary approach to investigating one or several environmental issues using monitoring data for a limited period without assessing the various components (e.g., landscape, stream channels, hydrology, water quality, habitat, biological diversity, etc.). Thus, the methodology suggested in this study is essential to explore the integrated influence of large-scale watersheds with various watershed characteristics and to assess the overall health of watersheds.

Therefore, the main objective of this study is to conduct a watershed health assessment analysis of the natural environment, hydrology, water quality, and aquatic ecology of the Han River basin (34,148 km²) in South Korea using monitoring data and SWAT modeling output. Detailed information regarding the framework is presented below.

2. Materials and methods

2.1 Methodology for watershed health assessment

The foundation of watershed health assessment is the compilation and summarization of watershed parameters based on the primary physical attributes of watershed conditions. According to the United States Environmental Protection Agency (U.S. EPA, 2012), there are six essential indicators fundamental to the assessment of watershed health: 1) landscape condition, 2) geomorphology, 3) hydrology, 4) water quality, 5) habitat, and 6) biological condition. A sub-index for each of the six components is developed from these indicators. The sub-index values are then aggregated into a single Watershed Health Index value for each watershed. This methodology can be used to assess the natural capacity of a watershed and its problems and to draft possible solutions for effective watershed management. All sub-index and index values are relative (i.e., "healthier" vs. "not as healthy") rather than absolute (i.e., no "healthy vs. unhealthy" cutoff score is identified) and thus are meant for comparing the relative differences among watersheds rather than precisely defining healthy vs. unhealthy watersheds.

In this study, the indicators for watershed health assessment are selected based on the six essential components and methodology suggested by the U.S. EPA. All of the indicators for watershed health are evaluated to match the situation in South Korea using measurable data or watershed modeling results. In particular, the methodology is developed to assess the effects of hydrology and water quality on watershed health to analyze the possible long-term changes in the watershed as simulated through a watershed-scale hydrological model, the SWAT. According to existing research that has assessed the long-term changes in the Han River basin, the changes in runoff due to climate change in Han River basin is expected to cause many changes to the future seasonal water volume, and water scarcity is predicted to increase in the long term (Jun et al., 2011; Kim et al., 2014). Urban land cover in the Han River basin is positively associated with increases in water pollution, which has increased for the majority of the monitoring stations (Chang, 2008). Healthy areas can be identified based on standard watersheds from Korea Hydrologic Unit Map. The Korea Hydrologic Unit Map is a standard map that combines data from national organizations for water resource development, planning, and management. The standard watersheds are the smallest hydrologic unit designated by the Korean government. Figure 1 shows a flowchart of the modeling procedures. The specific objectives of this study are as follows:

- To develop a method for reconstructing water quantity and quality time-series data of the basin using the SWAT model. The reconstructed time-series are used as water quantity and quality indicators and for sub-index development. Because watershed health assessment relies on the continuous flow of time-series information, the SWAT model was established and calibrated to obtain flow records at ungauged hydrology and water quality stations.
- To establish a reference condition for each indicator to assess the sub-index through normalization of the following components: landscape condition, geomorphology, hydrology, water quality, habitat, and biological condition.
- To assign integrated watershed health scores combining multiple indicators representing different attributes of healthy watersheds based on a standard watershed on the Korea Hydrologic Unit Map.

<Figure 1>

2.2 Study area description

The Han River basin (34,148 km²) is one of the five major river basins in South Korea (99,720 km²); it occupies approximately 31% of the country and falls within the latitude-longitude range of 36.03° N to 38.55° N and 126.24° E to 129.02° E, respectively (Figure 2). The basin has three main rivers, the North Han River (12,969 km²), the South Han River (12,894 km²), and the Imjin River (8,285 km²). The North Han River and South River merge and then flow into the metropolitan city of Seoul, a city of 10 million residents. The water resources of the river basin must be managed sustainably due to the expanding water demand of the Seoul area, including its satellite cities (12 million individuals), and the potential changes to water resources due to climate change must be evaluated (Ahn and Kim, 2016). The dominant land use of the Han River basin is forest (73%, 25,033 km²), followed by cultivated cropland in the lowland fertile areas (5,915 km²), including rice paddy fields (6%) and upland crops (12%) (Figure 2b). Over the 30 years of weather data from 1985 to 2014, the average annual precipitation is 1,395 mm and the annual mean temperature is 11.5 °C. Figure 2a shows the study area and the 237 sub-watersheds (within a standard watershed on the Korea Hydrologic Unit Map) delineated for the SWAT modeling and watershed health assessment, and Figure 2c shows the four test areas for comparison of the watershed health index scores.

<Figure 2>

2.3 Data collection

A summary of datasets and associated organization sources, metrics, and measurement methods used in the assessment is provided in Table 1. These data were used to calculate the health assessment components for each of the six watersheds.

For the landscape, stream geomorphology and aquatic habitat assessment, Geographic Information System (GIS) datasets were used. The elevation data used the 90 m grid size Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) supplied by the International Center for Tropical Agriculture (CIAT). The land cover map for nine classes of land cover (coniferous forest, deciduous forest, mixed forest, paddy rice, upland crop, urban, grassland, bare field, and water) for 2008 was obtained from the Korea Ministry of Environment (KME). The stream map for national and local streams was obtained from the Ministry of Land, Infrastructure, and Transport (MOLIT) of South Korea. The information on the location and number reservoirs for the Han River basin was obtained from the Korea Rural Community Corporation (KRC).

For the hydrology and water quality assessments, the SWAT modeling outputs for a total of 237 sub-watersheds for the Han River basin, including ungauged locations, were used. The monitoring data for hydrology include only streamflow and do not include data for the water balance components associated with the surface–groundwater interaction. The monitoring data for water quality are not exhaustive. The period of the water quality components of interest for this study, such as sediments, total nitrogen (T-N) and total phosphorus (T-P), is not sufficient to analyze long-term changes. The daily continuous record of precipitation (PREC), total runoff (TQ), surface runoff (SQ), infiltration (INFILT), soil water storage (SW), lateral flow (LQ), percolation (PERCOL), groundwater recharge (RECHARGE), and return flow (GWQ) data for the hydrology metric and sediment, T-N, and T-P for the water quality metric were obtained from SWAT modeling for a thirty-year period (1985–2014).

For the biological assessment, the monitoring data were obtained from the Korea Ministry of Environment (KME) in South Korea which has been monitoring river ecological data for 360 monitoring stations in the Han River and its tributaries since 2008. Samples of trophic diatom communities (339 species), benthic macroinvertebrate communities (344 species), and fish communities (394 species) were collected from the monitoring stations in September and October of each year during the six years (2008–2013) and the Trophic Diatom Index (TDI), Benthic

Macroinvertebrate Index (BMI), and Fish Assessment Index (FAI) were calculated and classified by ranking the arithmetic means. Details of the data collection and calculation procedures are provided in the Nationwide Aquatic Ecological Monitoring Program Report (Ministry of Environment, 2013).

<Table 1>

2.4 Hydrology and water quality simulations using the SWAT model

The SWAT model is a physically based, continuous, long-term, distributed parameter model designed to predict the effects of land management practices on hydrology and water quality in agricultural watersheds under varying soil, land use, and management conditions (Arnold et al., 1998). The SWAT model is based on the concept of hydrologic response units (HRUs), which are portions of a sub-basin with unique land use, management, and soil attributes. The runoff, sediment, and nutrient loadings from each HRU are calculated separately based on weather, soil properties, topography, vegetation, and land management and are then summed to determine the total loading from the sub-basin (Neitsch et al., 2002). A detailed description can be found in the Soil and Water Assessment Tool user’s manual and theoretical documentation (Neitsch et al., 2005).

The watershed health assessment requires the indicator data for hydrology and water quality to be simulated by the SWAT model, and the detailed component selection is presented in Sections 2.5.3 and 2.5.4. This section briefly summarizes the model data and implementation and the statistical results of calibration and validation.

2.4.1 Measured data for the SWAT model evaluation

The Han River Basin was divided into 237 sub-watersheds and 1,987 HRUs for SWAT modeling. The sub-watershed delineation was defined using the 90 m SRTM DEM supplied by the CIAT. A 2008 land cover map for nine classes (coniferous forest, deciduous forest, mixed forest, paddy rice, upland crop, urban, grassland, bare field, and water) were obtained from KME (Figure 2b). A soil map containing texture, depth and drainage attributes was rasterized to a 90 m grid size from a 1:25,000 scale vector map supplied by the Korea Rural Development Administration (RDA)

In this study, three multipurpose dams (Hoengseong, Soyang, and Chungju), one hydroelectric dam (Paldang), and three multifunction weirs (Kangcheon, Yeoju and Ipo) were selected as SWAT model calibration points (Figure 2a).

The Hoengseong Dam (HSD) and Chungju Dam (CJD), located in the upstream region of the South Han River basin, have storage capacities of 87 million m^3 and 2.8 billion m^3, respectively. Its storage capacity makes CJD the second largest dam in South Korea. The Soyang Dam (SYD), located upstream in the North Han River basin, has a storage capacity of 2.9 billion m^3, making it the largest dam in South Korea. The Kangcheon weir (KCW), Yeoju weir (YJW) and Ipo weir (IPW) were constructed by the government in 2012 to secure water resources and prevent flooding. These weirs are directly linked to the Paldang Dam (PDD), which can supply more than 2.6 million m^3 of water per day to Seoul and its metropolitan areas and has a storage capacity of 244 million m^3. The observation data were prepared to evaluate the SWAT model and simulate of the hydrological cycle and water quality including daily meteorological data, dam inflow, dam outflow, dam storage, evapotranspiration, soil moisture, sediments, T-N, and T-P. Thirty-one years (1984–2014) of daily meteorological data (precipitation, maximum and minimum temperature, relative humidity, wind speed, and solar radiation) were collected from nineteen weather stations of the KMA. For the calibration and validation of the watershed hydrology with dam operations, ten years (2005–2014) of daily dam inflow, outflow and storage volume data for the multipurpose dams were obtained from three water level stations (HSD, SYD and CJD) monitored by the Korea Water Resources Corporation and one water level station (PDD) monitored by the Korea Hydro & Nuclear Power Co., Ltd. In addition, two years (2013–2014) of daily measured dam inflow, outflow and storage volume data for the three multifunction weirs (KCW, YJW and IPW) monitored by the Korea Water Resources Corporation were used. For the calibration and validation of stream water quality, ten years (2005–2014) of eight-day intervals for sediments, T-N, and T-P data were obtained from seven stations (SG, CSG, JW, KCW, YJW, IPW, and PDD) for the hydrology monitored by the KME. Figure 2a shows the gauging stations for the SWAT modeling.

2.4.2 Calibration and validation of the model

The SWAT model was calibrated at seven locations in the main river reaches using five years (2005–2009) of daily inflow, storage volume data for the dams and weirs, sediments, T-N, and T-P data and was subsequently validated using another five years (2010–2014) of data using the average calibrated parameters. In addition, the model was spatially calibrated and validated using evapotranspiration and soil moisture data measured at two locations (SM and CM) and groundwater level data measured at five locations (GPGP, YPGG, YPYD, YIMP, and HCGD) over five years (2009–2013). The parameters were calibrated by trial and error until they achieved the necessary modeling performance. The calibrated parameters and hydrograph of the calibration results in the Han River basin were described by Chung et al (2017).

The statistical results for hydrology and water quality for the model calibration and validation are summarized in Table 2. The coefficient of determination (R^2), the Nash and Sutcliffe model efficiency (NSE), the root-mean-square error (RMSE), and the percent bias (PBIAS) were used to evaluate the ability of the SWAT model to replicate temporal trends in the observed hydrological and water quality data. In the case of dam inflow, the R^2 value was greater than 0.59. The average NSE was 0.59 at HSD, 0.78 at SYD, 0.61 at CJD, 0.79 at KCW, 0.77 at YJW, 0.88 at IPW, and 0.87 at PDD. The PBIAS values of HSD, CJD, SYD, KCW, YJW, IPW and PDD were 13.5%, 12.2%, 9.4%, 11.5%, 19.8%, 21.4%, and 4.5%, respectively. In the case of the dam storage volume, the average R^2 was between 0.40 and 0.96 and the PBIAS was between 0.9% and 18.9% for each calibration point. The average R^2 for evapotranspiration was between 0.70 and 0.81, the soil moisture was between 0.75 and 0.85, and the groundwater level was between 0.40 and 0.70 for each calibration point. The average R^2 for the sediment was between 0.54 and 0.90, T-N was between 0.46and 0.82, and T-P was between 0.47 and 0.80 for each calibration point. The calibration results were consistent with the SWAT calibration guidelines (NSE≥0.5, PBIAS≤28%, and $R^2 \geq 0.6$, Moriasi et al., 2007; Santhi et al., 2001) and were found to be satisfactory.

<Table 2>

2.5 Data reconstruction for watershed health assessment

2.5.1 Landscape condition

The area of natural land cover (forest, wetland, river, and natural grassland) within a watershed can be an important indicator of watershed health. Impervious land cover associated with roads and residential and urban areas can increase watershed runoff, leading to instream flow alteration, geomorphic instability, and increased pollutant loading. According to previous studies, a smaller area of impervious land cover may have significant impacts on aquatic ecosystem health (e.g., King et al., 2011; Wang and Yin, 1997).

The extent and connectivity of the natural land cover within a watershed are very important for ecological integrity. Natural land cover within the watershed, and especially within headwater areas and riparian corridors, helps to maintain the hydrologic regime, regulates inputs of nutrients and organic matter, and provides habitat for fish and wildlife (U.S. EPA, 2012). In the present study, assessing the connectivity of the natural land cover (forest, wetland, river, and natural grassland) of watersheds involved a green area assessment; green areas comprise areas of unfragmented natural land cover and corridors of sufficient width to allow the migration of wildlife between the watersheds (Figure 3a). For the 237 sub-watersheds of Han River basin, the percentage of each watershed area occupied by natural land cover (habitat blocks) was calculated using GIS techniques. The green area metric was calculated as follows:

$$Green\,area\,metric = \frac{Area\,(km^2)\,of\,natural\,land\,cover\,in\,watershed}{Total\,area\,(km^2)\,in\,watershed} \qquad (1)$$

The amount of natural land cover within the active river area is another important indicator of the landscape condition. The natural land cover within the active river area, including the river channel, lakes and ponds, and the riparian lands, is necessary for the physical and ecological functioning of the aquatic ecosystem (U.S. EPA, 2012). Active river areas, in their natural state, maintain the ecological integrity of rivers, streams, and riparian areas and the connection of those areas to the local ground water system (IPCC, 2007). The methods used to delineate the active river area involve GIS techniques and analyses of elevation, land cover, and wetlands data. For the streamside areas not yet decided the criteria for identifying, an area with a width of 30–50 meters can be used as a cutoff for identifying streamside material contribution areas (US. EPA, 2012). In this study, for the 237 sub-watersheds of Han River basin, the percentage of natural land cover within the riparian area within 50 meters of stream was calculated for each watershed using GIS techniques (Figure 3b). The active river area metric was calculated as follows:

$$Active\,river\,area\,metric = \frac{Area(km^2)\,of\,natural\,land\,cover\,in\,active\,river\,area}{Total\,area\,(km^2)\,in\,active\,river\,area} \qquad (2)$$

<Figure 3>

2.5.2 Stream geomorphic condition

The natural stream geomorphology can be an important indicator of watershed health because it can fragment both the terrestrial and aquatic habitats throughout a watershed. Kline et al. (2009) performed detailed assessments of stream geomorphic conditions using the Vermont Stream Geomorphic Assessment Protocols for the streams of

Vermont, USA. The assessment protocols are GIS-based analyses using elevation, land cover, and stream network data layers to classify stream types and evaluate the conditions of individual reaches based on a comparison to reference conditions for that stream type.

Table 3 provides descriptions of the stream geomorphic condition categories that are determined through the stream impact rating and the stream order for the watershed health assessment of the geomorphic condition in the Han River basin. In this study, the assessment of geomorphic condition was performed in a manner similar to that used for the stream condition categories of the Vermont Stream Geomorphic Assessment Protocols. The stream order was calculated for nine levels (Figure 4a) using a DEM and stream map, and four river classifications were created through follow-up with detailed land cover assessments (Figure 4b). There are four river classifications for reference (mountainous river, stream order 1), good (small river, stream orders 2–3), fair (local river, stream orders 4–5), and poor (urban and national river, stream orders 6–9). The percentage of the assessed stream length in the reference condition was calculated for each watershed. The stream geomorphology metric was calculated as follows:

$$Stream\,geomorphology\,metric = \frac{Stream\,length\,(km)\,of\,reference\,condition\,in\,watershed}{Total\,stream\,length(km)\,in\,watershed} \qquad (3)$$

<Figure 4>

<Table 3>

2.5.3 Hydrologic condition

The assessment of the hydrologic condition of a watershed requires long-term streamflow observation data for the 237 sub-watersheds of Han River basin. However, there were not enough gauging stations to fully assess the entire watershed over the full thirty-year period. There were no data for the water balance components associated with the surface–groundwater interaction, except for streamflow. Where long-term flow data are not available, they can be estimated using hydrologic modeling techniques. To this end, the SWAT hydrologic model was used to simulate the water balance components within the Han River basin.

To simulate the potentially available water quantity of the basin, the model was applied by dividing the basin into 237 sub-watersheds considering the water resources facilities operation (inflow and storage volume) of three multipurpose dams, one hydroelectric dam, and three multifunction weirs. The SWAT simulation outputs—including

PREC and TQ for the total processes; SQ for the surface processes; INFILT, SW, and LQ for the soil water dynamics; and PERCOL, RECHARGE, and GWQ for the groundwater dynamics—of each of the 237 sub-watersheds were reported. All the results of the SWAT model were output in mm.

The annual average water balance components at the surface, in the unsaturated zone, and in a shallow aquifer can serve as indicators of potential hydrologic alteration. The surface water and lateral groundwater flow interactions were of major importance for the water balance in the Han River basin. In particular, infiltration, return flow, and groundwater recharge were important factors for the whole hydrological cycle. In this study, the SWAT model results were used to reconstruct daily time-series for the hydrologic components PREC, TQ, SQ, INFILT, SW, LQ, PERCOL, RECHARGE, and GWQ for a thirty-year period (1985–2014) (Figure 5). The annual average value for the total of the 237 sub-watersheds during this period was used as the reference condition (Table 4). Dividing the simulated value of the watershed by the reference condition yields the storage ratio of the nine components. The storage ratios of the nine components were divided into four hydrologic classifications—total metric (PREC and TQ), surface processes metric (SQ), soil water dynamics metric (INFILT, SW, and LQ), and groundwater dynamics metric (PERCOL, RECHARGE, and GWQ)—for use in establishing specific management objectives. The storage ratio of each component for the four hydrology metrics was calculated for each watershed and used as a metric of the hydrologic condition. The hydrology metric was calculated as follows:

$$Hydrology\ metric = \frac{Simulated\ value\ (mm)\ (PREC, TQ, SQ, INFILT, SW, LQ, PERCOL, RECHARGE, and\ GWQ)\ of\ watershed}{Average\ value\ (mm)\ for\ all\ watersheds\ in\ basin} \qquad (4)$$

<Figure 5>

2.5.4 Water quality condition

The assessment of the water quality of the watershed also requires long-term observational data from the 237 sub-watersheds of the Han River basin. However, the monitoring data for water quality are not exhaustive and not sufficient to analyze long-term changes. In this study, the SWAT model was used to simulate the water quality sediment loads (tons), T-N (kg) and the T-P (kg) within the Han River basin.

The SWAT model results were used to reconstruct load-based daily time-series for the water quality constituents sediment (mg/L), T-N (mg/L), and T-P (mg/L) for a thirty-year period (1985–2014) (Figure 6). As part of the Basic

Environmental Policy Act (BEPA), South Korea has specified ecoregional water quality criteria for identifying the least-disturbed sites throughout South Korea. These criteria were used to identify the streams and lakes that are likely to be in the reference condition based on their sediment, T-N, and T-P concentrations. The "marginally good" level of a seven-point scale (excellent, very good, good, marginally good, fair, poor, very poor) of water quality criteria for streams and lakes was used for the reference condition (Table 4). The percentage of the assessed value in the reference condition was calculated for each watershed. The water quality metric was calculated as follows:

$$Water\ quality\ metric = \frac{Simulated\ value\ (mg/L)\ (sediment,\ \text{T-N, and T-P})\ of\ watershed}{Reference\ value\ (mg/L)\ in\ watershed} \qquad (5)$$

<Figure 6>

2.5.5 Aquatic habitat condition

The quality of aquatic habitat is dependent on the surrounding landscape and the hydrologic and geomorphic processes. Therefore, habitat condition is partly accounted for through indicators representing those assessment components. The potential for organisms to migrate upstream and downstream within a riverine system can also serve as an indicator of aquatic habitat condition. Lakeshores also have riparian zones that serve as a source of organic material to the lake aquatic habitat and help stabilize the lake perimeter (U.S. EPA, 2012). EPA's National Lakes Assessment (NLA) identified poor lakeshore habitat as the most prominent stressor to the biological health of lakes (U.S. EPA, 2009). The density of reservoirs per stream length was calculated and used as an indicator of aquatic habitat connectivity (Figure 7a). The aquatic habitat connectivity metric was calculated as follows:

$$Aquatic\ habitat\ connectivity\ metric = \frac{Number\ of\ reservoirs\ in\ watershed}{Total\ stream\ length\ (km)\ in\ watershed} \qquad (6)$$

Intact wetlands help to maintain natural hydrologic regimes, provide important habitat for fish and wildlife, and regulate water quality. The percentage of the watershed occupied by wetlands was calculated and used as an additional indicator of habitat condition for each watershed (Figure 7b). The wetland metric was calculated as follows:

$$Wetland\ metric = \frac{Area\ (km^2)\ of\ wetlands\ in\ watershed}{Total\ area\ (km^2)\ in\ watershed} \qquad (7)$$

<Figure 7>

2.5.6 Biological condition

Based on the understanding that aquatic ecological environmental degradation is one of the leading causes of stream impairment, the Ministry of Environment of South Korea began collecting variables of biological community diversity as part of its Nationwide Aquatic Ecological Monitoring Program for a six-year period (2008–2013). Based on a statistical evaluation of these data, three biological indicators (TDI, BMI, and FAI) were chosen to identify healthy instream conditions for the Han River basin. In the Han River basin, the TDI, BMI, and FAI were developed from epilithic diatoms, benthic macroinvertebrates, and fish assessments for estimating the overall biological condition during the six years (2008–2013); these data can be used to identify healthy instream conditions in the context of aquatic ecosystem health. Healthy watersheds should have TDI, BMI, and FAI scores close to the reference conditions. According to the Nationwide Aquatic Ecological Monitoring Program Report (Ministry of Environment, 2013), the indices with a range from 0 to 100 were classified on a four-point scale of best, good, fair, and poor for the biological condition criteria, and the best and good levels were used as the reference condition (Table 3). The percentage of the assessed scores on the TDI, BMI, and FAI in the reference condition was calculated for each watershed (Figure 8). The biological condition metric was calculated as follows:

$$Biological\ condition\ metric = \frac{Observed\ value\ (TDI, BMI, and\ FAI)\ of\ watershed}{Reference\ value\ for\ watershed} \qquad (8)$$

<Figure 8>

2.6 Watershed health index formulation

The definition of the watershed health index is presented by the U.S. EPA for integrated watershed health evaluations. Watershed health was evaluated by normalizing the metric scores to integrate the data on multiple healthy watershed attributes into a composite score. Normalization was conducted by simply defining a reference value for the indicator score that is considered healthy based on percentile rank. For communication purposes, the indicator score was scaled to normalize the final sub-index and watershed health index scores to range from 0 to 1. Table 4 shows the definition of the "healthy" reference value for the hydrology, water quality, and biological indicators. The indicator scores must also be directionally aligned, meaning that higher scores should equate to "better" conditions for each metric. For metrics that are not directionally aligned in their original units (e.g., water quality components), the inverse (1/X) of each value can be taken.

A composite index of watershed health was constructed by averaging the normalized indicator scores for each attribute. For attributes with more than one indicator, a sub-index was first calculated. The sub-indices were then averaged to obtain the integrated watershed health index score (U.S. EPA, 2012). Depending on the specific management objectives, it may be appropriate to place more weight on some ecological attributes than on others and to use optional sub-indexes. At that point, the process becomes subjective and a logical decision framework can be used to solicit and document expert opinion (Smith et al., 2003). Weighting was not used in this study for integrated assessment. The normalized metrics, sub-index, and integrated watershed health index were calculated as follows:

$$Normalized\ metric\ value = \frac{Observed\ or\ simulated\ metric\ for\ watershed\ x}{Reference\ metric\ value\ for\ all\ watersheds\ in\ basin} \qquad (9)$$

$$Sub\text{-}index = \frac{(Normailzed\ metric\ 1 + Normalized\ metric\ 2 + \cdots + Normalized\ metric\ x)}{Total\ number\ of\ metrics} \qquad (10)$$

$$Watershed\ health\ index = \frac{(sub\text{-}index1 + sub\text{-}index2 + \cdots + sub\text{-}indexx)}{Total\ number\ of\ sub\text{-}indices} \qquad (11)$$

<Table 4>

3. Results and discussion

3.1 Watershed health by each component in the Han River basin

Using the data reconstruction results for the six components of landscape, stream geomorphology, hydrology, water quality, aquatic habitat condition, and biological condition, the watershed health analysis for each component was conducted in 237 sub-watersheds as standard watersheds of the Han River basin. The sampling areas used to explain the differences in watershed health results for each component were standard watersheds 101206 (urban 1.4% and forest 88.1%), 100201 (urban 0.8% and forest 88.2%) and 101801 (urban 9.8% and forest 5%) (Figure 2a). The 101206, 100201, and 101801 standard watersheds are located in the upstream region of the Soyang Dam (SYD), in the upstream region of the Chungju Dam (CJD), and in the downstream region of the Paldang Dam (PDD), respectively.

Figure 3 shows the landscape condition for green area (Figure 3a) and active river area (Figure 3b) indicators in the Han River basin. Figure 12a shows the sub-index score for the watershed health assessment calculated according to these two assessment indicators. The spatial patterns of watershed health for green areas were healthier for upstream watersheds because the farther the watersheds are from the urban area, the greater in the increase in natural land cover. The spatial patterns of watershed health for the active river area within 50 m of a stream were healthier for the upstream watersheds for the same reason. For the 101206 standard watershed, the normalized values of the green area and the active river area were 0.93 and 0.82, respectively, and the sub-index score of 0.89, which integrated the two normalized values, indicated a very healthy watershed. For the 100201 standard watershed, the normalized values of the green area and the active river area were 0.78 and 0.57, respectively, and the sub-index score of .0.66, which integrates the two normalized values, indicates a less healthy watershed. In contrast, the 101801 standard watershed was revealed to be in very poor health, with a score of 0.17 for the sub-index, while the normalized values of the green area and active river area were 0.25 and 0.09, respectively. Hence, the study found that the downstream reaches of the Han River basin are in greater need of green areas and active river areas compared to the upstream.

Figure 4 shows the stream geomorphology condition in the Han River basin. Figure 12b shows the sub-index score for the watershed health assessment calculated using stream geomorphology indicators. The percentage of the length of the assessed stream channel in reference condition was greater for the upstream watershed than the downstream watershed. The high-gradient mountainous streams in the upstream watershed are characterized by relatively clean streams that have not been subject to land cover modifications and river improvement work.

Figure 5 shows the SWAT model results for use in assessing the condition of hydrologic components PREC (a), TQ (b), SQ (c), INFILT (d), SW (e), LQ (f), PERCOL (g), RECHARGE (h), and GWQ (i) for the period from 1985 to 2014 in the Han River basin. Figure 6 shows the SWAT model results for use in the water quality condition assessment of the water quality constituents sediment (a), T-N (b), and T-P (c) for the same period in the Han River basin. The sub-index results of the hydrologic and water quality conditions calculated are shown in Figure 12c and d, respectively. The precipitation in the watershed directly affects the surface runoff and sediment transport and is the most important factor impacting the maintenance of water quantity and can thus be used to identify areas critical for maintaining watershed health. Nutrient (T-N and T-P) loads are often correlated with surface runoff and sediment transport rates (USDA-SCS, 1972). The fugitive sediment from the landscape is carried by overland flow (surface runoff), and the dominant pathway for nitrate loss is through leaching to groundwater and then via baseflow (Randall and Mulla, 2001).

The sub-indices of hydrologic condition calculated by the four hydrologic classifications, such as the total metric (PREC and TQ), surface processes metric (SQ), soil water dynamics metric (INFILT, SW, and LQ), and groundwater dynamics metric (PERCOL, RECHARGE, and GWQ), and the water quality condition calculated by sediment, T-N, and T-P were split into three periods of ten years—1985–1994, 1995–2004, and 2005–2014—for the assessment of changes over time (Figure 9). The test areas used to explain the differences in the results of watershed health the for hydrologic and water quality components are the SYD watershed and CJD watershed located in the upstream region and the PDD watershed and lower watershed located in the downstream region (Figure 2c). For the SYD watershed (Figure 9a), the watershed health scores of the surface water, soil water, and groundwater hydrology increased in the recent past compared to the period 1985–1994 due to the slight increases in PREC and TQ; thus, the watershed water quality was diminished. The health of the hydrology in the CJD watershed showed a decreased tendency in contrast to the SYD watershed as a result of the decrease in PREC and TQ (Figure 9b). In the case of the PDD watershed and the lower watershed, the groundwater of the PDD watershed was not sufficient, but overall watershed health scores remained within their reference levels (approximately 0.5) (Figure 9c and d). This water quantity stress (large volume of water in the stream) may have negative effects on water quality, with a decreased watershed health score for the sediment, T-N, and T-P. In particular, the SYD watershed was rich in soil water and the CJD watershed was rich in surface and groundwater.

Figure 10 shows the watershed health index score changes for the hydrologic and water quality conditions during 1995–2004 and the most recent ten years (2005–2014) based on the reference period (1985–1994). Improved health, deteriorating health, and no change area in the Han River basin are illustrated with green, red, and white, respectively. On the whole, the watershed hydrologic condition was better in the North Han River basin compared to the South Han River basin. In particular, during the last ten years (Figure 10b), the watershed health was poorer due to worse results for the surface processes metric and soil water dynamics compared to the 1995–2004 period (Figure 10a). However, in the case of water quality, during the last ten years (Figure 10d), the watershed health increasingly improved in parts of Han River basin compared to 1995–2004 (Figure 10c), while the water quality of the Chungju dam (CJD) watershed was growing worse. The water quality policy of South Korea, developed after years of hard work and high costs, thus resulted in some improvements.

Figure 11 shows the overlay results (Figure 11c) showing the poor watershed health of both hydrology (Figure 11a) and water quality (Figure 11b). The five poor levels of hydrology and water quality were calculated as the difference between (b) and (a) of Figure 10 and between (d) and (c) of Figure 10, respectively. The spatial distributions of poor watershed health levels allow us to understand the vulnerable areas in parts of the CJD watershed, the upstream SYD watershed, and the downstream PDD watershed with respect to hydrology and water quality.

<Figure 9>
<Figure 10>
<Figure 11>

Figure 7 shows the aquatic habitat condition for the aquatic habitat connectivity (Figure 7a) and wetland (Figure 7b) indicators in the Han River basin. Figure 12e shows the sub-index score for the watershed health assessment calculated according to these two assessment indicators. The spatial distribution patterns of the reservoirs for aquatic habitat connectivity were concentrated in the downstream areas of the Han River basin. The spatial distribution patterns of the wetlands seem to follow a similar pattern. For the 101206 standard watershed, the normalized values of the aquatic habitat connectivity and wetland were 0.00 (no reservoir) and 0.99, respectively, and the sub-index score of 0.90, which integrates the two normalized values, indicates a very healthy watershed. In contrast, for the 100201 standard watershed, the normalized values of the aquatic habitat connectivity and wetland were 0.46 and 0.34, respectively, and the sub-index score of 0.28, which integrates the two normalized values, indicated an unhealthy watershed. At the 101801 standard watershed, the aquatic habitat condition results from the aquatic habitat connectivity (0.77) and wetland (0.66) indicators show a relatively high value of 0.68.

The biological pollution classes of the TDI, BMI, and FAI were examined by ecoregion and river basin (Figure 8). These relationships were found to be significantly correlated. In the downstream areas, the TDI, BMI, and FAI are worse. However, the degree to which the TDI, BMI and FAI predict trophic diatom, benthic macroinvertebrate, and fish communities depends on the presence and levels of other stressors, such as large amounts of chlorophyll-a (Chla), low dissolved oxygen (DO) and biochemical oxygen (BOD), and high temperature. The normalized values of TDI, BMI and FAI were 0.70, 0.98, and 0.92, respectively, in the 101206 standard watershed located upstream; 0.69, 0.98, and 0.72, respectively, in the 100201 standard watershed located upstream; and 0.32, 0.25, and 0.25, respectively, in the 101801 standard watershed located downstream.. The sub-index analysis of the TDI, BMI, and FAI was completed except in the no-data areas (North Korea) in the Han River Basin (Figure 12f). The sub-index scores integrating the three normalized values were 0.91 and 0.83 for the 101206 and 100201 standard watersheds, respectively, indicating very healthy watersheds, and the sub-index score of 0.26 at the 101801 standard watershed indicated an unhealthy watershed.

The outputs of the watershed health provide basic data for local communities to proactively plan for growth. The sub-index results of the watershed health assessment for each component can be optionally used to guide the master planning process for watershed management at the watershed scale depending on the specific management objectives and can be combined with any of the other sub-indices in the Han River basin for use in determining priority conservation areas.

3.2 Assessment of integrated watershed health

To assess the overall watershed health in the Han River basin, the results of the individual assessments were synthesized to provide an integrated watershed health index score for the thirty-year period (1985–2014). The sample areas used to explain the differences in watershed health results for each component were standard watersheds 101206 (urban 1.4% and forest 88.1%), 100201, (urban 0.8% and forest 88.2%) and 101801 (urban 9.8% and forest 55.7%) (Figure 2a). The 101206, 100201, and 101801 standard watersheds were located in the upstream region of the Soyang dam (SYD), in the upstream region of the Chungju dam (CJD), and in the downstream region of the Paldang dam (PDD), respectively.

Figure 12 displays the normalized scores for each of the six attribute sub-indices and integrated watershed health score. The integrated watershed health exhibited a decreased tendency farther down the watershed. The integrated watershed health of the 101206 and 100201 standard watersheds was revealed to be very good, with ratings of 1 and 0.91, respectively. However, the 101206 standard watershed exhibited distinctive weakness with respect to hydrologic condition (0.06), especially in the surface (0.16) and groundwater (0.17). Although the 100201 standard watershed was a very healthy watershed, like the 101206 watershed, it showed a distinctive weakness with respect to water quality (0.1) and aquatic habitat condition (0.28). It is important to develop systematic plans to suit watershed circumstances and characteristics so that watershed management is more effective. The 101801 watershed was revealed to be in poor health, with a water quality rating of 0.25. This area requires urgent action to restore the landscape, water quality, and biological conditions and to protect the water quantity. Table 5 shows watershed health scores in test areas (upper/lower stream) of the Han River basin.

<Figure 12>
<Table 5>

4. Conclusions

In this study, a watershed health assessment of the Han River basin in South Korea was performed using monitoring data and SWAT modeling results. Six essential indicators of healthy watersheds were used in the assessment: 1) landscape condition, 2) geomorphology, 3) hydrology, 4) water quality, 5) habitat, and 6) biological condition. In particular, the sub-index of watershed health related to hydrology and water quality was developed to assess the possible long-term changes in the watershed using SWAT modeling results.

During the most recent ten-year period (2005–2014), the watershed health declined, as indicated by the worse results for the surface processes metric and soil water dynamics compared to the 1995–2004 period. The spatial distributions of poor watershed health levels revealed the vulnerable areas in parts of the CJD watershed, upstream of the SYD watershed, and downstream of the PDD watershed with respect to hydrology and water quality.

The sub-index results of the watershed health assessment for each component can be used to guide the master planning process for watershed management at the watershed scale based on specific management objectives and can be combined with any of the other sub-indices in the Han River basin for use in determining priority conservation areas.

Acknowledgments

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Figure 1. Flowchart of the study procedure for the watershed health assessment.

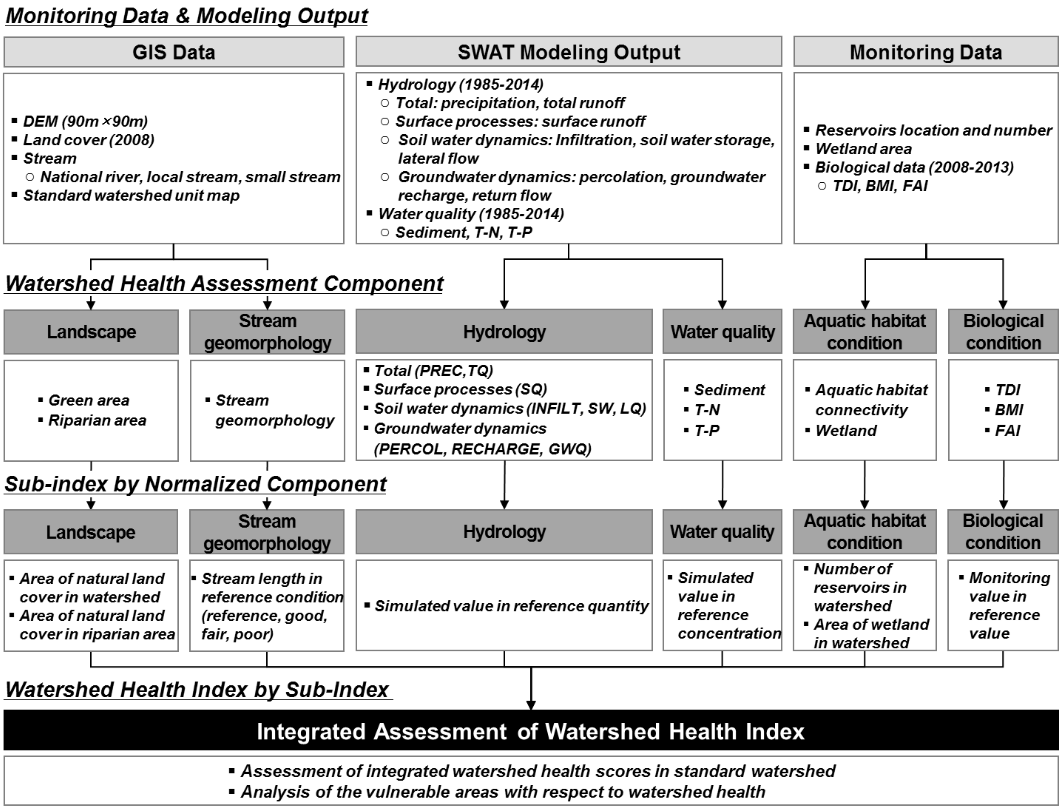


Figure 2. Locations of (a) the Han River basin boundaries and gauging stations for the watershed (SWAT) modeling, (b) land cover classification, and (c) test area.

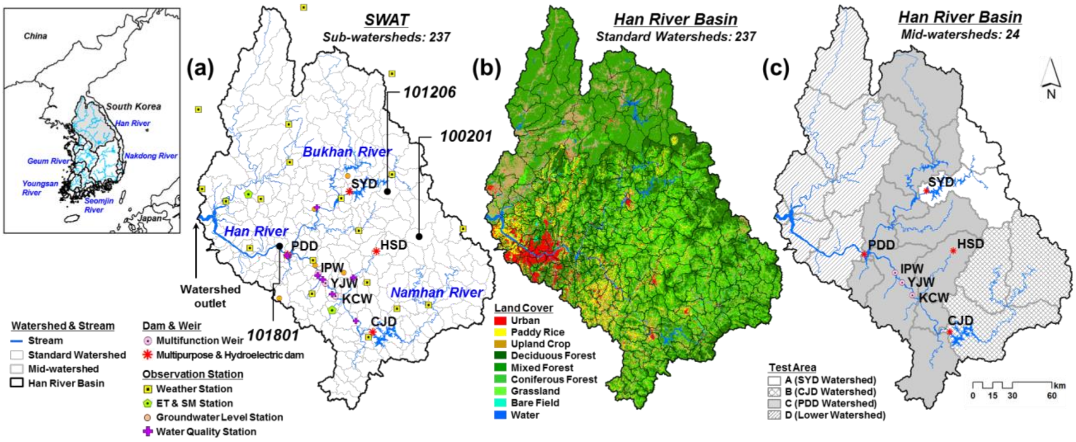


Figure 3. Landscape condition for (a) green area and (b) riparian area.

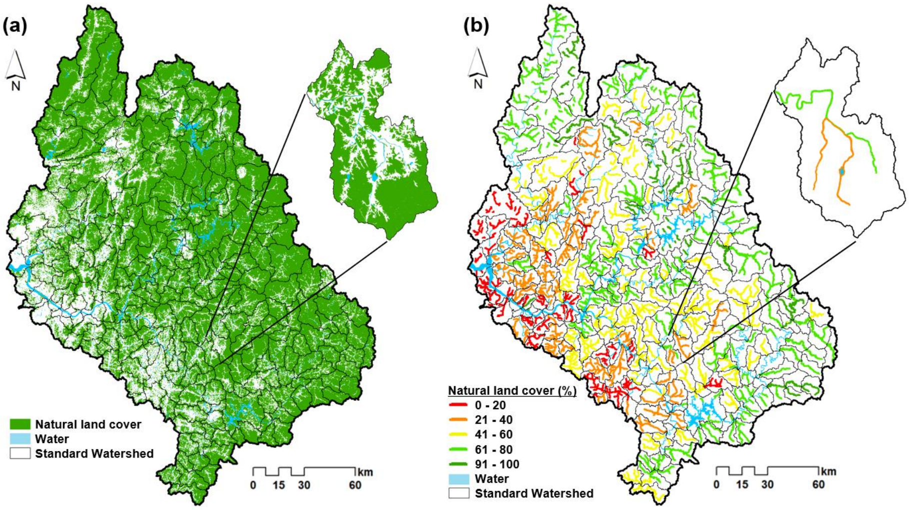


Figure 4. Stream geomorphic conditions: (a) stream order and (b) stream geomorphic conditions.

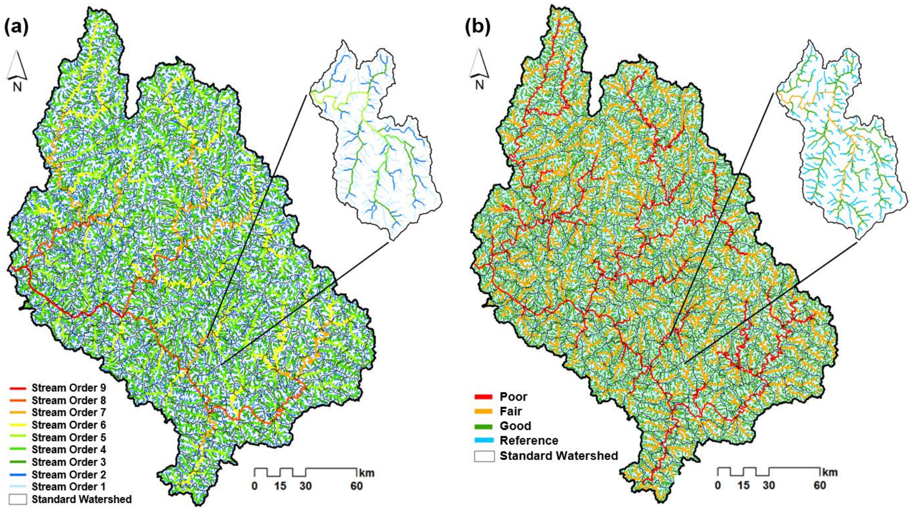


Figure 5. Hydrologic condition for (a) precipitation, (b) total runoff, (c) surface runoff, (d) infiltration, (e) soil water storage, (f) lateral flow, (g) percolation, (h) groundwater recharge, and (b) return flow according to the hydrological (SWAT) modeling for the period from 1985 to 2014 in the Han River basin.

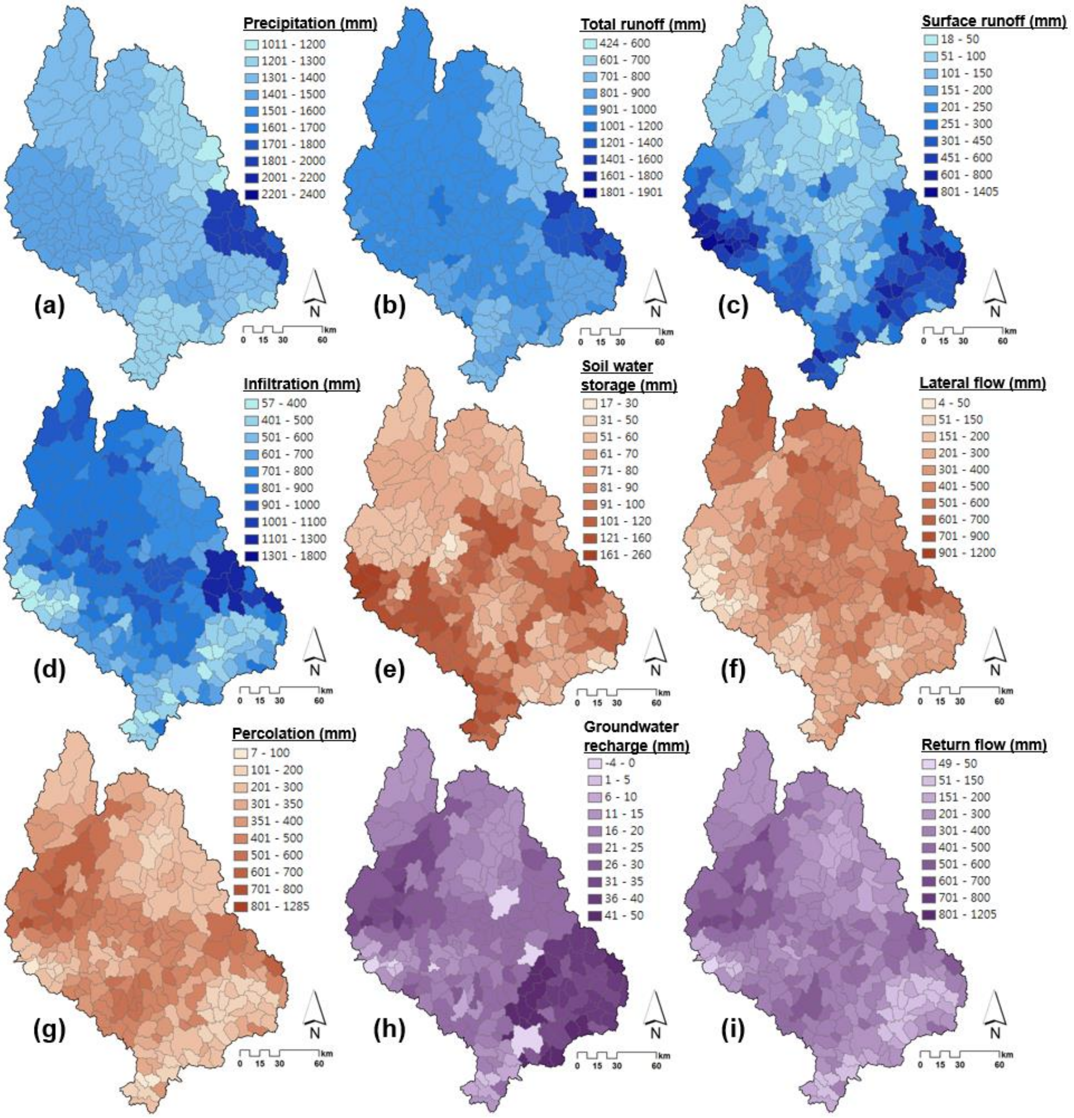


Figure 6. Water quality condition for (a) sediment, (b) T-N and (c) T-P according to the hydrological (SWAT) modeling for the period from 1985 to 2014 in the Han River basin.

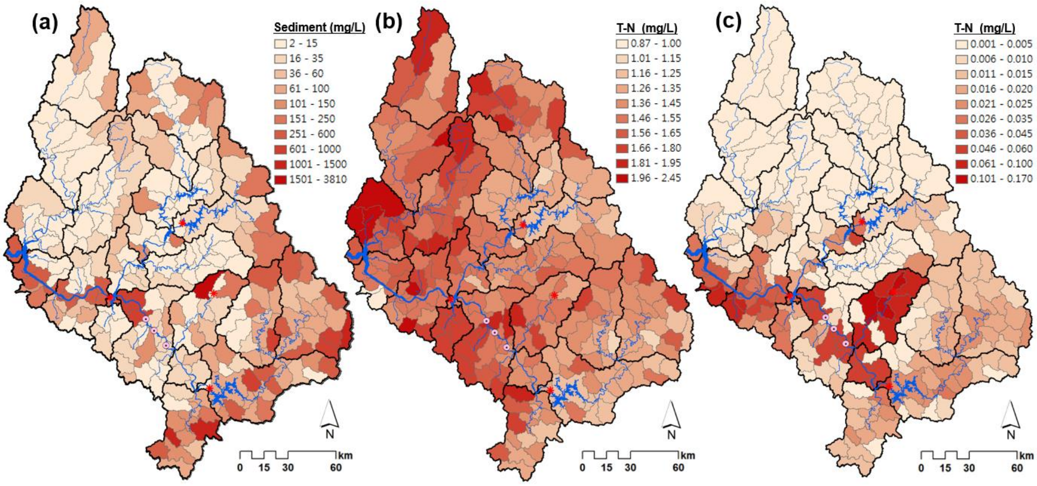


Figure 7. Aquatic habitat conditions for (a) aquatic habitat connectivity and (b) wetland.

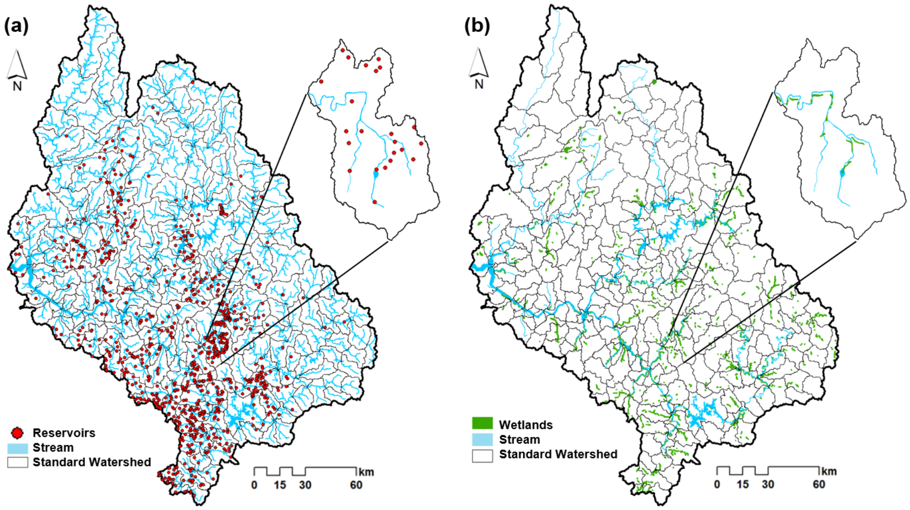


Figure 8. Biological conditions of (a) FAI, (b) BMI and (c) FAI according to the observed monitoring data for the period from 2008 to 2013 in the Han River basin.

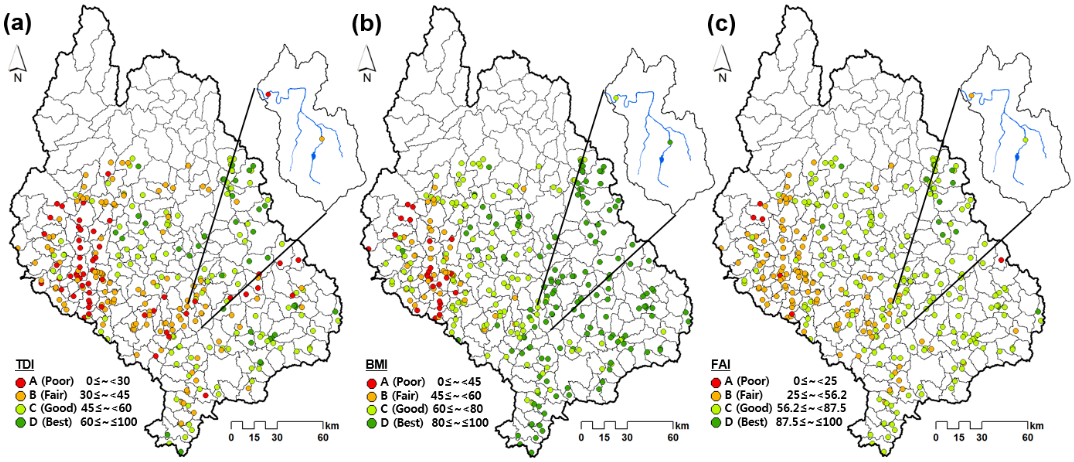


Figure 9. Change in hydrology and water quality for (a) A (SYD watershed), (b) B (CJD watershed), (c) C (PDD watershed), and (d) D (lower watershed) test areas for three ten-year periods.

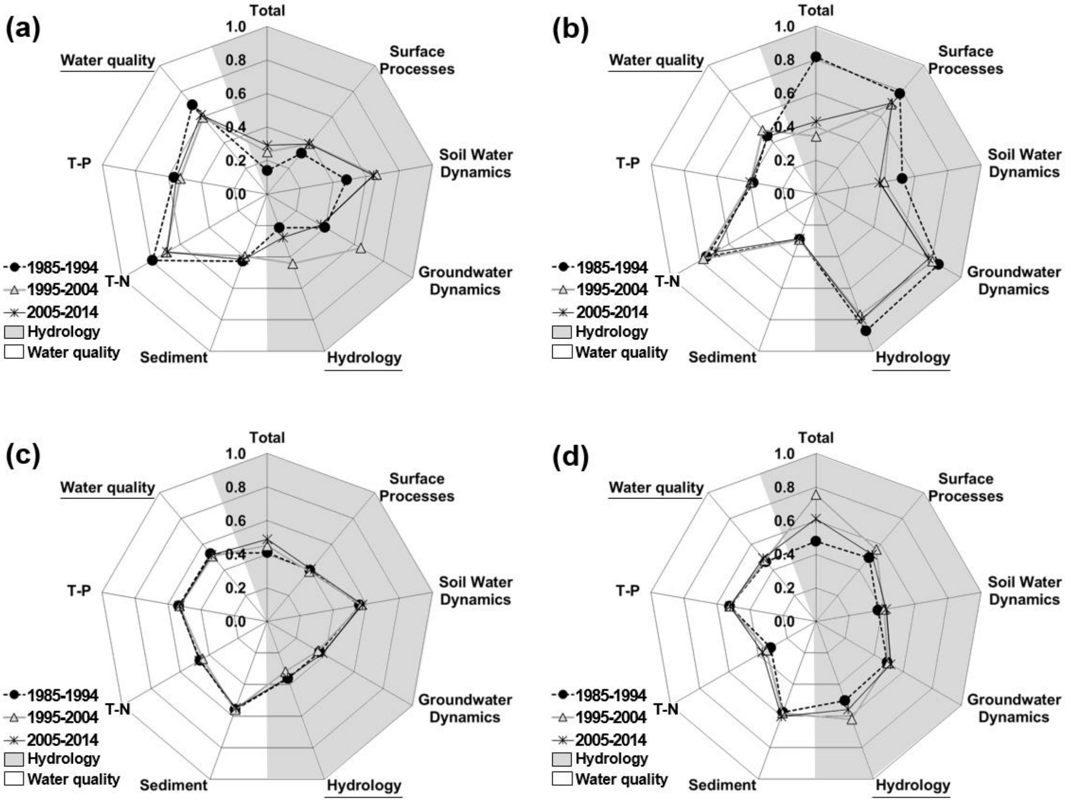


Figure 10. The watershed health index score changes for the hydrologic (a and b) and water quality (c and d) conditions during the period 1995–2004 and the most recent ten-year period (2005–2014) based on the reference period (1985–1994).

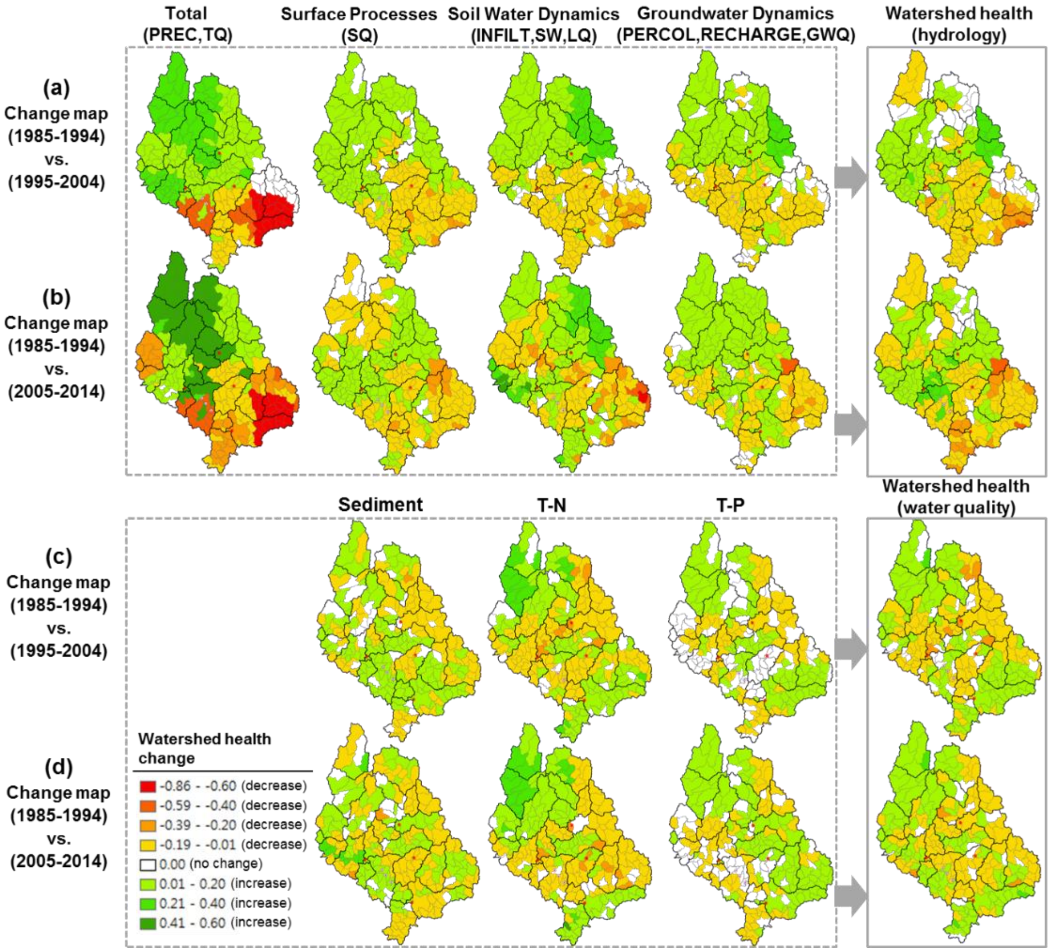


Figure 11. The poor watershed health revealed by (a) hydrology, (b) water quality, and (c) overlay results.

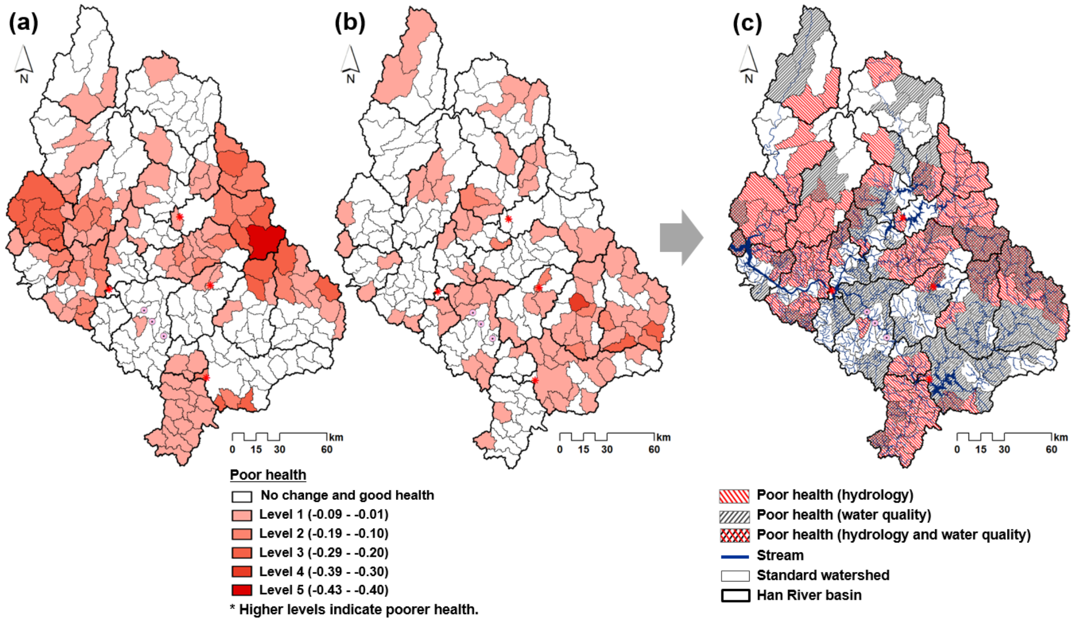
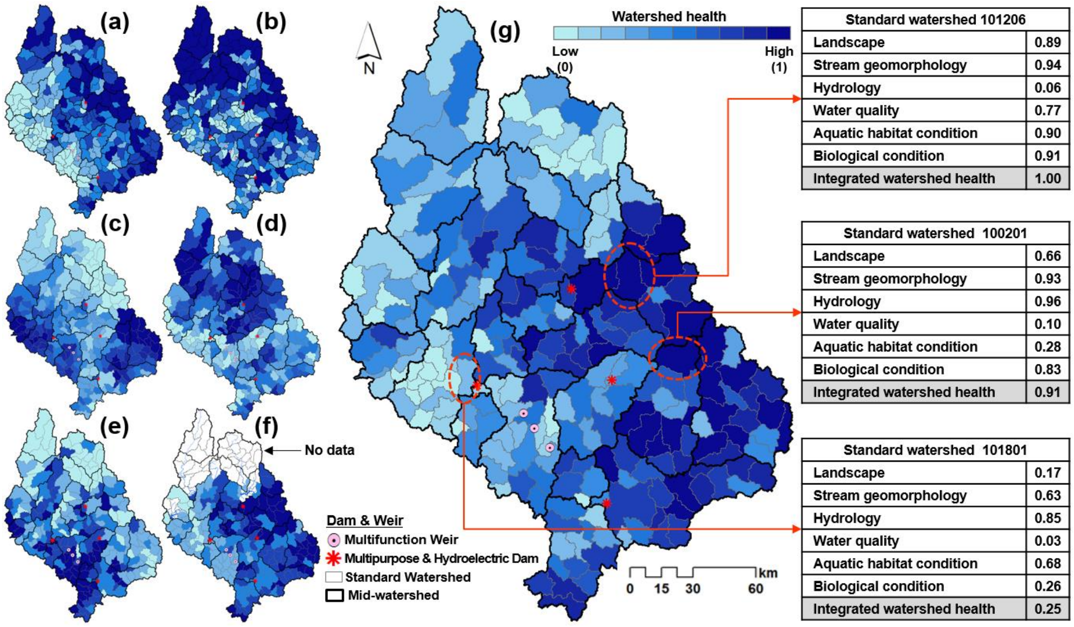


Figure 12. The results of the watershed health index for (a) landscape, (b) stream geomorphology, (c) hydrology, (d) water quality, (e) aquatic habitat, (f) biological condition, and (g) integrated watershed health.



Standard watershed 101206	
Landscape	0.89
Stream geomorphology	0.94
Hydrology	0.06
Water quality	0.77
Aquatic habitat condition	0.90
Biological condition	0.91
Integrated watershed health	1.00

Standard watershed 100201	
Landscape	0.66
Stream geomorphology	0.93
Hydrology	0.96
Water quality	0.10
Aquatic habitat condition	0.28
Biological condition	0.83
Integrated watershed health	0.91

Standard watershed 101801	
Landscape	0.17
Stream geomorphology	0.63
Hydrology	0.85
Water quality	0.03
Aquatic habitat condition	0.68
Biological condition	0.26
Integrated watershed health	0.25

Table 1 Metrics and summary dataset used for the assessment of watershed health in the study watershed

Component (metric)	Measurement method	Dataset
Landscape		*GIS data*
Green infrastructure metric	Percentage of watershed occupied by natural land cover	Land cover 2008[a]
Active river area metric	Percentage of natural land cover within the active river area	Land cover 2008, stream[b]
Geomorphology		*GIS data*
Stream geomorphology metric	Percentage of assessed stream length in reference condition	SRTM DEM (90×90)[c], stream
Hydrology		*SWAT modeling data (1985–2014)*
Total metric	Precipitation and total runoff storage ratio	PREC, TQ
Surface processes metric	Surface runoff storage ratio	SQ
Soil water dynamics metric	Infiltration, soil water and lateral flow storage ratio	INFILT, SW, LQ
Groundwater dynamics metric	Percolation, groundwater recharge and return flow storage ratio	PERCOL, RECHARGE, GWQ
Water quality		*SWAT modeling data (1985–2014)*
Water quality metric	Percentage of assessed value in reference criteria	Sediment, T-N, T-P
Aquatic habitat condition		*GIS data*
Habitat connectivity metric	Reservoir density (number of reservoirs per stream length)	Reservoir location map[d], stream
Wetland metric	Percentage of watershed occupied by wetlands	Land cover 2008
Biological condition		*Monitoring data (2008–2013)*[e]
Biological metric	Percentage of assessed score in reference condition	TDI, BMI, FAI

Main data sources included [a] the Korea Ministry of Environment (KME); [b] the Ministry of Land, Infrastructure, and Transport (MOLIT) in South Korea; [c] the International Center for Tropical Agriculture (CIAT); [d] the Korea Rural Community Corporation (KRC); and [e] the Korea Ministry of Environment (KME) in South Korea (Ministry of Environment, 2013).

Table 2 Calibration and validation results for dam inflow, dam storage volume, evapotranspiration and soil moisture, groundwater level fluctuation, sediments, T-N, and T-P at each calibration point.

Model output	Evaluation criteria	Cal.	Val.	Cal.	Val.	Cal.	Val.	Cal.	Val.	Cal.	Val.	Cal.	Val.	Cal.	Val.
Dam inflow (mm)	Locations	HSD		SYD		CJD		KCW		YJW		IPW		PDD	
	R^2	0.82	0.84	0.90	0.89	0.81	0.74	0.90	0.63	0.91	0.62	0.93	0.59	0.92	0.88
	NSE	0.61	0.57	0.78	0.78	0.63	0.58	0.78	0.79	0.77	0.76	0.81	0.95	0.83	0.76
	RMSE (mm/day)	7.9	9.3	3.8	3.9	3.5	3.1	6.5	0.7	9.1	2.4	9.2	2.9	0.8	2.3
	PBIAS (%)	14.5	12.5	10.3	14.0	8.9	9.9	18.0	4.9	25.5	14.1	25.6	17.2	2.2	6.8
Dam storage (10^6 m^3)		HSD		SYD		CJD		KCW		YJW		IPW		PDD	
	R^2	0.73	0.77	0.94	0.96	0.87	0.84	0.57	0.85	0.47	0.83	0.47	0.79	0.40	0.44
	PBIAS (%)	18.9	9.9	16.3	9.3	18.2	15.2	5.1	7.4	3.7	11.1	9.1	7.2	0.9	1.4
Evapotrans-piration (mm)	Locations	SM		CM		-		-		-		-		-	
	R^2	0.81	0.73	0.70	0.74	-	-	-	-	-	-	-	-	-	-
	NSE	0.64	0.45	0.50	0.55	-	-	-	-	-	-	-	-	-	-
	RMSE (mm/day)	2.3	9.1	4.0	3.0	-	-	-	-	-	-	-	-	-	-
	PBIAS (%)	9.6	30.2	11.6	23.7	-	-	-	-	-	-	-	-	-	-
Soil moisture (%)	Locations	SM		CM		-		-		-		-		-	
	R^2	0.85	0.75	0.78	0.78	-	-	-	-	-	-	-	-	-	-
Grounwater level (EL.m)	Locations	-		-		GPGP		YPGG		YPYD		YIMP		HCGD	
	R^2	-	-	-	-	0.70	0.63	0.64	0.45	0.70	0.41	0.53	0.40	0.69	0.67
	Locations	SG		CSG		JW		KCW		YJW		IPW		PDD	
Sediment (ton)	R^2	0.78	0.70	0.78	0.76	0.90	0.71	0.54	0.64	0.84	0.54	0.69	0.66	0.72	0.80
T-N (kg)	R^2	0.58	0.71	0.64	0.71	0.82	0.68	0.50	0.61	0.52	0.49	0.46	0.62	0.66	0.62
T-P (kg)	R^2	0.77	0.77	0.88	0.88	0.80	0.56	0.56	0.58	0.50	0.47	0.66	0.70	0.74	0.69

[a] Cal. = calibration period (HSD, SYD, CJD and PDD: 2005-2009, KCW, YJW and IPW: 2013) and Val. = validation period (HSD, SYD, CJD and PDD: 2010-2014, KCW, YJW and IPW: 2014)

Table 3 Description of the stream geomorphic condition categories (Kline et al., 2009) and stream order for watershed health assessment of geomorphic condition in the Han River basin

Condition	Description	River classification	Stream order (1–9)
Reference	In Equilibrium – no apparent or significant channel, floodplain, or land cover modifications; channel geometry is likely to be in balance with the flow and sediment produced in its watershed.	Mountainous river	1
Good	In Equilibrium but may be in transition into or out of the range of natural variability – minor erosion or lateral adjustment but adequate floodplain function; any adjustment from historical modifications nearly complete.	Small river	2–3
Fair	In Adjustment – moderate loss of floodplain function or moderate to major plan-form adjustments that could lead to channel avulsions.	Local river	4–5
Poor	In Adjustment and Stream Type Departure – may have changed to a new stream type, or central tendency of fluvial processes or significant channel and floodplain modifications may have altered the channel geometry such that the stream is not in balance with the flow and sediment produced in its watershed.	Urban river, National river	6–9

Table 4 Summary of hydrology, water quality and biological criteria used to screen for reference condition in the Han River basin

Component	Source	Reference condition
Hydrology		
Precipitation	River basin average of 30 years (1985–2014) simulated by SWAT	1,395.1 (mm)
Total runoff		919.5 (mm)
Surface runoff		249.4 (mm)
Infiltration		726.4 (mm)
Soil water storage		85.3 (mm)
Lateral flow		345.9 (mm)
Percolation		363.8 (mm)
Groundwater recharge		22.9 (mm)
Return flow		324.2 (mm)
Water quality		
Sediment	The levels greater than "marginally good" level on a seven-point scale (excellent, very good, good, marginally good, fair, poor, very poor) of water quality criteria for streams and lakes devised by the Basic Environmental Policy Act (BEPA) in South Korea.	15 (mg/L)
T-N		0.6 (mg/L)
T-P		0.05 (mg/L)
Biological condition		
TDI	The "best" and “good” levels on a four-point scale (best, good, fair and poor) of biological condition criteria devised by the Korea Ministry of Environment (KME) (Ministry of Environment, 2013).	72.5
BMI		80.0
FAI		78.1

755 Table 5 Results of watershed health score in each test area (upper/lower stream) of the Han River basin

Component	A (SYD watershed)	B (CJD watershed)	C (PDD watershed)	D (Lower watershed)
Landscape	**0.80**	**0.66**	**0.53**	**0.26**
Green infrastructure metric	0.85	0.67	0.52	0.25
Active river area metric	0.74	0.65	0.53	0.28
Geomorphology	**0.75**	**0.47**	**0.46**	**0.54**
Hydrology	**0.21**	**0.74**	**0.37**	**0.60**
Total	0.19	0.51	0.44	0.65
Surface processes	0.36	0.73	0.40	0.53
Soil water dynamics	0.61	0.44	0.58	0.39
Groundwater dynamics	0.30	0.55	0.45	0.58
Water quality	**0.63**	**0.45**	**0.52**	**0.48**
Sediment	0.40	0.29	0.55	0.61
T-N	0.76	0.70	0.49	0.32
T-P	0.52	0.40	0.53	0.53
Aquatic habitat condition	**0.39**	**0.43**	**0.55**	**0.45**
Habitat connectivity	0.22	0.30	0.52	0.40
Wetland	0.53	0.51	0.49	0.41
Biological condition	**0.92**	**0.73**	**0.47**	**0.23**
TDI	0.83	0.67	0.50	0.25
BMI	0.88	0.78	0.46	0.22
FAI	0.92	0.70	0.47	0.27
Integrated assessment	**0.82**	**0.75**	**0.47**	**0.30**