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Special Issue: Coupled terrestrial-aquatic approaches to watershed-scale water resource sustainability
Title: Assessment of Integrated Watershed Health based on the Natural Environment, Hydrology, Water Quality, and Aquatic Ecology
Journal: Hydrology and Earth System Sciences

Anonymous Referee #1

COMMENTS: This study evaluated health condition of a watershed of the Han River basin (34,148 km2) in South Korea was performed using monitoring data and SWAT modeling results. Six essential indicators of healthy watersheds were used in the assessment: landscape condition, geomorphology, hydrology, water quality, habitat, and biological condition. The research findings from this study provided guidance for watershed management at the watershed scale based on specific management objectives and can combined with any of the other sub-indices in the Han River basin for use in determining priority conservation areas. This paper is well organized and well written generally. Detailed method description was incorporated. The scientific results and conclusions were presented in a clear, concise, and well-structured way. The number and quality of references is appropriate. But method and results should be reduced. The importance of six essential indicators of healthy watersheds was not well described. More in-depth discussion should be included to support the interpretations and conclusions. This manuscript can be reviewed after major revisions. What is the novel idea this manuscript provided to scientific knowledge? Please describe it and use your results and discussion to support it.

General

1. The last sentence of the abstract "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." Is this the scientific questions being answered in this manuscript? Please provide specific discussion of results and summarize them in conclusion to support this point. Otherwise, I do not think this sentence should be here.

   ● Response:
   (Lines 27-32) We removed the last sentence of the abstract and revised this section as follows: "The results indicate that the watershed's health declined during the most recent ten-year period of 2005–2014, as indicated by the worse results for the surface process metric and soil water dynamics compared to those of the 1995–2004 period. The integrated watershed health tended to decrease farther downstream within the watershed."

2. 2.4 Hydrology and water quality simulations using the SWAT model: the session is mainly focus on basic information about SWAT. If it is not specific for your project, it is better to put information in the Introduction rather than in Methods. And authors already described data collection related to SWAT model setup and SWAT outputs in 2.3, thus it is better to introduce SWAT model before discussing data related to it.

   ● Response:
   (Lines 153-162, and 199-206) Section 2.4, "Hydrology and water quality simulations using the SWAT model", mainly focused on both basic information regarding the SWAT and the model calibration and validation for the hydrology and water-quality simulation data. The information in this section is very important for the watershed-health assessment. We added a new section 2.3, "SWAT model description", before section 2.4, "Data collection", and removed the basic information regarding the SWAT in section 2.5, "Hydrology and water quality simulations with the SWAT model".

3. Is 90 m grid size DEM data sufficient to accurately simulate hydrology and water quality at such a large area? Is there any higher resolution elevation data can be used?

● Response:

(Lines 212-213) Our study area included portions of North Korea. We had a 30-m DEM that covered South Korea, but we did not have data in North Korea. Therefore, we used a 90-m global DEM from the Shuttle Radar Topography Mission (SRTM) of the International Centre for Tropical Agriculture (CIAT). As shown Figures 1, 2, 3, and 4 below, the results for the hydrology and water quality were reasonable. I believe that precipitation had an even greater effect on the hydrologic simulations than the DEM resolution did. In addition, the resolution of the 90-m DEM was appropriate to simulate the watershed's hydrology for the 237 sub-watersheds (average area of 144 km^2) by using the SWAT model.

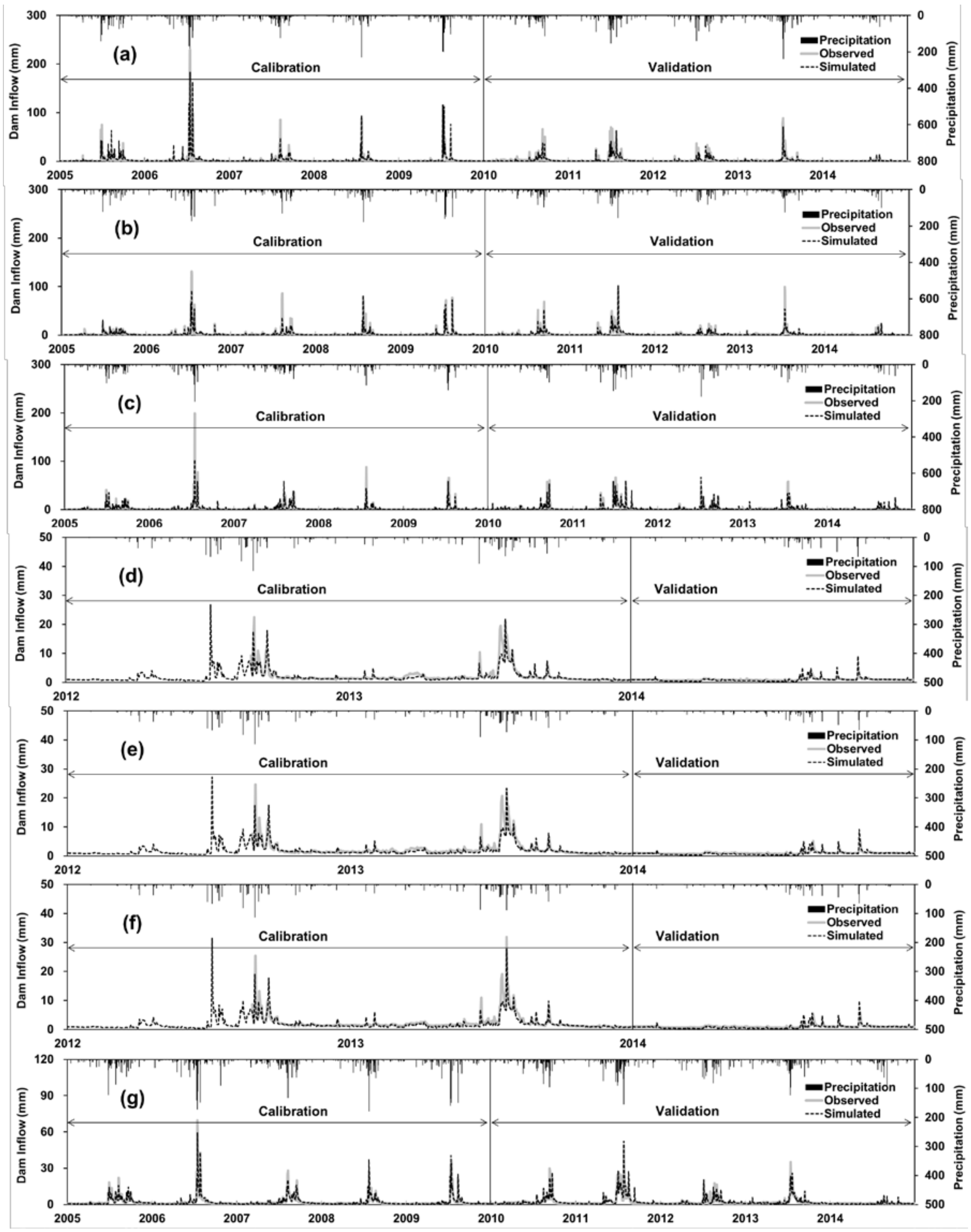

Figure 1 Comparison of the observed and SWAT-simulated daily dam inflow during the calibration (2005–2009) and validation (2010–2014) periods at (a) HSD, (b) SYD, (c) CJD, (d) KCW, (e) YJW, (f) IPW, and (g) PDD.

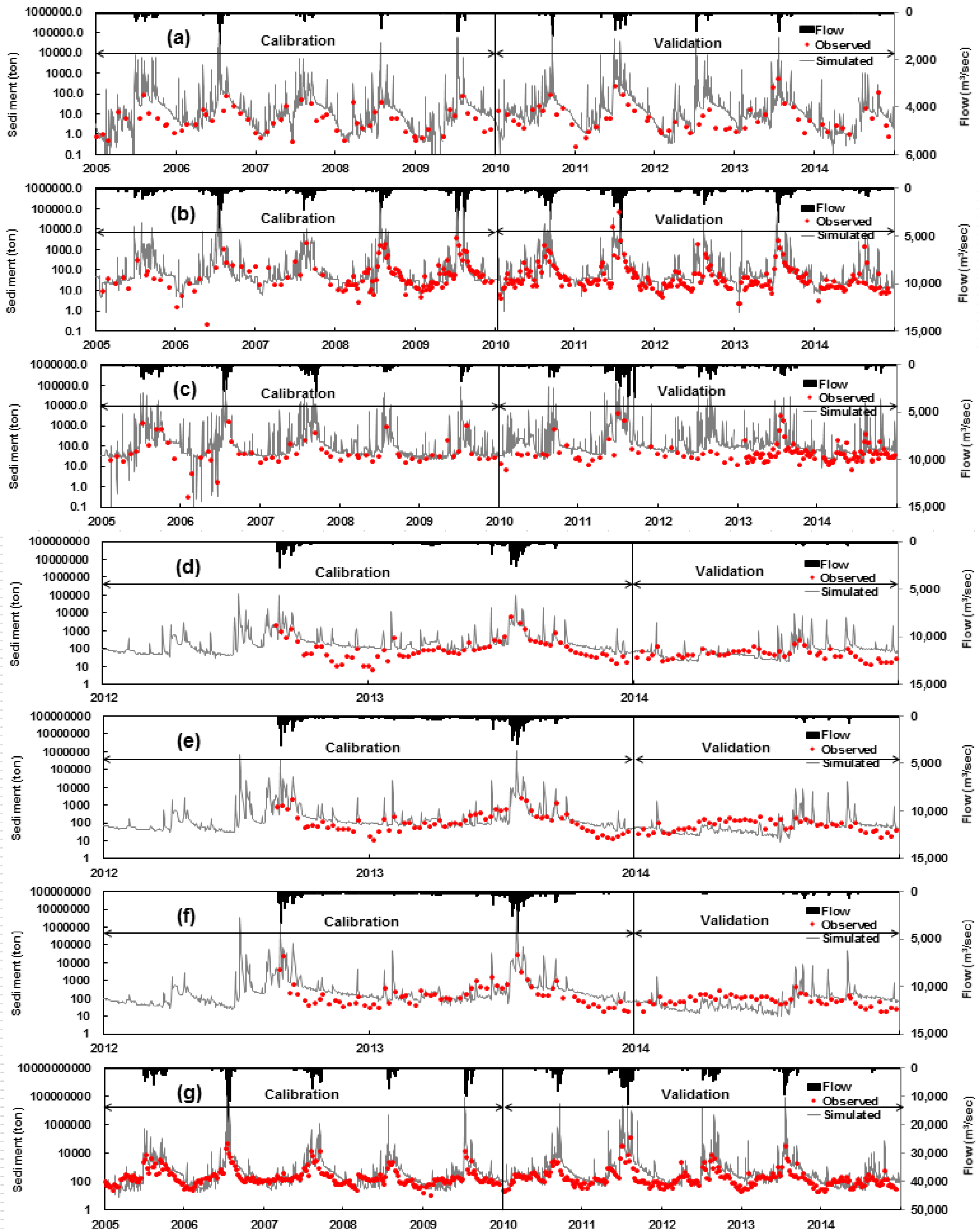

Figure 2 Comparison of the observed and SWAT-simulated daily sediment during the calibration (2005–2009) and validation (2010–2014) periods at (a) SG, (b) CSG, (c) JW, (d) KCW, (e) YJW, (f) IPW, and (g) PDD.

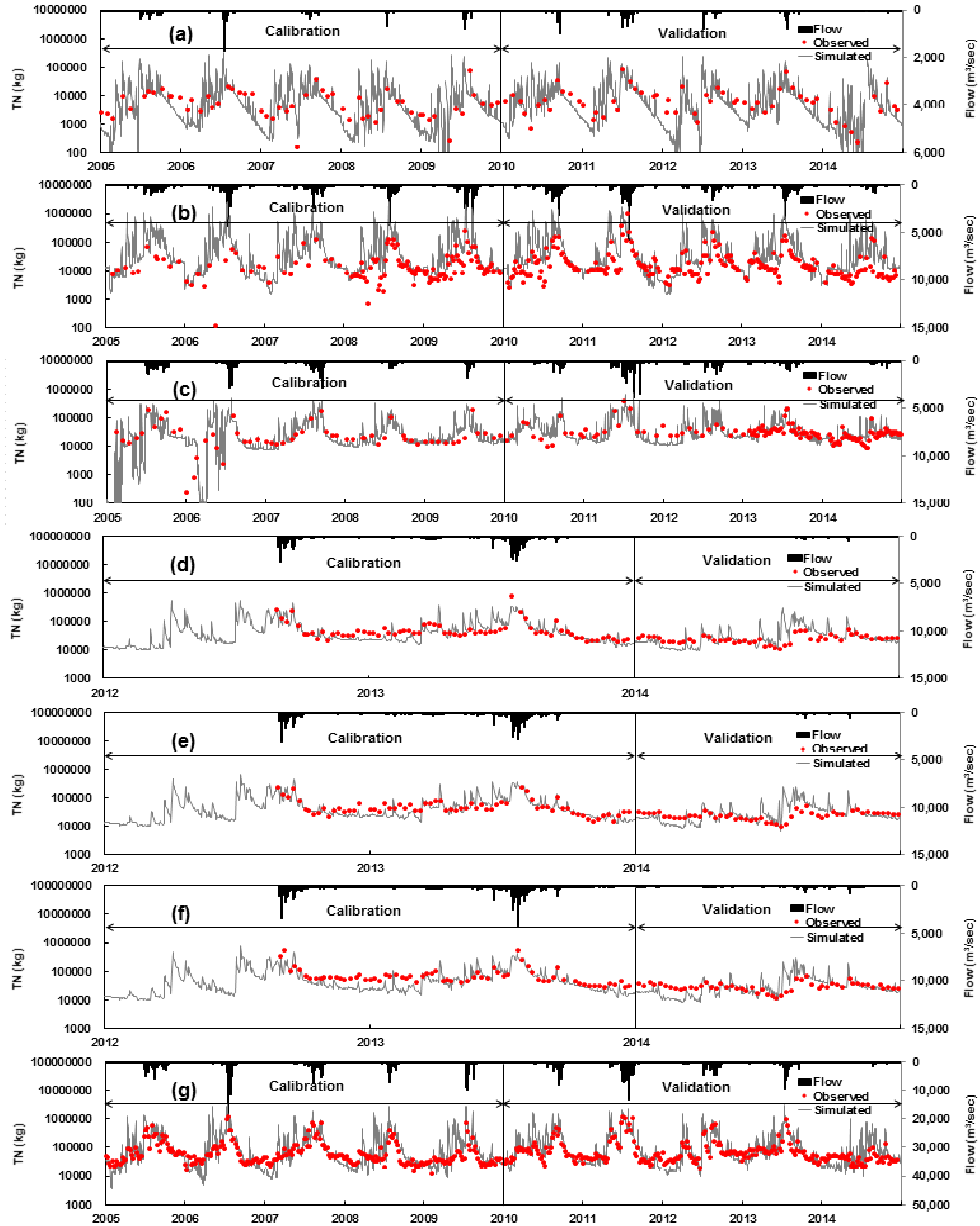

Figure 3 Comparison of the observed and SWAT-simulated daily T-N during the calibration (2005–2009) and validation (2010–2014) periods at (a) SG, (b) CSG, (c) JW, (d) KCW, (e) YJW, (f) IPW, and (g) PDD.

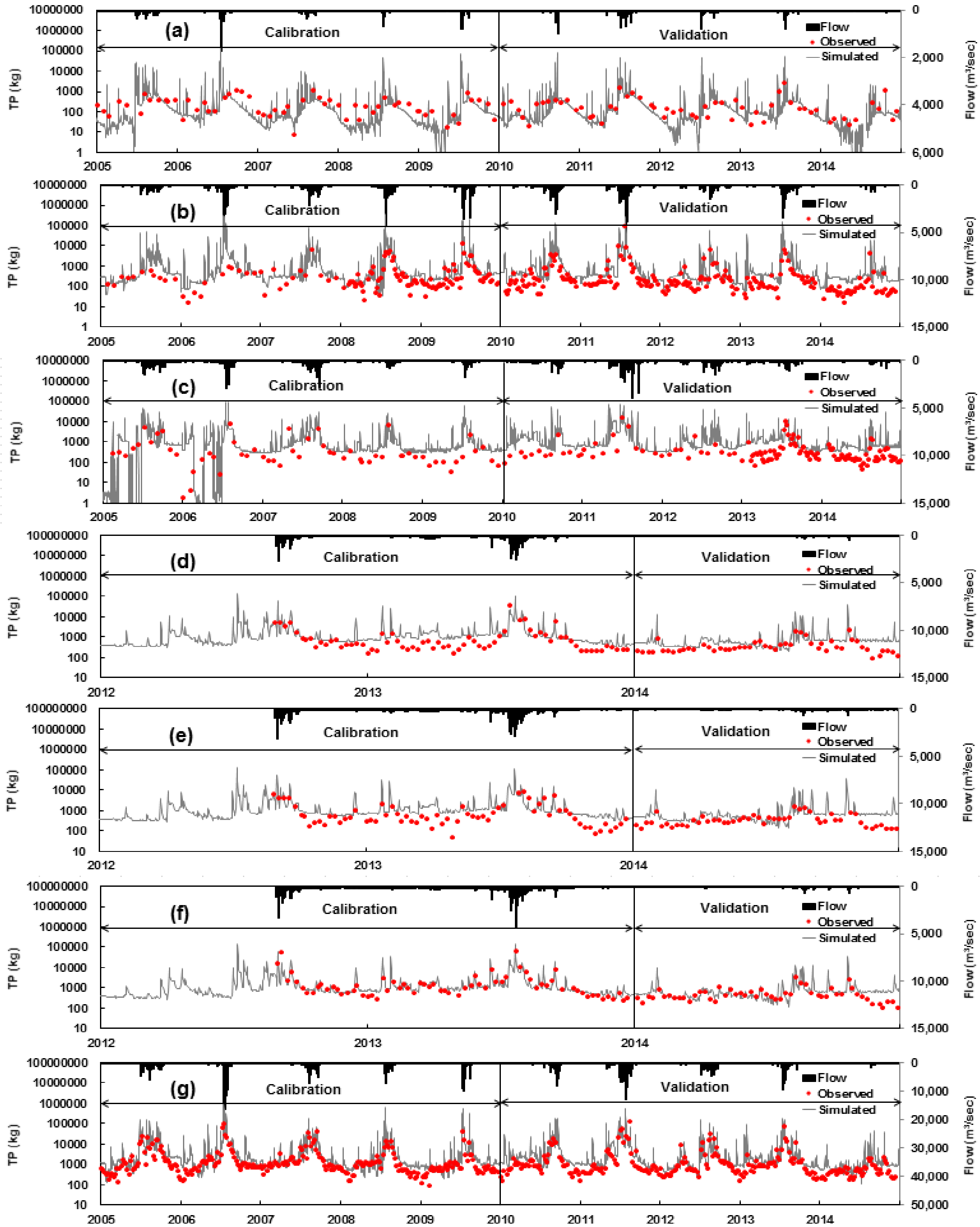

Figure 4 Comparison of the observed and SWAT-simulated daily T-P during the calibration (2005–2009) and validation (2010–2014) periods at (a) SG, (b) CSG, (c) JW, (d) KCW, (e) YJW, (f) IPW, and (g) PDD.

4. Is calibration period (2005–2009) and validation period (2010–2014) both incorporate wet and dry years?

● Response:

(Lines 249-254) We incorporated both wet and dry years in the calibration (2005–2009) and validation periods (2010–2014). The average annual precipitation of the Han River basin is 1,300 mm. For the calibration period (2005–2009), the wet and dry years were 2006 (1,625 mm) and 2008 (1,160 mm). For the validation period (2010–2014), the wet and dry years were 2011 (1,640 mm) and 2014 (734 mm).

5. Statistical evaluation criteria R2, NSE and PBIAS are all sensitive to high values. Criteria less sensitive to high values, such as Modified NSE and KGE, may could be incorporated.

● Response:

(Lines 291-293) We added the NSE with inverse discharge (1/Q) in Table 2. We also added the following sentences: “Additionally, the model calibration and validation included the NSE with inverse discharge (1/Q) for low flow. The average NSE with inverse discharge (1/Q) during the calibration (2005–2009) and validation (2010–2014) periods was 0.35 at HSD, 0.53 at SYD, 0.30 at CJD, 0.54 at KCW, 0.47 at YJW, 0.69 at IPW, and 0.58 at PDD.”

6. Page 8 line 197: this paragraph described a lot of detailed information about dams. It is better to condense it and save more space for in-depth discussions. How was dam information being set in SWAT model?

● Response:

(Lines 218-226 and 230-243) We removed the paragraph that described the dam informations. We added the following sentences regarding the dam information that was set in the SWAT model: “The flow and water quality of the Han River are affected by the discharge operations of these large dams and weirs; therefore, dam and weir operations must be incorporated into the modeling framework to enable successful modeling. In the SWAT model, dam operations are modeled based on measured daily discharges, measured monthly discharges, average annual discharges, or target storage volumes. In this study, the measured daily discharges from the four dams and three weirs were directly imported into the SWAT model.”

7. Page 9 line 226: “The calibrated parameters and hydrograph of the calibration results in the Han River basin were described by 227 Chung et al (2017).” Parameter definition, physical meaning, range used for calibration and calibrated values are very important information. Please describe this information in supplementary materials to prove that your calibration and validation is reliable.

● Response:

(Lines 269-276) We added the following sentences regarding information for the parameter definitions and physical meanings: “In this study, both calibration and validation were manually performed by using a trial-and-error approach within recommended ranges to maximize the expert knowledge of watershed characteristics and modeling experience. The final values were selected based on a statistical evaluation of the performance measures. Twenty of the most influential parameters were selected for calibration. These parameters are related to surface-runoff (CN2, CNCOEF, SURLAG, OV_N, and CH_N), evapotranspiration (ESCO), soil–water (SOL_AWC and SOL_K), groundwater (GW_DELAY, GWQMN, ALPHA_BF, REVAPMN, and GW_REVAP), and reservoir-operation (RES_ESA, RES_EVOL, RES_PSA, RES_PVOL, RES_VOL, RES_K, and EVRSV) processes.”

As shown below, the adjusted parameter values and definitions were included in Table 1 from Chung et al. (2017).

Table 1. Descriptions of calibrated parameters in Soil and Water Assessment Tool (SWAT) [32].

Parameter		Definition	Range	Adjusted Value (Average)	
				Dams	Weirs
Surface runoff	CN2	SCS curve number for moisture conditions	35–98	+12.5	+7
	CNCOEF	Plant ET curve number coefficient	0.5–2	2	2
	SURLAG	Surface runoff lag coefficient	1–24	4	4
	OV_N	Manning's "n" value for overland flow	0.01–30	0.14	0.14
	CH_N(1)	Manning's "n" value for tributary channels	0.01–30	0.014	0.014
Evapotranspiration	ESCO	Soil evaporation compensation coefficient	0–1	0.9125	0.95
Soil water	SOL_AWC	Available water capacity	0–1	0.135	0.14
	SOL_K	Saturated hydraulic conductivity (mm/hr)	0–2000	25.8	25.8
Ground water	GW_DELAY	Delay time for aquifer recharge (days)	0–500	29	31
	GWQMN	Threshold water level in a shallow aquifer for baseflow (mm)	0–5000	1375	1000
	ALPHA_BF	Baseflow recession constant	0–1	0.725	0.048
	REVAPMN	Threshold water level in a shallow aquifer for "revap" (mm)	0–1000	750	750
	GW_REVAP	Groundwater "revap" coefficient	0.02–0.2	0.02	0.02
Reservoir	RES_ESA	Reservoir surface area of the emergency spillway (km^2)	-	48.25	4
	RES_EVOL	Volume of water needed to fill the reservoir storage Volume of the emergency spillway (10^6 m^3)	-	1495.25	13.667
	RES_PSA	Reservoir surface area of the principal spillway (km^2)	-	43	3
	RES_PVOL	Reservoir storage volume of the principal spillway (10^6 m^3)	-	1257.25	11.33
	RES_VOL	Initial reservoir volume (10^6 m^3)	-	674.75	9
	RES_K	Hydraulic conductivity of the reservoir bottom (mm/hr)	0–1	0.2	0.3
	EVRSV	Lake evaporation coefficient	0–1	0.525	0.6

8. Results and discussion generally is redundant. This part need to be condensed. Some information can be incorporated in supplementary materials.

● Response:
(Lines 483-614) Following the reviewer's suggestion, the manuscript has been generally revised, and we removed duplicate information as much as possible to condense section 3, "Results and discussion".

9. Page 10 line 237: "T-N was between 0.46 and" There should be a space between "0.46" and "and".

● Response:
(Line 288) We added a space between "0.46" and "and".

10. Page 10 line 239: should there have a space before and after => ?

● Response:
(Line 290) We added a space before and after ≥.

11. Page 19 line 478: Please improve wording of the first sentence.

● Response:

(Lines 552-554) We revised this sentence as follows: “Figure 11 shows the poor watershed health in terms of the hydrology (Figure 11a), water-quality (Figure 11b), and overlay results (Figure 11c).”

12. Conclusion did not interpolate researching findings well. The results showed the watershed health declined and targeted the vulnerable areas, but what is boarder impacts of these results? How will it be beneficial for watershed management? It would be more meaningful if authors can incorporate this information.

● Response:
(Lines 633-638) We added the following sentences regarding the effects of the study results and beneficial effects for watershed management in the Conclusions section: “Listing all the information of the watershed-health assessment can indicate vulnerable or healthy regions in the desired area and can provide basic data for action. The effectiveness of the watershed-health evaluation in this study can produce reliable information because this approach is entirely physically based. This approach can be utilized in a number of standard watersheds, local communities, and regions throughout the Han River basin and can be practically implemented in the watershed as a comprehensive watershed management plan by government authorities or representative stakeholders.”

13. What is limitation of this study, such as water quantity, quality data, or model input limitations? How to improve it in the further study? What kind of take-home messages you would like to delivery to readers?

● Response:
(Lines 639-644) We added the following sentences regarding the limitations of this study in terms of the water quantity, quality data, and model input in the Conclusions section: “Finally, the limitations of this study include the simulation of water quantity and quality data for possible long-term changes in the watershed model. Although the prediction of long-term water quantity and quality data with this modeling is essential to assess water-resource systems, the hydrologic and water quality conditions cannot be perfectly projected because of uncertainties in the models, climate data and other inputs that are required for the simulations. However, the results of this study are useful in terms of identifying potential watershed-health issues regarding ongoing watershed changes.”

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Journal: Hydrology and Earth System Sciences

Anonymous Referee #2

COMMENTS: This study assesses health condition of the Han River basin in South Korea based on monitoring data, water quantity and quality time series simulations of the SWAT model and an ensemble of indicators related to 6 components of the watershed landscape related to stream geomorphology, hydrology, water quality, aquatic habitat condition, and biological condition. The paper deals with an interesting topic which is watershed health condition. Indeed, there is a weak understanding of the complex processes and watershed components interactions that govern the healthy/unhealthy state of the watershed and such paper is needed to bridge the gap. This is a nice paper, well written and structured in a coherent way. But to my opinion, the approach needs to be improved by including an uncertainty assessment/analysis of the SWAT model.
Authors used SWAT model simulations for water quality and quantity time series reconstruction which in-turn were used for indicators and sub-index development, as stated in the first specific object of the paper. Rely on model simulation for developing these indicators may add uncertainty in the indicators and sub-indexes. In addition, the definition of the reference condition here is crucial and used as a kind of "threshold" to discriminate between healthy and unhealthy watershed condition. This choice is based on SWAT simulation without any uncertainty analysis. I would prefer to see an acceptable range of reference condition based on model uncertainty analysis rather a single value of reference indicator.

General

1. lines 314-316: Authors mentioned that 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, groundwater recharge were important factors for the whole hydrological cycle. These results were based on SWAT simulations. Again, in absence of model uncertainty analysis the contribution of these components to the total water balance may vary or change depending on the parameter of the model. Therefore, I don't think that metrics developed based on the above results can be used for establishing specific management objectives as stated by the authors in line 323.

● Response:
(Lines 255-268) We added a new paragraph in section 2.5.2, "Calibration and validation of the model": "In this study, uncertainty analysis was performed for the hydrology by using the daily dam inflow with the SUFI-2 method. This method was chosen because of its applicability to both simple and complex hydrological models. SUFI-2 is convenient and easy to implement and widely used in hydrology (e.g., Freer et al., 1996; Cameron et al., 2000; Blazkova et al., 2002). In SUFI-2, parameter uncertainty considers all sources of uncertainty, e.g., input uncertainty, conceptual model uncertainty, and parameter uncertainty (Gupta et al., 2005). The degree to which uncertainties are considered is quantified by a measure called the P factor, which is the percentage of the measured data that are bracketed by the 95% prediction uncertainty (95PPU). Another measure that quantifies the strength of a calibration or uncertainty analysis is the R factor, which is the average thickness of the 95PPU band divided by the standard deviation of the measured data. The excellence of the calibration and prediction uncertainty is judged based on the closeness of the P factor to 1 and the closeness of the R factor to 0. Twenty parameters were selected by sensitivity analysis for the uncertainty analysis. In this study, three iterations were performed with 1,300 (100+200+1,000) model runs in each iteration. The coverages of the measurements (P factor) and the average thickness (R factor) of the 95PPUs for the model predictions were 0.79 and 0.32, respectively, for the dam inflow during the calibration and validation periods."

(Lines 291-293) We added the NSE with inverse discharge (1/Q) in Table 2. We also added the following sentences: “Additionally, the model calibration and validation included the NSE with inverse discharge (1/Q) for low flow. The average NSE with inverse discharge (1/Q) during the calibration (2005–2009) and validation (2010–2014) periods was 0.35 at HSD, 0.53 at SYD, 0.30 at CJD, 0.54 at KCW, 0.47 at YJW, 0.69 at IPW, and 0.58 at PDD.”

(Lines 639-644) We added new sentences about limitation of water quantity, quality data, and model input in Conclusion section as follows: “Finally, the limitations of this study include the simulation of water quantity and quality data for possible long--term changes in the watershed model. Although the prediction of long-term water quantity and quality data with this modeling is essential to assess water-resource systems, the hydrologic and water quality conditions cannot be perfectly projected because of uncertainties in the models, climate data and other inputs that are required for the simulations. However, the results of this study are useful in terms of identifying potential watershed--health issues regarding ongoing watershed changes.” We agree with your opinion. We recognized that the model involves uncertainty, so we attempted to simulate the spatial trends of the water quantity and quality. The indicator score for the hydrology metric was re-scaled to normalize each sub-index score to a range from 0 to 1 by using the percentile rank method. This index score shows the relative results for each standard watershed of the study area by calculating the various hydrologic components according to the reference condition.

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

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Abstract

The w~~W~~atershed health, including the natural environment, hydrology, water quality, and aquatic ecology, is~~was~~ assessed for the Han River basin (34,148 km^2) in South Korea by using the Soil and Water Assessment Tool (SWAT). The evaluation procedures follow~~ed~~ those of the Healthy Watersheds Assessment by the U.S. Environmental Protection Agency (EPA). Six~~To evaluate watershed health (basin natural capacity), 6~~ components of the watershed landscape are~~were~~ examined to evaluate the watershed health (basin natural capacity): stream geomorphology, hydrology, water quality, aquatic habitat condition, and biological condition. In particular,~~ for the hydrology and water quality components,~~ the SWAT is~~was~~ applied to~~for~~ the study basin for the hydrology and water quality components, including~~ with~~ 237 sub-watersheds (within a standard watershed on the Korea Hydrologic Unit Map) along with~~and including~~ three multipurpose dams, one hydroelectric dam, and three multifunction weirs. The SWAT is~~was~~ calibrated (2005–2009) and validated (2010–2014) by using each dam and weir operation, the flux-~~–~~tower evapotranspiration, the time-domain reflectometry (TDR) soil moisture, and groundwater level data for the hydrology assessment and by using sediment, total phosphorus, and total nitrogen data for the water quality assessment. The water balance, which considers~~ing~~ the surface–groundwater interactions and~~ the~~ variations in the stream-~~–~~water quality, are~~ were~~ quantified according to the sub-watershed-scale relationship between the watershed hydrologic cycle and stream-~~–~~water quality. We assess~~ed~~ 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.~~ The results indicate that the watershed's health declined during the most recent ten-year period of 2005–2014, as indicated by the worse results for the surface process metric and soil water dynamics compared to those of the 1995–2004 period. The integrated watershed health tended to decrease farther downstream within the watershed.

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 that is 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. R~~The r~~ivers are~~ is~~ a constituent element of~~ the~~ watershed ecosystems that are~~is~~ of primary concern for watershed management; ~~the ~~river discharge and water quality are key components of~~ the~~ watershed ecosystems, 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 that considers the~~ing~~ water supply, water-~~-~~quality improvement, and natural-~~-~~ecosystem maintenance and their interactions within the watershed has been~~was~~ lacking. A~~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 that affect~~ing~~ watershed health is important to~~for~~ identify~~ing~~ management actions to protect healthy watersheds. Without an integrated watershed-~~-~~health-~~-~~assessment system, any~~the~~ successes in restoring impaired waters will be limited and the many socioeconomic benefits of healthy watershed systems will be lost.

G~~In g~~enerally, 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 among~~between~~ in-stream health indicators (flow, sediment, and nutrient loads) by using the Soil and Water Assessment Tool (SWAT)~~ model~~ and the socioeconomic measures of communities by using spatial-~~-~~clustering techniques and confirmatory-~~-~~factor analysis in the Saginaw River watershed in Michigan. Cook et al. (2015) examined these relationships in five watersheds along the Virginia–Kentucky border and explored the effects of both the water quality and habitat on benthic macroinvertebrates by 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, and water-~~-~~quality parameters)~~, examining these relationships in five watersheds along the~~

~~Virginia–Kentucky border~~. Tango and Batiuk (2016) analyzed the interactions that affect~~ing~~ 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, t~~T~~he 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 uses~~d~~ 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 addresses the~~d~~ 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 evaluates~~d~~ the six essential ecological attributes of landscape status: hydrology/geomorphology, biotic condition, chemical/physical condition, natural disturbance regimes, and ecological condition (Shilling, 2007).

The r~~R~~egional water quantity and quality can be assessed through~~by~~ systematic modeling by 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 effects~~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-distribution~~s~~ changes in watershed information.

However, most previous studies~~ have~~ employed a fragmentary approach to investigate~~ing~~ one or several environmental issues by 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 that is 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 by using monitoring data and SWAT-~~-~~modeling outputs. 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 are fundamental to the assessment of watershed health: 1) the 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 that was suggested by the U.S. EPA. All ~~of ~~the indicators for watershed health are evaluated to match the situation in South Korea by 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, namely, the SWAT. According to existing research that~~ has~~ assessed the long-term changes in the Han River basin, the changes in runoff from~~due to~~ climate change in the Han River basin are~~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 the 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. These standard watersheds are the smallest hydrologic units that are designated by the Korean government.~~–~~ Figure 1 shows a flowchart of the modeling procedures. The specific objectives of this study are as follows:

- D~~To d~~evelop a method to~~for~~ reconstruct~~ing~~ water quantity and quality time-series data of the basin by using the SWAT model. The reconstructed time-series are used as water quantity and quality indicators and for sub-index development. W~~Because w~~atershed ~~-~~health assessment relies on the continuous flow of time-series information, so the SWAT model is~~was~~ established and calibrated to obtain flow records at ungauged hydrology and water ~~-~~quality stations.
- E~~To e~~stablish a reference condition for each indicator to assess the sub-index by~~through~~ normalizing~~ation of~~ the following components: the landscape condition, geomorphology, hydrology, water quality, habitat, and biological condition.
- A~~To a~~ssign integrated watershed health scores that combine~~ing~~ multiple indicators to represent~~ing~~ 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 km^2) is one of the five major river basins in South Korea (99,720 km^2). This basin~~; it~~ occupies approximately 31% of the country and falls within the latitude-longitude range from~~of~~ 36.03° N to 38.55° N and from 126.24° E to 129.02° E, respectively (Figure 2). The basin has three main rivers:~~,~~ the North Han River (12,969 km^2), the South Han River (12,894 km^2), and the Imjin River (8,285 km^2). The North and South Han Rivers ~~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 managed because of~~due to~~ the expanding water demand of the Seoul area, including its satellite cities (12 million individuals), and~~ the~~ potential changes to water resources from~~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 km^2), followed by cultivated cropland in the lowland fertile areas (5,915 km^2), 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 was~~is~~ 1,395 mm and the annual mean temperature was~~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) that were delineated for the SWAT modeling and watershed health assessment, and Figure 2c shows the four test areas for a comparison of the watershed-health index scores.

<Figure 2>

2.3 SWAT model description

The SWAT model is a physically based, continuous, long-term, distributed parameter model that is 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 the 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's user's manual and theoretical documentation (Neitsch et al., 2005).

2.~~3~~ 4 Data collection

A summary of the datasets and associated organization sources, metrics, and measurement methods that were 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.

Geographic Information System (GIS) datasets were used f~~F~~or 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) that was 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 of reservoirs for the Han River basin was obtained from the Korea Rural Community Corporation (KRC).

~~For the hydrology and water quality assessments~~T~~, t~~he SWAT~~-~~ modeling outputs for a total of 237 sub-watersheds for the Han River basin, including ungauged locations, were used for the hydrology and water-quality assessments. The monitoring data for the hydrology include only streamflow and do not include data for the water~~-~~-balance components that are associated with ~~the~~ surface–groundwater interactions. The monitoring data for the water quality are not exhaustive. The period of the water quality components of interest for this study, such as the sediments, total nitrogen (T-N) and total phosphorus (T-P), is not sufficient to analyze long-term changes. The ~~daily~~ continuous daily 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 the record of 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 over a~~during the~~ six~~-~~-year periods~~s~~ (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~~ 5 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).

WThe watershed-–health assessment requires the indicator data for the hydrology and water quality to be simulated by the SWAT model., and Tthe detailed component selection is presented in Sections 2.56.3 and 2.56.4. This section briefly summarizes the model data and implementation and the statistical results of the calibration and validation.

2.45.1 Measured data for the SWAT model evaluation

The Han River bBasin was divided into 237 sub-watersheds and 1,987 HRUs for SWAT modeling. The sub-watershed delineation was defined by using the 90-–m SRTM DEM fromsupplied 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) waswere obtained from the KME (Figure 2b). A soil map that containeding texture, depth and drainage attributes was rasterized to a 90-–m grid size from a 1:25,000 scale vector map that was 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. 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). 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 (Hoengseong Dam, HSD;, Soyang Dam, SYD; and Chungju Dam, CJD) that are monitored by the Korea Water Resources Corporation and one water level station (PDD) that is 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 (Kangcheon Weir, KCW;, Yeoju Weir, YJW; and Ipo Weir, IPW) that are monitored by the Korea Water Resources Corporation were used. The flow and water quality of the Han River are affected by the discharge operations of these large dams and weirs; therefore, dam and weir operations must be incorporated into the modeling framework to enable successful modeling. In the SWAT model, dam operations are modeled based on measured daily discharges, measured monthly discharges, average annual discharges, or target storage volumes. In this study, the measured daily discharges from the four dams and three weirs were directly imported into the SWAT model.

For the calibration and validation of the stream water quality, ten years (2005–2014) of eight-day intervals for sediments, T-N, and T-P data were obtained from seven hydrology stations (SG, CSG, JW, KCW, YJW, IPW, and PDD) that arefor the hydrology monitored by the KME. Figure 2a shows the gauging stations for the SWAT modeling.

2.45.2 Calibration and validation of the model

The SWAT model was calibrated at seven locations in the main river reaches by 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 by using another five years (2010–2014) of data withusing the average calibrated parameters. In addition, the model was spatially calibrated and validated by using evapotranspiration and soil moisture data that were measured at two locations (SM and CM) and groundwater level data that were measured at five locations (GPGP, YPGG, YPYD, YIMP, and HCGD) over five years (2009–2013).

In this study, uncertainty analysis was performed for the hydrology by using the daily dam inflow using the SUFI-2 method. This method was chosen because of its applicability to both simple and complex hydrological models. SUFI-2 is convenient and easy to implement and widely used in hydrology (e.g., Freer et al., 1996; Cameron et al., 2000; Blazkova et al., 2002). In SUFI-2, parameter uncertainty considers all sources of uncertainty, e.g., input uncertainty, conceptual model uncertainty, and parameter uncertainty (Gupta et al., 2005). The degree to which uncertainties are considered is quantified by a measure called the P factor, which is the percentage of the measured data that are bracketed by the 95% prediction uncertainty (95PPU). Another measure that quantifies the strength of a calibration or uncertainty analysis is the R factor, which is the average thickness of the 95PPU band divided by the standard deviation of the measured data. The excellence of calibration and prediction uncertainty is judged based on the closeness of the P factor to 1 and the closeness of the R factor to 0. Twenty parameters were selected by sensitivity analysis for the uncertainty analysis. In this study, three iterations were performed with 1,300 (100+200+1,000) model runs in each iteration. The coverages of the measurements (P factor) and the average thickness (R factor) of the 95PPUs for the model predictions were 0.79 and 0.32, respectively, for the dam inflow during the calibration and validation periods.

~~The parameters were calibrated by trial and error until they achieved the necessary modeling performance.~~ In this study, both calibration and validation were manually performed by using a trial-and-error approach within recommended ranges to maximize the expert knowledge of watershed characteristics and modeling experience. The final values were selected based on a statistical evaluation of the performance measures. Twenty of the most influential parameters were selected for calibration. These parameters are related to surface-–runoff (CN2, CNCOEF, SURLAG, OV_N, and CH_N), evapotranspiration (ESCO), soil-–water (SOL_AWC and SOL_K), groundwater (GW_DELAY, GWQMN, ALPHA_BF, REVAPMN, and GW_REVAP), and reservoir-–operation (RES_ESA, RES_EVOL, RES_PSA, RES_PVOL, RES_VOL, RES_K, and EVRSV) processes. 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 the 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. T~~In the case of dam inflow, t~~he R^2 value for the dam inflow 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. T~~In the case of the dam storage volume, t~~he average R^2 for the dam-storage volume 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, that for the soil moisture was between 0.75 and 0.85, and that for 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, that for the T-N was between 0.46 and 0.82, and that for the 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 ≥ 0.6;~~,~~ Moriasi et al., 2007; Santhi et al., 2001) and were found to be satisfactory. Additionally, the model calibration and validation included the NSE with inverse discharge (1/Q) for low flow. The average NSE with inverse discharge (1/Q) during the calibration (2005–2009) and validation (2010–2014) periods was 0.35 at HSD, 0.53 at SYD, 0.30 at CJD, 0.54 at KCW, 0.47 at YJW, 0.69 at IPW, and 0.58 at PDD.

<Table 2>

2.~~5~~ 6 Data reconstruction for the watershed~~-~~health assessment

2.~~5~~6.1 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 that is 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~~ significantly affect ~~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~~ maintains the hydrologic regime, regulates the inputs of nutrients and organic matter, and provides habitats for fish and wildlife (U.S. EPA, 2012). In this~~e 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 the Han River basin, the percentage of each watershed area that was occupied by natural land cover (habitat blocks) was calculated by using GIS techniques. The green area metric was calculated as follows:

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

(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 the~~o~~ese areas to the local ground~~-~~water system (IPCC, 2007). The methods that are used to delineate the active river area involve GIS techniques and analyses of elevation, land~~-~~ cover, and wetland~~s~~ data. For~~ the~~ streamside areas for which criteria have not yet been decided~~ the criteria for identifying~~, an area with a width of 30–50 m~~meters~~ can be used as a cutoff to~~for~~ identify~~ing~~ streamside material contribution areas (U.S. 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 m~~meters~~ of the stream was calculated for the 237~~each~~ sub-watersheds in the Han River basin by using GIS techniques (Figure 3b). The active river area metric was calculated as follows:

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

(2)

<Figure 3>

2.~~5~~6.2 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 by using the Vermont Stream Geomorphic Assessment Protocols for~~ the~~ streams in~~of~~ Vermont, USA. These assessment protocols are GIS-based analyses that use~~ing~~ 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 conditions~~ 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 assessed~~performed~~ in a ~~manner ~~similar manner to w~~t~~hat was used for the stream-~~–~~condition categories of the Vermont Stream Geomorphic Assessment Protocols. The stream order was calculated for nine levels (Figure 4a) by using a DEM and stream map, and four river classifications were created through follow-up analyses with detailed land-~~–~~cover assessments (Figure 4b). F~~There are f~~our river classifications were used: ~~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:

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

(3)

<Figure 4>

<Table 3>

2.~~5~~6.3 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, insufficient~~there were not enough~~ gauging stations were available to fully assess the entire watershed over the entire~~full~~ thirty-year period. No~~There were no~~ data were available for the water-~~–~~balance components that were associated with ~~the~~ surface–groundwater interactions, except for the streamflow. Where unavailable, these long-term flow data ~~are~~ could~~not available, they can~~ be estimated by using hydrologic modeling techniques. Thus~~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 according to~~considering~~ the operation of water-~~–~~resource~~s~~ facilities ~~operation~~ (inflow and storage volume) in~~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 millimeters~~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. SThe surface--water and lateral groundwater flow interactions arewere veryof major importantce for the water balance in the Han River basin. In particular, the infiltration, return flow, and groundwater recharge arewere important factors for the entirewhole 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 overfor 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 yieldeds the storage ratio of the nine components. The storage ratios of the nine components were divided into four hydrologic classifications—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)—tofor 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:

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

(4)

<Figure 5>

2.56.4 Water quality condition

AThe assessingment of the water quality of athe 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 sediments (mg/L), T-N (mg/L), and T-P (mg/L) overfor a thirty-year period (1985–2014) (Figure 6). As part of the Basic Environmental Policy Act (BEPA), South Korea has specified eco-regional water--quality criteria tofor 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 values in the reference condition was calculated for each watershed. The water quality metric was calculated as follows:

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

(5)

<Figure 6>

2.~~5~~6.5 Aquatic habitat condition

The quality of aquatic habitats~~ is~~ depends~~ent~~ on the surrounding landscape and~~ the~~ hydrologic and geomorphic processes. Therefore, the habitat condition is affected~~partly accounted for~~ by~~through~~ indicators that represent~~ing~~ the~~o~~se assessment components. The potential for organisms to migrate upstream and downstream within a riverine system can also serve as an indicator of the 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). The EPA's National Lakes Assessment (NLA) identified poor lakeshore habitats 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:

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

(6)

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

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

(7)

<Figure 7>

2.~~5~~6.6 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 a component~~part~~ of its Nationwide Aquatic Ecological Monitoring Program for a six-year period (2008–2013). ~~Based on a statistical evaluation of these data,~~ T~~t~~hree biological indicators (TDI, BMI, and FAI) were chosen based on a statistical evaluation of these data 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 to~~for~~ estimate~~ing~~ the overall biological condition during the six-~~–~~year period~~s~~ (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 that are close to the reference conditions.~~ According to the Nationwide Aquatic Ecological Monitoring Program Report (Ministry of Environment, 2013), the~~ I~~i~~ndices 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 according to the Nationwide Aquatic Ecological Monitoring Program Report (Ministry of Environment, 2013), 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:

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

<Figure 8>

2.~~6~~7 Watershed~~-~~health index formulation

The definition of the watershed~~-~~health index was~~is~~ created~~presented~~ by the U.S. EPA for integrated watershed~~-~~health evaluations. The w~~W~~atershed 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 was~~is~~ considered healthy based on the 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. The inverse (1/X) of each value can be taken f~~F~~or 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 the watershed health was constructed by averaging the normalized indicator scores for each attribute. A sub-index was calculated first f~~F~~or 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~~ placinge more weight on some ecological attributes than on others and to use optional sub-indices may be appropriate~~exes~~. At this~~at~~ point, the process becomes subjective and a logical decision framework can be used to solicit and document expert opinions (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:

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

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

(10)

$$Watershed\ health\ index = \frac{(sub\text{-}index\ 1 + sub\text{-}index\ 2 + \cdots + sub\text{-}index\ x)}{Total\ number\ of\ sub\text{-}indices} \quad (11)$$

<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~~W~~, the w~~atershed health analysis for each component was conducted in the 237 sub-watersheds ~~as standard watersheds~~ of the Han River basin by using the data reconstruction results for the six components. The sampling areas that were used to explain the differences in the watershed~~-~~health results for each component were the 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 scores for the watershed~~-~~health assessment ~~calculated~~ according to ~~these~~ two assessment indicators (Figure 3). The spatial patterns of the watershed health for green areas were healthier in~~for~~ upstream watersheds because the natural land cover was greater the farther the watersheds were~~are~~ from~~ the~~ urban areas~~, the greater in the increase in natural land cover~~. The spatial patterns of the 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 integrated~~s~~ 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, this~~e~~ 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 reaches.

~~Figure 4 shows the stream geomorphology condition in the Han River basin.~~ Figure 12b shows the sub-index scores for the watershed~~-~~health assessment when~~calculated~~ using stream geomorphology indicators (Figure 4). The percentage of the length of the assessed stream channel in the reference condition was greater for the upstream watershed than for 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 or~~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 (Figure 5) and water-~~-~~quality (Figure 6)~~–~~ conditions ~~calculated~~ are shown in Figures 12c and d, respectively. The precipitation in the watershed directly affects the surface runoff and sediment transport and is the most important factor that affects~~impacting~~ the maintenance of the water quantity and can thus be used to identify~~ areas~~ critical areas 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 into groundwater and then via base flow (Randall and Mulla, 2001).

The sub-indices of the hydrologic condition that were calculated by the four hydrologic classifications, such as the total metric~~ (PREC and TQ)~~, surface process~~es~~ metric~~ (SQ)~~, soil water dynamics metric~~ (INFILT, SW, and LQ)~~, and groundwater dynamics metric~~ (PERCOL, RECHARGE, and GWQ)~~, and the water quality condition that was calculated by the sediment, T-N, and T-P were split into three periods of ten years—1985–1994, 1995–2004, and 2005–2014—to~~for the~~ assess~~ment of~~ changes over time (Figure 9). The test areas that were used to explain the differences in the~~ results of~~ watershed-~~-~~health results~~the~~ for the hydrologic and water quality components were~~are~~ the SYD~~ watershed~~ and CJD watersheds~~ located~~ in the upstream region and the PDD~~ watershed~~ and lower watersheds ~~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 because of~~due to~~ the slight increases in PREC and TQ; thus, the watershed water quality decreased~~was diminished~~. The health of the hydrology in the CJD watershed showed a decreasing~~ed~~ tendency in contrast to the SYD watershed because~~as a result~~ of the decrease in PREC and TQ (Figure 9b). T~~In the case of the PDD watershed and the lower watershed, t~~he groundwater of the PDD watershed was not sufficient, but the overall watershed-~~-~~health scores for the PDD and lower watersheds 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 negatively a~~e~~ffected the~~s 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 changes in 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. T~~On the whole, t~~he watershed's 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's health was poorer because of~~due to~~ worse results for the surface process~~es~~ metric and soil water dynamics compared to those of the 1995–2004 period (Figure 10a). However,~~ in the case of water quality,~~ during the last ten years (Figure 10d), the watershed's health increasingly improved in portions~~parts~~ of the Han River basin compared to 1995–2004 (Figure 10c), while the water quality of the Chungju dam (CJD) watershed deteriorated~~was growing worse~~. The water~~-~~quality policy of South Korea, which was 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).~~ Figure 11 shows the poor watershed health in terms of the hydrology (Figure 11a), water~~-~~quality (Figure 11b), and overlay results (Figure 11c)~~ of a combination of both.~~ The five poor levels for the~~of~~ hydrology and water quality were calculated as the difference between (b) and (a) in~~of~~ Figure 10 and between (d) and (c) in~~of~~ Figure 10, respectively. The spatial distributions of the poor watershed~~-~~health levels enable~~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 the 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 scores for the watershed~~-~~health assessment~~ calculated~~ according to ~~these ~~two assessment indicators (Figure 7). 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 seemed 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 integrated~~s~~ 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 for the 100201 standard watershed were 0.46 and 0.34, respectively, and the sub-index score of 0.28, which integrated~~s~~ the two normalized values, indicates~~d~~ 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 showed 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).~~ A sub-index analysis of the TDI, BMI, and FAI (Figure 8) was conducted, except in the no-data areas (North Korea) in the Han River basin (Figure 12f).~~ These~~ The relationships of the TDI, BMI, and FAI were found to be significantly correlated. T~~In the downstream areas, t~~he TDI, BMI, and FAI were~~are~~ worse in the downstream areas. 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 (Chl-a), low dissolved oxygen (DO) and biochemical oxygen (BOD), and high temperature. The normalized values of the 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 after 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 to~~for use in~~ determine~~ing~~

priority conservation areas.

3.2 Assessment of the 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 that were used to explain the differences in the watershed ~~-~~health results for each component were the 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 scores. The integrated watershed health exhibited a decreasing~~ed~~ 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 a distinctive weakness with respect to the hydrologic condition (0.06), especially in the surface (0.16) and groundwater (0.17). Although the 100201 standard watershed was a very healthy watershed, similar to~~like~~ the 101206 watershed, the former~~it~~ showed a distinctive weakness with respect to the water quality (0.1) and aquatic habitat condition (0.28). S~~It is important to develop s~~ystematic plans must be developed 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 the watershed ~~-~~health scores in the 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 by using monitoring data and SWAT modeling results. Six essential indicators of healthy watersheds were used in the assessment: 1) the landscape condition, 2) geomorphology, 3) hydrology, 4) water quality, 5) habitat, and 6) biological condition. In particular, a~~the~~ sub-index of the watershed health that was related to the hydrology and water quality was developed to assess ~~the~~ possible long-term changes in the watershed by using SWAT modeling results.

During the most recent ten-year period (2005–2014), the watershed's health declined, as indicated by the worse results for the surface process~~es~~ metric and soil water dynamics compared to those of the 1995–2004 period. The spatial distributions of the poor watershed-health levels revealed ~~the~~ vulnerable areas in portions~~parts~~ of the CJD watershed, upstream ~~of the~~ SYD watershed, and downstream ~~of the~~ PDD watershed with respect to the 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 to~~for use in~~ determine~~ing~~ priority conservation areas. Listing all the information of the watershed-health assessment can indicate vulnerable or healthy regions in the desired area and can provide basic data for action. The effectiveness of the watershed-health evaluation in this study can produce reliable information because this approach is entirely physically based. This approach can be utilized in a number of standard watersheds, local communities, and regions throughout the Han River basin and can be practically implemented in the watershed as a comprehensive watershed-management plan by government authorities or representative stakeholders.

Finally, the limitations of this study include the simulation of water quantity and quality data for possible long-term changes in the watershed model. Although the prediction of long-term water quantity and quality data with this modeling is essential to assess water-resource systems, the hydrologic and water quality conditions cannot be perfectly projected because of uncertainties in the models, climate data and other inputs that are required for the simulations. However, the results of this study are useful in terms of identifying potential watershed-health issues that are associated with ongoing watershed changes.

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

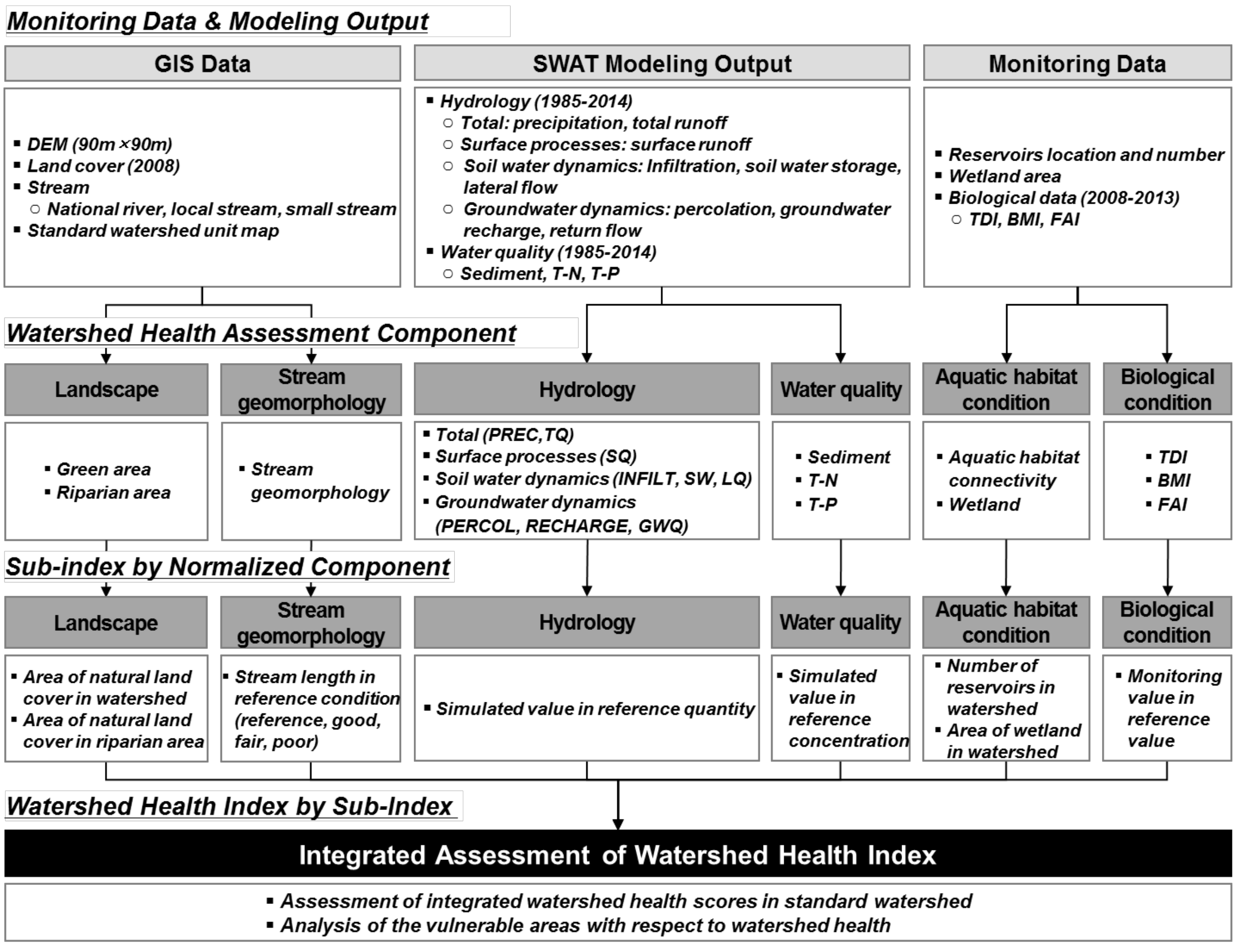

Figure 2. Locations of the (a) the Han River basin's boundaries and gauging stations for the watershed (SWAT) modeling, (b) land--cover classification, and (c) test area.

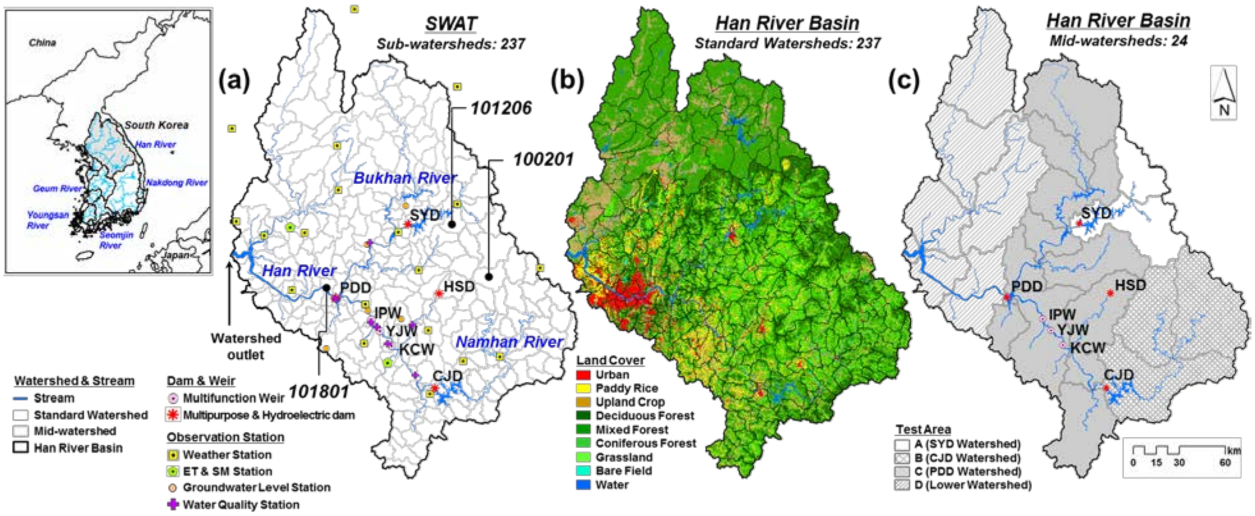

Figure 3. Landscape condition for the (a) green area and (b) riparian area.

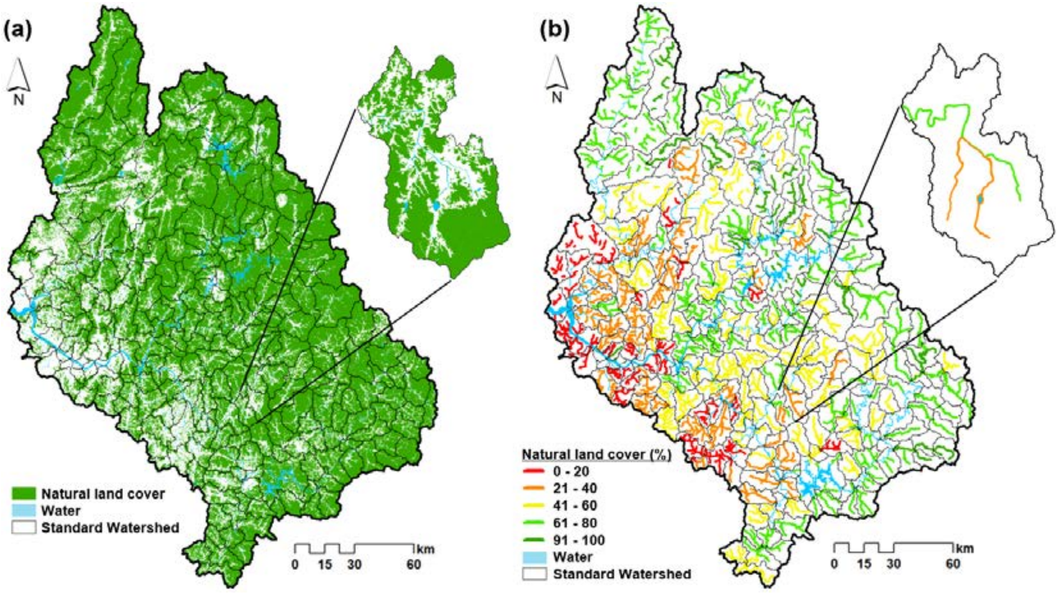

Figure 4. Stream geomorphic conditions: (a) stream order and (b) stream geomorphic conditions.

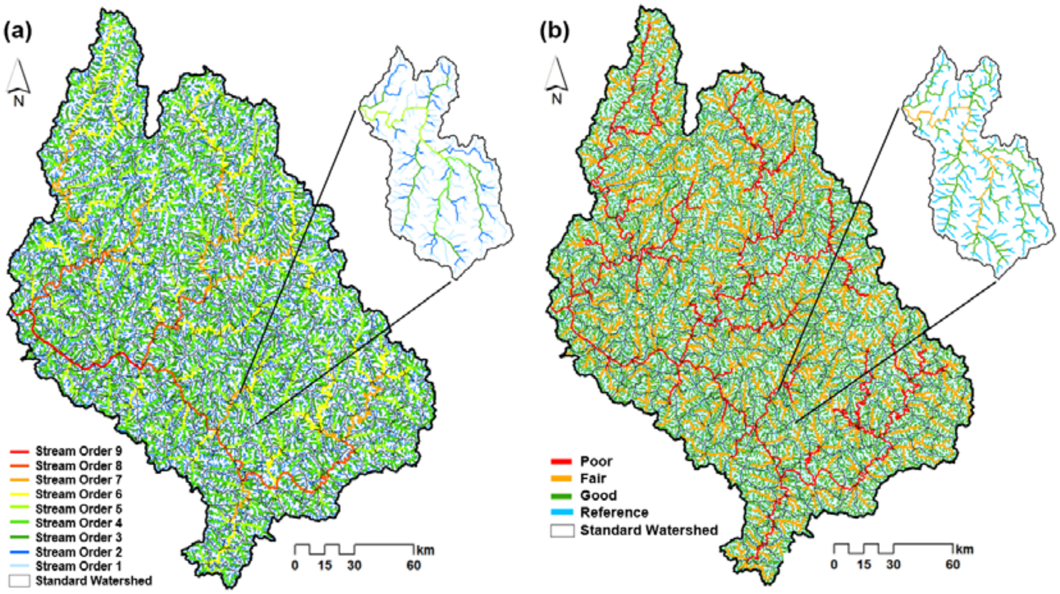

Figure 5. Hydrologic condition for the (a) precipitation, (b) total runoff, (c) surface runoff, (d) infiltration, (e) soil water storage, (f) lateral flow, (g) percolation, (h) groundwater recharge, and (ib) return flow according to the hydrological (SWAT) modeling for the period from 1985 to 2014 in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

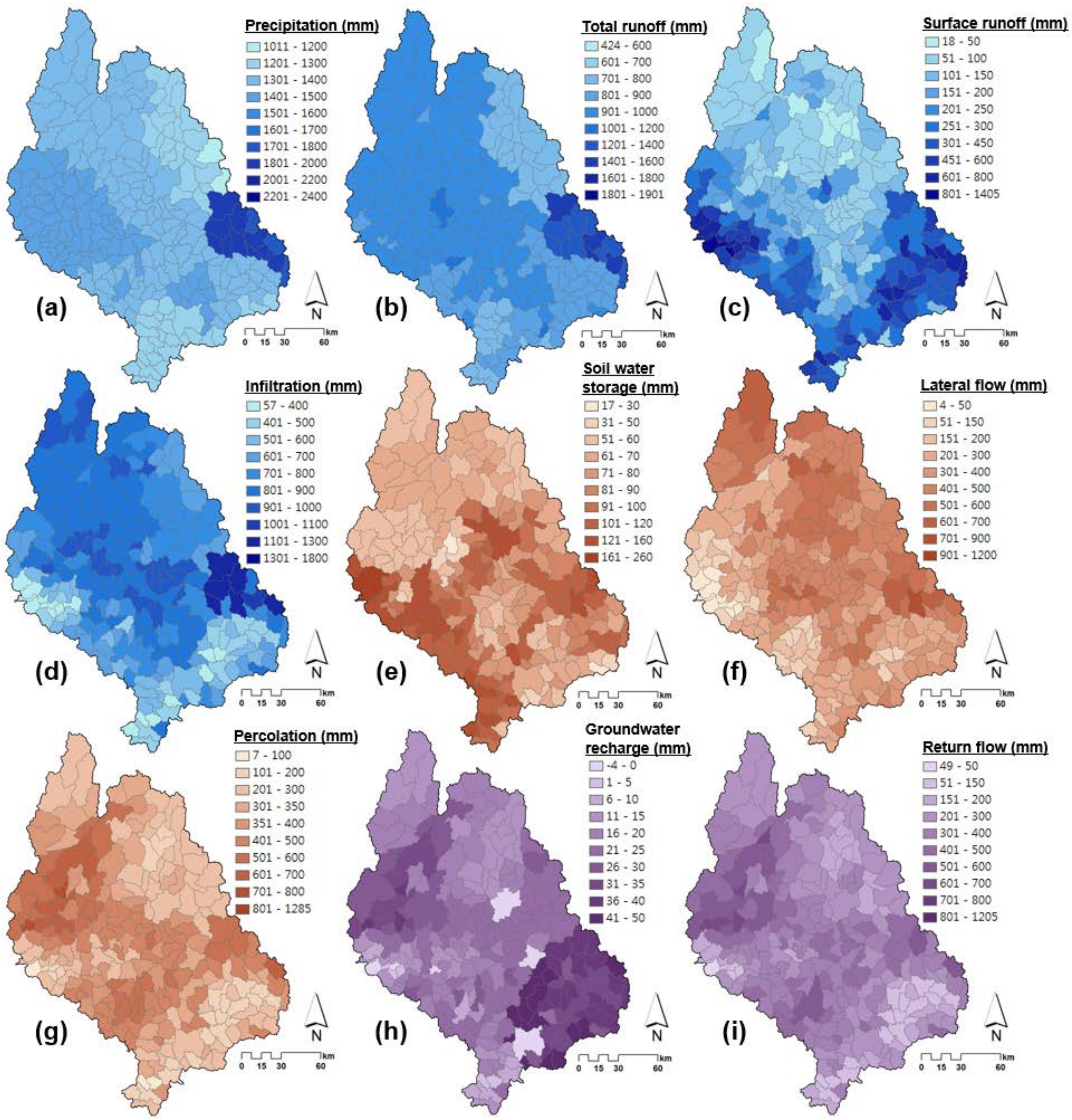

Figure 6. Water quality condition for the (a) sediment, (b) T-N and (c) T-P according to the hydrological (SWAT) modeling for the period from 1985 to 2014 in the Han River basin.

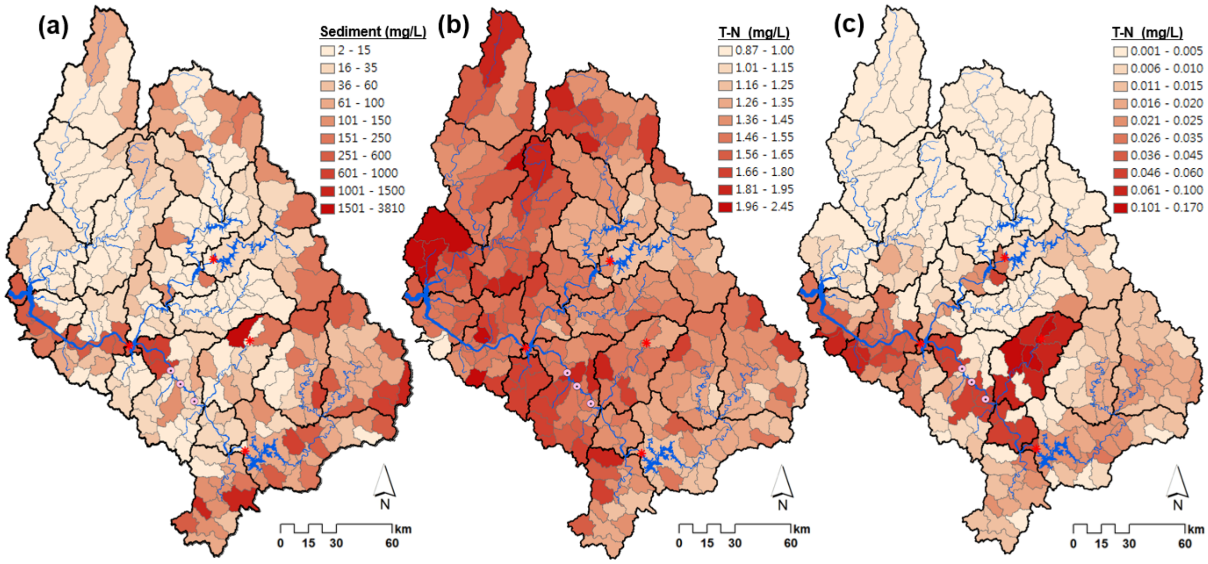

Figure 7. Aquatic habitat conditions for the (a) aquatic habitat connectivity and (b) wetlands.

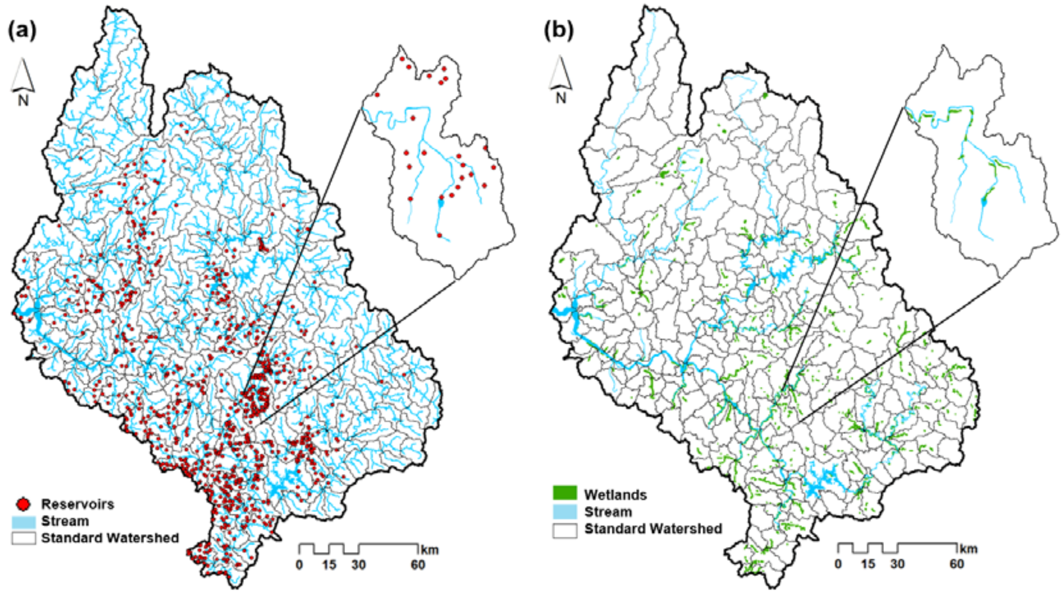

Figure 8. Biological conditions of the (a) FAI, (b) BMI and (c) FAI according to the observed monitoring data for the period from 2008 to 2013 in the Han River basin.

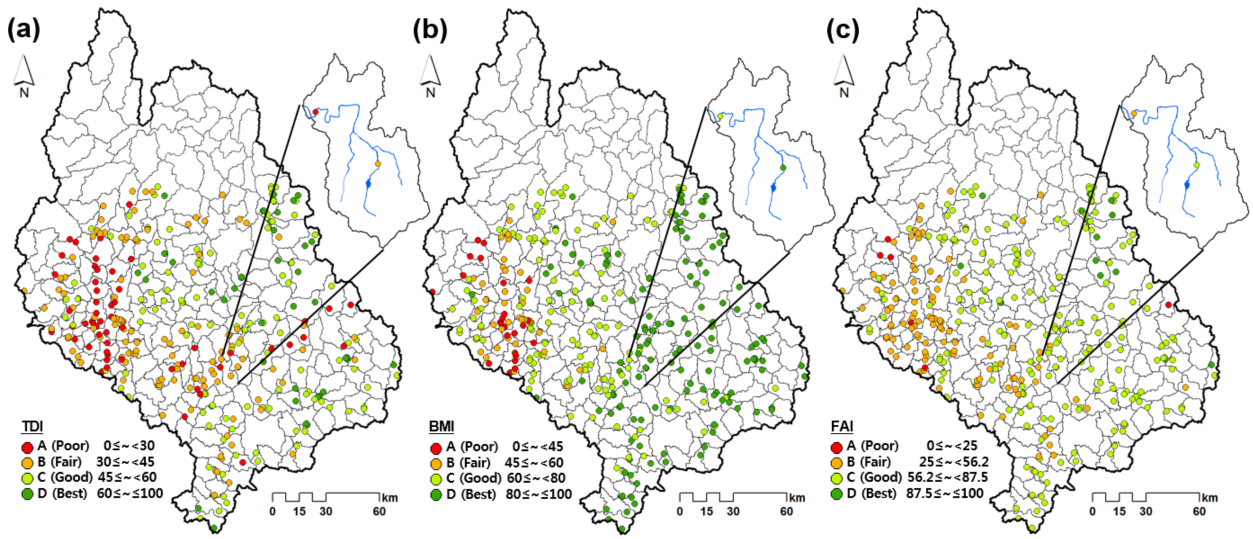

Figure 9. Change in hydrology and water quality for the (a) A (SYD watershed), (b) B (CJD watershed), (c) C (PDD watershed), and (d) D (lower watershed) test areas for three ten-year periods.

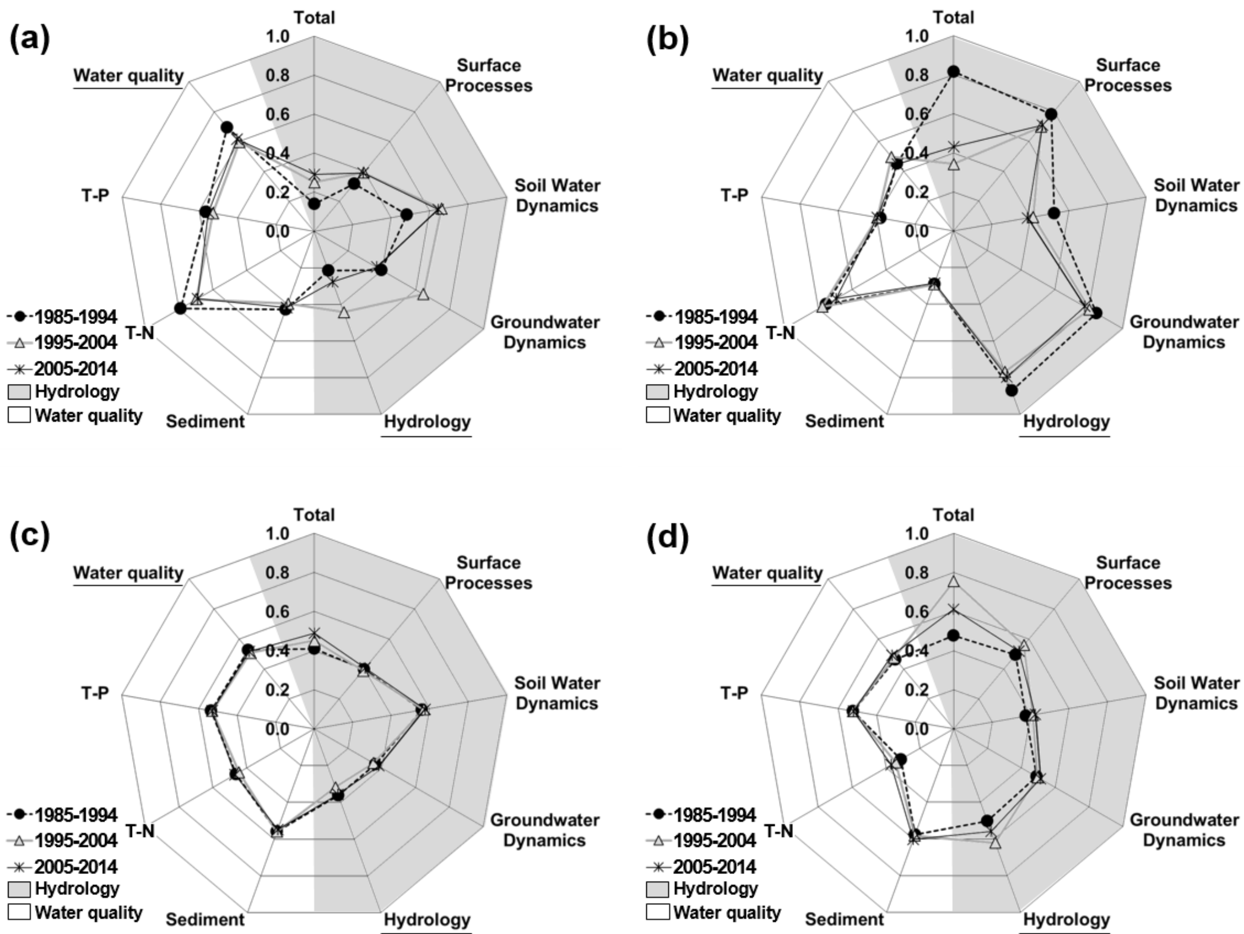

Figure 10. WThe watershed--health index score changes for the hydrologic (a and b) and water quality (c and d) conditions during the period 1995–2004 and the most recent ten-year period (2005–2014) based on the reference period (1985–1994).

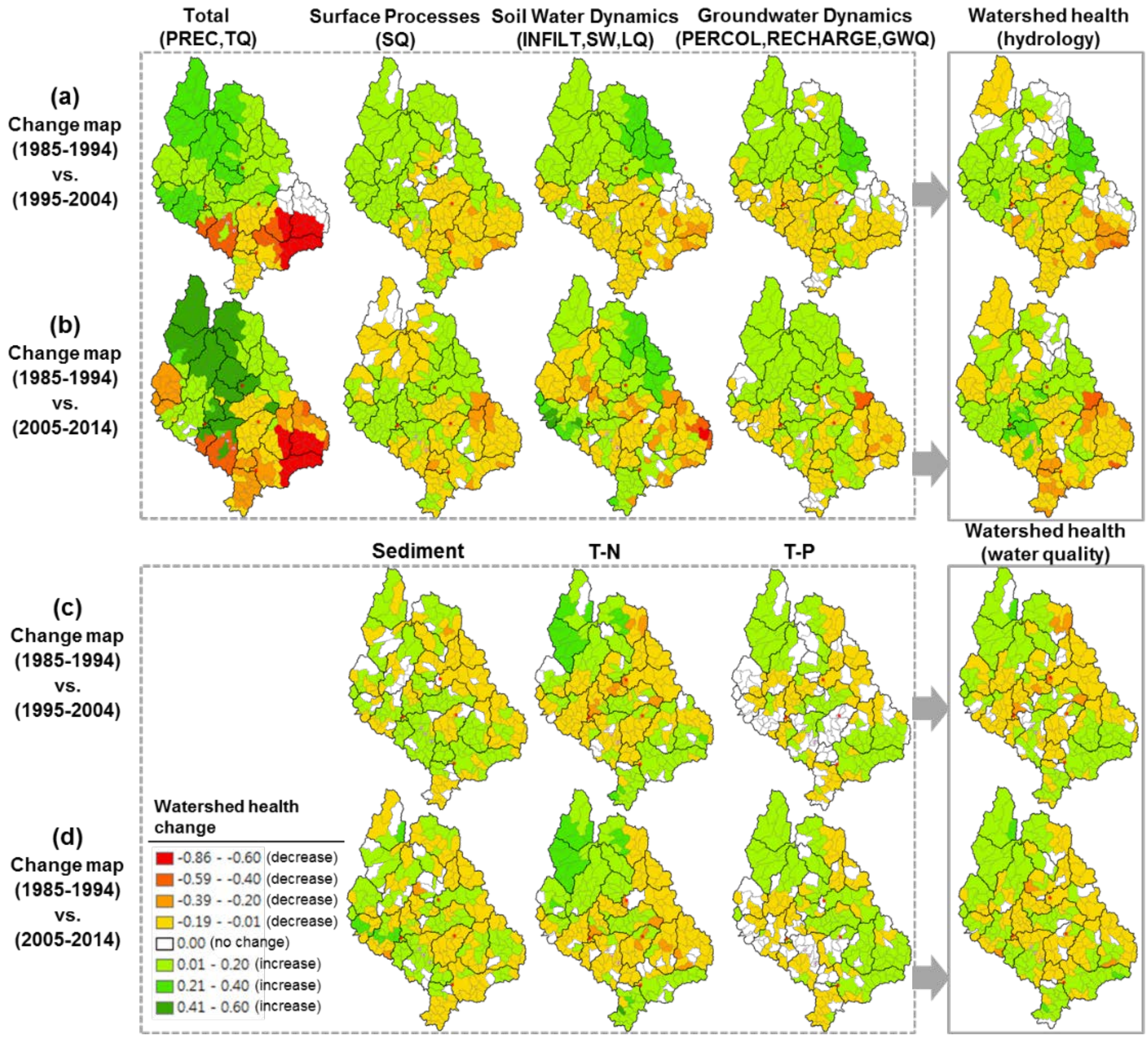

Figure 11. P~~The p~~oor watershed health as revealed by the (a) hydrology, (b) water ~~-~~quality, and (c) overlay results.

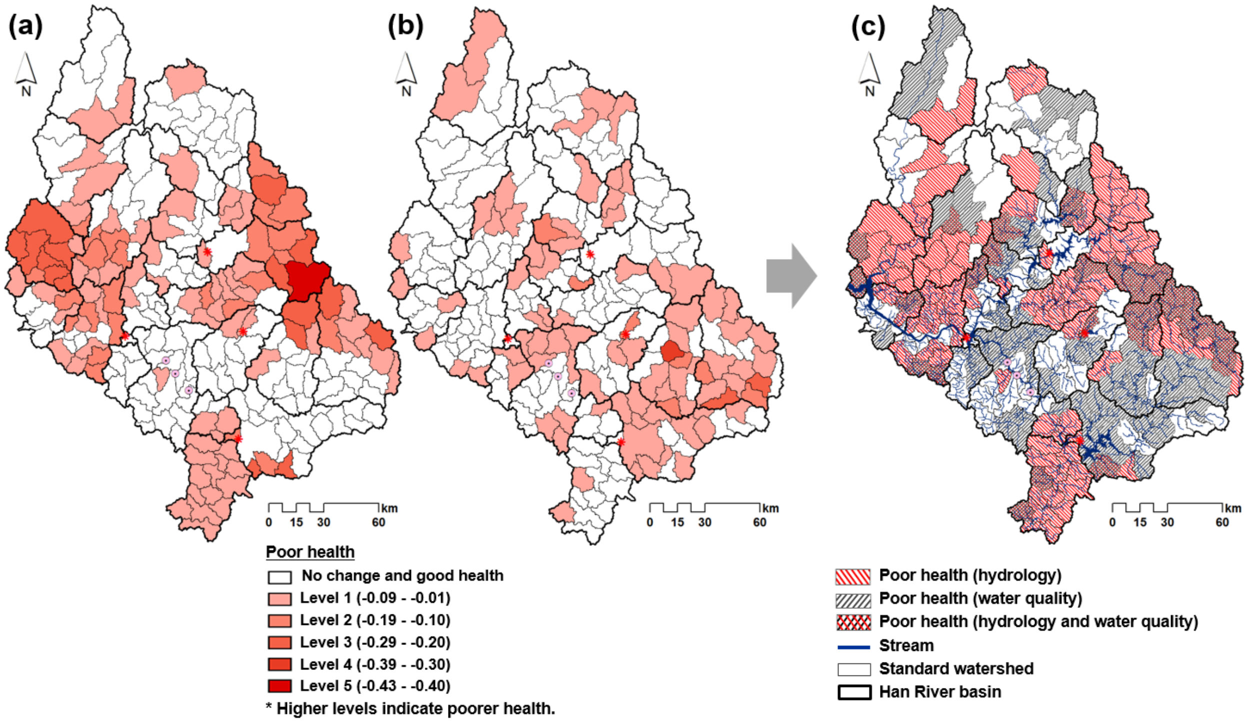

Figure 12. W~~The results of the w~~atershed~~-~~ health index results for the (a) landscape, (b) stream geomorphology, (c) hydrology, (d) water quality, (e) aquatic habitat, (f) biological condition, and (g) integrated watershed health.

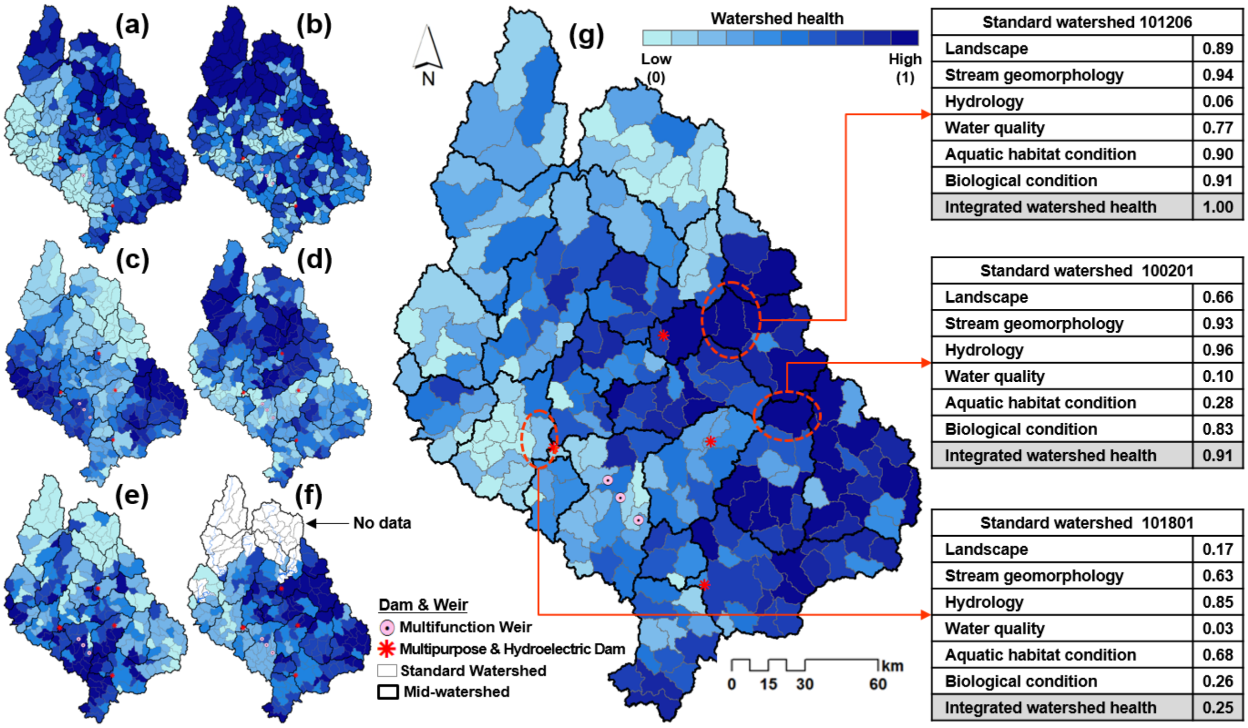

Table 1 Metrics and summary dataset that was used to~~for the~~ assess the~~ment of~~ watershed health in the study watershed.

Component (metric)	Measurement method	Dataset
Landscape		*GIS data*
Green infrastructure metric	Percentage of the watershed that is 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 the 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 the assessed value in the 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 the watershed that is occupied by wetlands	Land cover 2008
Biological condition		*Monitoring data (2008–2013)*[e]
Biological metric	Percentage of the assessed score in the 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 the 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
	NSE (1/Q)	0.44	0.26	0.49	0.56	0.34	0.25	0.47	0.60	0.46	0.47	0.62	0.75	0.65	0.51
	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	-	-	-	-	-	-	-	-	-	-
Groundwater 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
Sediment (tons)	Locations	SG		CSG		JW		KCW		YJW		IPW		PDD	
	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 conditions categories (Kline et al., 2009) and stream order for the watershed--health assessment of the 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; the channel geometry is likely to be in balance with the flow and sediment that are 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 adjustments 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 that are produced in its watershed.	Urban river, National river	6–9

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

Component	Source	Reference condition
Hydrology		
Precipitation	River~~-~~-basin average of 30 years (1985–2014) as 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	L~~The l~~evels greater than the "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 as 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~~ "B~~b~~est" 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

Table 5 W~~Results of w~~atershed~~-~~health score results 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**