# Effect of climate change on long-term river geometric variation in Andong Dam watershed, Korea

Jong Mun Lee, Jungkyu Ahn, Young Do Kim and Boosik Kang

## ABSTRACT

Because of multifunctional weirs installed as part of large river regulation works in Korea, water quality problems have arisen from environmental changes in tandem with decreased flow rates. However, there has been limited research into the green algae removal effect, water quality improvement in congested waters, dam and weir operations, and consequential riverbed changes. Studies regarding outflow in a basin, the application and development of sediment load output analysis methods, feasibility of related dam operations, and riverbed patterns have been separately performed. However, basins and rivers should be analyzed by an integrated method instead of an individual one. Therefore, in the present study, the effect of congestion on a river connected to a dam/weir and estuary bank was analyzed based on climate change scenarios HadGEM3-RA RCP 4.5 and 8.5, with the aim of integrating individual studies using watershed and river models. Flow was controlled by dam- and weir-related discharge simulations. Variations in the riverbed caused by the transfer of suspended load in the downstream region were analyzed for both long and short durations. The results of this analysis suggest that given future climate change scenarios, the width of the river and riverbed variations in the riverbed are expected to rise.

**Key words** | climate change scenario, river model, riverbed variation, suspended load, watershed model

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## HIGHLIGHTS

- Impact of long-term geometric variation in rivers.
- Analysis of climate change scenarios.
- Integrate watershed and river.
- Variations in the riverbed for both long and short durations.
- Analysis of both watershed runoff and sediment transport in a river.

## INTRODUCTION

Global warming and climate change are now some of the gravest threats on earth, a fact agreed upon by most countries. Currently, climate variability is unpredictable. This has led to changes in various systems such as ecosystem formation, biological growth, human life, and the hydrologic cycle. Many studies have aimed to develop strategic responses at a national level, such as policies to reduce greenhouse gas emissions, to mitigate in advance the risks of climate change and destruction of social systems (Mora & Zapata 2013).

Recently, waterfront facilities in Korea have increased because of the Four Major Rivers Project. There is also a growing demand for technology to ensure the safe and

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efficient management of river and waterside facilities. For this reason, systematic prediction and management of erosion and sedimentation based on the characteristics of sediment transport is required. Specifically, eroded sediment from developed areas is transported downstream, which increases the turbidity of downstream water for long periods, causing water quality problems for drinking water, deteriorating the water environment, and affecting ecological habitat. In addition, the shape of a stream changes because of sediment load in a river that flows from the basin. Nevertheless, changes in river geomorphology have not been considered in the planning of river emergence, flood control, and environmental functions. For example, estimates of rainfall, discharge, and hydrologic curves made over tens to hundreds of years are applied to the shape of the current stream to estimate flood level during the design stage of river management plans. However, these flood levels correspond to past measurements of river geometry, and future floods may occur several years to several decades later. In other words, future phenomena predictions using historical data may be erroneous because of different timescales. The shape of a river varies with time and should be considered not as a condition of a given river but as an object that requires prediction. Considerations of stream shape variation should be included in all future river planning.

A total of 10 multipurpose dams are located in the Nakdong River basin. The role of multipurpose dams is flood control, water supply, and electricity production. However, problems are caused by artificial facilities such as dams. First is sudden bad weather caused by artificial topographic change, and second is deterioration of the surrounding environment caused by change and destruction of the balance between regional ecosystems and symbiosis (Jeon *et al.* 2002). Climate change from dam construction can be caused by artificial lakes. Fresh water in lakes has a much higher heat capacity and lower water volume than soil. In summer, the water temperature is lower than in the atmosphere, which reduces the temperature. In winter, the temperature rises. In addition, the area around a lake, which has a large surface area and a small amount of water, has a more unusual climate than inland areas because of evaporation at the lake surface and the entry of heat (Lee *et al.* 1990). In addition, there is an increase in the number of fog days and the fog duration is long, so the photosynthesis rate is reduced because of the decrease in sunshine duration. As a result, the production capacity of crops can be reduced, resulting in substantial economic damage (Yoon *et al.* 1997).

Since the 1990s, there have been many studies to assess the impact of climate change on water resources. Recently, as abnormal weather phenomena have become more frequent, interest in the influence of river flow rate and water quality because of climate change has increased (Kang *et al.* 2013a). In the mid- and late 1990s, the effects of future climate change on the water cycle of watersheds were investigated (Lins 1994; Mitosek 1995). Moreover, numerical modeling techniques and climate and hydrologic model developments have attempted to quantitatively evaluate the variability of future water resources (Vogel *et al.* 1997; Lettenmaier *et al.* 1999).

In a study of the effect of domestic climate change on water resources, Jung *et al.* (2011) evaluated the influence of increased climate variability on the flow and water quality in the Andong Reservoir watershed. In addition, Special Report on Emission Scenarios (SRES) A1B scenarios for the Namgang Reservoir watershed were produced using downscaling methods and future climate scenarios, and applied to the Soil and Water Assessment Tool (SWAT) model to predict future water quality and outflow (Kang *et al.* 2013a; Lee *et al.* 2013). Kang *et al.* (2013b) discussed the A1B scenario for the Seo Nakdong River basin, and then applied it to the SWAT model to analyze how climate change affects water quality and runoff in a test watershed. Kim *et al.* (2011) created a future scenario based on the A2 scenario provided by the Intergovernmental Panel on Climate Change (IPCC) and used SWAT to simulate floodgate and hydrologic influences over sub-basin rural areas based on climate and land-use changes.

Using statistics, Arnell & Reynard (1996) estimated future rainfall and runoff for the watersheds of several rivers in the UK and compared them with their current values. Kling *et al.* (2012) constructed a model using 120 years of historical data to determine the appropriate watershed runoff and calculated future runoff in the Danube Basin of Austria using the A1B scenario. Willson & Weng (2011) used the B1 and A1B scenarios to produce climate change scenarios up to the year 2030 using the downscaling method and analyzed runoff and water quality changes in the Des Plaines River watershed, Illinois, using the SWAT model. Mango *et al.* (2011) estimated runoff in Kenya's Mara River basin using statistical methods and randomly generated a land-use scenario and rainfall-runoff model.

Regarding research on river geometric variations under climate change conditions, Nathalie *et al.* (2003) used geographic information system (GIS) incorporated models to evaluate the potential impacts of climate and land-use changes on the fine suspended sediment load and transported sediments in the Upper Rhine River Delta. According to the United Kingdom Meteorological Office High-Resolution General Circulation Model climate change scenario, the erosion rate in the Alps is increasing, while those in some watersheds in Germany are declining. Average erosion in the entire Upper Rhine River Delta watershed is expected to increase by ~12%. However, the sediment load in the delta decreased by ~13%. Samaras & Koutitas (2014) studied the impacts of climate change on the amount of watershed-coastal sediment loads. They analyzed the correlation between the SWAT and PELNCON-M (a shoreline evolution model), numerical modeling based on the sandy coast and upstream watershed of Chalkidiki, northern Greece, applying the results to watershed and coastal areas with extreme rainfall.

Chao *et al.* (2016) used dynamic downscaling climate projection data to evaluate bed changes and sediment transport in the Gaoping River in southern Taiwan. As a result, the peak runoff was 1.48 times greater in the late 21st century than in the late 20th century. However, the Thalweg declined 19%, negatively correlating with peak emissions in extreme floods. Sanyal (2017) analyzed riverbed changes caused by dam construction along the Teesta River in India, using the Delft3D model. In post-dam scenarios, bed transfer may be reduced, resulting in more frequent flooding. Alizadeh *et al.* (2017) explored two ideas for improving artificial neural network-based models for suspension sediment prediction in several steps. The Skagit River in the United States was selected as a case study. The results of that study show that it is possible to achieve acceptable prediction of daily suspended sediment concentrations up to 3 days prior, using the proposed method.Yaseen *et al.* (2019) presented a comprehensive review and application of the Extreme Learning Machine (ELM) model. To illustrate the application of that model, the Kelantan River on the Malay Peninsula was selected as a case study. The review consists of all implementations of the hydrologic process. In river flow prediction, the improved ELM performed adequately. Ahn *et al.* (2019) developed a riverbed variation scheme with consideration of climate change for the Nakdong River in Korea. The hydraulic model GSTARS was used to analyze the sensitivity of bed changes according to the number of stream tubes and a sediment transport formula. As a result, riverbed changes were appropriately simulated when there were three stream tubes and the Yang sediment transport formula was applied. As the flow rate increased because of climate change, riverbed change was large and the channel tended to narrow.

Studies have analyzed riverbed changes in watersheds and rivers, but the main causes of river changes are inflow, sediment load, and amount of pollutants from the watershed. Thus, it is necessary to develop a method to analyze both the watershed and stream channel simultaneously. In the present study, we developed a technique to integrate and analyze watersheds and rivers, and verified its applicability to the Nakdong River basin in Korea for predicting future river flow and channel geometric changes. The diagram of the study is shown in Figure 1. We modified data and research results of Lee (2016). Among the Fifth Assessment Report (AR5) scenarios provided by the IPCC, Hadley Centre Global Environmental Model version 3 regional climate model (HadGEM3-RA) Representative Concentration Pathway (RCP) 4.5 and 8.5 scenarios were used to consider the impact of climate change on the predictions. We predicted future climate scenarios from 2016 to 2100 and applied the scenarios to the hydrologic model SWAT to predict sediment yield and inflow changes in the basin. Runoff and sediment load variations of the Nakdong Basin under climate change were compared and analyzed with respect to the climate scenarios. In addition, we analyzed the influence of climate change and discharge changes of the dam and weir on the major flow characteristics. The aim was to investigate the influence of discharge changes from the dam and weir on variation of the upstream and downstream riverbed.

## MODEL DESCRIPTION

In order to develop a method to simulate climate change, watershed runoff, and long-term river geometric change

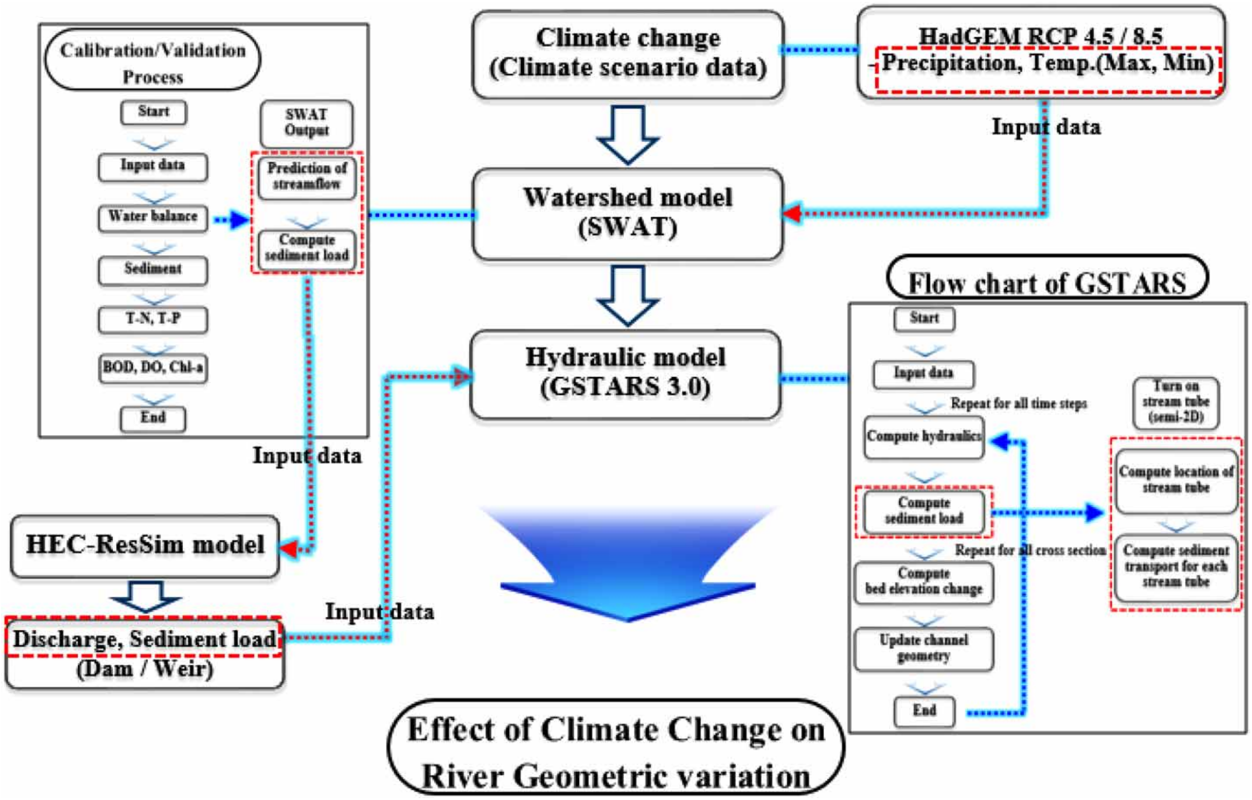

**Figure 1** | Schematic diagram of this study.

patterns in a sequential manner, suitable models were used for each analysis. The characteristics of each model are described in this chapter.

## Climate change scenarios

In IPCC AR4, factors affecting future greenhouse gas emissions, such as population, technology, and economic development, are divided into four SRES scenarios (A1, A2, B1, and B2). In contrast, the RCP in AR5 estimates those concentrations as human activity affecting the atmosphere. The RCP scenario was developed because of the need to introduce new scenarios to compensate for the aging and relevance of SRES data and to improve accuracy. There are many types of socioeconomic scenarios, one of which has the meaning ‘representative’. The word ‘pathway’ is also used to highlight changes in greenhouse gas concentrations over time. The RCP scenario is divided into RCP 2.6, 4.5, 6.0 and 8.5, depending on the radiative forcing (W/m$^2$) (NIMR 2011).

To simulate changes in rainfall patterns caused by climate change, standard meteorological agency scenario HadGEM3-RA data were used, based on HadGEM2-AO, a global atmosphere-ocean coupled model at the Hadley Center (Table 1). The Climate Change Information Center has provided its own data for the Korean peninsula (12.5 km), which consists of various types, such as Korean peninsula forecast data (12.5 km), South Korea detailed forecast data (1 km), the climate extremes index, and data for each administrative district, but only using single model data developed in the UK.

**Table 1** | HadGEM3-RA models and related institutions

| Modeling center | Model | Institution |
|---|---|---|
| KMA | HadGEM3-RA | Korea Meteorological Administration |

## SWAT (Soil and Water Assessment Tool)

After simulating changes in rainfall patterns, it is necessary to predict the flow, sediment load, and pollution load into a river watershed based on the results. The SWAT model developed by the Agricultural Research Service of the United States Department of Agriculture was selected for hydrologic water simulation. SWAT is a physical, semi-distributed, long-term rainfall-runoff model consisting of four parent types, i.e., hydrology, soil loss, nutrients, and channel tracing. It is used to predict the impact of land management methods on runoff, sediment load and agro-chemical behavior, depending on soil type, land use, and land management status in large, complex watersheds over a long period (Arnold *et al.* 1998). Regarding the hydrology parent type, surface runoff was calculated using the Soil Conservation Service (SCS) runoff curve method and the Green and Ampt penetration method by Hydrologic Response Unit (HRU). Lateral runoff is based on the kinematic storage model. Lateral subsurface flow, or interflow, is the streamflow contribution that originates below the surface but above the zone where rocks are saturated with water. Lateral subsurface flow in the soil profile (0–2 m) is calculated simultaneously with redistribution. A kinematic storage model is used to predict lateral flow in each soil layer. The model accounts for variations in conductivity, slope, and soil water content. Infiltration was calculated by subdividing soils into as many as 10 layers using the linear low-water discharge tracing method. The Hargreaves, Priestley-Taylor, and Penman-Monteith methods were used to calculate potential evapotranspiration. The Ritchie method was used to isolate and simulate the evapotranspiration of crops and soil.

## HEC-ResSim

HEC-ResSim is a program developed as a part of the next generation of software development projects to simulate the behavior of reservoirs with various requirements and constraints (Klipsch & Hurst 2007). The program is designed to support reservoir flood control, water supply planning, detailed reservoir regulation, and real-time decision-making. The purpose of this program is to optimize operation of the reservoir system for making the most of water to meet flood control needs and maximize water supply reliability under a variety of constraints. Limitations of the model are imposed by the characteristics and problems of storage systems with multiple storage and control points.

## Generalized sediment transport model for alluvial river simulation, version 3.0 (GSTARS 3.0)

Numerical studies of riverbed variation can be divided into 1, 2, and 3D numerical models, depending on the size of the model. Two- and three-dimensional models are useful for estimating short-term bed changes in short segments, such as near piers and drainage structures. Long-term simulation of relatively long sections is time-consuming and laborious. To calibrate 2D and 3D numerical simulation models, one needs data in two and three dimensions. However, owing to time and budget limitations, data are limited in some regions, and 1D measurements are by far the most common (Ahn 2016). For this reason, many researchers have concluded that 1D numerical models of long-term fluctuations are appropriate (White 2001; Yang & Simões 2008; Morris & Fan 2010). Long-term changes of river geometry are predicted by the amount of flow and sediment entering from the basin. For this purpose, the GSTARS3 semi-2D stream channel geometric model was used. GSTARS3, developed by Yang & Simões (2002) of the U.S. Bureau of Reclamation, has the capability of predicting hydraulic properties and geometric changes in alluvial channels. It can only simulate steady or quasi-steady flows, so it is limited in its application to extreme changes in flow rate and water level with time. However, there is no major difference between simulations of steady and unsteady flow for long-term riverbed changes (Ahn *et al.* 2013). The GSTARS3 model simulates flow and bed variations in a semi-2D manner. For 2D simulations such as in Figure 2, the stream tube concept was applied. This concept divides the river cross-section by a stream tube, and flow velocity and riverbed changes are calculated for each tube individually.

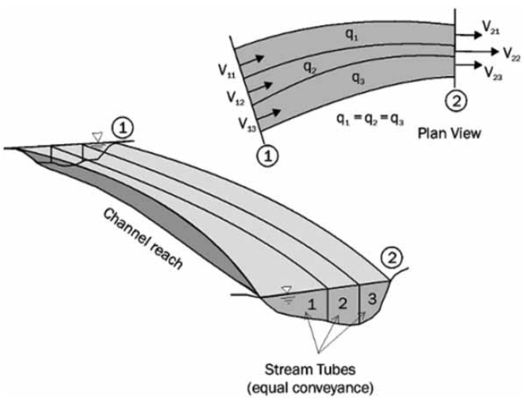

**Figure 2** | Schematic representation of stream tube concept (Yang & Simões 2002).

### Sediment transport functions: Yang (1973) + Yang (1984)

When the riverbed material is sand, Yang's non-dimensional flowing water force equation is used:

$$\log C_{ts} = 5.435 - 0.286\log\frac{wd}{v} - 0.457\log\frac{U*}{w} + \left(1.799 - 0.409\log\frac{wd}{v} - 0.314\log\frac{U*}{w}\right) \times \log\left(\frac{VS}{w} - \frac{V_{cr}S}{w}\right) \quad (1)$$

where $C_{ts}$ is the sediment load concentration (ppm by weight), $w$ is the sedimentation velocity of sediment load particles, $d$ is the sediment particle diameter, $v$ is the kinematic viscosity of water, $U*$ is the shear velocity, $V$ is the average flow velocity, $VS$ is the unit stream power, $S$ is water surface or energy slope, and $V_{cr}$ is the flow velocity at the initial motion of riverbed particles.

When the riverbed is composed of gravels, the following should be applied instead:

$$\log C_{tg} = 6.681 - 0.633\log\frac{wd}{v} - 4.816\log\frac{U*}{w} + \left(2.784 - 0.305\log\frac{wd}{v} - 0.282\log\frac{U*}{w}\right) \times \log\left(\frac{VS}{w} - \frac{V_{cr}S}{w}\right) \quad (2)$$

where $C_{tg}$ is the total gravel concentration in parts per million by weight. The coefficients in Equation (2) were determined from 167 sets of laboratory flume data.

## METHODOLOGY

### Study area

The study area was the Nakdong River basin in South Korea (Figure 3). This basin is in the southeast of the peninsula, between 127°29′ and 129°18′E and 35°03′ and 37°13′N. It is the second-largest Korean basin in width, bounded by the Han River basin in the north, Geum and Seomjin River basins in the west, and the Taebaek mountain range in the east, which forms the east coast basin. The watershed area is 23,384.21 km, or 25.9% of South Korea, and the river length is 510.36 km. As of 2015, total precipitation in the Nakdong River basin was 1,207.9 mm. From upstream of Andong Dam to the Sangju weir area was 984.84 mm. The average annual temperature is 12.5 °C. Water quality of biochemical oxygen demand (BOD) and total phosphorus (T-P) downstream of Andong Dam, a representative point in the middle region, was 1.0 and 0.015, respectively, which satisfies the target qualities of 2.0 and 0.04.

The Nakdong River basin is smaller than the United States or Europe and has a steep watershed slope. It is steep and a hydrologic feature that flows out at a time because of heavy rainfall (MOLIT 2009). Recently, the Korean government constructed 16 multifunctional weirs and performed dredging in connection with the Four Major Rivers Restoration Project. Among these, eight weirs were built along the Nakdong. Construction of artificial structures such as dams and weirs in rivers can

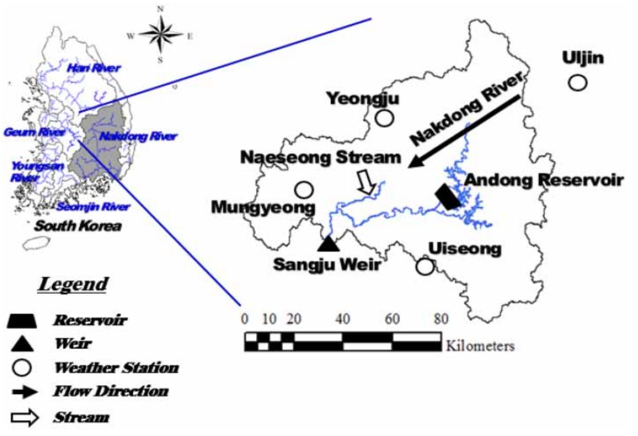

**Figure 3** | Study area.

adversely affect flow rate changes and water quality. Therefore, the Andong Dam – Sangju weir area, where the dam and the double weirs are constructed, was selected as the research area.

The specific simulation area was the section from downstream of Andong Reservoir to the Sangju weir. It is necessary to analyze bed variations because of weir construction, but it is difficult to simulate these variations and acquire data by artificially manipulating weir gates and structures. Therefore, the chosen simulation section had no artificial structures. The main stream length is 76.7 km, and the tributaries are Banbyeon Stream, Naeseong Stream, and Yeong River. The Yeong River is 12.5 km from the Sangju weir, which is at the downstream boundary. Naeseong Stream is 20.4 km upstream and Banbyeon Stream is 76.2 km upstream. During the Four Major Rivers Project, a total of 40.9 million $m^3$ was constructed.

## Research methods

We developed a technique to integrate and analyze watersheds and rivers, and verify its applicability to the Nakdong River basin for predicting future river flow and channel geometric changes.

We used the HadGEM3-RA RCP 4.5 and 8.5 climate scenarios for future climate scenario analysis. Using the dynamic quantile mapping technique, future rainfall was calculated for 2016–2100 and applied to the SWAT model. We calculated future discharge amounts and sediment load data through SWAT simulations. From the calculated data, the discharge amount and sediment load for Andong Reservoir were applied to the GSTARS3 model as a future scenario to analyze long- and short-term riverbed adjustments under the climate change scenario.

### Prediction of climate scenarios

For the climate scenarios, we used daily temperature and precipitation from 2016 to 2100. Full-watershed data under the two climate change scenarios (HadGEM3-RA RCP 4.5/8.5) can be used to predict long-term runoff inputs and future available water resources. We used data from four meteorological measurement stations in the Nakdong River basin (Figure 3). Daily maximum and minimum temperature and precipitation data were produced and used as SWAT inputs. The baseline period was 1 January 1981 to 31 December 2000 and verified against future scenario results.

### SWAT data

*Topographic data*. To determine model applicability and physical characteristics of the watershed, we used GIS-based data in the SWAT model (Figure 4). A digital elevation model (DEM) with resolution 30 m was used to pre-process terrain during SWAT model construction. The land-use index was derived from a 30-m land-cover map provided by the Ministry of Environment's environmental spatial information service. Soil maps are key data for water

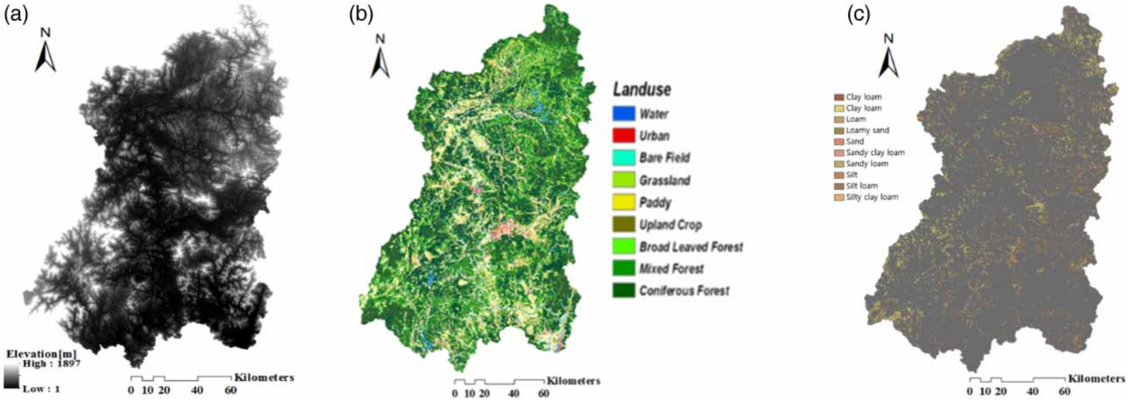

**Figure 4** | Topographic data of the SWAT model. (a) DEM; (b) land use; and (c) soil.

balance analyses. We used a 1:25,000 precision soil map provided by the Rural Development Administration's Soil Environmental Information System.

*Validation of flow and water quality*. To simulate long-term runoff using SWAT, we performed multi-point detection and correction sequentially from the most upstream part of the study area to the final exit point. Therefore, the HRU was constructed considering the location of the dam and weir, then calibrated and corrected. Tables 2 and 3 show the sequential flow of water quality tests and calibration section of the upstream Andong Reservoir and Naeseong Stream tributary in Nakdong Basin, respectively.

## HEC-ResSim setup

Flow into the river from the watershed is affected by the operation of reservoirs in that watershed. Thus, it was necessary to predict the discharge from Andong Reservoir. In other words, the flow data of that reservoir calculated by SWAT simulations was converted into discharge amounts, and the HEC-ResSim model was used. Operational conditions of Andong Reservoir were used in the simulation as shown in Table 4.

## GSTARS setup

We studied the upper stream of the Nakdong River basin and the section between the downstream area of Andong Reservoir and Sangju weir. Riverbed variations related to erosion and sedimentation were investigated around the study area. The study reach length and the dredged volume during the Four Major Rivers Project are summarized in Table 5.

Table 6 lists boundary conditions in the GSTARS model. Daily discharge data derived from the two climate scenarios (HadGEM3-RA RCP 4.5/8.5) for Andong Reservoir from 2016 to 2100 were used as upstream and downstream boundary conditions. Terrain data was based on station number from the Ministry of Land Infrastructure & Transport (MOLIT) (2012). The roughness of the reach was considered using Manning's $n$ coefficient, which varies from 0.026 to 0.028 as determined by MOLIT (2012). Similarity data of the applied section were input to the SWAT data of the watershed model, which is the SWAT model result after applying the future climate scenario. Sediment load data were also derived from the SWAT model result using the future climate scenario.

The bed material particle size distribution was determined from bed material survey results, which involved characterization of the riverbed, calculation of the roughness coefficient, analyses of erosion in the upstream watershed and river sediment transport, application of the sediment load formula and bed variation model, and

**Table 2** | Calibration and validation of flow

| Stream name | Station name | Period | Reference |
|---|---|---|---|
| Andong Reservoir | Andong Reservoir | 2006–2015 | WAMIS |
| Naeseong Stream | Jukjeon | 2008–2015 | WAMIS |

**Table 3** | Calibration and validation of water quality

| Stream name | Station name | Period | Reference |
|---|---|---|---|
| Andong Reservoir | Andong Reservoir | 2006–2015 | Water Information System |
| Naeseong Stream | Naeseong B | 2008–2015 | Water Information System |

**Table 4** | Operation rule of HEC-ResSim simulation (Andong Reservoir)

| Operation rule | Value |
|---|---|
| Flood control storage | 110.0 (million m$^3$) |
| Full reservoir level discharge | 1,224.0 (million m$^3$) |
| Low water level discharge | 237.4 (million m$^3$) |
| Spillway design flood | 4,600 (million m$^3$) |
| Design flood level | 161.7 (EL.m) |
| Full reservoir level | 160.0 (EL.m) |
| Low water level | 130.0 (EL.m) |
| Spillway crest level | 151.0 (EL.m) |

**Table 5** | Analysis section of riverbed variation

| Section | Section length (km) | Dredging volume (Million m$^3$) |
|---|---|---|
| Andong Reservoir – Sangju Weir | 80.7 | 40.9 |

**Table 6** | Configuration and data source of boundary conditions

| Data | | Configuration | Source |
|---|---|---|---|
| Channel Geometry | | Configuration of Cross-Section Data | MOLIT (2012) |
| Hydraulic Data | Upstream Boundary Conditions | Discharge Data | WAMIS |
| | Downstream Boundary Conditions | Water Stage Data | WAMIS |
| | Roughness Coefficient | Manning's Equation | MOLIT (2012) |
| Sediment Data | Sediment Inflow Data | Sediment Rating Curve | MOLIT (2012) |
| | Bed Material | Particle Size Distribution, Specific Gravity, and Dry Specific Weight | MOLIT (2012) |
| | Fall velocity | Water Temperature Data (Viscosity) | MOLIT (2012) |
| | Angle of repose | Above water surface Below water surface | |

WAMIS stands for WAter resources Management Information System.

investigation of the river environment (such as river habitat). Samples were collected in the appropriate way in the field and then analyzed in the laboratory, before being divided into the following sizes for processing and analysis: larger than pebbles, sand, and smaller than silt (MOLIT 2012).

## RESULTS AND DISCUSSION

### Climate change projection (rainfall)

Rainfall was analyzed by the climate scenario for 2100 (Figure 5). The future analysis period was split into three sections as a foreseeable future scenario (FFS, 2016–2040), mid-term future scenario (MFS, 2041–2070), and long-term future scenario (LFS, 2071–2100). Trends were analyzed.

HadGEM3-RA RCP 4.5 and 8.5 were compared based on the baseline (1981–2000). As a result of the quantitative analysis shown in Table 7, rainfall was 1,272.4 mm in RCP 4.5 (6.4%) and 1,344 mm in RCP 8.5 (12.4%). Variability was prominent in the extreme RCP 8.5 scenario. Total summer rainfall was heavy and the rate of change in winter was greatly increased in RCP 8.5, to 41.5%.

### Hydrologic model (SWAT)

#### Validation of flow

We determined the range of parameters related to runoff based on the characteristics of each small basin. Calibrations were performed by a simple trial-and-error method, varying by parameter in an appropriate range with reference to the aforementioned literature regarding SWAT. All other parameters were set to their default values. Each parameter was adjusted/calibrated until the simulated streamflow closely represented the observed. Three types of runoff

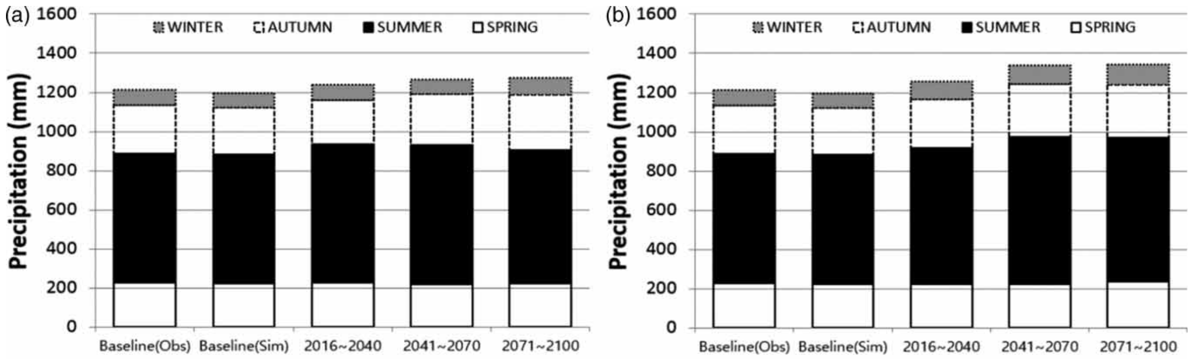

**Figure 5** | Seasonal trend analysis of Andong Reservoir watershed. (a) HadGEM3-RA RCP 4.5; (b) HadGEM3-RA RCP 8.5.

**Table 7** | Seasonal trend analysis of Andong Reservoir watershed (rainfall)

| | | | **HadGEM3-RA RCP4.5** | | | **HadGEM3-RA RCP8.5** | | |
|---|---|---|---|---|---|---|---|---|
| **Season** | | **Baseline (1981–2000)** | **FFS (2016–2040)** | **MFS (2041–2070)** | **LFS (2071–2100)** | **FFS (2016–2040)** | **MFS (2041–2070)** | **LFS (2071–2100)** |
| Spring | Dec. | 57.2 | 52.2 | 50.1 | 53.1 | 52.2 | 44.4 | 53.5 |
| | Jan. | 76.2 | 80.1 | 72.3 | 83.6 | 74.8 | 77.6 | 88.2 |
| | Feb. | 88.0 | 93.0 | 96.7 | 85.8 | 97.7 | 102.0 | 95.4 |
| | Sum | 221.4 | 225.3 (1.8%) | 219.1 (−1%) | 222.5 (0.5%) | 224.8 (1.5%) | 224 (1.2%) | 237 (7%) |
| Summer | Mar. | 161.3 | 189.2 | 206.8 | 174.2 | 176.3 | 199.6 | 208.3 |
| | Apr. | 246.3 | 280.5 | 281.3 | 272.1 | 272.5 | 274.9 | 267.1 |
| | May | 252.2 | 238.8 | 222.7 | 238.1 | 242.5 | 276.9 | 256.2 |
| | Sum | 659.8 | 708.5 (7.4%) | 710.8 (7.7%) | 684.4 (3.7%) | 691.3 (4.8%) | 751.3 (13.9%) | 731.5 (10.9%) |
| Autumn | Jun. | 155.1 | 140.7 | 162.4 | 191.5 | 161.7 | 176.6 | 180.1 |
| | Jul. | 44.2 | 46.8 | 55.7 | 47.8 | 51.9 | 42.3 | 46.6 |
| | Aug. | 42.4 | 38.0 | 42.2 | 40.3 | 36.0 | 47.3 | 45.3 |
| | Sum | 241.8 | 225.5 (−6.7%) | 260.2 (7.6%) | 279.6 (15.6%) | 249.6 (3.2%) | 266.2 (10.1%) | 272 (12.5%) |
| Winter | Sep. | 17.3 | 30.4 | 26.7 | 30.0 | 34.2 | 29.7 | 26.5 |
| | Oct. | 24.6 | 19.1 | 19.3 | 24.1 | 24.4 | 29.8 | 28.2 |
| | Nov. | 31.4 | 30.6 | 29.5 | 31.8 | 30.2 | 38.3 | 49.1 |
| | Sum | 73.3 | 80.1 (9.3%) | 75.6 (3.1%) | 85.9 (17.2%) | 88.8 (21.1%) | 97.8 (33.4%) | 103.7 (41.5%) |
| Annual | | 1,196.3 | 1,239.4 (3.6%) | 1,265.7 (5.8%) | 1,272.4 (6.4%) | 1,254.5 (4.9%) | 1,339.3 (12%) | 1,344.2 (12.4%) |

FFS, foreseeable future scenario, 2016–2040; MFS, mid-term future scenario, 2041–2070; LFS, long-term future scenario, 2071–2100.

components – surface, interflow, and active groundwater runoff – are basically hydrologic processes. SWAT hydrologic simulation uses the HRU concept to divide the watershed into so-called homogeneous HRUs. According to Yang *et al.* (2012), to identify how the key parameters and physical processes interact, it is important to investigate other model setups to ensure the validity of the calibration affecting the simulation model. In our study, after considering knowledge from sensitivity analysis and hydrologic processes, we evaluated the following parameters in model calibration (Table 8).

As an objective function to determine the suitability and correlation of the model according to the calibration and verification results, the decision coefficient ($R^2$) and root mean square error (RMSE) were used. The efficiency of the model was tested using the model efficiency coefficient (NSE) proposed by Nash and Sutcliffe (1970). For Corr, $R^2$, and NSE, a value close to 1 indicates better correlation, and for RMSE, a value close to 0 indicates such correlation. Green *et al.* (2006) reported $R^2$ and NSE values of $\geq 0.5$ and $\geq 0.4$, respectively. Chung *et al.* (1999) reported an $R^2$ of $\geq 0.5$, and Ramanarayanan *et al.* (1997) and Santhi *et al.* (2001a, 2001b) suggested that if $R^2$ is $>0.6$ and NSE $>0.5$, the model simulates natural phenomena well. The coefficient of determination ranges from −1 to 1 and is 1 when simulated and observed values are equal.

Figure 6 shows the calibration and correction results for the runoff of Andong Reservoir and Naeseong stream basin. The validation periods for the reservoir are 2009–2010 and 2012–2014, respectively (Table 9). The $R^2$ of monthly average runoff is 0.89 and 0.69, and NSE 0.74 and 0.64, respectively. The validation periods for Naeseong stream are 2009–2010 and 2011–2012, respectively. The $R^2$ of monthly average runoff is 0.69 and 0.95, and NSE 0.74 and 0.94, respectively.

## Validation of water quality

Sediment calibration follows the hydrologic calibration and must precede water quality calibration. Calibration of the parameters involved in simulation of watershed sediment erosion is more uncertain than hydrologic calibration because of less experience with sediment simulation in different regions of the country.

For pollutant simulation by SWAT, numerous variables – sediment, nitrogen forms including nitrate, phosphorus

**Table 8** | List of adjusted hydrologic parameters of SWAT

| **Input file** | **Parameter** | **Definition** | **Range**<br>**Minimum** | <br>**Maximum** |
|---|---|---|---|---|
| .gw | ALPHA_BF | Baseflow recession constant | 0 | 1 |
| | GW_DELAY | Delay time for aquifer recharge | −10 | 10 |
| | GW_REVAP | Revap coefficient | −0.036 | 0.036 |
| | GWQMN | Threshold water level in shallow aquifer for base flow | −1,000 | 1,000 |
| .hru | EPCO | Plant uptake compensation factor | 0 | 1 |
| | SLSUBBSN | Average slope length | –25 | 25 |
| .mgt | CN2 | SCS runoff curve number | –25 | 25 |
| .rte | CH_K2 | Effective hydraulic conductivity of channel | 0 | 150 |
| | CH_N | Manning coefficient for channel | 0 | 1 |
| .sol | SOL_AWC | Available water capacity of the soil layer | –25 | 25 |
| | SOL_K | Saturated hydraulic conductivity | –25 | 25 |

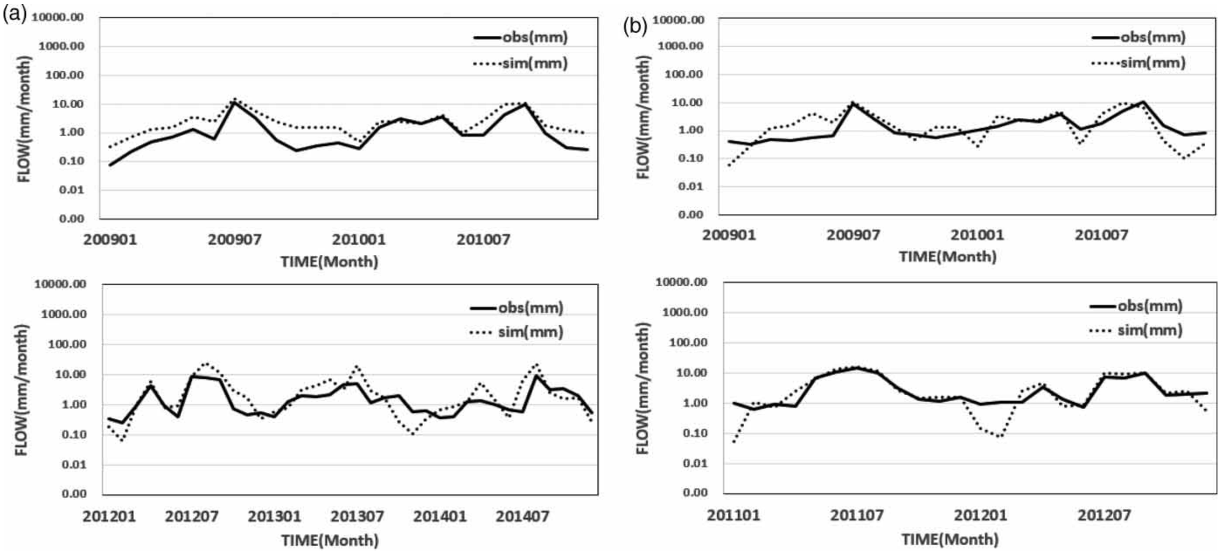

**Figure 6** | Comparison between observed and simulated flow. (a) Andong Reservoir; (b) Naeseong Stream.

**Table 9** | Result of flow calibration and validation

| **Stream** | **Flow station** | **Period Calibration validation** | **Corr.** | **$R^2$** | **RMSE** | **NSE** |
|---|---|---|---|---|---|---|
| Andong Reservoir | Andong Reservoir | 2009–2010 | 0.94 | 0.89 | 2.51 | 0.74 |
| | | 2012–2014 | 0.83 | 0.69 | 8.45 | 0.64 |
| Naeseong Stream | Jukjeon | 2009–2010 | 0.83 | 0.69 | 2.40 | 0.74 |
| | | 2011–2012 | 0.98 | 0.95 | 1.88 | 0.94 |

forms as biological processes – were dominant. Therefore, calibration of nutrients (nitrogen and phosphorus) had to be carried out iteratively. The following parameters in Table 10 must be input for water quality calibration and SWAT.

Water quality was analyzed on the same section as the flow calibration and correction results (Table 11). SS (suspended solids), T-N (total nitrogen), and T-P were studied. As a result of the suitability and correlation analysis of the model in Table 11, the validation periods for Andong Reservoir were 2011–2012 and 2013–2015, respectively, with Corr and $R^2$ values for SS at 0.71 and 0.73, and 0.51 and 0.52, respectively. For T-N and T-P, Corr and $R^2$ values are >0.8 and 0.7, respectively. The validation periods for Naeseong stream were 2009–2010 and 2011–2012, with Corr and $R^2$ values for SS at 0.99 and 0.95, and 0.99 and 0.90, respectively. For T-N and T-P, Corr and $R^2$ values are >0.6 and 0.7, respectively.

## Prediction of streamflow

Table 12 shows simulation of runoff variability was analyzed by applying the climate scenario to the SWAT model. In the runoff scenario simulations for Andong Reservoir and Naeseong Stream, the result of scenario HadGEM3-RA RCP 8.5 is more than 5% greater than that of scenario 4.5. The greatest total runoff was simulated for summer. The rate of change in winter was largely the same in both climate scenarios.

**Table 10** | List of adjusted water quality parameters of SWAT

| Input file | Parameter | | Definition | Range | |
|---|---|---|---|---|---|
| | | | | Minimum | Maximum |
| .rte | SS | CH_COV | Channel cover factor | −0.001 | 1 |
| | | CH_EROD | Channel erodibility factor | −0.05 | 0.6 |
| .hru | | LAT_SED | Concentration of sediment in lateral and groundwater flow | 0 | 5,000 |
| crop.dat | | USLE_C | Minimum value for the cover and management factor for the land cover | 0.001 | 0.5 |
| .sol | | USLE_K | USLE equation soil erodibility factor | 0.0 | 0.65 |
| .chm | TN | SOL_NO3 | Initial $NO_3$ concentration in soil layer | 0 | 100 |
| | | SOL_ORGN | Initial humic organic nitrogen in soil layer | 0 | 100 |
| .gw | | SHALLST_N | Amount of nitrate in the shallow aquifer | 0 | 1,000 |
| .bsn | | NPERCO | Nitrate percolation coefficient | 0 | 1 |
| .chm | TP | SOL_ORGP | Initial humic organic phosphorus in soil layer | 0 | 100 |
| .bsn | | PPERCO | Phosphorus percolation coefficient | 10 | 17.5 |
| .gw | | GWSOLP | Soluble phosphorus concentration in groundwater flow | 0 | 1,000 |

**Table 11** | Results of water quality calibration and validation

| Stream | Flow Station | Period Calibration validation | SS | | T-N | | T-P | |
|---|---|---|---|---|---|---|---|---|
| | | | Corr. | $R^2$ | Corr. | $R^2$ | Corr. | $R^2$ |
| Andong Reservoir | Andong Reservoir | 2011–2012 | 0.71 | 0.51 | 0.93 | 0.86 | 0.87 | 0.75 |
| | | 2013–2015 | 0.73 | 0.52 | 0.92 | 0.85 | 0.87 | 0.75 |
| Naeseong Stream | Naeseong B | 2009–2010 | 0.99 | 0.99 | 0.78 | 0.61 | 0.83 | 0.70 |
| | | 2011–2012 | 0.95 | 0.90 | 0.73 | 0.53 | 0.60 | 0.35 |

**Table 12** | Results of change in future outflow

| | **HadGEM3-RA RCP 4.5** | | | | **HadGEM3-RA RCP 8.5** | | | |
|---|---|---|---|---|---|---|---|---|
| **Water body** | **Baseline (1981–2000)** | **2016–2040** | **2041–2070** | **2071–2100** | **Baseline (1981–2000)** | **2016–2040** | **2041–2070** | **2071–2100** |
| Andong Reservoir | 16,303 | 17,493<br>(7.3%) | 19,945<br>(22.3%) | 18,666<br>(14.5%) | 16,303 | 17,291<br>(6.1%) | 19,980<br>(22.6%) | 18,019<br>(10.5%) |
| Naeseong Stream | 9,902 | 13.378<br>(35.1%) | 14,932<br>(50.8%) | 13,688<br>(38.2%) | 9,902 | 13,243<br>(33.7%) | 15,249<br>(54%) | 13,262<br>(33.9%) |

## Sediment transport model (GSTARS)

Because the analysis of the two climate scenario conditions through the year 2100 involved a long period, the FFS period from 2016 to 2040 was established and examined. Based on the simulated results of SWAT runoff from the reservoir basin for each scenario, annual reservoir inflow was extracted and the probability of occurrence exceedance was calculated. Riverbed adjustments under climate change were estimated based on that probability. For each period, we selected years that were extreme hydrologic equivalents of wet years (10%), normal years (50%), and dry years (90%). HadGEM3-RA RCP 4.5 and 8.5 future climate scenarios and discharges from Andong Reservoir are shown in Table 13.

As a simulation scenario for the GSTARS sensitivity analysis, the roughness coefficient was the same as MOLIT (2012). The simulations were performed by setting the parameters according to the sediment load formula in Table 14 and number of stream tubes.

Using measured riverbed data of 2014, verification and calibration were made possible, and future predictions will be more accurate. No data is available after 2014, river geometric data has not been released after the Four Major Rivers Project. The present study focused on riverbed changes in terms of the effects of climate change. Therefore, we used a method to compare the simulated results of the initial riverbed (2012) with the simulated results for 40 years. Three stream tubes were used to simulate semi-2D bed variations, a unique feature of GSTARS3. The Yang (1973) + Yang (1984) sediment transport equation, which is the optimal condition, was applied to the standard of the similarity equation by referring to the comparison result of bed variation according to Ahn *et al.* (2019). When using one stream tube, the fluctuation width of the bed was too small to simulate 2D bed elevation variations. Therefore, three stream tubes were required to simulate those variations, as mentioned by Ahn & Yen (2015) and Ahn *et al.* (2019).

**Table 13** | Analysis of future discharge (Andong Reservoir)

| **Period** | | | **Sum** | **Maximum** | **Minimum** |
|---|---|---|---|---|---|
| HadGEM3-RA RCP 4.5 | 10% (Rainy year) | 2025 | 19,863 | 490.5 | 14.3 |
| | 50% (Normal year) | 2031 | 10,967 | 622.6 | 14.3 |
| | 90% (Dry year) | 2034 | 7,131 | 147.6 | 14.3 |
| HadGEM3-RA RCP 8.5 | 10% (Rainy year) | 2031 | 15,135 | 544.0 | 14.3 |
| | 50% (Normal year) | 2039 | 10,141 | 454.0 | 14.3 |
| | 90% (Dry year) | 2028 | 6,399 | 30.3 | 14.3 |

## Thalweg change

The runoff scenario computed by the hydrologic model was applied to the GSTARS model to simulate riverbed

**Table 14** | Numerical simulation cases

| **Climate change scenarios (×2)** | **FFS (×3)** | **Sediment transport equation (×1)** | **Number of stream tubes (×1)** |
|---|---|---|---|
| HadGEM3-RA RCP 4.5 | 10% (Rainy year)<br>50% (Normal year)<br>90% (Dry year) | Yang (1973) + Yang (1984) | 3 |
| HadGEM3-RA RCP 8.5 | 10% (Rainy year)<br>50% (Normal year)<br>90% (Dry year) | | |

changes in the study reach. The probability of occurrence exceedance was calculated, years were sorted into wet (10%), normal (50%), and dry (90%), and riverbed variation results were analyzed according to two climate scenarios (Figure 7). Thalweg analysis showed that the riverbed was wide in wet years because of increased flow velocity, caused by an increase of rainfall and discharge. Bed width decreased in dry years. The flow rate was 1.05 $m^3$/s in wet years for RCP 8.5 and higher than 1.02 $m^3$/s for RCP 4.5. Riverbed variability in wet years in the RCP 4.5 and RCP 8.5 scenarios was 4.14 and 4.29 m, respectively, indicating more erosion. RCP 8.5 scenarios are more extreme than RCP 4.5 scenarios (Table 15). To study the effects of stream tributaries, we analyzed riverbed changes at the inlet points of Mi and Naeseong streams. The change in bed phase was not substantial after the inflow of Mi Stream tributaries. RCP 8.5 had strong volatility in the lower phase from −3.5 to −3.7 m in RCP 4.5, and −2.97 to −3.6 m in RCP 8.5, but not much in the downstream. On the other hand, after the inflow of Naeseong Stream tributaries, riverbed variation appeared. For 10% (wet) in RCP 4.5, the riverbed rose to −3.06 to 1.89 m. For 10% of RCP 8.5, the range was −1.34 to 3.26 m, which is more influential than in RCP 4.5. The impact of climate change is considered strong. This result is consistent with the literature on the flow rate and sediment downstream of the resistant stream (Ji *et al.* 2013; Jang 2017).

## Cross-section change

Cross-sections were investigated to examine the meandering pattern of the stream. Figure 8 shows the cross-section analysis of Section 1 according to the direction of flow downstream of Mi Stream.

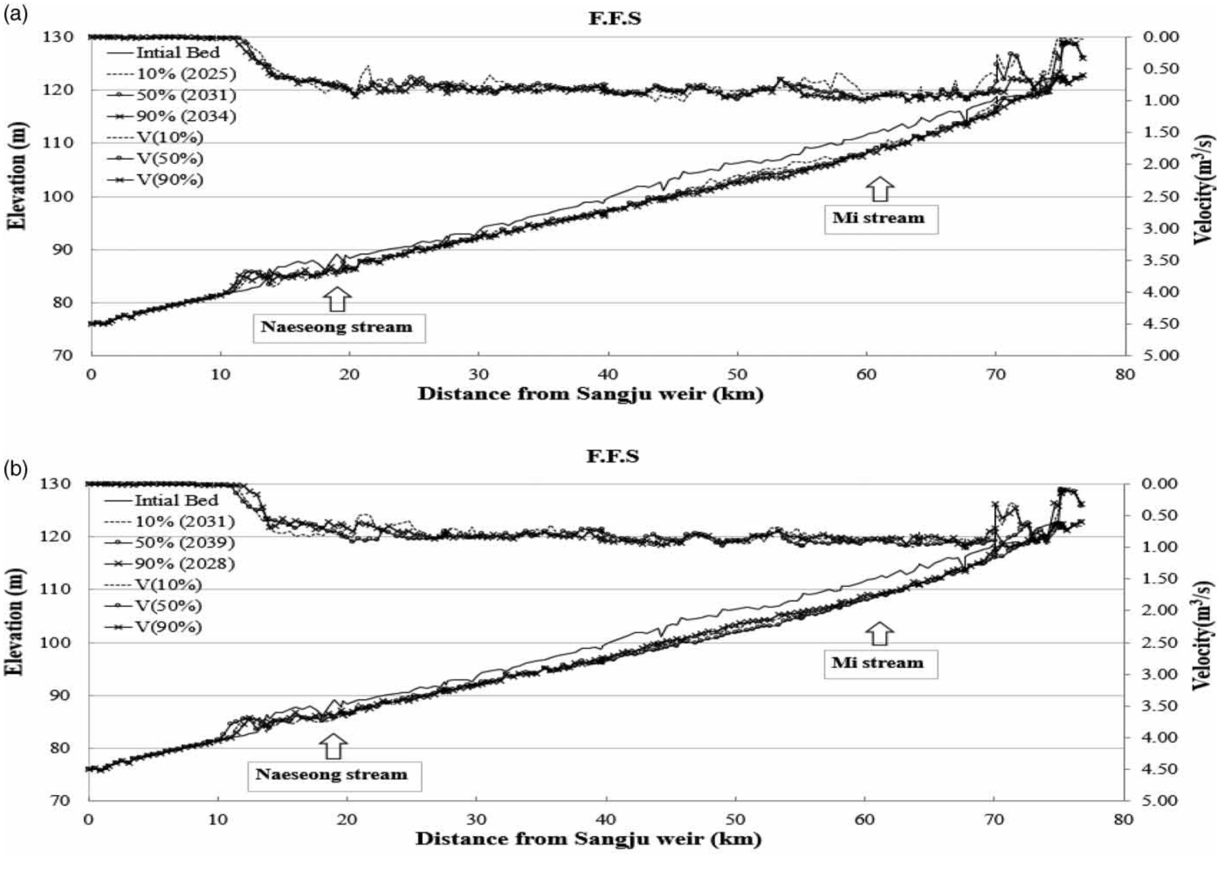

**Figure 7** | Thalweg elevation changes – FFS. (a) HadGEM3-RA RCP 4.5; (b) HadGEM3-RA RCP 8.5.

**Table 15** | Results of Thalweg changes

| | | | | Velocity ($m^3/s$) | | | Bed change (m) | |
|---|---|---|---|---|---|---|---|---|
| **Scenario** | **Year** | | | **Average** | **Maximum** | **Minimum** | **Maximum** | **Minimum** |
| HadGEM3-RA RCP 4.5 | FFS | 10% | 2025 | 0.62 | 1.02 | 0.01 | 3.11 | −4.14 |
| | | 50% | 2031 | 0.65 | 0.99 | 0.01 | 3.26 | −4.09 |
| | | 90% | 2034 | 0.68 | 1.00 | 0.01 | 3.05 | −4.48 |
| HadGEM3-RA RCP 8.5 | FFS | 10% | 2031 | 0.65 | 1.05 | 0.01 | 3.26 | −4.29 |
| | | 50% | 2039 | 0.68 | 0.99 | 0.01 | 3.09 | −4.93 |
| | | 90% | 2028 | 0.65 | 0.99 | 0.01 | 2.98 | −4.09 |

To calculate the hydrologic coefficient, sediment load, sediment transport, and cross-sectional area were analyzed according to flow velocity. Meanders were explored by cross-section analysis in Figure 9 and Table 16. Erosion increased from the left to right bank. In wet years (10%) with faster flow velocity, flow rate and cross-sectional area both increased. The results show that sediment transport and load increased accordingly. Bed width fluctuations from the left to right bank also amplified. In dry years, however, the flow rate was small, and the cross-sectional area and sediment load both decreased. In the extreme scenario, HadGEM3-RA RCP 8.5, the difference was substantial.

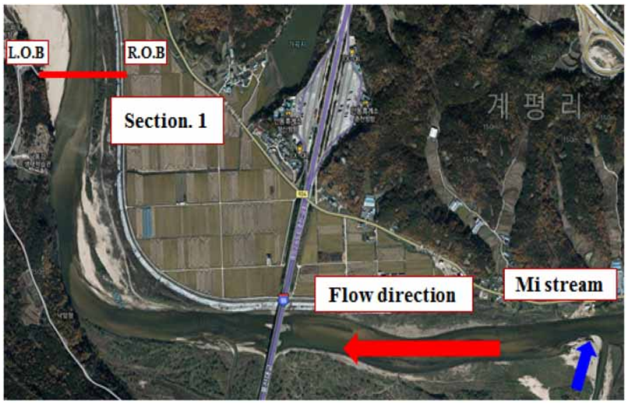

**Figure 8** | River structure of Section 1.

## CONCLUSIONS

We predicted hydrologic quantities according to future climate change scenarios and verified the method's applicability to the Nakdong River basin in Korea, by proposing a method to sequentially predict resulting riverbed changes. For climate scenarios, we used HadGEM3-RA RCP 4.5 and 8.5 to predict climate scenarios through the 21st century. By applying the climate scenario to watershed model SWAT, we compared and analyzed runoff and sediment transport in the basin. The effect of discharge

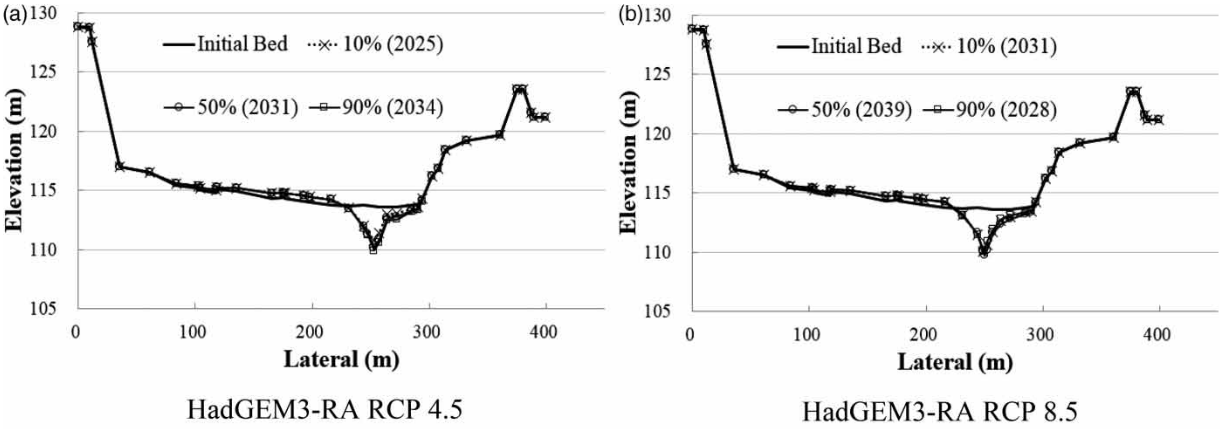

**Figure 9** | Cross-section changes at Section 1. (a) HadGEM3-RA RCP 4.5; (b) HadGEM3-RA RCP 8.5.

**Table 16** | Cross-section changes at Section 1

| | | | | Hydraulic results | | | Bed change (m) | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Scenario** | **Year** | | | ***V*** **(m³/s)** | **Flow area (m²)** | ***H*** **(m)** | **Maximum** | **Minimum** | **Sediment capacity (ton/day)** | **Sediment transport (ton/day)** |
| HadGEM3-RA RCP 4.5 | F | 10% | 2025 | 0.96 | 15.76 | 2.48 | 0.50 | −2.25 | 19.55 | 19.52 |
| | F | 50% | 2031 | 0.94 | 16.04 | 3.27 | 0.49 | −2.77 | 21.97 | 18.68 |
| | S | 90% | 2034 | 0.89 | 18.28 | 3.77 | 0.50 | −3.00 | 15.52 | 15.35 |
| HadGEM3-RA RCP 8.5 | F | 10% | 2031 | 0.89 | 16.71 | 1.97 | 0.48 | −2.22 | 11.79 | 12.03 |
| | F | 50% | 2039 | 0.96 | 14.77 | 2.02 | 0.47 | −2.13 | 10.28 | 10.00 |
| | S | 90% | 2028 | 0.87 | 16.63 | 2.07 | 0.48 | −2.22 | 13.00 | 11.80 |

variations on flow characteristics of the main stream in the dam and weir sections was also examined. Finally, short-term and long-term bed variations were studied using the GSTARS model. As a result, we investigated the effect of changes in dam and weir discharge on the top and bottom stream sections.

Using a baseline (1981–2000), HadGEM3-RA RCP 4.5 and 8.5 climate scenarios were studied. Rainfall was 1,272.4 mm (6.4%) in RCP 4.5 and 1,344 mm (12.4%) in RCP 8.5, and the extreme 8.5 scenario showed large variability. Total rainfall was heavy in summer, and the rate of change increased substantially to 41.5% in winter for RCP 8.5.

Climate scenarios were applied to the SWAT hydrologic model to analyze runoff and water quality load variability. The runoff scenario simulation showed an increase in all rivers of $\geq$5% in RCP 8.5 compared to RCP 4.5. Total runoff was maximum during summer, and the rate of change in winter was large, revealing the influence of the climate scenario.

The runoff scenario using the hydrologic model was applied to the GSTARS model to simulate riverbed variations. The probability of occurrence exceedance was calculated, years were sorted into wet (10%), normal (50%), and dry (90%), and riverbed variation results were explored according to two climate scenarios. The river became wide in wet years because of increased flow velocity, caused by an increase of rainfall and discharge. Channel width decreased in dry years.

We proposed a method combining basin and stream channel models to analyze future riverbed variations under various climate change scenarios. This approach can be applied to predicting both climate change and riverbed variations. However, error rates can result in a model linking process. In future research, it is necessary to perform error analysis and improve the error rate during model linkage. Finally, it is necessary to improve the research results through comparative analysis of riverbed changes.

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## DATA ACCESSIBILITY

This study predicted changes in the water environment of rivers due to climate change. In the future, various climate change scenarios can be applied to account for changes in river runoff or bed changes. In addition, dams or weirs operation can be considered through climate change pattern analysis.

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