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Assessing environmental flows of coordinated operation of dams and weirs in the Geum River basin under climate change scenarios

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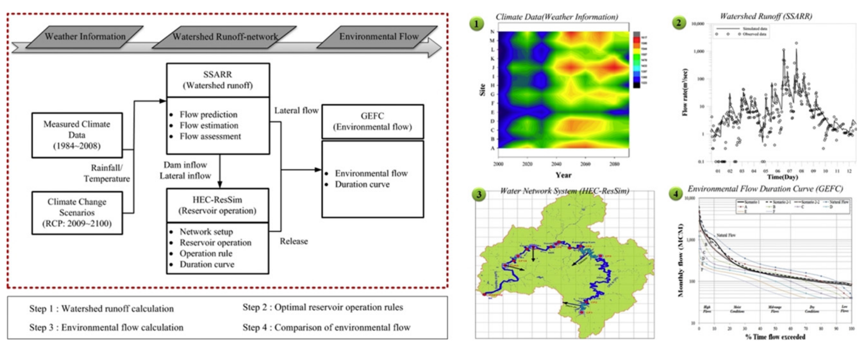
HIGHLIGHTS

- We assessed the environmental management class of the changing riverine environment.
- We assessed countermeasures to mitigate resulting adverse environmental impacts.
- The presence of dam/weir controls optimizes the river flow for socioeconomics and the environment.
- We assessed current and future environmental flows under climate change.

GRAPHICAL ABSTRACT



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ABSTRACT

The International Panel on Climate Change (IPCC) has predicted frequent and severe droughts and floods caused by irregular climatic conditions in the future, making water resources management difficult. Within the field of integrated watershed management, the concept of 'environmental flow' is being increasingly studied. In Korea, the Four Major Rivers Restoration Project was carried out as part of the plan to manage future water resources, particularly in response to climate change. In order to improve comprehensive water resources management, there is an interest in integrating into the operation of the existing dams the multi-functional weirs constructed under the said project. To date, there is an absence of studies comprehensively considering climate change, runoff volume, reservoir operations, and environmental flow, with most of the existing studies focusing only on one or the other of these factors. In this study, we presented a method to evaluate the river environment that considers all the said factors. To evaluate how environmental flow is influenced by the changes in river flow due to climate change and hydraulic structure operation, the Streamflow Synthesis and Reservoir Regulation (SSARR) was used as the hydrological model, HEC-ResSim was used as the hydraulic structures operational model, and the Global Environmental Flow Calculator (GEFC) was used as the method to evaluate environmental flows. RCP climate change scenarios, provided by the Climate Change Information Center (CCIC), a branch of the Korea Meteorological Administration, were applied to analyze the future watershed runoff characteristics of the Geum River Basin under different hydraulic structure operation modes. This study concludes that efficient use of water resources can be achieved through the integrated operation of the dams and multi-functional weirs in times of water shortage. Comparing the results of modelling under a no carbon reduction scenario on one hand, and a scenario in which emissions were reduced on the other hand, differences were found in flows during floods, in the mean annual runoff ratio in accordance with the environment management class, and in the

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environmental flow rating. It appears that a new water resources management plan is required to respond to climate change as indicated by the shift of the flow duration curve to a lower environmental management class (EMC) under climate change scenarios.

1. Introduction

“Environmental flow” is a rising paradigm in basin management for the conservation of aquatic and aquatic-terrestrial boundary ecosystems. The term is mainly used to indicate the flow regime of a river designed to maintain the river in a specific ecological condition (Smakhtin and Anputhas, 2006). However, the use of the term varies in the literature. For instance, it can also encompass instream flow requirements (IFRs), maintenance IFRs, drought IFRs, and minimum flow (Ministry of Land, Infrastructure, and Transport, 2007; Smakhtin and Anputhas, 2006). The flow regime consists of various components, all of which have unique roles and functions. For example, the deep regions of a river influence the maintenance of the waterway or the flooding of wetlands, while the shallow regions regulate algal growth or fish spawning. Therefore, the best way to ensure a healthy river is to maintain all components of the flow regime as they naturally occur. However, the unprecedented growth in human requirements for water has required the development of various water resources, which has led to changes in the ecology of rivers. Thus, it is nearly impossible to maintain naturally-occurring flow regimes. To improve the self-purification capacity of a river and restore its original functions, a number of actions are necessary, such as creating an environment that can support aquatic life, eliminating pollution sources, and ensuring adequate river flow.

Satisfying water demand for human use while maintaining the health of water resources is a national objective of most, if not all, countries; thus, evaluating and allotting environmental flow are critical (The Nature Conservancy, 2006; Kashaigili Japhet et al., 2007). However, calculation of environmental flow volumes can be complex and difficult due to the lack of appropriate theoretical background or associated data required to quantitatively analyze the influence of change in the flow characteristics on river ecosystems (Hughes, 2001). The evaluation of the hydro-ecological health of a river must be performed using a diverse range of hydraulic, hydrologic, and ecologic data and analytical models. Welsh et al. (2013) introduced the Source Integrated Modelling System (IMS), and describes the individual modelling components and how they are integrated within it and described the methods employed for tracking and assessment of uncertainties, as well as presenting outcomes of two case study applications. Lin and Rutten (2016) studied to extend previous state-of-the-art reviews in the operational management of a network of multi-purpose reservoirs with recent developments and to focus on the application of Model Predictive Control for real time control of a reservoir system.

Korea mandates the setting of instream maintenance flows to maintain the original function and state of the country's streams; however, the calculated final maintenance flows are generally actually average drought IFRs. The Ministry of Land, Infrastructure, and Transport (2000) introduced the concept of river environment, integrating a method of calculating instream maintenance flow, but use of this methodology was not made mandatory. Environmental flows (EF) define the quantity, timing, and quality of river flows needed to preserve freshwater ecosystems while assuring the continuity of human use (Miguel et al., 2018). Insofar as they reduce water availability and condition agricultural and industrial uses, EF represent a constraint, but they also hold out new opportunities for development.

When calculating environmental flows, flow variability is one of the key hydrological characteristics (Bunn and Arthington, 2002) that must be considered. Recently, the International Water Management Institute (IWMI) proposed a method and program, the Global Environmental Flow Calculator (GEFC), that allow for a high-level environmental flow volume calculation within a basin based on the movement characteristics of flow-duration curve (Smakhtin and Eriyagama, 2008). A flow-duration curve represents the relationship between the flow rate and the percentage of time the flow exceeds a given value. It is a hydrological tool that is used to evaluate the flow variability at a specific point of the river. Therefore, the characteristics of the flow-duration curve under specific conditions provide a general idea on the ecological conditions of the target basin. The GEFC analyzes the flow-duration curve at each environmental management class to model the unique runoff characteristics of the river as well as the river flow changes and influences on the aquatic ecosystem due to basin development such as multi-purpose dam construction, and is an effective method given its simple structure. The GEFC was applied to the Geum River Basin in Korea by Kim and Choi (2010), who by analyzing the ratio of mean annual runoff per environmental management class concluded that the results were in line with existing study results (Tennant, 1976; Jones, 2002). Lee and Kim (2011) applied the climate change scenarios from GCMs on the Nakdong River Basin, using the Tank model to calculate runoff and calculated the environmental flow using the GEFC to analyze the influence of climate change. Sood et al. (2017) utilized the GEFC to provide information on global environmental flows for sustainable development. Meanwhile, Salik et al. (2016) provided an assessment of ecological conditions of the Indus Delta under different climate change scenarios by using the ecological health of the Indus River as a proxy variable. They assessed the existing state of the deltaic ecology and categorized it into an arbitrary environmental management class (EMC). However, they did not analyze under different hydraulic structure operation modes and climate change scenarios to integrate climate change and hydrological model, reservoir operation model and environmental flow. Stamou et al. (2018) proposed the novel integrated modelling procedure 3H-EMC for the determination of the environmental flow in rivers and streams; 3H-EMC combines Hydrological, Hydrodynamic and Habitat modelling with the use of the Environmental Management Classes (EMCs) that are defined by the Global Environmental Flow Calculator. However, the study of Stamou et al. (2018) did not consider the operation of dams and multi-functional weirs and climate change.

This study applied the environmental flow calculation method developed by IWMI to the Geum River Basin in Korea, with the objectives of evaluating the present environmental flow and the future environmental flow under different operation modes of the hydraulic structure climate change. The Streamflow Synthesis and Reservoir Regulation (SSARR) hydrological model was used to calculate the natural flow in the 14 sub-basins of the Geum River hydrological system. A network was constructed using Hec-ResSim and then the integrated dam-weir operation model was applied. Using the constructed model, hydrological analysis of one water level station (Gyuam) was conducted considering the integrated dam operations and the integrated dam-weir operations in the hydrological system. Additionally, the GEFC was used to conduct an environmental flow and flow change analysis of the stream and surrounding areas in order to evaluate response strategies to the changing stream environment. Identifying how climate change will affect runoff volume in the Geum River Basin and assessing the variation in downstream water quality due to the operation of the existing hydraulic facilities are critical for the comprehensive water management of the basin system.