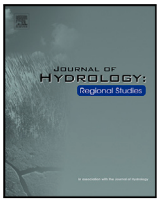
Journal of Hydrology: Regional Studies 53 (2024) 101842

Contents lists available at ScienceDirect

Journal of Hydrology: Regional Studies

journal homepage: www.elsevier.com/locate/ejrh



Climate change impact assessment on water resources management using a combined multi-model approach in South Korea

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ARTICLE INFO

Keywords:
Water supply
Flood risk
Climate change
Ensemble
Reservoir

ABSTRACT

Study Region: Hapcheon and Seomjingang Basins, South Korea

Study Focus: This study investigated the impacts of climate change on water supply reliability and flood risk in two East Asian basins in South Korea. By employing three coupled hydrological and reservoir operation models, the analysis considered projections under SSP2-4.5 and SSP5-8.5, projected using 12 global climate models.

New Hydrological Insights: Our results indicated that under SSP2-4.5, water supply reliability did not considerably decrease compared to the historical period (1995–2014), whereas it was reduced under SSP5-8.5 in one basin, Hapcheon. Meanwhile, a substantial increase in flood risk was modeled in both basins under both scenarios. The impact of climate change was amplified through a cascade from rainfall to runoff and then to flood volume, resulting in heightened flooding risk. In the far future (2081-2100) under SSP5-8.5, the dam-released flood volume was projected to increase rapidly by 73.2% and 74.1% in the Hapcheon and Seomjingang Basins, respectively, indicating considerable changes in flood risk due to climate change. Compared with SSP2-4.5, SSP5-8.5 exhibited more variability among climate models, especially in the far future period (2081–2100), leading to more uncertain projections in drought and flood risk assessments.

1. Introduction

Climate change has presented considerable challenges for water resource management, encompassing issues such as water scarcity, the escalation of waterborne diseases, infrastructure damage, and intensified competition for water resources, necessitating adaptation and mitigation strategies. In accordance with the recent Intergovernmental Panel on Climate Change (IPCC) report (IPCC, 2021), extreme weather events, which occurred once per decade before human influence, were now anticipated to become more frequent with a 2 °C temperature rise. This change was projected to result in a 70 percent higher likelihood of heavy rain and a twofold increase in drought occurrence. Over the last few decades, an extensive body of research has been conducted to assess the influence of climate change on local water resource management systems, considering diverse hydro-meteorological and geophysical conditions (Sivakumar, 2011; Olmstead, 2014; Mohammed et al., 2022; Zhao and Boll, 2022).

To comprehend the impact of climate change on water resource management, a comprehensive modeling framework that considered both hydrological responses and reservoir operation was indispensable. Numerous modeling approaches have been

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https://doi.org/10.1016/j.ejrh.2024.101842
Received 30 December 2023; Received in revised form 7 May 2024; Accepted 18 May 2024

employed to assess the impact of climate change on reservoir operations (Gopalan et al., 2020; Lee and Shin, 2021; Noh et al., 2023). Acknowledging that individual models might exhibit structural biases and unexpected behaviors under changing climate conditions, a multi-model approach has been adopted to mitigate uncertainty (Dams et al., 2015; Donnelly et al., 2017; Krysanova et al., 2018; Sognnaes et al., 2021). Najafi and Moradkhani (2015) found that ensemble modeling approaches had the potential to reduce model structural uncertainty and improve projection accuracies. However, climate models and future emissions have been identified as the most important sources of uncertainty in hydrological modeling chains (Teng et al., 2012; East et al., 2022).

Woo et al. (2023) recently conducted a comparative analysis of discharge variations under climate stress scenarios using two hydrological models: IHACRES and GR4J. This investigation revealed that the disparity in simulated stream flows between the two models became more pronounced with intensified changes in precipitation and temperature, despite both models exhibiting analogous hydrological behaviors during historical periods. Reservoir operation modeling has become a standard practice for addressing the influence of human activities on water resource management (Firoz et al., 2018; Saab et al., 2022; Dong et al., 2023). For instance, Firoz et al. (2018) employed an HEC-ResSim reservoir operation model to analyze hydrological drought using naturalized and reconstructed streamflow data. Despite its evident necessity and significance, limited research has simultaneously explored both water supply and flood risks in water resource management in the context of climate change.

The main aim of this study was to evaluate how climate change impacts water resource management, particularly in terms of water supply and flood risk, employing a comprehensive multi-model approach. This integrated methodology involved using three conceptual hydrological models coupled with a reservoir operation model. Numerical experiments were conducted in two East Asian basins in South Korea, incorporating multiple outcomes from global climate models under two climate change scenarios: SSP2-4.5 and SSP5-8.5. Our investigation explored how the variability and uncertainty in climate projections affect the reliability and vulnerability of water supply and flood risk, employing various assessment indices.

2. Methods

2.1. Study site

To investigate the effects of climate change on water resource management, we selected the Hapcheon (35°32′01.34″N 128°01′55.12″E) and Seomjingang (35°32′29.03″N 127°32′16.48″E) Basins in South Korea as our study sites. Both basins contained multipurpose reservoirs constructed during the 1970s–80s to fulfill various societal needs, such as flood control, agricultural and industrial water supply, hydropower generation, and recreation. The locations of these two basins were shown in Fig. 1. The Hapcheon and Seomjingang Basins covered 763 and 925 km^2, respectively. Approximately 24% of the Hapcheon Basin featured gradients of 20% or less (Kim, 2015). Regarding land use, 18% consisted of agricultural land, while the remainder was predominantly forested. However, the Seomjingang Basin was characterized by its mountainous terrain and steeper downward slopes compared to the other basin, ranging from 1/300 to 1/900 in the upper reaches, from 1/1000 to 1/5000 in the middle reaches, and from 1/3000 to 1/7000 in the lower reaches. In essence, the two study sites displayed distinct characteristics.

The study sites underwent significant seasonal fluctuations in precipitation, with over half of the annual precipitation falling during the summer monsoon season. Consequently, effective climate change adaptation and disaster risk reduction measures were necessary for sustainable water management, given that monsoon precipitation constituted the primary source of water supply and flooding in these areas. We analyzed the precipitation and temperature data at the study sites using observational data from the Korea Meteorological Administration. From 1995 to 2014, the Seomjingang basin received annual precipitation of 1440 mm, with a standard deviation of 12.01 mm, while the Hapcheon basin received 1360 mm annually, with a standard deviation of 12.19 mm. During the same period, the mean annual temperatures were 11.10 °C and 11.97 °C in the Seomjingang and Hapcheon Basins, respectively, with the temperature ranges of −13.58 to 28.6 °C and −9.7 to 28.9 °C, respectively. Like many other regions in South Korea, these basins have witnessed gradual increases in temperature over the past decades.

2.2. Models

2.2.1. Hydrological models

In this subsection, we outline a series of hydrological models linked with a reservoir operation model to evaluate the effects of climate change on water resource management. We employed lumped models for the hydrological component (Fig. 2), including Rural Engineering with four Daily Parameters (GR4J), Identification of Unit Hydrographs and Component Flows from Rainfall, Evapotranspiration, and Stream Data (IHACRES), and Technische Universitat Wien (TUW). We developed a rule-based structure for the reservoir model, similar to the reservoir system simulation of the Hydrologic Engineering Center (HEC-ResSim).

GR4J was a lumped rainfall-runoff model with four parameters, utilizing two conceptual buckets in the basin, and stream routing was performed using a unit hydrograph. This model has been widely applied in hydrological studies (Faty et al., 2018; Kunnath-Poovakka and Eldho, 2019; Pastén-Zapata et al., 2022). Meteorological input data for the model included rainfall depth (P) and potential evapotranspiration (E). The model output was river flow expressed daily in millimeters. We utilized the airGR R package, which incorporated the GR family models, to simulate GR4J.

IHACRES was a conceptual rainfall-runoff model designed to characterize the hydrological dynamics of a basin using six parameters in the loss and unit hydrograph modules (Jakeman et al., 1990). The model received daily time series data of precipitation and temperature, which were subsequently converted into a daily runoff time series. A nonlinear module estimated the effective

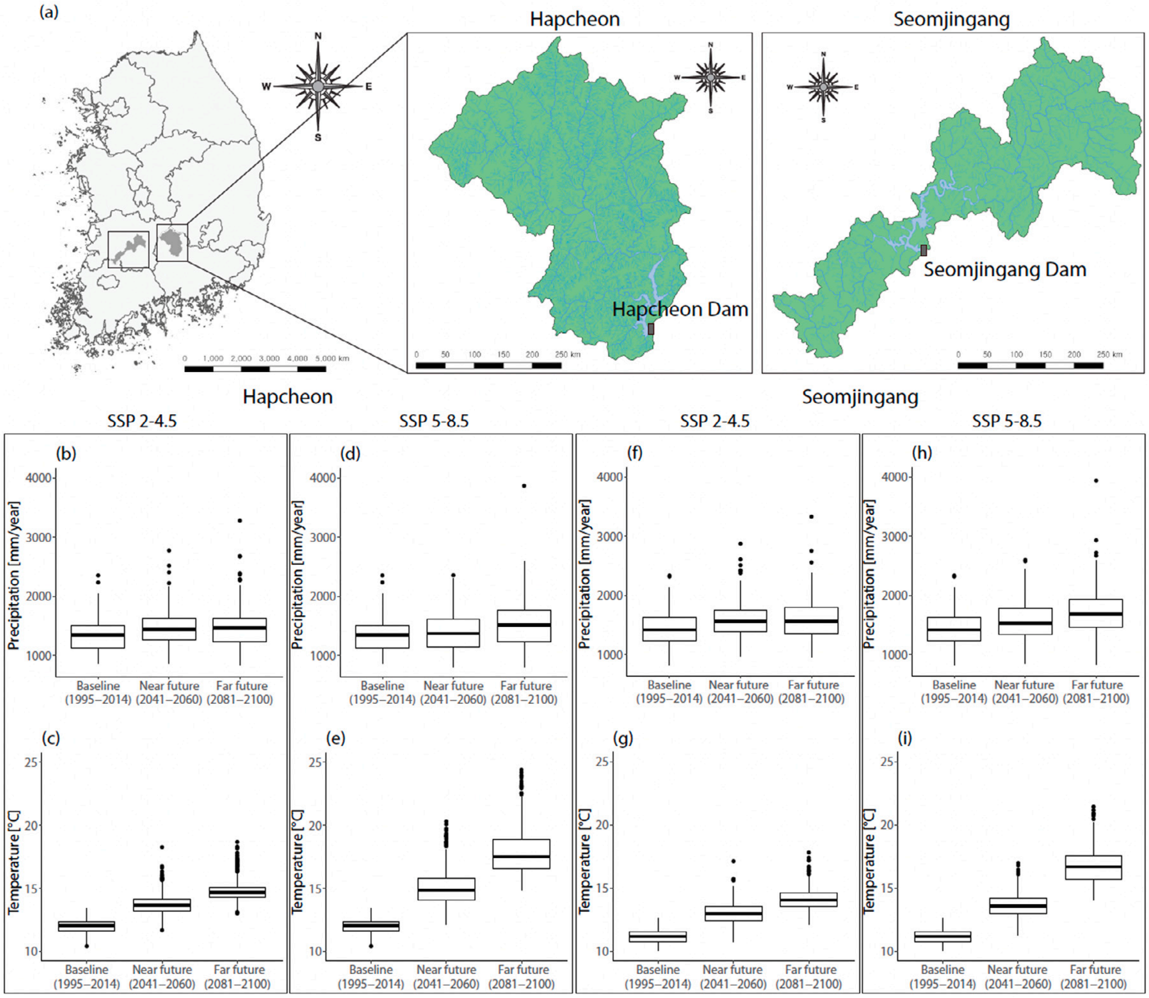

Fig. 1. Study sites and climate change scenarios. (a) Map displaying the Hapcheon and Seomjingang Basins with the reservoirs. (b–i) Illustration of precipitation and temperature during the baseline (1995–2014), near future (2041–2060), and far future (2081–2100) under SSP2-4.5 and SSP5-8.5 in (b–e) the Hapcheon and (f–i) Seomjingang Basins.

precipitation contributing to reservoir inflows, while two parallel linear modules were employed for routing effective precipitation. One module handled slow flow, akin to groundwater and base flow, and the other managed fast flow, akin to surface runoff.

The TUW hydrological model, developed at the Vienna University of Technology in Austria, was a rainfall-runoff simulation tool (Parajka et al., 2006). The model integrated both physical and empirical equations to simulate the water balance of river basins, incorporating precipitation, temperature, and potential evapotranspiration inputs. The model included several modules to simulate various hydrological processes, such as snow accumulation and melting, soil moisture dynamics, infiltration, evapotranspiration, surface runoff, and groundwater recharge and discharge. The model employed a distributed approach to divide an entire basin into sub-basins and simulate the hydrological processes in each sub-basin separately. These approaches enabled a more detailed representation of the spatial variability of hydrological processes.

Despite sharing similarities in handling hydrological variables in a lumped manner, the three models exhibited distinctive structural features. Notably, the connectivity of soil water storage with other processes differed considerably among the models. In GR4J, a conventional one-bucket production store represented average soil and groundwater while IHACRES featured parallel quick- and slow-flow components. TUW considered the effects of snow accumulation and melts on flow processes, making it particularly suitable for evaluating the impacts of winter snowfall on water resources. Despite sharing a lumped modeling approach, these unique features of each model made them valuable tools for exploring water resource management, both collectively and individually, in this research.

2.2.2. Reservoir operation model

The R programming language was utilized to develop a rule-based code for simulating reservoir operations for water supply and flood management. While the operational structure of the reservoir model resembled that of HEC-ResSim, the R-based model in this

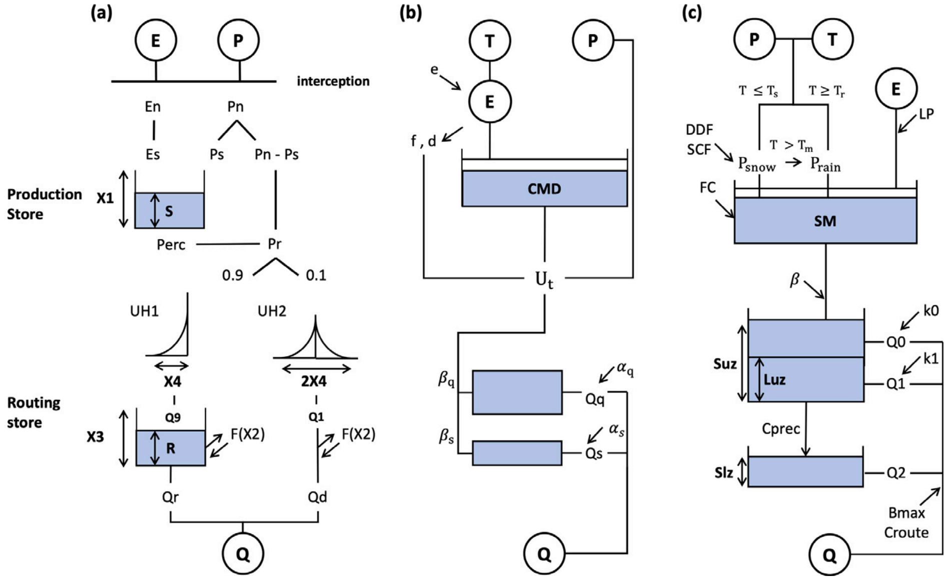

Fig. 2. Lumped hydrological models used in this study: (a) GR4J, (b) IHACRES, and (c) TUW. The descriptions of the symbols were presented in Table S1 to S6 in the Supplementary Information. The blue boxes, circles, and lines represent storages, model inputs and outputs, and connections. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

study proved more adept at estimating inflow scenarios from various hydrological models, as well as facilitating water supply and flood risk assessments. This operational model calculated the daily water budget in a reservoir, encompassing inflow, water supply for multiple demands, and flood control. Specifically, the reservoir operation model released the entire inflow when the water level exceeded the flood-control threshold. Conversely, when the water level fell below the dead storage level, the water supply was contingent solely upon the inflow.

2.3. Climate scenarios

We utilized two climate change scenarios from the Shared Socioeconomic Pathway (SSP) framework: SSP2-4.5 and SSP5-8.5. The SSP2-4.5 scenario entailed an additional radiative forcing of 4.5 W/m^2 by 2100, resulting in a global temperature rise of approximately 1.14 to 3.08 °C by the end of the century compared to pre-industrial levels (Tebaldi et al., 2021). This scenario involved moderate efforts to mitigate climate change, including increased utilization of renewable energy and enhanced technological efficiency. Conversely, the SSP5-8.5 scenario assumed an additional radiative forcing of 8.5 W/m^2 by 2100, leading to a global temperature increase of about 2.42 to 5.64 °C by the end of the century, precipitating catastrophic climate impacts, such as irreversible damage to ecosystems. By employing these two disparate scenarios, this study aimed to elucidate the potential ramifications of climate change on future water management.

The SSP2-4.5 and SSP5-8.5 climate scenarios were obtained from the Climate Data Store (https://cds.climate.copernicus.eu), which provided results from 12 distinct global climate models spanning historical (1995–2014) and projection (2015–2100) periods. The SSP projections utilized in this study emanated from the following models: ACCESS-CM2 (Australia), CESM2 (USA), CMCC-CM2-SR5 (Italy), CNRM-ESM2-1 (France), EC-Earth3-CC (Europe), GFDL-ESM4 (USA), INM-CM5-0 (Russia), IPSL-CM6A-LR (France), MIROC-ES2L (Japan), MIROC6 (Japan), MRI-ESM2-0 (Japan), and NorESM2-MM (Norway).

To minimize discrepancies between observed and simulated weather patterns, we conducted bias correction on the SSP2-4.5 and SSP5-8.5 climate change scenarios using quantile mapping, as proposed by Themeßl et al. (2011). This correction was based on observed precipitation and temperature data spanning 20 years (1995–2014). The bias-corrected climate change scenarios were illustrated in Fig. 1b–i. Both scenarios exhibited an increase in precipitation amount and variability. For instance, under the SSP5-8.5 climate scenario, the average linear increase in precipitation amount and standard deviation across all models during the projection period (2015–2100) for the Hapcheon basin was 5.7 mm/year and 315.7 mm/year, respectively. Similarly, for the Seomjingang basin, these values were 6.6 mm/year and 344.5 mm/year, respectively. Temperature increases projected under both SSP2-4.5 and SSP5-8.5 climate scenarios indicated a linear increment of 0.04 °C/year and 0.08 °C/year for the Hapcheon Basin, and 0.04 °C/year and 0.09 °C/year for the Seomjingang Basin, respectively.

2.4. Experiment designs and assessment measures

Fig. 3 illustrated the schematic diagram of the numerical experiments designed for this study. To reduce modeling uncertainty, we calibrated the parameters of the three lumped models using historical streamflow observations from the outlets of the two basins

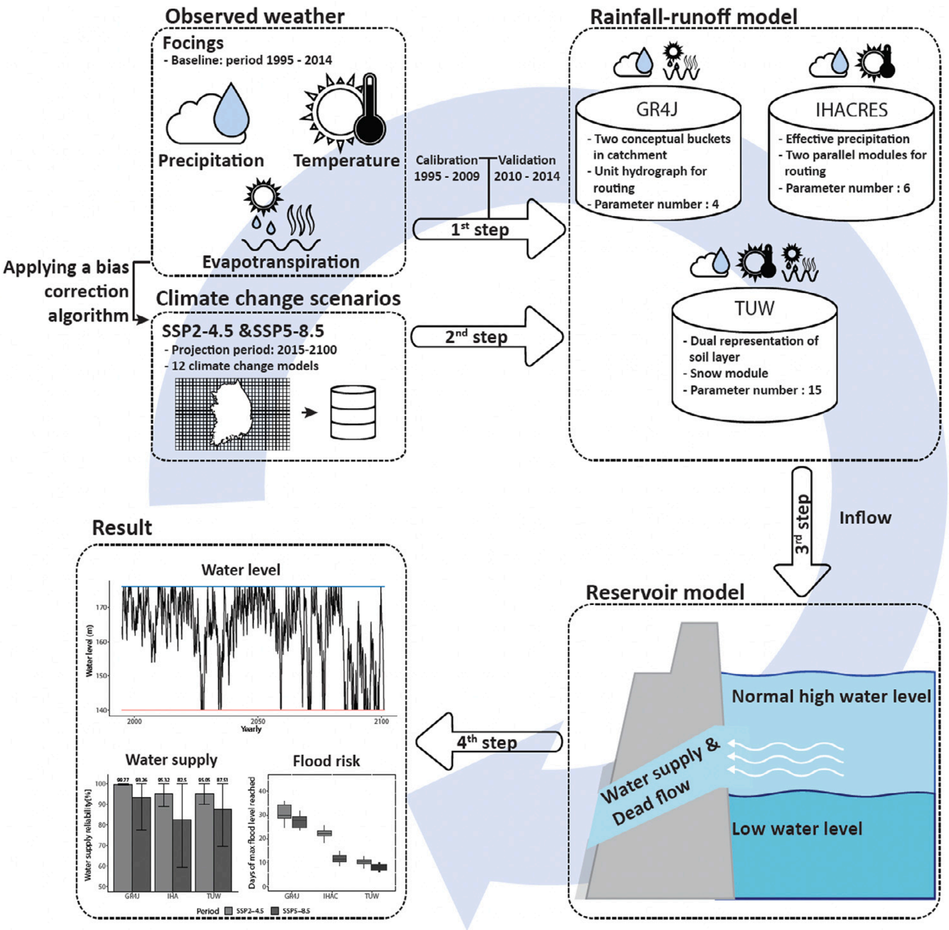

Fig. 3. Schematic diagram outlining numerical experimental designs. Based on observed weather data, three rainfall-runoff models (GR4J, IHACRES, and TUW) were calibrated from 1995 to 2008 and validated from 2009 to 2014. Utilizing 12 distinct bias-corrected SSP2-4.5 and SSP5-8.5 projections, reservoir inflows were estimated using the validated rainfall-runoff models. These inflows were then employed to estimate reservoir water levels, enabling exploration of water supply reliability and flood risk under future climate conditions.

over 14 years (1995–2008) and validated the models with streamflow observations from 2009 to 2014 (6 years). The calibration and validation results were presented in Section 3.1, "Model Validation". Kling-Gupta Efficiency (KGE) was employed as the objective function for calibrating the parameters of GR4J and IHACRES, while a combination of multiple objective functions, such as NSE, was used for calibrating the parameters of the TUW model based on model structure and prediction performance. The three developed lumped models were used to explore the impacts of climate change on water resource management using the SSP2-4.5 and SSP5-8.5 scenarios.

The impacts of climate change on water resources management were assessed in terms of drought and flood. The reliability of water supply during reservoir operation, essential for assessing drought, was evaluated using the water supply reliability index (Rel) proposed by Hashimoto et al. (1982), as indicated below:

$$Rel = \Sigma T_{low} / T_{total} \tag{1}$$

where T_{low} represents the number of temporal evaluation units, ranging from 1 d to 1 year, during which the reservoir level fell below the dead storage. T_{total} represents the total number of temporal evaluation units. We selected a 5-day temporal evaluation unit for drought analysis. This decision was informed by the recognition that a 5-day interval efficiently captured short-term variations in reservoir levels (Sung et al., 2022; Noh et al., 2023). Additionally, this choice was congruent with the standard operational schedules of water resource management agencies, facilitating the practical application of our findings.

The flood vulnerability (F_{vul}) was estimated by the index shown below.

$$F_{vul} = \Sigma T_{high} / T_{total} \tag{2}$$

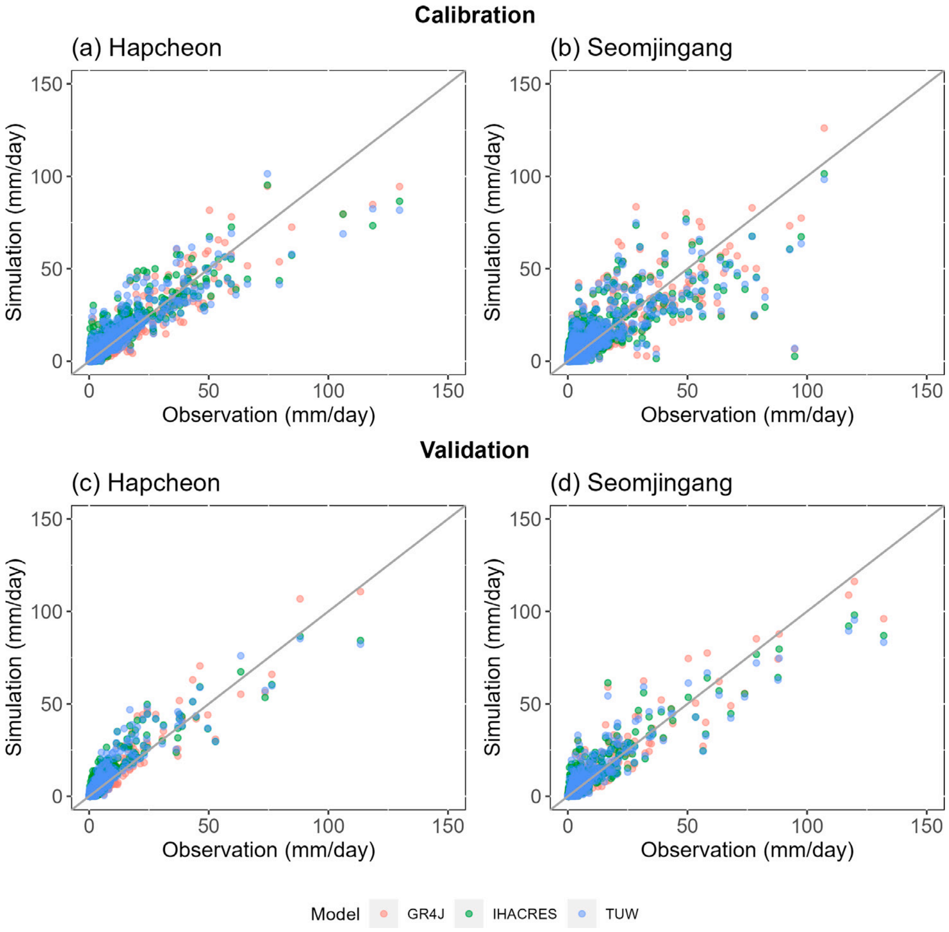

Fig. 4. Comparison between modeled (x-axis) and observed (y-axis) reservoir inflows during the (a, b) calibration and (c, d) validation periods for the Hapcheon (left column) and Seomjingang Basins (right column). The colors red, green, and blue correspond to the GR4J, IHACRES, and TUW models, respectively. The black line represents a 1:1 relationship. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

where T_{high} represents the number of temporal evaluation units (d) when the reservoir level exceeds the flood control level. Flood vulnerability was assessed using a multiyear moving window (T_{total}) to capture the flood risk trends in reservoir operations. A higher value of F_{vul} indicated an increase in the vulnerability of the reservoir to flood risks.

3. Results and discussion

3.1. Model validation

The accuracy of the modeled reservoir water inflow and level was evaluated through model validation utilizing historical discharge data and the water supply reliability index for both the calibration period (1995–2008) and the validation period (2009–2014), as depicted in Fig. 4. The closer the Kling–Gupta Efficiency (KGE) values were to 1, the higher the model accuracy. During the calibration period, the KGE values for the Seomjingang and Hapcheon reservoir inflows estimated using GR4J, IHACRES, and TUW were 0.87, 0.83, and 0.81, 0.94, 0.91, and 0.91, respectively. Similarly, during the validation period, the corresponding KGE values were 0.92, 0.91, and 0.84 for Seomjingang, 0.77, 0.85, and 0.77 for Hapcheon (Table S7). Overall, among the models employed in this study, GR4J demonstrated the highest accuracy in modeling the inflow. The performance of the modeled Hapcheon reservoir inflow surpassed that of Seomjingang. Minor discrepancies were noted between the estimated and modeled water-supply reliabilities for the Seomjingang Basin. In the case of the Hapcheon Basin, the water supply reliability estimated using the TUW inflow was slightly higher than that observed, with a difference of approximately 5.8%. IHACRES exhibited approximately 3.3% differences and GR4J yielded approximately 2.8% differences between simulated and observed water supply reliability. Overall, the modeled variables exhibited a strong agreement with the observed data, instilling confidence in the utilization of the three distinct hydrological and reservoir operation models.

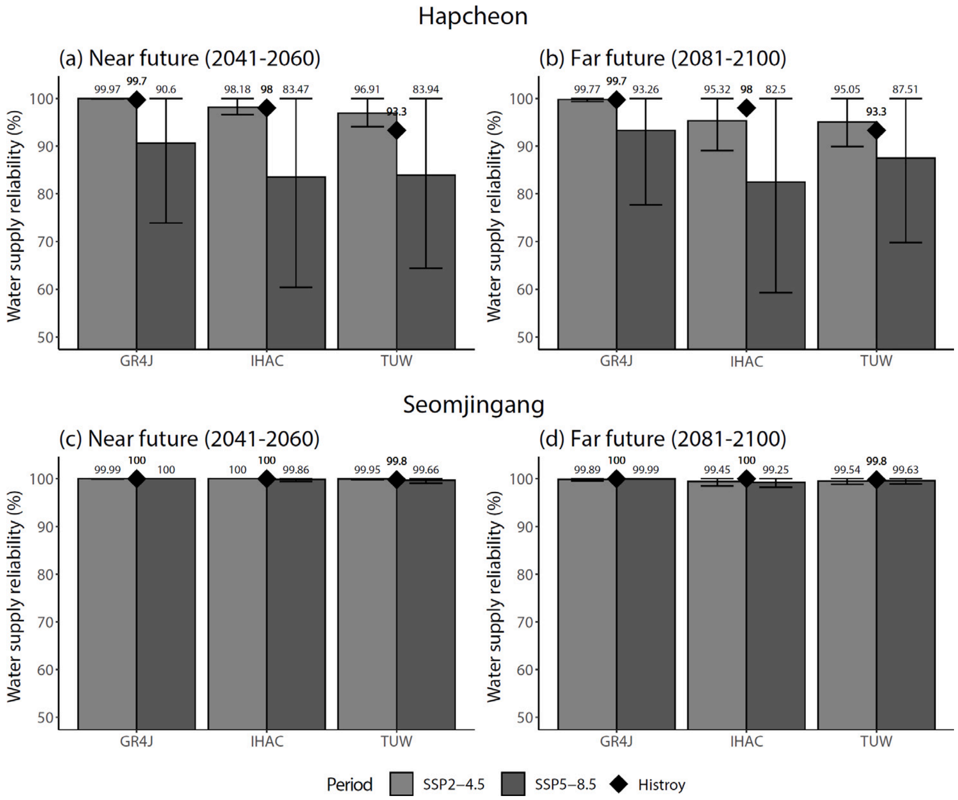

Fig. 5. Water supply reliability estimated in the Hapcheon Basin for (a) the near future (2041–2060) and (b) the far future (2081–2100) and in the Seomjingang Basin for (c) the near future and (d) the far future. The error bars represent the standard deviation, and the rhombus represents water supply reliability under the baseline (1995–2014).

3.2. Water supply reliability under climate change

We evaluated water supply reliability using three rainfall-runoff models across 12 distinct climate change scenarios. In the Hapcheon Basin (Fig. 5a, b), the uncertainty in projected water-supply reliability under SSP2-4.5 was relatively minor compared to that under SSP5-8.5. These uncertainties primarily stemmed from considerable variations among climate change scenarios rather than hydrological models. It was noteworthy that under the SSP2-4.5 scenario, water supply reliability did not decrease considerably compared to the baseline, unlike the SSP5-8.5 scenario. Among these models, IHACRES projected the lowest water supply reliability, while GR4J projected the highest for Hapcheon Reservoir. Shifting our focus to the Seomjingang Basin (Fig. 5c, d), we projected almost no water supply pressure under both SSP2-4.5 and SSP5-8.5, as indicated by all models and across all climate change scenarios. These results suggested that anticipated climate change would not considerably disrupt the relatively stable water supply from the Seomjingang reservoir in the future. These findings aligned with those of previous studies (Park and Kim, 2014; Qin et al., 2020), which demonstrated similar trends in the reliability of water supply systems under changing climatic conditions. However, an increase in precipitation intensity in the coming decades would lead to heightened flood risks.

3.3. Flood risk under climate change

To assess future flood risks amidst changing climate conditions, we employed two primary metrics: the annual average number of days that reached flood levels (depicted in Figs. 6 and 7, Table S8), and the total volume of dam release during flood events (Fig. 8, Table S9). The former indicated the number of days surpassing water level thresholds critical for stable reservoir operations during flood seasons, termed “flood days”, while the latter signified the cumulative discharge when floodwater levels were reached, referred to as “flood volume”. To mitigate year-to-year variability and identify long-term trends, we applied a 5-year moving average to the combined rainfall-runoff and reservoir operation data for flood risk analysis.

In the Hapcheon Basin (Fig. 6a,b, Table S8) and the Seomjingang Basin (Fig. 6c,d), an increase in flood days was projected using the combined GR4J and TUW models, alongside reservoir operation models, under both climate change scenarios compared to the historical period. Conversely, when employing the coupled IHACRES and reservoir operation model, a decrease in flood days was projected relative to the historical period. Thus, under climate change scenarios, the consistent projection of increasing flood days by GR4J and TUW suggested a robust pattern, whereas IHACRES exhibited an opposite trend. Further investigation

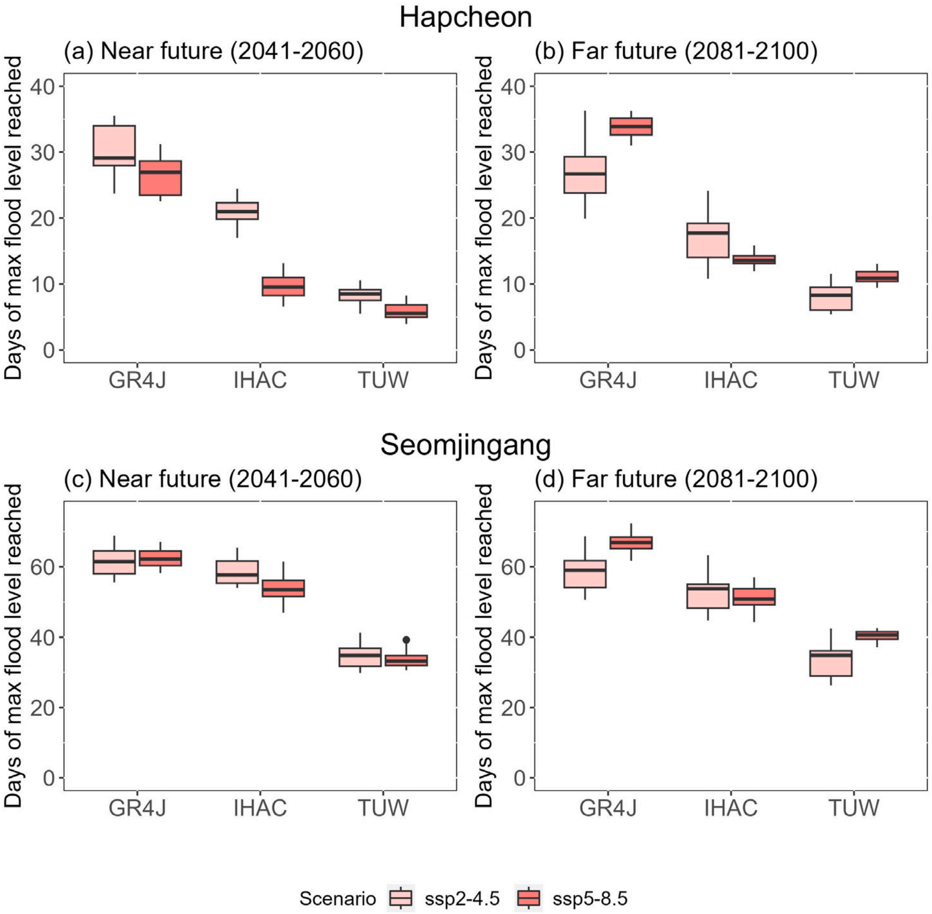

Fig. 6. Number of days reaching maximum flood level during (a, c) the near future (2041–2060) and (b, d) far future (2081–2100) in the Hapcheon (top panel) and Seomjingang (bottom panel) Basins, respectively.

was warranted to comprehend the factors contributing to the divergent responses of IHACRES compared to GR4J and TUW. This disparity underscored the importance of incorporating multiple modeling approaches when evaluating the impacts of climate change on hydrological processes.

A consistent trend was generally modeled in the single hydrological model-based simulations of flood occurrences under both historical and future scenarios. However, a considerable disparity in the frequency of flood events emerged among different models. This model-specific bias was particularly evident in hydrological simulations for future periods but not during calibration or historical analyses. Hence, caution was warranted when aggregating the results of hydrological and reservoir operation simulations across various models for assessing future changes.

While Fig. 6 displayed the average flood occurrences across all climate models, Fig. 7 depicted flood occurrences simulated by GR4J using forcings projected by 12 climate models to evaluate the uncertainties introduced by these models. Flood occurrences under SSP5-8.5 (Fig. 7c) exhibited greater climate-induced variability compared to those under the historical period and SSP2-4.5 (Fig. 7a, b). Similarly, heightened variability in flood occurrences under SSP5-8.5 was observed in the Seomjingang Basin (Fig. 7f), as simulated by GR4J. A comparative analysis of flood occurrences estimated by IHACRES and TUW across different climate models was provided in the Supplementary Material (Figs. S1, S2).

Fig. 8 compared the flood volumes, which represented the annual accumulated amount of water released from the reservoir when the reservoir flood control levels were reached. Increases in flood volumes were modeled in both the Hapcheon and Seomjingang Basins under SSP2-4.5 and SSP5-8.5, respectively, compared with the historical period. The flood risk estimated using the coupled IHACRES and reservoir operation model in the Seomjingang Basin showed evident variations compared with the results estimated using the other models. Although the number of flood days decreased compared with the historical period for both climate change scenarios, the flood volume was projected to increase. Overall, future flood risk was projected to increase compared to the historical period.

We evaluated the percentile changes in rainfall, runoff, and flood volume under climate change scenarios compared to the historical period to examine the cascade of variability from climate to runoff and then to flood risks in reservoir operation using the

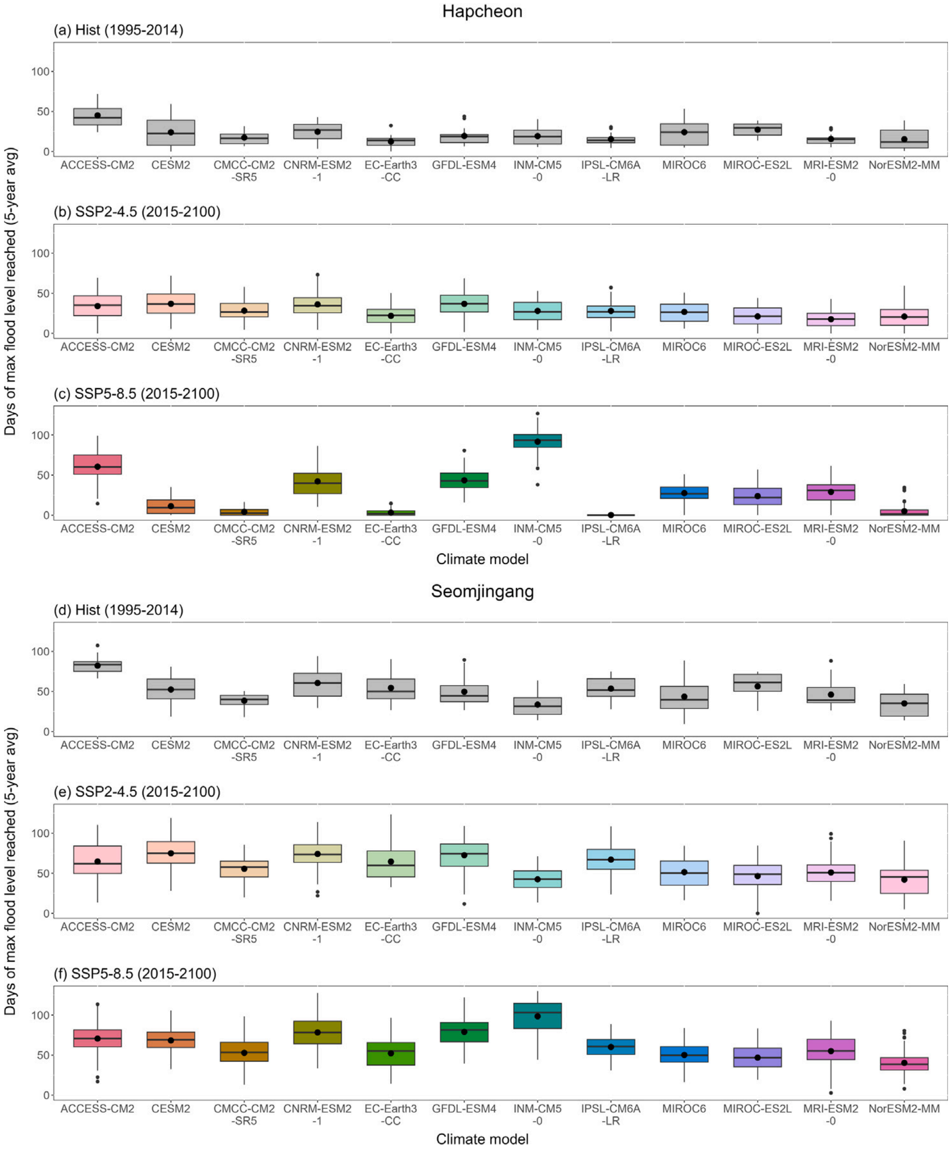

Fig. 7. Number of days reaching maximum flood level using GR4J during the (a, d) historical period, (b, e) SSP2-4.5, and (c, f) SSP5-8.5, projected by 12 distinct global climate models in the Hapcheon and Seomjingang Basins, respectively.

coupled GR4J and reservoir operation models (Fig. 9, Table S10). In both the Hapcheon and Seomjinjang Basins, throughout the entire future period (2015–2100), all three variables (rainfall, runoff, and flood volume) indicated an increase under both SSP2-4.5 and SSP5-8.5, compared to the historical period. Furthermore, this increasing trend was amplified through a cascade from rainfall to runoff, and then to flood volume. In the Hapcheon Basin, an 8.7% percentile increase in rainfall induced increases in runoff and flood volume of 19.9% and 42.9%, respectively. Particularly in the far future (2081–2100) under SSP5-8.5, the flood volume would increase rapidly by 73.2% and 74.1% in the Hapcheon and Seomjingang Basins, respectively, indicating significant changes in flood risk due to climate change. The results of the other two hydrological models were provided in the Supplementary Material (Figs. S3, S4). While consistent trends in all three variables were not modeled in every case, unlike GR4J, an increasing percentile change in flood volume was identified in two other hydrological model cases in both basins for the far future (2081–2100) under SSP5-8.5 (Figs. S5 to S28).

Several studies (Sadegh et al., 2019; Chevuturi et al., 2023; Gichamo et al., 2024) have shown that blending multiple models yielded superior results compared to conducting hydrological simulations using a single model. This suggested significant advancements in water resource management by providing a comprehensive perspective. While consistent with previous studies, our research demonstrated that hydrological models, though comparable during historical periods, might exhibit significant discrepancies in future projections. These findings suggested that relying solely on a single hydrological model for future projections might fail to

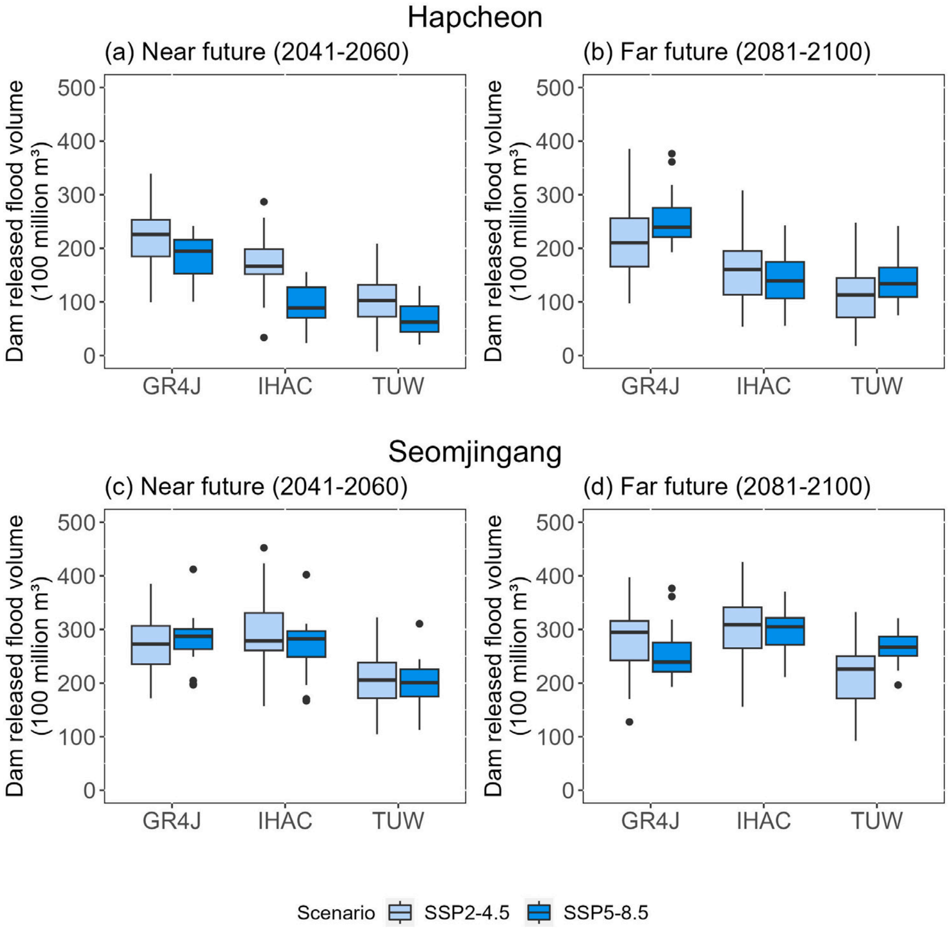

Fig. 8. Flood volume during (a, c) the near future (2041–2060) and (b, d) far future (2081–2100) in the Hapcheon (top panel) and Seomjingang (bottom panel) Basins, respectively.

capture the full spectrum of potential outcomes. By incorporating diverse modeling approaches, decision-makers could ensure more resilient and sustainable water resource management practices.

In contrast to the Mediterranean regions (Hrour et al., 2023) and West African Basins (Mbaye et al., 2020), which exhibited a pattern of decreasing precipitation and discharge under climate change conditions, Korean basins were anticipated to experience an increase in precipitation, runoff, and flooding risks under the two climate change scenarios. This expectation aligned with previous studies projecting intensified intensity and variability of the East Asian summer monsoon (You et al., 2022). Similar to discussions on the limitations of lumped modeling in addressing extreme droughts in a previous study (Fowler et al., 2020), the reliability of conceptual models for assessing extreme flood risks under climate change required verification across diverse regional conditions in future research endeavors. Despite the consistent increasing trend of flood risk across all models, significant biases between hydrological models were observed, which might not be easily resolved through conventional GCM-only ensembles (Muelchi et al., 2022) or multi-model approaches (Meresa et al., 2022). While the uncertainty of GCM remained predominant over that of hydrological and dam operation modeling, as noted in a previous study (Her et al., 2019), exploring potential remedies for systematic biases in future water resource projections, such as weight-based ensemble techniques (Pastén-Zapata et al., 2022), along with anticipated changes in water demand, warrants further investigation.

4. Conclusion

The study assessed the impact of climate change on water supply reliability and flood risk using an integrated approach, incorporating three conceptual hydrological and reservoir operation models. Simulations targeted two East Asian basins in South Korea under SSP2-4.5 and SSP5-8.5 projected by 12 global climate models. Key findings and recommendations for future research were outlined below.

1. Overall, neither the Hapcheon nor Seomjingang Basins showed a significant decrease in water supply reliability under SSP2-4.5 nor SSP5-8.5 compared to historical levels, indicating the maintenance of stable water supply.

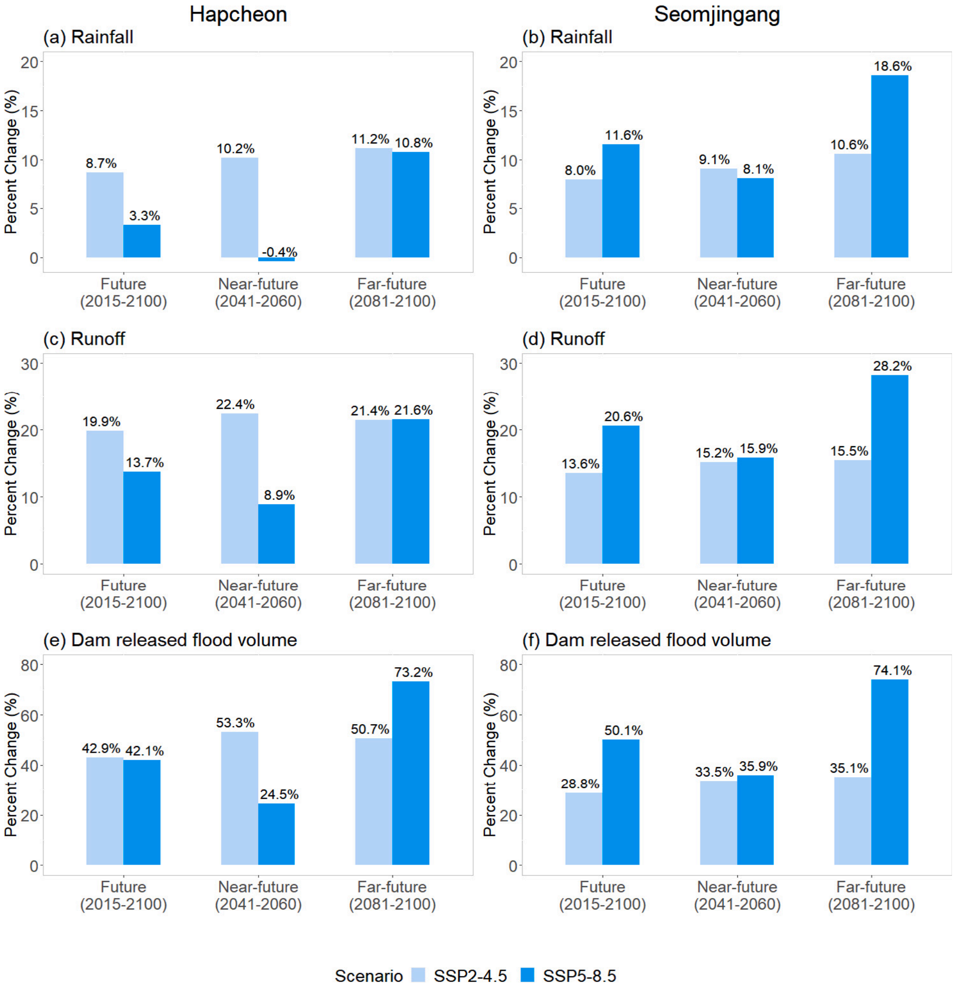

Fig. 9. Assessment of percentage changes in (a, b) rainfall, (c, d) runoff, and (e, f) dam-released flood volume modeled by GR4J during future (2015–2100), near future (2041–2060), and far future (2081–2100) under SSP2-4.5 and SSP5-8.5 compared to the historical period (1995–2014) in the Hapcheon (left column) and Seomjingang (right column) Basins.

2. Both the number of flood days and flood volume increased in the Hapcheon and Seomjingang Basins under SSP2-4.5 and SSP5-8.5, compared to historical levels.
3. An assessment of percentile changes in rainfall, outflow, and flood volume revealed substantial increases of 73.2% and 74.1% in flooding magnitude in the Hapcheon and Seomjingang Basins, respectively, under SSP5-8.5 for the distant future (2081–2100). These findings emphasized the heightened flood risk due to climate change.
4. SSP5-8.5 exhibited greater variability among climate models compared to SSP2-4.5, resulting in increased uncertainty in predictions for both drought and flood risk assessments, especially in the far future (2081–2100).
5. In the future, integrating feedback mechanisms between rainfall and runoff, along with reservoir models, coupled with dynamic human demand assessments, could enhance decision-making processes and facilitate the implementation of reliable water management practices.

Funding statement

This work was supported by Korea Environment Industry & Technology Institute (KEITI) grant, funded by Korea Ministry of Environment (MOE) (RS-2023-00218973), Korea Environmental Industry & Technology Institute (KEITI) through R&D Program for Innovative Flood Protection Technologies against Climate Crisis Project, funded by Korea Ministry of Environment (MOE) (2022003460002), and the National Research Foundation of Korea (NRF) grant, funded by the Korea government (MSIT) (RS-2023-00246532, RS-2024-00336959). These supports are gratefully acknowledged.

Code availability

Code is available upon request.

Consent for publication

All Authors consent to the article's publication after acceptance.

CRediT authorship contribution statement

Seong Jin Noh: Writing – review & editing, Writing – original draft, Supervision, Funding acquisition, Conceptualization. **Garim Lee:** Writing – original draft, Visualization, Validation, Data curation. **Bomi Kim:** Writing – original draft, Visualization, Validation, Data curation. **Songhee Lee:** Writing – original draft, Visualization, Validation, Formal analysis, Data curation. **Jihyeon Jo:** Visualization, Validation, Formal analysis. **Dong Kook Woo:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

We would like to express our gratitude to the editors and reviewers for their helpful comments.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.ejrh.2024.101842.

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