Assessing environmental flow alterations induced by dams and climate change using a distributed hydrological model at catchment-scalel

Haruki Mineda[1], Kei Nukazawa[1], and Yoshihiro Suzuki[1]

[1]University of Miyazaki

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Abstract

Hydrological alterations can reduce aquatic biodiversity by disrupting the life cycles of organisms. However, past studies have faced difficulties in quantifying the impacts of dams and climate change, which are major drivers of hydrological alterations. Here, we aimed to evaluate and compare the hydrological alterations caused by dams and climate change throughout the Omaru River catchment, Japan, using a distributed hydrological model (DHM). First, to assess the impacts of dam and climate change independently, we performed runoff analyses using either dam discharge or future climatic data (two future periods, 2031-2050 and 2081-2100 $\times$ three representative concentration pathways). Subsequently, we derived indicators of hydrologic alterations (IHA) to quantify changes in flow alterations by comparing them to IHA under natural conditions (i.e., without dam or climate change data). The runoff analysis was calibrated and validated by comparing with daily streamflow at a site with minimal effects of substantial abstraction, and showed high reproducibility from 2010 to 2019 (Nash-Sutcliffe efficiency = 0.921–0.964). We found that dams altered IHAs more than climate change. However, on a catchment-scale standpoint, climate change induced wider ranges of flow alterations, such as low flow metrics along the tributaries and uppermost main stem, suggesting a catchment-level shrinkage in important corridors of aquatic organisms by reducing upstream length and water level. We also observed that the altered flow by water withdrawals were ameliorated by the confluence of tributaries and downstream hydropower outflows. Our approach using a DHM captured the various patterns of flow alterations by dams and climate change.

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H. Mineda[1], K. Nukazawa[1], and Y. Suzuki[1]

[1] University of Miyazaki, Department of Civil and Environmental Engineering, Miyazaki 889-2192, Japan.

Corresponding author: Kei Nukazawa (nukazawa.kei.b3@cc.miyazaki-u.ac.jp)

Key Points:

- A distributed hydrologic model is used to assess streamflow alterations induced by dams and climate change.
- Dams altered most environmental flow metrics more than climate change effects.
- Climate change had widespread effects, decreasing low flow metrics in upland streams and tributaries.

Abstract

Hydrological alterations can reduce aquatic biodiversity by disrupting the life cycles of organisms. However, past studies have faced difficulties in quantifying the impacts of dams and climate change, which are major drivers of hydrological alterations. Here, we aimed to evaluate and compare the hydrological alterations caused by dams and climate change throughout the Omaru River catchment, Japan, using a distributed hydrological model (DHM). First, to assess the impacts of dam and climate change independently, we performed runoff analyses using either dam discharge or future climatic data (two future periods, 2031-2050 and 2081-2100 × three representative concentration pathways). Subsequently, we derived indicators of hydrologic alterations (IHA) to quantify changes in flow alterations by comparing them to IHA under natural conditions (i.e., without dam or climate change data). The runoff analysis was calibrated and validated by comparing with daily streamflow at a site with minimal effects of substantial abstraction, and showed high reproducibility from 2010 to 2019 (Nash-Sutcliffe efficiency = 0.921–0.964). We found that dams altered IHAs more than climate change. However, on a catchment-scale standpoint, climate change induced wider ranges of flow alterations, such as low flow metrics along the tributaries and uppermost main stem, suggesting a catchment-level shrinkage in important corridors of aquatic organisms by reducing upstream length and water level. We also observed that the altered flow by water withdrawals were ameliorated by the confluence of tributaries and downstream hydropower outflows. Our approach using a DHM captured the various patterns of flow alterations by dams and climate change.

Key-words

flood protection, hydropower, indicators of hydrologic alteration, regulation, runoff analysis, catchment-scale

1 Introductions

Natural flow regimes in rivers worldwide have been altered through flood control, water resource development, and climate change (Nilsson et al., 2005; Poff et al., 1997). Researchers have found that changes in flow regimes can decrease riverine biodiversity through disruption of life cycles and habitat degradation (Poff et al., 1997; Lytle and Poff, 2004). Hence, it is necessary to understand the extent of the changes in the flow regimes resulting from anthropogenic factors. Dams are anthropogenic factors that greatly modify natural riverine flow with different alteration patterns according to their type (Richter et al., 1996; Nislow et al., 2002). For example, dams for flood control suppress seasonal fluctuations of natural flow by truncating peak discharges during potentially devastating flooding events, resulting in less variable flow patterns (Munn and Brusven, 1991). In addition, water withdrawal by large dams (e.g., for hydropower generation) often creates a section where the river flow is dramatically decreased (Li et al., 2017; Nukazawa et al., 2020). On the other hand, due to changing climates, extreme and frequent rainfall events, which have been observed recently in Japan, have triggered unexpected magnitude of floods and led to changes in river flow regimes (Sato et al., 2012). Döll and Zhang (2010) demonstrated that climate change has a greater impact on ecologically relevant river flow characteristics than dams and water withdrawals. Therefore, quantifying the extent to which dams and climate change alter flow regimes is a central challenge for river managers to safeguard riverine environments.

There have been many attempts to evaluate changes in flow regimes, although most have been limited to specific sites where flow data are available, such as the outlet of dams or reaches with a gauging station (Richter et al., 1998; Larned et al., 2011; Nukazawa et al., 2020). However, at a certain spatial scale, such as a catchment scale, attempts which rely on local flow data provide spatially insufficient information on river flow alteration as the alteration can be exacerbated or mediated through additional abstractions or convergences of small-to-large tributaries, respectively. To fill this gap, the application of distributed hydrological models (DHMs) is a promising approach. DHMs reflect spatial information, including altitude and land use/land cover, to estimate hydrological processes throughout a catchment of interest. Therefore, by using DHMs to obtain longitudinal profiles of river flow data at a given period and catchment, we can infer the spatial patterns of flow regimes and their alterations caused by dams/weirs and climate change. To date, DHMs have been used to evaluate changes in the flow regimes by dams and weirs (Ryo et al., 2015, Mineda et al., 2020; Jardim et al., 2020). Although many studies have evaluated the impact of climate change on environmental flows (Mahmoodi et al., 2021), to the best of our knowledge, those evaluations have been limited to specific sites such as reaches with a gauging station and estuary. Schneider et al. (2013) assessed the impact of climate change on environmental flows across Europe. Since they used a global scale model (5 arc min grid size), they evaluated differences in impacts between climate zones, but does not grasp differences in impacts along segments in a catchment (i.e., up- and down-stream gradients). Fatichi et al. (2015) have assessed the impact of climate change on spatial distributions of streamflow regime such as minimum and maximum streamflow while considering dam operations, although the authors did not focus on potential changes in a variety of environmental flow metrics typically assessed using IHA or its equivalents. Since IHA considers five critical components of the flow regime regulating ecological process in river: the magnitude, frequency, duration, timing, and rate of change of hydrologic conditions, IHA provides more comprehensive information which is useful to assessing the impact of alteration on the ecological status in river (Richter et al., 1996). However, no study has evaluated the impact of climate change on environmental flows in an entire catchment using a DHM and its spatial heterogeneity.

Previous studies evaluating dam-induced flow alteration have generally adopted an approach that compares flow data before and after dam construction and defines the alteration as the degree of change in flow regimes in the presence of the dam (Zuo and Liang, 2015; and Faye, 2018). However, as the calculation periods typically cover several decades (Lu et al., 2018), this approach could be subject to the effects of climate change (Cui et al., 2020). Consequently, the extent of flow regime alterations by dams cannot be appropriately evaluated. Therefore, it is of primary importance to separately assess the impacts of such anticipated anthropogenic factors (i.e., flow regulations and climate change) on environmental flow for adequate water resource management and environmental conservation (Goldstein and Tarhule, 2014).However, few previous studies have proposed frameworks to separate the impacts of dam and climate change when quantifying the impacts of dam (Lu et al., 2018 and Cui et al., 2020). For example, Cui et al. (2020) estimated the flow alteration due to dam construction by comparing observed pre-impact (i.e., before dam construction) and post-impact flow regime indicators value while excluding the impact of climate change estimated based on differences between the observed pre-impact value and post-impact value simulated by a hydrological model. However, the authors stated that the influences of all dams located in the study catchment and other human activities such as land-use change on flow regimes were not always addressed. In addition, previous works comparing pre- and post- impact periods remain to estimate indirect measures of alteration since the two periods may involve distinctive flow events even without any other potential anthropogenic effects.

The present study aims to evaluate and compare the changes in flow regimes caused by dams and climate change throughout a river catchment. First, we will apply a DHM to the Omaru River catchment in southwest Japan, which contains multiple dams and intake weir. Then, we will perform runoff analyses using dam discharge data to adequately quantify the spatial patterns of dam-induced flow alteration. Similarly, using future climatic data acquired from general circulation models (GCMs) or not, we will run a DHM to evaluate the impacts of climate change on environmental flow regimes in the study catchment. Finally, we will compare the extent and patterns of flow alteration between dams and climate changes. Our approach will provide important environmental implications as spatial extents of flow regime alteration by such major anthropogenic impacts.

2 Study area

We investigated the Omaru River (catchment area: 474 km2), which originates in the Sampo Mountains, flows 75 km east, and drains into the Pacific Ocean (Figure 1). The mean annual temperature, annual precipitation, and elevation are approx. 14.9 °C, 3,100 mm, and 250 m at the Mikado meteorological station, and approx. 17.6 °C, 2,300 mm, and 57 m at the Takanabe meteorological station in the downstream terrain (http://www.qsr.mlit.go.jp/miyazaki/kasen/omaru/gaiyou/omaru_saigai.html). The major land uses/land covers in the catchment are forests (~87 %), agricultural fields (~10 %), and urban areas (~3 %) (Figure S1(a)). There are two dams for flood control and hydropower generation (Dogawa and Matsuo Dams), the two dams only for hydropower generation (Tozaki and Ishikawauti Dams), as well as a dam for irrigation and hydropower generation in the catchment

(Table S1). A weir for abstraction (Kijino weir) is installed in the uppermost stream to supply river water to the Dogawa Dam reservoir. As key characteristics of each dam, the ages, heights, and reservoir capacities are, respectively, 65 yr, 62.5 m, and 143,000 m3 for the Dogawa Dam, 70 yr, 68 m, and 168,000 m3 for the Matsuo Dam, 78 yr, 25 m, and 25,000 m3 for the Tozaki Dam, 14 yr, 47.5 m, and 134,000 m3 for the Ishikawauti Dam, and 82 yr, 23.6 m, and 34,000 m3 for the Matsuo Dam.

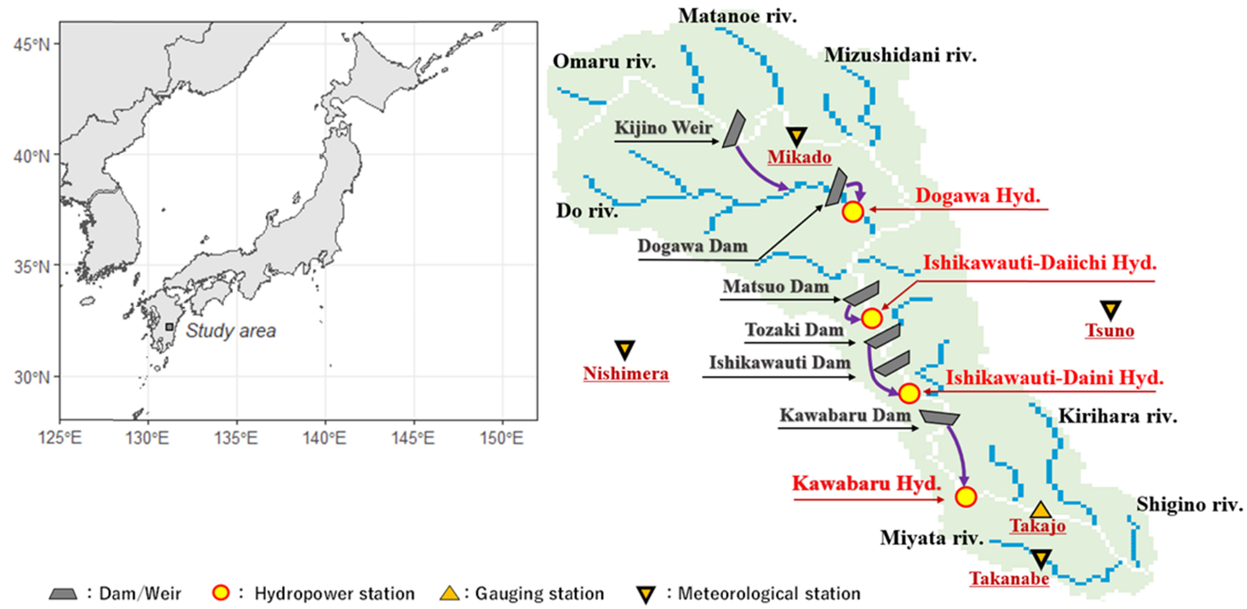

Figure 1. The Omaru River catchment (catchment area: 474 km^2) with the spatial distributions of the studied dams, weir, hydropower stations, and meteorological and gauging stations. The main stem and tributaries handled as channel parts in hydrologic modeling are depicted by white and blue colors, respectively. Arrows indicate water conveyance from the dams to the hydropower stations. The outflow data time series available at all weir, dams, and Hydropower stations are used for the model input. Observed daily discharge data at the Dogawa Dam, Matsuo Dam, and Takajo gauging station are used for the model validation.

3 Material and methods

3.1.1 Geographic data

We acquired digital elevation model (DEM) data at a spatial resolution of 250 m (Figure S1(b)) from the Ministry of Land, Infrastructure, Transportation, and Tourism. We used the spatial distribution of land use/land cover at a resolution of 100 m and converted its spatial resolution to 250 m (Figure S1(a)). Based on the DEM, the slope and flow directions in the catchment were estimated while correcting the pans (a mesh with lower elevation than surrounding eight meshes), so the direction was properly determined in the analyses. To do so, the altitudes of pans were slightly raised repeatedly, and finally, corrected DEM and flow direction maps were created for use in subsequent runoff analyses.

3.1.2 Meteorological data

Observed precipitation data were acquired from Automated Meteorological Data Acquisition System (AMeDAS) data at three meteorological stations (Takanabe, Mikado, and Tsuno) inside and outside the Omaru catchment, and from the Dogawa and Matsuo Dams (Figure 1). Data on air temperature, wind speed, and sunshine duration were acquired from the AMeDAS data at three meteorological stations (Takanabe, Nishimera, and Mikado). For the cloud cover, atmospheric pressure, and humidity observation data, we used data from the Miyazaki Local Meteorological Observatory, which is the local meteorological station closest to the Omaru River catchment. The temperature, wind speed, and precipitation were spatially interpolated by averaging the weights of geographical distance based on the point data at the meteorological stations and were input over the study catchment.

For future climate data, we used eight GCMs (Table S2) provided by the Earth System Grid Federation (http: //esgf-node.llnl.gov/search/cmip5). We acquired monthly surface temperature and precipitation data from each of the eight GCMs targeting the two future periods, the near future (2031–2050) and the far future (2081–2100). Future emissions and radiative forcing were considered using three representative concentration pathways (RCP2.6, RCP4.5, and RCP8.5; following numerals indicate anticipated radiative forcing around 2100).

3.1.3 Bias correction

To adequately estimate regional temperature and precipitation in the future from GCMs that only have low spatial resolution, it is necessary to eliminate systematic errors (bias). Therefore, we corrected biases in temperature and precipitation data for each future period using monthly temperature and precipitation data from the baseline period (1981–2000) and each future period, as well as monthly temperature and precipitation data from AMeDAS meteorological stations (i.e., Takanabe, Nishimera, Mikado, and Tsuno). First, the GCM temperature and precipitation data in each RCP and future period were extracted in a raster mesh including the Omaru River catchment on QGIS (Quantum GIS ver. 2.18.23). Subsequently, assuming that the temperature and precipitation follow normal distribution and lognormal distribution, respectively (see full description of bias correction in Supplementary Methods), in the present and future periods, bias-corrected temperature and precipitation were obtained based on the difference and ratio between the future and present GCM output values corresponding to the inverse cumulative distribution functions (CDFs) (Figure S2) for each meteorological station and month. The formulae for deriving the bias-corrected temperature and precipitation are as follows:

$$T_c = T_o + F_f^{-1}\left(F_{oN}(T_o)\right) - F_c^{-1}\left(F_{oN}(T_o)\right) \quad (1)$$

$$P_c = P_o * F_f^{-1}\left(F_{oN}(P_o)\right) / F_c^{-1}\left(F_{oN}(P_o)\right) \quad (2)$$

where T_c is the bias-corrected hourly temperature (°C), T_o is the observed hourly temperature at each meteorological station (°C), F_f^{-1} is the inverse CDF of GCM output values for each RCP and future period, F_c^{-1} is the inverse CDF of the GCM output values for the baseline period, F_{oN} is the CDF of observed values, P_c is the bias-corrected hourly precipitation (mm), and P_o is the observed hourly precipitation (mm). For details, see Text S1.

3.2 Distributed hydrological model

We developed a DHM for the studied catchment by slightly modifying the DHM originally developed for the Natori River catchment in northeast Japan (Figure S3) (Kazama et al., 2007; Nukazawa et al., 2011; Kazama et al., 2021). The model's spatial resolution is 250m. In brief, DHM estimates the direct flow, base flow, river channel flow, and evapotranspiration using the kinematic wave model (Lighthill and Whitham, 1995), storage function method (Kimura, 1961), dynamic wave model (Ligget, 1975; Ligget et al., 1975), and Modified Penman-Monteith equation, respectively, at the channel and hillslope parts separately. For details, see Text S2.

The kinematic wave model tracks hydraulic rainwater runoff over the hillslope part in the model based on the equation of motion and the continuity equation (Lighthill and Whitham, 1995). The storage function method was used to represent the transformation from rainfall input into baseflow runoff over the hillslope part by conceptualizing catchment storage and the delay time of runoff (Kimura, 1961). The water equivalent of snow cover was estimated using the snow/snowmelt model.

The snow cover model discriminates the precipitation form at each mesh and calculates the snow cover depth when the precipitation form is snowfall. We used the degree-day method to calculate the amount of snowmelt as a linear function of air temperature (Martinec, 1960). While earlier studies used a satellite-based vegetation index to infer evapotranspiration (Kazama et al., 2007; Nukazawa et al., 2011), the present study estimated the spatial distribution of evapotranspiration in the catchment using the modified Penman-Monteith equation based on heat budget concepts (Allen et al., 1998).

A one-dimensional dynamic wave model was used in the channel parts. The channel parts were manually designated, including the mainstem, the Do River, and 15 tributaries (Figure 1). The dynamic wave model was operated using the backward difference method at the downstream ends (i.e., the meshes upstream of the estuary, dams, and weir), the forward difference method at the upstream ends (i.e., the meshes at the upstream ends of the channels and outlets of the dams and weir), and the central difference method at the other channel meshes. We provided the observed discharges from the dams and hydropower plants at the outlet meshes. In addition, the observed discharge bypassed from the Kijino Weir to the Dogawa Dam reservoir was given to an upstream mesh of the Dogawa Dam.

3.3 Model evaluation

The DHM was run from 2008 to 2019. A warm-up period of two years was allocated (2008 to 2009) prior to the 10-years evaluation period. Subsequently, the model parameters were determined based on a comparison of observed and simulated daily discharge data at an inflow mesh of the Dogawa Dam (hereafter the Dogawa inflow mesh), which was not affected by the boundary conditions (i.e., the observed dam and hydropower discharges). The Nash-Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970), Percent bias (PBIAS) (Moriasi et al., 2007) and reproducibility of the hydrograph (magnitudes and timings of peak discharges and falling limbs) were used to evaluate the model performance. For details, see Text S3-4.

We validated the final model at three points (the Dogawa and Matsuo inflow meshes and the Takajo gauging station provided at http://www1.river.go.jp/) from 2010 to 2019 using NSE and PBIAS. The model performance can be considered satisfactory if NSE ≥ 0.7 and PBIAS $\leq \pm 15$ % (Moriasi et al., 2007; Matsubara et al., 2015). Negative/positive PBIAS indicates that the model is overestimated or underestimated.

3.4 Evaluation of flow alterations

3.4.1 Runoff analysis without the boundary conditions of dams and weir

To quantify flow alterations by dams and climate change, we performed runoff analyses without boundary conditions (e.g., intake or bypassed discharge by dams and weir; no-dam scenario) as well as the above-mentioned analyses with boundary conditions (dam scenario) from 2010 to 2019. Because discharge depends on upstream boundary conditions (i.e., discharge from weir, dams, and hydropower stations), under the dam scenario, over- or underestimated flow does not propagate downstream. On the other hand, under the no-dam scenario, if discharge is over- or underestimated upstream, it propagates downstream and influences the analysis. Therefore, we confirmed the10-year average discharge difference and the ratio between the scenarios at meshes not affected by the boundary conditions of the dams, weir, and hydropower plants (e.g., upstream of the Kijino Weir), an upstream mesh from the Matsuo Dam, and the Takajo gauging station.

3.4.2 Runoff analyses under climate change

Using bias-corrected future climate data of air temperature and precipitation instead of current climate data, we performed hydrologic analyses to simulate hydrological conditions under climate change (hereafter, climate change scenario). This scenario eliminated the boundary conditions (e.g., dam discharges) to individually represent the impacts of climate change on the flow regimes in the study catchment. In total, 48 patterns of future climate data (eight GCMs × two future periods × three RCP scenarios) were used to create 48 patterns of future flow regime projections. Subsequent flow alteration assessments were carried out using mean discharges among the eight GCMs for each future period and the RCP scenario (i.e., with six patterns of future flow regime outputs).

3.4.3 Flow regime metrics

We used the indicators of hydrologic alteration (IHA) to assess changes in the flow regimes caused by dams and climate change (Richter et al., 1996; iha, R ver. 3.6.3). The IHA is composed of 33 ecologically relevant indicators, which are classified into five groups: 1) magnitude of the monthly discharge; 2) magnitude and duration of the annual extreme flow; 3) timing of the annual extreme flow; 4) frequency and duration of low and high pulses; and 5) rate and frequency of flow changes (Table 1). We derived the IHA from the daily average discharge for each calendar year of the study period. Because there was no zero-flow days in this catchment during the study period, we excluded zero flow days from subsequent analyses. Using the following equations, we evaluated the extent of alteration of IHA in the Dam scenario and the climate change scenario compared to IHA in the no-dam scenario.

Table 1. The 32 Indicators of Hydrologic Alterations (IHA) indicators used in this study

IHA parameters group		Hydrologic parameters	Unit
Group1	Magnitude of the monthly discharge	Median monthly streamflow	($m^3 s^{-1}$)

Group2	Magnitude and duration of the annual extreme flow	1-, 3-, 7-, 30-, 90-d. Min	(m^3 s^{-1})
		1-, 3-, 7-, 30-, 90-d. Max	(m^3 s^{-1})
		Baseflow index	(m^3 s^{-1})
Group3	Timing of the annual extreme flow	T-Min	(day)
		T-Max	(day)
Group4	Frequency and duration of low and high pulse	Low and high pulse number	(Number)
		Low and high pulse duration	(days)
Group5	Rate and frequency of flow changes	Rise and fall rate	(m^3 s^{-1})
		Reversals	(Number)

(i) given that the unit of IHA is m^3 s^{-1}, number, or days,

$$R_1 = \frac{IHA_i - IHA_0}{IHA_0} \times 100\ (i = 1, 2) \qquad (3)$$

(ii), given that the unit of IHA is day,

$$R_2 = IHA_i - IHA_0\ (i = 1, 2) \qquad (4)$$

where both R_1 and R_2 are percent changes (% and day, respectively), IHA_0 is IHA in the no-dam scenario, IHA_1 is IHA in the dam scenario, and IHA_2 is IHA in the climate change scenario. We used the means of the percent change metrics of the 10 calendar years for subsequent evaluations of the flow regime alterations.

If the absolute value of percent change is greater than 20 % or day, IHA is considered significantly altered (Richter et al., 2012; Yang et al., 2017). Furthermore, we counted the number of significantly altered IHA to evaluate the extent of the flow regime alterations; no flow alteration occurred when the number of significantly altered IHA was 0 (i.e., all IHA falls into 0–20 absolute value of percent change), while small, moderate, and large alterations occurred when the number of significantly altered IHA was 1–10, 11–20, and ≥ 21, respectively (Yang et al., 2017; Laizé et al., 2014). The percent changes of each IHA and the number of significantly altered IHA were derived for all river channel meshes (n = 555) and visualized throughout the catchment.

4 Results

4.1 Model validation

The NSE and PBIAS for the 10 years evaluation period were 0.921 and 4.0 % at the Dogawa Dam inflow mesh, 0.964 and 3.9 % at the Matsuo Dam inflow mesh, and 0.957 and 4.0

% at the Takajo gauging station (Table 2 and Figure 2 and S4), suggesting high accuracy of runoff modeling throughout the studied catchment while involving little error in the dam and hydropower outflow data.

At the mesh not affected by the boundary conditions (e.g., upstream of the Kijino Weir), there was no difference in the 10-year average discharges of the no-dam and dam scenarios. The discharges at the Matsuo Dam inflow mesh and Takajo gauging station under the no-dam scenario were 0.34 $m^3 s^{-1}$ (1.3 %) and 0.63 $m^3 s^{-1}$ (1.9 %) smaller than those under the dam scenario, respectively. Considering the small fractions of the differences in the average discharge, the hydrologic balance between the scenarios in the study catchment was mostly negligible.

Table 2. The Nash-Sutcliffe efficiency (NSE) and Percent bias (PBIAS) for the Dogawa and Matsuo Dams and Takajo gauging station from 2010–2019.

	Dogawa Dam		Matsuo Dam		Takajo	
Year	NSE	PBIAS	NSE	PBIAS	NSE	PBIAS
2010	0.906	3.1 %	0.968	4.2 %	0.975	4.9 %
2011	0.938	-0.5 %	0.995	4.6 %	0.995	2.0 %
2012	0.951	3.1 %	0.974	7.8 %	0.994	-3.5 %
2013	0.883	-12.2 %	0.927	4.3 %	0.950	4.6 %
2014	0.942	-3.1 %	0.958	9.8 %	0.982	11.0 %
2015	0.870	6.9 %	0.975	-4.6 %	0.986	9.0 %
2016	0.934	9.3 %	0.978	0.8 %	0.980	11.4 %
2017	0.890	9.4 %	0.964	-1.1 %	0.995	7.9 %
2018	0.945	13.1 %	0.949	5.8 %	0.997	2.4 %
2019	0.782	6.3 %	0.933	3.6 %	0.989	-6.4 %
10 years	0.921	4.0 %	0.964	3.9 %	0.957	4.0 %

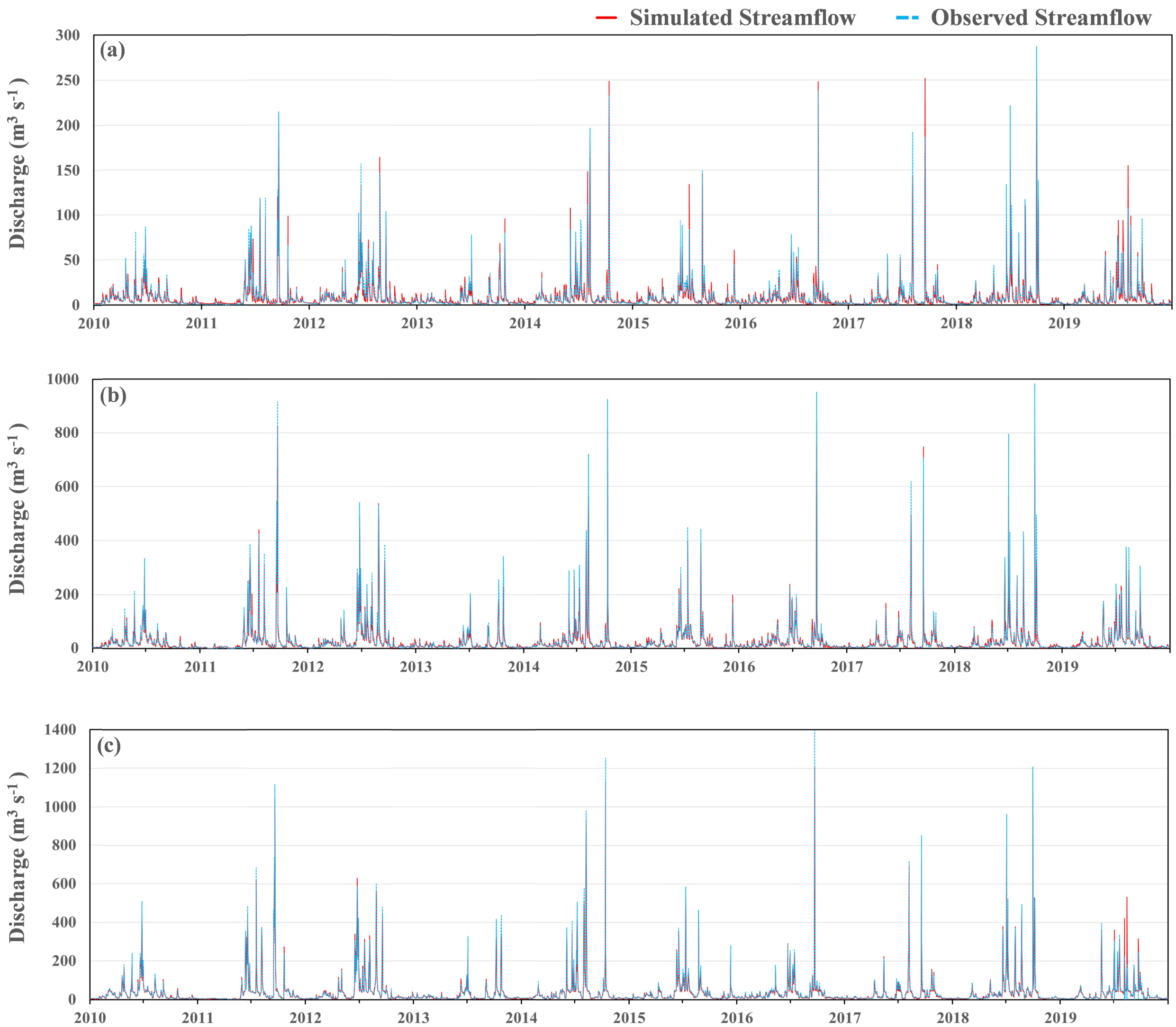

Figure 2. Hydrographs at the inflow meshes of (a) the Dogawa Dam and (b) the Matsuo Dam, and (c) Takajo gauging station from 2010 to 2019.

4.2 Flow alteration by dams and weir

Figures 3 and 4(a) illustrate the number of significantly altered IHA caused by dams and weir in the catchment. We found moderate to large alterations (the number of significantly altered IHA ranged from 12–21) in the river section from downstream of the Kijino Weir to the mesh upstream of the Do River confluence, large alterations (25–27) in the river section downstream of the Dogawa Dam to the mesh upstream of the confluence with the mainstem, and moderate to large alterations (14–27) in river sections downstream of the Matsuo Dam and the river mouth. Tables 3-4 and S3-4 show the percent changes of each IHA and the number of significantly altered IHA at the selected meshes, for example, outlets of the weir, dams, and hydropower plants. The general patterns among the assessed meshes were negatively altered rise rate (the percent change ranged from -99.5 % to -64.7 %) and fall rate (-99.7 % to -27.7 %), and no significant alteration in the date of annual maximum flow (-15.1 days to -3.4 days).

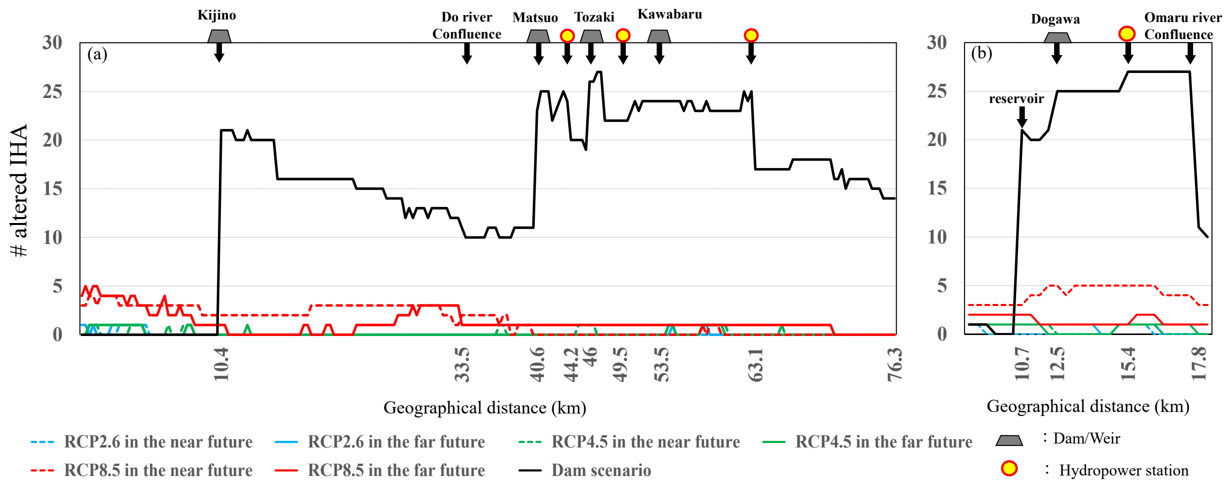

Figure 3. The number of significantly altered IHA (# altered IHA) along the geographical distances from the upstream ends of the (a) Omaru River and (b) Do River under the Dam scenario and Climate change scenarios. The hydropower plants located on the Omaru River are, in order from upstream, Ishikawauti-Daiichi, Ishikawauti-Daini, and Kawabaru Power Plants.

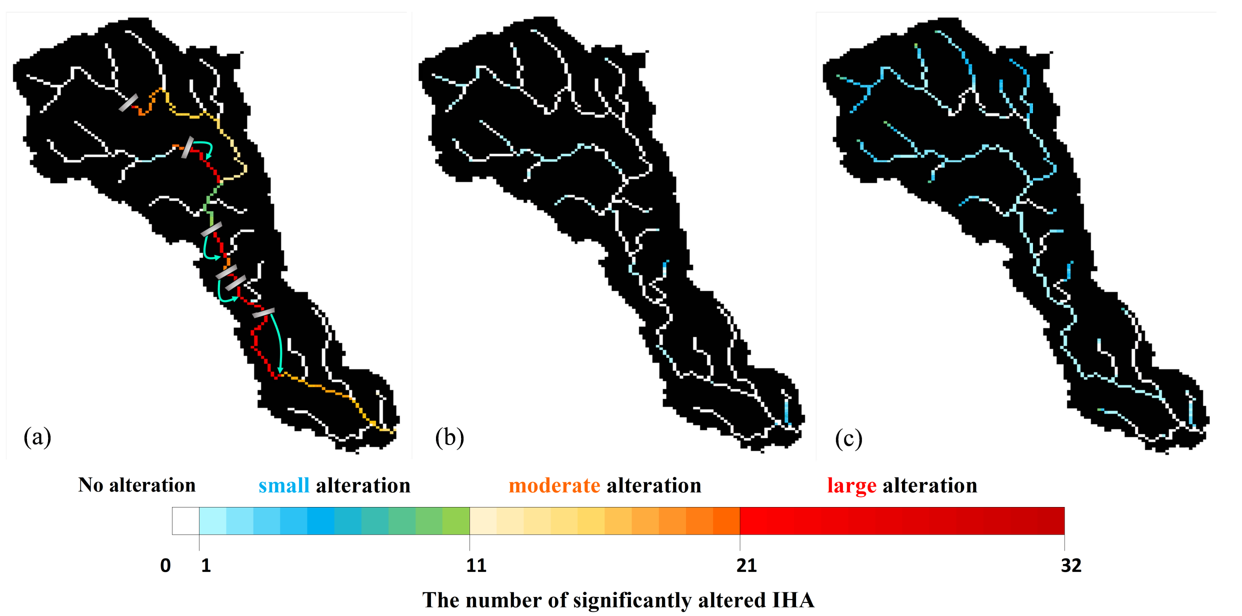

Figure 4. The spatial distributions for the number of significantly altered IHA under the (a) Dam scenario, (b) RCP4.5 in the near future, and (c) RCP8.5 in the far future. Arrows indicate water conveyance from the dams to the hydropower stations.

Table 3. The percent changes of selected Indicators of Hydrologic Alterations (IHA) and the number of significantly altered IHA (# altered IHA) at the selected meshes; outlets of the weir and dams. Values are boldfaced if absolute values are larger than 20. PN and PD represent pulse number and pulse duration, respectively.

	Weir	Dam

IHA	Kijino	Matsuo	Kawabaru	
Dec	**-75.7**	**-98.6**	**-76.4**	(%)
90-d. Min	**-76.0**	**-97.3**	**-83.1**	(%)
1-d. Max	**-35.5**	-11.9	-11.8	(%)
90-d. Max	-6.7	**-39.7**	**-37.2**	(%)
T-Max	-5.3	-3.5	-11.5	(day)
High PN	**-46.3**	**-23.0**	-2.9	(%)
Low PD	8.8	**30.9**	**-27.8**	(%)
High PD	**39.2**	**34.5**	-9.6	(%)
Rise rate	**-91.2**	**-99.5**	**-97.3**	(%)
Fall rate	**-99.7**	**-99.5**	**-98.2**	(%)
Reversals	-3.0	-13.7	13.1	(%)
# altered IHA	21	25	24	

Table 4. The percent changes of selected Indicators of Hydrologic Alterations (IHA) and the number of significantly altered IHA (# altered IHA) at the selected meshes; up- (U) and down-stream (D) meshes of the hydropower plants. Values are boldfaced if absolute values are larger than 20. PN and PD represent pulse number and pulse duration, respectively.

	Ishikawauti-Daini		Kawabaru		
IHA	U	D	U	D	
Aug	**-83.9**	**126.8**	**-79.0**	**113.3**	(%)
Dec	**-76.5**	-8.3	**-71.2**	-6.6	(%)
30-d. Min	-10.4	**23.5**	-9.8	10.2	(%)
1-d. Max	-14.3	13.1	-12.0	-3.2	(%)
T-Max	-9.9	-3.5	-9.8	-9.8	(day)
Low PN	11.4	**-22.2**	**46.2**	15.7	(%)
High PN	2.1	**-58.6**	**-32.3**	**-56.3**	(%)
High PD	-2.7	**93.3**	-2.8	**110.8**	(%)

Rise rate	**-98.7**	**-83.6**	**-94.2**	**-77.3**	(%)
Fall rate	**-99.3**	**-43.7**	**-93.1**	**-27.7**	(%)
Reversals	-2.2	**44.9**	**20.7**	**36.8**	(%)
# altered IHA	22	22	25	17	

4.2.1 Effects of water withdrawals by the dams and weir

Large alterations (number of significantly altered IHA ranged from 22–26) were detected along river sections where the river water was abstracted (Figures 3-4(a) and Tables 3 and S3). We found large negative alterations in all the median monthly streamflow (the percent change ranged from -98.6 % to -48.6 %), minimum flows (-98.7 % to -42.3 %), and maximum flows at longer time-windows (i.e., 30–90 days) (-51.7 % to -25.1 %) (Tables 3 and S3). The percent changes in the maximum flows at shorter time windows (i.e., 3–7 days) showed significant negative alterations (-28.1 % to -23.0 %) at the Dogawa and Tozaki Dams. For the base flow index, the Dogawa, Matsuo, and Tozaki Dams had large negative alterations (-96.4 % to -50.4 %). The patterns of alterations in the pulse metrics differed depending on the dams. For example, while the high pulse number was negatively altered at the Matsuo and Tozaki Dams (-23.0 % and -45.4 %, respectively), the high pulse duration was positively altered at Matsuo Dam (34.5 %). We found large negative alterations in the low flow metrics, such as the median monthly flows in autumn to winter (i.e., November to February) and the 90-day minimum downstream of the Kijino Weir (-81.0 % to -74.2 %). On the other hand, negative alterations in the high flow metrics, such as some median monthly flows in rainy seasons (i.e., May to October) and the maximum flows (i.e., 7–90 days) were suppressed (-16.6 % to 6.1 %). This result is consistent with that of a previous study in Taiwan; weir intake reduced low flows rather than high flows (Shiau and Wu, 2004). This is ascribed to the smaller amount of water abstraction at the Kijino Weir than at the dams.

4.2.2 Effects of outflows from hydropower plants

Despite the combined outflow from hydropower plants, moderate to large flow alterations were observed at the outlet meshes of the plants (# altered IHA ranged 17–27) (Figures 3-4(a) and Tables 4 and S4). As a global trend, the median monthly streamflow in rainy seasons such as May and August (the percent change ranged from 40.3 % to 299.1 %), high pulse duration (36.5 % to 110.8 %), and the reversals (26.8 % to 44.9 %) exhibited positive alterations at these meshes, while the high pulse number showed negative alterations (-58.6 % to -49.1 %). The Dogawa hydropower station displayed distinct patterns of alterations, for example, positive alterations in the median flow in February, June, December, and 90-day minimum (26.2 % to 56.2 %). The discharge bypassed from the Kijino Weir increased the discharge in the Do River, resulting in positive alterations in the median monthly streamflow. The Kawabaru hydropower station also displayed different patterns of alterations, such as negative alterations in the date of annual minimum flow (-67.1 days) and 90-days minimum (-22.2 %).

The combined outflow from the hydropower stations, however, ameliorated the severe negative alterations in the minimum and maximum flows that occurred in the sections where the river flow dramatically decreased downstream of the dams, and even caused positive alterations (Tables 4 and S4). For instance, the positive alteration of the low pulse number at the Kawabaru hydropower station was ameliorated (from 46.2 % to 15.7 %), while negative alteration occurred at the Ishikawauti-Daiichi hydropower station (from 11.49 % to -22.2 %).

4.2.3 Ameliorating flow alterations by confluence of tributary

We found that the confluence of tributaries with varying catchment areas ameliorated flow alterations; that is, the percent changes of each IHA approached 0 and the number of significantly altered IHA decreased throughout the catchment (Figure 4(a) and Tables 5 and S5). Downstream of the Kijino Weir, the confluences of the Matanoe and Mizushidani rivers ameliorated the negative alterations in the minimum flows and reduced the number of significantly altered IHA from 20 to 15. In the section between the Kawabaru hydropower station and the river mouth, the tributaries such as Kirihara River ameliorated alterations in flow metrics (e.g., the negative alteration in the 30-days maximum and the positive alteration in the low pulse number), which led to a decrease in the number of significantly altered IHA from 18 to 14. A previous study has successfully demonstrated mathematically that the alteration of a maximum flow metric (equivalent to the 1-day maximum flow) was ameliorated by a confluence of tributary (Volpi et al., 2018; Clipollini et al., 2022). On the one hand, the amelioration phenomena observed in our physically based model could be illustrated explicitly (Text S5), suggesting that the amelioration is a general phenomenon regardless of configurations of alterations and confluences (e.g., spatial allocations of withdrawal and tributaries), such observed in a previous study that focused on flow duration curve metrics (e.g., Q75; Mineda et al., 2020). However, we found the exacerbated flow alteration such as February median at the Kirihara River, Low PN at the Matanoe River, and High pulse metrics at the Do River. These cases are explained by the timing at which the indicators are calculated under each scenario do not match or flow in tributary is altered due to anthropogenic factors (i.e., climate change and water conveyance at the Do River in the present study) (Text S5).

Table 5. The percent changes of selected Indicators of Hydrologic Alterations (IHA) and the number of significantly altered IHA (# altered IHA) at the meshes up- (U) and down-stream (D) of confluences of the selected tributaries. Values are boldfaced if absolute values are larger than 20. PN and PD represent pulse number and pulse duration, respectively.

	Matanoe		Do		Kirihara		
IHA	U	D	U	D	U	D	
Feb	**-69.1**	**-51.3**	**-34.3**	1.8	-7.5	-8.2	(%)
1-d. Min	**-20.9**	-14.1	-9.1	-7.4	**22.3**	**21.8**	(%)
90-d. Min	**-24.9**	-16.5	-10.5	-1.0	**38.9**	**35.7**	(%)
30-d. Max	**-63.8**	**-45.9**	**-28.4**	-7.4	**-20.5**	-19.2	(%)
T-Min	**-67.1**	**-67.1**	**-67.5**	14.4	**-66.6**	**-92.1**	(day)

Low PN	-10.8	-14.0	-5.9	-15.4	**22.0**	19.3	(%)
High PD	**33.8**	**29.2**	5.8	**20.3**	**98.3**	**84.4**	(%)
Fall rate	**-81.4**	**-55.0**	**-27.0**	-18.3	**-23.5**	**-20.9**	(%)
Reversals	1.1	-1.3	-2.2	12.7	**35.1**	**35.0**	(%)
# altered IHA	20	16	12	11	18	16	

4.3 Projection of flow regime alteration under future climate change

Under all climate change scenarios (two future periods × three RCPs), a limited number of IHA were projected to be altered (0 to 10 IHA) (Figures 4 (b)(c) and S5). Under RCP2.6 and RCP4.5, fractional alteration was projected in the partial river meshes. A larger number of significantly altered IHA were projected at most river meshes under RCP8.5, compared to RCP2.6 and RCP4.5. Figure 5 shows the percent changes of selected IHA from upstream to downstream along the mainstem under each climate change scenario. Note that the variation in the percent changes, here climatic change-induced flow alteration, is prone to be large because the discharges at uppermost meshes are extremely small.

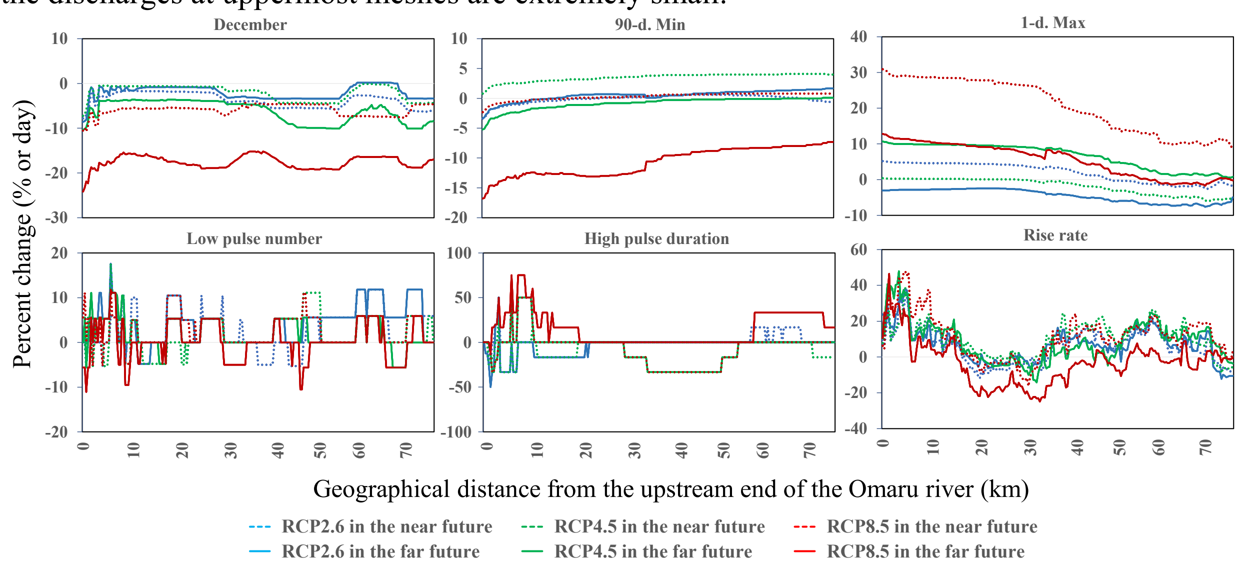

Figure 5. The percent changes of selected IHA from up- to down-stream along the mainstem under each climate change scenario.

Decreasing trends were identified in the January, April, August, November, and December streamflow throughout the catchment, specifically upstream, under all climate change scenarios (Figures 5 and S6). This was most apparent under RCP8.5 in the far future; the percent changes of the January, April, November, and December flows reached around -20 % throughout the catchment. The negative alterations for the low-flow metrics such as minimum flows and base flow index were more prominent upstream and, in the tributaries where the discharges were smaller (Figures 5 and S6-7).

Low flows such as minimum flows at longer time-windows (i.e., 90 days) were projected to decrease (-17.5 % to -7.0 %) the most throughout the mainstem under RCP8.5 in the far future (Figure S7), whereas such a decline was rarely observed in the other scenarios. High flows such as September and maximum flows were projected to increase upstream and in the tributaries under many climate change scenarios. Specifically, under RCP8.5 in the near future, high flows increased markedly, characterized by positive alterations in the 1-day maximum (22 % to 30 %) upstream (Figure S8). However, the 1-day maximum under RCP8.5 in the near future would be overestimated due to an outlier projected with the CSIRO-MK3.6 (Figure S9). In contrast, the maximum flow metrics were projected to decrease throughout the catchment under RCP2.6 in the far future.

In the river section downstream of the Kawabaru hydropower station to the river mouth, which is surrounded by relatively populated cities, high flows at shorter time windows, such as 1-day max, increased by 9.4 % to 11.6 % under RCP8.5 in the near future, while it declined (-7.6 % to 5.3 % under RCP2.6 in the far future and RCP4.5 in the near future) or was unchanged in the other scenarios (Figures S6 and S8).

For the date of annual minimum and maximum flow, little change was projected throughout the catchment under all climate change scenarios (Figure S6). However, in the Do River, the annual minimum flow was significantly altered at 41 meshes under all climate change scenarios with varying percent changes from -273 days to 197 days (Figure S10). The low and high pulse numbers were projected to vary spatially under all climate change scenarios (Figures 5 and S6). The percent changes were approximately ±10 % for the low pulse number and ±15 % for the high pulse number. The low and high pulse durations were significantly altered under many climate change scenarios with varying percent changes depending on the climate change scenario and location. The highest percent changes were projected for the high (75.0 %) and low pulse duration (50.0 %) under RCP8.5 in the far future. The percent change of rise rate tended to vary under RCP8.5 in the far future; reaching a highest value of 46.5 % around the uppermost meshes and lowest value of -24.9 % near the Do river confluence. On the other hand, the percent changes in fall rate and reversals tended to fall negative under most climate change scenarios (Figures 5 and S6).

5 Discussion

5.1 Evaluation of environmental flow alterations using DHM

Our catchment-scale evaluations of the environmental flow alterations based on a distributed hydrologic model enables us to understand the overall picture of such alterations due to various water intakes/supplies as well as climate change. Previous studies have attempted to separate the impacts of complex factors (e.g., dam and climate change) and estimate contributions of a given factor to flow alteration (e.g., Cui et al., 2020). Though, because dam-induced impact on flow regimes was estimated by subtracting those induced by climate change from overall impacts, it involves other withdrawal or anthropogenic factors, and thereby, is difficult to identify the impacts of dam and climate change. Moreover, since the cumulative impacts of many small dams on flow regimes are significant or cannot be ignored (Deitch et al., 2013; Kibler and Tullos, 2013; and Lu et al., 2018), all dams located in a study catchment should be considered as possible for accurately quantifying the impact of dam. Therefore, earlier works have not yet sufficiently considered a separation of these impacts, highlighting a uniquness or novelty of our approach, which inputs the impacts of dams and climate change on the model independently and compares the resulting environmental flow alterations. The independent analyses can directly quantify each impact of dam and climate change without other impact factors. In addition, our approach rigorously considered the impacts of major water withdrawals and hydropower discharges in the study catchment, which enables to quantify and visualize spatial patterns of impacts of these manipulations. Therefore, our approach may contribute to seeking effective counter measures of climate change (Haddeland et al. 2014).

Our approach evaluated the spatial heterogeneity of changes in the flow regimes by dam and climate change in the entire catchment, which is novel results and useful for understanding the river environmental management. We demonstrated that the flow alterations caused by water withdrawals were ameliorated by the confluence of tributaries and hydropower outflows downstream (e.g., downstream sections of the Kijino Weir and Kawabaru Dam; Figure 4(a)). Furthermore, we detected the localized impacts of climate change on upstream flow alterations (Figures 5 and S6). In particular, the impacts of climate change on the low and high pulse metrics and the rise/fall rates were highly spatially variable; hence, attention should be given to local alteration patterns of these flow metrics in cases of catchment managements and future studies. In this sense, developing our model at a finer spatial resolution would be a promising future work to better capturing localized patterns of flow regime alteration in uppermost small streams.

Although our hydrologic model showed high accuracy throughout the study period, the flow peak extremes tended to be underestimated at all gauging sites (Figure 2). This is presumably because the limited information on rainfall inputs (i.e., point data from the five meteorological stations) could not reflect the spatial and temporal heterogeneity of heavy rainfall, such as during typhoons and torrential rainfall events. Consequently, some IHA in terms of high flows might contain relatively larger uncertainties than the others.

5.2 Dam scenario

Large negative alterations were detected in the median monthly streamflow, the maximum flows, especially at the longer time-windows (30–90 days maximum), and the minimum flows at all the sections where the river water was abstracted (Tables 3 and S3). Such decreases in streamflow could affect the community structures of many organisms, including fish and benthic animals (e.g., Tipulidae, Baetidae, and Heptageniidae) inhabiting in the studied catchment, by decreasing the habitable area downstream of dams and weirs (Nukazawa et al., 2020). All studied dams were used for water abstractions (mainly for power generation), while the Dogawa and Matsuo Dams were also used for flood control. The decreases in low flows (e.g., minimum flows) and maximum flows are characterized by dams used for hydropower generation and flood control, respectively (Lu et al., 2018). Because the effects of flood control at the Dogawa and Matsuo Dams propagated downstream, both characteristics were observed in the downstream sections of all dams.

In the section downstream of the Tozaki Dam, the high pulse duration exhibited no clear change and the high pulse number decreased (Tables 3 and S3), which led to a reduction in the connectivity between river channels and floodplains and a decline in biodiversity (Lu et al., 2018). In the section downstream of the Matsuo Dam, positive alterations occurred in the low and high pulse durations. An increase in low pulse duration has negative impacts on ecosystems as it decreases habitable area, the detachment opportunity for attached algae, and the connectivity with lentic habitats. On the other hand, an increase in the high pulse duration promotes more connections among lotic-lentic habitats and provides opportunities for plant seed establishment (Riis et al., 2008).

We found that the date of maximum flow only showed insignificant changes downstream of the weir, dams, and hydropower stations (Tables 3-4 and S3-4). This result indicates that the timing of the peak discharge is not affected by the dam operation regardless of its purpose. The rise and fall rates decreased significantly downstream of the weir, dams, and hydropower stations (Tables 3-4 and S3-4). In the sections downstream of the dams and weir, the daily flow fluctuations and small peak discharges typically seen in the natural flow regime were suppressed, and the residual flows were characterized by prolonged small constant flow, except during extreme rainfall events, resulting in decreasing rise and fall rates. In the meshes downstream of the hydropower stations, the smaller rise and fall rates were presumably ascribed to the decreased number of small pulse discharges and constantly kept daily discharge due to the electricity supply and demand. Decreases in the rise and fall rates could have negative impacts on emergent vegetation because they can reduce or even eliminate the patch size, and often facilitate the colonization of invasive species (Small et al., 2009). In addition, less frequent small floods may reduce the chances of algal detachment and regrowth, resulting in a dominant mature algal riverbed, which is generally not favored by algal feeders (e.g., *Plecoglossus altivelis*) and aquatic insects.

The percent changes of the reversals downstream of the dams were small but they were larger downstream of the hydropower stations (Tables 3-4 and S3-4). Because the daily discharge from hydropower plants varied depending on the electricity supply and demand, the fractional variations contributed to higher flow reversals, while the daily discharge of residual flow (i.e., downstream of the dams) was rigorously controlled to constant values. Although the outflow from the hydropower stations ameliorated the alterations (Figures 3 and 4(a) and Tables 4 and S4), especially decreased monthly and minimum flow metrics, in the sections downstream of the dams, the alterations of some metrics such as high pulse metrics and rise/fall rates were observed (Tables 4 and S4). This suggests that ameliorations of natural flow regime by hydropower outflows in the catchment remained insufficient in light of potential environmental impacts.

The median monthly streamflow showed positive alterations downstream of the hydropower stations (Tables 4 and S4). This may be attributed to the typical operation of hydropower generation that supplies stable daily electricity (i.e., daily discharge). In such a case, the median daily discharge in a certain period (here monthly) is probably larger than that under the natural condition (the no-dam scenario).

5.3 Climate change scenario

Under most climate change scenarios, the low flow metrics were projected to change slightly throughout the catchment, while the high flow metrics were projected to increase in the upstream and tributary meshes with smaller discharges (Figures 5, S6-7, and S11). The increased/decreased maximum/minimum flows typically observed under RCP8.5, in the far future, may play important roles in regulating patchy habitats of rivers, including floodplains, to accommodate some species of plants (Chen, 2012). The maximum flows downstream of the Kawabaru hydropower station surrounded by relatively populated cities were projected to increase under RCP 8.5, while they were projected to decrease or remain unchanged under the other climate change scenarios. Therefore, if high radiative forcing is maintained in the future, further engineering works using climate change-based flood design should be considered. In addition, augmented maximum flows at shorter time windows (e.g., 1-day maximum) observed over a wide range of upstream may trigger a greater riverbed disturbance in this region (Figures 5, S6, and S8). This will promote riverbed erosion (de Mello et al., 2015) as well as the passive migration of benthic organisms (Gibbins et al., 2007), resulting in widespread changes in the upstream environment.

5.4 Comparison of the impacts of dams and climate change

In the Omaru River and a major tributary (the Do River), the percent changes of most IHA were greater under the dam scenario than under the climate change scenario and a greater number of IHA were significantly altered (Figures 3-5 and S5-6 and Tables 3-4 and S3-4). This finding is consistent with a previous study that compared the impacts of dam and future climate change on hydrological regimes, specifically focusing on extreme flow events (e.g., maximum, and minimum flows) in the Rhone River catchment (Fatichi et al., 2015). Conversely, flow alteration in the Upper Yellow River can be mainly attributed to climate change than dam although the impact of dam would be underestimated (Cui et al., 2020). However, evaluation relying on the number of IHA may fall into a pitfall; partial IHA potentially behaves similarly as the others, resulting in an overestimation of the number of altered IHA. Indeed, according to the cross correlation among IHAs at up- and down-streams, some IHAs, especially monthly streamflow and low flow metrics, were highly correlated (Table S6). These results suggest that future studies are required to understand how such redundancy of metrics contribute to alteration levels over a certain geographical scale such as a catchment.

In a catchment-scale standpoint, widespread flow alterations were projected in the tributaries and uppermost main stem, where unaffected by the dams under the climate change scenario. Researchers have pointed out that even small alterations can trigger potential population losses for species dependent on the hydraulic conditions (e.g., rheophilic species), resulting in the loss of biodiversity (Yang et al., 2017; Schneider et al., 2013). Therefore, adequate environmental countermeasures for climate change should be implemented to safeguard biodiversity in tributaries because these marginal corridors account for most of the total streamflow length in river systems. Our results are consistent with a previous study that found dams further affected the streamflow regime such as minimum and maximum streamflow than climate change in the upper Rhone catchment. Since processes behind these results may not be comparable (e.g., different snowmelt due to climate change), further studies targeting catchments with different climates will provide insights into factors that govern extents of alterations by dams and climate change.

Under the dam scenario, decreases in the low flow metrics were greater only in the sections downstream of the dams and weir (Tables 3-4 and S3-4). Whereas under the climate change scenario, decreases in low flow metrics were greater in the tributaries and upstream, and were unaffected by the dams and weir (Figures 5 and S5-6). The reduced low flow, which typically involves a lower flow velocity, leads to poor water quality due to the deposition of pollutants (Smakhtin et al., 2001). Although the anthropogenic pollutant loads were limited in the uppermost streams and tributaries, decreases in the low flow metrics can reduce the habitable area of riverine organisms through decreasing the water level and streamflow length. These negative ecological consequences of climate change can propagate downstream and impact catchment biodiversity.

Under all climate change scenarios, the median flow in January, April, August, November, and December showed a decreasing trend throughout the catchment (Figures 5 and S5). Therefore, for a sustainable power supply, dam managers should be required to operate dams considering the extent and timing of flow reduction expected under climate change in the future.

The 1-day maximum declined by 18.9 % and 11.9 % downstream of the Dogawa and Matsuo Dams, respectively, under the dam scenario, while it was projected to increase by 28.8 % and 19.0 % under RCP8.5, respectively (Tables 3 and S3 and Figure S8). Therefore, the flood control operations of the Dogawa and Matsuo Dams would need to be reconsidered, given that radiative forcing continues to increase in the near future.

6 Conclusion

In this study, a distributed hydrological model (DHM) was applied to the Omaru River catchment to evaluate the spatial extent of flow alteration throughout the catchment. The model was used to quantify flow alterations caused by dams and climate change based on Indicators of Hydrologic Alterations (IHA). The DHM was developed, calibrated, and validated for the study catchment. The model predicted discharges with high accuracy along up- to down-streams for 10 years (NSE = 0.921–0.964, PBAIS = 3.9–4.0 %). The flow alterations by the weir and dams were projected to be moderate to large, however the alterations were ameliorated slightly by the discharge from hydropower plants. Such mitigation effects were also observed at confluences of downstream tributaries. The flow alterations due to climate change were projected to be fractional in partial river sections under RCP2.6 and RCP4.5, while they remained small throughout the catchment under RCP8.5. In the Omaru and Do Rivers, a greater number of IHA were significantly altered by dams than by climate change. At the catchment scale, climate change was projected to alter flow regimes widely in the tributaries and uppermost main stem, suggesting a catchment-level shrinkage in important corridors of aquatic organisms through decreases in upstream length and water level.

While the model showed sufficient accuracies not only in the Omaru River catchment but in the other catchment (NSE>0.7, The Natori River catchment in northeast Japan; Nukazawa et al., 2015), the model tended to underestimate flow peak extremes at all gauging sites. This is presumably because the limited information on rainfall inputs (i.e., hourly point data from the five meteorological stations) could not reflect the spatial and temporal heterogeneity of heavy rainfall. Thus, future studies should attempt to input radar-based rainfall distribution data to better describe high flow patterns in the catchment. Furthermore, future studies also should test this approach in different catchments with contrasting climates, geologies, and water uses to highlight the differences in flow alterations between dams and climate change depending on background parameters. In addition, it is of great importance to examine the predictive abilities of our model for environmental and biological forecasting (e.g., environmental suitability or ecological niche models). The proposed framework will be useful for river managers when redesigning a management plan, for example, revising dam operations, retrofitting, or constructing new flood control structures, because the extent of flow alterations downstream, which have important implications for environmental protection, can be predicted. Furthermore, our study can provide reliable criteria for flood design considering the anticipated impacts of climate change scenarios. As promising future research, a combined impact scenario where both dams and climate change were included would be beneficial to discuss alteration in future environmental flows. To adequately develop a combined impact scenario based on our approach, future dam outflow time-series under climate change will be required. However, the methodology to develop the future dam outflow time-series across the entire regional network of rivers has yet to be established (Ehsani et al., 2017). Moreover, the response of reservoir performance of hydropower generation to changes in climate is far more complicated than other reservoirs (Qin et al., 2020) in spite of the fact that all dams in the studied catchment are used for hydropower generation. Once these challenges are addressed, an assessment of combined impacts at a catchment scale is able to be implemented in our modeling approach.

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