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Impacts of dam-regulated flows on channel morphology and riparian vegetation: a longitudinal analysis of Satsunai River, Japan

Mayumi Takahashi・Futoshi Nakamura

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M. Takahashi (Corresponding author) F. Nakamura
Graduate School of Agriculture, Hokkaido University, N9W9, Sapporo 060-8589, Japan
e-mail: mayumi92@for.agr.hokudai.ac.jp

Keywords

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Abstract

We examined the impacts of the Satsunai River Dam on the hydrology and development of riparian vegetation along the upper and lower reaches of the Satsunai River downstream from the dam. We estimated frequency curves of the flood discharge during the pre-dam (1976–1996) and post-dam (1997–2006) periods and simulated the flood frequency at sampling points within sites under pre-dam, post-dam and dam-removal (using the pre-dam flood discharge and post-dam cross-sections) scenarios. Changes in channel morphology and land cover were investigated by analyzing aerial photographs. Our results indicate that the 20-year flood at the upper site decreased substantially (from 599 to 271 m^3/s) after dam operation, while that of the lower site decreased slightly (from 1025 to 977 m^3/s). Within the upper site, the proportion of 20-year return periods increased considerably (from 31.0 to 48.6%) while the proportion of 1- to 20-year return periods decreased (from 30.5 to 8.9%) after dam operation. Flood frequency results for the dam-removal scenario were similar to those for the pre-dam period, suggesting that a return to pre-dam discharge rates would restore the pre-dam distribution of flood frequency at the upper site. Within the lower site, however, the distribution of flood frequency varied little between the pre- and post-dam scenarios, because tributary inflows between the sites mitigated the impacts of dam-regulated flows. Land cover types were associated with flood frequency at both sites. The reduced flood frequency of the upper site resulted in increased area of riparian vegetation and decreased area of active channel.

Introduction

Conservation and restoration of river and riparian environments have attracted attention worldwide (Nagayama and Nakamura 2009; Nakano et al. 2008; Shafroth et al. 2002a). In 1997, "maintenance and conservation of the fluvial environment" was added to the objectives of the River Law of Japan, meaning that river development projects were now expected to perform not only flood control and water use functions but also to satisfy the ecological needs of plant and animal communities (Akasaka et al. 2009; Nagayama et al. 2008; Takahasi and Uitto 2004). River channel morphology reflects complex interactions between processes and forms in channel–floodplain systems (Ito et al. 2006; Zanoni et al. 2008). In multi-channel gravel-bed rivers, these interactions can create variable and complex arrangements of channels, gravel-bars and floodplains (Keith et al. 2002). However, since the 1950s, river and riparian areas have been dramatically modified from their natural conditions (Nakamura and Komiyama 2009; Nilsson and Berggren 2000; Petts and Gurnell 2005). Gravel-bed rivers in many mountainous regions have been simplified by human activities such as regulation of flow, in-channel structures, levee embankments and deforestation (Wohl 2006). Dams are one of the main causes of these changes. New management strategies are needed to minimize the negative impacts of dams in order to maintain river and riparian environments.

Dams alter natural flows and downstream flood regimes and interrupt the continuity of sediment transfer from headwaters. Hydrological changes include reduction in peak flow, reduced flood frequency and altered seasonal flow patterns. These hydrological changes and the interruption of sediment transfer alter the physical environments and geomorphological processes in rivers (Nilsson and Berggren 2000; Petts and Gurnell 2005). Changes in channel morphology eventually influence the establishment and growth of riparian vegetation (Azami et al. 2004; Merritt and Cooper 2000; Nakamura and Shin 2001; Rood and Mahoney 1990; Shafroth et al. 2002b); for example, Merritt and Cooper (2000) found that the channel form of a dammed river had undergone a complex series of morphological changes, while an undammed river had remained in a state of relative quasi-equilibrium of its discharge and sediment regimes. Nakamura and Shin (2001) predicted that reduced flood frequency and magnitude due to dams would cause a shift of riparian vegetation from pioneer to late-successional species, because the distributions of riparian tree species were associated with different types of geomorphic surfaces characterized by flood frequency (Takagi and Nakamura 2003).

Dams are usually located in the upper reaches of river systems, and the impacts of the hydrological changes may decrease along the river as more tributaries join and the catchment area (CA) increases. Ward and Stanford (1983, 1995) proposed the serial discontinuity concept, which predicts river ecosystem recovery as a function of distance downstream from the dam. The confluence-related changes in channel morphology in the main stem were related to the size of the tributary relative to the main stem (Benda et al. 2004). Tributary confluences can mitigate the dam-induced impact on the stream substrate, and they can eventually recover aquatic animal communities (Katano et al. 2009; Takao et al. 2008). However, very few studies have examined the mitigating effects of tributary inflows on vegetation establishment below dams.

Understanding the variability of the downstream effects of dam-regulated flows is essential to making accurate predictions of future changes in river and riparian areas. However, many previous studies of the downstream impacts of hydrological changes have focused on a single, limited area below the dam (Azami et al. 2004; Takagi and Nakamura 2003). Analyses of longitudinal changes along rivers remain rare, especially regarding plant communities. Consequently, in this study we compared the hydrological and ecological impacts of the Satsunai River Dam between the upper and lower reaches of the river downstream from the dam. We also evaluated the mitigating effects of tributary inflows between the two reaches.

First, we simulated flood discharges for different return periods during the pre- and post-dam periods and estimated flood frequency under three scenarios (pre-dam, post-dam and dam-removal). Comparisons among the three scenarios showed which hydrological or geomorphic factors were responsible for the changes in flood frequency after construction of the dam. Second, we evaluated the spatial and temporal changes in channel morphology and riparian vegetation between the pre- and post-dam periods by analyzing aerial photographs. Finally, we determined how the changes in riparian vegetation were related to the flood frequency of the study sites.

Methods

Study site

This study was conducted in the Satsunai River (CA 725 km^2), which runs from Mt. Satsunai (42°41′N, 142°47′E; 1895 m above sea level) in the Hidaka Mountain Range to the Tokachi River in Hokkaido Prefecture, Japan (Fig. 1). The mean annual air temperature in 2006 was 5.3°C, and monthly mean air temperatures ranged from -10.3°C in January to 20.9°C in August. The average annual precipitation between 1978 and 2007 (excluding 1997, for which data were unavailable) was 1259 mm (Kamisatsunai observatory; 42°38′N, 143°05′E) (Japan Meteorological Agency 2008).

Partial operation of the Satsunai River Dam (42°35′N, 142°56′E; 374 m above sea level) began in 1997, and full operation began in 1998 for the purposes of flood control, water utilization and power generation. The CA of the dam reservoir is 118 km^2; the volume of water stored is 54 million m^3, and the maximum discharge is 150 m^3/s. Annual peak flow is strongly regulated by the dam, which reduces flood peaks from snowmelt in the spring and typhoon rainstorms in the summer and fall (see Kamisatsunai in Fig. 2).

The upper and lower study sites were selected to compare the downstream effects of the dam on channel morphology and riparian vegetation (Fig. 1). We selected the study sites based on the availability of historical aerial photographs and cross-sectional profiles and proximity to gauging stations with flow data. The Hokkaido Regional Development Bureau (HRDB) has installed kilometer posts (KP), signs indicating the distance along the main channel from the junction with the Tokachi River, at intervals of about 200 m on both banks. The upper site was located between KP 41.6 and KP 45.6, and the lower site was located between KP 15.0 and KP 21.0. The Kamisatsunai gauging station (CA 189 km^2; KP 41.8) was located at the lower end of the upper site, while the lower site was located between the Dainiokawa Bridge gauging station (CA 580 km^2; KP 20.7) and the Nantai Bridge gauging station (CA 608 km^2; KP 15.0). The Tottabetsu River (CA 340 km^2), which is unregulated by dams, joins the Satsunai River between the upper and lower sites (KP 24.8), and the discharge of the Tottabetsu River was measured at the Nakajima Bridge gauging station (CA 295 km^2). Another small stream joins the river in the middle of the lower site (KP 18.6) (Fig. 1).

Cross-sections across the river from the KP on the left bank to the KP on the right bank were surveyed in 1990 and 2007 by the HRDB.

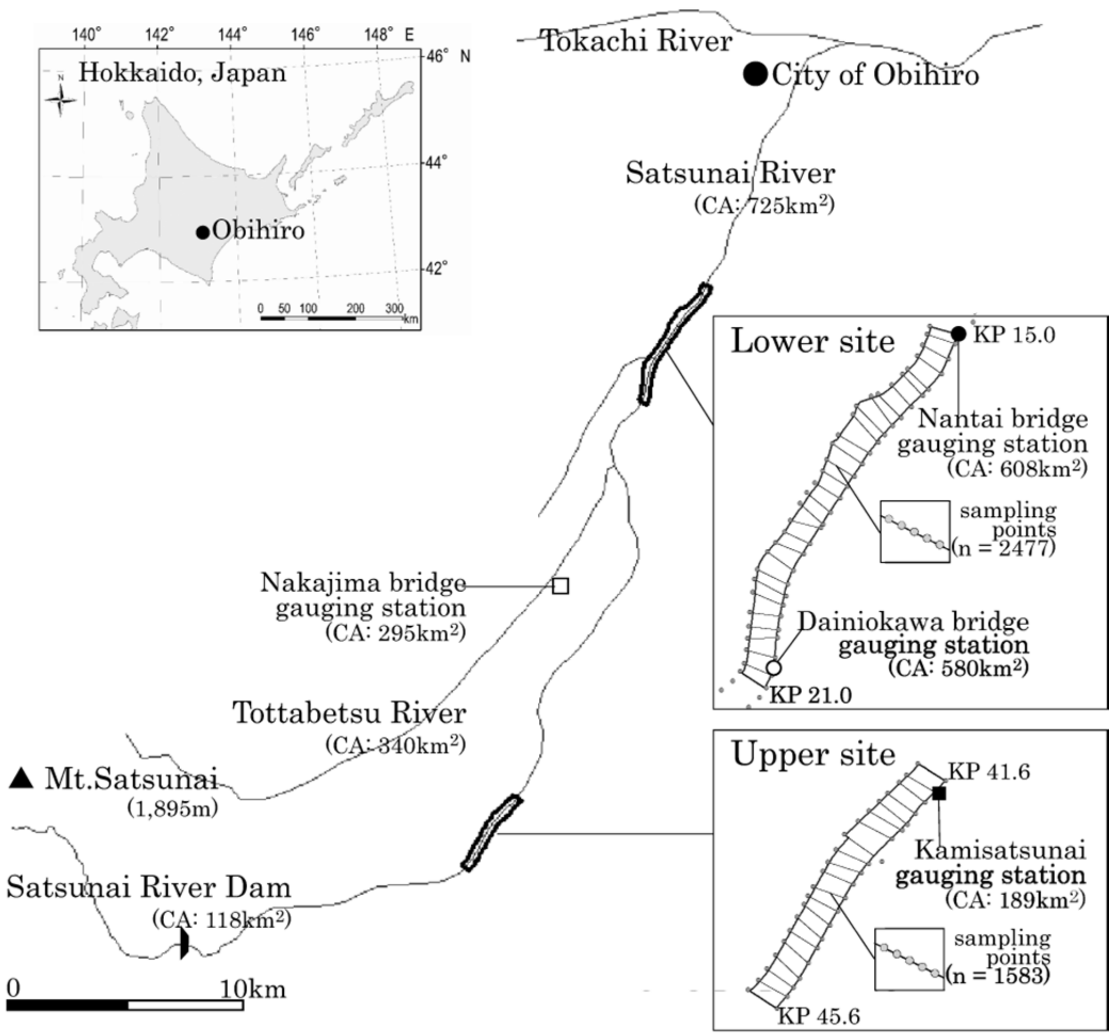

Fig. 1 Map of study sites and river gauging stations along the Satsunai River in Hokkaido, Japan. Cross-sectional profiles were surveyed every 200 m within each site, and flood frequency was simulated at sampling points located every 5 m along the cross-sections (see details in ‘‘Methods’’)

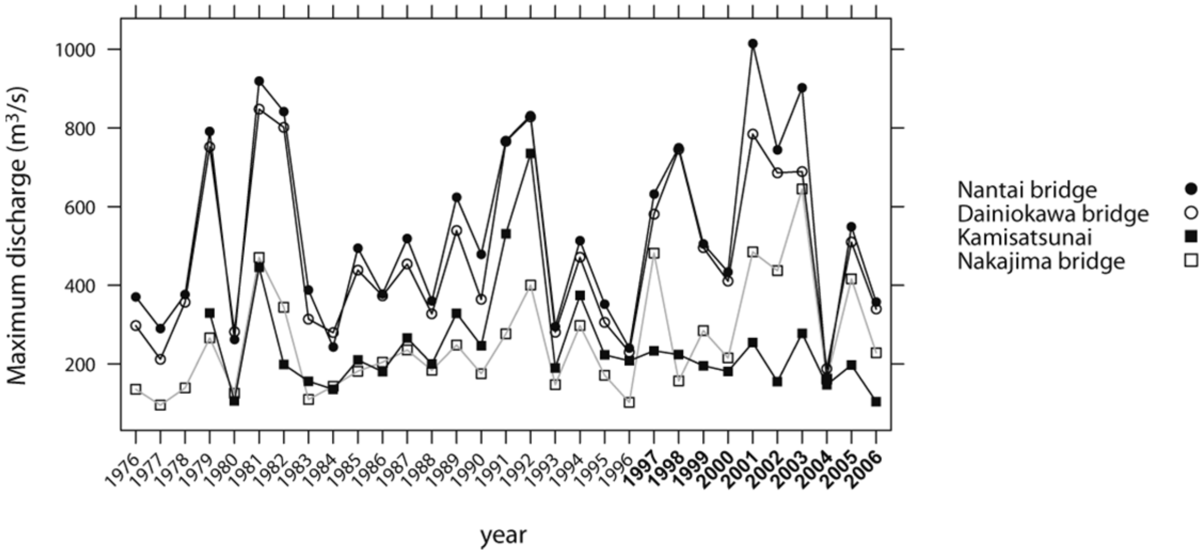

Fig. 2 Maximum discharge of the Satsunai River (black lines) and the Tottabetsu River (gray line) for the pre-dam (1976–1996) and post-dam (1997–2006) periods.
Discharge data from Kamisatsunai station were not available for 1976–1978

Simulation of flood discharges for different return periods and water stages

Flooding is a natural and recurring event for a river or stream. The magnitude of flooding is usually characterized in terms of its statistical frequency; for example, a flood having a 20-year return period, the so-called "20-year flood", describes a flood discharge that has a 1/20 chance of happening in any given year.

Flood discharges (m^3/s) for different return periods at the three gauging stations along the Satsunai River were estimated using maximum-likelihood fitting of the generalized extreme value (GEV) distribution (Coles 2001) for the annual maximum discharge dataset based on hourly data. The GEV distribution, which has three parameters (μ, σ and ξ), is commonly used to describe hydrologic data involving maxima, such as annual flood peaks (Magilligan et al. 2003). The GEV distribution was fit to the pre-dam dataset from 1976 (1979 for Kamisatsunai station) to 1996 and the post-dam dataset from 1997 to 2006 (Fig. 2) by using the statistical software program R version 2.9.0 (R Development Core Team 2009) using the gev.fit function of the ismev package (Coles 2001). Flood discharge for the T-year return period, $q(T)$, was expressed using the following equation:

$$q(T) = \mu + \frac{\sigma}{\xi}\left(\left(\frac{1}{T}\right)^{-\xi} - 1\right) \quad \text{for } \xi \neq 0$$

where μ, σ and ξ are parameters estimated by the GEV fits.

Water stages under pre-dam, post-dam and dam-removal scenarios were simulated on the series of cross-sections using HEC-RAS software (US Army Corps of Engineers 2008). The pre-dam scenario simulated water stages using data from the pre-dam period, while the post-dam scenario simulated water stages 10 years after the dam began to operate, because of the availability of the most recent crosssectional profiles. The dam-removal scenario simulated water stages using the pre-dam frequency curve of flood discharge and the post-dam cross-sections and hydraulic roughness (Table 1). The estimated frequency curve of the flood discharge at Kamisatsunai station was used to simulate water stages from KP 41.8 to KP 45.4 of the upper site, while those from the Nantai Bridge station were used for KP 15.2 to KP 18.6 of the lower site and those from the Dainiokawa Bridge station were used for KP 18.8 to KP 21.0, and the influence of the confluence of a small tributary near KP 18.6 was taken into account. HEC-RAS performs a steady-flow analysis using a series of cross-sections representing hydraulic roughness (Manning's n) and topography using the standard step method, which sequentially solves a one-dimensional energy equation between cross-sections. Manning's n was assigned to the cross-sections based on land cover types from aerial photographs (details in the next section): 0.1 for dense vegetation, 0.05 for sparse vegetation, 0.035 for gravel and water and 0.05 for other cover types.

Analysis of flood frequency

For the analyses of flood frequency and land cover, sampling points (upper site: n = 1583; lower site: n = 2477) were generated every 5 m on the cross-sections from the left KP to the right KP by ArcGIS version 9.2 (ESRI). In order to estimate the flood frequency of the study sites, the flood return period was calculated at each sampling point on the cross-sections and grouped into four categories: 0–1, 1–5, 5–20 and >20 years. The frequency (%) of each return-period category was calculated as (the number of points in the category)/(the total number of sampling points) × 100. A comparison of flood frequency patterns between the pre-dam and dam-removal scenarios indicates the effects of the changes in cross-sections and hydraulic roughness, and a comparison between the post-dam and dam-removal scenarios indicates the effects of the changes in the frequency curve of flood discharge (Table 1).

We used an information-theoretic approach to compare flood frequency patterns among the three scenarios, because we were interested not only in the differences among scenarios but also in the similarities among scenarios. Contingency tables can be analyzed by a method similar to regression models for continuous response variables (Agresti 2002). Log-linear models apply to count data and assume a Poisson distribution. Generalized linear models (GLM) with a Poisson distribution and log link function were used to analyze how the return period (RP) (four levels: 0–1, 1–5, 5–20 and >20), SCENARIO (pre-dam, post-dam and dam-removal) and the interactions between RP and SCENARIO affected the frequency of sampling points (Freq). We developed five models for each site with levels defined by different combinations of the SCENARIO categories, which was described by a combination of a, b and/or c. For example, (a, a, b) indicates that the pre- and post-dam scenarios are in the same level and dam-removal is in a second level. Akaike's information criterion (AIC) was used to compare models. The model with the smallest AIC was selected as the best model, and ΔAICs were calculated to examine differences between the best model and other models.

Table 1 Data used in flood stage simulations

	pre-dam scenario	post-dam scenario	dam-removal scenario
Flood discharge: $q(T)$*	pre (1976-1996**)	post (1997-2006)	pre (1976-1996**)
Cross-sections	pre (1990)	post (2007)	post (2007)
Hydraulic roughness***	pre (1991)	post (2006)	post (2006)

Numbers in parentheses indicate the year in which the data were collected.
*Flood discharge (m^3/s) having T (year) return period was simulated using maximum discharge datasets from the pre- and post-dam periods (Table 2)
**Maximum discharge at Kamisatsunai station was not available for 1976-1978.
***Hydraulic roughness were assigned from land cover types (see details in “Methods”)

Land cover mapping from aerial photographs

A GIS database was developed to analyze the changes in channel morphology and riparian vegetation within the upper and lower sites. Digital photo datasets were generated from a series of colour aerial photographs taken in 1991, 1995, 2000 and 2006 by the HRDB. ERDAS Imagine version 9.2 (Leica Geosystems) was used to correct the geometrical distortion of the aerial photos, which were referenced to topographical maps (1:25000 scale, Geographical Survey Institute) by marking roads and bridges. The corrected aerial photographs were manually interpreted and classified into five types of land cover: (1) dense vegetation (area covered by deciduous trees with crown closure >25%); (2) sparse vegetation (area covered by young trees and grasses, including shrubs and patchy trees, with canopy cover ≤25%); (3) gravel (gravel and sand); (4) water (open water); and (5) other (levees, roads, grounds, etc.). Land cover layers in vector format were prepared using ArcGIS version 9.2 (ESRI) and then converted to raster data with resolution of 25 m^2.

Although the aerial photographs were taken during low-flow conditions, the areas of water and gravel may change from day to day and with seasons, because they are related to flow discharge. The area of water increases and that of gravel decreases with increasing discharge. Thus, the active channel, defined as the union of water and gravel, was used to analyze the changes in channel morphology.

Analysis of edge density

Total edge density for each land cover (dense and sparse vegetation, active channel and water) was calculated to evaluate the complexity of the riparian landscape. The upper and lower study sites were divided into sections defined by the area between two adjacent cross-sections (upper site: n = 20; lower site: n = 30). Edge_density (m/ha) was calculated for each section as Edge_length / area = (total edge length of land covers)/(the area between two adjacent cross-sections) and averaged for each site.

In order to compare the edge density among the four land cover maps for each site, GLMs were performed with Edge_length as a response variable, YEAR with up to four levels (1991, 1996, 2000 and 2006) as an explanatory variable, and ln(Area) as an offset term (Faraway 2006). The offset term was included to control the effect of Area, such that the interpretation of the response variable essentially became density. We used a gamma error distribution and a natural log link function, because the values of the response variable were continuous and positive. We developed fifteen models for each site with different combinations of YEAR levels in a manner similar to SCENARIO in the GLMs of flood frequency. AIC was used to compare models and to select the model best supported by the data.

Relationship between flood frequency and land cover

In order to describe the relationship between flood frequency and the riparian vegetation, we conducted overlay analyses of the land cover in 1991 and 2006 and the sampling points for pre- and post-dam flood frequency. The land cover maps were overlaid with the flood frequency sampling points, and a land cover type was assigned to each sampling point. Based on contingency tables of land cover and flood frequency, the frequency (%) of the sampling points of each category (land cover × flood frequency) was calculated as (the number of sampling points in the category)/(the total number of sampling points) × 100.

Results

Frequency curves of flood discharge

The maximum discharge observed at the Kamisatsunai and Nakajima Bridge stations showed a similar pattern during the pre-dam period, and that at Nantai and Dainiokawa Bridge stations also showed a similar pattern (Fig. 2). However, during the post-dam period, the discharge at Kamisatsunai station was greatly reduced by dam operation and differed from that of the other stations.

One-, 5-, and 20-year floods were estimated by a GEV model (Table 2; Fig. 3) based on the maximum discharge datasets. Flood discharge in a given return period at Kamisatsunai station was predicted to decrease substantially after the dam began to operate (Fig. 3a; Table 2). The post-dam floods were much lower than the pre-dam floods. For example, the post-dam 20-year flood (270.8 m^3/s) was almost the same as the pre-dam 2-year flood (269.0 m^3/s). At the Dainiokawa Bridge and Nantai Bridge stations, the 20-year floods during the post-dam period (768.4 and 977.3 m^3/s, respectively) were smaller than those of the pre-dam period (1003.1 and 1024.9 m^3/s, respectively), while the 1- and 5-year floods during the post-dam period were greater than those of the pre-dam period (Fig. 3b, c; Table 2). The maximum discharge observed during the post-dam period at the Nantai Bridge station (1014.3 m^3/s in 2001) and at the Dainiokawa Bridge station (784.2 m^3/s in 2001) were smaller than the pre-dam 20-year flood, and the maximumdischarge at Kamisatsunai station (254.3 m^3/s in 2003) was smaller than the pre-dam 2-year flood (Fig. 2; Table 2).

Table 2 Estimated GEV parameters and flood discharge by return period

	Kamisatsunai		Dainiokawa Bridge		Nantai Bridge	
	pre	post	pre	post	pre	post
Parameters						
μ	204.7	183.6	333.9	520	373.7	523.9
σ	84.2	53.2	116.1	227.1	137	251.4
ζ	0.3	-0.5	0.4	-0.8	0.3	-0.4
Flood discharge (m^3/s)						
T: 1 (year)	204.7	183.6	333.9	520	373.7	523.9
2 (year)	269	215.3	426.6	639.3	478.8	677.4
5 (year)	375.7	244.4	595.7	720.3	654.1	828.1
10 (year)	476.6	259.7	771.5	751.2	821.1	912.3
20 (year)	599.1	270.8	1003.1	768.4	1024.9	977.3

Flood discharge was calculated by the following equation:

$$q(T) = \mu + \frac{\sigma}{\xi}\left(\left(\frac{1}{T}\right)^{-\xi} - 1\right)$$

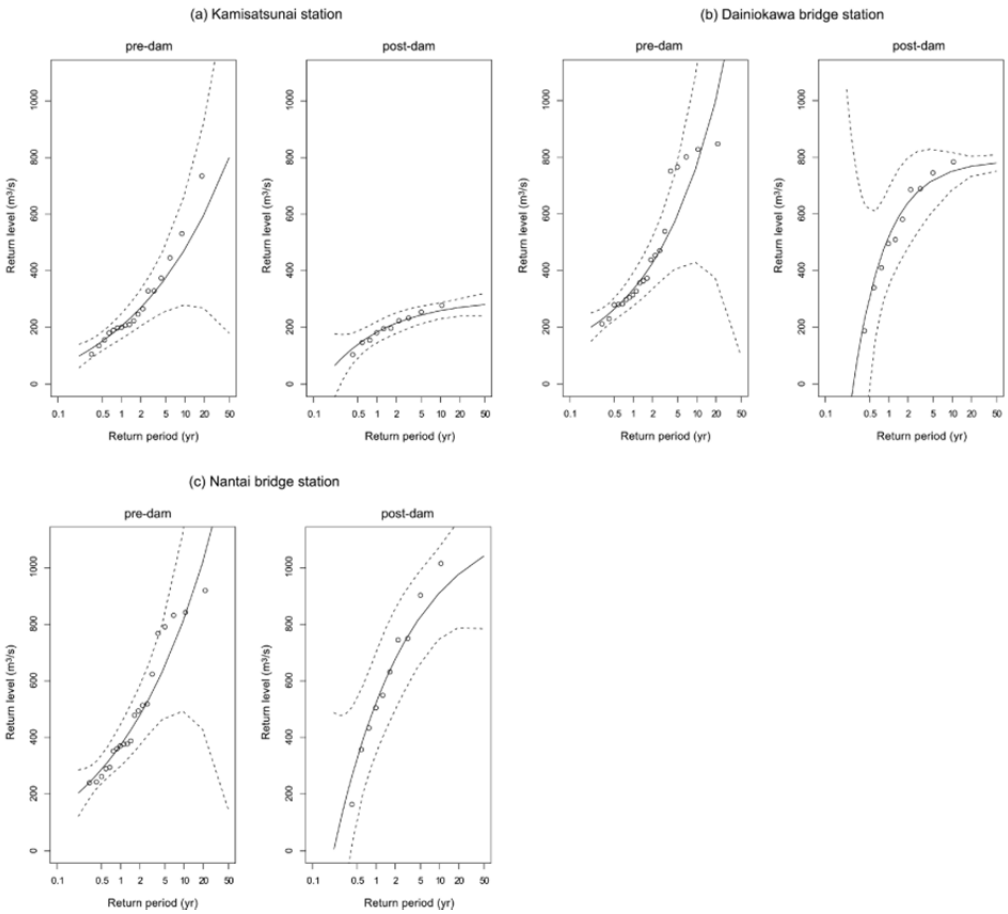

Fig. 3 Return level plots for (a) Kamisatsunai, (b) Dainiokawa Bridge and (c) Nantai Bridge stations during the pre-dam (1976–1996) and post-dam (1997–2006) periods. Solid lines indicate flood discharges versus return period calculated by the GEV models (Table 2), and dashed lines indicate 95% confidence intervals of the flood discharge

Flood frequency

Flood frequencies at the upper and lower sites were estimated under the three scenarios (Fig. 4). The change between the pre-dam and post-dam scenarios in the return period at each sampling point is shown in Table 3. Fiftyeight percent (=28.6% + 2.1% + 0.5% + 26.8%) of the sampling points within the upper site remained in the same return period category after the dam began to operate, while 81.5% (=48.6% + 2.3% + 0.2% + 30.4%) of points within the lower site remained in the same category.

In the GLM analysis of the contingency tables of RP × SCENARIO, the model including SCENARIO with three levels (a, b, c) was best supported by the data for both sites (AIC 114.3 for the upper site, 118.0 for the lower site) (Table 4). The model with SCENARIO levels (a, b, a) was the second best for the upper site (AIC 138.6, ΔAIC 24.3), while the model with SCENARIO levels (a, a, b) was the second best for the lower site (AIC 123.6, ΔAIC 5.6). The ΔAIC of the third best model was substantially greater than the best and second best models.

For the upper site, the best and second best models indicated that the distributions of flood frequency were different between the pre-dam and post-dam scenarios (Table 4). The frequency of sampling points with return periods greater than 20 years increased from 31.0% in the pre-dam scenario to 48.6% in the post-dam scenario, while the frequency of points with 1- to 5-year return periods and of points with 5- to 20-year return periods decreased from 15.6 and 14.9%, respectively, in the pre-dam scenario to 6.9 and 2.0%, respectively, in the post-dam scenario (Fig. 4; Table 7 in Appendix). Almost half of the points with greater than 20-year return period in the post-dam scenario shifted from the 0- to 1-year, 1- to 5-year and 5- to 20-year categories in the pre-dam scenario (5.8, 4.9, and 11.2%, respectively) (Table 3). However, at the upper site, the differences between the pre-dam and dam-removal scenarios were supported by the best model but not by the second best model (Table 4). Although small differences between the pre-dam and dam-removal scenarios were supported by the best model but not by the second best model (Table 4). Although small differences between the pre-dam and dam-removal scenarios were predicted by the best model, the distributions of flood frequency under pre-dam and dam-removal scenarios were similar: the frequency of the greater than 20-year return period category under the dam-removal scenario (27.9%) was similar to that in the pre-dam period (31.0%), whereas the frequency was much greater in the post-dam scenario (48.6%) (Fig. 4; Table 6 in Appendix).

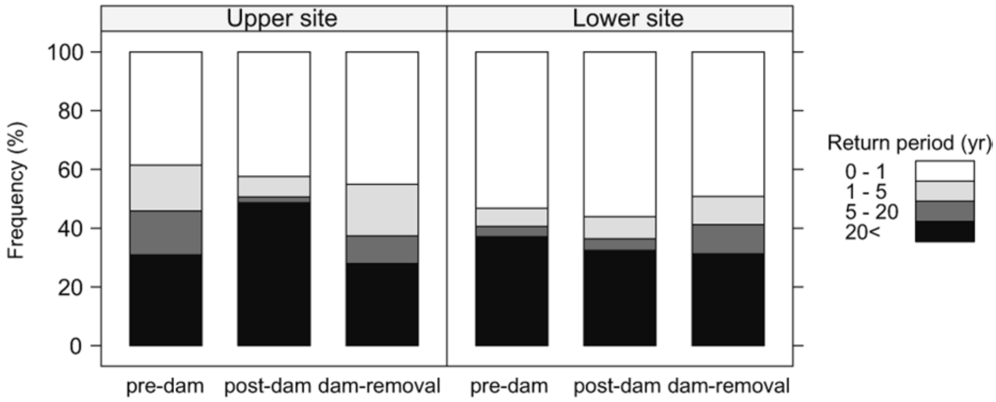

Fig. 4 Frequency (%) of sampling points by return period for the three scenarios. Frequency (Table 6 in Appendix) was calculated as (the number of points in each return period category)/(the total number of points; upper = 1583, lower = 2477) × 100

Table 3 Proportion of sampling points in each return period in the pre- and post-dam scenarios

Upper site (n=1583)						Lower site (n=2477)				
	Post-dam RP*					Post-dam RP*				
		0–1	1–5	5–20	>20		0–1	1–5	5–20	>20
		42.4	**6.9**	**2.0**	**48.6**		**56.1**	**7.5**	**4.0**	**32.4**
Pre-dam RP*										
0–1	**38.5**	28.6	3.2	0.9	5.8	**53.2**	48.6	3.6	0.4	0.7
1–5	**15.6**	8.3	2.1	0.4	4.9	**6.1**	3.1	2.3	0.5	0.2
5–20	**14.9**	2.3	0.9	0.5	11.2	**3.6**	1.8	0.4	0.2	1.1
>20	**31.0**	3.2	0.8	0.2	26.8	**37.1**	2.5	1.2	2.9	30.4

* RP represents the category of return period (in years). The figures represent relative frequency (%) of each category, which was calculated as (the number of sampling points in each category)/(the total number of sampling points; upper = 1583, lower = 2477) × 100. Bold font indicates the total frequency (%) of each return period category

Table 4 The five generalized linear models for the frequency of sampling points (Freq) evaluated for each site ranked by AIC and ΔAIC

Levels of SCENARIO variables				
Pre-dam	Post-dam	Dam-removal	AIC	ΔAIC
Upper site (n = 1583)				
a	b	c	114.3	0.0
a	b	a	138.6	24.3
a	b	b	354.7	240.5
a	a	b	401.4	287.1
a	a	a	473.0	358.7
Lower site (n = 2477)				
a	b	c	118.0	0.0
a	a	b	123.6	5.6
a	b	b	192.5	74.4
a	b	a	222.6	104.6
a	a	a	246.5	128.4

All of the above models include RP (four levels: 0–1, 1–5, 5–20 and >20), SCENARIO (one to three levels) and their interactions. The levels of SCENARIO variables (pre-dam, post-dam and dam-removal) were described by the combinations of letters (a, b and/or c); see Sect. ‘‘Analysis of flood frequency’’ for more details. The models are ranked in ascending order of AIC

For the lower site, differences between the pre- and post-dam scenarios were supported by the best model but not by the second best model (Table 4). Although small differences between the pre- and post-dam scenarios were predicted by the best model, the distributions of flood frequency under pre- and post-dam scenarios were similar: the 0- to 1-year category was the most frequent under both scenarios (53.2 and 56.1%, respectively), followed by the longer than 20-year category (37.1 and 32.4%, respectively) (Fig. 4; Table 6 in Appendix). On the other hand, the differences between the post-dam and dam-removal scenarios were supported by the best and second best models (Table 4). The total frequency of the 1- to 5-year and 5- to 20-year categories was only 9.7% under the predam scenario and 11.5% under the post-dam scenario (Fig. 4). In contrast, the total frequency of the 1- to 5-year and 5- to 20-year categories increased to 19.5% under the dam-removal scenario.

Changes in land cover

The composition of the land cover changed from the pre-dam period (1991 and 1995) to the post-dam period (2000 and 2006) at both the upper and lower sites, but the patterns of change differed between the sites (Figs. 5, 6). At the upper site, sparse vegetation substantially decreased during the pre-dam period. Most of the sparse vegetation in 1991 changed into dense vegetation by 1995 (Figs. 5a, 6), and there was nearly no new sparse vegetation. However, there was an increase in sparse vegetation in 2000 at points that were gravel and water in 1991 and 1995, and these points had changed into dense vegetation by 2006. For example, some secondary channels became narrower and changed into dense vegetation by 2006 (Fig. 5a, red circles). We compared the amount of dense and sparse vegetation in order to gain insight into the colonization of tree species on the floodplains. The total frequency of dense and sparse vegetation did not change in the pre-dam period (60.5% in 1991 and 60.3% in 1995) but increased in the post-dam period (from 65.8% in 2000 to 70.1% in 2006) (Fig. 6). The total frequency of gravel and water in the post-dam period decreased. At the lower site, sparse vegetation gradually changed into dense vegetation from the pre-dam period to the post-dam period (Figs. 5b, 6). The total frequency of dense and sparse vegetation was almost constant through both periods, as was the total frequency of gravel and water (Fig. 6).

Edge density

There were no clear trends in edge density between pre- and post-dam periods at either the upper or lower sites (Table 5). For the upper site, the GLM including YEAR with three levels (b, a, c, a) (AIC 1286.3) was best supported, indicating that the edge density in 1995 and 2006 (382 and 379 m/ha, respectively) was smaller than in 1991 and 2000 (638 and 468 m/ha) (Table 7 in Appendix). For the lower site, the model including YEAR with two levels (b, a, b, b) (AIC 1888.3) was best supported (Table 7 in Appendix), indicating that the edge density in 1995 (433 m/ha) was greater than in 1991, 2000 and 2006 (358, 353 and 335 m/ha).

Relationship between flood frequency and land cover

The proportions of land cover classes depended on the flood return period (vertical axes in Fig. 7). Within both the upper and lower sites, the total frequency of dense and sparse vegetation increased as return period lengthened, while that of gravel and water decreased. Because the frequency of return periods longer than 20 years increased substantially from the pre-dam period to the post-dam period within the upper site (Fig. 4, horizontal axes in Fig. 7), dense vegetation, which dominates points with return periods greater than 20 years, increased within the upper site (Fig. 7a). On the other hand, the distribution of flood frequency within the lower site changed little between the pre- and post-dam periods (Fig. 4, horizontal axes in Fig. 7), where the total frequency of dense and sparse vegetation remained constant from the pre-dam period to the post-dam period (Fig. 7b).

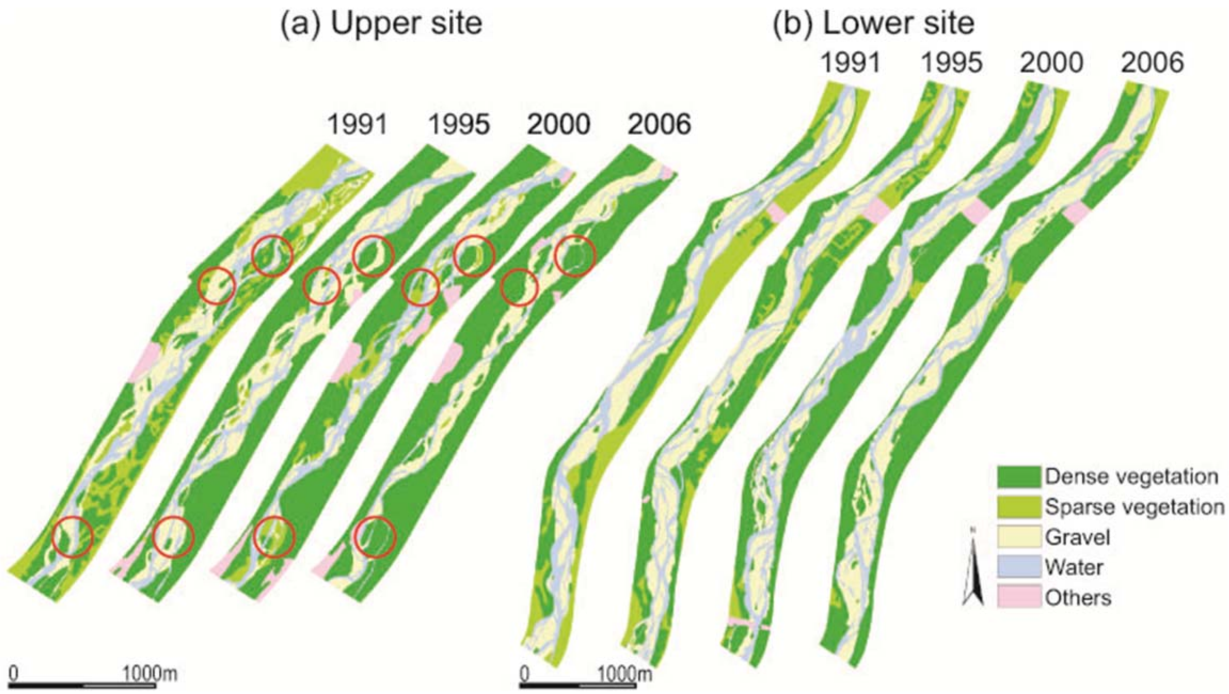

Fig. 5 Land cover maps for the pre-dam (1991 and 1995) and post-dam (2000 and 2006) periods at the upper (a) and lower (b) sites along the Satsunai River. Red circles indicate secondary channels that became forested after the dam began to operate. Green dense vegetation, light green sparse vegetation, yellow gravel, blue water, pink others

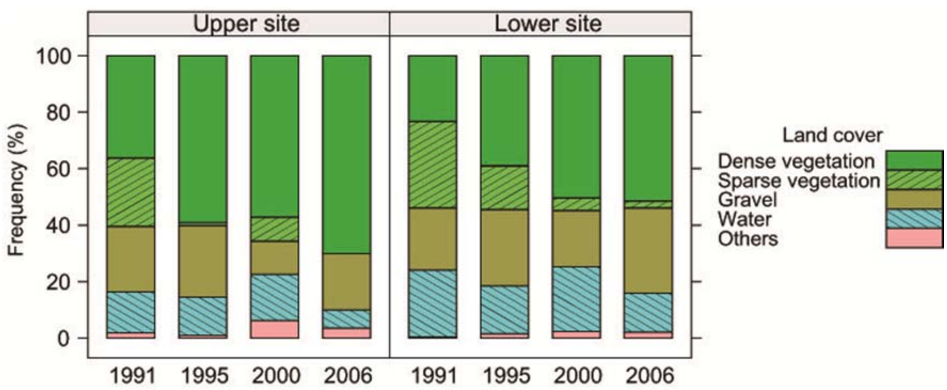

Fig. 6 Frequency (%) of sampling points by land cover classes during the pre-dam (1991 and 1995) and post-dam (2000 and 2006) periods within the upper and lower sites. Frequency (%) was calculated as (the number of points in each land cover category)/(the total number of points; upper = 1583, lower = 2477) × 100

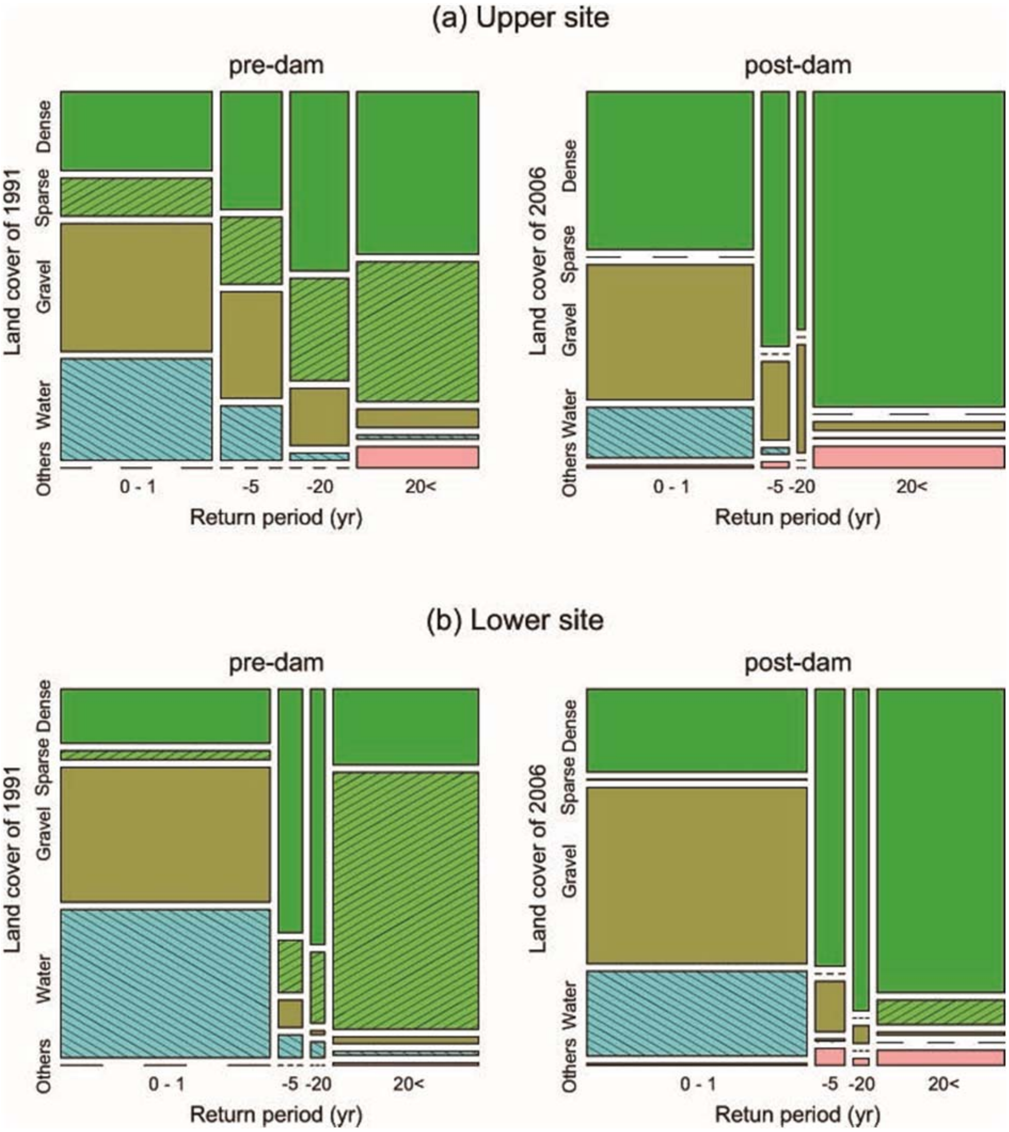

Fig. 7 Overlay analysis of sampling points by land cover and return periods within the upper (a) and lower (b) sites. The width of each horizontal axis represents the proportion of the sampling points in each return period (Fig. 4, pre-dam and post-dam), and the height of each vertical axis represents the proportion of sampling points of each land cover within a return period category. The size of each rectangle shows the proportion of sampling points in each category (land cover 9 return period) (Table 8 in Appendix). Green dense vegetation, light green sparse vegetation, brown gravel, blue water, pink others

Table 5 Edge density of active channel by sites

Year	Upper site	Lower site
1991	638	358
1995	382	433
2000	468	353
2006	379	335

Study sites were divided into twenty (upper site) and thirteen (lower site) sections by cross-sections. Edge density (m/ha) was calculated for each section as (total edge length of land cover)/(the area between two adjacent cross-sections) based on Figs. 1 and 5, and averaged for each site. See Table 7 in Appendix for GLM results on edge density and year

Discussion

Studies on the impacts of dam-regulated flows (Braatne et al. 2008; Gordon and Meentemeyer 2006; Katano et al. 2009; Katz et al. 2005; Shafroth et al. 2002b) have emphasized the importance of the natural river flow in regulating the dynamics of river and riparian systems. Our study indicates that dam-regulated flows have changed the river landscape, especially in reaches relatively close to the dam. Land cover types are associated with flood frequency, and the reduced flood frequency has induced changes in land cover, increasing the area of riparian vegetation and decreasing that of active channel.

Changes in flood frequency along the river

The area just below the dam is influenced most strongly by the operation of the dam, and the influence of regulated flows can be mitigated by tributary inflows in the lower reaches. Takagi and Nakamura (2003) investigated the downstream effects of the Satsunai River Dam in the area close to the dam (1.6–4.4 km downstream from the dam) in 2001 and predicted that the 0- to 1-year and 1- to 20-year flood areas (22.1 and 66.5%, respectively) would decrease to 6.0 and 14.0% after the dam began to operate, while the longer than 20-year flood area (11.4%) would increase to 70.4%. Our results for the upper site (Fig. 4) are similar, but the patterns are less distinct, because our upper site is situated 17 km downstream from the dam and the impacts of reduced flood discharge may be partly diminished due to the inflow of water from adjacent hillslopes.

Comparing the three scenarios at the upper site (Fig. 4; Table 4), hydrological impacts, i.e. decreases in flood discharge induced by the dam, were primarily responsible for the changes in the distribution of flood frequency after the dam began to operate, whereas changes in cross-sections and hydraulic roughness had small impacts. Therefore, restoring the original hydrological regime is expected to be an effective method to recover the original distribution of flood frequency.

At the lower site, however, changes in flood discharge, cross-sections and hydraulic roughness affected the distribution of flood frequency, although differences in the distribution of flood frequency among the scenarios were small. At the Dainiokawa and Nantai Bridge stations, in spite of the operation of the dam, post-dam 5-year flood levels (720.3 and 828.1 m^3/s, respectively) were greater than those of the pre-dam period (595.7 and 654.1 m^3/s) while in the upper reach (Kamisatsunai station) (Table 2), the post-dam 1-year flood level (183.6 m^3/s) was even smaller than that of the pre-dam period (204.7 m^3/s). Postdam 20-year floods in the lower site were, however, smaller than those of the pre-dam. Thus, tributary inflows mainly from the Tottabetsu River seemed to mitigate the reduction in flood levels of the relatively short return period categories. In addition to the hydrological changes, there were changes in the cross-section and land cover, which affected hydraulic roughness, and the interaction between those hydrological and morphological changes resulted in similar distributions of flood frequency under both the pre- and post-dam scenarios.

Changes in riparian landscape

Edge density (a measure of the complexity of the riparian landscape) is expected to decrease in the post-dam period; however, different patterns were observed (Table 5). At the upper site, the edge density in 1991 was high primarily because of the complicated shape of dense and sparse vegetation (Fig. 5a). The expansion of vegetated sandbanks in the channel increased the edge density in 2000, but areas of sparse vegetation became dense vegetation in 2006, resulting in decreased edge density. The area of active channel decreased (Fig. 6) and narrowed in the post-dam period, but flows of secondary channels still existed in 2006. If the secondary channels become more vegetated and disappear in the future, then the riparian landscape will become more simplified. At the lower site, the edge density in 1995 was high because of the complicated shape of dense and sparse vegetation. Vegetated sandbanks occurred in the middle of the channel in the post-dam period (Fig. 5b), but unlike at the upper site, the vegetated areas were constant through both periods (Fig. 6). This suggests that the increase in riparian vegetation was balanced by a decrease in vegetation being disturbed or eroded by stream flows, even in the post-dam period. The size of the tributary relative to the main stem is related to the mitigating effects of tributary inflow (Benda et al. 2004). At the lower site, the confluence of the Tottabetsu River appeared to maintain stream disturbances that balanced the area of active channel with the amount of riparian vegetation.

Impacts on riparian vegetation

Hydrological changes caused by dams may also induce changes in composition of riparian plant communities. Sparse vegetation frequently appeared in the longer than 20-year flood area during the pre-dam period (Fig. 7) and changed into dense vegetation during the post-dam period. Under the natural flow regime, spatial–temporal dynamics in river form are accompanied by colonization and destruction of riparian vegetation (Nakamura et al. 2007; Zanoni et al. 2008). In our study site, however, 20-year floods were diminished, even in the lower reaches, and the pre-dam 20-year flood levels are unlikely to recur under the dam operation. The vegetation in the longer than 20-year flood area is not likely to be disturbed by large floods, as occurred during the pre-dam period. Previous studies have found that riparian vegetation changed from pioneer species adapted to frequently flooded areas into upland species suited to little-disturbed environments after construction of dams (Azami et al. 2004; Johnson et al. 1976; Nakamura and Shin 2001). Takagi and Nakamura (2003) surveyed riparian vegetation along the Satsunai River 3 years after the dam was completed and found that seedlings of latesuccessional species dominated the geomorphic surfaces that were widely distributed in the pre-dam period. Furthermore, a reduction or lack of intermediately disturbed areas, where middle-aged stands dominate, may cause a discontinuity in the life history of riparian plant species (Nakamura et al. 2007).

Management implications

Increasing concerns about the negative impacts of dams have led to growing calls for new management strategies (Hart et al. 2009). Dam managers have tried to reduce the impacts of dams by modifying dam operations to mimic natural flow patterns, including periodic releases of flushing flows and increased minimum flows (Bednarek and Hart 2005; Hueftle and Stevens 2001; Scheurer and Molinari 2003; Travnichek et al. 1995). Several dams have been removed to restore river environments, and dam removal poses important new challenges for watershed management (Hart et al. 2009; Shafroth et al. 2002a). In our study, the simulated restoration of the original hydrological regime (i.e., the dam-removal scenario) largely restored pre-dam flood frequency patterns at the upper site (Fig. 4). Reducing the peak discharge of large floods is, however, one of the purposes of dams and is needed to protect public safety. In order to achieve both public safety and river conservation, flexible dam operations that allow flood disturbance within certain tolerance limits are required. Restoration efforts that modify dam operations may be less effective long after dam regulations started, and adaptive management planning (Walters 1997) with the beginning of dam operation is preferred if possible. Our study suggested that secondary channels will become narrower or disappear, and floodplains and banks will become more stable with the establishment and growth of riparian vegetation. Therefore, in order to prevent the entire floodplain of the Satsunai River from becoming forested, discharge regulations to mimic natural flow patterns should be implemented as soon as possible. In addition to dam construction in upper basins, Japanese rivers have been altered by levee construction associated with urbanization and agricultural development in lower reaches (Takahasi and Uitto 2004; Yoshimura et al. 2005). Our results indicate that simplification of river morphology and colonization of floodplains by plant communities are symptoms of ecosystem degradation. Therefore, restoration plans must be built upon longitudinal linkages throughout the entire catchment.

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Appendix

See Tables 6, 7 and 8.

Table 6 Frequencies (%) of sampling points by flood return period for the three scenarios (Fig. 4)

Return period (years)	Upper site (n = 1583)			Lower site (n = 2477)		
	Pre-dam	Post-dam	Dam-removal	Pre-dam	Post-dam	Dam-removal
0-1	38.5	42.4	45.1	53.2	56.1	49.2
1-5	15.6	6.9	17.6	6.1	7.5	9.6
5-20	14.9	2.0	9.4	3.6	4.0	9.9
›20	31.0	48.6	27.9	37.1	32.4	31.3

Table 7 GLM results for edge density: the fifteen models evaluated for each site ranked by AIC and ΔAIC

Levels of YEAR variables											
1991	1995	2000	2006	AIC	ΔAIC	1991	1995	2000	2006	AIC	ΔAIC
Upper site (n = 20)						Lower site (n = 30)					
b	a	c	a	1286.3	0.0	b	a	b	b	1888.3	0.0
a	b	c	d	1288.3	2.0	a	b	a	c	1889.0	0.7
b	a	a	c	1294.6	8.3	b	c	a	a	1889.7	1.4
b	c	a	a	1295.1	8.8	a	b	c	a	1890.1	1.9
a	b	b	b	1295.8	9.4	a	b	c	d	1890.9	2.7
a	b	a	b	1302.0	15.7	a	a	b	b	1898.1	9.8
a	b	a	c	1304.0	17.6	a	a	b	c	1899.3	11.1
b	b	b	a	1327.1	40.7	a	b	b	a	1899.8	11.5
b	a	b	b	1327.8	41.5	b	a	a	c	1900.7	12.4
a	a	b	c	1327.9	41.6	b	b	b	a	1901.8	13.5
a	b	c	a	1328.7	42.4	a	b	a	b	1904.9	16.6
a	a	b	b	1331.3	45.0	a	a	a	a	1906.0	17.7
a	b	b	a	1331.8	45.5	b	b	a	b	1906.6	18.3
a	a	a	a	1336.9	50.6	b	a	c	a	1906.8	18.5
b	b	a	b	1338.9	52.6	a	b	b	b	1907.2	18.9

Models are ranked in ascending order of AIC. Letters indicate levels. A response variable and an offset term are included in the models but not shown in the table (see ‘‘Methods’’ for details)

Table 8 Proportion of sampling points in each category (land cover × flood frequency) for the pre- and post-dam scenarios (Fig. 7)

	Pre-dam					Post-dam				
	Return Period (years)					Return Period (years)				
		0–1	1–5	5–20	>20		0–1	1–5	5–20	>20
Upper site (n=1583)										
		38.5	**15.6**	**14.9**	**31.0**		**42.4**	**6.9**	**2.0**	**48.6**
Dense veg.	**36.3**	8.8	5.3	7.7	14.5	**70.1**	19.3	5.1	1.4	44.3
Sparse veg.	**24.2**	4.2	3.0	4.4	12.5	**0.0**	0.0	0.0	0.0	0.0
Gravel	**23.1**	14.2	4.8	2.5	1.6	**20.0**	16.6	1.6	0.6	1.2
Water	**14.5**	11.3	2.5	0.3	0.4	**6.4**	6.2	0.1	0.0	0.1
Others	**1.9**	0.0	0.0	0.0	1.9	**3.5**	0.3	0.1	0.0	3.0
Lower site (n=2477)										
		53.2	**6.1**	**3.6**	**37.1**		**56.1**	**7.5**	**4.0**	**32.4**
Dense veg.	**23.4**	8.3	4.3	2.6	8.1	**51.6**	13.4	6.0	3.7	28.4
Sparse veg.	**30.6**	1.4	0.9	0.7	27.5	**2.4**	0.1	0.0	0.0	2.3
Gravel	**22.0**	20.7	0.5	0.0	0.8	**30.1**	28.5	1.1	0.2	0.3
Water	**23.8**	22.8	0.4	0.2	0.4	**13.8**	13.7	0.0	0.0	0.0
Others	**0.3**	0.0	0.0	0.0	0.3	**2.1**	0.3	0.4	0.1	1.4

Relative frequency (%) of each category (land cover × flood frequency) is calculated as (the number of sampling points in the category)/(the total number of sampling points) × 100. Bold font indicates the total frequency (%) of land cover or return period categories

References

Agresti A (2002) Categorical data analysis. Wiley, Hoboken

Akasaka T, Nakano D, Nakamura F (2009) Influence of prey variables, food supply, and river restoration on the foraging activity of Daubenton's bat (Myotis daubentonii) in the Shibetsu River, a large lowland river in Japan. Biol Conserv 142:1302– 1310. doi:10.1016/j.biocon.2009.01.028

Azami K, Suzuki H, Toki S (2004) Changes in riparian vegetation communities below a large dam in a monsoonal region: Futase Dam, Japan. River Res Appl 20:549–563. doi:10.1002/rra.763

Bednarek AT, Hart DD (2005) Modifying dam operations to restore rivers: ecological responses to Tennessee River Dam mitigation. Ecol Appl 15:997–1008. doi:10.1890/04-0586

Benda L, Andras K, Miller D, Bigelow P (2004) Confluence effects in rivers: interactions of basin scale, network geometry, and disturbance regimes. Water Resour Res 40:W05402. doi:10.1029/2003WR002583

Braatne JH, Rood SB, Goater LA, Blair CL (2008) Analyzing the impacts of dams on riparian ecosystems: a review of research strategies and their relevance to theSnakeRiver throughHellsCanyon. Environ Manag 41:267–281. doi:10.1007/s00267-007-9048-4

Coles S (2001) An introduction to statistical modeling of extreme values. Springer, London

Faraway JJ (2006) Extending the linear model with R: generalized linear, mixed effects and nonparametric regression models.Chapman & Hall/CRC, London

Gordon E, Meentemeyer RK (2006) Effects of dam operation and land use on stream channel morphology and riparian vegetation. Geomorphology 82:412–429. doi:10.1016/j.geomorph.2006.06.001

Hart DD, Johnson TE, Bushaw-Newton KL, Horwitz RJ, Bednarek AT, Charles DF, Kreeger DA, Velinsky DJ (2009) Dam removal: challenges and opportunities for ecological research and river restoration. Bioscience 52:669–682. doi:10.1641/0006-3568 (2002)052[0669:DRCAOF]2.0.CO;2

Hueftle SJ, Stevens LE (2001) Experimental flood effects on the limnology of Lake Powell Reservoir, Southwestern USA. Ecol Appl 11:644–656. doi:10.1890/1051-0761(2001)011[0644:EFEOTL]2.0.CO;2

Ito H, Ito S, Matsui T, Marutani T (2006) Effect of fluvial and geomorphic disturbances on habitat segregation of tree species in a sedimentation-dominated riparian forest in warm-temperate mountainous region in southern Japan. J For Res 11:405–417. doi:10.1007/s10310-006-0224-9

Japan Meteorological Agency (2008) Climate statistics (in Japanese). http://www.jma.go.jp/jma/menu/report.html. 15 June 2008

Johnson WC, Burgess RL, Keammerer WR (1976) Forest overstory vegetation and environment on the Missouri River floodplain in North Dakota. Ecol Monogr 46:59–84

Katano I, Negishi JN, Minagawa T, Doi H, Kawaguchi Y, Kayaba Y (2009) Longitudinal macroinvertebrate organization over contrasting discontinuities: effects of a dam and a tributary. J North Am Benthol Soc 28:331–351. doi:10.1899/08-010.1

Katz GL, Friedman JM, Beatty SW (2005) Delayed effects of flood control on a flood-dependent riparian forest. Ecol Appl 15:1019– 1035. doi:10.1890/04-0076

Keith R, James B, Francine H (2002) Geomorphic dynamics of floodplains: ecological implications and a potential modeling strategy. Freshw Biol 47:559–579. doi:10.1046/j.1365-2427.2002.00920.x

Magilligan FJ, Nislow KH, Graber BE (2003) Scale-independent assessment of discharge reduction and riparian disconnectivity following flow regulation by dams. Geology 31:569–572. doi: 10.1130/0091-7613(2003)031¥0569:saodra[2.0.co;2

Merritt DM, Cooper DJ (2000) Riparian vegetation and channel change in response to river regulation: a comparative study of regulated and unregulated streams in the Green River Basin, USA. Regul River 16:543–564. doi:10.1002/1099-1646(200011/12)16:6<543:AID-RRR590>3.0.CO;2-N

Nagayama S, Nakamura F (2009) Fish habitat rehabilitation using wood in the world. Landsc Ecol Eng. doi:10.1007/s11355-009-0092-5

Nagayama S, Kawaguchi Y, Nakano D, Nakamura F (2008) Methods for and fish responses to channel remeandering and large wood structure placement in the Shibetsu River Restoration Project in northern Japan. Landsc Ecol Eng 4:69–74. doi:10.1007/s11355-008-0039-2

Nakamura F, Komiyama E (2009) A challenge to dam improvement for the protection of both salmon and human livelihood in Shiretoko, Japan's third Natural Heritage Site. Landsc Ecol Eng. doi:10.1007/s11355-009-0083-6

Nakamura F, Shin N (2001) The downstream effects of dams on the regeneration of riparian tree species in Northern Japan. In: Dorava JM, Montgomery DR, Palcsak BB, Fitzpatrick FA (eds) Geomorphic processes and riverine habitat, American Geophysical Union, Washington DC, pp 173–181

Nakamura F, Shin N, Inahara S (2007) Shifting mosaic in maintaining diversity of floodplain tree species in the northern temperate zone of Japan. For Ecol Manag. doi:10.1016/j.foreco.2006.12.022

Nakano D, Nagayama S, Kawaguchi Y, Nakamura F (2008) River restoration for macroinvertebrate communities in lowland rivers: insights from restorations of the Shibetsu River, north Japan. Landsc Ecol Eng 4:63–68. doi:10.1007/s11355-008-0038-3

Nilsson C, Berggren K (2000) Alterations of riparian ecosystems caused by river regulation. Bioscience 50:783–792

Petts GE, Gurnell AM (2005) Dams and geomorphology: research progress and future directions. Geomorphology 71:27–47. doi:10.1016/j.geomorph.2004.02.015

R Development Core Team (2009) R: a language and environment for statistical computing. RFoundation for Statistical Computing, Vienna

Rood S, Mahoney J (1990) Collapse of riparian poplar forests downstream from dams in western prairies: probable causes and prospects for mitigation. Environ Manag 14:451–464. doi:10.1007/BF02394134

Scheurer T, Molinari P (2003) Experimental floods in the River Spo¨ l, Swiss National Park: framework, objectives and design. Aquat Sci 65:183–190. doi:10.1007/s00027-003-0667-4

Shafroth PB, Friedman JM, Auble GT, Scott ML, Braatne JH (2002a) Potential responses of riparian vegetation to dam removal. Bioscience 52:703–712. doi:10.1641%2F0006-3568%282002%29052%5B0703%3APRORVT%5D2.0.CO%3B2

Shafroth PB, Stromberg JC, Patten DT (2002b) Riparian vegetation response to altered disturbance and stress regimes. Ecol Appl 12:107–123. doi:10.1890/1051-0761(2002)012[0107:RVRTAD] 2.0.CO;2

Takagi M, Nakamura F (2003) The downstream effects of water regulation by the dam on the riparian tree species in the Satsunai River (in Japanese). J Jpn For Soc 85:214–221

Takahasi Y, Uitto JI (2004) Evolution of river management in Japan: from focus on economic benefits to a comprehensive view. Glob Environ Chang Part A 14:63–70. doi:10.1016/j.gloenvcha.2003.11.005

Takao A, Kawaguchi Y, Minagawa T, Kayaba Y, Morimoto Y (2008) The relationships between benthic macroinvertebrates and biotic and abiotic environmental characteristics downstream of the Yahagi Dam, Central Japan, and the state change caused by inflow from a tributary. River Res Appl 24:580–597

Travnichek VH, Bain MB, Maceina MJ (1995) Recovery of a warmwater fish assemblage after the initiation of a minimumflow release downstream from a hydroelectric dam. Trans Am Fish Soc 124:836–844. doi:10.1577/1548-8659(1995)124¥0836:ROAWFA[2.3.CO;2

U.S. Army Corps of Engineers (2008) HEC-RAS river analysis system, user’s manual. Version 4.0. U.S. Army Corps of Engineers, Hydrologic Engineering Center, Davis, CA

Walters C (1997) Challenges in adaptive management of riparian and coastal ecosystems. Conserv Ecol. 1:1. http://www.consecol.org/vol1/iss2/art1/

Ward JV, Stanford JA (1983) Serial discontinuity concept of lotic ecosystems. In: Fontaine TD, Bartell SM (eds) Dynamics of lotic systems. Ann Arbor Science Publishers, Ann Arbor, pp 29–42

Ward JV, Stanford JA (1995) The serial discontinuity concept: extending the model to floodplain rivers. Regul River 10:159–168. doi:10.1002/rrr.3450100211

Wohl E (2006) Human impacts to mountain streams. Geomorphology 79:217–248. doi:10.1016/j.geomorph.2006.06.020

Yoshimura C, Omura T, Furumai H, Tockner K (2005) Present state of rivers and streams in Japan. River Res Appl 21:93–112. doi:10.1002/rra.835

Zanoni L, Gurnell A, Drake N, Surian N (2008) Island dynamics in a braided river from analysis of historical maps and air photographs. River Res Appl 24:1141–1159. doi:10.1002/rra.1086