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Evaluation of river rehabilitation techniques on the impact of native and exotic fish species in the urbanized Yada River, Japan

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Abstract Previous studies poorly document the biological invasion of tolerant and exotic aquatic species as a result of river rehabilitation efforts. In this study, we designed 2 methods of rehabilitation for a river system including (1) partial river widening (PRW), which creates an area of reduced water flow, and (2) the groin (GRO) method, which creates an area of high water flow. The impact of these 2 methods on both native and exotic fishes inhabiting the river basin was assessed for 4 years. Following rehabilitation, the heterogeneity of river morphology, substrate composition, and water velocity were enhanced in areas using both PRW and GRO methods. Fish abundance and species richness also increased. Positive effects were indicated by the first-time capture of certain native fish fauna, and the increased presence of endangered *Oryzias latipes*. Negative effects included the recorded presence of exotic species. The abundance of exotic species increased in the backwater area, with the proliferation of *Gambusia affinis* contributing to a reduction in biodiversity. Statistical models indicated that a faster current velocity of 5 cm/sec would be effective at reducing the number of exotic species, with a predicted 77% decrease in *Gambusia affinis* and 89% decrease in *Lepomis macrochirus* numbers in the backwater zone. The models were supported by our field results, when we created a flowing channel by excavating a sandbar to restore a backwater area. Our research results support that the creation of flowing water in backwater areas is an effective tool to prevent the establishment of exotic species.

Key words Adaptive management, Fish assemblages, *Gambusia affinis*, Groin, Regulated river, River widening

Introduction

Since early civilization, urban rivers have been altered by channel straightening and revetment work (i.e., concrete bank protection) for the efficient use of land, flood control, and irrigation. Urbanization further added to these landscape changes by altering sediment and water supply, which led to water quality degradation and the consequent decline in the biotic integrity of urban rivers (e.g., Lenat and Crawford 1994 ; Roy et al. 2003). In order to resolve these problems, various small-scale to basin-wide restoration actions for urban rivers have been developed and implemented across the world. Hence, there are numerous reports about water quality improvement (e.g., Harremoes et al. 1996 ; Alvarez et al. 1999 ; Adams et al. 2000), design and planning focusing on water use and amenities for mankind (e.g., Ellis 1995 ; Powell and Bails 2000 ; Gregory and Chin 2002), and quantitative assessment of the habitats of aquatic fauna (e.g., Francis and Hoggart 2008 ; 2009) after restoration. However, assessments that focus on balances between native and exotic species in relation to restoration and rehabilitation projects remain limited.

Urban rivers are reported to be highly specialized due to an increase in the number of exotic animals that have strong environmental tolerance and a tendency for omnivory (Horwitz et al. 2008). Throughout the world, there has been controversy over the dominance of exotic species, such as *Micropterus salmoides*, *Lepomis macrochirus*, and *Gambusia affinis*, causing the loss of native species (e.g., Azuma 1992 ; Welcomme 1992 ; Maezono and Miyashita 2003 ; Ishida et al. 2007). Recently, there have been attempts to remove exotic species through capture techniques, particularly in lentic ponds or lakes of many countries (Knapp and Matthews 1998 ; Nishizawa et al. 2006 ; Knapp et al. 2007), yet these methods do not serve

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as long-term solutions for the eradication of exotic species. In lotic rivers and streams, eradication has not been used effectively due to the length and size of flowing areas. Hence, exotic species are distributed in the tributaries, where they may become widespread across the entire watershed area due to flow connectivity. By creating uninhabitable environments, river rehabilitation methods that are effective in excluding exotic species and including native species, should be preferentially applied. However, measures to restore and counteract invasive species by using specific rehabilitation techniques have not yet been documented.

Channel straightening reduces the volume of shallow, high-velocity currents and deep, low-velocity pools, resulting in the formation of stable flowing monotonous river channels (e.g., Takahashi and Higashi 1984 ; Brookes 1988). In natural river environments, diverse water depths and velocities support a wide range of aquatic organisms. In contrast, the homogenous environment in straightened rivers restricts the number of habitats that are available and causes a decrease in species density and diversity (e.g., Elser 1968 ; Swales 1982). Based on the known impact of these environmental alterations, large-scale re-meandering restoration projects have been implemented to increase the complexity of river channel morphology and biotic diversity (e.g., Kern 1992 ; Toth et al. 1993 ; Kawaguchi et al. 2005). However, it is difficult to adapt large-scale restoration projects to urban rivers because of high property values, finely subdivided land, and dense human infrastructure (Bernhardt and Palmer 2007). Therefore, river rehabilitation, focusing on the re-creation of habitat diversity, likely is a more practical solution for urban rivers.

For decades, there have been many attempts to increase river habitat diversity by adding physical structures or manipulating channel morphology of straightened river channels (Gore et al. 1995 ; The River Restoration Center 1999). Furthermore, there are many reports on the effect of additional construction methods on aquatic organisms in mountain and natural alluvial rivers. Such methods include the use of fallen trees (e.g., Hubbs et al. 1932 ; Nagayama and Nakamura 2010), groins (e.g., Saunders and Smith 1962 ; Hunt 1976), boulder and gabion inputs (e.g., House and Boehne 1985 ; Klassen and Northcote 1988), riffle and pool creation (e.g., Edwards et al. 1984 ; Jungwirth et al. 1993), backwater pool formation (Shields et al. 2005 ; Nakajima et al. 2008), secondary channel restoration (e.g., Schropp 1995 ; Buijse et al. 2002), sediment input (e.g., Yrjänä 1998), and river widening (Rohde et al. 2005). However, the impact of these rehabilitation methods on mountain and natural alluvial rivers may not be representative of lowland urban regulated channels, due to the uniqueness of these ecosystems.

In this study, we designed and constructed 2 habitat rehabilitation methods in a lowland urban regulated river: (1) partial river widening (PRW) to create slow flow areas and (2) a groin (GRO) to create high flow areas. We assessed the effect of these 2 methods on the physical environment and fish assemblage, including native and exotic species. The results of the study provide management and conservation suggestions on the use of habitat rehabilitation to inhibit or minimize colonization and establishment of exotic species in urban river channels.

Methods

1. Study sites

The study was conducted at a rehabilitation site (RS) and a control site (CS) on the Yada River (river length: 23.7 km), which is a tributary of the Shonai River (Fig. 1) in Japan. The downstream reaches of Yada River originally flowed in a southward direction before severe flooding occurred in 1767, which led to the current channel being positioned to flow alongside the Shonai River. In 1767, dikes were constructed to fix the channel in position (Fig. 1 (a)). The river channel continued to erode and accrete by meandering between the dikes, but was straightened by modern channelization with re-excavation and low water concrete revetments from 1950 to 1970 (Fig. 1 (b), (c)). The watershed has become highly urbanized, and a golf course, cycling path, and parks were recently constructed in the riparian area. Hence, while in the past the Yada River meandered with definite riffles and pools with sandbars, it is now a straightened urban river with a monotonous flow through metropolitan Nagoya (Fig. 1 (d), 2).

The RS is 350 m in length and is located 2.7 km upstream from the confluence of the Shonai River (Fig. 2).

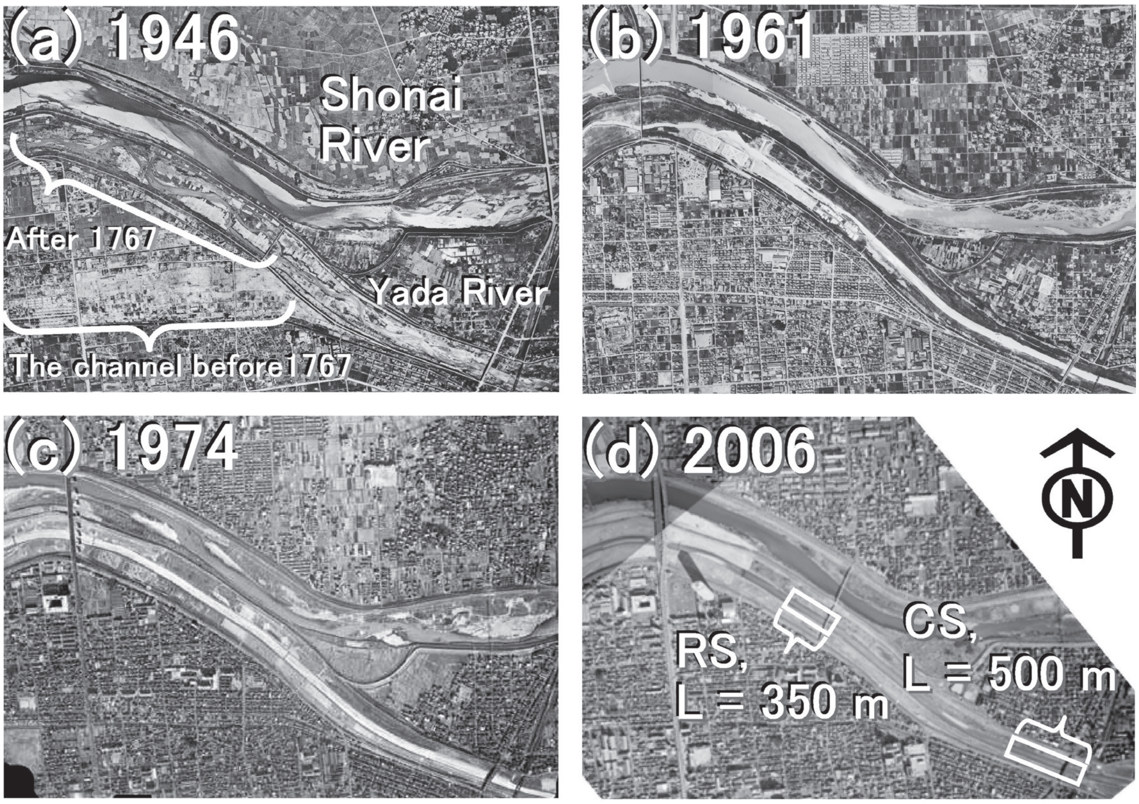

Fig. 1. Landscape changes of the Yada River during the course of urbanization. Photograph (a) is before the modern channelization project (MCP) conducted during the 1950－60s and (b) is during the period of MCP, and (c) and (d) show the period following MCP.

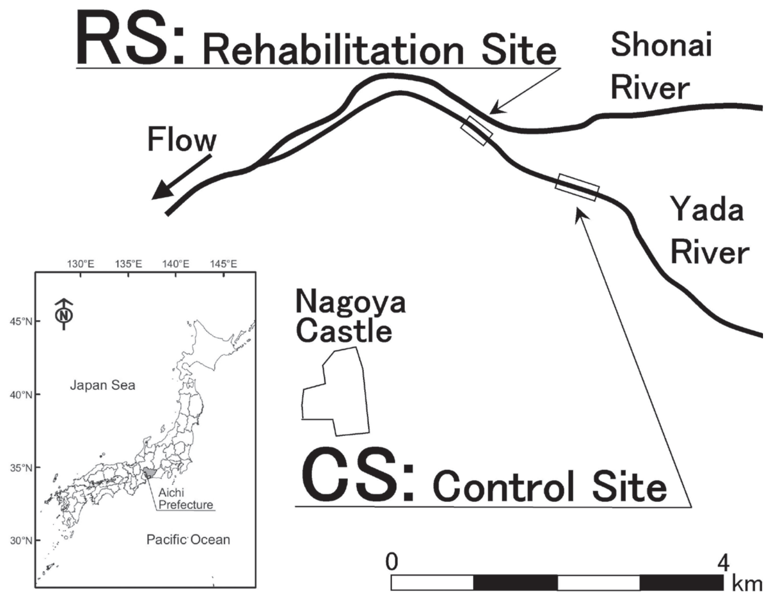

Fig. 2. Location of the Yada River, including the control site (CS) and the rehabilitation site (RS) at Aichi prefecture Japan.

The width between dikes is 180 m, the low water channel width is 35 m, the bed slope is 1/840, and the bed material is composed of sand and gravel, with scarcely developed sandbars (Fig. 1).

The CS was located 1.1 km upstream from the RS. The environmental characteristics of the river at the CS, which had been straightened and lacking vegetation since 1961, were similar to those of the stable RS.

2. Rehabilitation methods

To create the low flow zone and high flow zone in the homogenous river channels, PRW and GRO rehabilitation techniques were introduced at the right bank of the mid-reach and at the left bank of the upper-reach of the RS (Fig. 3) in October 2007 to January 2008. The plain view of the PRW shape is trapezoidal, with a 140m base connected to the main channel, and is 35 m high. The low water revetment was removed, and the land was excavated towards the riverbed height of the main channel. We constructed riprap work in the PRW section to prevent the scouring of land at 4 areas (I, II, III, and V), and to facilitate sediment deposition by the flow regime in 1 area (IV). GROs were made from concrete blocks and boulders of medium diameter (about 30 cm) and were placed at opposite sides of a small riffle, which was located on the right side of the bank, to facilitate enlarging the existing riffle.

3. Surveys in RS

3－1) Geomorphological survey

Surveys of the geomorphological structure and physical environment of RS were conducted on 26 September 2007 (1 month before rehabilitation) and on 25 September 2008 (8 months after rehabilitation). Mean discharge was similar on both surveys days (before: 1.56 m^3/sec, after: 1.93 m^3/sec). We divided the RS study site into 3 reaches: a downstream reach included no rehabilitation methods (Lower-Reach), a mid-stream included the PRW (Mid-Reach), and an upstream reach included GRO (Upper-Reach). Two cross-sectional transects were established for the Mid-Reach, and 1 was established for each of the other 2 reaches (Fig. 3). At equally spaced points (every

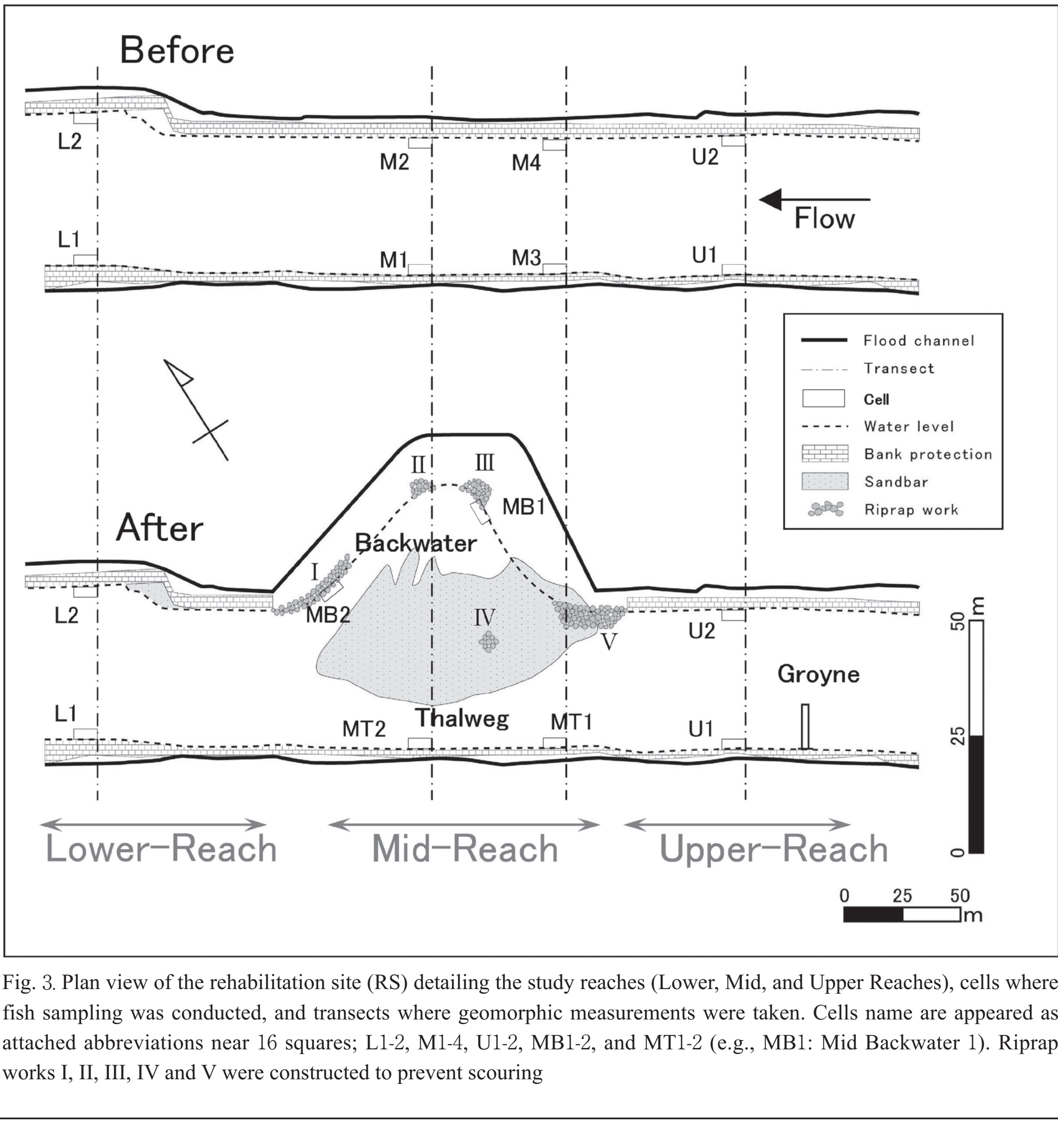

Fig. 3. Plan view of the rehabilitation site (RS) detailing the study reaches (Lower, Mid, and Upper Reaches), cells where fish sampling was conducted, and transects where geomorphic measurements were taken. Cells name are appeared as attached abbreviations near 16 squares; L1-2, M1-4, U1-2, MB1-2, and MT1-2 (e.g., MB1: Mid Backwater 1). Riprap works I, II, III, IV and V were constructed to prevent scouring

Table 1. Fish sampling effort at each of the 7 reaches in the RS, Yada River, before and after rehabilitation.

Area	Methods	Before			After			
		Lower-Reach	Mid-Reach	Upper-Reach	Lower-Reach	Mid-Reach		Upper-Reach
						Thalweg	Backwater	
Shore area	Double pass electrofishing	2 cells (L1, L2)	4 cells (M1, M2, M3, M4)	2 cells (U1, U2)	2 cells (L1, L2)	2 cells (MT1, MT2)	2 cells (MB1, MB2)	2 cells (U1, U2)
Mid-channel area	8 mm mesh cast net	10 casts	10 casts	10 casts	10 casts	10 casts	10 casts	10 casts

2 m) across the transects, water depth, current velocity, and river bed materials were measured using a laser level (RL-HA, VK1704; Topcon Co. Ltd., Tokyo, Japan) and an electromagnetic current meter (AEM-1D; Alec Electronics Co. Ltd., Kobe, Japan). Dominant substrate size around the transect points was recorded by visual examination using 7 size categories: (1) concrete, (2) silt (<0.062 mm), (3) sand (0.062 – 2 mm), (4) gravel (2 – 16 mm), (5) pebbles (16 – 64 mm), (6) cobbles (64 – 256 mm), and (7) boulders (>256 mm).

3 – 2) Fishes and physical parameter survey

Surveys of fishes and physical habitat were conducted on the same day as, but immediately prior to, the geomorphological survey. Fishes were captured in the Lower, Mid, and Upper Reaches of RS before and after rehabilitation. However, after rehabilitation, surveys were conducted in backwater and thalweg habitats of the Mid Reach because the Mid Reach was morphologically divided by the sandbar deposited sediment (Fig. 3, Table 1). At the shore areas, we set up cells defined 20 m^2 areas (2 m x 10 m) on both banks of each transect (Fig. 3). Fish were sampled using double-pass depletion methods and a model 12B Smith-Root electrofishing unit. In the mid-channel area, we used a cast net (mesh size: 8 mm, circular diameter: 3.2 m) to catch fishes. The net was thrown 10 times at random in each reach (Table 1). All individuals caught at the shore and mid-channel areas were counted and identified to the species level and subsequently released live back to the study sites. Because the backwater appeared after the rehabilitation process, the positions of cells M4 and M2 on the right bank in the Mid-Reach were changed to cells MB1 (Mid Backwater 1) and MB2, respectively. M1 and M3 before rehabilitation were changed to MT1 (Mid Thalweg 1) and MT2 after rehabilitation. After the fish survey, we immediately measured physical factors at 25 measurement points, which were selected based on equal cell divisions. Water depth (cm), current velocity (cm/sec), bed material type (concrete block, pebbles, and boulders) and vegetation appearance (1: present, 0: absent) were recorded at all measurement points on the purpose of constructing habitat statistical models for exotic and endangered fish species.

4. Survey in CS

Existing reports of fish capture surveys for CS before restoration were obtained from the National Census on River Environments (NCRE) for the spring, summer, and autumn of 1993, 1997, 2001, and 2006 (Ministry of Land, Infrastructure, Transport, and Tourism 2010a). The NCRE used unified methods to ensure once-only capture during sampling by using a cast-net and a D-shaped net set along the entire 500-m reach length in the CS. However, these surveys were not conducted after rehabilitation. Hence, on 29 October 2008, we conducted a fish survey in the CS, which was surveyed randomly and continually using a cast net and D-shaped net according to the methods of the NCRE. All individuals caught were counted and identified to species and subsequently released live back to the study sites.

5. Data analyses

5 – 1) Comparison of RS and CS

We calculated the Morisita-Horn index of similarity and used the transformed data percentages for the 3 fish surveys of this study (RS 2007, RS 2008, and CS 2008) and 4 NCRE fish surveys (CS 1993, CS 1997, CS 2001, and CS 2006). The indexes were applied to cluster analysis by using the group average method to classify these surveys (Cluster analysis I). Before analysis, we prepared an adjustable dataset for RS 2007 and 2008 to conform to the random and continual survey method of the NCRE. The adjustable data were used to accumulate counts of both once (not twice) captured fish species by the depletion method at the 8 cells and those by the cast net method at all reaches. These analyses were performed with the “R” statistical and programming environment version 2.9.2 (R Development Core Team 2009) and the “vegdist” functions in the “VEGAN” package (Oksanen et al. 2009). We extracted endemic and dominant indicator species from the species observed in each survey. Indicator species were defined as “observed only” (i.e., endemic: not observed in other surveys) and “mainly abundant” (i.e., dominant: captured more than 80% for all counts in a survey) species in each survey.

5－2) Assessment of PRW and GRO

At the RS, the abundance of each aquatic organism per cell (i.e., 20 m^2) was estimated by means of double-pass depletion methods using the Mbh removal estimator (Pollock and Otto 1983) in the program CAPTURE (White et al. 1978). We used catch per unit effort (CPUE), which was defined as total species abundance for 2 cells (i.e., 40 m^2) and 10 cast nets for each study reach. For the Mid-Reach, we added half values of all 4 cells (for a total of 2 cells and 10 cast nets), which were calculated and used for all subsequent analyses. The Shannon diversity index ($H' = -\sum pi \ln pi$, where pi is the relative abundance of a species; Shannon and Weaver 1949) was calculated for each study reach. Morisita-Horn index of similarity and cluster analysis by using the group average method were conducted to classify the study reaches before and after rehabilitation, according to fish assemblages (Cluster analysis II). We extracted endemic and dominant indicator species from the species observed in each reach.

5－3) Exotic and endangered species habitat modeling

For a total of 16 cells, the estimated abundance (explanatory variables) of exotic and endangered fish species that were captured in each cell in relation to 7 physical factors (dependent variables) was modeled using generalized linear mixed models (GLMM; with a log link, a Poisson error, and research years as a random effect). The 7 physical factors used in the model were mean bank slope (%), mean water depth (cm), mean current velocity (cm/sec), and the percentage of coverage (%) of concrete bank, cobble, boulder, and riparian vegetation of each bank. Full and best models of GLMM were fitted using the “glmmML” and stepAIC functions in the “MASS” package of R.

5－4) Adaptive management

Adaptive management was conducted in the backwater in order to prevent exotic fishes. We selected physical factors from the calculated GLMM models to prevent exotic fishes effectively, and we introduced re-rehabilitation methods in the backwater. We monitored the effect on the exotic species by using the same fish captured methods (double-pass depletion methods) at the MB1 same cell positions, which were conducted before and after re-rehabilitation during October 2010.

Results

1. Geomorphic changes in RS

After rehabilitation work on the river, sedimentation from several spring floods (discharge exceeded 100 m^3/sec) formed a sandbar around the riprap work of area IV in the mid-reach of the river. As the sandbar grew in size, the single channel was divided into 2 channels (Fig. 4 (a)). Several summer floods (discharge exceeded 250 m^3/sec) caused the accumulation of sediments, which closed the top of the right flow way, leading to the formation of backwaters (Fig. 4 (a), Fig. 5). The relative elevation from water height to sandbar height in the wide channel mid-reach gradually increased by more than 30 cm (Fig. 5). While water depth, current velocity, and substrate coarseness in the mid-reach of the cross sectional transects for both in the widen and narrow channels were uniform before rehabilitation, the rehabilitation works generated a high-velocity thalweg area with boulder bed material forming along the left bank and a low reversal velocity area in the backwater (Fig. 4 (a), Fig. 5 Mid-Reach Wide Channel). In comparison, in the upper-reach of the river, the GRO expanded a high-velocity riffle area from the right bank towards the center of the channel, and increased the size of the bed materials (Fig. 4 (b), Fig. 5 Upper Reach). Furthermore, sections of the lower and reverse velocity area, which were absent before rehabilitation, appeared in the lower reach of the river below the

Fig. 4. Landscape changes observed from the fixed point at both the Mid- (a) and Upper (b) reaches before and after rehabilitation.

GRO area. At the lower-reach, water depth, current velocity, and bed materials along the cross-sectional transect were entirely homogeneous before rehabilitation. However, after rehabilitation, similar changes in current velocities and bed materials to those observed in the upper and mid-reaches were not recorded in the lower-reach (Fig. 5), except for the scouring of the riverbed.

2. Fish assemblage classifications for the RS and CS

The cluster analysis I produced 2 distinct clusters; 1 cluster (Cluster I-2) for the "RS 2008 (after)" survey site and a second cluster (Cluster I-1) for all others (Table 2). The survey sites that were included in Cluster I-1 had the same dominant species, *Zacco platypus*. In contrast, the most dominant species in Cluster I-2 at the "RS 2008 (after)" survey site was *Gambusia affinis*. Cluster I-2 also had the largest overall fish capture numbers, taxa numbers, and Shannon diversity index compared to the other surveys, with 744 individuals of all 18 taxa including 13 native taxa, and a Shannon diversity index (H') of 1.97 compared to all other surveys (Table 2).

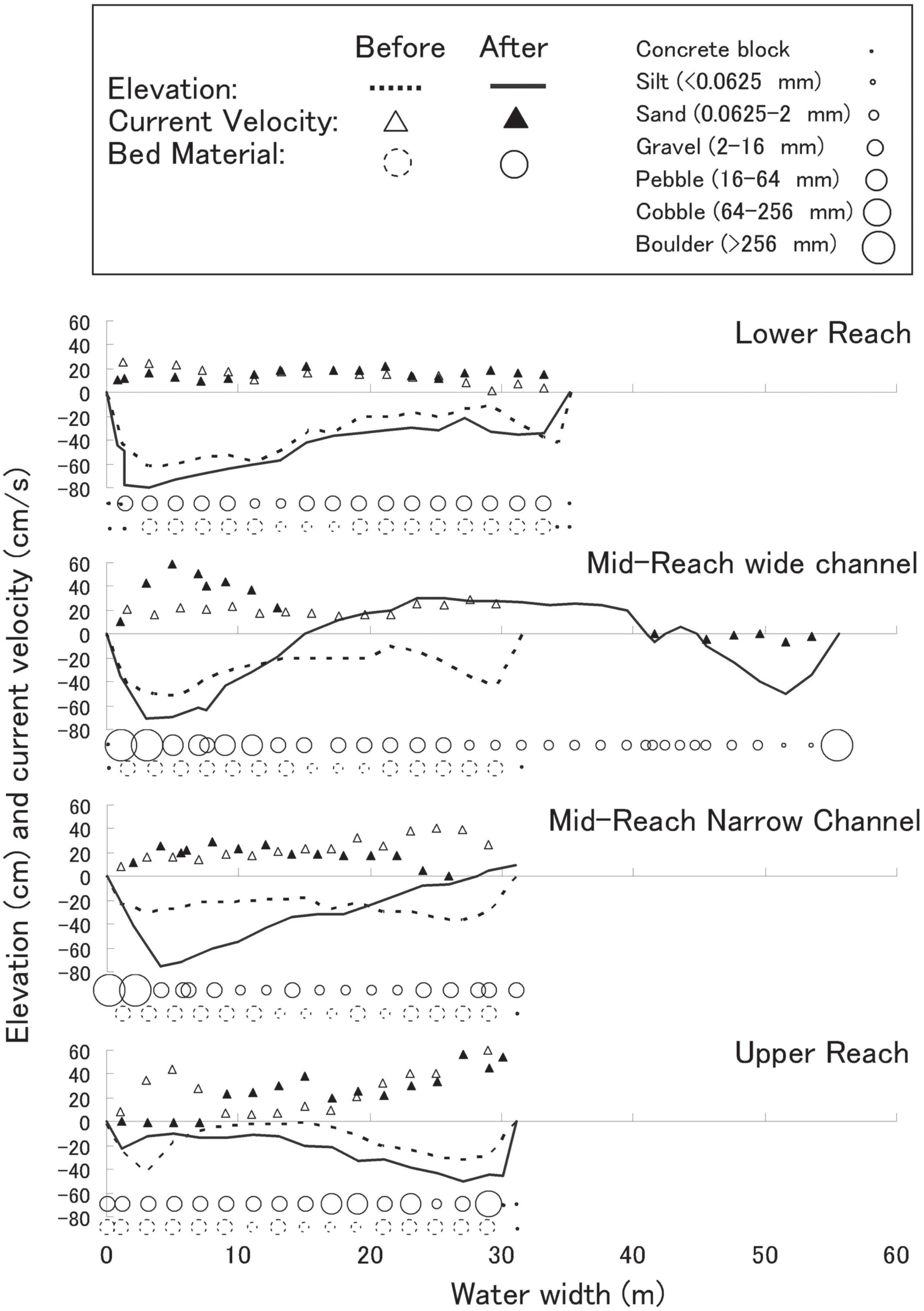

Fig. 5. Changes in water depth, current velocity, and bed materials before and after rehabilitation in the Lower Reach, Mid-Reach (Wide and Narrow Channels), and Upper Reach in RS. Open and solid triangles show current velocities before and after rehabilitation, and various sizes of circle demonstrate the diameter of the bed materials (see symbol legend).

3. Changes in fish assemblages at RS

In total, 1,602 fishes were captured during the survey, representing 20 taxa. Across all study reaches, the fish CPUE and taxon richness values increased after rehabilitation. CPUE increased from 143.0 to 394.8, taxon richness increased from 13 to 19. However, the Shannon diversity index didn't change from 1.72 to 1.71 (Table 3). Only *Squalidus* sp. was observed before river rehabilitation, while the following species were observed only after rehabilitation: *Plecoglossus altivelis*, *Cyprinus carpio*, *Lepomis macrochirus*, *Micropterus salmoides*, *Misgurnus anguillicaudatus*, *Silurus asotus* and *Tridentiger brevispi-*

Table 2. Fish capture numbers for each survey in autumn. Each number in the CS is the accumulated number of once-only captures by a cast-net and D-shaped net for the entire 500 m reach length. Each number in the RS is adjustable data from accumulated counts using once (not twice) captured individuals by the double-pass depletion method at 8 cells and the cast net method at all reaches. I-1 and I-2 were classified by cluster analysis I, using Morisita-Horn index calculated by the fish assemblage data in each of the 7 annual surveys conducted at the rehabilitation site (RS) and the control site (CS). The values of 1993－2008 indicate survey year, and “before” and “after” in parentheses show the rehabilitation stage of this study.

		CS: Control Site					RS: Rehabilitation Site	
		1993 (Before)	1997 (Before)	2001 (Before)	2006 (Before)	2008 (After)	2007 (Before)	2008 (After)
	Classified clusters	I-1						I-2
Water-column fish	*Hypomesus nipponensis*	0	0	4[e]	0	0	0	0
	Plecoglossus altivelis	1	0	0	0	1	0	1
	Zacco temminckii	0	0	0	2[e]	0	0	0
	Zacco platypus	20[d]	72[d]	230[d]	168[d]	128[d]	172[d]	114[d]
	Gnathopogon elongatus	1	1	7	1	0	40[d]	30[d]
	Pseudorasbora parva	6[d]	2	26[d]	4	16	7	15
	Squalidus sp.	0	12[d]	45[d]	7	22[d]	17	0
	Hemibarbus sp.	0	2	0	8	16	8	91[d]
	Cyprinus carpio	0	1	2	3	5	0	18
	Carassius sp.	3	7[d]	1	2	0	6	25
	Oryzias latipes	0	0	0	4	43[d]	2	30[d]
	Cyprinidae spp. (larvae)	0	0	0	0	0	0	9[e]
	Gambusia affinis	4	0	0	1	8	85[d]	318[d]
	Micropterus salmoides	0	0	0	5	0	0	5
	Lepomis macrochirus	0	0	4	4	0	0	35[d]
Demersal fish	*Anguilla japonica*	1	0	3	0	0	6	1
	Pseudogobio esocinus	5[d]	4	20	9[d]	18[d]	27[d]	22
	Misgurnus anguillicaudatus	0	0	0	1	1	0	8
	Cobitis biwae	0	0	0	1[e]	0	0	0
	Silurus asotus	0	1	0	3	0	0	0
	Rhinogobius sp.	18[d]	4	25	14[d]	5	5	19
	Tridentiger brevispinis	0	0	7	0	0	0	1
	Gymnogobius urotaenia	0	0	0	0	0	3	2
	Acanthogobius flavimanus	0	0	1[e]	0	0	0	0
	Total	59	106	375	237	263	378	744
	Number of taxa	9	10	13	17	11	12	18
	H′	1.71	1.22	1.42	1.33	1.68	1.67	1.97

Indicator species (d: dominant species: captured more than 80% for all counts in a survey, e: endemic species: not observed in other surveys), bold italics: exotic species, *H′*: Shannon-Wiener index

nis (Table 3). The dominant taxa (i.e., those that reached 80%) of captured fishes before rehabilitation were *Zacco platypus*, *Gambusia affinis*, *Gnathopogon elongates*, and *Pseudogobio esocinus*. After rehabilitation, dominant taxa included *Gambusia affinis*, *Zacco platypus*, *Hemibarbus* sp. and *Oryzias latipes*. In the 2 years of surveying, *Zacco platypus* and *Gambusia affinis* were dominant, comprising 65% more of all captured individuals. Of the dominant and endemic taxa after rehabilitation, *Gambusia affinis*, *Lepomis macrochirus*, and *Micropterus salmoides* represented exotic taxa termed as invasive alien species (IAS), with these 3 species comprising over 56.1% of all captured individuals. The endangered species *Oryzias latipes* (Ministry of the Environment Government of Japan 2003) was observed, and it became a dominant species only after rehabilitation.

Within the reaches of RS, a tremendous change was recorded for the mid-reach (before) and the mid-backwater (after) (Table 3). The CPUE increased from 104 to 832 and Shannon diversity decreased from 1.43 to 0.83. These

Table 3. Catch-per-unit-effort (CPUE) for each study reach before and after rehabilitation. CPUE was defined as species abundance per 2 cells and the 10 cast nets of each study reach. II-1,2 and 3 were classified by cluster analysis II, using Morisita-Horn index calculated by the CPUE data for each study reach.

		Before			After					
						Mid		Upper		
		Lower	Mid	Upper	Lower	Thalweg	Backwater	Groyne	Before Whole	After Whole
	Classified clusters			II-1			II-2	II-3		
Water-column fish	*Plecoglossus altivelis*							1^{e}		0.3^{e}
	Zacco platypus	20^{d}	55.0^{d}	97^{d}	157^{d}	122^{d}	3	7	57.3^{d}	72.3^{d}
	Gnathopogon elongatus		3.0	43^{d}		35^{d}	9		15.3^{d}	11.0
	Pseudorasbora parva		2.5	8	11	3	2	14	3.5	7.5
	Squalidus sp.	16^{d}	0.5						5.5^{e}	
	Hemibarbus sp.			8				92^{d}	2.7	23.0^{d}
	Cyprinus carpio						18^{e}			4.5^{e}
	Carassius sp.		1.0	6	1		24	1	2.3	6.5
	Oryzias latipes		1.0	4			2	64^{d}	1.7	16.5^{d}
	Cyprinidae spp. (larvae)			2	9	3	24		0.7	9.0
	Gambusia affinis	5	27.5^{d}	88^{d}	72^{d}		687^{d}	68^{d}	40.2^{d}	206.8^{d}
	Micropterus salmoides						5^{e}			1.3^{e}
	Lepomis macrochirus				1	2	39	12		13.5^{e}
Demersal fish	*Anguilla japonica*		2.0	2		2			1.3	0.5
	Pseudogobio esocinus	10^{d}	4.0	14	1	15	7	7	9.3^{d}	7.5
	Misgurnus anguillicaudatus				2		9	5		4.0^{e}
	Silurus asotus					1^{e}				0.3^{e}
	Rhinogobius sp.		5.5	1	5	30^{d}	3	1	2.2	9.8
	Tridentiger brevispinis				1^{e}					0.3^{e}
	Gymnogobius urotaenia		2.0	1		2			1.0	0.5
	Total	51	104.0	274	260	215	832	272	143.0	394.8
	Number of taxa	4	11	12	10	10	13	11	13	19
	H'	1.28	1.43	1.64	1.11	1.35	0.83	1.67	1.72	1.71

Indicator species (d: dominant species: captured more than 80% for all counts in a survey, e: endemic species: not observed in other surveys), bold italics: exotic species, H': Shannon-Wiener index

changes were influenced by population explosions of the exotic species *Gambusia affinis*. In contrast, no changes were observed for the mid-reach (before), the mid-thalweg (after), and the lower-reach before and after.

4. Assessment of indicator species in RS

The cluster analysis was used to classify the 7 reaches that were delineated before and after rehabilitation into 3 clusters (Clusters II-1,2,3). However, Cluster II-1 contained 3 reaches before rehabilitation, in addition to the mid-reach thalweg and lower-reach after rehabilitation. The other groups (Clusters II-2, II-3) contained just 1 reach each (Table 3). In Cluster II-1, *Zacco platypus* was the dominant taxon before and after rehabilitation. Endemic taxa of Cluster II-2 included *Cyprinus carpio* and *Micropterus salmoides*. The dominant taxa of Cluster II-2 only included *Gambusia affinis*. Furthermore, almost all *Carassius* sp., Cyprinidae spp. (larvae) and *Lepomis macrochirus* were observed in this backwater after rehabilitation. The exotic species *Micropterus salmoides* dominated the deeper part of the central river area, while *Gambusia affinis* and *Lepomis macrochirus* dominated the shore areas. In Cluster II-3, *Plecoglossus altivelis* represented endemic taxa, while *Oryzias latipes*, *Hemibarbus* sp. and *Gambusia affinis* represented dominant taxa (upper-reach after rehabilitation). In addition, and *Plecoglossus altivelis* and *Hemibarbus* sp. were distributed at the central area riffle, while *Oryzias latipes* and *Gambusia affinis* dominated the low-velocity area (U1) below the GRO area.

5. Statistical models for exotic and endangered fish species

A suitable model fit was obtained between the observed and predicted values for *Gambusia affinis* and *Lepomis macrochirus* (Table 4), which had a smaller residual deviance than the degree of freedom (Crawley 2005, Table 4). The full model for *Gambusia affinis* had the best fit. Wald test was used to determine the statistical significance of 6 explanatory variables. Of these variables, negative coefficients were obtained for bank slope, current velocity, cobble, and boulder. In contrast, positive coefficients were obtained for water depth and cover (Table 4). The selected explanatory variables for the best model of *Lepomis macrochirus* were water depth, current velocity, block, and cobble, while water depth had a positive correlation, and all other coefficients had a negative correlation. Both current velocity and block showed statistical significance. The model of *Oryzias latipes* did not converge under GLMM analysis (Table 4).

6. Execution and effects of adaptive management

Our findings suggest an increase in current velocity may function as a means of prevention for 2 exotic species (*Gambusia affinis* and *Lepomis macrochirus*). Therefore, we attempted to identify the limiting values of current velocity that would prevent the occurrence of both exotic species. After rehabilitation, cell MB1 exhibited a high abundance of both species; hence, we estimated that the individuals would be regulated by current velocities of 0 − 30 cm/sec on the basis of GLMM best-fit models (Fig. 6). These models were based on the conditions that were measured at the same site after rehabilitation. These estimations indicated that an increase in current velocity would clearly contribute to the exponential decline in individuals of these species. We showed that an increase in velocity of 5 cm/sec led to a 77% decline in *Gambusia affinis* (estimated number of individuals: 212.8/20 m^2), and an 89% decline in *Lepomis macrochirus* (estimated number of individuals: 3.0/20 m^2). A further increase in velocity to more than 15 cm/sec led to a 99% decline in *Gambusia affinis* (estimated number of individuals: 11.4/20 m^2), and an almost 100% decline in *Lepomis macrochirus* (estimated number of individuals: 0.04/20 m^2). Based on these results, in September 2010 the sediment deposit was excavated to restore the backwater at the closed upper part of the river, with area V of Riprap work being removed, which created a segment of flowing water at a velocity of 5.9 cm/sec in the backwater (Fig. 7). We monitored the effect on the 2 exotic species by using the same methods at the same cell positions, which were surveyed before and after rehabilitation during October 2010. A dramatic decline in both species was recorded (Fig. 8, *Gambusia*

Table 4. Results of the generalized linear mixed model (GLMM) for the individuals of dominant indicator fish species (using Poisson distribution; random effect: occasion).

		Exotic			Endangered
		Gambusia affinis	*Lepomis macrochirus*		*Oryzias latipes*
		Full & Best model	Full model	Best model	Error
Residual deviance		3.7	3.3	5.3	
Degrees of freedom		7	7	10	
AIC		21.72	21.29	17.28	
Coefficient	Intercept	− 5.82 *	− 0.03	0.59	
	Bank slope	− 0.08 **	− 0.18		
	Water depth	0.22 **	0.34	0.19	
	Current velocity	− 0.29 ***	− 0.34 **	− 0.44 **	
	Block	0.02	− 0.14	− 0.11 *	
	Cobble	− 0.09 ***	− 0.10	− 0.08	
	Boulder	− 1.30 ***	− 0.05		
	Cover	0.32 ***	− 0.02		

Wald test; *: $0.01<P<0.05$, **: $0.001<P<0.01$, ***: $P<0.001$

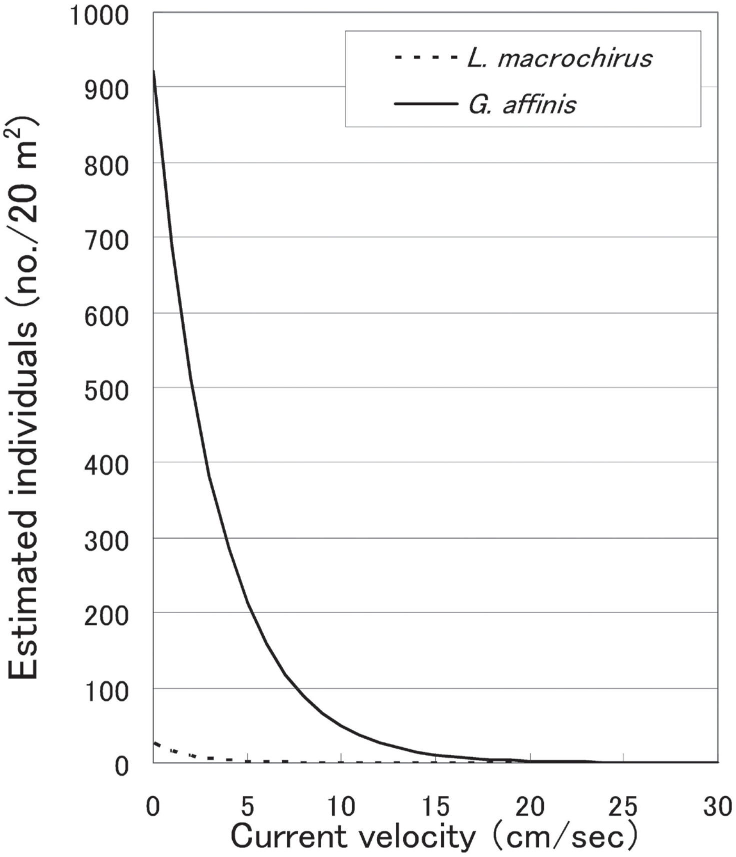

Fig. 6. Estimated individuals of Gambusia affinis (full line) and Lepomis macrochirus (dotted line) controlled by current velocity, for which the best models calculated by GLMM are used.

affinis: 175/20 m^2, which showed a 75% decline; *Lepomis macrochirus*: 3.0/20 m^2, which showed an 89% decline), with similar declines in the level of abundance to that indicated by the models at water flow velocities of 5 cm/sec.

Discussion

1. Positive effects of rehabilitation

Our findings support that the recorded change in aquatic organism assemblage at the RS occurred due to the implementation of rehabilitation techniques. In the RS, environmental changes were not detected in the lower-reach, where rehabilitation methods were not conducted. However, noticeable geomorphic and hydraulic changes were recorded at both the mid- and upper-reaches, which were subjected to rehabilitation that created variable water velocities. In the mid-reach, PRW generated high- and low-velocity areas, which appeared in the thalweg along the left shoreline and in the backwater at the right side of the river. In the upper-reach, a high-velocity riffle widened from the mid-channel to the right bank due to the use of the GRO technique, while a low-velocity area appeared downriver of the GRO along the left bank.

After rehabilitation, the diversity generated by changes in the physical environmental parameters increased the richness of aquatic taxa by 1.5 times and the fish CPUE throughout all reaches of the river by 2.8 times. Positive effects included new records for native species, such as *Plecoglossus altivelis*, *Cyprinus carpio*, *Misgurnus anguillicaudatus*, *Silurus asotus* and *Tridentiger brevispinis*. In addition, the endangered *Oryzias latipes* became a dominant species, despite recorded declines in recent years (Ministry of the Environment Government of Japan 2003). The PRW technique diversified river geomorphology and flood-plain habitat, which increased the amount of endemic vegetation in the floodplain (Rohde et al. 2005). In comparison, GRO has been used as a river rehabilitation technique since the 1960s, with a large number of recorded positive effects, such as the diversification

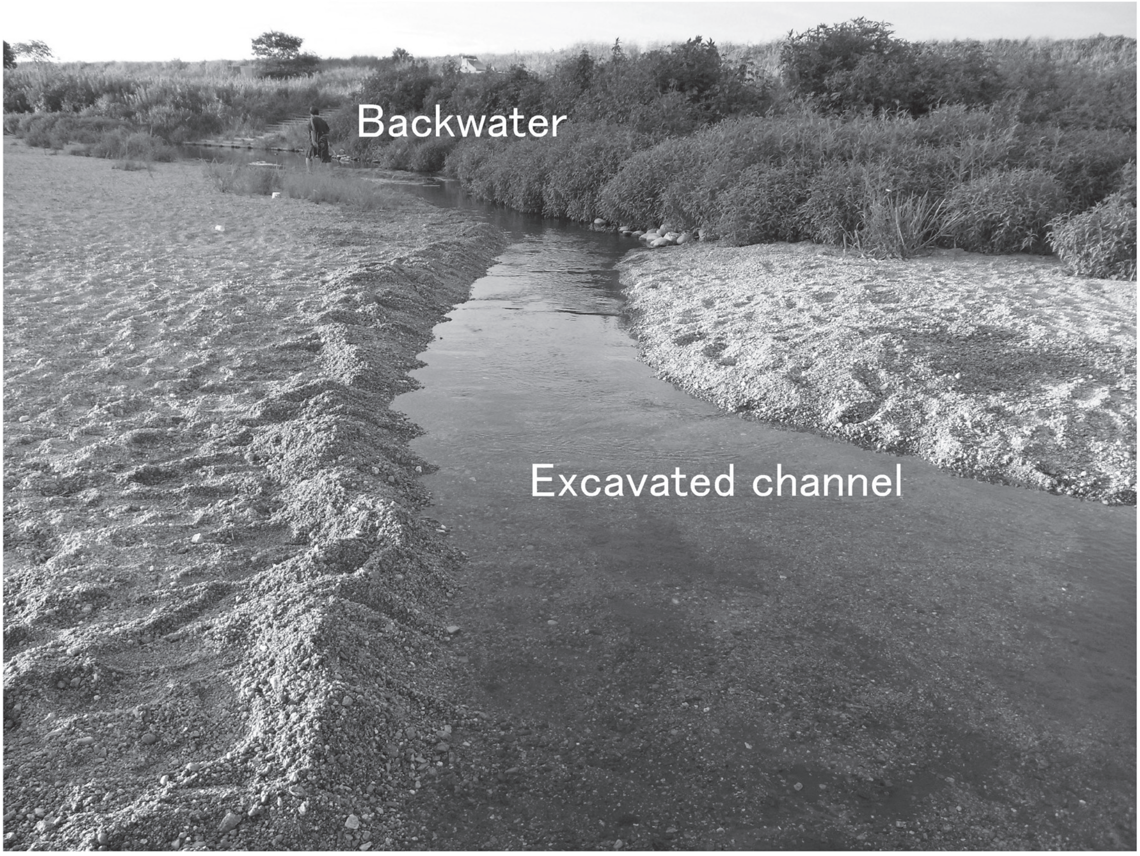

Fig. 7. Photograph of the excavated channel connecting the backwater to the main channel of the Yada River after restoration.

of river geomorphology, increased species numbers, and/or abundance of aquatic organisms (e.g., Saunders and Smith 1962; Hunt 1976). In our study, both rehabilitation methods caused various effects, which included the deposition of sediments during several water level fluctuations, gradual geomorphic changes after each flooding, and an increase in coarse substrates in the riffle and thalweg sections. Furthermore, these forms of diversification generated new habitats for the aquatic organisms, in contrast to the monotonic straight channel. Mizoguchi (2010) reported that flooding volumes of 70－150 m^3/sec led to the evolution of large sand bars and sediment deposition at the upper area of the Yada River, which is located 1.2 km from the upper-reach of our study area. In addition, during flood volumes of more than 250 m^3/sec channel bed materials changed widely, with the formation of a 10－20 cm thick layer. These results suggest that the rich sediment supplies of the Yada River watersheds provided material for significant changes to the channel morphology in a short period of time.

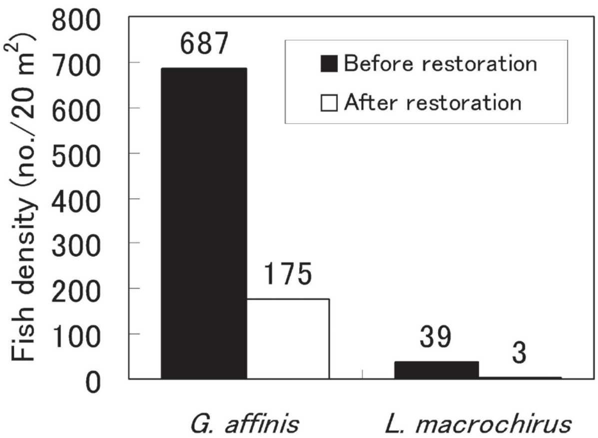

Fig. 8. Fish density changes for both Gambusia affinis and Lepomis macrochirus in the backwater cell (MB1) before and after restoration.

2. Rehabilitation led to backwater fish diversity declines

In the mid-reach (Backwater), species total abundance and richness increased after rehabilitation, while the diversity index declined significantly. Native *Cyprinus carpio*, *Carassius* sp. and Cyprinidae (larvae) preferentially inhabited low-velocity areas in the mid-reach (Backwater), along with exotic species *Gambusia affinis*, *Micropterus salmoides* and *Lepomis macrochirus* species. Hence, the particularly noticeable increase in exotic species contributed to the decline in organism diversity. *Lepomis macrochirus* and *Micropterus salmoides* have been shown to be dominant in areas of stagnant water in North America (Lambou 1959), with densities of *Lepomis macrochirus* being 20 times greater in backwaters compared to the main channel (Scott and Nielsen 2006). Previous research has shown that *Gambusia affinis* dominates downstream uniform reaches of low velocities, and cannot inhabit mid- or up-stream reaches where pool-riffle sequences are present (Sahara and Kouchi 1980). Hence, while the appearance of the low-velocity area at the mid-reach (Backwater) functioned as favorable habitat for native *Carassius* sp. and Cyprinidae (larvae), the stagnant water facilitated a large increase in the numbers of exotic species (particularly *Gambusia affinis*), which caused a loss of diversity in the backwater area.

3. Rehabilitation benefits for endangered Oryzias latipes

Oryzias latipes were selected as an indicator species in the upper-reach after rehabilitation. *Oryzias latipes* was observed on occasion at the negative velocity area located in the lower section of the GRO. These results indicate that the diversified geomorphological and physical environments generated by the GRO may have contributed to *Oryzias latipes* inhabiting the area. However, the location (U1) at which *Oryzias latipes* was observed resembled the low-velocity area in the backwater, which was dominated by *Gambusia affinis*. In contrast, the dominance of *Gambusia affinis* in U1 was inhibited. The GLMM for *Oryzias latipes* did not converge, which meant that the critical habitat factors for this species were not included in this study. While knowledge about the habitat preference of *Oryzias latipes* is limited in natural disturbed flowing rivers, *Oryzias latipes* and *Gambusia affinis* dominate certain rivers on Okinawa Island. In these rivers, *Oryzias latipes* selects the high-velocity upstream reaches, which are represented by pool-riffle sequences, while *Gambusia affinis* selects the low-velocity downstream reaches, which are represented by a monotonous environment. This indicates that the tolerance to velocity may differ between the 2 species, with *Oryzias latipes* being better adapted to tolerate stream turbulence and flooding events (Sahara and Kouchi 1980). An experimental study reported that the swimming ability of *Oryzias latipes* was more effective than that of *Gambusia affinis* (Nao et al. 2002). This information indicates that the tolerance ability against severe flooding is higher in *Oryzias latipes* than in *Gambusia affinis*. Our study showed that *Oryzias latipes* selected U1, which is an unstable area just downriver of the GRO, where the mid-flowing main channel was clearly joined. In comparison, *Gambusia affinis* was entrenched in a stable backwater, which was isolated from the main channel and was only impacted when severe flooding occurred. Therefore, the temporal flowing conditions at U1 were subject to constant change in response to water level fluctuations in the main channel, which is quite different to the stable water flow conditions at the isolated backwater. These results indicate that extreme stresses during flooding or constant fluctuations in water flow may contribute to the different observed distribution patterns of *Oryzias latipes* and *Gambusia affinis*. Conversely, severe interspecific competition between these 2 species has been reported (Ito et al. 2006), with an additional report of the extinction of *Oryzias latipes* in a sympatric experimental study (Sato and Okubo 1972). Therefore, it may be difficult to discern the cause of distribution of *Oryzias latipes* in this study. Subsequent studies are required to further clarify the mechanisms of coexistence between these 2 species, particularly with respect to cross-sectional flood pulse rates, turnover rates in the backwater, discharge-duration characteristics at high and low flood water levels, and interspecific competition.

4. Rehabilitation strategy to inhibit exotic fish species

Our results suggest that the restoration of just a small amount of running water is required to regulate *Lepomis macrochirus* and *Gambusia affinis*. For example, the creation of two-way channels by the excavation of the closed upper part of the backwater might prove a highly effective method to prevent the establishment of populations of these 2 exotic species. However, our results based on once monitoring just after the restoration, it may change with the passage of time. In Turner et al. (2003), long-term monitoring is an essential to clarify dispersal of exotic species, and Søndergaard et al. (2008) assessed lake restoration by fish removal with monitoring over 10 years. So we have to carry out continual monitoring.

In this study, we confirmed the effects of PRW on aquatic communities, which indicated a combination of both increased numbers of native aquatic species and population explosions of exotic species. Alterations of native aquatic ecosystems leading to the introduction of exotic species have been reported throughout the world (Courtenay and Stauffer 1984; Gido and Brown 1999; García-Berthou et al. 2005). Therefore, by creating uninhabitable environments, river rehabilitation methods that are effective in the exclusion of exotic species and inclusion of native species, should be preferentially applied. In addition, new guidelines have been provided for river improvement in Japan, with the inclusion of "river technology criteria," which were established by the Japanese government in August 2010 (Ministry of Land, Infrastructure, Transport, and Tourism 2010[b]). Within this framework, river widening is listed as one of the fundamental methods to restrict flow volume, and hence avoid flooding, which might result in backwaters having both positive and negative effects on river ecosystems. Thus, river widening projects would deliberately create backwaters, which if managed incorrectly, could provide a stronghold for exotic species and the destruction of native ecosystems for all rivers throughout Japan. Therefore, it is essential to monitor the strategies of native and exotic species before and after rehabilitation to ensure appropriate management actions are taken.

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Appendix

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都市河川である矢田川におけるリハビリテーションが在来魚および外来魚の生息状況に与える影響の評価

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摘　要

本研究では，愛知県の都市域を流れる矢田川において，（1）部分的な河道拡幅による低流速域の創出および，（2）水制工の造成による高流速域の創出といった2つの工法により，リハビリテーションを実施した．これらのリハビリテーションの結果，河道地形や河床材料，流速の変化が2つの工法区間ともに認められ，それに伴い，魚類の個体数や種数が増加した．正の効果として，在来魚種の増加や絶滅危惧種であるミナミメダカの個体数の増加がみられたが，その一方で，ワンド域では，在来魚類の多様性を低下させるカダヤシの個体数の急増にみられるように，外来魚種の個体数の増加といった負の効果がみとめられた．一般化線形混合モデルによる解析の結果，ワンド域において流速を5 cm/s以上にすることにより，カダヤシで77%，ブルーギルで89%の個体数の減少が予測された．この予測は，現地における追加の施工（掘削による流水の確保）により実証された．以上より，本研究成果は，外来魚の定着を抑制するためには，ワンド内に流水域を創出することが有効であることを示唆するものである．

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