Paper:

Effectiveness of Flexible Dam Operation and Sediment Replenishment at Managawa Dam, Japan

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A field demonstration project on flexible dam operation at the Managawa dam in the Kuzuryu River Basin has been implemented since 2000. The goal is to restore flow and sediment regimes in the Managawa River, which flows along the Ono-city and is located below the dam. Flexible dam operation stores inflow discharge into a reservoir, which generally uses part of the flood control capacity and appropriately discharges the stored water to the river, also known as the "flood pulse," for restoring dynamic fluvial systems and the resulting ecological processes. In addition, other options have been carried out in combination with flexible dam operation, for example, sediment replenishment since 2003 and channel rehabilitation since 2007. This article reveals the positive impacts and effectiveness of flexible dam operation, sediment replenishment, and channel rehabilitation, and discusses challenges and future prospects toward translating the field demonstration project into dam management on the ground level. First, we classified reach types to identify the impact of various management options, e.g., flexible dam operation, sediment replenishment, and channel rehabilitation. These management options can influence respected reaches. We conducted a macro-scale analysis to understand the relationship between the aforementioned management options and dynamic fluvial systems, addressing changes in gravel riverbed, vegetation, and habitat types (riffles and pools). Second, a micro-scale analysis was conducted to understand the relationship between the management option and changes in attached algae to sediment and macro-invertebrates, etc. The results show the effectiveness of the middle-scale flood pulse to restore dynamic fluvial systems, increase habitat diversity, and sustain ecological processes. Furthermore, we discussed the impacts of such options on the flow and sediment regimes in Managawa River and revealed that flexible dam operation reduces the occurrence of low flow and midscale floods. It was also revealed methods such as sediment replenishment and channel rehabilitation play an important role in increasing the effectiveness of the middle-scale flood pulse and restoring dynamic fluvial systems, even though sediment replenishment is not sufficient to restore sediment regimes (i.e., bring then back to pre-dam conditions).

Keywords: flexible dam operation, flood pulse, sediment replenishment, channel rehabilitation, flow and sediment regime

1. Introduction

1.1. Managawa Dam

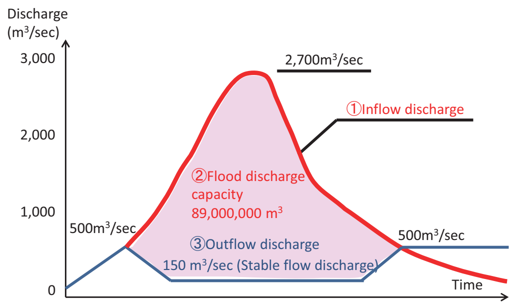
The Managawa River is part of the Kuzuryu River Basin located in the Reihoku district in Fukui Prefecture, Japan (**Fig. 1**). This basin has low temperature during the winter season due to the northwest monsoon, often leading to snowfall. It also has heavy annual precipitation of 2,000 to 2,200 mm, particularly 2,600 to 3,000 mm in the mountainous area within the basin [1].

The consecutive occurrence of heavy rains in September 1965 such as Typhoon No.23 on 10 September, Okuetsu heavy rain on 14 September, and Typhoon No.24 on 17 September, caused flood disasters far exceeding the design discharge for flood management in the Kuzuryu River Basin in Ono city, Katsuyama city, Old-Nishitani district, Old-Izumi district, etc. In particular, the Old-Nishitani district suffered devastating consequences. The Okuetsu heavy rain has led to overflow of the Sasogawa dam, a levee breach in Managawa River and its tributaries, floodplain inundation, and landslides at the mountainous area [2].

These flood disasters highlight the need to thoroughly review the flood management plan for the Kuzuryu River Basin. The Kinki Regional Development Bureau (KRDB), Ministry of Construction in Japan amended the flood management plan in June 1968. The Okuetsu heavy rain was considered one of the principal events determining design discharge, and a set of dams including Managawa Dam were planned for construction [1]. Managawa Dam was constructed and completed in 1979 [2].

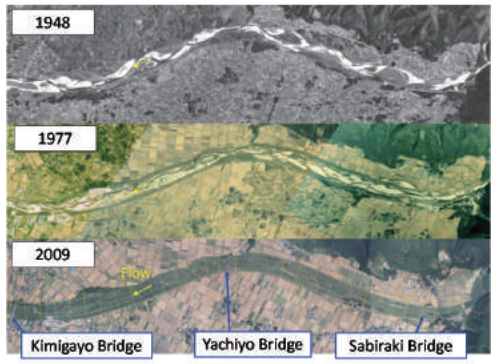
Another challenge to building counter-measures

Fig. 1. Location of Managawa dam.



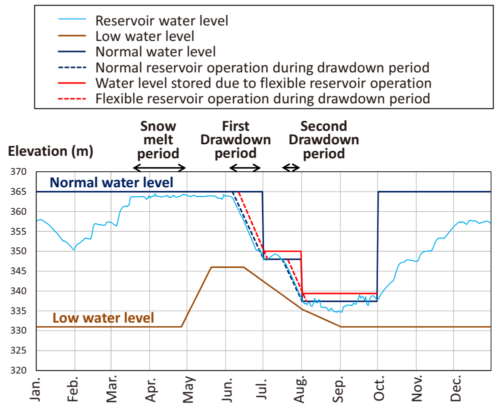
Source: Ministry of Land Infrastructure, Transport and Tourism, Japan, edited by the author.

Fig. 2. Operation of Managawa Dam.



Source: Ministry of Land Infrastructure, Transport and Tourism, Japan, edited by the author.

Fig. 3. Morphological changes of the downstream Managawa River before and after construction of Managawa Dam in 1979.



Source: Committee on flexible dam operation of the Managawa dam (2016)

Fig. 4. Schematic diagram of flexible dam operation at Managawa dam.

against the Okuetsu heavy rains in 1965 was the development of a sediment management plan. The upper area of Managawa River Basin was devastated by landslides due to a series of heavy rains, and addressing the need for sabo works as part of an overall sediment management plan. The construction of dams and sabo works was jointly conducted not only for basic surveys but also for developing these plans [2].

1.2. Reservoir Operation

Managawa Dam is a multi-purposed dam constructed for purposes of flood control, hydroelectric power generation, and unspecified use, and it has the total gross reservoir capacity of 115 million m^3 and can convey 500 m^3/s flood discharge without inundation overflowing onto the floodplains of the downstream Managawa River [1].

Figure 2 shows operation of Managawa Dam, which has two operation systems for flooding period (i.e., drawdown periods) and non-flood period. For flood control during the flood period, when inflow discharge is smaller than 500 m^3/s, inflow and outflow discharge are kept equal. When inflow discharge rises larger than 500 m^3/s, outflow discharge is operated with stable discharge of 150 m^3/s until inflow discharge is reduced by 500 m^3/s. Flood discharge capacity for the second drawdown period is kept at 89 million m^3 [3]. On the other hand, low flow discharge during dam operation is 2.67 m^3/s.

1.3. Downstream Impacts of Managawa Dam

Figure 3 shows aerial photos taken in 1948, 1977, and 2009, depicting morphological changes in the downstream Managawa River before and after construction of Managawa Dam in 1979. Changes in flow and sediment regimes could result in fixing of river channels, vegetation encroachment from gravel riverbed to riparian forests, deposition of fine sediment and reduced seasonal succession of attached algae, thus deteriorating the river environment.

1.4. Objectives

A field demonstration project on flexible dam operation has been implemented at Managawa Dam. Flexible dam operation stores inflow discharge into a reservoir, which generally uses part of the flood control capacity and appropriately discharges stored water to the river, also known as the "flood pulse" [4]. This restores dynamic fluvial systems and the resulting ecological processes. **Fig. 4** shows a schematic diagram of flexible dam operation. In addition, other options have been explored in combination with flexible dam operation, for example, sediment

Table 1. Records of managed flows by flexible dam operation at the Managawa dam.

Source: Committee on flexible dam operation of the Managawa dam (2017), edited by the author.

Peak flow discharge		**Flexible reservoir operation**		**Sediment replenishment**				**Channel rehabilitation**	
Month/Year	Discharge (m^3/s)	Type of operation	Period	Month	Amount (m^3)	Sediment type	Source	Type of restoration	Place
Aug 2003	185	Natural flood	Flood period						
Sep 2003	25	Small-scale flood Pulse	Flood period						
Jun 2004	373	Natural flood	Flood period						
Nov 2004	45	Small-scale flood Pulse	Autumn	Nov 2003	220	Upstream reservoir sediment	Left bank at 8.0 k-point		
Aug 2005	25	Small-scale flood Pulse	Flood period						
Sep 2005	164	Natural flood	Flood period						
Dec 2005	40	Small-scale flood Pulse	Winter	Dec 2004	200	Dredged gravel riverbed	Left bank at 5.2 k-point		
Jul 2006	234	Natural flood	Flood period						
Nov 2006	45	Small-scale flood Pulse	Autumn	Nov 2005	200	Upstream reservoir sediment	Left bank at 5.4 k-point		
Jul 2007	137	Natural flood	Flood period					- Secondary channel in 2007	- Left bank at 5.6 k-point
Nov 2007	45	Small-scale flood Pulse	Autumn	Nov 2006	330 +650	Upstream reservoir sediment and dredged gravel riverbed	Left bank at 5.6 k-point		
Sep 2008	33	Natural flood	Flood period						
Nov 2008	45	Small-scale flood Pulse	Autumn	Nov 2007	100	Dredged gravel riverbed	Left bank at 5.6 k-point		
Jul 2009	16	Natural flood	Flood period					- Secondary channel in 2008 - Removal of ripatian vegetation in 2008 - Back water in 2009	- Left bank at 7.0 to 7.4 k-point - Left bank at 7.6 to 7.8 k-point - Left bank at 8.3 k-point
Apr 2010	70	Small-scale flood Pulse	Spring	2009	140	Dredged gravel riverbed	Left bank at 8.8 k-point	- Back water in 2010	- Left bank at 8.8 k-point
Jul 2010	100	Natural flood	Flood period						
Apr 2011	136	Middle-scale flood pluse (natural flood)	Snow melt period	Dec 2010	280	Upstream reservoir sediment	Left bank at 9.0 k-point	- Rehabilitation of riparian zone in 2011	- Left bank at 7.5 to 10.1 k-point and Right bank at 10.0 to 10.1 k-point
Sep 2011	365	Natural flood	Flood period						
Apr 2012	50	Middle-scale flood pluse (natural flood)	Snow melt period	Nov 2011	360	Upstream reservoir sediment	Left bank at 9.0 k-point	- Rehabilitation of riparian zone in 2012	- Right bank at 8.4 to 8.7 k-point and left bank at 8.7 to 8.8 k-point
Sep 2012	230	Natural flood	Flood period						
Apr 2013	30	Managed middle flood (natural flood)	Snow melt period	Dec 2012	320	Upstream reservoir sediment	Left bank at 9.0 k-point	- Rehabilitation of riparian zone in 2013	- Right bank at 8.7 to 8.8 k-point
Jul 2013	213	Natural flood	Flood period						
Sep 2013	319	Natural flood	Flood period						
Mar 2014	132	Middle-scale flood pluse (natural flood)	Snow melt period					- Rehabilitation of riparian zone in 2013	- Left bank at 10.2 to 10.3 k-point
Aug 2014	407	Natural flood	Flood period						
Apr 2015	198	Middle-scale flood pluse	Snow melt period					- Rehabilitation of riparian zone in 2015	- Right bank at 6.9 k-point and 9.5 to 9.7 k-point, and left bank at 10.1 to 10.2 k-point
Sep 2016	109	Natural flood	Flood period						

replenishment since 2003 and channel rehabilitation since 2007.

This article reveals positive impacts and effectiveness of flexible dam operation, sediment replenishment, and channels rehabilitation, and discusses challenges and future prospective toward translating the field demonstration project into dam management on the ground level.

2. Flexible Operation of Managawa Dam for Creating Managed Flow

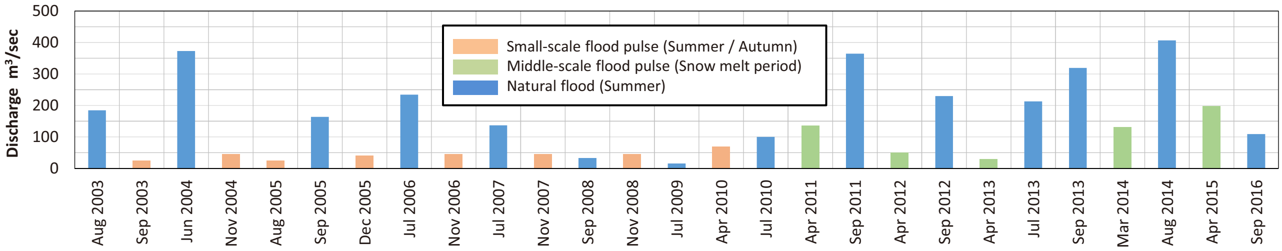
2.1. Outline of the Flexible Reservoir Operation

Managed flows from Managawa dam have been carried out as a field demonstration project. The small-scale flood pulse has been flushed with approximately 45 m^3/s discharge during a flood period (summer) and autumn since 2003 to 2010. The mid-scale flood pulse was discharged at 200 m^3/s for 6 hours during a snow melt period since 2011 in an effort to restore dynamic fluvial systems and the resulting ecological processes in Managawa River [5].

Table 1 summarizes records of managed flows at Managawa dam, and **Fig. 5** shows discharge of annual maximum floods and relevant floods.

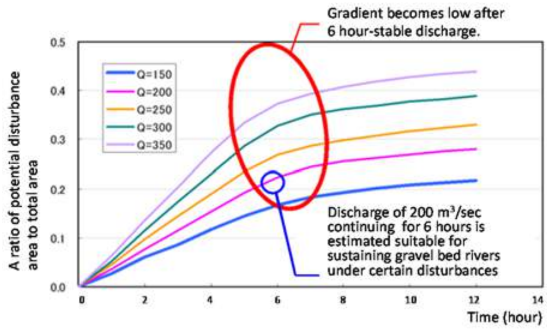
The mid-scale flood pulse for 6 h was adopted, based on an estimation using a 2D flow and riverbed variation model. Both non-dimensional shear stress was estimated to be larger than 0.05, and its duration was estimated to be longer than 3 h as a condition of disturbance regimes required for sustaining the gravel riverbed in Managawa River based on the field surveys. Given stable discharge at 150, 200, 250, 300, and 350 m^3/s for 12 h, riverbed variation was calculated and areas that could satisfy the condition were analyzed. **Fig. 6** shows suitable flow regimes to sustain gravel riverbeds in Managawa River. The result shows that the gradient becomes low after 6 h-of stable discharge in each case. 200 m^3/s discharge satisfies 20% of the gravel riverbed area (i.e., a reasonable spatial distribution for the gravel riverbed in Managawa River) [6].

Flexible dam operation has been carried out in consultation and collaboration with the Committee on Flexible Dam Operation of the Managawa Dam. The committee



Source: Committee on flexible dam operation of the Managawa dam (2017)

Fig. 5. Annual maximum flood and relevant flood records. It noted that colors used in this figure correspond to those in **Table 1**.



Source: Committee on flexible dam operation of the Managawa dam (2017)

Fig. 6. Suitable flow regimes to sustain gravel bed rivers in Managawa River.

was established in 2000 and consists of various stakeholders such as Ministry of Land, Infrastructure, Transport and Tourism in Japan, Fukui prefecture (managing Managawa River), Ono-city, Hokuriku Electric Power Company (cooperating Managawa Dam), Kansai Electric Power Company, Inc., Fishery Corporation, and academic experts.

2.2. Sediment Replenishment

In addition to flexible operation of Managawa Dam, other options for restoring the downstream environment have been implemented such as sediment replenishment and channel rehabilitation. **Table 2** shows classification of reaches and influencing options such as managed flows by flexible dam operation, sediment replenishment, and channel rehabilitation in Managawa River. **Fig. 7** also shows a schematic diagram which indicates where such options have been carried out.

Sediment replenishment has been carried out at the upstream site of the Kimigayo Bridge on the left bank around 5.2 to 5.6 k-point (i.e., distance from the confluence of Managawa and Kuzuryu River) from 2003 to 2007. The sediment replenishment location was moved upstream of the Yachiyo Bridge on the left bank around 8.8 to 9.0 k-point and it has been carried out since 2010.

Sediment used for the replenishment contained gravel dredged from Managawa riverbed, but also the reservoir-deposited sediment of Managawa Dam, which were composed of sediment particles similar to the Managawa riverbed [5].

2.3. Channel Rehabilitation

Channel rehabilitation has been carried out since 2007 (see **Table 2** and **Fig. 7**). Secondary channels have been restored at the left bank of 5.6 k-point in 2007 and at the left bank of 7.0 to 7.4 k-point in 2008, These relevant channel rehabilitation options positively influence the dynamic state of the riverbed. Other options for channel rehabilitation include removal of riparian vegetation and riparian zone dredging [5].

3. Effectiveness of Managed Flows, Sediment Replenishment, and Channel Rehabilitation

3.1. Methodology

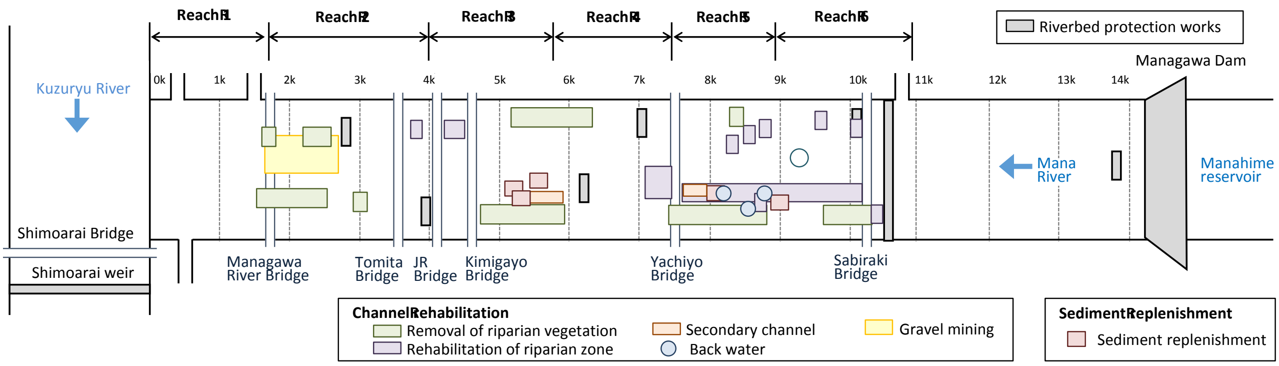
It is important to quantitatively assess the effectiveness and challenges of managed flows by flexible dam operation, but also sediment replenishment and channel rehabilitation. However, numerous options have been carried out, making it difficult to quantitatively assess the consequences of different options. Therefore, reaches and options are identified and classified as shown in **Table 2** and **Fig. 7**. Managed flows by flexible dam operation can be classified as influential to all reaches, since they can receive almost the same increased flood pulse (discharge). Sediment replenishment can be classified as influential to limited reaches where sediment is replenished and less influential on downstream reaches, since replenished sediment particles are gravels and quantities are small as compared to those in pristine conditions before the dam construction. It is difficult to transport gravel over long distances, and gravel is less influential further downstream within a short time period. Channel rehabilitation can be classified as influential only on reaches where the options are carried out, since the amount of sediment to be transported further downstream is limited compared to an option that can trigger restoration of dynamic fluvial systems. Therefore, we address in particular Reach 3 and Reach 5, where disturbances are high and influential for restoring dynamic fluvial systems by integration of managed flows, sediment replenishment, and channel rehabilitation. Therefore, macro- and micro-scale analyses were conducted in order to evaluate the effectiveness of various options.

In the macro-scale analysis, changes in gravel bars (without vegetation), vegetation, and habitats such as rif-

Table 2. Classification of reaches and influencing options such as managed flows, sediment replenishment, and channel rehabilitation in Managawa River.

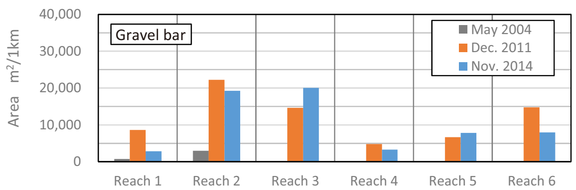
Source: Committee on flexible dam operation of the Managawa dam (2017), edited by the author.

Reach No.	Reach 1	Reach 2	Reach 3	Reach 4	Reach 5	Reach 6
Reach name	Backwater reach from the Kuzuryu River	Gravel riverbed reach	Downstream reach from the sediment replenishment sites in 2004-2007	Downstream reach from the Yachiyo Bridge	Downstream reach from the sediment replenishment site in 2009-2012	Upstream reach
Location	0.0 to 1.6 k-point	1.6 to 4.0 k-points	4.0 to 5.8 k-point	5.8 to 7.4 k-points	7.4k to 9.0 k-point	9.0 to 11.0 k-point
Managed flows by flexible dam operation	Influenced	Influenced	Influenced	Influenced	Influenced	Influenced
Sediment replenishment	Less influenced	Less influenced	Influenced	Less influenced	Influenced	Not influenced
Channel rehabilitation	Not influenced	Directly influenced by removal of riparian vegetation and gravel mining	Directly influenced by channel rehabilitation	Not influenced	Directly influenced by secondary channel	Influenced by channel rehabilitation



Source: Committee on flexible dam operation of the Managawa dam (2017), edited by the author.

Fig. 7. Schematic diagram on managed flows, sediment replenishment, and channel rehabilitation in Managawa River.



Source: Committee on flexible dam operation of the Managawa dam (2017), edited by the author.

Fig. 8. Change in gravel-bar area.

fles and pools were identified, the causes of which were analyzed addressing managed flows, sediment replenishment, and channel rehabilitation. As for the micro-scale analysis, change in attached algae and benthic macroinvertebrates was assessed. Furthermore, annual hydrographs on inflow and outflow discharges are used to analyze the trend and roles of all managed flows in terms of discharge magnitude and duration in Managwa River.

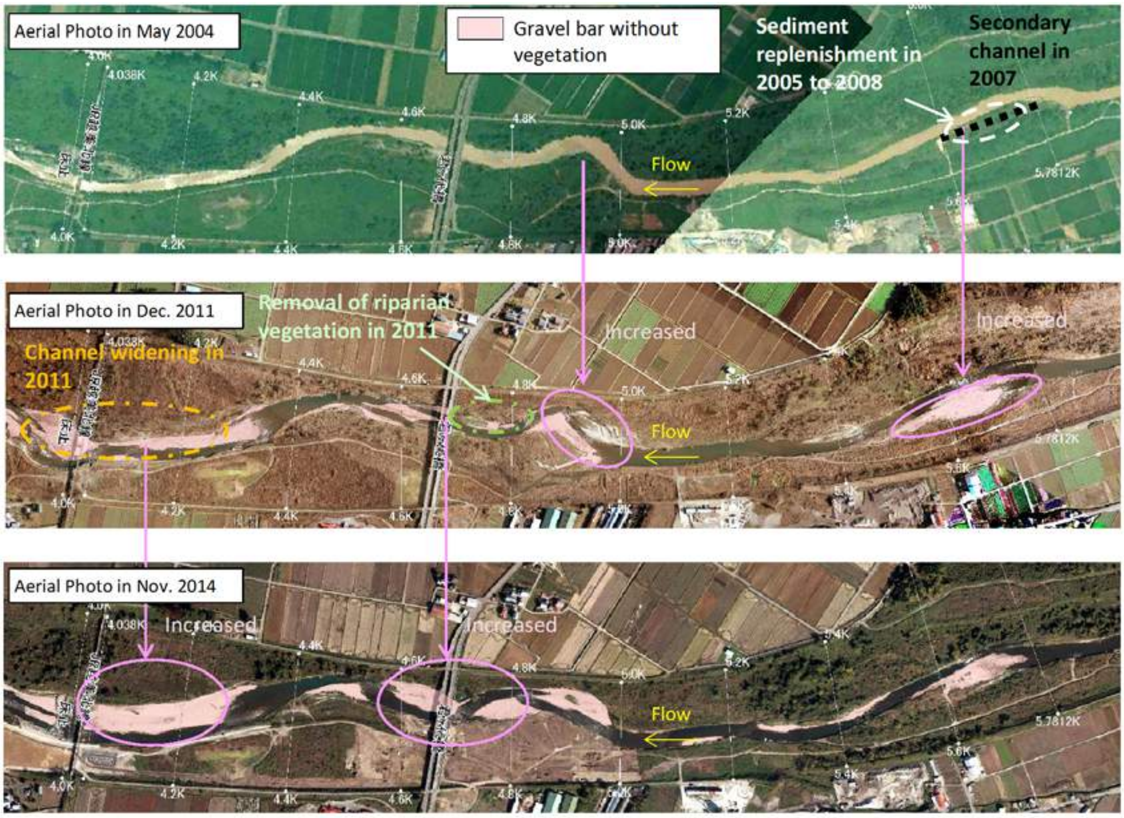
3.2. Macro-Scale Analysis

3.2.1. Gravel River Bed

Aerial photos taken in May 2004, Dec. 2011, and May 2014 were used to extract and calculate the area of gravel bars. As shown in **Fig. 8**, the result shows that the gravel-bar area increased at Reach 2, 3, 5, and 6. **Fig. 9** shows an example where Reach 3 is used to analyze the relationship between changes in gravel bar area and a combination of options in Managawa River. Where a secondary channel was restored in 2007, the gravel-bar area increased from 2004 to 2011 and remained constant from 2011 to 2014. At the downstream site of the secondary channel, the gravel-bar area increased at 4.8 to 5.0 k-point from 2004 to 2011. The area also increased at 4.0 to 4.2 k-point and 4.6 to 4.8 k-point from 2011 to 2014, where channel widening and removal of riparian vegetation was carried out in 2011. These results show that: channel rehabilitation played a role in inducing disturbances on the riverbed, and sediment replenishment supplied sediment for modifying fixed channel shapes, in combination with floods and managed flows, thereby creating and maintaining gravel bars at these reaches [5–7].

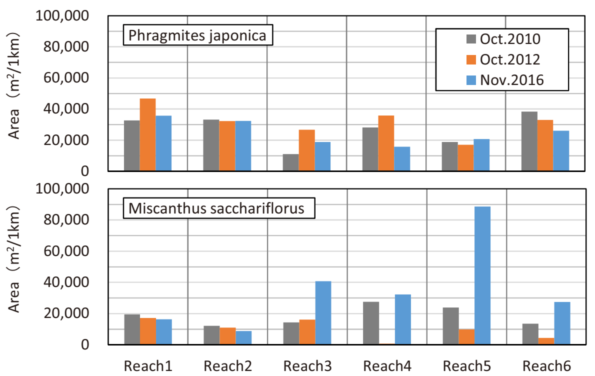
3.2.2. Vegetation Encroachment

Vegetation surveys were conducted in Managawa River in 2010, 2012, and 2016, where different vegetation area changes were analyzed. As shown in **Fig. 10**, at Reach 6, the area occupied by *Phragmites japonica* decreased in the riparian zone, while *Miscanthus saccariflorus* increased on higher ground. Channels at Reach 6 were narrowly confined and fixed, and channel rehabilitation was carried out in a limited area, thereby making it difficult for river channels to migrate within rivers and leading to homogeneous riverbed features [5].



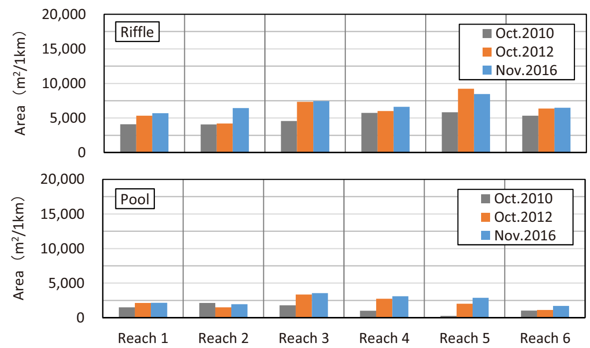
Source: Hyodo et al. (2017).

Fig. 9. An example of Reach 3 for analyzing relationships between change in gravel bar areas and a combination of options.



Source: Committee on flexible dam operation of the Managawa dam (2017), edited by the author.

Fig. 10. Change in the area occupied by Phragmites japonica and Miscanthus sacchariflorus.



Source: Committee on flexible dam operation of the Managawa dam (2017), edited by the author.

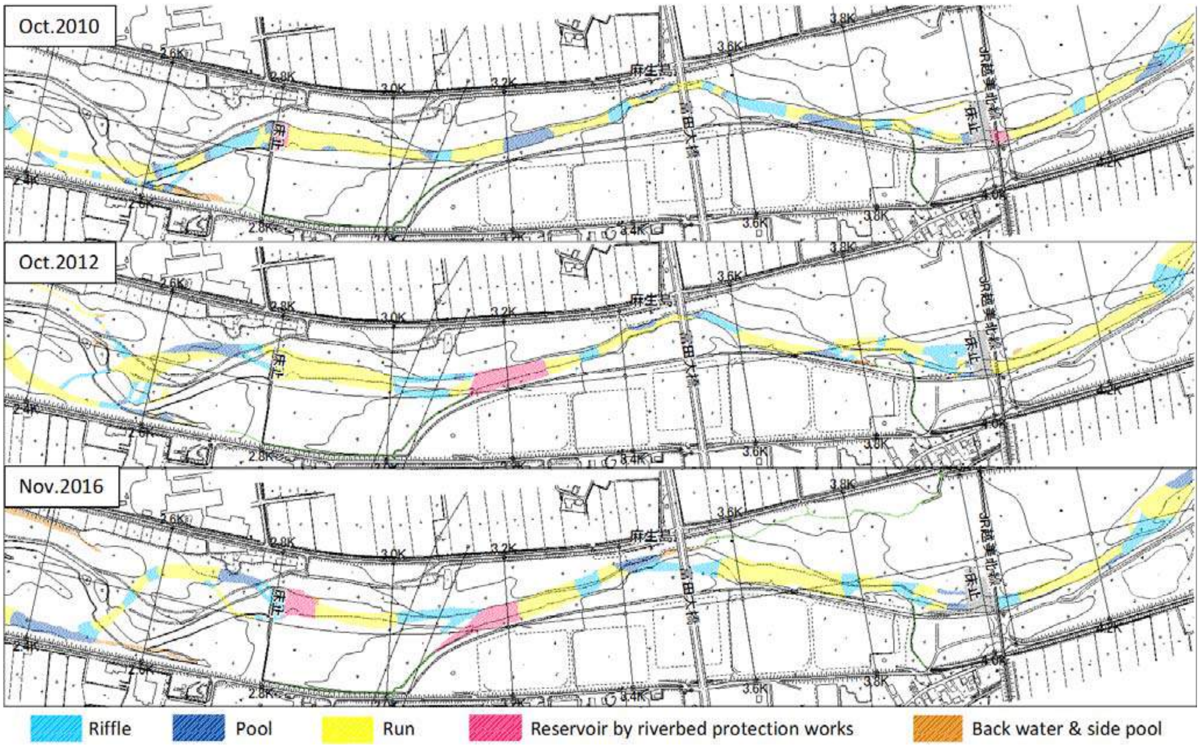
Fig. 11. Change in area of riffles and pools.

3.2.3. Habitat Diversity and Heterogeneity

Habitat surveys were conducted in 2010, 2012, and 2016, based on which, in-habitat area changes were analyzed (e.g., riffles and pools). As shown in **Fig. 11**, riffle and pool areas increased at nearly all reaches. As far as looking at habitat maps of Reach 2 (see **Fig. 12**), the amount of habitat does not seem to be reduced, assuming that heterogeneous habitats were created. In particular, riffles and pools increased at Reach 3 and Reach 5, where secondary channels were restored in 2007 and 2008 respectively. These results may arise due to channel rehabilitation and sediment replenishment in combination with managed flows. These measures may have positive effects in restoring dynamic fluvial systems [5].

3.3. Micro-Scale Analysis

Continuous monitoring was conducted at secondary channel sites in 2007 at the left bank of 5.8 k-point, riparian zone rehabilitation sites from 2011 to 2015 at the left bank of 8.8 k-point, and gravel bars at the right bank of 2.4 k-point. A micro-scale analysis was conducted at these three sites. The influence of managed flows is nearly the



Source: Committee on flexible dam operation of the Managawa dam (2016), edited by the author.

Fig. 12. An example of Reach 2 for analyzing relationships between change in habitat area and a combination of options.

same for each site. Each site was influenced by channel rehabilitation such as the secondary channel and riparian zone rehabilitation. Even though gravel bars at the 2.4 k-point were newly created by Typhoon No. 15 in 2011, removal of riparian vegetation was carried out [5].

3.3.1. Benthic Macro-Invertebrates

Indicator species were selected based on "life type" and favored riverbed material. We use life type to analyze benthic macro-invertebrates, which was originally categorized by Merrit and Cummins in 1996 [8] and adopted by Takemon in 2005 to Japanese plants [9].

Trichoptera with the net-spinners life type was selected, since they have increased when the riverbed is unable to move due to fewer disturbances. The net-spinners index was used, which is a value of wet weight of net-spinners divided by that of all sampled species and represents the level of disturbance in the riverbed (i.e., when the value is high, the riverbed is immobile).

Trichoptera with the case-bearers life type was also selected, since they favor growing in sand and gravel, of which *Glossosoma* sp. is addressed. Most Trichoptera falling under case-bearers found through continued surveys are those that favor growing in sand rather than gravel on the riverbed.

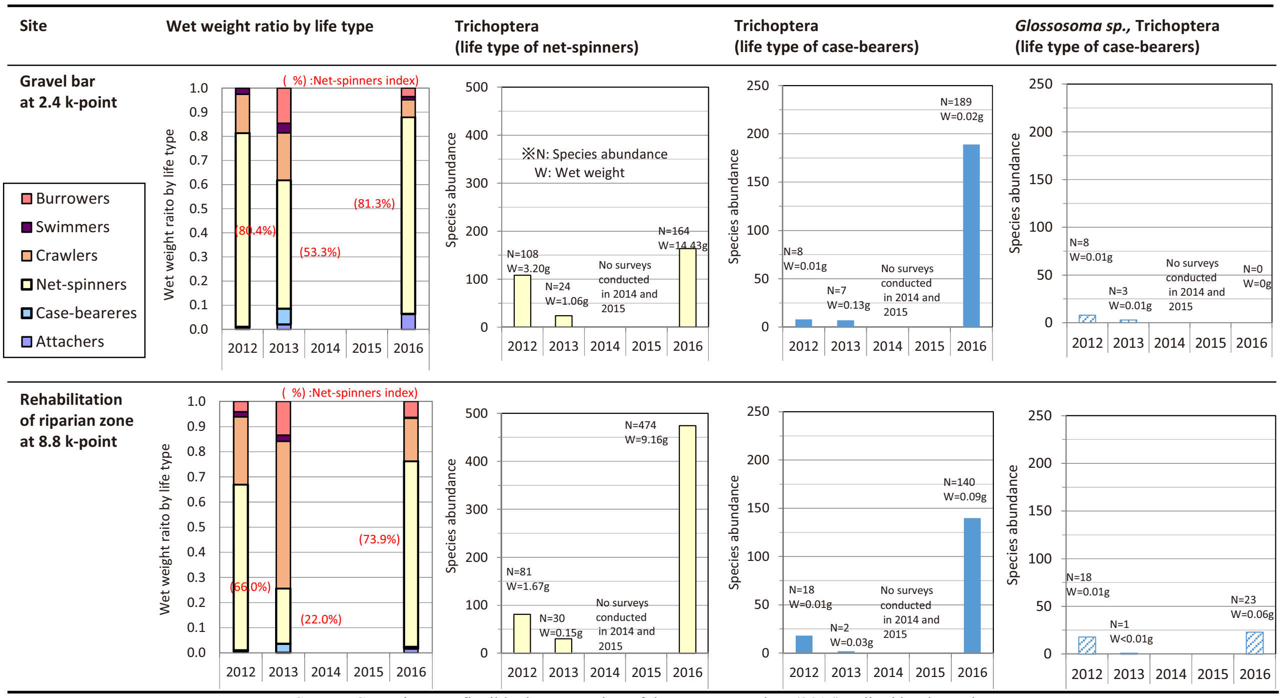
Figure 13 shows results from continued surveys on benthic macro-invertebrates at the 2.4 k-point gravel bar and riparian zone rehabilitation at 8.8 k-point. Several flood events with more than 200 m^3/s discharge occurred just before the surveys conducted in 2012 and 2013. On the other hand, a flood event (larger than 200 m^3/s) only occurred one and a half year before the survey was conducted in 2006.

Species abundance of Trichoptera (life type of net-spinners) did not increase in 2012 and 2013, but did increase in 2017 when a flood event larger than 200 m^3/s has been absent for one and a half years. The abundance of Trichoptera and *Glossosoma* sp. (case-bearers life type) increased in 2017 as well. From a micro-scale perspective, both sites experienced fewer disturbances due to absence of floods in 2017, resulting in an immobile riverbed. This result explains how flood events, particularly those larger than 200 m^3/s play an important role in forming dynamic fluvial systems [5].

3.3.2. Attached Algae

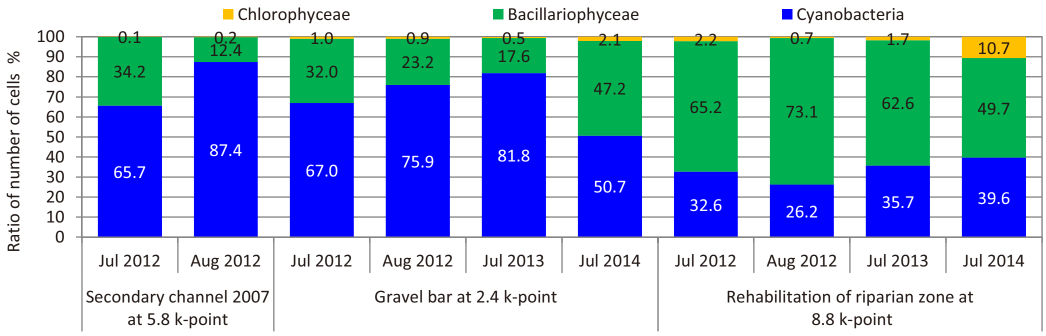
Figure 14 shows the result of continued surveys on attached algae at secondary channel sites in 2007 at 5.8 k-point, gravel bar at 2.4 k-point and riparian zone rehabilitation at 8.8 k-point. Bacillariophyceae and Cyanobacteria were highly dominant (with value larger than 89% even at the minimum at 8.8 k-point in 2014). Particularly, Cyanobacteria consists mostly of *Homoeothrix janthina*, which is generally attached to cobbles and preferably fed by *Plecoglossus altivelis altivelis* (Ayufish). Here, Ayufish is an amphidromous fish, which is born in the upstream of a freshwater river, and migrates to estuaries and ocean as larvae to grow up and spawn. Ayufish is considered to be one of the most important resources in many Japanese freshwater rivers.

Figure 15 shows a bite mark index for Ayufish, which represents how Ayufish uses attached algae as a feeding



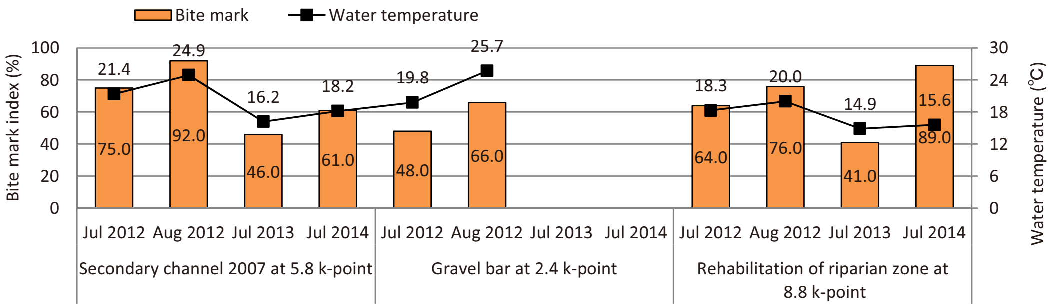
Source: Committee on flexible dam operation of the Managawa dam (2016), edited by the author.

Fig. 13. Micro-scale analysis on benthic macro-invertebrates.



Source: Committee on flexible dam operation of the Managawa dam (2016), edited by the author.

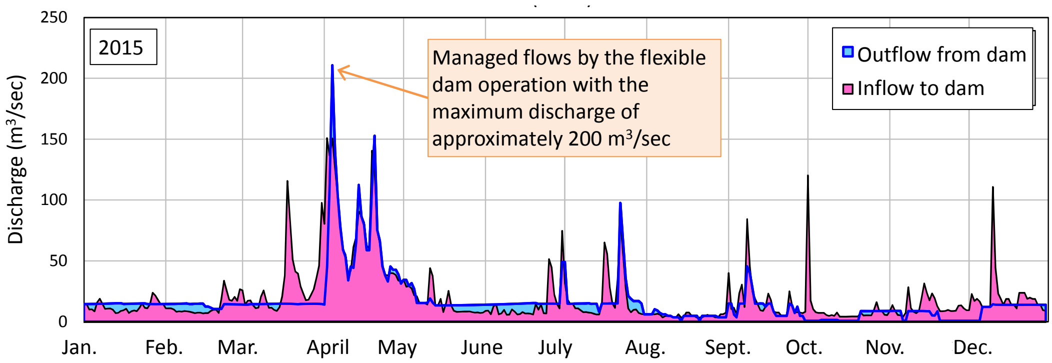
Fig. 14. Micro-scale analysis on attached algae.



Source: Committee on flexible dam operation of the Managawa dam (2016), edited by the author.

Fig. 15. Micro-scale analysis on attached algae by bite mark index for *Plecoglossus altivelis altivelis* (Ayufish).

habitat. The high ratio indicates the attached algae are preferred by Ayufish as a food source. Every site shows high value of 46 to 92% at 5.8 k-point, 48 to 66% at 2.4 k-point, and 41 to 89% at 8.8 k-point. This result shows that flexible dam operation of Managawa Dam in combination with sediment replenishment and channel rehabilitation maintain a relatively preferred feeding habitat for Ayufish [5].



Source: Committee on flexible dam operation of Managawa Dam (2016), edited by the author.

Fig. 16. An example of discharge hydrograph of inflows and outflows of Managawa Dam in 2015.

4. Discussion

4.1. Positive Aspects of Managed Flows

4.1.1. Roles of Managed Flows in Improving Flow Regimes

We discuss impacts of options on the flow and sediment regimes in Managawa River and the roles of flood pulses in restoring the downstream river environment. **Fig. 16** shows an example discharge hydrograph of inflows and outflows from Managawa Dam in 2015 [5]. This hydrograph reveals that outflows increased low flows throughout the year by 10 to 20 m^3/s compared to inflows, indicating that dam operation has a positive effect in sustaining ecological processes in the downstream ecosystem. Small-scale flood pulses were flushed downstream in Managawa River (with 45 m^3/s discharge) from 2003 to 2010 are larger than low flows and provide a trigger for disturbances between the intensity of low flows and mid-scale flood pulses. Looking at mid-scale flood pulses, the occurrence and duration of outflows larger than 180 m^3/s are reduced, indicating the importance of supplementing such flood events (naturally and manually by dam operation). The mid-scale flood pulses reached outflows of 200 m^3/s. This outflow value is regarded as the maximum discharge in 2015 [7].

4.1.2. Effectiveness of Sediment Replenishment for Improving Sediment Regimes

The role of sediment replenishment in improving sediment regimes in Managawa River is one of the important aspects to be discussed. Sediment replenishment is assessed by comparing the reservoir sedimentation volumes with those of sediment replenishment. The accumulated reservoir sedimentation volume was 2,237,000 m^3 as of 2016 since the dam operation started in 1979. This indicates that approximately 56,000 m^3/year is annually trapped and deposited in the reservoir of Managawa Dam. Except for reservoir sedimentation of 1,078,000 m^3/year due to an extraordinary Fukui heavy rain in 2004, approximately 30,000 m^3/year is trapped in the reservoir. On the other hand, sediment replenishment volume, which was carried out since from 2003 to 2010, ranged from 100 to 360 m^3/year. This volume is much smaller compared to that of reservoir sedimentation, indicating that the current sediment replenishment volume is not sufficient to restore sediment regimes to pre-dam conditions.

However, sediment replenishment has the possibility of playing an important role as a trigger for rivers under the current flow regimes (including managed flows) and the narrowed width of river corridors. This perspective should be considered when the sediment replenishment volume is being planned to increase.

From a perspective of sediment particle distributions, we compared the Managawa riverbed with replenished sediment [4]. The representative diameter (d_{60}) of the riverbed in Managawa River range from 20 to 60 mm, and that of the replenished sediment ranges from 7 to 50 mm. Even though relatively small sediment is included in the replenished sediment, they have been changed to sediment similar to Managawa River since 2010, indicating sediment replenishment has not had a negative impact.

4.2. Other Possible Impacts on Downstream Rivers

4.2.1. Water Temperature

Average daily water temperature from 1977 to 2016 was compared between sites upstream of the dam, e.g., the Saso River and Kumo River, and downstream at Gojoho in Managawa River [5]. Cold water outflows with temperature lower by 5°C compared to upstream sites have not been observed since 1989. On one hand, outflows of warm water with temperature higher by 5°C compared to upstream sites have not been observed. These results indicate that the operation of Managawa dam has less impact on the downstream ecosystems in terms of water temperature, particularly for fish species.

4.2.2. Ground Water Recharge

Ground water data around Managawa River Basin are used to understand the impacts of managed flows by comparing ground water stages between before flexible dam operation (i.e., from 2006 to 2010) and after flexible dam operation (i.e., from 2011 to 2016). Outflows larger than 1.0 m^3/s were used for analysis in order to avoid impacts of precipitation occurring during flood and snow-melt periods [5]. At adjacent observation sites, ground water stages increased due to increased outflow discharge during dam operation. On one hand, ground water stages did not respond to outflow discharge farther downstream. However, we confirmed that negative impacts (such as lowering ground water stages due to dam operation) were identified [5].

4.2.3. Downstream Impact

Naruka Dam and Shimoarai Dam in the Kuzuryu River, are located downstream of Managawa River. When flexible operation of Managwa Dam is discussed, the impacts on other downstream dams should be taken into account. The relationship between inflows and outflows of the Naruka Dam Shimoarai Dam, and Managawa Dam was analyzed. When Managawa Dam operates with high discharge flows including mid-scale flood pulses, the Kuzuryu River also has high water stages before reaching Naruka Dam. As for the Shimoarai Dam, operation begins when discharge from the Kuzuryu River exceeds 1,500 m^3/s. These results indicate that discharge of 200 m^3/s from Managawa Dam seem to have less impact on Naruka Dam operation and Shimoarai Dam operation [5].

5. Conclusions and Future Perspectives

5.1. Conclusions

Flexible dam operation has been carried out as a field demonstration project in consultation and collaboration with the Committee on Flexible Dam Operation of Managawa Dam, which was established in 2000. A set of results shows positive effects of flexible dam operation in combination with sediment replenishment and channel rehabilitation on restoration of the downstream river environment. Dynamic fluvial systems have been restored as a result of increase in gravel bars, habitat diversity in the form of riffle and pool structures, etc. Particularly, reaches, for which a combination of options was carried out, can have positive and relevant effects. This article also discussed the roles of low flows, small-scale flood pulses, and mid-scale flood pulses in restoring downstream ecological processes.

In Japan, managed discharges of 200 m^3/s are larger than similar projects on other rivers. This situation often makes it difficult for decision-making processes involving various stakeholders. However, since this flexible dam operation has been carried out in consultation and collaboration with the Committee, numerous positive outcomes have been obtained, knowledge has been accumulated, and future challenges have been identified.

5.2. Future Perspectives

Flexible dam operation has been successfully carried out as a field demonstration project. Translation of this demonstration project into dam operation management at the ground level requires amendment of rules and regulation of dam operation and further collaboration and negotiations with stakeholders (such as Fukui prefecture, Ono-city, Hokuriku Electric Power Company, Fishery Corporation, etc.).

Future challenges would be to enhance the forecasting accuracy of inflows to the dam during a snow-melt period. Since the dam plays the role of hydroelectric power generation, reservoir water stages should not be simply lowered and a kind of guarantee is required for the electric power company to secure power generation. For flexible dam operation, Water stages should be kept higher than the reservoir than normal dam operation, and it is important that dam operation not be delayed to secure water storage capacity during flood periods.

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