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Study on a Comprehensive Evaluation Method for Reorganizing Water-Use Systems

Yoko Yamamoto & Tadahiro Toyoda
National Institute for Land and Infrastructure Management (NILIM), Tsukuba, Japan
yamamoto-y92td@nilim.go.jp

Shinya Mitsuishi
International Centre for Water Hazard and Risk Management(ICHARM), Tsukuba, Japan

Okito Mukouzaka & Saeko Osaki
CTI Engineering Co., Ltd., Tokyo, Japan

ABSTRACT:
The reorganization of water-use systems in river basins is an important water issue in Japan. It may involve different types of measures, such as rescheduling the water intake period for agricultural purposes, upstream intake and rearrangement of water intake and drainage. However, these measures typically produce conflicting results, with negative impacts on the river environment and benefits for water users. Therefore, this paper proposes function equations to comprehensively evaluate such conflicting effects, not only on rivers but also on entire basins. According to this method, evaluatory items potentially involved in the restructuring measures are listed and converted into monetary terms to facilitate a comprehensive evaluation. Impacts on the river environment are evaluated, for example, by estimating the costs of dam heightening for extra water supply to increase river discharge. The paper also reports on a case study conducted to demonstrate the applicability of the developed functions in evaluating the impacts of rescheduling an agricultural water intake period. The results suggest that the benefits from accelerated water intake would exceed the negative impacts on the river environment, while delayed water intake would work to the contrary. The case study confirmed that the evaluation method can be a useful tool for decision-making in water-cycle restructuring.

Keywords: Water cycle, comprehensive evaluation, upstream intake, reorganization of intake and drainage, rescheduled intake period

1. INTRODUCTION

Japan is located in the monsoon climate zone and has a wide variety of hydrological features such as *baiu* seasonal rain, typhoons and snowfall, and topographical features such as mountains and alluvial plains. From ancient times, people have taken advantage of these features and recycled river water repeatedly, for various purposes, from upstream to downstream. Unlike fossil fuels, water is recyclable resource and can be used repeatedly as long as proper water use and drainage are practiced. However, unprincipled water intake and drainage lead to scarce water resources and poor water quality, and eventually impair the soundness of the basin's water environment. Therefore, restructuring of the water cycle should be addressed to ensure a sounder water cycle for the future. In this paper, "a sound water cycle" refers to "a state in which the functions of water are ensured for both human activity and environmental conservation in a well-balanced manner from upstream to downstream in a river basin". To realize this state, water-cycle projects (e.g., forest conservation, water resources recharge, water resources allocation, water quality conservation, construction and operation of water supply facilities, and waste water treatment including sewage systems) should be designed on each basin basis, in line with a system that best coordinates such projects when necessary.

In Japan, water demand sharply increased during the post-war high economic growth period (1950s-1970s) characterized by rapid urbanization and industrialization. Water resources were developed to meet that fast-growing water demand, and this caused river environmental issues such as reduced water levels and poor water quality. Generally, because river water is used for so many purposes in Japan, limited water resources need to be allocated properly among conflicting interests in a given basin, with consideration of the benefits to agricultural, industrial and domestic water users, and the impacts on the river environment and fishery. Furthermore, recent socio-economic changes have also affected water-use patterns, and the current locations and periods of water intake and drainage have not always been efficient, in many cases. The reorganization of current water-use systems will solve these problems, realize an optimized allocation of limited water resources, and play a crucial role in ensuring a sound water cycle.

Therefore, in this study, we aimed to develop a rational method to evaluate measures for the reorganization of water-use systems. Reorganizing a water-use system involves reorganizing water intake and drainage, and rescheduling the water intake periods, which will affect the river environment by causing negative changes in river discharge and water quality. On the other hand, such reorganization will benefit water users by improving agricultural productivity and reducing costs for the operation and management of water intake/drainage facilities. It will also reduce CO_2 emissions due to decreased facility operation. Considering these conflicting results of such reorganization, the study developed comprehensive evaluation functions to measure its positive and negative impacts. We also conducted a case study in which the developed functions were applied to an actual river.

2. MAIN MEASURES FOR REORGANIZING A WATER USE SYSTEM

In Japan, water resources were developed as water demand increased. Because of this, the structures and facilities for water-resource management and water intake and drainage are not always effectively located in their respective river basins. Moreover, with socio-economic change, water-use patterns have themselves been changing in recent years. Water users have now begun asking river administrators to reschedule the periods of water intake for agricultural use, relocate domestic-water intake points upstream, and rearrange the locations of water intake and drainage. Rescheduling the periods of water intake for agricultural use (accelerated or delayed water intake) means using river water for agricultural purposes either before or after the regular period guaranteed by the current water rights. This, if implemented, will make it possible to plant early rice varieties that are highly marketable, diversify the risks of flood and salt damage, use water for the maintenance of irrigation channels, and prolong the growing period to produce higher-quality agricultural products. Upstream intake which means the upstream relocation of water intake points from the current locations will lead to some cost-reduction benefits. Water purification will cost less because water is cleaner when taken upstream. Water transmission costs will also decrease because gravity flow occurs by taking water at upstream points. The rearrangement of water intake and drainage refers to switching the locations of water intake and drainage points. For example, when a domestic-water intake point is located immediately downstream from a sewage drainage outlet or polluted tributary, the locations will be switched to protect drinking-water safety from heavy metals and polluted water, and reduce water purification costs. As explained above, water users can receive considerable benefits, in terms of farming and water quality, from the reorganization of a water-use system. And it may also benefit the entire basin by reducing CO_2 emissions in water transmission and purification. However, reduced water sections emerging in different locations may deteriorate the river environment, negatively affecting water quality, ecosystems and river fisheries. Fig.1. shows impacts, benefits, and costs expected to accompany water system reorganization.

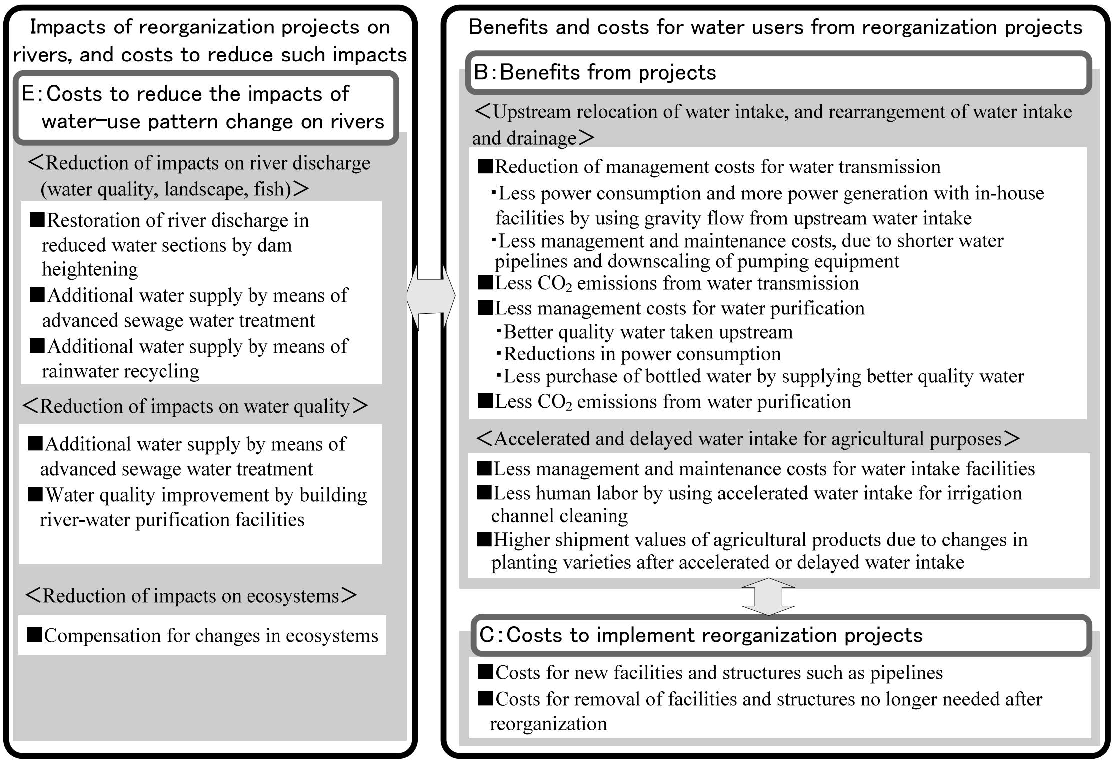

Figure 1. Impacts, Benefits and Costs of water use system reorganization

3. DEVELOPMENT OF COMPREHENSIVE EVALUATION FUNCTIONS

Discussion has been held on various occasions regarding the implementation of measures, such as those described above, to reorganize a water-use system. For instance, a study group aiming to create a sounder river-water environment in the Tonegawa River, with an aim of better water quality, examined the possibility of changing the courses of polluted rivers and relocating water intake points upstream. Also, a committee dedicated to achieving a better water cycle in the Tokyo metropolitan area studied a borderless water cycle across municipal jurisdictions in an effort to integrate water-supply systems over a wide area. Despite demands from water users, and discussions by study groups, consideration of the reorganization of water-use systems has not seen much progress, except in a limited number of measures. The main reason for this is that previous impact assessments did not take a comprehensive approach capable of evaluating both positive and negative impacts, despite the fact that water-system reorganization may create reduced water sections that can affect the river environment in a negative way. It is important to estimate impacts comprehensively, by considering both advantages for water users and disadvantages for the river environment, which are typically in conflict with each other. In the words, a comprehensive approach is needed in order to assess the economic benefits to society as a whole, through analysis and assessment of water discharge, water quality, river ecosystems, fisheries, CO_2 emissions, costs for the construction and management of water intake/drainage facilities, farming costs, and other factors, which all take a unique evaluation viewpoint.

In Japan, river management projects have been evaluated in economic terms by comparing expected project costs and damage reduction. River environment projects, on the other hand, have been evaluated by comparing costs and benefits in the virtual market using CVM and other methods. However, no methods have yet been developed for evaluating these two types of projects comprehensively. In this paper, we propose comprehensive evaluation functions that can be applied to evaluation items sorted into three categories of potential costs and benefits resulting from changing current water-use patterns: costs required to reduce impacts on the river environment, benefits for water users, and reorganization costs for water users.

$$F = \left(-\sum_i E_i \right) + \left(\sum_i B_i - \sum_i C_i \right) \tag{1}$$

F: Evaluation function for reorganization measures
E: Costs to reduce the impacts of water-use-pattern change on rivers
B : Benefits from reorganization measures
C : Costs to implement reorganization measures
i : Evaluation items

Each evaluation item is present-valued to the base year by applying a deflator, in order to take the measure and service periods into account. The items are then evaluated based on their total values in the evaluation period.

3.1. Impacts on Rivers, and Impact Reduction Measures

Reorganizing a water-use system may create reduced water sections downstream, leading to deterioration of water quality, ecosystems and landscapes, as well as other negative impacts for water users. Such impacts are estimated in monetary terms by calculating the implementation costs of possible impact reduction measures. Table 1 lists possible impacts and measures to reduce those impacts.

Table 1. Items for comprehensive evaluation in a reorganizing a water use system

Evaluation items	Secondary impacts	Impact reduction measures
Decreased river discharge (occurring reduced water sections)	Impacts on water quality, ecosystems, river landscapes, and other water-user concerns due to decreased river discharge	Discharge restoration in reduced water sections by dam heightening E_1
		Additional water supply by rainwater recycling E_2
		Additional water supply & water quality improvement by advanced sewage water treatment E_3
Change in water quality	Impacts on ecosystems due to change in water quality	Water purification by building river-water purification facilities E_4
Ecosystem		Mitigation for changes in ecosystems E_5

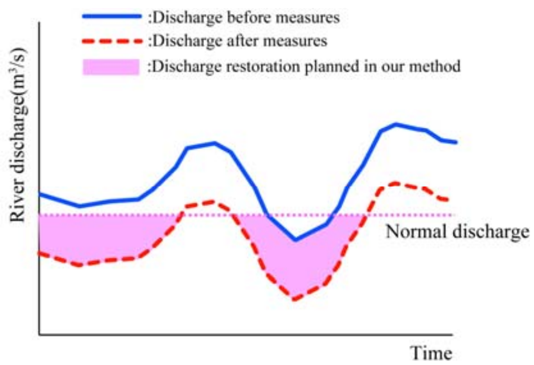

Figure 2. River discharge restoration

Fig.2. shows how decreased river discharge and its impacts on water quality are evaluated with the developed method. If the reorganization of a water-use system results in reduced river-water sections, it will be necessary to take measures to mitigate the impacts of the reduced water levels. The equation below is designed to estimate the water supply required from dams in order to increase the respective river discharge of the reduced water sections up to its normal discharge level. Normal discharge levels are designated, by the Fundamental River Management Policy, as the minimum amounts of discharge required for appropriate river management in terms of downstream

water intake, ecosystems, water quality, landscapes and other aspects. Generally, measures that may force discharge levels below normal discharge levels should at least be avoided to prevent negative river-environment impacts. In our method, if the discharge level at a control point is already below its normal discharge level before measures are implemented, additional water will be supplied only up to the original level. Expected water supply is defined as the annual maximum (V) of the annual total deficit to the normal discharge (V_t) derived from 5-day water use calculated based on the flow regime of the study year.

$$V_t = -\sum_{1}^{t} (\Delta q_i) \tag{2}$$

$$\Delta q_i = \begin{cases} q_{nomal} - q_2 & (q_{nomal} \le q_1) \\ q_1 - q_2 & (q_{nomal} > q_1) \end{cases} \quad (\Delta q_i \le 0) \tag{3}$$

V_t : Total water supply up to a 5-day period t (m^3)
Δq_i: Daily deficit of each 5-day period (m^3/day)
q_{nomal}: Normal discharge (m^3/day)
q_1: Daily discharge at the water intake point before measures (m^3/day)
q_2: Daily discharge at the water intake point after measures (m^3/day)

The most economical water-supply option should be selected from among the options of dam heightening, advanced sewage treatment or rainwater recycling. However, this paper explains specifically about dam heightening because of space limitations. Dam heightening cost (E_1) will be estimated for dams located upstream of the low-water sections (Fig.3.).

$$E_1 = C \times \Delta V \times (1 + \alpha) \tag{4}$$

$$\Delta V = \{H_2(D_{B2} + D_{T2})/2 - H_1(D_{B1} + D_{T1})/2\} \cdot B \tag{5}$$

$$N = H_2 - H_1 = V \ / U \tag{6}$$

C: Construction cost per m^3 of dam volume (yen/m^3)
ΔV: Dam volume required for dam heightening(m^3)
α: Percentage of other costs required for management facilities, temporary facilities and power used for construction
$H_{1,2}$: Dam height (m)
$D_{B1,B2}$: Dam base width (m)
$D_{T1,T2}$: Dam crown width (m)
B: Dam body length (m)
N: Increased height (m)
V: Water supply by the target dam(m^3)
U: Reservoir area of the target dam(m^2)

The measure cost per m^3 of dam volume is estimated by using an empirical formula derived from the construction costs of 21 concrete dams, including the Ohmachi and Sameura dams managed by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) and the Japan Water Agency. The cost estimate is then multiplied by the deflator and converted into 2010 terms. Note that the estimate includes neither land compensation that may accompany the heightening, nor possible impacts on the surrounding environment or on water quality in downstream areas.

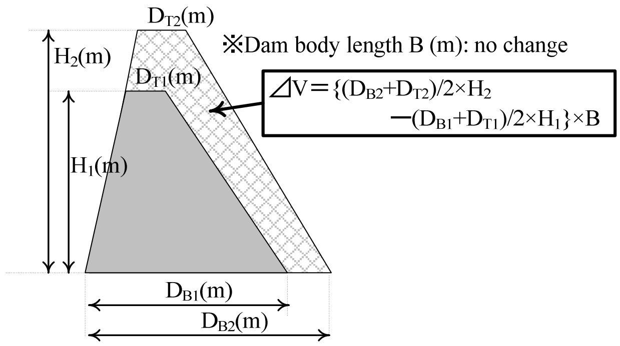

Figure 3. Estimation of concrete for dam heightening

3.2. Costs and Benefits of Rescheduling Water Intake Periods for Agricultural Use

This section explains in detail the evaluation of accelerated and delayed agricultural water intake. Fig.4. shows possible rescheduling of water-intake periods for agricultural use: 1) accelerated water intake for labor reduction in irrigation channel maintenance, 2) delayed water intake for a prolonged growing period. Refer to Mitsuishi et al. (2011) for further information on the upstream relocation of water intake points, and the reorganization of water intake and drainage. Table 2 shows the expected costs and benefits in relation to the implementation of the rescheduling measures.

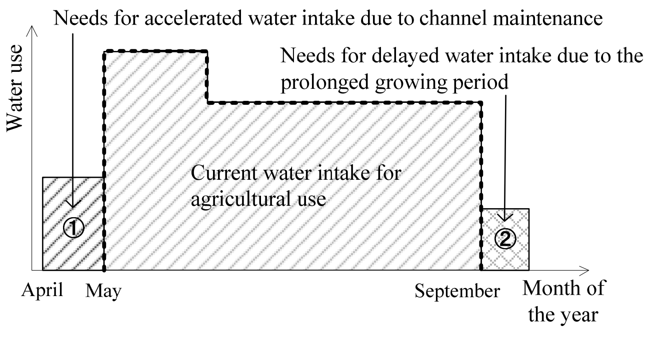

Figure 4. Outline of rescheduling water intake periods for agricultural use

Table 2. Items for cost-benefit evaluation for water users

Facility management	Change in the management cost of water intake facilities after smoothing the operation period for agricultural water intake B_1
	Labor reduction in irrigation channel cleaning and other chores after accelerated water intake (for channel maintenance) B_2
Shipment value	Increase in market-value of agricultural products after accelerated or delayed agricultural water intake B_3

This paper mainly addresses two types of benefits as major benefits from changes in the cost of water intake facility management after smoothing the period for agricultural water use. One is the change in power consumption (B_1) caused by the change in pump operation time for water intake due to the change in the amount of water intake. The other is the possibility of facility downscaling after smoothing the maximum discharge (B_2). The respective equation below shows how the benefits are defined, in terms of the amount of intake, as the amount of intake changes.

$$B_1 = \mu \cdot \left\{ \sum_1^i (M_1 \cdot T_1) - \sum_1^i (M_2 \cdot T_2) \right\} \quad (7)$$

μ: Cost of power per kWh (yen/kWh)
M_n: Power consumption by pumps in each period (kW)
T_n: Pump operation hours (h)
n: before(1) or after(2) measures

When accelerated water intake is utilized for irrigation channel maintenance, human labor otherwise needed to clean the channels can be reduced. This benefit is estimated below.

$$B_2 = \tau \cdot K \cdot (\phi_1 - \phi_2) \quad (8)$$

φ_n: Number of people needed for cleaning (person-day/m)
τ: Labor cost per person (yen/person-day)
K: Length of the target channel (m)
n: before(1) or after(2) measures

Increases in the market-value of agricultural products (B_3) due to accelerated or delayed water intake should also be considered. This paper assumes two cases in which agricultural products may increase in economic value: yield increase, and change in market value due to improved quality, better shipment timing or both. As Fig.5. shows, the benefits are estimated in comparison with the current yields, quality and prices.

$$B_3 = (P_2 \cdot a_2 \cdot \theta_2 \cdot \sigma_2 - P_1 \cdot a_1 \cdot \theta_1 \cdot \sigma_1) \cdot A \quad (9)$$

P_n: Base price by rice variety (yen/kg)
a_n: Yield per unit area (kg/10a)
θ_n: Percentage of first-class rice by rice variety

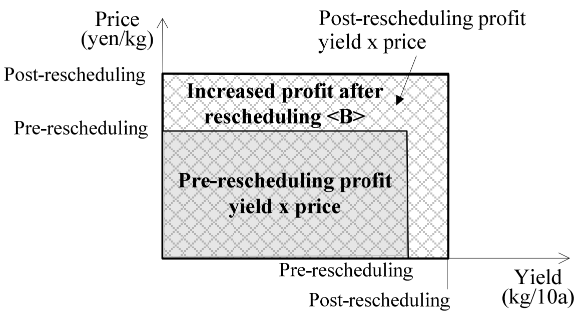

Figure 5. Conceptual image of the increase in shipment value of agricultural products

σ_n: Price fluctuation rate to the base price at shipment
A: Target irrigation area (10a)
n: before(1) or after(2) measures

The yield and quality of rice are estimated based on the change in yield after switching rice varieties, and on the percentage of first-class rice, respectively, in reference to cases found in Niigata Prefecture[8]. Price fluctuations in different periods are also estimated based on the free-market rates[9] of five rice varieties, including the *Koshihikari* variety. No cost is involved in carrying out accelerated or delayed agricultural water intake, because these only require rescheduling of water-intake periods while utilizing existing facilities and structures.

4. CASE STUDY

A case study was conducted on an actual river (River A) to evaluate the impacts of accelerated and delayed water intake on agricultural use. In the River A basin, a deterioration in rice quality has been noted, owing to higher temperatures during the grain-filling period. To address this problem, farming advisors have encouraged the transplantation of rice plants at an appropriate growing period. Also, more and more farmers are prolonging the growing period to improve rice quality. In addition, there is a strong need to utilize water for irrigation channel maintenance, in order to spare human labor otherwise employed in that task before the irrigation season.

We conducted to case studies. In case1, an additional water intake of 2.0m^3/s was planned for the period of April 6th-26th, beyond the regular intake specifically employed for channel maintenance. In case2, Delayed water intake was conducted at a rate of 5.1m^3/s for five days, from September 1st to 5th, primarily for product-quality improvement, by switching mid-season varieties (currently accounting for 80%) to late-season varieties. The irrigation area was about 28km^2 in the study district, but the evaluation was done for an area 30 times larger than that, because the need for delayed water intake is assumed to be high among other neighboring districts. The 1994 flow regime, which was observed to be the worst in recent years and equivalent to the 20-year return period drought level, was applied to the case study. The measure period was set at five years, the service period at 50 years, and the evaluation base year at 2010.

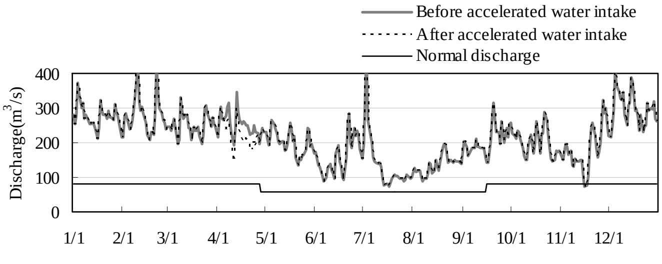

Figure 6. Flow regime change at River A-Location S (Case 1)

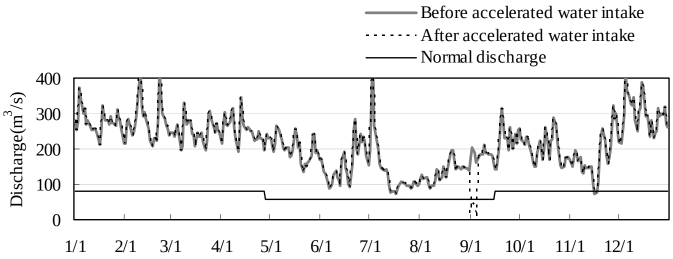

Figure 7. Flow-regime change at River A-Location S (Case 2)

Fig.6. shows the change in flow regime in the case of accelerated water intake. The accelerated water intake was conducted from April 6th to 26th, during the snowmelt season, when the flow regime well exceeds the normal discharge. The results found that such intake in this area has no negative impact on the normal discharge, and is even better for river management than water intake during low water flow in May and June. Fig.7. shows the flow-regime change after the delayed water intake. The delayed intake from September 1st -5th resulted in a below normal discharge, requiring a total water supply of 15,123,000 m^3/year. Dam heightening, rainwater recycling and advanced sewage treatment are options for water supply sources, but the last was excluded in this case because the nearest sewage outlets are located outside the basin. In this study, comparison was made between two water-supply plans: dam heightening only, and a combination of dam heightening and rainwater recycling.

In the dam-only plan, the target dam was Dam B with a reservoir area of 1.1 km^2. To supply 15,123,000 m^3/year of water, the heightening was estimated to be 13.7 m with a body volume of 658,000 m^3. In the combination plan, because 1994 was a dry year, with only a small amount of rainwater available, the additional water supply required from Dam B was estimated to be 15,036,000 m^3/year, which was calculated to require a dam heightening of 13.7 m (that is, as high as that in the dam-only plan). The comparison between the two plans found that the dam-only plan was less costly than the other; therefore the dam-only plan was adopted.

Table 3. Evaluation results of accelerated and delayed water intake (in million yen)

	Accelerated water intake	Delayed water intake
River management cost (*E*)	0	43,058
Dam heightening (E_1)	0	43,058
Water users' benefits (*B*)	261	3,903
Facility downscaling (B_1)	0	0
Human labor reduction (B_2)	261	0
Shipment value increase (B_3)	0	3,903
Water users' costs (*C*)	0	0
Total cost evaluation (*F*)	261	-39,155

The case study found that the benefits from the accelerated water intake would exceed the negative impacts on the river environment, while the delayed water intake would have a contrary effect, as shown in Table 3, in the river A basin. No additional cost was estimated for river management in the case of the accelerated intake, because it did not cause reduced water below the normal discharge in the calculation, and the benefit of human labor reduction was large for water users. On the other hand, the delayed water intake resulted in a below-normal discharge, which would require dam heightening for compensatory water supply, and would affect ecosystems. The measure costs to deal with those negative impacts were estimated to be larger than the benefits water users would receive. Because this case study involved no expanding or downscaling of water intake facilities, water users' costs (*C*) and downscaling benefits (B_1) were not estimated.

5. CONCLUSION

In this case study, the disadvantage of the delayed water intake was evident because the evaluation was done for an irrigation area 30 times larger than the study area. However, we also confirmed that no below-normal discharge occurred, because of the delayed intake, if the irrigation area was limited only to the study area of 2,800 ha. Since this implies a social issue regarding how river water, as a limited water resource, should be shared among water users in the basin, careful discussion is essential before making any decisions in this matter. As the case study demonstrated, the comprehensive evaluation method we propose can be a useful tool when decisions must be made in relation to the reorganization of a water-use system. In addition, it should be noted that evaluation items must be appropriately selected based on the needs and conditions of target locations, when employing this comprehensive evaluation method.

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