

WATER-SAVING EFFECTS OF INDIVIDUAL VOLUMETRIC WATER CHARGE SYSTEMS IN JAPANESE IRRIGATION DISTRICTS

EFFETS DES SYSTÈMES INDIVIDUELS DE TARIFICATION VOLUMÉTRIQUE DE L'EAU SUR LES ÉCONOMIES D'EAU DANS LES PÉRIMÈTRES IRRIGUÉS JAPONAIS

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ABSTRACT

Global water demand is rising owing to population growth and increasing food demand. As agriculture uses the majority of the world's freshwater, improving irrigation water-use efficiency is essential. Volumetric water charge systems (volumetric systems), which charge farmers based on actual water use, are expected to promote efficient water use by internalizing the economic value of water. However, such systems remain limited in large-scale irrigation districts in Japan and many other regions, where area-based water charge systems typically prevail. Consequently, empirical evidence on the volumetric system remains limited. This study examined the water-saving effects of individual volumetric water charge systems (individual volumetric systems) by focusing on the Miyako and Ishigaki irrigation districts in Japan. These areas represent large-scale irrigation districts that have implemented the individual volumetric system, making them highly exceptional cases both internationally and within Japan. By using water consumption data from farm ponds (FPs) in Miyako and reservoir discharge and farm-level water use data in Ishigaki, an analysis was conducted to evaluate changes in irrigation water use following the introduction of the system. The results showed that in the Miyako irrigation district, annual water use decreased by approximately 20–40% in most FPs after implementation, except during the extreme drought year of 2022. Monthly analysis revealed that the strongest water-saving effects occurred in July, when irrigation demand was the highest. In the Ishigaki irrigation district, the estimated average annual water-saving volume was approximately 177 mm. Furthermore, larger farms exhibited greater water-saving behavior, likely due to their increased cost sensitivity under the volumetric system. These findings suggest that individual volumetric systems can effectively promote agricultural water conservation, particularly during peak demand periods and among larger-scale farms.

Keywords: Irrigation districts; Water demand; Volumetric systems; Agricultural water conservation; Larger-scale farms.

RÉSUMÉ

La demande mondiale en eau augmente sous l'effet de la croissance démographique et de la hausse de la demande alimentaire. L'agriculture utilisant la majeure partie de l'eau douce mondiale, il est essentiel d'améliorer l'efficacité d'utilisation de l'eau d'irrigation. Les systèmes de tarification volumétrique de l'eau (systèmes volumétriques), qui facturent les agriculteurs en fonction de leur consommation réelle, devraient favoriser une utilisation efficace de l'eau en internalisant sa valeur économique. Toutefois, ces systèmes restent peu répandus dans les grands périmètres irrigués du Japon et de nombreuses autres régions, où la tarification est généralement fondée sur la superficie. Par conséquent, les données empiriques relatives aux systèmes volumétriques demeurent limitées. Cette étude a examiné les effets des systèmes individuels de tarification volumétrique de l'eau

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(systèmes volumétriques individuels) sur les économies d'eau, en se concentrant sur les périmètres irrigués de Miyako et d'Ishigaki, au Japon. Ces zones sont de grands périmètres irrigués ayant mis en œuvre un système volumétrique individuel, ce qui en fait des cas tout à fait exceptionnels, tant au niveau international qu'au Japon. Une analyse a été menée à partir des données de consommation d'eau des bassins agricoles (FP) de Miyako ainsi que des données de débit des réservoirs et d'utilisation de l'eau à l'échelle des exploitations à Ishigaki, afin d'évaluer l'évolution de l'utilisation de l'eau d'irrigation après l'instauration du système. Les résultats ont montré que, dans le périmètre irrigué de Miyako, l'utilisation annuelle d'eau avait diminué d'environ 20 à 40 % dans la plupart des FP après la mise en œuvre du système, sauf pendant l'année de sécheresse extrême de 2022. L'analyse mensuelle a révélé que les économies d'eau les plus importantes avaient été réalisées en juillet, lorsque la demande d'irrigation était la plus élevée. Dans le périmètre irrigué d'Ishigaki, le volume annuel moyen d'eau économisé a été estimé à environ 177 mm. En outre, les grandes exploitations ont adopté des comportements plus économes en eau, probablement en raison de leur plus grande sensibilité aux coûts dans le cadre du système volumétrique. Ces résultats indiquent que les systèmes volumétriques individuels peuvent favoriser efficacement les économies d'eau en agriculture, en particulier pendant les périodes de pointe de la demande et dans les exploitations de plus grande taille.

Mots clés : Périmètres irrigués; Demande en eau; Systèmes volumétriques; Economies d'eau en agriculture; Exploitations de plus grande taille.

1. INTRODUCTION

Global water demand is rising owing to population growth, increasing food demand, and climate change. As agriculture accounts for 70% of freshwater withdrawals, improving irrigation efficiency is an urgent priority (UN, 2025). As a strategy to promote the efficient use of irrigation water, conserve water resources, and ensure a sense of equity among beneficiary farmers, “volumetric water charge systems” (volumetric systems) have attracted significant attention. Under these systems, irrigation fees are levied on farmers based on the actual volume of water they use. However, most large-scale irrigation districts in Asia, Africa, and Japan still employ area-based water charge systems, where uniform irrigation fees are charged according to the acreage cultivated by individual farmers. Districts that implement volumetric systems are extremely rare. Therefore, empirical research on the effectiveness of introducing volumetric systems has been severely limited (Uchimura et al., 2014). In Japan, volumetric systems applied at the block level for paddy fields spanning dozens of hectares have been shown to exhibit water-saving effects during non-drought periods (Uchimura et al., 2014). In other countries, a study in Peru demonstrated both water-saving effects and high fee collection rates (Vos & Vincent, 2011). Nevertheless, there is a notable lack of research on the efficacy of “individual volumetric water charge systems” (individual volumetric systems)—systems where water consumption is metered and charged at the individual farm plot level. Therefore, this study aims to clarify the water-saving effects of individual volumetric systems by focusing on the Miyako and Ishigaki irrigation districts in Japan. These districts represent large-scale irrigation districts that have implemented the individual volumetric system, making them highly exceptional cases both internationally and within Japan.

2. STUDY AREA

2.1 Overview of Climate and Irrigation

The study areas, the Miyako and Ishigaki irrigation districts, are located on Miyako Island and Ishigaki Island in Okinawa Prefecture, the southernmost region of Japan. Both islands feature a subtropical climate, with mean monthly temperatures above 18°C throughout the year. Although the annual precipitation is high at 2,086 mm, it is distinctly divided into a rainy season (May–June) and a non-rainy season (July–April). Notably, in July, immediately following the end of the rainy season, precipitation drops significantly, with the average rainfall over the past five years recorded at only 147 mm. The primary crop is sugarcane, which accounts for approximately 60% of the irrigated area in both districts. Water requirements for sugarcane peak during the summer months of July and August.

Conversely, irrigation is suspended prior to harvest in January to increase the sugar content of the crop.

2.2 Irrigation System and Water Charge System in the Miyako Irrigation District

In the Miyako irrigation district, the total irrigated area encompasses approximately 9,540 ha. The primary water source is groundwater, supported by four “Underground Dams”—reservoirs created by blocking groundwater—with a total storage capacity of $24 \times 10^6 \text{ m}^3$ (Figure 1). Water pumped from these dams is temporarily stored in six farm ponds (FPs) located on hills, from which it is distributed via pipelines through gravity flow. Concurrent with the initiation of the irrigation project, a land improvement district (LID)—a water users' association of beneficiary farmers—was established. This LID collects water charges from the beneficiary farmers and is responsible for the distribution, operation, and maintenance of the irrigation facilities.



Figure 1. Overview of the study areas: (Left) Miyako Irrigation District and (Right) Ishigaki Irrigation District

At the onset of irrigation operations, water charges were levied under an area-based water charge system at a rate of 20,000 JPY/ha (approximately 125 USD/ha, based on an exchange rate of 1 USD = 160 JPY as of 2026). However, subsequent excessive water use by farmers raised concerns regarding the depletion of groundwater resources in the dams. To address this issue, the installation of water meters at approximately 16,000 locations—corresponding to each 0.4 ha plot—was initiated, and the individual volumetric system based on annual water consumption was introduced in fiscal year (FY) 2020. Under this current system, the base charge is 20,000 JPY/ha for annual water consumption up to 2,600 m^3/ha , with an additional volumetric charge of 15 JPY/ m^3 levied for any consumption exceeding this threshold. In Japan, farmers typically bear 10%–20% of irrigation project costs. However, for Miyako and Ishigaki, located on remote islands of Okinawa, the national and prefectural governments provided a 100% subsidy. Consequently, farmers did not oppose the individual volumetric system due to the absence of introduction costs.

2.3 Irrigation System and Water Charge System in the Ishigaki Irrigation District

In the Ishigaki irrigation district, the planned irrigation area covers approximately 4,330 ha, but the infrastructure for water supply to individual farm plots remains under development. As of 2025, the actual irrigated farmland is limited to approximately 65%. The primary water sources consist of five above-ground dams, and the irrigation district is divided into three sub-districts based on these water sources (Figure 1). This study focuses on the Miyaragawa sub-district, which draws water from two dams (with a total storage capacity of $14.95 \times 10^6 \text{ m}^3$) and a river, spanning a planned irrigation area of 3,460 ha. Water is pumped from an intake weir constructed on the river, temporarily stored in an FP, and subsequently distributed to individual plots via pipelines through gravity flow. Like the Miyako LID, the Ishigaki LID collects water charges from the farmers and manages the operation and maintenance of these irrigation facilities.

The Ishigaki LID introduced the individual volumetric system to promote the efficient use of irrigation water and ensure a sense of equity among beneficiary farmers. In the Miyaragawa sub-district, the individual volumetric system was launched in FY 2012, and the target areas have since been expanded in a stepwise manner. As of July 2024, the area billed under the individual volumetric system in the Miyaragawa sub-district reached 394.5 ha, while the remaining areas are still managed under the area-based water charge system. In the areas where the individual volumetric system has been introduced, the water charge consists of a base fee of 25,000 JPY/ha (area-based pricing) combined with a volumetric rate of 5.0 JPY/m³ based on water consumption. In contrast, the irrigation fees under the area-based water charge system vary by sub-district, ranging from 39,000 JPY/ha to 49,000 JPY/ha.

3. METHODOLOGY AND DATA SOURCES

3.1 *Evaluation of Water-Saving Effects by Irrigation Block*

In this study, the water-saving effects of the volumetric system were verified through comparative analyses. For the Miyako irrigation district, irrigation water consumption within the same irrigation blocks was compared before and after the introduction of the volumetric system on both an annual and a monthly basis. For the Ishigaki irrigation district, irrigation water consumption was compared between irrigation blocks managed under the individual volumetric system and those under the area-based water charge system within the same year on an annual basis. Because irrigation water consumption can be influenced by precipitation and, over the long term, by shifts in farmers' motivation for cultivation and changes in crop varieties, both precipitation patterns and yearly trends were controlled for in the analysis.

For the Miyako irrigation district, water consumption data obtained from the FPs of four irrigation blocks were utilized. The volume of water used was divided by the corresponding irrigated area to calculate the annual and monthly water withdrawal depths (expressed in mm). Linear regression lines were derived from the relationship between precipitation and water withdrawal on both an annual and a monthly basis during the pre-introduction period of the volumetric system (FYs 2011 to 2019). Based on these regression equations, the estimated water supply was simulated for the post-introduction period under the assumption that the area-based water charge system had remained in place. To ensure validity and reliability, only models with $R^2 \geq 0.3$ were selected. The water-saving volume was defined as the difference between the estimated water supply and the actual water withdrawal, and the water-saving rate was calculated by dividing this water-saving volume by the estimated water supply.

For the Ishigaki irrigation district, water distribution data for each individual FP were unavailable. Therefore, this study focused on the discharge volumes from the Sokobaru and Maesato dams, which serve as the primary water sources for the Miyaragawa sub-district. This sub-district is divided into 77 irrigation blocks, approximately 80% of which continue to employ the area-based water charge system. Consequently, the annual dam irrigation discharge (expressed in mm) was treated as the baseline water withdrawal for the area-based districts. This baseline was then compared with the annual water withdrawal (mm) of an irrigation block that had implemented the volumetric system—the Arakawa district, which features an irrigated area of approximately 62 ha, with 107 beneficiary farm households. The annual water withdrawal for the Arakawa district was determined by aggregating the individual annual water consumption data obtained from each farmer. Since the actual water withdrawal in the dam beneficiary areas includes both dam irrigation water and naturally flowing water downstream of the dam, it exceeds the recorded dam irrigation discharge. Consequently, the actual water-saving effect is likely even greater than the estimate obtained in this study.

3.2 *Analysis of Farmers' Water-Saving Behavior under the Individual Volumetric System*

To investigate the potential of the volumetric system to incentivize water-saving behavior among farmers, changes in the irrigation fees paid by farmers before and after the implementation of the system were analyzed. Due to the unavailability of individual farm-level records in the Miyako LID, this

analysis focuses exclusively on the Ishigaki LID. For the Ishigaki LID, individual water withdrawal data for each farm household were obtained within the irrigation block where the volumetric system had been introduced. Based on these data, the irrigation fees paid by individual farmers under the individual volumetric system were compared with the hypothetical fees that would have been charged under the area-based water charge system. By comparing these cost differentials with the gross revenue generated from sugarcane sales, this study examined whether the differences in irrigation fees under the volumetric system are substantial enough to motivate farmers to conserve water.

3.3 Data Sources and Acquisition Methods

Precipitation data were obtained from the Automated Meteorological Data Acquisition System (AMEDAS) via the official website of the Japan Meteorological Agency, covering the periods from 2002 to 2024 for the Ishigaki Island Station and from 2011 to 2023 for the Miyako Island Station. Water distribution data for the FPs managed by the Miyako LID (from 2002 to 2023) were sourced directly from the internal records of the LID. For the Ishigaki LID, irrigation discharge data from the dams, as well as the individual water withdrawal records of farmers in the Arakawa district and other irrigation blocks under the volumetric system, were acquired from the water-use logs maintained by the LID and the Yaeyama Agriculture, Forestry and Fisheries Promotion Center of the Okinawa Prefectural Government. In addition to the secondary data, field surveys were conducted to gather primary qualitative and quantitative information. Field investigations were conducted on Miyako Island from July 1 to July 5, 2024. Two separate field surveys were conducted on Ishigaki Island: the first from July 1 to July 5, 2024, and the second from November 25 to November 29, 2024.

4. RESULTS AND DISCUSSION

4.1 Evaluation of Water-Saving Effects by Irrigation Block

4.1.1 Analysis of the Miyako Island Irrigation District

Table 1 summarizes the annual water-saving evaluation for each FP. Following the system's introduction, a distinct water-saving effect was observed across all FPs, with reduction rates consistently ranging from 20% to 40%, except in 2022. This 2022 anomaly was driven by an extreme meteorological drought from late April to July, when precipitation dropped to approximately 30% of the historical average. The resulting rainfall deficit during peak-demand months (July and August) triggered unprecedented water withdrawals, obscuring any water-saving effects.

Table 1. Annual water-saving evaluation of each farm pond

Farm Pond	Year	Water Supply (mm)	Estimated Water Supply (mm)	Water Savings (mm)	Water Savings Rate (%)
Noharadake	2020	211	258	47.00	0.20
	2021	302	412	110.00	0.30
	2022	242	31	-211.00	-6.80
	2023	328	412	85.00	0.20
Higashiyama	2020	252	354	102.00	0.30
	2021	380	559	179.00	0.30
	2022	314	72	-242.00	-3.40
	2023	358	570	212.00	0.40
Pinpudake	2020	184	237	53.00	0.20
	2021	279	375	96.00	0.30
	2022	200	48	-152.00	-3.20
	2023	308	384	76.00	0.20
Nakaodake	2020	206	356	150.00	0.40
	2021	326	553	227.00	0.40
	2022	232	88	-144.00	-1.60
	2023	312	567	254.00	0.40

Next, linear regression lines were derived from the relationship between monthly precipitation and monthly water withdrawal during the pre-introduction period of the volumetric system. Through this procedure, monthly analysis confirmed positive water-saving effects in approximately 73% of the analyzed months. Both the monthly water withdrawal and corresponding savings peaked in July,

coinciding with the maximum agricultural water demand. The largest reduction was recorded in the Nakaodake block in July 2020, with maximum water savings of 50.50 mm. Conversely, a negative water-saving effect (i.e., increased water withdrawal) was observed in May from 2020 to 2022. This anomaly can be attributed to the exceptionally heavy rainfall during those months. Under conditions of soil saturation, the empirical model likely underestimated the baseline irrigation demand, thereby generating predicted values that were systematically too low. This discrepancy occurs because the linear regression model cannot account for the physical ceiling of soil moisture absorption during extreme rainfall events, where additional precipitation no longer reduces agricultural water demand.

Consequently, it can be concluded that the individual volumetric system successfully induces substantial water-saving effects on an annual basis under normal climatic conditions; furthermore, a monthly analysis reveals that these savings are most pronounced during July, when sugarcane water requirements reach their annual peak.

4.1.2 Analysis of the Ishigaki Island Irrigation District

For the Ishigaki irrigation district, the annual dam discharge—the baseline for area-based sub-districts—was, on average, approximately 177 mm higher than the annual water withdrawal of the volumetric system district. This difference remains substantial, even when factoring in a hypothetical conveyance loss of 15%. Given that the actual water withdrawal under the area-based system is expected to be even higher than this conservative estimate, these results indicate that water consumption in the individual volumetric system district is lower than that in the area-based water charge system sub-district. Consequently, the implementation of the volumetric system can be considered to have a distinct water-saving effect.

4.2 Changes in Irrigation Fees and Variations in Water-Saving Rates by Scale of Operation Induced by the Individual Volumetric System

Figure 2 presents a box plot illustrating the individual irrigation fees based on the water withdrawal data of the 12 sugarcane farm households in the Ishigaki irrigation district. Comparing the actual irrigation fees paid under the volumetric system with the hypothetical fees under an area-based system reveals two key trends. First, in terms of median values, large-scale agricultural holdings exhibited both a greater absolute reduction in irrigation fees and a higher rate of reduction per unit area following the system's introduction. Second, larger agricultural holdings demonstrated narrower fluctuations between the maximum and minimum irrigation fees paid. These findings indicate that under the volumetric system, large-scale farmers exhibit higher sensitivity and motivation toward water conservation than small-scale farmers. Consequently, large-scale farmers actively practice highly efficient irrigation management, successfully suppressing excess water use even in dry years when the district's average water demand is typically elevated.

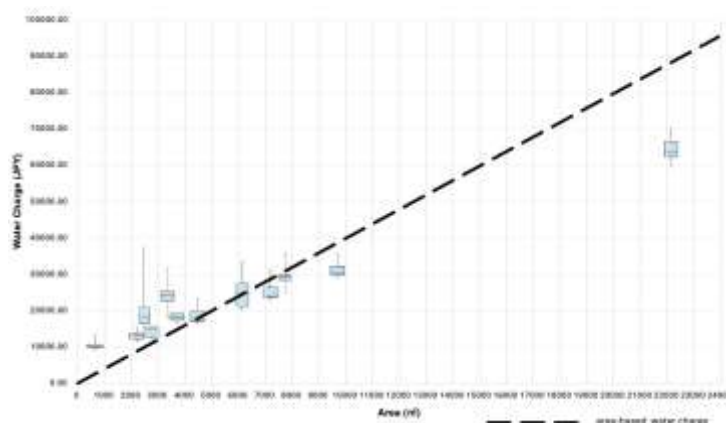


Figure 2. Comparison of irrigation fees among farm households under the individual volumetric system by cultivated acreage.

4.3 Determinants of Water Conservation Under the Volumetric System

While the individual volumetric system exhibited distinct water-saving effects, whether this outcome is driven solely by straightforward price incentives requires careful examination. Sugarcane irrigation fees account for only 1.49% of gross revenue in Miyako and 2.55% in Ishigaki; even under increased water usage, these ratios remain low. This minimal economic pressure suggests fee fluctuations impose limited financial liability, requiring alternative conservation mechanisms to be discussed. One primary factor is the effect of the farming scale. As demonstrated in Section 4.2, the absolute amount of irrigation fees reduced through water conservation is greater for large-scale farmers than for small-scale ones. Currently, sugarcane farming scales are expanding on both islands. Under these prevailing farming conditions, large-scale farmers have a stronger incentive to conserve water because the absolute financial savings derived from their efforts are substantially greater. Furthermore, in the Miyako district,

additional volumetric charges are levied if water withdrawal exceeds the threshold of 2,600 m³/ha annually. This structure likely prompted farmers to adjust their water-use behavior with a strong awareness of this baseline. Conversely, in the Ishigaki district, the irrigation fee is structurally determined in direct proportion to the volume of water withdrawn from the reservoir. In this case, the visualization of water consumption likely heightened farmers' awareness of their actual water use, thereby encouraging water-saving practices. In conclusion, the effectiveness of the volumetric system may not be attributed solely to a simple price incentive. Instead, it is highly plausible that water conservation was driven by behavioral modifications facilitated by the establishment of consumption thresholds and the visualization of water-use data.

CONCLUSION

This study analyzed the water-saving effects of the individual volumetric system by focusing on two irrigation districts in Japan, primarily characterized by sugarcane cultivation. The empirical results demonstrated that the implementation of the volumetric system successfully reduced both annual and monthly water withdrawal volumes. Furthermore, the analysis revealed that large-scale farmers, who face a more pronounced financial impact from changes in irrigation fees, achieved higher water-saving rates than small-scale farmers. While these findings clarify the substantial water-saving potential of the individual volumetric system, when this system is applied to other areas, careful consideration must be given to the following aspects: (1) adaptation to regional climate, farming patterns, and water resource availability; (2) the projected scale of localized water-saving effects; and (3) the comprehensive cost-effectiveness of system implementation.

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