Potential for and feasibility of small hydropower generation at headworks in Japan

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Abstract:

In this research, power generation potential is estimated using overflow discharge for eight headworks (Inuyama, Meiij-yousui, Muromatsubara, Kansakawa, Furikusa, Onyu, Hosokawa and Okajima) located in Aichi and Gifu Prefectures, and the characteristics of their power generation are clarified in order to evaluate the feasibility of small hydropower plants. The results are as follows. Firstly, overflow discharge is more stable than the discharge of intake water at the headworks, which suggests that power generation using overflow discharge is more suitable for actual power generation. Secondly, maximum power outputs of 43 kW to 2,002 kW, under a discharge utilization factor of 60%, show great potential for power generation at these eight headworks. Finally, fluctuations in monthly power generation are higher than that of annual power generation due to the influences of irrigation and seasonal changes in precipitation on water intake.

KEYWORDS small hydropower generation; headwork; overflow discharge; intake water; maximum power output; discharge utilization factor

INTRODUCTION

Since the accident at the Fukushima Daiiichi Nuclear Power Plant in 2011, the Japanese government has emphasized the further development of renewable energy, such as solar, wind power, thermal power, small hydropower and biomass, through the introduction of a feed-in tariff (FIT) (Goto et al., 2012). The FIT is a policy designed to accelerate investments in renewable energy technologies by offering long-term contracts to renewable energy producers (Huenteler et al., 2012; Goto et al., 2012). As an alternative source of energy, attention is increasingly being focused on small-scale hydropower generation in the agricultural sector.

There is no clear official definition exists for small hydropower facilities in each country. However, small hydropower generation is generally defined around the world as a maximum power output of 10 MW (Paish, 2002; Bockman et al., 2008). Small hydropower generation is regarded in Japan as having power output from 1 MW to 10 MW (Ministry of the Environment, 2003). According to the National Small Hydropower Promotion Council (Japanese Water Agency, 2019), power output of less than 1 MW is recognized as new energy which is supported by measures in the Renewables Portfolio Standard. The purpose of these measures are to promote the use of new energy through the obligatory utilization of a certain amount of electricity obtained from new energy by power generation industries. Here, the global definition for the most widely accepted value of power output up to 10 MW is used; it is herein referred to as small hydropower generation (SHP).

In Japan, 95% of the water used in agriculture comes from rivers (Okuda, 2010). However, it is difficult to control the amount of water intake under natural river conditions due to large changes in river water levels accompanying changes in flow rate because Japanese rivers are characterized by steep gradients and short lengths (Ueda et al., 2013). Therefore, by installing headwork across a river, the stable water level necessary for water intake can be secured, and water demand for the entire beneficiary area can be supplied downstream using gravitational potential energy. Since Japanese topography is steep, many drop works, torrent works, etc. were constructed in agricultural waterways, and SHP has been actively introduced utilizing these existing works. This kind of power generation is called the agricultural water-dependent type of power generation. It has many advantages, such as being carried out within the range of agricultural water, so it does not require the acquisition of new water rights for power generation, and it generates power using existing water supply facilities, which save construction and other costs. However, because fluctuations in flow rate between irrigation and non-irrigation periods is large with this type of power generation, it has low power generation efficiency. On the other hand, in order to maintain the river water level necessary for water intake at the headwork, surplus water (hereinafter called overflow discharge) will flow downstream by overflowing the spillway. Thus, headworks can be considered as candidate sites for high-quality power generation that can secure a certain flow rate throughout the year and a stable water level. However, only two SHP facilities have been installed at headworks in Japan to date (Miyai et al., 2018), even though there are 8,250 headworks in the coun-

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try (Ministry of Agriculture, Forestry and Fisheries, 2008). The two facilities are the Shintawaraizeki Power Plant in Okayama Prefecture, with a capacity of 2,400 kW, and the Gojyo Power Plant in Niigata Prefecture, with a capacity of 1,100 kW; they utilize the effective head and the downstream discharge (Miyai et al., 2018). The reason for the small number of SHP installations at headworks is that a certain procedure must be followed for obtaining water rights for power generation: permission must be obtained from the river manager to construct the SHP facility in the river, and the river maintenance flow rate must be considered in the area of reduced water in the actual planning. In recent years, in order to promote SHP facilities, the procedure for obtaining water rights for power generation, based on the non-agricultural water-dependent type of power generation, has been simplified (Ministry of Agriculture, Forestry and Fisheries, 2014). As a result, active introduction of small hydropower generation facilities at more and more headworks can be expected in the future. Therefore, the purpose of this research was to clarify the feasibility of SHP generation at headworks by analyzing the power generation potential and the characteristics of seasonal fluctuations at the eight representative headworks located in Aichi and Gifu Prefectures.

**MATERIALS AND METHODS**

**Introduction of research sites**

The daily overflow discharge of eight headworks located in Gifu and Aichi Prefectures has been recorded by the Land Improvement District for more than five years, as shown in Figure 1 and Table I.

Inuyama headwork (IY) is located about 59 km upstream from the mouth of the Kiso River in Aichi Prefecture. It takes water (max: 51.06 m$^3$/s) from the Kiso River to the Kotsu, Hashima and Miyata irrigation districts (total of 9,353 ha). Meiji-yousui headwork (MJ) is located about 35 km upstream from the mouth of the Yahagi River in Aichi Prefecture. It takes water (max: 42.19 m$^3$/s) from the Yahagi River to the Meiji-yousui district for agricultural, domestic and industrial use. No individual or entity is responsible for using the amount of water being discharged from MJ to the downstream of the Yahagi River; and therefore, it is possible for MJ to take the maximum amount of water as is possible within the limits of the government’s rules on water rights.

Five other headworks were constructed for the purpose of supplying water to the Toyokawa-yousui district in Aichi Prefecture. The water of the Toyokawa-yousui district is basically sourced from Ure and Oshima Dams. The water released from these dams flows to the upstream of Ohno headwork (OH). The water demand of the Toyokawa-yousui district is taken by OH for agricultural, domestic and industrial use. Kansakawa headwork (KS) takes water from the Toyokawa River to the upstream of OH. Furthermore, in the downstream of OH in the Toyokawa River, there is the Muromatsubara headwork (MM) which supplies water to Toyohashi City and its surrounding area. The catchment area for Ure Dam is too small to supply the water demand of the Toyokawa-yousui district. Thus, Onyu headwork (ON) placed in the Onyu River and Furikusa headwork (FK) placed in the Ochise River are integrated to supply water to Ure Dam. Almost all the water taken by OH is used to meet the demand for water in the Toyokawa-yousui district, for which very little overflow discharge occurs, including fishways to the downstream of OH. This is the reason why OH was not selected for the analysis of water as is possible within the limits of the government’s rules on water rights.

![Figure 1. Locations of the test headworks](image)

**Table I. Details and available data for the 8 test headworks**

| Headwork       | Location (°) | Weir height (m) | Weir length (m) | Effective head (m) | Max. intake (m$^3$/s) | Analysis duration (y.m.d~y.m.d) | Available data (days) |
|----------------|--------------|-----------------|-----------------|-------------------|----------------------|------------------------------|-----------------------|
| Inuyama (IY)   | 35.39 NL, 35.89 EL | 4.5             | 420             | 5.8               | 51.06                | 2008.1.1~2017.12.31           | 3,329                 |
| Meiji-yousui (MJ) | 35.05 NL, 35.89 EL | 5.6             | 167             | 5.6               | 42.19                | 1997.4.1~2018.03.31           | 7,669                 |
| Muromatsubara (MM) | 34.88 NL, 35.89 EL | 3.3             | 196             | 3.3               | 8.00                 | 2002.1.1~2017.12.31           | 5,842                 |
| Kansakawa (KS) | 34.97 NL, 35.89 EL | 3.9             | 58              | 3.9               | 15.00                | 2002.1.1~2017.12.31           | 5,844                 |
| Furikusa (FK)  | 35.08 NL, 35.89 EL | 2.5             | 34              | 2.5               | 15.00                | 2002.1.1~2017.12.31           | 5,691                 |
| Onyu (ON)      | 35.14 NL, 35.89 EL | 3.8             | 30              | 3.8               | 5.00                 | 2002.1.1~2017.12.31           | 5,429                 |
| Hosokawa (HK)  | 35.03 NL, 35.89 EL | 2.1             | 64              | 2.1               | 18.71                | 2012.1.1~2017.12.31           | 2,188                 |
| Okajima (OK)   | 35.48 NL, 35.89 EL | 3.3             | 162             | 3.3               | 21.70                | 2013.8.1~2018.05.31           | 1,465                 |
power generation in this research.

Hosokawa headwork (HK) is located in the Tomoe River which is a tributary of the Yahagi River and takes water (max: 18.71 m$^3$/s) for agricultural, domestic and industrial use.

Okajima headwork (OK) is located about 60 km upstream from the mouth of the Ibi River in Gifu Prefecture, and takes water (max: 21.71 m$^3$/s) from the Ibi River to the Seino irrigation district (5,332 ha).

**Methods**

The daily overflow discharge is expressed as a percentage value which is defined as an exceedance probability (%). The relationship between the discharge utilization factor (%) and the exceedance probability of the overflow discharge (%) was obtained as seen in Figure 2a when the corresponding daily overflow discharge was used as the maximum discharge for power generation.

Here, “discharge utilization factor” is an index expressed as the mean actual discharge divided by maximum discharge. The “mean actual discharge” is the average daily discharge throughout the year under the upper limitation of the maximum discharge, while the “facility utilization factor” is represented by the actual power generation divided by possible power generation. The “possible power generation” means the annual amount of power generation produced under the maximum power output (kW) throughout the year, and the “actual power generation” means the amount of power generation that is produced by the actual discharge at the headwork under the limitation of the above-mentioned maximum discharge. It is obvious that the facility utilization factor increases with the decrease in the maximum power output produced by maximum discharge. According to the nonlinear relationship between the discharge and the power output, the facility utilization factor is 5% to 10% (median value: 7.5%) smaller than the discharge utilization factor (New Energy Foundation, 2013).

In formulating the power generation plan, the facility utilization factor is adopted as being from 45% to 60% (median value: 52.5%) (Ministry of Economy, Trade and Industry Agency for Natural Resources and Energy, 2005). In this analysis, the discharge utilization factor was assumed as the sum of the two median values, namely, 60% (= 52.5% + 7.5%), in order to obtain the maximum power output. Power generation was estimated using this maximum power output.

The analytical method employed was used by Wang et al. (2018) to analyze the power generation potential, as described below. Using the effective head and the daily overflow discharge (Table I), the power output was calculated with the following equation:

$$P = g \times \eta \times Q \times H$$

($P$: power output [kW], $g$: gravitational acceleration [m/s$^2$], $\eta$: general efficiency (= 0.72), $Q$: flow rate [m$^3$/s] and $H$: effective head [m]).

Here, the effective head of IY and MJ was assumed to be the difference between the upper and lower water levels, namely, 5.8 m and 5.6 m, respectively. For the other six headworks (MM, KS, FK, ON, HK and OK), the weir height was used as the effective head (Table I). The general efficiency is expressed by the product of the turbine efficiency and the generator efficiency. According to the Hydro Valley Plan Guidebook (Ministry of Economy, Trade and Industry Agency for Natural Resources and Energy, 2005), turbine efficiency is 0.75 to 0.90 (average value: 0.825) for small and medium hydraulic turbine generators and the generator efficiency is about 0.82 to 0.93 (average value: 0.875); therefore, the general efficiency is 0.72 (= 0.825 $\times$ 0.875).

The maximum power output with a discharge utilization factor of 60% at each headwork is determined in the following two steps. Firstly, the exceedance probability of the overflow discharge, corresponding to a discharge utilization factor of 60%, is obtained as shown in Figure 2a. Secondly, the maximum power output corresponding to each exceedance probability of the discharge utilization factor (60%) is obtained as shown in Figure 2b. Furthermore, the exceedance probabilities for the intake discharge with a discharge utilization factor of 60% were also obtained in order to compare them with the exceedance probability of the overflow discharge.
The annual and monthly power generation at each headwork were estimated under the upper limitation of the maximum power output. The effective heads adopted in this analysis are assumed to be the difference between the upper and lower water levels and the weir heights at the headworks, as previously mentioned, which could be considered the minimum values for SHP generation. This is because, when an SHP generation facility is actually installed at a headwork, if the overflow discharge is taken at the headwork and led downstream by a canal, the difference between the water surface heights of the canal and the river near the canal must be increased to a level higher than the effective head of the headwork.

RESULTS AND DISCUSSION

Maximum power output with discharge utilization factor of 60%

Figure 2a shows the relationship between the exceedance probability and the discharge utilization factor, and Figure 2b shows the relationship between the exceedance probability and the maximum power output. The exceedance probability of the overflow discharge corresponding to a discharge utilization factor of 60% varied from 18.2% (OK) to 32.0% (MJ). The maximum power output corresponding to each exceedance probability of the discharge utilization factor (60%) ranged widely from 43 kW (FK) to 2,002 kW (IY). The results are summarized in Table II. However, even if the maximum output shown in Table II was adopted, the discharge utilization factor would be less than 60% when unexpected droughts with more than a 21-year return period occur.

The exceedance probabilities of the intake discharge with a discharge utilization factor of 60% were 57.2% (IY), 31.3% (MJ), 36.7% (MM), 25.6% (HK) and 30.0% (OK), respectively. The intake discharge at KS, FK and ON headworks were quite small compared to those of the overflow discharge, so the exceedance probabilities of the intake discharge at these three headworks were not analyzed in this study. The exceedance probability of the intake discharge was almost equal to or greater than that of the overflow discharge, which shows that the overflow discharge was more stable than the intake discharge, because the lower the exceedance probability, the greater the discharge available for maximum power output. Based on the above, it is supposed that the power generation using the overflow discharge was more stable than that using the intake discharge, and thus, overflow discharge is more suitable for actual power generation at these headworks.

Annual and monthly power generation under the discharge utilization factor of 60%

Table III shows the annual and monthly power generation at each headwork using the maximum power output. The maximum power output ranged widely from the smallest value of 43 kW (FK) to the largest value of 2,002 kW (IY), which shows great potential for power generation at these eight headworks. This is because the maximum power output, due to the use of water for agriculture, was less than 1,000 kW at around 90% of the SHP facilities that were installed from 1915 to 2015 (Miyai et al., 2018). Moreover, this maximum power output is directly related to the amount of power generation. When the maximum power output is larger, a greater amount of power generation can be obtained. It is shown in Table III that both the annual power generation and the monthly power generation were the largest at IY followed by MJ, MM, KS, OK, ON and FK.

The ratio of the standard deviation to the average of the annual power generation and the monthly power generation in Table III expresses the fluctuation rate of the power generation. For the annual power generation, the fluctuation rates fell in the range 0.14 to 0.39, with the average fluctuation rate being 0.21. For the monthly power generation, the fluctuation rates fell in the range 0.25 to 0.39, with the average fluctuation rate being 0.32. The fluctuation in the monthly power generation is thus greater than that in the annual power generation.

The maximum monthly power generation of MJ, MM and HK occurred in October, that of IY in March and that of OK in April (Table III). The irrigation period is generally from April/May to September/October, when the intake water from the headwork increases greatly due to irrigation. As a result, the amounts of overflow discharge at the headworks reached their peak in the months just before and just after the irrigation period. The power generation amount also reaches its peak accordingly. The maximum monthly power generation at KS, FK and ON occurred in July (Table III), when the precipitation reached its peak level, and there was very little water intake from these headworks to the beneficiary area in the downstream relative to the overflow discharge.

The minimum monthly power generation occurs separately in June (IY; MJ, HK and OK) and in January (MM, KS, FK and ON) (Table III). During the irrigation period, especially in June, a large amount of agricultural water is taken from the headworks, and the overflow discharge and power generation are minimal compared to the other months. As for the other three headworks (KS, FK and ON) in Toyokawa-yousui, there is no direct water intake for the beneficiary area downstream. Just a small amount of water is led into the upstream of Ure Dam and OH headwork.

### Table II. Maximum power output (kW) for a discharge utilization factor of 60%

| Headwork | IY | MJ | MM | KS | FK | ON | HK | OK |
|----------|----|----|----|----|----|----|----|----|
| Exceedance probability (%) | 23.7 | 32.0 | 26.0 | 27.7 | 24.6 | 26.6 | 27.6 | 18.2 |
| Overflow discharge (m³/s) | 45.7 | 23.5 | 18.9 | 5.7 | 2.4 | 3.2 | 11.1 | 5.8 |
| Maximum power output (kW) | 2002 | 947 | 468 | 168 | 43 | 91 | 167 | 143 |
downstream. In addition, precipitation is the lowest in the winter season, especially in January; consequently, the overflow discharge and the power generation potential are the smallest during this month.

In order to clearly compare the fluctuation in monthly power generation among the headworks, the ratio of the average power generation of each month (Gm) to the average annual power generation (Gy) is expressed in Figure 3, which shows that there are two types of monthly changes in power generation. In the first, power generation in the irrigation period is lower than that in the non-irrigation period, such as for IY, MJ, MM, HK and OK headworks. In the second, power generation in the summer season is higher than that in the winter season, as for KS, ON and FK headworks. These two types of monthly changes are mainly influenced by two factors, namely, the amount of water intake in the irrigation period and seasonal rainfall fluctuations.

### CONCLUSIONS

There is potential for SHP generation at headworks in Japan because of the advantage of overflow discharge and existing headwork infrastructure. In this research, eight headworks located in Aichi and Gifu Prefectures were selected (Inuyama, Meiji-yousui, Muromatsubara, Kansakawa, Furikusa, Onyu, Hosokawa and Okajima) for an evaluation of their power generation potential. The difference between the upstream and downstream water levels and the weir heights at the headworks was assumed to represent the effective head. The maximum power output for the SHP was determined under a discharge utilization factor of 60%, and annual and monthly power generation were calculated. This revealed, firstly, that the exceedance probabilities of the overflow discharge ranged from 18.2% to 32.0% and intake discharge from 25.6% to 57.2%. This means that overflow discharge is more stable than the intake discharge usually applied to SHP generation. This is because a large amount of water is taken during the irrigation period for paddy fields, but the intake discharge shows an extreme decrease and sometimes there is no intake during the non-irrigation period. Meanwhile, the overflow discharge at the headworks decreased mainly due to the amount of intake for irrigation, but it increased due to the runoff discharge from the upstream areas due to precipitation. Furthermore, the overflow discharge sometimes functions as a river maintenance discharge during the year and the water is used for agricultural, domestic and industrial purposes.
purposes at the downstream area. Secondly, the maximum power output ranged from 43 kW to 2,002 kW, which demonstrates great potential for power generation at these eight headworks. However, fluctuations in both the annual and monthly power generation were evident, with the annual fluctuation smaller than the monthly. The monthly fluctuations in power generation were mainly influenced by two factors: the amount of water intake during the irrigation period and seasonal rainfall fluctuations. These factors cause two patterns in monthly power generation: (1) power generation that is smaller during the irrigation period when a large amount of agricultural water is taken and (2) power generation that is larger in the summer season because there is indirect water intake in the beneficiary areas and the precipitation rate is higher in summer.

ACKNOWLEDGMENTS

This research was supported by the United Land Improvement District of Seinou-yousui, the Land Improvement District of Meiji-yousui, Aichi Prefecture, and the Japan Water Agency Toyogawa Canal Management & Construction Department.

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