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REVIEW

Perspectives of Small-scale Hydropower Generation Using Irrigation Water in Japan

Tatsuki UEDA*, Masahiro GOTO, Atsushi NAMIHIRA and Yuichi HIROSE

Renewable Resources Engineering Research Division, National Institute for Rural Engineering, National Agriculture and Food Research Organization (NARO) (Tsukuba, Ibaraki 305–8609, Japan)

Abstract

This study aims to review previous studies and projects on hydropower generation using irrigation canals in Japan, and discusses their future perspectives. The Japanese agricultural sector uses around two thirds of the total water abstracted, which is channeled through dams, headworks, as well as 40,000 km of canal networks. Although such infrastructure would collectively have significant hydropower generation potential, it has attracted scant attention, due to the relatively low individual potential at each site. To effectively utilize such small and diffuse potentials, we would need to: (1) develop small waterwheels operable with small water heads and low flow rates; (2) develop techniques to identify suitable waterwheel sites within an existing canal system taking channel slopes and sidewall heights and seasonal variations in flow rates into consideration; (3) investigate the possibility of locally utilizing electricity on a micro-scale of a few kW, rather than selling it to the grid; and (4) modify the water management scheme where possible by, for instance, smoothing out flow rates across seasons and thus increasing the cost-effectiveness of power generation.

Discipline: Agricultural engineering
Additional key words: irrigation canal, paddy field, water management, waterwheel

Introduction

Japan, located within the Asian monsoon climate region, is endowed with rich water resources and has an average annual rainfall of around 1,700 mm. It is an island nation with high mountain ranges and short steep rivers that discharge rainwater into the sea relatively swiftly. Such topography necessitates careful control of water with dams and canals to effectively utilize water resources for irrigation. Accordingly, Japanese agricultural engineers have constructed around 40,000 km of major irrigation canal networks (or 400,000 km including branch canals)[7] for distributing irrigation water to farmlands, within the auspices of the Farmland and Rural Improvement Project subsidized by national and local governments[9].

Such infrastructure constitutes significant hydropower generation potential. However, hydropower development in Japan to date has been dominated by large- and medium-scale hydropower stations (with purpose-built hydropower dams), with output exceeding 10 MW and comprising 84% of existing hydropower capacities[1]. Conversely, hydropower generation using irrigation infrastructure remains sporadic, partly because the output of each station would be relatively small, mostly less than 1,000 kW, and it is thus considered less cost-effective.

Nevertheless, waterwheels were traditionally a popular means of obtaining power in rural areas in Japan. For instance, in 1942, around 78,000 waterwheels were in operation along irrigation canals and small streams, supplying power for rice milling etc., while right after World War II, more than 200 small hydropower plants were constructed in remote rural areas, still beyond the reach of grid power at the time[3].

Utilizing such small but plentiful hydropower resources scattered across rural areas is now attracting increasing attention, reflecting the need to cut greenhouse gas emissions and build robust power generation systems in case of big natural disasters. This report therefore aims to review studies on hydropower generation potential in Japan using irrigation infrastructure and discuss future related perspectives, as well as possible barriers to fur-

*Corresponding author: e-mail tued@affrc.go.jp
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ther development. To focus the arguments, we will concentrate on small-scale hydropower generation using irrigation canals, the power sector facing distinctive problems, as will be discussed in the following sections. Although part of the discussions may only be relevant to the natural and socioeconomic conditions in Japan, some arguments may also apply to other countries, especially in rice-producing monsoon Asia.

Existing small hydropower plants within irrigation canal systems

Although still sporadic, twelve small hydropower plants were constructed (as of 2005) in irrigation canal systems, within the scope of the Farmland and Rural Improvement Project (Table 1). These plants have output capacities exceeding 200 kW, which is generally considered the minimum to ensure economic viability, given the electricity sale price[a] of around 10 Yen/kWh[5]. As the flow rates of irrigation canals in Japan are relatively low, generating output on such a scale requires a large water head[b,c]. In fact, existing plants in Table 1 have water heads of between 5.5 and 117 m, with an average of 44.3 m. Obtaining such a water head within a canal system generally requires bypassing open canals with tunnels and pipelines (Fig. 1)[d]. Accordingly, most existing plants were installed when part of the canal network was replaced with pipelines, with water turbines suitable for such conditions (Table 1).

Micro-scale hydropower potentials along branch open channels

The previous section showed that all existing hydropower plants were installed by connecting two points in a canal system via a tunnel and/or pipeline, thereby obtaining a large water head. Nevertheless, constructing such plants and associated structures not only involves significant civil engineering work, but also prevents the diversion of water for irrigation in the middle of a pipelined segment of channel (Fig. 1). These conditions often discourage attempts to generate electricity on a micro-scale in the lower reaches of a canal network, along branch and distributary (on-farm) canals. Thus, the hydropower potential at such sites has largely been neglected to date, except for certain experimental or demonstrational projects. This section therefore envisages the feasibility and issues surrounding such hydropower generation.

The characteristics of such sites (branch and distributary canals) can be summarized as follows:

1. The flow rates running through them are relatively low, typically less than a few tons per second.
2. Most of the branch canals supplying water to paddy fields are open[e]. Furthermore, channels located in steep alluvial fans tend to have many small drops and chutes[f] (Fig. 2), typically less than a meter in height.
3. Flow rates running through those channels often fluctuate across seasons (e.g. Horikawa et al.[6]). In many regions, the water flow is also completely suspended

a Until July 2012, the sale price had been determined through individual negotiations between a plant operator and a grid power operator. However, a new feed-in-tariff (FIT) scheme, in which electricity companies are obliged to buy renewable energy, including small hydropower, at a prescribed price, has been introduced since July 2012 in Japan. Under the new scheme, the sale prices of small hydropower are set at 34, 29 and 24 Yen/kWh (FY2012) for an output scale <200 kW, 200-1000 kW and 1000-30000 kW, respectively, which exceed current prices.

b [Theoretical electricity output (kW)] = 9.8 × [flow rate (m^3/s)] × [water head (m)]. The actual output is less than this figure due to energy losses in waterwheels, power generators, friction in pipes etc.

c The water head is the measurement of energy contained in a fluid, expressed in terms of the height of a water column, and defined as the sum of the elevation head, pressure head and velocity head. However, for a pipeline, it is usually approximated by: [the difference in elevations between both ends (intake and discharge points) + water depth at the intake] × [a conversion (loss) factor]. For an open channel accommodating a waterwheel, calculating the available water head is relatively difficult, but it is roughly equivalent to: [the difference between water surface levels just upstream and downstream of a waterwheel] + [velocity head, i.e. the energy of moving fluid running through the wheel].

d This is because a pipeline can convert an elevation head (i.e. the energy of water sitting on higher ground) to a pressure head at the lower endpoint, thereby generating a significant water head if there is a considerable difference in elevation between both ends of the pipe (see footnote (c)). In contrast, for an open channel, it is often difficult to obtain a water head of more than a few meters, as the head is essentially restricted by the slope and flow velocity of the channel.

e Pipeline systems at on-farm levels have also become popular in recent decades, partly because they allow more flexible irrigation schedules for farmers. However, generating hydropower at such sites is difficult, given the tendency for intermittent water flows and is hence not covered here.

f These facilities are aimed at rendering a canal slope within the safety limit. In other words, they are installed where the ground slope is so steep that the water flow speed would be excessive without them.

Table 1. Existing small hydropower generation plants using irrigation canals

Project	Water head	Max. flow rate	Max. output	Pipe length[a]	Intake point	Discharge point	Type in Fig. 1	Water turbine
	m	m^3/s	kW	km				
Ohnobaru	117.0	0.3	260	5.27	dam	canal	1	Pelton
Yasukawa	21.0	4.0	640	0.40	division work	canal	4	Francis
Nishime	116.0	0.8	740	0.82	headwork	farm pond	2	Francis
Aimoto-shin	33.0	2.0	530	1.44	canal	canal	3	Francis
Nasuno-gahara	28.0	1.6	340	1.40	canal	farm pond	2	Francis
Kamigo	12.7	6.5	640	1.57	canal	canal	3	Tubular
Shimeno	8.0	8.6	550	1.29	division work	canal	4	Tubular
Gojou	24.0	5.4	1,100	0.67	headwork	canal	3	Francis
Kanonomata	60.3	2.0	960	2.58	dam	canal	1	Francis
Kawakoda	19.0	5.0	720	0.16	n/a	n/a	-	Francis
Asaka-sosui	87.3	3.2	2,260	n/a	canal	canal	3	Francis
Shichika-yosui	5.5	15.0	640	0.45	canal	canal	3	Tubular
Average	44.3	4.5	782					

Source: NIRE (2010)[11]
Note: [a] The length of tunnels and/or pipelines connecting the intake point and the hydropower plant.

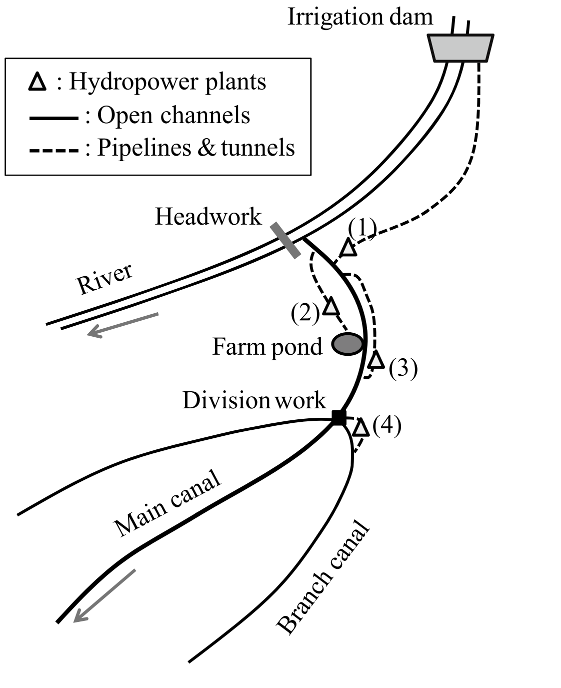

Fig. 1. Schematic diagram of possible hydropower generation sites in an irrigation canal system

Type (1): Irrigation water is delivered from a dam reservoir to a canal system via a tunnel and/or a pipeline instead of a river and downstream headwork.
Types (2) and (3): A segment of main canal (open channel) is bypassed through a tunnel and/or a pipeline. Water can also be discharged into a farm pond (Type 2).
Type (4): Just downstream of a division work, a large water head is sometimes available, depending on the local topography. At such points, chutes can be replaced by pipelines.

Fig. 2. Examples of a chute (top, Toyama Prefecture) and a drop (bottom, Tochigi Prefecture) along an irrigation channel

during the non-irrigation season from September to April.
4. Canal systems are generally managed by the Land Improvement District, which is a public organization of farmers using irrigation water via the canal[7].

The possible implications of the above characteristics on hydropower generation are as follows:

1. As mentioned in footnote (d), the available water head when placing a waterwheel in an open channel is mostly less than a few meters, even where drops or chutes are available. Such a small water head, combined with the low flow rate of typical branch canals, imply that the potential electricity outputs at each site would likely be less than a few kW (see footnote (b)), which naturally increases the unit cost of power production.
2. Irrigation canals are actually aimed and designed to facilitate the passage of irrigation water to farmlands. However, a waterwheel installed in an open channel essentially hinders such smooth water flow and tends to raise water levels immediately upstream[2] (called "backwater"). Besides, trash flowing down a channel may choke waterwheels, thereby further obstructing the water flow[2]. Although the depths of open channels are normally designed with some safety margin to prevent overflows due to heavy rain etc., the backwater induced by a waterwheel should be contained within that margin. In other words, we must carefully balance the two competing objectives of canals, namely smooth water conveyance and hydropower generation.
3. Seasonal fluctuations in flow rates result in corresponding fluctuations in output, which not only inconvenience electricity users, but are also likely to reduce the extent to which dynamo capacity can be utilized (as it cannot be operated at full capacity all the time), which tends to increase the unit cost of power generation.
4. The fact that irrigation canals are managed by farmers themselves implies that farmers have incentives to develop hydropower generation, as they could be the main beneficiaries of the project.

The above discussions suggest the following future trajectories for technological development and water management strategies:

1. We should develop technologies for small waterwheels or turbines suitable for generating electricity on a micro-scale with a low water head (< 1 m or so) and a low flow rate (< 1 m^3/s or so), to reduce costs as much as possible. First, when a waterwheel is to be placed onto a canal bed (without a drop or chute), its impact on water flow (i.e. backwater) peaks. Under such circumstances, therefore, the major options currently available are limited to paddle (undershot) wheels (Fig. 3) or their variants. More recently, the National Institute for Rural Engineering developed a "cascade turbine"[4] (Fig. 4) capable of generating around 1.0 to 1.5 kW of electricity at a flow rate of 1.5 m^3/s and a water head of 0.2 m. Second, when a waterwheel can be placed at a small drop or chute, a wider range of options may be available, such as Archimedes wheels (Fig. 5), breast-

Fig. 3. A paddle (undershot) wheel (Tochigi Prefecture)
Max. output: 1.8 kW; flow rate: 0.6 m^3/s; diameter of wheel: 6 m.

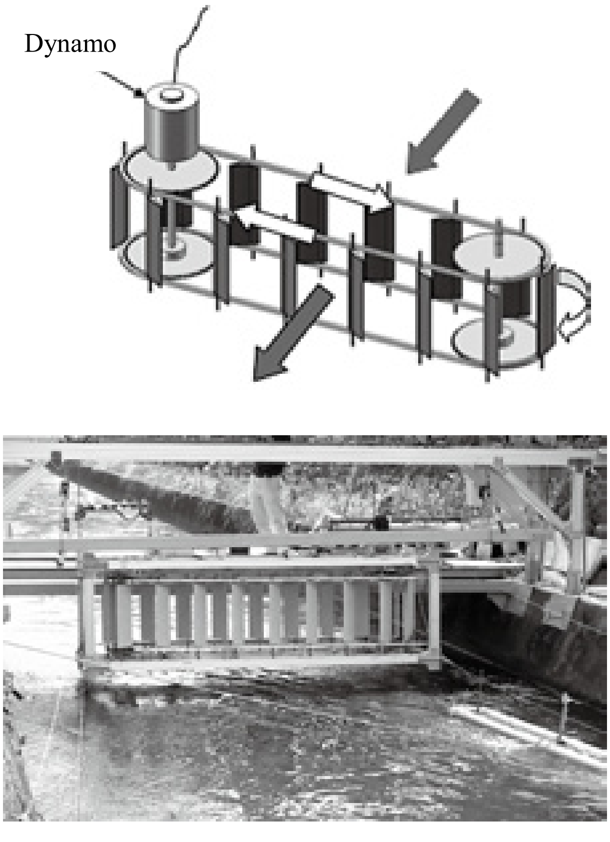

Fig. 4. A cascade turbine[4]
Output: 1.0 to 1.5 kW; flow rate: 1.5 m^3/s; water head: 0.2 m.

shot/overshot wheels (Fig. 6) and crossflow wheels. In addition, some variants of propeller turbines fitted in a tube may also be installed if the conditions (drop and flow rate) allow (Fig. 7).

2. We have argued that accommodating waterwheels in an irrigation channel is a relatively tricky issue, because they tend to induce backwater upstream. Therefore we must develop techniques to identify suitable sites for installing waterwheels within an existing canal system, by taking into account channel slopes and sidewall heights, as well as seasonal variations in flow rates. Furthermore, it would be useful to develop a method to redesign a canal system and optimize it with respect to hydropower generation[3], in case the canal should undergo renovations sometime in future.
3. To increase the economic viability of micro-scale hydropower generation (e.g. <50 kW), it is worth considering utilizing electricity locally, rather than selling it to the grid. This is because, if the electricity were to be sold to the grid, the grid-operating company would often demand a steady output, which would, in turn, necessitate the installation of expensive power regulators at each site. Besides, a long power line would be necessary for transmitting electricity from distant sites to the grid. Therefore, it was alternatively proposed that such micro-scale electricity might as well be utilized for directly recharging electric farming machines[3] such as lawnmowers. Since irrigation canals are often managed by farmers' organizations, such electricity utilization could earn their consensus. However, since few studies have demonstrated this kind of combined system comprising micro-hydropower and electric farming machines, the conditions to ensure economic viability should be investigated.
4. As we have discussed, seasonal variations in water flow tend to reduce the cost performance of hydropower generation. Therefore, if there were some spare flow capacity in rivers to be diverted to irrigation systems in winter, it would be worth considering using such water for continuous power generation in channels[5]. Furthermore, it may be a good idea to potentially seek a means of smoothing out flow rates during the irrigation season by adjusting the irrigation schedules of each farm plot.

Fig. 5. An Archimedes wheel (Yamanashi Pref.)
Max. output: 7.3 kW; max. flow rate: 0.99 m^3/s; water head: around 1.0 m; length of wheel: 2.89 m; diameter: 1.6 m.

Fig. 6. An overshot wheel (Yamanashi Pref.)
Max. output: 19 kW; max. flow rate: 0.99 m^3/s; water head: around 3.5 m; diameter of wheel: 3 m.

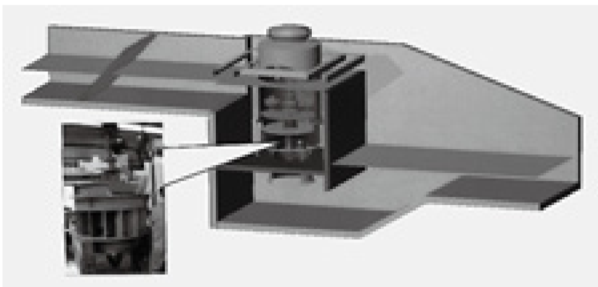

Fig. 7. Water turbine (Kaplan) installed at a drop along an open channel (Tochigi Pref.)
Max. output: 30 kW; water head: around 2 m; max. flow rate: 2.4 m^3/s.

Estimation of hydropower generation potential using irrigation canals

We claimed that designing hydropower generation using an irrigation canal would require careful consideration of its main function, i.e. smooth water conveyance to farmlands. The mere existence of a sloping canal is not therefore sufficient to install a waterwheel on-site. For this reason, estimating the hydropower potential in irrigation canals is not straightforward, despite having been attempted in a few studies to date. For instance, the MOE[8] inferred the potential from the estimated slopes of canals using a geographical information system (GIS), whereas NEF[10] evaluated the same by aggregating the capacities of each potential site, such as drops, chutes and pressure reducers, based on questionnaires to the Land Improvement Districts operating the canal systems. Their different approaches resulted in significant discrepancy among the total potential estimates across Japan: 299 MW by MOE[8] versus 21 MW by NEF[10]. It is suspected that MOE[8] would not sufficiently consider the specification details of canal systems (like the backwater issue) as such information is not available in GIS, whereas NEF[10] might possibly fail to list every potential site since they relied on the questionnaire. Future studies should thus seek a method to estimate this potential more reliably and precisely.

Conclusions

This study has discussed the utilization of small and diffuse hydropower potentials using irrigation canals. Such hydropower generation differs from other types in that we must carefully balance two competing objectives of the canals: smooth water conveyances and power generation. Therefore, we should develop a methodology to locate waterwheels and turbines, as well as optimize water management, whilst maintaining that balance.

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