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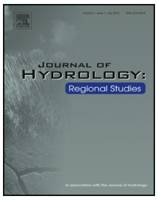

Assessment of the potential for developing mini/micro hydropower: A case study in Beppu City, Japan

Masahiko Fujii [a,*], Soichiro Tanabe [b,c], Makoto Yamada [d], Taketoshi Mishima [e], Takahiro Sawadate [b], Shinji Ohsawa [e]

[a] *Faculty of Environmental Earth Science, Hokkaido University, N10W5, Kita-ku, Sapporo, Hokkaido 060-0810, Japan*
[b] *Graduate School of Environmental Science, Hokkaido University, N10W5, Kita-ku, Sapporo, Hokkaido 060-0810, Japan*
[c] *Now at Satake Corporation, 2-30 Saijo Nishihonmachi, Higashi-Hiroshima, Hiroshima 739-8602, Japan*
[d] *The Research Institute for Humanity and Nature, 457-4 Motoyama, Kamigamo, Kita-ku, Kyoto, Kyoto 603-8047, Japan*
[e] *Beppu Geothermal Research Laboratory, Institute for Geothermal Sciences, Graduate School of Science, Kyoto University, 3088 Noguchibaru, Beppu, Oita 874-0903, Japan*

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ABSTRACT

Study region: Beppu City, Oita Prefecture, Japan was selected as a site of this study.
Study focus: This study aims to provide quantitative guidelines necessary for capacity building among various stakeholders to minimize water-energy conflicts in developing mini/micro hydropower (MHP), a baseload renewable energy that is socially necessary, not only to reduce greenhouse gas emissions but also to vitalize local economies by creating jobs related to MHP operations. Using three different methods to calculate river water levels and discharges, the potential power generation by MHP was estimated for six rivers in Beppu City.
New hydrological insights: Our results show that installation of MHP facilities can provide stable electricity for tens to hundreds of residents in local communities along the rivers. However, the results are based on the existing infrastructure, such as roads and electric lines. This means that greater potential is expected if additional infrastructures are built to develop further MHP facilities. On the other hand, in Japan, river laws and irrigation right regulations currently restrict new entry by actors to rivers. Therefore, to further develop MHP, deregulation of the existing laws relevant to rivers and further incentives for business owners of MHP facilities, along with the current feed-in tariffs, are required. Meanwhile, possible influences to riverine ecosystems when installing new MHP facilities should also be taken into account.

1. Introduction

1.1. Renewable energy

Reduction of man-made greenhouse gas emissions to the atmosphere is necessary to mitigate global warming and ocean acidification. As the energy transformation sector is one of the largest CO_2-emitting industrial sectors, and CO_2 is the most

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* Corresponding author.
E-mail address: mfujii@ees.hokudai.ac.jp (M. Fujii).

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influential anthropogenic greenhouse gas, shifts from thermal power generation using coal, oil, and natural gas to less CO_2-emitting power generation are socially required.

Japan is the world's fifth most CO_2-emitting country, and therefore has a large responsibility to reduce greenhouse gas emissions. Until the end of the 2000s, the Japanese government attempted to reduce CO_2 mainly by shifting from thermal power generation to nuclear power generation. However, after the great east Japan earthquake on March 11 2011, and the following accident of the Fukushima Daiichi Nuclear Power Station, all nuclear power plant operations in domestic Japan have stopped. Instead, dependence on thermal power generation has increased after the great east Japan earthquake, leading to greater CO_2 emissions.

Considering the current situation, development of renewable energy is crucial and pressing. For this purpose, the Japanese government introduced a feed-in tariff (FIT) in July 2012. The strategy attained certain results by providing economic incentives for developing renewable energy, but the effect was relatively limited, primarily to solar power, with little development of other renewable energy sources.

On the other hand, Japan has great potential for developing mini/micro hydropower (MHP). MHP is favorably located at sites with steep geographies and sufficient water, and Japan has a considerable number of favorable sites from this point of view. The main reasons that MHP has not been well developed are the lack of incentives and the many obstacles. For example, to install new MHP facilities, sufficient consensus building with local stakeholders is necessary. The contentions differ among nations and regions with different situations, but in Japan most are strongly related to irrigation rights, fish rights, and riverine ecosystems.

Our ultimate intent is to provide scientific and objective guidelines for developing policy and management options that maximize security and minimize risk within the water–energy-food nexus (Taniguchi et al., 2013), especially focusing on conflicts and trade-offs between energy generated by MHP and food represented by riverine resources such as salmon, trout, eel and sweetfish. The purpose of this study is to establish methods of estimating the potential power generation from MHP that are simple and universal enough to be applied to various regions, both inside and outside Japan. Most previous studies that assessed power generation potential used geographic information systems (GIS) without explicit consideration of artificial influences to river discharge. However, to build a concrete consensus with stakeholders in installing new MHP facilities, scientific, objective, and quantitative data about the effectiveness of MHP in advance are needed. This study aims to provide guidelines based on natural science insights, focusing particularly on the potential power generation, which is information necessary for the next step of consensus building with local stakeholders.

1.2. *Mini/micro hydropower*

In this study, we focus on MHP, the capacity of which is less than 1000 kW, as defined by the New Energy Law established in 1997. Compared to solar power and wind power generation, MHP has several advantages. First, MHP generation is not strongly affected by weather and the capacity operating rate is as high as 70%. Second, the life cycle CO_2 emission in generating 1 kWh of electricity is 11 g-CO_2, one of the lowest among the various energy sources (Imamura and Nagano, 2010). Third, unlike nuclear power plants, MHP does not require advanced techniques to facilitate and operate, which means that the installation and operation can be done by local communities, leading to local vitalization by creating jobs related to MHP operations.

Until the 1950s, hydropower was the most effective electric energy source and there were many MHP facilities in Japan. Most of the MHP facilities were located in mountainous regions with steep geographies. This is because a natural head and a large amount of running water are necessary to generate electricity effectively, as described in Section 2.3. The rapid decline of MHP after the 1960s was primarily due to Japan's electric energy policy toward thermal and nuclear power.

Therefore, unlike other renewable energy sources, MHP is not "new energy", and the technology is well developed and has the potential to be an important electric energy source once incentives to develop MHP facilities begin again in the future to reduce dependency on thermal and nuclear power.

1.3. *Study site*

Most previous studies assessing the potential power generation by MHP have used GIS and focused on mountainous regions because such regions generally have steep geographies and rivers that provide natural heads, and therefore, high potential power generation is expected (e.g., Larentis et al., 2010; Yi et al., 2010; Punys et al., 2011). However, if we consider that MHP has an operating life of tens of years and that electricity supply structures are expected to shift from central (such as thermal and nuclear power plants) to more distributed and local facilities in the future, it is possible that MHP facilities would be installed further downstream on rivers near villages and towns, as well as upstream, which would have greater potential power generation, but fewer people. In installing MHP facilities downstream, we might need to consider the human impacts on the rivers and MHP facilities. However, such considerations have rarely been taken into account in previous studies.

This study was performed in Beppu City, Oita Prefecture, Japan. Beppu City is famous as the world's second largest source of thermal spring water, following Yellowstone National Park in the United States of America. Beppu City has both the most headsprings and the most hot springs in Japan. The hot springs attract 8,000,000

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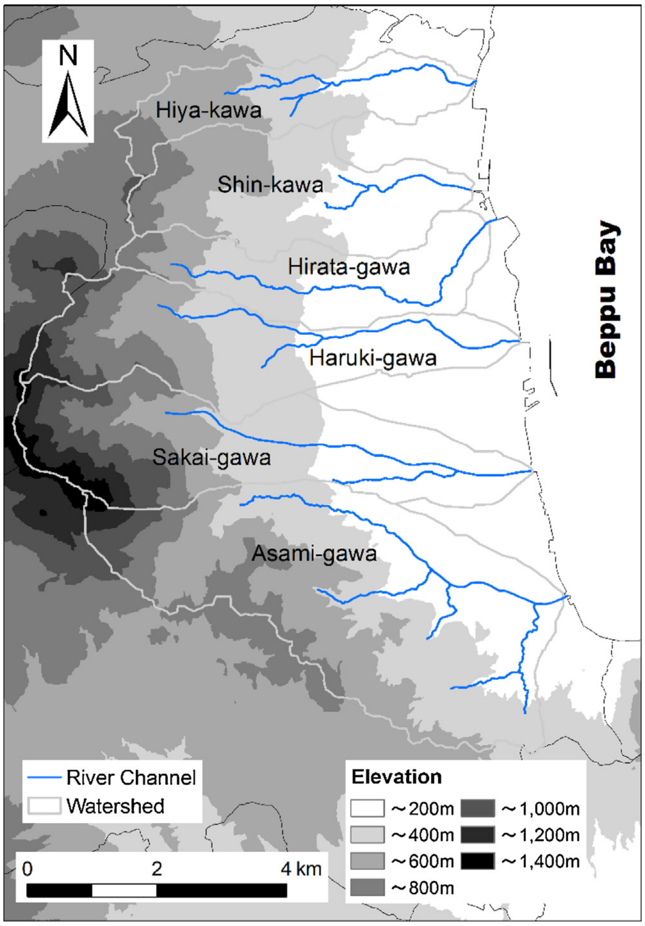

Fig. 1. Location of the six rivers and their watersheds in Beppu City.

tourists yearly to the city, which has a population of only 121,000 (Beppu City Tourist Information Website; https://www.city.beppu.oita.jp/02kankou/english/index.html).

There are six rivers running through Beppu City, the Hiya-kawa River, Shin-kawa River, Hirata-gawa River, Haruki-gawa River, Sakai-gawa River, and Asami-gawa River, from north to south (Fig. 1). As the city lies between mountains and the ocean, all of the rivers have relatively steep gradients, which would be beneficial to the development of MHP. However, their lengths are short, from 3 to 6 km, and human activities directly affect the rivers by discharging hot spring and domestic wastewater. The impacts of hot spring wastewater on the rivers are unique to Beppu City (e.g., Kawano, 1998; Ohsawa et al., 2008, 2009; Yamada et al., in this volume). Higher water temperatures and additional inputs of nutrients have resulted in several kinds of tropical fish that are not indigenous to Japan being found in several rivers in Beppu City (e.g., Hiramatu et al., 1994; Yamada et al., in this volume).

2. Methodology

We estimated the water level, discharge, and potential power generation by MHP at the point 500 m from the mouth of each river, as described below in detail. We chose the point in several reasons: downstream of the points 500 m from the mouth of rivers in Beppu City is not appropriate for MHP installation because the points are flat without sufficient natural head, and tidal effects are significant. On the other hand, most of upstream of the points 500 m from the mouth of rivers in Beppu City is not appropriate for MHP installation, either, because the geography is too steep to install and maintain the MHP facilities, and there is relatively little river discharge. The study period was from May to December 2014.

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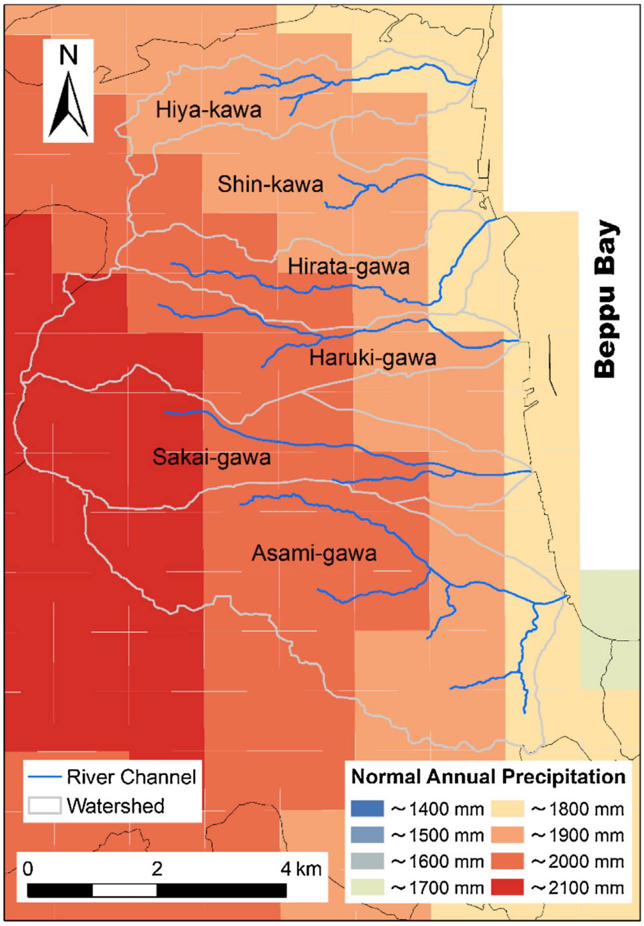

Fig. 2. Annual precipitation (mm year^{-1}) in Beppu City.

2.1. Water level

Using a water level logger (Onset HOBO U2 water level data logger), the water level of each river was continuously measured every 30 min at the points 500 m from the mouths of each river. Hourly water level data provided by a telemeter system of the Ministry of Land, Infrastructure, Transport, and Tourism was also referred to for Asami-gawa River.

2.2. Discharge

Discharge (Q) cannot be measured directly or constantly. Instead, there are three methods of estimating discharge, as follows:

(1) Discharge estimates based on the area of the drainage basin, precipitation, and the discharge coefficient of each land use pattern, using GIS.
(2) Discharge estimates based on the water level (H) using the rating curve, also known as the Height–Quantity (H–Q) curve.
(3) Discharge estimates as the product of the cross-sectional average velocity and the discharge area of each river.

2.2.1. Estimation using GIS

The amount of water discharged to the river in each drainage basin (V, m^3) was assumed to be determined by the precipitation (P, mm km^{-2}), the area of drainage basin (A, km^2), and the discharge coefficient (L):

$$V = P \times A \times L \tag{1}$$

We obtained climatological precipitation from mesh data of the National Land Numerical Information, the spatial resolution of which is 1 km (Fig. 2). The area of the drainage basin (A) was determined by the elevation. Different discharge coefficients (L) were given to each grid according to the land use patterns (Table 1, Fig. 3).

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Table 1
Discharge coefficient for each land use pattern.

Land-use pattern	Discharge coefficient
Paddy field	0.2
Other agricultural land	0.2
Forest	0.3
Wasteland	0.5
Land for building	0.9
Road	0.9
Railway	0.9
Other land	0.8
Rivers and lakes	1.0
Golf course	0.5

Source: Ministry of Land, Infrastructure, Transport, and Tourism website (http://www.mlit.go.jp/river/pamphlet_jirei/kasen/gaiyou/panf/tokutei/).

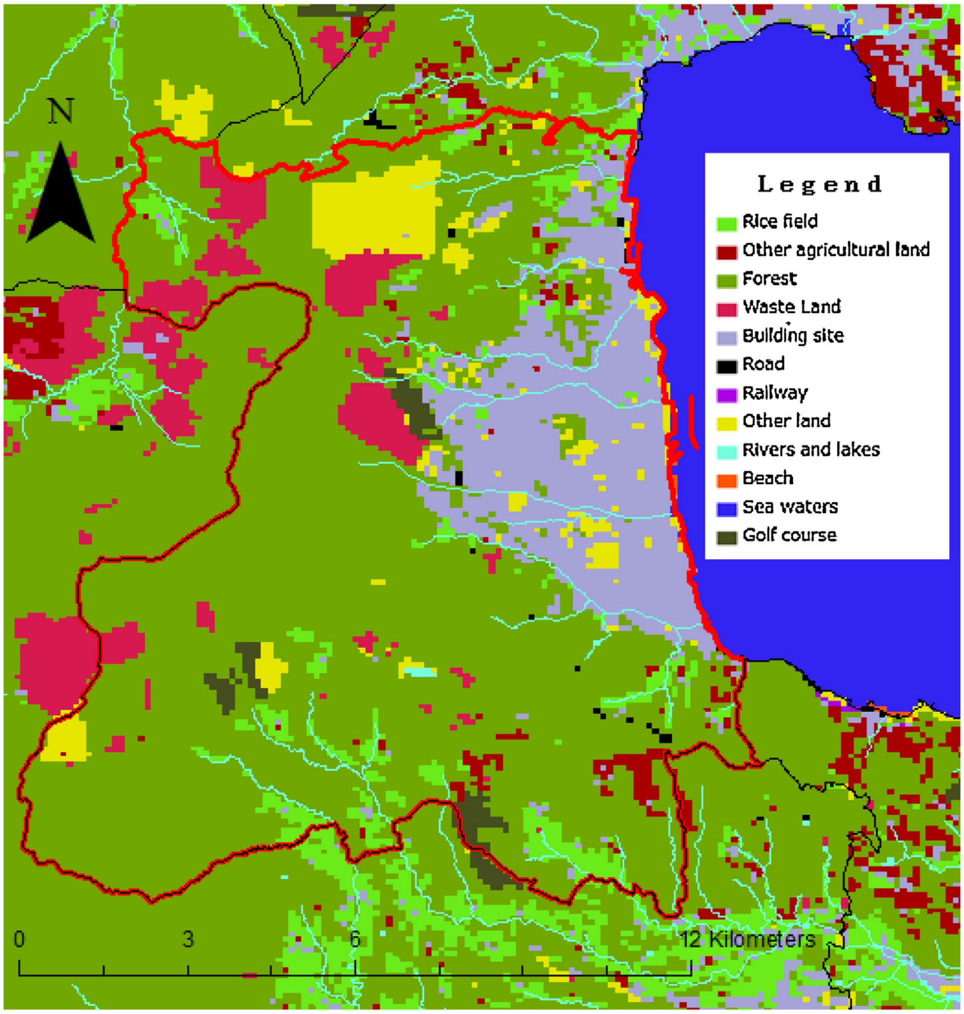

Fig. 3. Land use patterns in Beppu City.

2.2.2. Estimation using the H–Q curve

Discharge was also estimated from continuously measured water levels, using the H–Q curve. The rating curve is expressed as:

$$Q = a(H - b)^c \tag{2}$$

where Q is the discharge of the river ($\mathrm{m^3\,s^{-1}}$); H is the water level (m); and a, b, and c are constants, independently given to each river to optimize the observed relationship between H and Q.

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Table 2
Snap-shot discharge ($m^3\ s^{-1}$) directly measured at each river on May 23rd, July 14th–16th, September 25th and 26th, November 19th–21th and December 22nd, 2014.

	Sakai-gawa River	Haruki-gawa River	Hirata-gawa River	Shin-kawa River	Asami-gawa River	Hiya-kawa River
May 23rd	0.11	0.12	0.25	0.07	No data	0.03
July 14th–16th	0.15	0.15	0.46	0.15	0.71	0.04
September 25th and 26th	0.09	0.18	0.41	0.21	0.57	0.06
November 19th–21st	0.13	0.24	0.33	0.13	1.37	0.10
December 22nd	0.14	0.23	0.36	0.17	1.42	0.06

The Manning formula is often used to obtain the uniquely determined form of the rating curve (e.g., Manning, 1891). The Manning formula is expressed as:

$$v = \frac{1}{n} R^{\frac{2}{3}} I^{\frac{1}{2}} \tag{3}$$

where v is the cross-sectional average velocity ($m\ s^{-1}$); n is the Manning coefficient of roughness ($s\ m^{-1/3}$); R is the hydraulic radius (m); and I is the slope of the hydraulic grade line ($m\ m^{-1}$). Based on the Japan Road Association (1987), different values of n were given to each river according to the major materials of the side surfaces and bottoms of water channels: 0.015 for Asami-gawa River, 0.020 for Shin-kawa River, 0.030 for Sakai-gawa, Haruki-gawa, and Hirata-gawa Rivers, and 0.035 for Hiya-kawa River. The hydraulic radius (R) and the slope of the hydraulic grade line (I) were obtained by direct measurements at each river (Tanabe, 2015). The discharge (Q, $m^3\ s^{-1}$) is expressed as the product of the cross-sectional average velocity (v) and the discharge area (S, m^2) obtained by integrating the width and depth of each river.

2.2.3. *Estimation based on directly measured current velocity*

Snap-shot discharge was obtained as the product of the cross-sectional average velocity (v) directly measured by hydrometers and the discharge area (S) of each river on May 23, July 14–16, September 25 and 26, November 19–21, and December 22, 2014. The discharge area (S) was calculated by integrating the width and depth of each river.

The discharge obtained by this procedure is shown in Table 2, and was used to verify the discharge estimated by the other two procedures using GIS and the Manning formula.

2.3. *Potential power generation by MHP*

The potential power generation by MHP (P, kW) can be calculated as:

$$P = g \times H \times Q \times E \tag{4}$$

where g is the gravitational constant ($9.8\ m\ s^{-2}$); H is the natural head (m); Q is the discharge of the river ($m^3\ s^{-1}$); and E is the efficiency of MHP, for which the typical value of 0.7 was used in this study. The natural head (H) is obtained from elevation and flow path, both of which were estimated by digital maps provided by the Geospatial Information Authority of Japan.

3. Results and discussion

3.1. *Water level*

As mentioned above, the water level of each river was continuously measured at the points 500 m from mouths of each river every 30 min using a water level logger. While there were no data for Hitara-gawa River because the logger was lost during the study period, water level data were obtained for the other five rivers.

The temporal water level trend was similar among the rivers, although the degree of fluctuation differed (Fig. 4). The water level fluctuation during the study period was largest (1.5 m) for Haruki-gawa River and smallest (0.8 m) for Asami-gawa and Hiya-kawa Rivers. The water level is affected by precipitation, and the highest water level appeared on October 13, 2014, just after a heavy rainfall on the same day, in the Sakai-gawa, Haruki-gawa, and Shin-kawa Rivers. As the banks of rivers in Beppu City are paved with concrete, rainwater that falls near a river flows to the river rapidly.

In Shin-kawa and Hiya-kawa Rivers, there has been a trend of high water levels for several years. This is affected by the tide. In particular, Tanabe (2015) found that the water level for Shin-kawa River was strongly correlated with sea level in Beppu Bay. This means that water level measurement was partly disturbed by water level changes caused by the tide. Also, this suggests that the effects of seawater on MHP facilities, such as rust, should be considered when installing MHP facilities in downstream areas.

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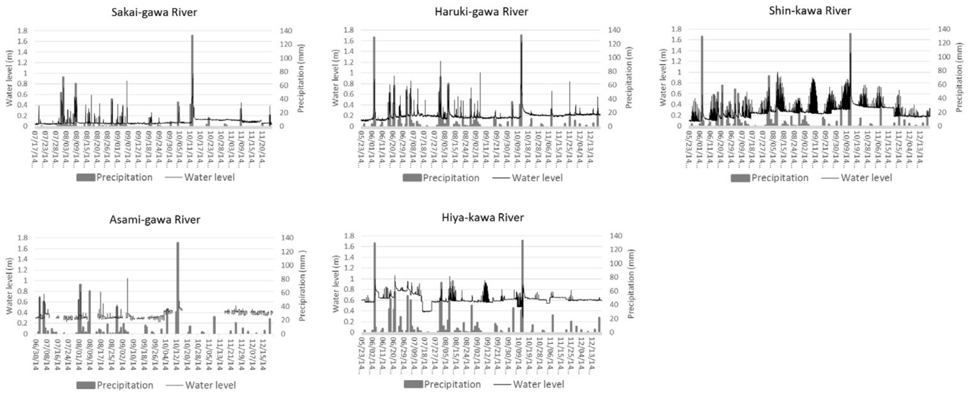

Fig. 4. Observed water levels (m) at the points 500 m from the mouths of Sakai-gawa, Haruki-gawa, Shin-kawa, Asami-gawa, and Hiya-kawa Rivers, and daily precipitation (mm) in Oita City, Oita Prefecture, Japan (precipitation data from the Japan Meteorological Agency website). There are no data for July 16, 2014 for Sakai-gawa River or for June 29, July 11–14, July 18–20, July 28, August 8–14, September 3–4, September 12, September 19 and 20, October 10–13, October 17 through November 16, November 20 and 21, December 4 and 5, and December 20 for Asami-gawa River.

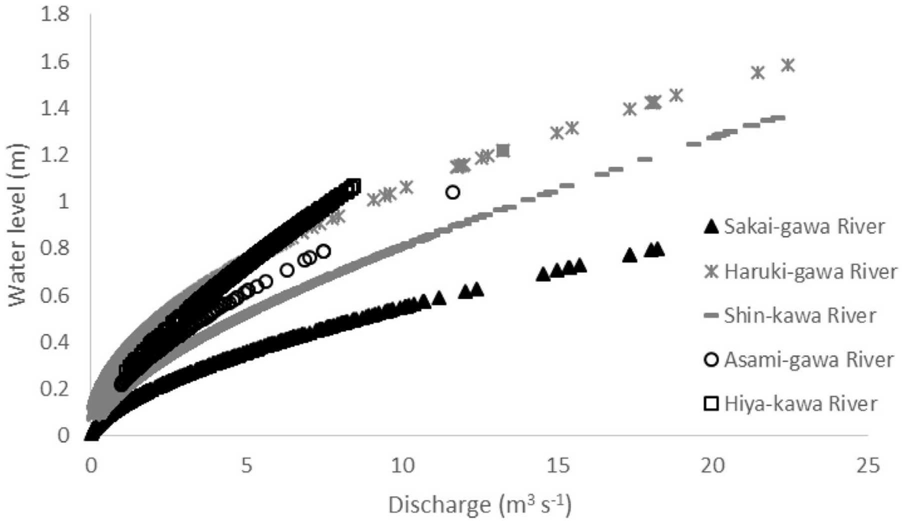

Fig. 5. The H–Q curves estimated by the Manning equation at points 500 m from the mouths of Sakai-gawa, Haruki-gawa, Shin-kawa, Asami-gawa, and Hiya-kawa Rivers.

3.2. Discharge

The rating curve for each river was obtained as follows and is shown in Fig. 5:

$$H = 26.27(Q - 0.00)^{1.61} \quad \text{for Sakai-gawa River} \tag{5}$$

$$H = 8.97(Q - 0.02)^{1.98} \quad \text{for Haruki-gawa River} \tag{6}$$

$$H = 14.24(Q - 0.02)^{1.52} \quad \text{for Shin-kawa River} \tag{7}$$

$$H = 10.92(Q\text{-}0.00)^{1.60} \quad \text{for Asami-gawa River} \tag{8}$$

$$H = 8.32(Q - 0.05)^{1.32} \quad \text{for Hiya-kawa River} \tag{9}$$

Using the rating curve, the observed water level was converted to the discharge for each river. The estimated discharge changed from almost 0 $\mathrm{m^3\,s^{-1}}$ to 18–22 $\mathrm{m^3\,s^{-1}}$, but usually stayed small for Sakai-gawa, Haruki-gawa, and Asami-gawa Rivers (Fig. 6). For Sakai-gawa, Haruki-gawa, Shin-kawa, and Asami-gawa Rivers, the typically small discharge was coincident with the discharge estimated from directly measured current velocities on May 23, July 14–16, September 25 and 26, November 19–21, and December 22, 2014, ranging from 0.069 $\mathrm{m^3\,s^{-1}}$ to 0.236 $\mathrm{m^3\,s^{-1}}$. The disagreement in the discharge for Hiya-kawa River estimated by the two methods likely results from tidal effects on water level, as mentioned in Section 3.1.

The discharge estimated from directly measured current velocities for each river was also compared with the GIS-based estimation of the annual mean discharge (Fig. 7a). The discharge was largest in Asami-gawa River and smallest in Hiya-kawa River for both the GIS-based estimation and the measurement-based estimation in all months. The GIS-based annual-mean

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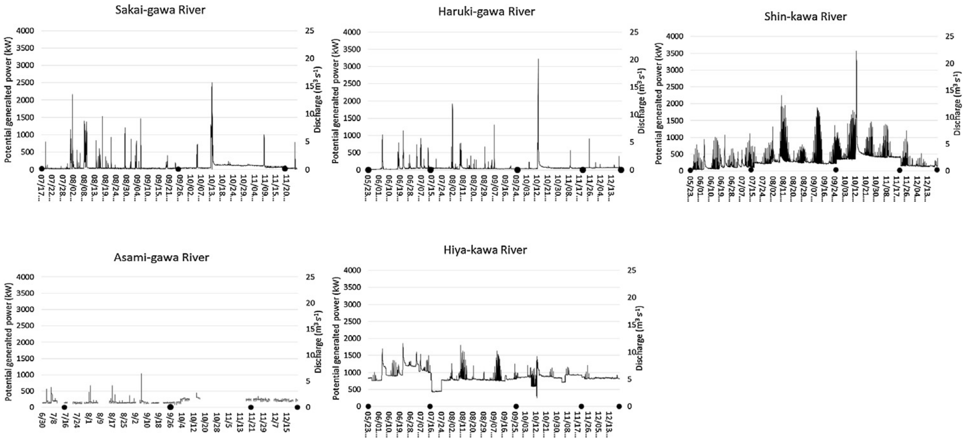

Fig. 6. Discharge ($m^3\ s^{-1}$) and potential power generation (kW) estimated by the Manning equation at the points 500 m from the mouths of Sakai-gawa, Haruki-gawa, Shin-kawa, Asami-gawa, and Hiya-kawa Rivers. Black solid circles denote discharge ($m^3\ s^{-1}$) obtained by direct measurement on May 23, July 14–16, September 25 and 26, November 19–21, and December 22, 2014, of which values are denoted in Table 2. For Sakai-gawa and Asami-gawa Rivers, the periods of missing data are the same as in Fig. 4.

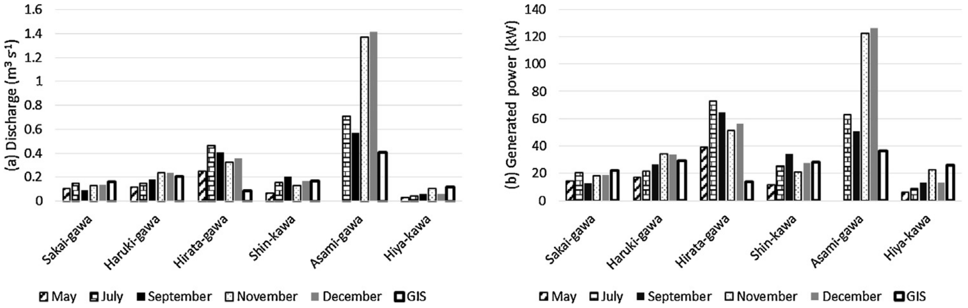

Fig. 7. (a) Discharge ($m^3\ s^{-1}$) and (b) potential power generation by MHP (kW) estimated by direct measurement of discharge on May 23, July 14–16, September 25 and 26, November 19–21, and December 22, and the annual-mean discharges estimated using GIS at the points 500 m from the mouths of six rivers in Beppu City.

discharge accounted for 107–178%, 87–175%, 19–35%, 82–247%, 29–72%, and 114–427% of the measurement-based discharge for Sakai-gawa River, Haruki-gawa River, Hirata-gawa River, Shin-kawa River, Asami-gawa River, and Hiya-kawa River, respectively. This means that the GIS-based discharge agreed well with the measurement-based discharge for Haruki-gawa and Shin-kawa Rivers, overestimated the measurement-based discharge for Sakai-gawa and Hiya-kawa Rivers, and underestimated the measurement-based discharge for Hirata-gawa and Asami-gawa Rivers.

The underestimation of the GIS-based discharge compared to the measurement-based discharge was especially significant for Hirata-gawa River, by more than 65%. The underestimation is reasonable if we consider that there are a large number of hot springs within the drainage basin of Hirata-gawa River and that the contribution of wastewater from hot springs is high; the contribution of wastewater to the total water volume in Hirata-gawa river is reported to be as high as 38% (Yamasaki, 2005), which cannot be taken into account by the GIS-based estimation. The strong influence of the wastewater from hot springs is also verified by the fact that the water temperature in Hirata-gawa River remains over 20 °C year round, which is 10 °C higher than in Hiya-kawa River, which has no hot springs within its drainage basin. Also, Nile tilapia (*Oreochromis niloticus*), a tropical species, has taken permanently residence in Hirata-gawa River and even accounts for 80% of the total fish biomass (Yamada et al., in this volume). The suitable environment for Nile tilapia is also supported by their abundant diatom prey, which are stimulated by the dissolved silica provided by hot spring water discharged to Hirata-gawa River.

3.3. Potential power generation

Using Eq. (4), the measurement-based discharge of each river was converted to the potential power generation by MHP (Fig. 6).

The estimated average potential power generation during the study period (from May to December 2014) at the points 500 m from the mouths of each river ranged from 67 kW for Haruki-gawa River to 870 kW for Hiya-kawa River (Table 3). The potential corresponds to typical electric demands for 88–2,071 households, provided that the electric demand of a typical household in Japan is 300 kW per month, or 0.42 kWh (The Federation of Electric Power Companies of Japan website). Also, it is likely that electric demands for 26–588 households are guaranteed for Haruki-gawa, Shin-kawa, Asami-gawa, and

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Table 3
Potential generated power (kW) estimated by the Manning formula at the point 500 m from the mouth of each river. Values in parentheses denote the number of households that can be serviced by the potential power generation assuming that the typical electric power consumption is 300 kWh per month (or 0.42 kW) (The Federation of Electric Power Companies of Japan website (http://www.fepc.or.jp/enterprise/jigyou/japan/sw_index_04/)).

	Sakai-gawa River	Haruki-gawa River	Shin-kawa River	Asami-gawa River	Hiya-kawa River
Maximum	2501 (5955)	3230 (7690)	3637 (8660)	1037 (2469)	1856 (4419)
Minimum	2 (5)	11 (26)	39 (93)	86 (205)	247 (588)
Average	72 (171)	67 (88)	325 (774)	190 (452)	870 (2071)

Hiya-kawa Rivers at the lowest water levels; however, the minimum potential for Sakai-gawa River is as low as 2 kW, or electricity for only 5 households. The results suggest that installation of MHP facilities can provide stable electricity for tens to thousands of residents in local communities along the rivers in Beppu City.

Characteristics of the potential power generation estimated from directly measured water levels at each river on May 23, July 14–16, September 25 and 26, November 19–21, and December 22, were similar to that of the discharge (Fig. 7). However, the potential power generation of Asami-gawa River was assessed to be lower than estimated based on the discharge, because the natural head was smallest at Asami-gawa River (13 m) compared to the other rivers (20 m, 21 m, 23 m, 24 m, and 32 m for Sakai-gawa River, Haruki-gawa River, Hirata-gawa River, Shin-kawa River, and Hiya-kawa River, respectively).

The ratio of the GIS-based annual-mean potential generated power by MHP to the measurement-based potential generated power is identical to that of the discharge for each river and each month. The GIS-based annual mean potential generated power is estimated to be 31 kW, 30 kW, 14 kW, 28 W, 36 kW, and 26 kW for Sakai-gawa, Haruki-gawa, Hirata-gawa, Shin-kawa, Asami-gawa, and Hiya-kawa Rivers, respectively. The potential corresponds to the demand for more than 75, 71, 33, 67, 87, and 62 households, respectively. The potential is comparable to the average potential obtained by using the Manning formula for Haruki-gawa River (for 88 households; Table 3). On the other hand, the GIS-based annual-mean potential generated power substantially underestimates the average potential obtained by using the Manning formula for Sakai-gawa, Haruki-gawa, Shin-kawa, Asami-gawa, and Hiya-kawa Rivers. One possible reason for the discrepancy in the estimation is that the average potential obtained by using the Manning formula for each river does not include results in late December through mid-May when precipitation is relatively low in Beppu City. In addition, for Shin-kawa and Hiya-kawa Rivers, tide-enhanced water levels magnify the discrepancy.

3.4. Possible obstacles and the solutions in developing MHP

We focused on the water level, discharge, and potential power generation by MHP at the point 500 m from the mouth of each river in Beppu City. The potential power generation is expected to be high in the upper rivers, with steeper geographies, higher natural heads, and fewer anthropogenic influences. However, the mountainous areas generally have less of the infrastructures, such as roads and electric lines, which are necessary to install and maintain MHP facilities. To develop new infrastructure for installing MHP facilities, the initial cost and the extent of the local consensus must be taken into account.

An inherent obstacle in developing MHP in Beppu City is related to waste water from hot springs. As mentioned in Section 3.2, hot spring wastewater increases the discharges of rivers and affects riverine ecosystems. The chemical impacts of hot spring water on MHP facilities have not been clarified, but they may affect MHP devices, such as by corrosion of mill wheels.

To further develop MHP, deregulation of current laws relevant to rivers is required. To motivate business proprietors and the other stakeholders to install new MHP facilities locally, further additional incentives, such as carbon pricing, might also be necessary. The FIT, an incentive to develop renewable energy, was introduced in July 2012 in Japan. The exercise price of electricity generated by MHP is 21–34 yen/kWh in 2015, depending on the capacity and other conditions (Agency for Natural Resources and Energy website), and the price is guaranteed for 20 years.

However, unlike solar power, MHP was not well deployed even after the FIT was introduced. This is primarily because to install hydropower plants, regardless of the capacity, the agreement of all the stakeholders with irrigation rights for each river is required, and the paperwork is relatively complicated. In addition, if we plan to install MHP facilities in rivers in which fisheries are carried out, we will need to build a consensus with fisheries people with fish rights of the rivers and optimize water-energy-food nexus (Taniguchi et al., 2013), especially by minimizing conflicts between energy generated by MHP and river ecosystem or food such as salmon, trout, eel and sweetfish.

4. Conclusion

When estimating potential power generation by MHP, GIS-based estimation is often used because the procedure is universal and can be performed without direct measurements. However, few previous studies have verified the performance of GIS-based estimation by comparing the results to those obtained using other procedures. In this study, we compared the results of water level, discharge, and potential power generation estimates obtained using the Manning formula, direct measurement, and GIS for six rivers in Beppu City, Oita Prefecture, Japan.

The results show that water level and discharge were highly influenced by rainfall. We also found that both estimations using the Manning formula and GIS well represented the measurement-based estimations of discharge and potential power

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generation for each river. It is likely that installation of a MHP facility downstream on any river in Beppu City would guarantee power generation sufficient to supply electricity for tens to hundreds of households in the local community along the river.

Misfits in the estimations among the three methods substantially differed between rivers. This was mainly because the river discharges were affected by wastewater from hot springs and households, especially for Hirata-gawa River, the river most significantly influenced by hot spring wastewater; the GIS-based estimation only accounted for 35% of the discharge and potential power generation by MHP of the measurement-based estimation. The absence of data in late December through mid-May with relatively low rainfall may have caused an overestimation of average discharge and potential power generation by MHP using the Manning formula. The tidal effect on water level for the Shin-kawa and Hiya-kawa rivers is also a cause of uncertainty in the estimation.

This study aimed to suggest a simplified procedure for estimating potential power generation by MHP that could be applied locally, and to provide a new guideline for consensus building in developing MHP among local stakeholders in Japan. Preferable sites for operating MHP are often located in mountain areas, most of which have steep geographies and excessively declining populations. Therefore, developing and operating MHP facilities locally would not only result in CO_2 reductions, mitigating global warming and ocean acidification, but also would presumably lead to regional vitalization by creating new jobs locally. Applying the procedures of this study to various sites with different natural and social conditions, we could hopefully provide guidelines for determining promising sites for new MHP facilities in many candidate sites.

Conflict of interest

The authors declare no conflict of interest associated with this manuscript.

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