Research article

GIS-based Analysis for the Energy Potential and Social Feasibility of Small-Scale Run-Off-River Hydropower in Yahagi River, Japan

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Abstract Due to the increase in international energy demand and the focus on the realization of a decarbonized society, small-scale hydropower plant is attracting attention in Japan as an important supply of renewable energy. While Japan has a significant amount of precipitation and mountains, it is suitable to establish hydropower plants; however, hydropower energy currently represents only about 10% of the total energy mix. Generally, a small-scale hydropower facility has relatively little impact on the environment and is expected to play a role as a distributed power source. However, it has not been included in the survey of hydropower potential, and a study on its viability and the development of potential sites is limited. Here, we created an electricity generating capacity map for small-scale run-off-river hydropower plant of the Yahagi River system in Aichi, Japan. We calculated the river flow rate and potential electricity generating capacity at every 10 m on the river line of the Yahagi River system using the digital elevation model, published by the Geospatial Information Authority of Japan. We overlapped various kinds of social conditions and risks on the map of electricity generating capacity and proposed a suitable site where the development of potential small-scale run-off-river hydropower plant is high.

Keywords small-scale run-off-river hydropower plant, renewable energy, GIS, Yahagi River

INTRODUCTION

Due to rapid increase in the number and degree of natural disasters in Japan, the dissemination and promotion of renewable energy and distributed power sources have become a more critical policy issue (Agency for Natural Resources and Energy, 2018). In recent years, the following three conditions have been identified for energy supply: (1) securing small-scale and distributed generation functions to mitigate the risk of a sudden drop in power supply in the event of a disaster, (2) enhance base-power supply capacity to respond to peak demand in summer and winter, and (3) a generator that is self-sufficient and does not emit greenhouse gases (Ueda et al., 2012). Small-scale hydropower is generally considered to create a low environmental load and a high degree of affinity for distributed power supply.

However, there are few noticeable cases of mini and micro hydropower projects that target the power generation output of around 100 kW. Hydropower plants are mainly of two types of namely, reservoir and run-off-river hydropower plants. While reservoir-types such as dams can generate medium to large-scale hydropower, the places where power plants can be installed are limited, and the installation costs are relatively high. Conversely, a run-off-river type can generate small-scale hydropower and the installation of plants is relatively easy. Also, power generation is possible even in complex terrain conditions such as mountainous areas. Recently, European attractive policies are favoring the construction of new small-scale hydropower plants, i.e., in most cases, correspond to run-of-river hydropower plants (Garegnani et al., 2018).

While estimating the feasibility of renewable energy development projects, a fundamental challenge is to determine the availability of the natural resources. In the planning process, further restrictions in the exploitation of natural resource (e.g., technical, environmental, legal, and social) should be considered (Moriarty et al., 2012; Resch et al., 2008). For example, in Japan, the Ministry of the Environment Government of Japan estimates the medium to small-scale hydropower energy potential values in rivers and agricultural water by prefecture (the Ministry of the Environmental Government of Japan, 2011). Also, the potential of small hydropower is estimated around the world (Cuya et al., 2013; Kusre et al., 2010; Yah et al., 2017).

In this study, the development of a potential estimation method for small-scale hydropower, which can be applied more simply and on a global scale in the future, is considered by assuming a run-of-river type and low-drop type power plants. Also, the electricity generating capacity of small-scale hydropower and the amount of power required were compared.

METHODOLOGY

Study Sites

In this case, the Yahagi River system was targeted for the case study (Fig. 1). The Yahagi River system flows down to Nagano Prefecture, Gifu Prefecture, and Aichi Prefecture, which has a total stream length of 117 km and a catchment area of 1,830 km^2.

Creation of Potential Estimation Point for Small-scale Hydropower

The ArcGIS (Ver.10.4 and Ver.10.6) calculated the stream length and the catchment area, and the Digital Map 10 m Grid (Elevation) published by the Geospatial Information Authority of Japan (GIS) and the Hydrology analysis tools of Spatial Analyst (ArcGIS) were used. The streamline was selected using the Digital Map, and the point data were created on the streamline at 10-meter intervals as a potential estimation point of hydropower (Fig. 2). We calculated the watershed area at each point.

Estimation of the River Discharge

The river discharge at each potential estimation point was estimated. A specific discharge rate was used to calculate the river discharge. The actual river discharge values obtained from six observation sites of Water Information System (MILT of Japan, 2018), i.e., Sumigase, Kugyudaira, Yonedu, Kido, Takahashi, and Iwadu, were then corrected. At these sites, normal flow rates were calculated using the river discharges per day from January 1st, 2016 to December 31, 2016. A normal flow rate represents river discharges that do not fall below this value for 185 days throughout one year. There was a significant correlation between the watershed area and a normal flow rate at these six observation sites (correlation coefficient (r) = 0.93, p values of significance test (p) < 0.01). In addition, the potential estimation points correspond to the six observation sites of Water Information System. There was a significantly strong correlation of watershed areas between of the potential estimation points and of the six observation sites ($r = 0.99$, $p < 0.01$). From these results, the specific discharge rate of the Yahagi River system (0.0254) was calculated, and the river discharges at each potential estimation point was calculated by multiplying a watershed area by the specific discharge rate.

Calculation of Electricity Generating Capacity

The electricity generating capacity of a small-scale hydropower is expressed by the formula (1).

$$P_e = 9.8 \times Q \times H_e \times \eta \tag{1}$$

where P_e is the amount of power generated (kW), Q is the river discharge (m^3/s), H_e is the height difference between inlet and outlet of stream (m), and η is a dimensionless efficiency of the turbine.

Out of these, the height difference can be adjusted according to the local topography or the amount of electricity. In this study, since the target is the small-scale and low-drop hydropower plants, the H_e is uniformly set to 5 m at each point. Furthermore, in this study, we targeted on the power generation amount ranged from 30 to 500 kW, and values less than 30 kW and greater than 500 kW were excluded from the potential estimation analysis.

Extraction of a Social Condition

(1) Spatial duplication in a nature reserve area:
Since the artificial development practices are regulated in the area designated as the nature reserve are, the points located in the nature reserve area among the potential estimation points were excluded. The potential estimation points were excluded in the Natural park areas (MILT of Japan, 2015a), Nature conservation areas (MILT of Japan, 2015b) and Wildlife management areas (MILT of Japan, 2015c) and within their 100 m buffer areas.

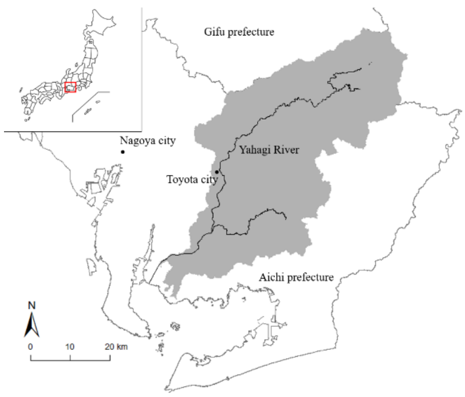

Fig. 1 Location of the Yahagi River

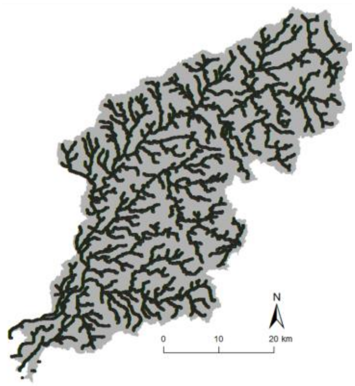

Fig. 2 The potential estimation points of small-scale hydropower

(2) Spatial duplication in disaster risk areas:
Since the establishment of small-scale hydropower facilities in areas designated as disaster risk areas are not realistic, the points located in the disaster risk area of the potential estimation points were excluded. Sediment disaster hazard areas (MILT of Japan, 2010) and landslide special warning areas (MILT of Japan, 2017) are targeted in a 50 m buffer area, and the flood eliminate area (MILT of Japan, 2012) excluded points that were included within a 100 m buffer area.

(3) Distance from the existing road:
When constructing a small-scale hydropower facility, its distance from the existing road influences the installation cost. Therefore, the linear distance from the newly-installed power generation facility to the existing road was calculated using the Road Edge data published by Geospatial Information Authority (GSI, 2017), assuming the necessity of laying the power distribution for the

construction and management of roads. Out of the estimated linear distances, the potential value was calculated as the maximum value of 1.0 in the case of 100 m or less, and the potential value using formula (2) when it was larger than 100 m.

$$P_n = \frac{100}{D_n} \quad (2)$$

where P_n is a potential value of the potential estimation point's number n, and D_n (m) is the nearest distance from the potential estimation point. The potential value decreased as the distance from the potential estimation point to the existing road increased.

Estimation of the Required Power

The amount of power required per year was calculated by multiplying the number of houses, included in the concentric circle at center of the potential estimation point, by the power usage per household at each potential estimation point. With respect to the number of houses, assuming one urban area cell (10 m) as one household from the JAXA (2016) High Resolution Land-Use and Land-Cover Map (Ver. 16.09; 10 m × 10 m spatial resolution), the total number of urban area cells included in the 1.0 km circles are used to obtain the potential estimation point. An average value ((kWh / h / household) of electricity consumption in the five years from 2005 to 2010 is calculated from the "Trend of power consumption per household" provided by The Federation of Electric Power Companies of Japan (2017), which is multiplied by the number of households to calculate the power requirement.

Reclassifying of the Potential Estimation Points into Sections

The consecutive points, excluding spatial duplication points in the nature reserve and disaster risk areas, were grouped as one section. Using neighbor analysis of ArcGIS, the points adjacent in eight directions from the potential estimation point were reclassified as a single section.

Site reconnaissance:
We investigated the local conditions of the potential estimation points created and excluded by GIS. On December 21, 2018, seven locations in Ena City and Toyota City were surveyed. Survey items included river width, seawall structure of riverbed, right bank and left bank, and the presence of transmission line.

RESULTS AND DISCUSSION

In the Yahagi River system, the potential estimation points were created at 10 m intervals. Then we excluded the potential estimation points by the spatial duplicated area of the nature reserve and the disaster risk areas. Moreover, where the amount of power generation is less than 30 kW and greater than 500 kW were also excluded. The potential estimation points were narrowed down to 4,038 points from 106,494 points (Fig. 3).

The minimum value of power generation at 4,038 points was 30.1 kW, the maximum value was 397 kW, and the average value was 113 kW. Besides, 57% of the 4,038 points had a micro-scale power generation of 50 kW or less (Fig. 4). When classifying the points as connected in eight directions out of a potential estimated number of points, 4,038 points were sorted into 125 sections. Moreover, 125 sections were located in five areas of the Yahagi River system.

Based on the distance of the existing road from the small-scale hydropower facility, we determined the cost of installation of this facility. The distance to the existing road at 4,001 points out of 4,038 points was 100 m or less. Hence, it is possible to install and manage the facilities using existing roads at most potential estimation points.

The amounts of required power generation within 1 km from the potential estimation point were compared. In this instance, the power generation amount and the required power amount were converted into annual values. The annual power generation amount at 4,038 points ranged from

264 to 3,480 MW/y, and the average value was 996 MW/y (Fig. 5). The number of points where the ratio of the power generation amount to the required amount was less than 100% (except 0%) was 1,186 points, i.e., 51 sections. Among these points, the points below 10% of the ratio of the power generation amount to the required amount were 402 points, i.e., 24 sections, and these sections were located in the population concentrated areas within Toyota City (Fig. 6). The population within 1 km from these potential estimation points is relatively large; the required amount is also large compared to the amount of power generation. For this reason, the installation of small-scale hydropower facilities in this section can be considered unsuitable.

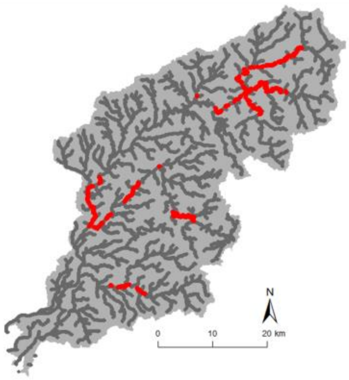

Fig. 3 Potential estimation points (red colored points)

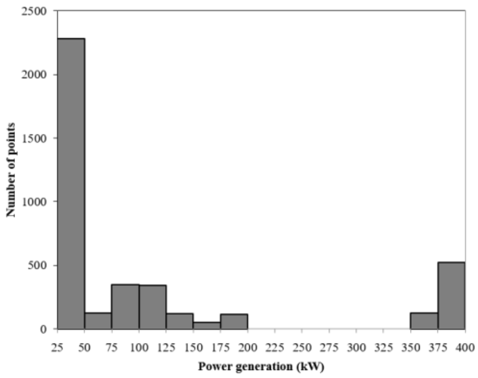

Fig. 4 Histogram of power generation

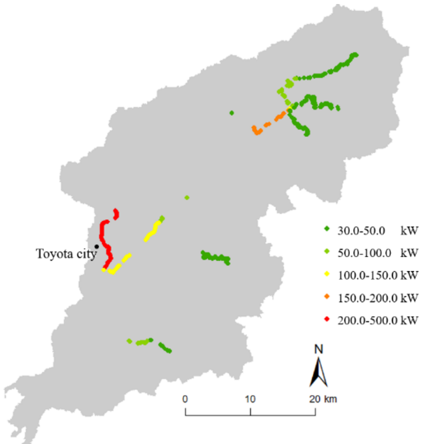

Fig. 5 Power generation of 4,038 of potential estimation points

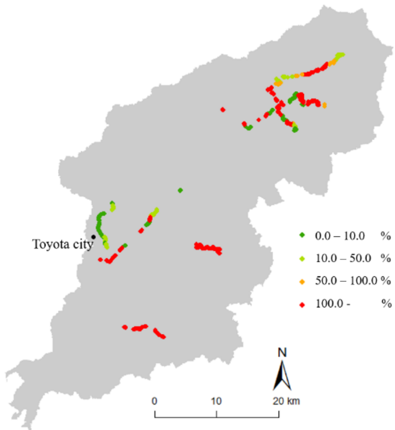

Fig. 6 Ratio of the demand to the power generation

Conversely, at 784 points, where the ratio of the power generation amount to the required amount is higher than 10% and less than 100%, small-scale hydropower facility is useful for local production and consumption.

At around 100% (2,443 points), where the population concentration is low, and the amount of power generated exceeds the requirement, small-scale hydropower facility can be used for power-selling.

Based on these results, to evaluate the validity of the potential estimation points of small-scale hydropower facility published by GIS, a site reconnaissance was conducted in three areas, as shown in Fig. 7. These three areas have relatively lower population concentration and are located in the mountainous regions of Japan.

In the section where the village is near the river, it is generally accepted that the small-scale hydropower facility for the local production and consumption type is sufficient. By site reconnaissance, roads and power transmission lines are being maintained, the river is also managed, and the flow conditions are stable. From this, it was inferred that even in the mountainous areas, it is possible to install a power generation facility at a relatively low cost near the settlement, and a small-scale power generation facility according to the size of the village is suitable.

Conversely, since most of the target sections have few settlements, it is considered that the use as a power-selling type is suitable.

In these sections, it was confirmed that there is an existing road near the river, but there is no power transmission line. In addition, there are many natural rivers, including sprawl points, where flow paths are complicated with big rocks of river beds. At such points, there is a concern that high costs will be incurred for the installation of power generation plants. In the case of valley terrain, the distance from the existing road to the river is long, and there is a concern that the installation and management of the power plant are complicated.

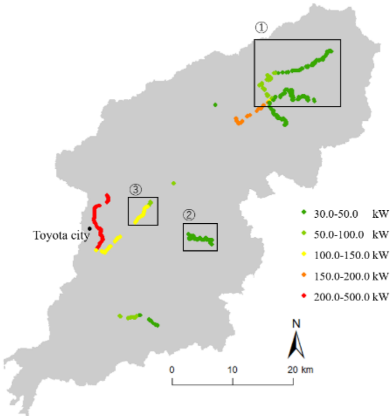

Fig. 7 Location of site reconnaissance

However, even if there are no settlements near the points, small-scale hydropower plant with existing irrigation facilities such as weirs is considered to be effective. In the vicinity of irrigation facilities, since the river flow is stable, low cost and stable power generation are expected. By combining existing irrigation facilities with small-scale hydropower facilities, it is possible to allocate administrative expenses for irrigation facilities.

Several tasks remain to apply the potential estimation method of this study in other regions and on a global scale. In this study, we set the buffer to 100 m in the extraction of social conditions; it is necessary to verify the proper distance. In the calculation of the distance to existing roads, 100 m buffer from the center point of the river was used as the standard. However, it is expected that the river width dramatically varies depending on the size of the river. For example, the river width in the upstream river is small in general, and even if the distance from the center of the river is within 100 m, the distance could be far away from the estimation point.

Conversely, when large rivers are included, the river width may be 100 m or more, and it may be impossible to calculate the distance to existing roads. It is necessary to change the distance to the existing road for each point considering the width of the river, the topography, and the flow rate. Based on the results of the site reconnaissance, it showed that the utilization of existing irrigation facilities is useful. However, position information on small facilities such as weirs is often not released as GIS data, and it is difficult to estimate the potential considering existing facilities. Likewise, we have not considered the positional relationship with existing power generation facilities. However, considering the balance with the demand amount, it will be necessary to consider the necessity of the power generation facilities to be nearby.

CONCLUSION

In this paper, we suggest a potential estimation method for a small-scale hydropower plant. The results showed a suitable point for small-scale hydropower generation facilities in more detail by public information. It is necessary to confirm the environmental conditions around the river and near the field by the site reconnaissance in the mountainous areas where the population is low. Also, in order to evaluate the more realistic energy potential, it is necessary to identify the location of existing irrigation facilities and power generation facilities and to examine the relevance of small-scale hydropower generation.

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