Application of a hydrological model to evaluate the potential hydro energy in a mountainous small river basin of Japan

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Abstract The low flow from mountainous basins has long been developed to supply water to urban areas downstream. Little attention was paid to developing hydro-electricity for the community in the hilly and mountainous regions. After the disaster of TEPCO's Fukushima no. 1 nuclear power plant, a new energy policy of Japan directs a decrease on the dependence on nuclear power. Feed-in tariff (FIT) of renewable energy was enacted on 1 July 2012 to cope with the increasing small-scale distributed types of natural energy development, including mini-hydro-power. The aim of this study is to apply the hydrological model (Fujimura *et al*., 2012) with an hourly time scale coupling the Diskin–Nazimov infiltration model for the mini-hydropower development. The Seto River basin (53.7 km^2), which is located in the central mountain region of Shikoku in western Japan, was selected to develop mini-hydro-electricity for the local community. The low flow of the Seto River, which is being diverted to supply M&I water for Kochi city by tunnels with a differential head of 25 m, is not used for mini-hydropower. The optimal parameters of the storage function equation for low flow are estimated on the basis of hydrological model analysis. The discharge duration curve and the potential hydropower duration curve are calibrated by the hydrological model to apply 20 years of hourly time-series data (1991–2010) using optimized parameters. The results of the analysis of the Seto River basin indicate that: (i) the set of two parameters in the storage function equation for the low flow in the hydrological model is identified, and (ii) the potential of the mini-hydropower is evaluated to satisfy local power demand as well as restoring the economy of the handicapped community with the surplus hydropower electricity.

Key words hydrological analysis; low flow; storage function equation; optimal parameters; hydropower duration curve

INTRODUCTION

The mountainous areas occupy about 70% of the land area in Japan and its climate is subject to the influence of the Asia monsoon which brings much rainfall and snowfall in mountainous areas in the summer and the winter. Water resources in Japan are therefore obtained from the mountainous areas, especially for the low flow from the basin.

Hydroelectric power in Japan began in 1888 at Miyagi Boseki Sankyozawa silk spinning plant in Sendai, Miyagi Prefecture. Since then many low head hydropower plants were developed as the main energy at the time. However, in the last half century, most of the plants disappeared because of the shift from hydropower to thermal power and nuclear power as the main energy sources. Water resources in mountainous areas are used to supply water for the urban areas downstream. In recent years little attention has been paid to economically vitalize the regional community using the low head hydropower in the hilly and mountainous regions. After the serious disaster of TEPCO's Fukushima no. 1 nuclear power plant on 11 March 2011, the new energy policy of Japan has tried to decrease the dependence on nuclear power. A feed-in tariff (FIT) for renewable energy was started on 1 July 2012, owing to increasing the small-scale distributed type of natural energy development, including mini-hydropower.

Reliable estimation of the available runoff water for the hydropower in mountainous basins is important for the local community due to vitalization. The daily hydrological model for a hilly and mountainous basin was proposed by Ando (1988), and was based on earlier studies by Ando *et al.* (1983, 1984). Owing to the advances in computer and gauging technology, which have promoted the development of new methods for analysing hydrological processes, Fujimura *et al.* (2012) developed the hourly hydrological model based on the Diskin-Nazimov infiltration model (Diskin

& Nazimov, 1995, 1996) and the storage function method for the direct runoff for mountainous basins, and applied the hydrological model to 16 years of data for the Sameura Dam basin located in Kochi Prefecture, in the mountains of Shikoku in western Japan. Although the model shows satisfactory to good performance in terms of obtaining accurate long-term hydrographs and can be used to reproduce the hydrographs for flood events, the parameters used in the model are determined by trial-and-error.

The aim of this study was to apply the hourly hydrological model which was developed for the mountainous basins to the mini-hydropower development in local communities. The specific objectives were to: perform a sensitivity analysis using the hourly hydrological model and to identify the optimal parameters in the storage function equation for low flow; and to estimate the discharge duration curve and the potential hydropower duration curve for 20 years hourly time-series data (1991–2010) using optimized parameters.

MATERIALS AND METHODS

Seto River basin

The Seto River basin (Fig. 1) is located within the Sameura Dam basin, which is in the central mountain region of Shikoku in western Japan. The basin area is 53.7 km^2 for the Seto River basin and 472 km^2 for the Sameura River basin. The elevation in the Seto River basin ranges from 369 to 1498 m a.s.l. and its average elevation is 911 m a.s.l. The land is completely covered with forest and there are few houses are in the Seto River basin. The low flow of the Seto River is being diverted to supply M&I water for Kochi City by two tunnels of the Seto River Diversion and the Jizoji River Diversion. The Seto River Diversion has a head water differential of 25 m which is not used for mini-hydropower, therefore the Seto River basin is selected to develop a mini-hydropower for the local community in this study.

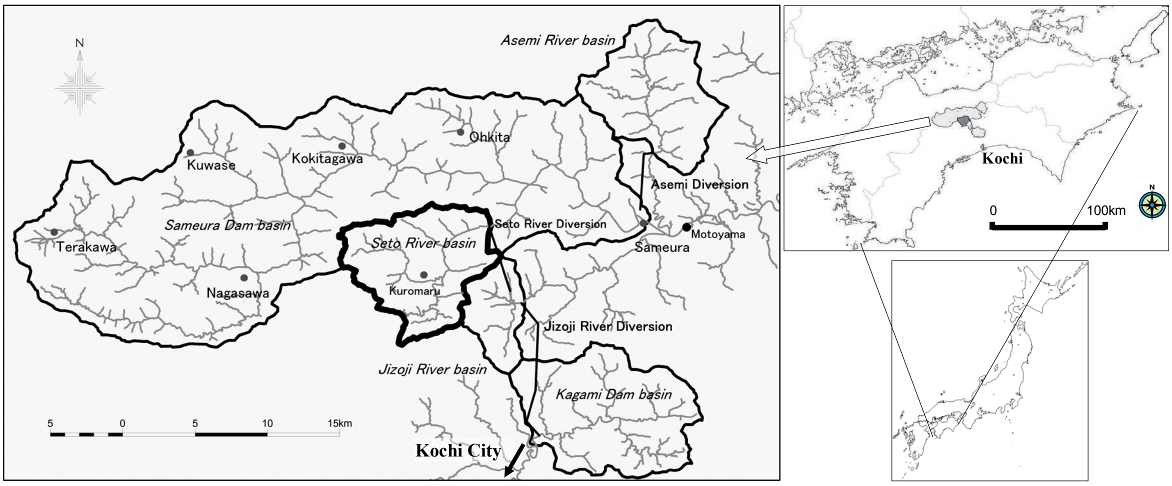

Fig. 1 Map of the Seto River basin and hydrological stations.

Data

To analyse the hydrological process with an hourly time step, hourly rainfall, temperature and discharge into the tunnel at the Seto River Diversion weir are used in this study. The rainfall data at Kuromaru station in the basin and the discharge data at the weir are measured by the Ministry of Land, Infrastructure and Transport. The temperature data at Motoyama station obtained by the Automated Meteorological Data Acquisition System (AMeDAS) of Japan Meteorological Agency is used. The period of data is the 20 years from 1991 to 2010. The DEM data with 50 m resolution were obtained from the Geospatial Information Authority of Japan. The annual rainfall during 20 years varies from 2192 mm as minimum value to 6523 as maximum value, and the average and median annual rainfall are 3353 mm and 3234 mm. The seasonal variation of rainfall as maximum, average, median and minimum in a 10 day period for 20 years at Kuromaru station are shown in Fig. 2. The maximum and minimum rainfall have a significant difference throughout the year. Except from February to June, the average and median rainfalls are different. There are extreme rainfalls both at the high and low values in the Seto River basin in the year.

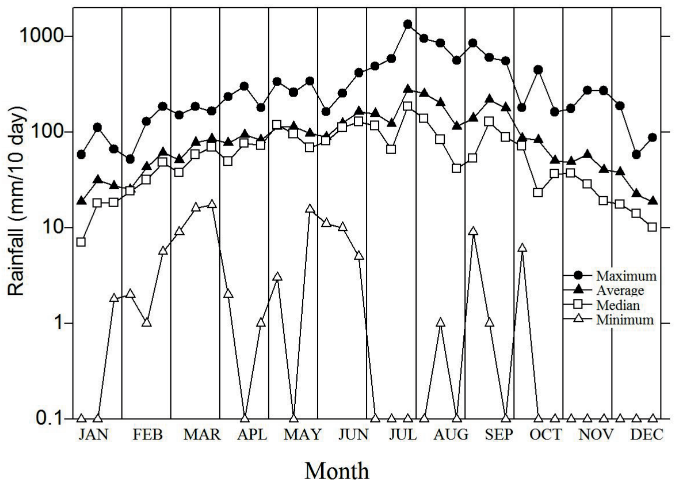

Fig. 2 Seasonal variation of rainfall based on 10 day period in the Seto River basin; maximum, average, median and minimum data in 20 years from 1991 to 2010.

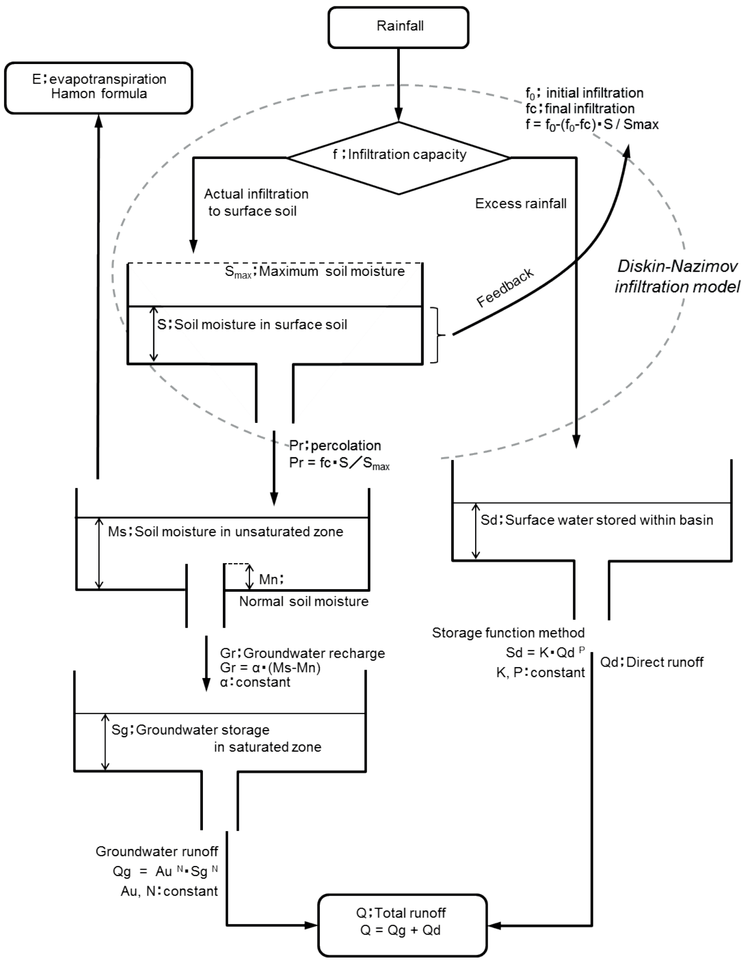

Fig. 3 Simplified schematic of the hourly hydrological model.

Hydrological model

The schematic structure of the hourly hydrological model is shown in Fig. 3. The model is comprised of four components: infiltration and soil moisture in surface soil, soil moisture in unsaturated zone, groundwater storage in saturated zone, and direct runoff component as surface water storage within the basin. The output from each reservoir element uses the linear function and the nonlinear function. The Diskin-Nazimov model was used to calculate infiltration on surface soil, which accounts for the variable intensity of the rainfall.

APPLICATION

Sensitivity analysis

Nonlinearity of the low flow from a basin is calculated by the storage functional equation of the groundwater runoff in the hydrological model. The equation is expressed by:

$$Qg = Au^N \cdot Sg^N \tag{1}$$

where Au is the fractional recession constant in mm $^{(1-N)/N}$, Sg is the groundwater storage in the saturated zone in mm, Qg is the groundwater runoff in mm h^{-1}, and N is the exponent value.

Since the two parameters, the fractional recession constant Au and the exponent value N, are determined by trial-and-error, there is a remaining uncertainty in these parameters. In order to evaluate these two parameters for the low flow, a sensitivity analysis was carried out in this study. In the analysis the Au value ranges from 0.0002 to 0.0080 in steps of 0.0002, with a total of 40 steps, and the N value ranges from 2.0 to 16.0 in steps of 0.5, with a total of 29 steps; therefore the total number of simulations was 1160 (40 × 29). One simulation for the 20-year period took approx. 1.366 minutes on an Intel® Core™ i7-975 at 3.33GHz. Each simulation and two parameters were assessed using the average daily runoff relation error ($ADRE$) of the hydrological result by the model:

$$ADRE = \frac{1}{n} \times \sum \left(\frac{\left| Q_{cd} - Q_{od} \right|}{Q_{od}} \times 100 \right) \quad (\%) \tag{2}$$

where Q_{cd} is the calculated mean daily total runoff, Q_{od} it the observed mean daily total runoff, and n is the number of evaluated observations.

The results of this sensitivity analysis are shown in Fig. 4. Visualized $ADRE$ with respect to the relationship between the Au and the N is shown in Fig. 4 left. The lower relative error of the

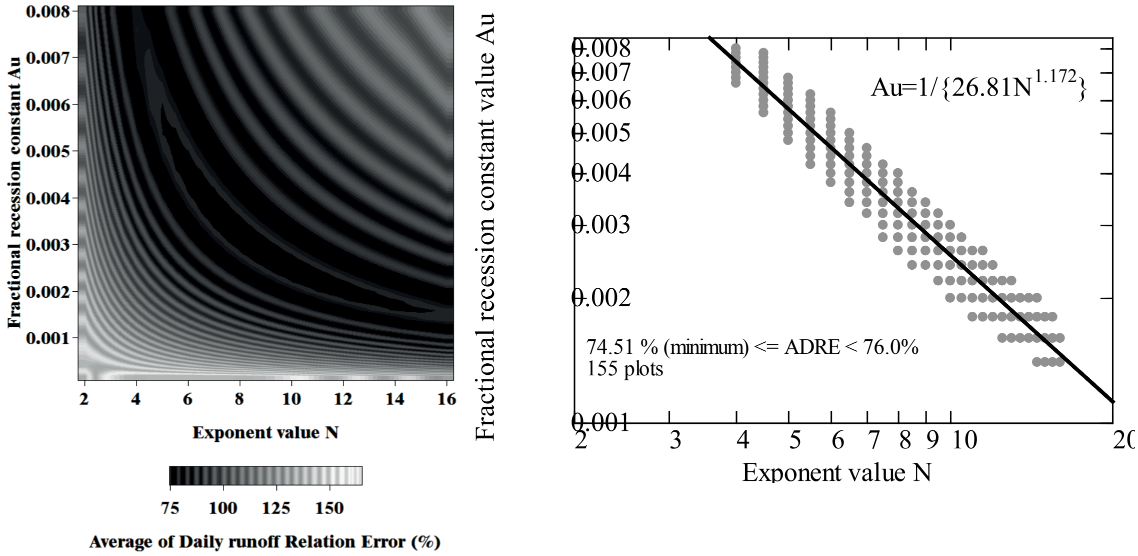

Fig. 4 Visualized $ADRE$ (left) and selected $ADRE$ values (right) with respect to the relationship between the Au value and the N value in the storage functional equation for the low flow.

ADRE, was around 75%, and is shown in the central region of Fig. 4 left. The selected *ADRE* of 155 values out of 1160 results, between the minimum value of 74.51% and the value of 75.99% are shown in Fig. 4, right. For the basin of the Seto River, the relationship between the fractional recession value *Au* and the exponent value of *N* are formulated as the following exponent equation;

$$Au = \frac{1}{26.81 \cdot N^{1.172}} \tag{3}$$

The optimum values of the *Au* and the *N* in the storage function equation for low flow is identified by the exponent equation in regard to the relationship of the *Au* and the *N* value.

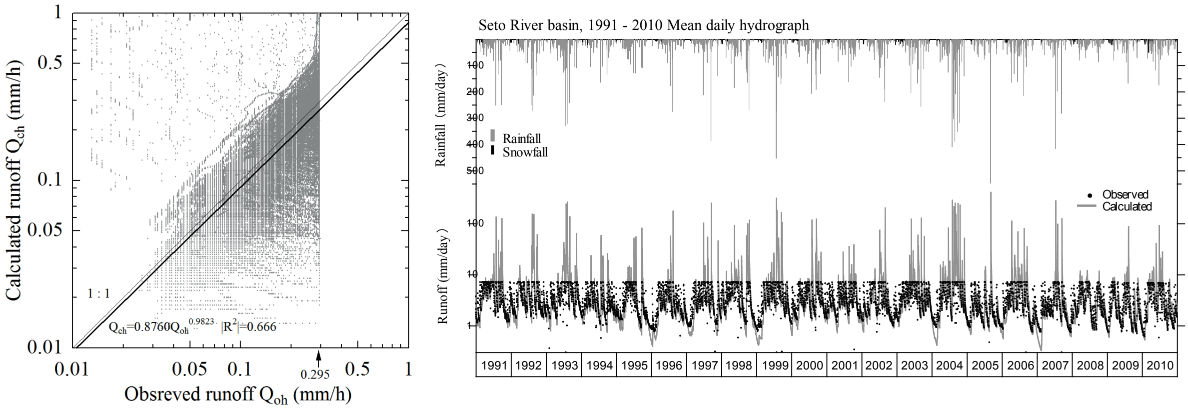

Fig. 5 Comparison between the observed and calculated runoffs shown as log–log graph (left) and mean daily hydrograph (right) calculated by the hourly hydrological model using the optimized parameters of the values $Au = 0.0028$ and $N = 9.0$.

Hydrological analysis

An analysis using the hourly hydrological model involving the optimal parameters in the storage function equation for the low flow was carried out for the 20 years of hourly data between 1991 and 2010. The observed runoff data is the discharge which was measured at the entrance of the diversion tunnel of the Seto River Diversion weir. The weir is a fixed type so that the under flow at the weir height flows to the diversion tunnel, while the overflow at the weir flows downstream to the Sameura Dam. Therefore the maximum value of the observed runoff is 4.4 m^3/sec, 7.08 mm/day and 0.295 mm/h for the basin area of 53.7 km^2. Scatter plots of the hourly hydrograph is shown as log–log graphs in Fig. 5 (left). The square of the correlation coefficient (R^2) indicated as 0.666 and the relationship between the calculated runoff and the observed runoff were roughly in agreement with the model performance. This is because the flood runoff occurs frequently in year. When the water levels rise due to floods, it disturbs the water level measurement. When the sand trap is controlled the data measurements are also disturbed. Figure 5 (right) shows the observed and calculated hydrograph for 20 years. The observed hydrograph is under 7.08 mm/day because of the diversion discharge. However, the value of the *ADRE* is 74.51% for the observed runoff discharge of under 7.08 mm/h, it also shows rough agreement with the calculated hydrograph. The hydrograph greater than the value of 7.08 mm/h is simulated.

Potential hydropower duration curve

In order to estimate the potential hydropower for the Seto River basin, the simulated hydrograph is used for the discharge duration curve and the potential hydropower duration curve. Figure 6(a) shows the discharge duration curve for 20 years. The runoff height of 7.08 mm/day is the maximum discharge of the Seto River Diversion. In Fig. 6(a), the runoff height of 7.08 mm/day is the runoff of the 1096th day of a total of 7305 days of the 20 years. It is equivalent to the 55 day runoff in 365 days of a year. Therefore the 7.08 mm/day runoff from day 1 to day 55 is effective for hydropower. The effective runoff of the hydropower from day 56 to day 365 is subjected to simply the discharge duration curve. The practical hydropower output is calculated by the following equation:

$$P = 9.8\, Q H \eta_t \tag{4}$$

where P is the hydropower output in kW, Q is the discharge in m^3 s^{-1}, H is the differential water head (= 25 m) and η_t is the synthesis efficiency coefficient (assuming 0.7).
Daily hydropower generation is calculated by:

$$P_d = 24 \times 9.8 Q_{day}\, H \eta_t \tag{5}$$

where P_d is the daily hydropower output in kWh, P is the hydropower output in kW and Q_{day} is the daily discharge in m^3 s^{-1}.

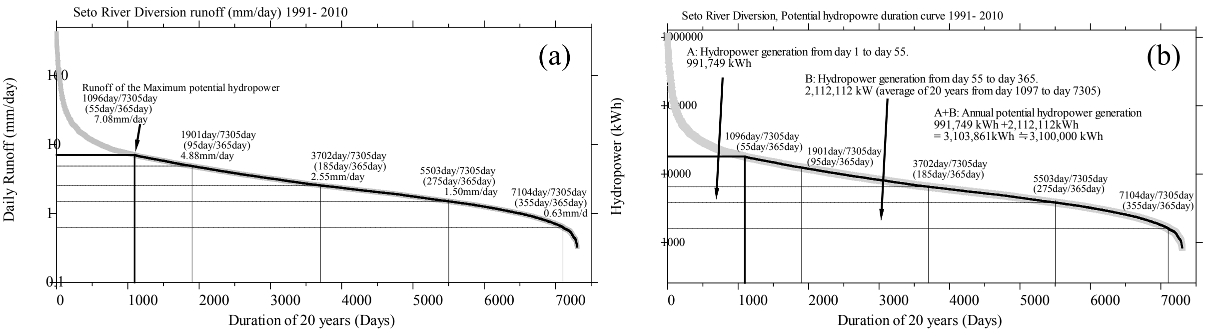

Fig. 6 (a) 20 years duration curve of the daily runoff and (b) the potential hydropower duration curve of the Seto River Diversion simulated by the hourly hydrological model.

Figure 6(b) shows the potential of the annual hydropower calculated by using equations (4) and (5). The potential of annual hydropower generation is evaluated to be 3 100 000 kWh assuming the hydropower duration curve in Fig. 6(b). Annual income of the hydropower generation is estimated to be JPY89 900 000 (USD934 061), assuming the unit price of feed in tariff (FIT) of JPY29/kWh (USD0.30/kWh), for which the unit price is derived from the new feed in tariff (FIT) in July 2013, and JPY100 is converted to USD1.04. The mini-hydropower project satisfies the local power demand and generates the surplus economic benefit to the local community in the mountainous small river basin.

CONCLUSION

In this study, the two parameters of the storage function equation for low flow, the recession coefficient constant *Au* and the exponent value *N*, were identified and formulated by the exponent equation based on a sensitivity analysis using the hourly hydrological model. As an application of the hydrological cycle model using the optimized hydrograph, the Seto River basin was evaluated for the potential hydropower generation for the local community in the mountainous basin in Japan.

REFERENCES

Ando, Y., Musiake, K. & Takahasi, Y. (1983) Modelling of hydrologic processes in a small natural hillslope basin, based on the synthesis of partial hydrological relationships. *Journal of Hydrology* 64, 311–337.

Ando, Y., Musiake, K. & Takahasi, Y. (1984) Modelling of hydrologic processes in a small urbanized hillslope basin with comments on the effect of urbanization. *Journal of Hydrology* 68, 61–83.

Ando, Y. (1988) A daily rainfall–runoff model for a mountainous basin. *Journal of Hydroscience and Hydraulic Engineering,* 5(2), 53–64.

Diskin, M. H. & Nazimov, N. (1995) Linear reservoir with feedback regulated inlet as a model for the infiltration process. *Journal of Hydrology* 172, 313–330.

Diskin, M. H. & Nazimov, N. (1996) Ponding time and infiltration capacity variation during steady rainfall. *Journal of Hydrology* 178, 369–380.

Fujimura, K., Shiraha, K., Kanae, S. & Murakami, M. (2012) Development of the hourly hydrological model for mountainous basins using the storage function method and the Diskin–Nazimov infiltration model. In: *Models – Repositories of Knowledge* (ed. by E. Sascha *et al.*), 338–344. IAHS Publ. 355. IAHS Press, Wallingford, UK.