CATCHMENT STORAGE ESTIMATION BASED ON TOTAL RAINFALL-TOTAL LOSS RAINFALL RELATIONSHIP FOR 47 CATCHMENTS IN JAPAN

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One of the main objectives of research in hydrology is to improve the accuracy of catchment storage estimation for water resources management and flood prediction purposes. Rain water falling to the ground surface will either run off along the surface or infiltrate into the soil. The infiltrated water which is defined as loss rainfall can be used to estimate the potential catchment storage.

Total rainfall-total loss rainfall relationship has been developed to estimate catchment storage by using tanh function fitting curve for 47 catchments located in 16 prefectures in Japan between 2002 and 2011 (June to October). The obtained results indicate that runoff parameters in the tanh function represented by a and b parameters can be utilized to estimate the potential water storage for catchments having stabilized tanh curve type. Among 47 catchments, only 23.4% of the overall catchments have stabilized tanh curve types which are located in Honshu Island.

Key Words : *Catchment Storage, Total Rainfall-Total Loss Rainfall, Runoff Parameters*

1. INTRODUCTION

Total loss rainfall represents the spatial and temporal averaged behavior of the infiltration capacity during a rainfall event which is controlled by the soil properties, and is independent of the rainfall intensity¹⁾. Infiltration capacity analysis is necessary to estimate the potential catchment storage as one of the main variables in the general water balance equation. The water balance equation can be applied for water supply management and for water shortages prediction.

The non-linearity of surface runoff phenomena in the mountainous basins based on universal lumped kinematic wave model has been studied^{2),3),4)}. Runoff in mountainous basins are uniquely determined by model parameters concerning slope gradient, slope length, the thickness of surface soil layer, unsaturated hydraulic conductivity, and effective porosity^{3),4)}.

Other methods for estimating water storage capacity is to use a scatter plot of measured interception versus precipitation, and then validating the result by measuring water storage using

microwave transmission with a vertically moving system⁵⁾ and by estimating spatial mean volumetric soil water content (θ) using measured θ from the Most Time Stable Locations (MTSLs) to estimate mean θ in an adjacent or distant area while negating the impact of variability in soil, vegetation, and topographic properties⁶⁾.

The purpose of this study is to estimate the potential catchment storage by utilizing hourly rainfall and hourly runoff observation data for 47 gauged catchments located in 16 prefectures in Japan (see **Table 1**). The potential catchment storage is expressed by a parameter and the curve gradient which controls the a parameter is expressed by b parameter. The values of a and b parameters are obtained by plotting total rainfall-total loss rainfall using tanh function fitting curve.

Section 2 describes the research methodology. Section 3 shows the geographical distribution of total rainfall and total loss rainfall relationship. Section 4 shows the relationship of a and b values, and conclusions are explained in Section 5.

2. METHODOLOGY

(1) Data

Hourly rainfall and hourly runoff data for 47 catchments located in 16 prefectures in Japan are obtained from Ministry of Land, Infrastructure, and Transport (MLIT) website⁷⁾. The study period is during summer time from month of June to month of October for 10 years (2002-2011).

Table 1 presents the list of 47 catchments and their catchment areas. The information of average daily runoff and obtained results (a values, b values, and curve types) for each catchment is also presented in **Table 1**. The average daily runoff is obtained by averaging total daily runoff within 10 years from month of June to month of October.

Table 1 List of 47 catchments in 16 prefectures in Japan (a denotes the potential catchment storage, b denotes the curve gradient, and curve type is classified into 3 groups i.e. linear, non-stabilized tanh curve, and stabilized tanh curve)

NO.	DAM NAME	PREFECTURE (Latitude, Longitude)	CATCHMENT AREA (km ²)	AVERAGE DAILY RUNOFF (m ³ /s)	a	b	CURVE TYPE
1	Houheikyou	Hokkaido (42.92, 141.15)	136.10	171.41	361.70	0.00213	Non stabilized tanh curve
2	Iwaonai	Hokkaido (44.12, 142.71)	341.58	297.56	613.89	0.00131	Non stabilized tanh curve
3	Izarigawa	Hokkaido (42.85, 141.45)	113.25	115.89	1810.99	0.00047	Linear
4	Jyouzankei	Hokkaido (42.98, 141.16)	103.59	78.07	765.76	0.00092	Non stabilized tanh curve
5	Kanayama	Hokkaido (43.13, 142.44)	410.81	449.21	760.62	0.00103	Non stabilized tanh curve
6	Katsurazawa	Hokkaido (43.24, 142)	162.50	201.57	277.97	0.00191	Non stabilized tanh curve
7	Nibutani	Hokkaido (42.63, 142.15)	1155.45	1271.19	322.15	0.00253	Non stabilized tanh curve
8	Pirika	Hokkaido (42.47, 140.19)	114.44	191.84	660.99	0.00099	Non stabilized tanh curve
9	Satsunaigawa	Hokkaido (42.59, 142.92)	116.63	270.08	454.01	0.00100	Non stabilized tanh curve
10	Taisetsu	Hokkaido (43.68, 143.04)	289.26	400.36	4025.39	0.00021	Linear
11	Takisato	Hokkaido (43.44, 142.29)	1369.37	1411.59	1290.17	0.00051	Linear
12	Tokachi	Hokkaido (43.24, 142.94)	598.24	332.79	5037.92	0.00016	Linear
13	Aseishigawa	Aomori (40.6, 140.69)	227.53	274.79	1538.63	0.00036	Non stabilized tanh curve
14	Tamagawa	Akita (39.83, 140.64)	283.59	549.45	48.05	0.01217	Stabilized tanh curve
15	Gosho	Iwate (39.69, 141.03)	635.17	1027.06	1244.27	0.00044	Non stabilized tanh curve
16	Ishibuchi	Iwate (39.11, 140.9)	145.75	269.23	53.01	0.01137	Stabilized tanh curve
17	Shijushida	Iwate (39.75, 141.15)	1178.38	1043.20	124.25	0.00342	Non stabilized tanh curve
18	Tase	Iwate (39.34, 141.32)	727.63	602.94	79.07	0.00824	Non stabilized tanh curve
19	Yuda	Iwate (39.3, 140.89)	576.45	885.85	51.22	0.01126	Stabilized tanh curve
20	Gassan	Yamagata (38.58, 139.89)	237.47	244.02	2692.35	0.00023	Linear
21	Sagae	Yamagata (38.46, 140.04)	227.58	565.79	176.41	0.00198	Non stabilized tanh curve
22	Shirakawa	Yamagata (37.97, 139.92)	205	267.00	62.53	0.00738	Non stabilized tanh curve
23	Kamafusa	Miyagi (38.2, 140.7)	196.09	267.08	49.14	0.01156	Stabilized tanh curve
24	Naruko	Miyagi (38.75, 140.7)	208.54	329.11	67.56	0.00740	Non stabilized tanh curve
25	Shichikashuku	Miyagi (37.96, 140.51)	230.61	210.19	55.62	0.01216	Stabilized tanh curve
26	Miharu	Fukushima (37.4, 140.47)	227.63	146.91	181.27	0.00367	Non stabilized tanh curve
27	Sagurigawa	Niigata (37.52, 139)	61.36	132.52	1114.41	0.00049	Non stabilized tanh curve
28	Kawaji	Tochigi (36.9, 139.69)	320.74	165.41	765.77	0.00121	Non stabilized tanh curve
29	Fujiwara	Gunma (36.8, 139.04)	400.20	816.73	824.23	0.00064	Non stabilized tanh curve
30	Kusaki	Gunma (36.54, 139.37)	263.85	448.58	739.23	0.00086	Non stabilized tanh curve
31	Naramata	Gunma (36.88, 139.08)	95.40	101.70	753.24	0.00099	Non stabilized tanh curve
32	Shimokubo	Gunma (36.13, 139.02)	323.65	287.59	413.12	0.00186	Non stabilized tanh curve
33	Sonohara	Gunma (36.64, 139.18)	601.06	369.84	625.13	0.00139	Non stabilized tanh curve
34	Yagisawa	Gunma (36.91, 139.06)	165.54	405.06	345.41	0.00190	Stabilized tanh curve
35	Futase	Saitama (35.94, 138.91)	170.58	166.83	528.18	0.00137	Non stabilized tanh curve
36	Urayama	Saitama (35.95, 139.05)	52.14	54.83	125.98	0.00709	Stabilized tanh curve
37	Koshibu	Nagano (35.61, 137.98)	289.57	236.85	359.60	0.00246	Stabilized tanh curve
38	Makio	Nagano (35.82, 137.6)	307.79	479.82	436.91	0.00164	Stabilized tanh curve
39	Misogawa	Nagano (35.98, 137.77)	54.21	84.57	71.32	0.01126	Non stabilized tanh curve
40	Miwa	Nagano (35.81, 138.08)	311.03	383.34	826.13	0.00099	Non stabilized tanh curve
41	Kuzuryu	Fukui (35.89, 136.69)	390.36	508.59	114.48	0.00569	Stabilized tanh curve
42	Agigawa	Gifu (35.42, 137.43)	81.8	122.39	47.43	0.01217	Non stabilized tanh curve
43	Iwaya	Gifu (35.76, 137.16)	1695.75	744.99	185.56	0.00342	Non stabilized tanh curve
44	Yokoyama	Gifu (35.59, 136.46)	470.71	662.16	1419.33	0.00049	Non stabilized tanh curve
45	Shintoyone	Aichi (35.13, 137.76)	111.44	356.46	486.60	0.00092	Non stabilized tanh curve
46	Yahagi	Aichi (35.24, 137.42)	504.62	834.21	767.03	0.00099	Non stabilized tanh curve
47	Hachisu	Mie (34.38, 136.21)	80.9	211.17	411.26	0.00175	Stabilized tanh curve

(2) Streamflow hydrograph separation

A hydrograph separation technique to separate a streamflow hydrograph into base flow and surface runoff components was introduced by U.S. Geological Survey (USGS). The technique is called local minimum method and was developed by Pettyjohn and Henning in the year 1979⁸⁾. The original hourly rainfall and hourly runoff data are converted into daily values format. The runoff refers to the dam inflow (inlet flow).

The local minimum method checks each day to determine if it is the lowest discharge in a specific given interval before and after the day being considered. If it is, then it is a local minimum and is connected by straight lines to adjacent local minimums. The base flow values for each day between local minimums are estimated by linear interpolations^{8),9)} (see Fig.1).

The duration of surface runoff is calculated from the empirical relation⁸⁾:

$$N = A^{0.2} \quad (1)$$

,where N is the number of days after which surface runoff ceases, and A is the drainage area in square miles. The interval used to determine the lowest discharge is specified as below:

$$I = 0.5(2N^* - 1) \quad (2)$$

,where I is the interval used for hydrograph separation (days), and $2N^*$ is the odd integer between 3 and 11 and nearest to $2N^8)$.

Fig.1 Streamflow hydrograph separation by using local minimum method. The surface runoff is denoted by red line, whereas the base flow is denoted by blue line.

(3) Relationship between total rainfall and total loss rainfall

Total rainfall is defined as the total amount of rainfall within 1 rainfall event, whereas total surface runoff is defined as the total amount of surface runoff within 1 rainfall event. The surface runoff (excess rainfall intensity) is subtracted from the actual rainfall intensity (total rainfall) to obtain the loss rainfall. Total loss rainfall is defined as total amount of rainfall that infiltrates into the ground.

The numbering of rainfall events is determined by utilizing surface runoff data after obtaining rainfall events as the output of a streamflow hydrograph separation.

Total rainfall and total loss rainfall for 47 catchments are plotted by using tanh function to obtain a and b values as runoff parameters^{3),4)}.

$$y = a \tanh(bx) \quad (3)$$

,where y is the total loss rainfall (mm), x is the total rainfall (mm), and a and b are runoff parameters.

3. GEOGRAPHICAL DISTRIBUTION OF TOTAL RAINFALL AND TOTAL LOSS RAINFALL RELATIONSHIP

(1) Total rainfall and total loss rainfall relationship for 47 catchments

The obtained results by applying Eq.(3) for 47 catchments are plotted in Fig.2.

Fig.2 (a) Relationship between total rainfall and total loss rainfall for different areas: green lines denote Hokkaido Prefecture, yellow line denotes Aomori Prefecture, cyan line denotes Akita Prefecture, dark blue lines denote Iwate Prefecture, light yellow lines denote Yamagata Prefecture, purple lines denote Miyagi Prefecture, navy line denotes Fukushima Prefecture, dark cyan line denotes Niigata Prefecture, dark gray line denotes Tochigi Prefecture, orange lines denote Gunma Prefecture, pink lines denote Saitama Prefecture, violet lines denote Nagano Prefecture, dark yellow line denotes Fukui Prefecture, red lines denote Gifu Prefecture, magenta lines denote Aichi Prefecture, black line denotes Mie Prefecture. (b) All of catchments show linear curve up to 60 mm total amount of rainfall in 1 rainfall event.

Fig.2a shows catchments located in the same prefecture can have different curve types. All of catchments show linear curve up to 60 mm total amount of rainfall in 1 rainfall event (see Fig.2b). This implies that for overall catchments, when there is a rainfall event, at least 60 mm total amount of rainfall can infiltrate into the ground and there is no amount of rainfall that contributes to surface runoff.

Fig.3 (a) Linear curve type of Taisetsu dam in Hokkaido prefecture. (b) Non-stabilized tanh curve type of Kusaki dam in Gunma prefecture. (c) Stabilized tanh curve type of Hachisu dam in Mie prefecture.

As shown in **Fig.3a**, Taisetsu dam catchment in Hokkaido prefecture has never experienced heavy rainfall events during the last 10 years between June and October. Based on 154 rainfall events occurred within the last 10 years, in average 83.06% total amount of rainfall infiltrated into the ground, and only 16.94% became surface runoff. Therefore, the curve shows linear type because the infiltration is dominant over the surface runoff.

Based on 159 rainfall events occurred at Kusaki dam catchment in Gunma prefecture, in average

70.94% total amount of rainfall infiltrated into the ground, and only 29.06% became surface runoff (see **Fig.3b**). In terms of frequency, the number of heavy rainfall events having similar values of total rainfall amount was not adequate for making stabilized tanh curve. Thereby, the curve shows transition curve from linear to stabilized tanh curve which is named non-stabilized tanh curve.

For Hachisu dam catchment in Mie prefecture, based on 162 rainfall events, in average 67.37% total amount of rainfall infiltrated into the ground, and 32.63% became direct runoff. In terms of frequency, there were some heavy rainfall events in the range of 794 mm and 1345 mm of total rainfall amount which occurred for 23 times. These rainfall events were considered heavy rainfall events compared with normal events which ranged from 3 mm and 464 mm. Therefore, adequate number of heavy rainfall events can make a stabilized tanh curve type as seen in **Fig.3c**.

When the curve has reached its stable condition, the total loss rainfall tends to be constant for any kind of total rainfall. It means that the catchments soils have become saturated and the major portion of rainfall will become surface runoff. Therefore, a parameter as the maximum height of a stabilized tanh curve can be used to estimate the potential amount of rain water which can be stored in the respective catchment.

The same amount of total rainfall in 1 rainfall event may result in different amount of total loss rainfall (see **Fig.3a-3c**). The results have shown that a parameter obtained by plotting total rainfall and total loss rainfall using tanh function contains the value of standard deviation (1σ) (see **Fig.4**).

This standard deviation value represents the initial soil moisture condition of the respective catchment. The negative value of standard deviation can represent the wet initial soil moisture condition, whereas the positive value of standard deviation can represent the dry initial soil moisture condition.

Fig.4 Scatter diagram of a parameter and its absolute value of standard deviation for catchments having stabilized tanh curve types.

Geographical distribution of a parameter is shown in Fig.5.

The range of a values for catchments having:

Linear curve Non-stabilized tanh curve

● 1290.17301
● 2227.11019
● 3164.04737
● 4100.98455
● 5037.92173
▲ 47.42713
▲ 420.22670
▲ 793.02627
▲ 1165.82584
▲ 1538.62541

Stabilized tanh curve

◆ 48.05252
◆ 145.26758
◆ 242.48264
◆ 339.69769
◆ 436.91275

Fig.5 Geographical distribution of a parameter (red circles denote 5 catchments having linear curve, green triangles denote 31 catchments having non-stabilized tanh curve, and orange diamonds denote 11 catchments having stabilized tanh curve).

4. RELATIONSHIP OF a AND b VALUES

(1) Scatter diagram of a and b parameters

The values of a and b parameters are obtained by plotting total rainfall (mm) and total loss rainfall (mm) using Eq.(3). Scatter diagram of a and b parameters for 47 catchments is shown in Fig. 6.

Fig.6 Scatter diagram of a and b parameters (red circles denote catchments having linear curve, green triangles denote catchments having non-stabilized tanh curve, and orange diamonds denote catchments having stabilized tanh curve). The values of a and b for 11 catchments having stabilized tanh curve are plotted in the curve for different range of total rainfall amount (yellow square: 0-50 mm, blue cross: 0-100 mm, red cross: 0-150 mm, black plus: 0-200 mm).

Based on the result showed in Fig.6, b parameter is a function of a parameter based on empirical equation as follows:

$$b = 0.4667 \times a^{-0.943} \quad (4)$$

$$a = \left(b / 0.4667 \right)^{-1.0604} \quad (5)$$

Hence Eq.(3) can be rewritten as follows:

$$y = a \tanh (0.4667 a^{-0.943} x) \quad (6)$$

,where y is the total loss rainfall (mm), x is the total rainfall (mm), and a is potential catchment storage.

(2) Estimation of a value for different amount of total rainfall in 1 rainfall event

As shown in Fig.6, a and b values obtained from tanh fitting curve for 11 catchments having stabilized tanh curve are overplotted in the curve fitting for different range of total amount of rainfall. Results show that the values are well fitted to the curve. Therefore, the obtained empirical equation can be utilized to estimate the value of a parameter regardless the total amount of rainfall occurred in 1 rainfall event.

(3) Validation of obtained empirical equation

The validation of obtained empirical equation has been done by comparing the a values obtained from Eq.(5) against the a values obtained from tanh fitting curves for catchments having stabilized tanh curve type.

Fig.7 Validation of a for total rainfall ranged from

(a) 0 mm to 50 mm (b) 0 mm to 100 mm

(c) 0 mm to 150 mm (d) 0 mm to 200 mm.

The validation has been done for several cases i.e. for maximum total amount of rainfall within 1 rainfall event ranged from 0 mm to 50 mm, 0 mm to 100 mm, 0 mm to 150 mm, and 0 mm to 200 mm (see **Fig.7a, b, c, and d**, respectively).

Fig.7a-7d indicate that a values obtained from empirical equation show good correlation with a values obtained from tanh fitting curves for catchments having stabilized tanh curve types when there is relatively high total rainfall amount.

5. CONCLUSIONS

Conclusions of the current research results can be summarized as follows:

- Out of 47 catchments located in 16 prefectures in Japan, 5 catchments have linear curve, 31 catchments have non-stabilized tanh curve, and only 11 catchments have stabilized tanh curve. It means majority of catchments in Japan have not experienced saturated condition yet and have the capability to store rain water whenever there is a rainfall event.
- The minimum catchment storage in 1 rainfall event for overall catchments is approximately 60 mm amount of rain water.
- Parameter a in the tanh function is the maximum height of a stabilized tanh curve which can represent the potential catchment storage. Further studies are needed to explain the physical meaning of a parameter in relation to catchment characteristics (soil types, terrain types, rock types, and land use types).
- Parameters a and b for stabilized tanh curve can be correlated by using an empirical equation i.e. $b = 0.4667 * a^{-0.943}$ where a and b are runoff parameters. This empirical equation can be applied regardless the total amount of rainfall occurred in 1 rainfall event.
- Loss of infiltrated rainfall is independent of the total amount of rainfall but correlated to the initial soil moisture content. Total loss rainfall is dependent of potential catchment storage which is represented by a parameter.
- The obtained empirical equation can be used to estimate the value of a during saturated condition if there is longer data set which contains heavy rainfall events.

ACKNOWLEDGMENT: This study was partially supported by Research Program on Climate Change Adaptation (RECCA), MEXT, Japan, the MEXT SOUSEI program (theme C-i-C), the Integrated Study Project on Hydro-Meteorological Prediction and Adaptation to Climate Change in Thailand (IMPAC-T), the JST-JICA, and the CREST/JST.

REFERENCES

- 1) Brutsaert, W.: An Introduction of Hydrology, *Cambridge University Press*, pp.343-344, 2005.
- 2) Yamada, T., Yamazaki, K.: The Influence of The Distribution of Field Moisture Capacity on Runoff, *JSCE Hydraulic Journal*, Vol.27, pp.385-392, 1983.
- 3) Yamada, T.: Studies on Non-Linear Runoff in Mountainous Basins, *JSCE Hydraulic Journal*, Vol.47, pp.259-264, 2003.
- 4) Kure, S., Yamada, T.: A Study on The Non-Linearity of Runoff Phenomena and Estimation of Effective Rainfall, *Proceedings of the 2nd Asia Pacific Association of Hydrology and Water Resources Conference*, Vol.2, pp.76-85, 2004.
- 5) Klaassen, W., Fred, B., E. de, W.: Water storage and evaporation as constituents of rainfall interception, *Journal of Hydrology*, Vol.212-213, pp.36-50, 1996.
- 6) Wei, H., Ming, A. S., Mei, T. H., Dong, L. S., Bing, C. S.: Mean soil water content estimation using measurements from time stable locations of adjacent or distant areas, *Journal of Hydrology*, Vol.497, pp.234-243, 2013.
- 7) Water Information System: Ministry of Land, Infrastructure, and Transport (MLIT), Japan, <http://www1.river.go.jp/>.
- 8) Sloto, R. A., Crouse, M. Y.: Hysep: A Computer Program for Streamflow Hydrograph Separation and Analysis, *U.S. Geological Survey, Water-Resources Investigations Report* 96-4040, 1996.
- 9) Dukic, V.: Modelling of base flow of the basin of Kolubara river in Serbia, *Journal of Hydrology*, Vol.327, pp.1-12, 2006.
- 10) Hino, M., Odaka, Y., Nadaoka, K. and Sato, A.: Effect of Initial Soil Moisture Content on The Vertical Infiltration Process: A Guide To The Problem of Runoff-Ration and Loss, *Journal of Hydrology*, Vol.102, pp.267-284, 1988.
- 11) Tachikawa, Y., Nawarathna, B., Vieux, B., Takara, K.: Hydrologic Prediction Using Weather Radar Information and Distributed Hydrologic Modelling, *The XXIII General Assembly of the International Union of Geodesy and Geophysics, Sapporo, Japan*, 2003.
- 12) Shiiba, M., Takasao, T., Nakakita, E.: Investigation of short term rainfall prediction method by a translation model, *Proceedings of the 28th Annual Conference on Hydraulics, JSCE*, pp.423-428.

(Received September 30, 2013)