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Analysis on the long term discharge of a catchment

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Abstract: In this study, the characteristics of the long term discharge of a Terraced Paddy Field Catchment are studied. 2 Kind of Tank Models are proposed and used to simulate the discharge of the catchment. The characteristics of the model simulations of the discharge of the catchment are analyzed and compared with those of a forest catchment.

Key words: long term discharge; model simulation; terraced paddy field catchment

Introduction

It is well known that the characteristics of the catchment discharge will change with land use. In this paper, the focus is to discuss the model of long term discharge of catchment which includes two kinds of land use: one is forest at the upper part of the catchment, another is paddy field at the lower part of catchment. The catchment is located in Ehime Prefecture, Japan. It has long series of hydrologic data and meteorologic data.

There have been many types of models proposed for runoff analysis. Since it was developed, tank model has been widely used for discharge analysis. At the very beginning, it had no physical meaning. With the introduction of physical analysis of the process, it is much improved. For example, for the first tank, Manning Equation is used to calculate the surface flow; Green-Ampt Equation is used to analyze the infiltration process, and so on.

According to Ichikawa *et al*. (Ichikawa, 1997), the complex tank model proposed reflects water management effects by changing the corresponding height of the outlet. The modified tank model proposed by Masumoto (Masumoto, 1994) distinguishes between the cultivated paddy fields and abandoned paddy fields in the mountainous area by considering the difference of percolation effects of the two kinds of paddy fields. The model also incorporates the water management effects by changing the height of the outlet hole of the surface tank model according to irrigation and drainage activity. The low-land tank model proposed by Hayase *et al*. (Hayase, 1993) focuses on the inter-flow between paddy fields and rivers. These low land models calculate the inter-flow between the paddy fields tank and river tank by using weir formula.

1 Structure of the model

1.1 Lumped tank model

In this study, a simple tank model of 4 layers of tanks is constructed. The surface flow is expressed by the 1st tank. The prompt subsurface flow is expressed by the 2nd tank. The delayed subsurface flow is expressed by the 3rd tank, and the groundwater flow is expressed by the 4th tank.

Principally, rainfall falling on the surface of the catchment can cause 3 kinds of hydrologic processes: surface runoff, infiltration and evapotranspiration. The infiltrated rainfall contributes to soil moisture, subsurface flow, evapotranspiration and groundwater percolation. Therefore, the basic structure of the 4-layer tank model can be expressed as:

$$dS_1(t)/dt = R - E_1 - G_1 - Q_1, \tag{1}$$

$$dS_2(t)/dt = G_1 - E_2 - Q_2 - G_2, \tag{2}$$

$$dS_3(t)/dt = G_2 - E_3 - Q_3 - G_3, \tag{3}$$

$$dS_4(t)/dt = G_3 - E_4 - Q_4. \tag{4}$$

where, S_i is the storages of the ith tank; R is rainfall intensity; E_i is evapotranspiration of the ith tank; G_i is percolation rate from the ith tank; Q_i is discharges from the i th tank; (i=1, 2, 3,

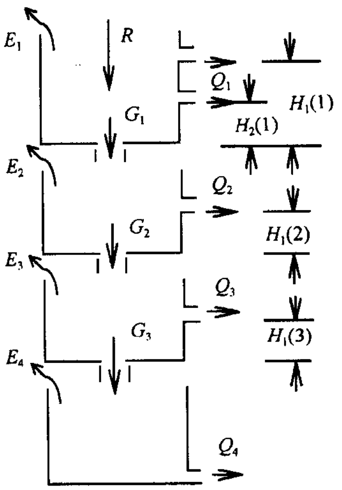

Fig.1 Structure of lumped tank model

4). It is shown in Fig.1.

1.2 Distributed tank model

As described by Hong *et al*. (Hong, 1998), stream discharge from the forest area flows into the paddy fields during irrigation seasons and it flows directly into streams during non-irrigation season in the catchment. Therefore, a distributed tank model is developed to take the difference of water management into account.

In this model, we use two sets of tanks. The first set of tanks represents the forest area of the catchment. The second set of tanks represents the terraced paddy field area of the catchment. They operate simultaneously as described in lumped tank model within the same set of tanks. The connection between the two sets of tanks is different in non-irrigation period and irrigation period.

1.2.1 Irrigation seasons model

During irrigation period, the two sets of tanks connect as Fig. 2. The outflows of the upper 3 tanks of the first set of the model, which represents the forest area, flow into the top tank of the second set of the model, which represent the paddy field area. The outflow of the 4th tank of the first set of tanks flows into the 4th tank of the second set of tanks.

1.2.2 Non-irrigation seasons model

During the non-irrigation seasons, the 2 sets of tanks connect as Fig.3. The discharges of the upper 3 tanks of the first set of model flow directly into the stream of the catchment without ponding in the terraced paddy field area. The 2 sets of tanks operate independently during this period.

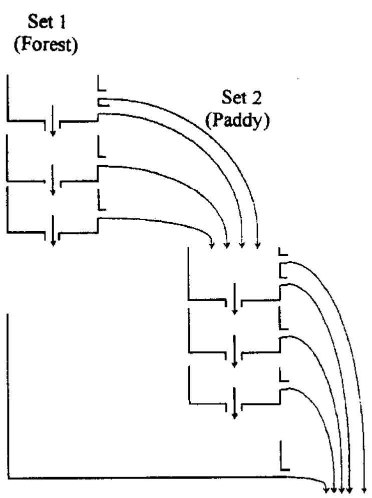

Fig.2 Structure of distributed tank model during irrigation seasons

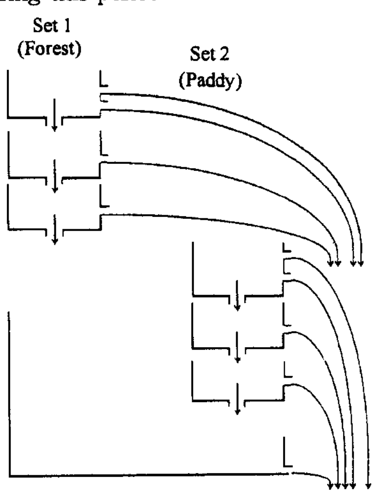

Fig.3 Structure of distributed tank model during non-irrigation seasons

1.3 Discharge model

The recession part of hydrographs can be expressed by an exponential equation:

$$Q_i(t) = Q_i(0)\exp(-\alpha_i t), \tag{5}$$

where, $Q_i(t)$ is discharge at any time t and $Q_i(0)$ is initial discharge at $t=0$; α_i is the recession coefficient; $i=1, 2, 3, 4$ respectively.

The concept underlying Equation (5) is that of a linear reservoir, whose outflow rate is proportional to the current storage:

$$Q_i(t) = \alpha_i S_i(t), \tag{6}$$

where, α_i is decided by optimization method.

Considering the retention effect of the tank, we introduce the outlet height $H_1(i)$ and $H_2(i)$ to represent the upper and lower retention depths of the tank i. Therefore, the Equation (6) is modified as:

$$Q_i(t) = \alpha_1(i)(S_i(t) - H_1(i)) + \alpha_2(i)(S_i(t) - H_2(i)), \tag{7}$$

where, $\alpha_1(i)$ and $\alpha_2(i)$ are recession coefficients of the first and second outlets of the ith tank; $H_1(i)$ and $H_2(i)$ are the heights of the first and the second outlets of the ith tank.

1.4 Evapotranspiration model

Though it is very difficult to estimate the actual evapotranspiration at the experimental catchment, the short term water balance method was applied to determine the monthly ratio of evapotranspiration, and to determine the daily and hourly actual evapotranspiration.

After the determination, actual evapotranspiration is deducted from the first tank if the storage of the first tank is enough. Otherwise the excessive evapotranspiration is deducted from the next tank, and suppose the storage of the first tank is 0. This process continues until all the amount of the evapotranspiration is subtracted.

1.5 Infiltration and percolation model

In this study, infiltration and percolation are considered by the same method of linear reservoir. The infiltration or percolation rate varies with the storage of the corresponding tank. The equation of the infiltration or percolation rate is:

$$G(i) = c(i)S(i), \tag{8}$$

where, $G(i)$ is percolation or infiltration from the ith tank; $S(i)$ is storage of the ith tank; $c(i)$ is coefficient, decided by optimization method.

2 Model identification

2.1 Identification of parameters

In this study, we used mathematic method (Powell Non-linear Programming) to optimize the parameters. The parameters in the model are: (1) recession coefficients $\alpha_1(i)$ and $\alpha_2(i)$; (2) infiltration or percolation coefficients $c(i)$; (3) height of outlets $H_1(i)$ and $H_2(i)$; (4) initial storage of the ith tank $S0\ (i)$.

The total number of the parameters for the whole tank model is 24. But in actual calculation, some of the parameters are fixed and no need to optimize. The definitions of the parameters are shown in Fig.4.

Totally there are 12 parameters to be optimized by the mathematical process. They are $\alpha_1(1)$, $\alpha_1(2)$, $\alpha_1(3)$, $\alpha_1(4)$, $\alpha_2(1)$, $H_1(1)$, $H_1(2)$, $H_1(3)$, $H_2(1)$, $c(1)$, $c(2)$, $c(3)$, i.e. the recession coefficients of the 4 tanks, the recession coefficient of the lower outlet of the 1st tank, the heights of the 1st, 2nd, and the 3rd tank, the height of the lower outlet of the 1st tank, and infiltration rate or percolation rate of the 1st, 2nd and the 3rd tank. The procedure of optimization is as follows:

First, we introduce the maximum values of parameters as Table 1. In Table 1, the maximum values of non-parameters, i.e., $H_1(4)$, $\alpha_2(4)$, $\alpha_2(3)$, $\alpha_2(4)$, $H_2(2)$, $H_2(3)$, $H_2(4)$, $c(4)$, $S0(1)$, $S0(2)$ and $S0(3)$ are 0. And $S0(4)$, the 4th tank initial water storage, is decided by:

$$S0(4) = Q_m(1,1,1)/\alpha_1(4), \tag{9}$$

where, $Q_m(1,1,1)$ is the observed discharge at the initial time.

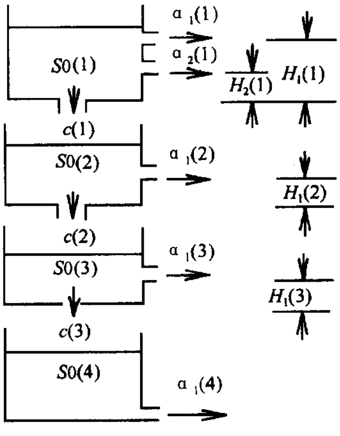

Fig.4 Definition of parameters

Table 1 Maximum values of the parameters

	$\alpha_1(i)$, d^{-1} or h^{-1}	$H_1(i)$, mm	$\alpha_2(i)$, d^{-1} or h^{-1}	$H_2(i)$, mm	$c(i)$, d^{-1} or h^{-1}	$S(i)$, mm
Tank 1	1.00	100.0	1.00	50.0	1.00	0.0
Tank 2	1.00	50.0	0.00	0.0	1.00	0.0
Tank 3	1.00	50.0	0.00	0.0	1.00	0.0
Tank 4	1.00	0.0	0.00	0.0	0.00	0.0

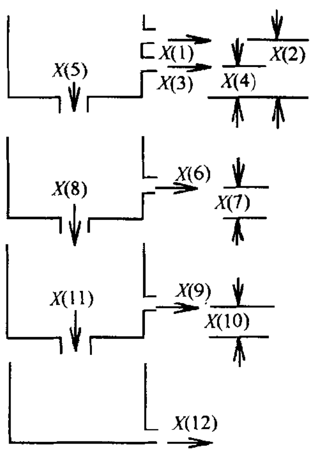

Fig.5 Definition of $X(i)$

Then, we substitute the 12 parameters by 12 variables, $X(i)$, ($i = 1$, 12). The ith parameter is equal to its maximum value multiplied by $X(i)$. Therefore, the $X(i)$ value ranges from 0 to 1.0. The relation between $X(i)$, and the parameters are shown in Fig.5.

Third, we give initial values for the $X(i)$, and use computer programs to optimize the value of $X(i)$. The objective function of the optimization is:

$$\min F = (1.0 + EF)\sum(Q_m - Q_c)^2/Q_m, \quad (Q_m > 0) \quad (10)$$

$$EF = \left| \sum Q_c - \sum Q_m \right| / \sum Q_m \quad (11)$$

where, F is objective function; Q_m is observed discharge; Q_c is calculated discharge; EF is the relative error between the total observed discharge and the total calculated discharge, considering the effect of total water balance.

The constraint conditions of the optimization include:

$$1.0 \geqslant \alpha_1(1) \geqslant \alpha_1(2) \geqslant \alpha_1(3) \geqslant \alpha_1(4) \geqslant 0.0, \quad (12)$$

$$1.0 \geqslant c(1) \geqslant c(2) \geqslant c(3) \geqslant 0.0, \quad (13)$$

$$H_1(i) \geqslant H_2(i) \geqslant 0.0, \quad (14)$$

$$1.0 \geqslant \alpha_1(i) + \alpha_2(i) + c(i) \geqslant 0.0, \quad (15)$$

$$1.0 \geqslant \alpha_1(i) \geqslant \alpha_2(i) \geqslant 0.0, \quad (16)$$

$$S(i) \geqslant 0.0, \quad (17)$$

$$Qc(i) \geqslant 0.0, \quad (18)$$

$$1.0 \geqslant X(i) \geqslant 0.0. \quad (19)$$

2.2 Tank model identification

In this study, we use the discharge, rainfall and evapotranspiration data during 1992—1994 to identify the parameters of the tank model. The 3 years are average water year (1992), wet year (1993) and dry year (1994), respectively.

2.2.1 Lumped tank model

First, we try to identify daily lumped tank model. The obtained values of parameters are listed in Table 2. The comparison between calculated and observed hydrographs is shown in Fig.6. The relative error between the calculated discharge and observed discharge is 33.52%. Judged from the great value of relative error, the result is considered to be not so good. Besides, the height of the first outlet $H_1(1)$ is too great (about 100 mm). It is impractical that the retention storage in the terraced paddy field catchment can be as high as 100 mm. The first problem is that

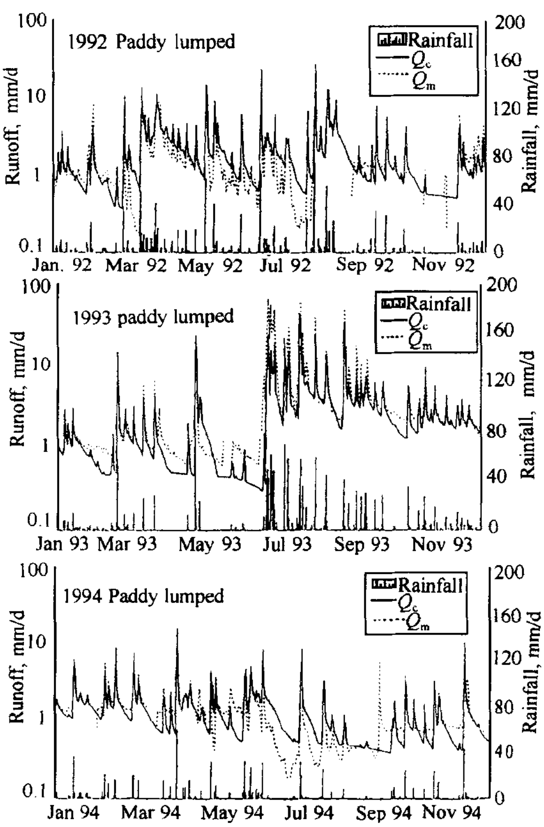

Fig.6 Hydrographs of lumped tank model for the terraced paddy field catchment

there is no consideration of difference of water management between irrigation and non-irrigation seasons. The second problem is that the data of the daily series of discharge, rainfall and evapotranspiration are used in the parameter optimization. The area of the terraced paddy field catchment is small, so it is better to use data of hourly series. Therefore, we try to develop an hourly distributed tank model by considering the difference of water management in different seasons.

Table 2 Values of lumped tank model parameters for daily analysis

	$\alpha_1(i)$, d^{-1}	$H_1(i)$, mm	$\alpha_2(i)$, d^{-1}	$H_2(i)$, mm	$c(i)$, d^{-1}	$S(i)$, mm
Tank 1	0.54	93.9	0.049	0.0002	0.41	0
Tank 2	0.017	50.0	0	0	0.0082	0
Tank 3	0.016	50.0	0	0	0.0082	0
Tank 4	0.011	0.0	0	0	0	79.8

2.2.2 Distributed tank model

For the distributed tank model, we need to identify the parameters of the forest area tank model (Set 1) and the terraced paddy field area tank model (Set 2). Supposing that the parameters of the forest area tank model are the same with the parameters of the forest catchment tank model, we identify the parameters of tank model of the forest area model (Set 1). Then, we identify the parameters of the terraced paddy field area tank model (Set 2).

The results of the forest area tank model (Set 1) and the terraced paddy field area tank model (Set 2) are listed in Table 3 and Table 4, respectively. The comparison between calculated and observed hydrographs of the terraced paddy field catchment is shown in Fig. 7. The relative error of the model simulation is 27.63%.

Table 3 Values of the forest area tank model parameters for hourly analysis

	$\alpha_1(i)$, d^{-1}	$H_1(i)$, mm	$\alpha_2(i)$, d^{-1}	$H_2(i)$, mm	$c(i)$, d^{-1}	$S(i)$, mm
Tank 1	0.069	41.7	0.0074	10.2	0.0207	0
Tank 2	0.0057	27.4	0	0	0.0046	0
Tank 3	0.0016	23.4	0	0	0.0019	0
Tank 4	0.0002	0	0	0	0	229.9

Table 4 Values of the terrace paddy field area tank model parameters for hourly analysis

	$\alpha(i)$, d^{-1}	$H_1(i)$, mm	$\alpha_2(i)$, d^{-1}	$H_2(i)$, mm	$c(i)$, d^{-1}	$S(i)$, mm
Tank 1	0.28	25.8	0.0667	0.0	0.1015	0.0
Tank 2	0.055	7.3	0	0.0	0.1014	0.0
Tank 3	0.0023	50.0	0	0.0	0.0002	0.0
Tank 4	0.0002	0.0	0	0.0	0	52.6

3 Discussion

By using the hourly data series to identify the distributed model, the result is improved. The relative error is still quite large. One reason is water saving activities by farmers in the terraced paddy field catchment. Another reason is due to deviation of time lag of peak discharge as analyzed by Sugawara. These problems remain to be researched in the future.

From Fig. 7 we can see that the calculated and observed hydrographs of the terraced paddy field catchment have greater differences during low flow seasons. This may be also due to the problem of evapotranspiration model.

By comparison between Table 3 and Table 4, we can see that the recession coefficients of the terraced paddy field catchment are greater than those of the forest catchment for the top 3 tanks, while those of the 4th tanks are the same. These results show that for surface flow, the discharge from the terraced paddy field catchment is greater than that from the forest catchment, and for groundwater flow, the discharge has the same recession trend with the forest catchment. Besides, the heights of the 1st and 2nd tank outlets of the terraced paddy field catchment model are smaller than those of the forest catchment model. This result shows that the retention capacity of the terraced paddy field catchment is smaller than that of the forest catchment. Finally, the infiltration

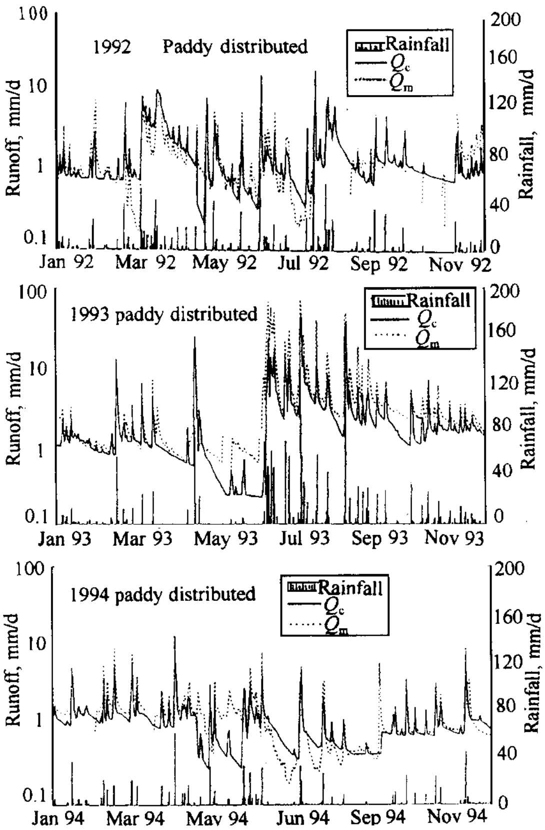

Fig.7 Hydrographs of distributed tank model for the terraced paddy field catchment

and percolation rates of the upper 2 tanks of the terraced paddy field catchment are greater than those of the forest catchment is smaller than that of the forest catchment. This result shows that the deep percolation rate of the terraced paddy field catchment is smaller than that of the forest catchment.

Furthermore, we analyzed the components of the runoff from the terraced paddy field catchment and the forest catchment.

First, we analyzed the amount and proportion of runoff components of the terraced paddy field catchment. The results are shown in Table 5.

From Table 5, we can see that averagely speaking, most runoff component of the terraced paddy field catchment is from the first tank as surface flow, and the least runoff is from the second tank as prompt subsurface flow. During average water year (1992), the most runoff is from the groundwater flow, then is from the surface flow, the delayed subsurface flow, and the least is from the prompt subsurface flow. But, during wet year (1993), the most runoff is from the surface flow, then the delayed subsurface flow, the groundwater flow, and the least is from the prompt subsurface flow. During dry year (1994), the order is the same with that of the average water year.

Second, we analyze the proportion of runoff components from the forest catchment. The results are shown in Table 6.

Table 5 Distribution of runoff from the terraced paddy field catchment

	Year	Tank 1	Tank 2	Tank 3	Tank 4	Total tank
Runoff, mm/a	1992	206.2	47.7	152.1	220.3	626.3
(Proportion, %)		(32.9)	(7.6)	(24.3)	(35.2)	(100)
	1993	403.4	48.3	265.1	197.0	913.8
		(44.1)	(5.3)	(29.0)	(21.6)	(100)
	1994	110.9	3.3	76.4	218.6	409.2
		(27.1)	(0.8)	(18.7)	(53.4)	(100)
	Mean	240.2	33.1	164.5	212.0	649.8
		(37.0)	(5.1)	(25.3)	(32.6)	(100)

Table 6 Distribution of runoff from the forest catchment

	Year	Tank 1	Tank 2	Tank 3	Tank 4	Total tank
Runoff, mm/a	1992	133.7	85.7	59.2	326.5	605.1
(Proportion, %)		(22.1)	(14.1)	(9.8)	(54.0)	(100)
	1993	364.3	123.7	102.0	191.2	781.2
		(46.6)	(15.8)	(13.1)	(24.5)	(100)
	1994	51.6	7.7	25.0	275.8	360.1
		(14.3)	(2.1)	(7.0)	(76.6)	(100)
	Mean	183.2	72.4	62.1	264.5	582.1
		(31.5)	(12.4)	(10.7)	(45.4)	(100)

From Table 6, we can see that averagely speaking, the most runoff component of the forest catchment is from the groundwater flow, the least is from the delayed subsurface flow. In average water year (1992), the most runoff is from the groundwater flow, the second is from the surface flow, the third is from the prompt subsurface flow, and the least is from the delayed subsurface flow. In wet year (1993), the most runoff is from the surface flow, the second is from the groundwater flow, the third is from the prompt subsurface flow, and the least is from the delayed subsurface flow. In dry year (1994), the most runoff is from the groundwater flow, the second is from the surface flow, the third is from the delayed subsurface flow, and the least is from prompt subsurface flow.

Further comparison of runoff components is conducted between the terraced paddy field catchment and the forest catchment in Table 7. From Table 7, we can see that for the terraced paddy field catchment, the most runoff component is from the surface flow; while for the forest catchment, the most runoff is from the groundwater flow. This result shows that compared with the natural forest catchment, the groundwater flow of the terraced paddy field catchment is reduced and the surface flow of the catchment is increased due to water management in the terraced paddy field catchment.

Table 7 Comparison of runoff components between the terraced paddy field catchment and the forest catchment

	Catchment	Tank 1	Tank 2	Tank 3	Tank 4	Total tank
Runoff, mm/a	Paddy	240.2	33.1	164.5	212.0	649.8
(Proportion, %)		(37.0)	(5.1)	(25.3)	(32.6)	(100)
	Forest	183.2	72.4	62.1	264.5	582.1
		(31.5)	(12.4)	(10.7)	(45.4)	(100)

4 Conclusions

From the study, the following conclusions are drawn: (1) For surface and sub-surface runoff, the discharge from the terraced paddy field catchment is greater than that from the forest catchment; while for groundwater flow, the discharge of the terraced paddy field catchment has the same recession trend with that of the forest catchment. (2) The deep percolation rate of the terraced paddy field catchment is smaller than that of the forest catchment. (3) Compared with the natural forest catchment the ground water flow is reduced and the surface flow of the terraced paddy field catchment is increased due to water management in the terraced paddy field catchment.

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