Properties of Hydrologic Cycle in Catchments in Different Land Use and Runoff Analysis by a Lumped Parametric Model

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ABSTRACT: In this paper, properties of hydrologic cycle in three experimental catchments were compared and different types of a lumped parametric model were applied to understand the hydrologic cycle in the catchments. One of them is a forest catchment and another one includes the reclaimed upland fields and last one does terraces paddy fields.

The comparison of hydrologic properties showed that the differences in land use have great influences on the soil properties of surface layer, which cause changes in hydrologic processes such as evapotranspiration and storm runoff et.al. By the runoff analysis models, good agreements between observed and calculated discharge from the catchments were obtained and it was found that the differences in values of optimized model parameters and water budget components reflect those in the hydrologic cycle among them.

1 INTRODUCTION

It is said that the problem of water resources, which means a problem of water quality as well as quantity, will be the most important one to be solved in next century. The cutting of forest for developing farm lands or urbanization has changed the hydrologic cycle in a region to cause serious problems of water such as flood disaster, decreasing groundwater or scarcity of water resource.

Hydrologic cycle has not only a direct relation on the water problems but also an indirect one. It contributes to water pollution through the ability to transport and disperse various type of materials and it also influences the meteorological condition through the redistribution of solar energy by evapotransiration.

In that sense, it is very important to understand the hydrologic cycle in a region for management and conservation of environment as well as water resource. Therefore, the author has been carrying out investigations of soil properties and observations of discharge, rainfall and meteorological factors in the three experimental catchments in different land use, which are a forest, an upland field and a terraced paddy field catchment. In this paper, the differences in the hydrologic properties among them will be discussed and analyzed.

2 OUTLINES OF EXPERIMENTAL CATCHMENTS AND MEASUREMENTS

Three experimental catchments has been established in Ehime Prefecture, Japan, to investigate the hydrologic properties. One of them is a forest catchment. Another one includes upland fields which were reclaimed by a national project and last one includes terraced paddy fields.

2.1 Catchment of forest

The forest catchment is located in 132° 27' east longitude and 33° 28' north latitude. Its area is about 21.0 ha and the elevation ranges from 210 m and 440 m. In the catchment, Japan cedar and Japanese cypress trees are grown. The generals of the catchment are shown in Figure 1. Discharge from the catchment was measured at the gaging station as shown in the figure. An automatic recorder was used to collect data of water level with a rectangular weir. The data were converted to those of volume of discharge by a formula related on the weir. Rainfall was also measured at a station close to the gaging station of stream flow.

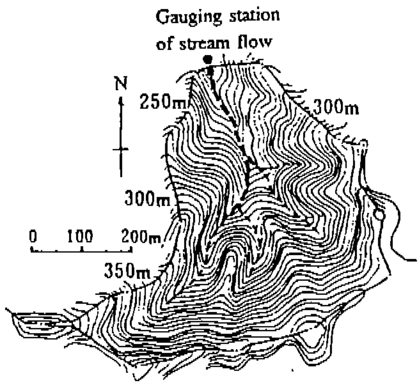

Fig. 1 Generals of forest catchment

2.2 Catchment of reclaimed upland field

The upland field catchment is located in 132° 30' east longitude and 33° 30' north latitude. The generals of the catchment are shown Fig.2. Its total area is about 11.7 ha and the elevation ranges from 25 m to 115 m. Almost half of its whole area is used as upland fields which were reclaimed in 1979 by a national project for reclamation of farm land and remaining part is maintained as forest. In most of the fields, water melon is grown in summer and Chinese cabbage in winter. Farming was started from autumn in 1979, six months after the reclamation. Farmers use a small irrigation system to supply water to their fields. However, the amount of irrigated water can be neglected for the water balance calculation, because it is very small comparing to the amount of rainfall and discharge. In the forest area, pine trees and Japanese cypress trees are grown.

Discharge from the catchment was measured at the gaging station as shown in Fig.2 with a rectangular weir. Rainfall was also measured in the upland fields. The catchment is about 10 kilometers apart from the forest catchment and the mean elevation is different. Therefore, it is thought that the meteorological conditions, which influence evapotranspiration, are a little different from that in the forest catchment.

2.3 Catchment of terraced paddy field

The terraced paddy field catchment is located in 132° 19' east longitude and 33° 12' north latitude. The generals of the catchment is shown in Fig.3. The total area is 10.2 ha and about a quater of the whole area is occupied by terraced paddy fields, which are located at the lower part of the catchment. The elevation ranges from 190 m to 290 m. The catchment is about 1 km apart from the forest one.

Every year, paddy rice is grown in the fields from May to September. After harvesting in October, no crop is grown. The irrigation and drainage system of the terraced paddy fields is shown in Fig.4. During irrigation seasons, the stream flow from the forest area is used for irrigation. The drained water is stored in the fields and then flows from plot to plot until it reaches to the gaging station. During non-irrigation season, from October to April, the runoff water from the forest area flows directly into the streams of the catchment without flowing into the paddy fields.

3 COMPARISONS OF SOME PROPERTIES OF CATCHMENT

Differences in land use change properties of catchment such as slope degree, total length of channels and soil property as well as vegetation and the change affects the hydrologic processes in the catchment. In the following section, such properties will be compared among three catchments.

3.1 Topographical Properties

In the upland fields, the slope was graded to 6° while the original slope of forest was almost 25°. Besides, the new drainage system was constructed to drain the rain

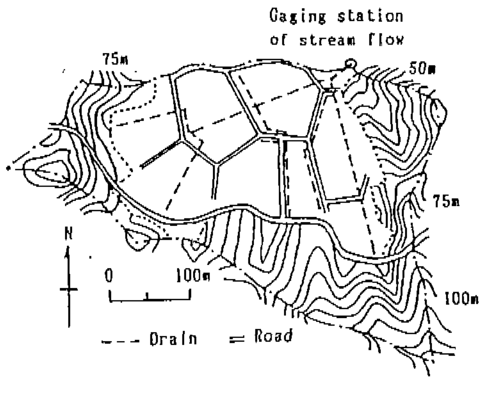

Fig.2 Generals of upland field catchment

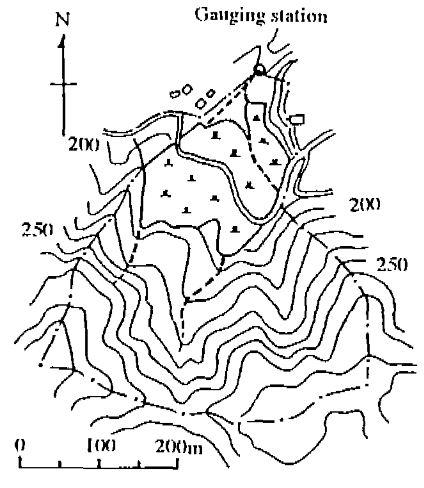

Fig.3 Generals of terraced paddy field catchment

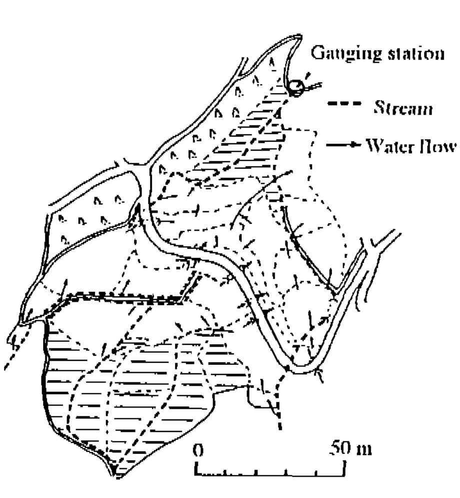

Fig.4 Irrigation and drainage system in terraced paddy filed catchment

water quickly from the fields. As a result, the total length of channels in the catchment was increased and the density of channels is up to 240 m/ha, which is about 3 times greater than that of the forest catchment. The slope of the terraced paddy fields was kept flat and the density of channels is about 100 m/ha. The differences in the both properties may affect the concentration time of rain water and may change the volume of peak discharge.

3.2 Soil properties

Cultivation and management of soil in farm lands change soil properties. Fig.5 shows water retention curves of soil in the upland field and the forest catchment. It is found that the capacity of water holding of soil in the upland field decreased dramatically by the reclamation and was gradually improved by cultivation and farming. In the terraced paddy fields, a impermeable layer of clay soil was found though little difference could be recognized.

According to investigations of infiltration property in the three catchments, it was found that the infiltration capacity of the forest soil is the highest and that of the terraced paddy field soil is the lowest. The final infiltration rate of soils in the forest, upland field and terraced paddy field, are about 10^2 mm/h, 10^1 mm/h and 10^0 mm/h, respectively. Such difference in the infiltration capacity may affect not only storm runoff but also long term runoff.

4 COMPARISONS OF HYDROLOGIC PROCESSES

4.1 Evapotranspiration

Difference in vegetation type affects interception of rainfall, root depth and net radiation of solar energy which is received at the surface and it causes the change in evapotranpiration from a catchment.

Water balance method was applied to estimate the annual amounts of evapotranspiration from the forest and the upland field catchment. Table 1 and Table 2 show the measured rainfall (R), discharge (Qt) and the estimated evapotranspiration (Et). In addition to the water balance components, the annual potential evaporation (Ep) and ratio of evapotranspiration to the potential evaporation (Et/Ep) are given in the table. It is difficult to compare the amounts directly and evaluate the influence of difference in land use on evapotranspiration, because the meteorological conditions are different from each other as stated in Chapter 2. The comparison of the ratio (Et/Ep) shows that

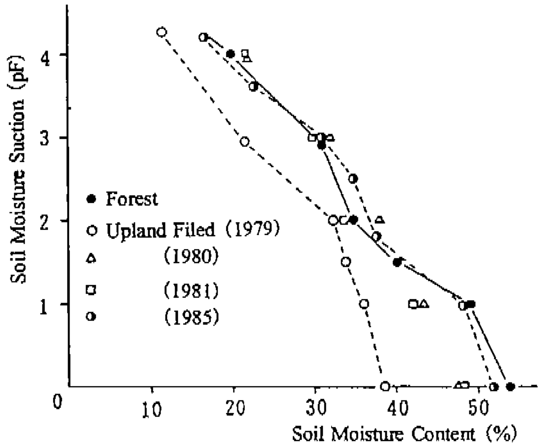

Fig. 5 Water retension curves in forest and upland field

Table 1 Water balance components in the upland filed catchment (Source:K.Takase, 1994)

Year	Period of observation	R (mm)	Qt (mm)	Et (mm)	Ep (mm)	Et (mm/d)	Et/Ep
1979	4/ 1 ~ 12/31 :	1649.0	1062.8	586.2	902.2	2.13	(0.65)
1980	1/ 1 ~ 12/31 :	2527.5	1741.0	786.5	913.9	2.15	(0 86)
1981	1/ 1 ~ 12/31 :	1554.5	941.6	612.9	956.8	1.68	(0.64)
1982	1/ 1 ~ 12/31 :	1787.5	1028 7	758.8	938.9	2.08	(0.81)
1983	1/ 1 ~ 12/31 :	1509.0	883.8	625.2	1037.1	1.71	(0.60)
1984	1/ 1 ~ 12/31 :	1275.0	635.4	639.6	1025.4	1.75	(0.62)
1985	1/ 1 ~ 12/31 :	1644.0	859.0	785.0	1051.4	2.15	(0.75)
1986	1/ 1 ~ 12/31 :	1482.0	890.1	591.9	1016.8	1.62	(0.58)
1987	1/ 1 ~ 12/31 :	1909.5	1006.7	902.8	949.5	2.47	(0.95)
1988	1/ 1 ~ 12/31 :	1584.0	833 7	750.3	900.1	2.05	(0.83)
1989	1/ 1 ~ 12/31 :	1852.0	1034.1	817.9	894.9	2.24	(0.91)
1990	1/ 1 ~ 12/31 :	1854.0	1024.3	829.7	985.1	2.27	(0.84)
1991	1/ 1 ~ 12/31	1795.0	972.0	823.0	909.7	2.25	(0.90)

Table 2 Water balance components in the forest catchment

Year	Period of observation	R (mm)	Qt (mm)	Et (mm)	Ep (mm)	Et (mm/d)	Et/Ep
1985	1/ 1 ~ 12/31 :	1612.5	808.3	804.2	927.3	2.20	(0.87)
1986	1/ 1 ~ 12/31 :	1617.0	914.1	702.9	891.7	1.93	(0.79)
1987	1/ 1 ~ 12/31 :	1856.0	991.9	864.1	825.4	2.37	(1.05)
1988	1/ 1 ~ 12/31 :	1624.0	913.4	710.6	775.8	1.94	(0.92)
1989	1/ 1 ~ 12/31 :	2103.5	1155.2	948.3	770.8	2.60	(1.23)
1990	1/ 1 ~ 12/31 :	1884.0	1074.5	809.5	861.7	2.22	(0.94)
1991	1/ 1 ~ 12/31 :	1682.0	1015.5	666.5	785.9	1.83	(0.85)

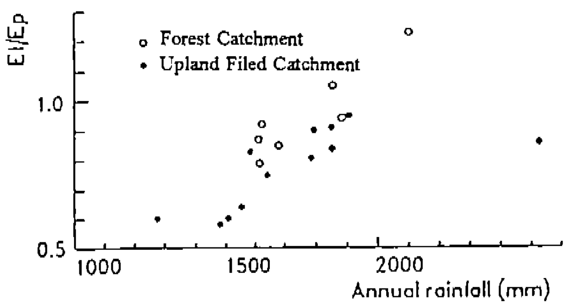

Fig.6 Relationships between annual Et and Et/Ep

the values of the ratio of the forest catchment are greater than those of the upland filed catchment.

For both catchment, it is also observed that the ratio may be dependent on annual rainfall. The relationship between them is shown in Fig.6. It reveals that the value of ratio (Et/Ep) decreases as the amount of annual rainfall becomes less and less and the tendency of decreasing is emphasized more clearly for the upland field catchment than for the forest catchment. These tables and figure suggest that the evapotranspiration from the upland field catchment may be less than that from the forest catchment if meteorological conditions are same.

Dennis et al(1982) reported that the amount of annual discharge had been increased after clear cutting of forest and they concluded that it was due to decrease of evapotranspiration. Maruyama(1982) investigated the water balance in a reclaimed catchment and reported that the amounts of annual evapotranspiration might be less than those reported for forest catchments.

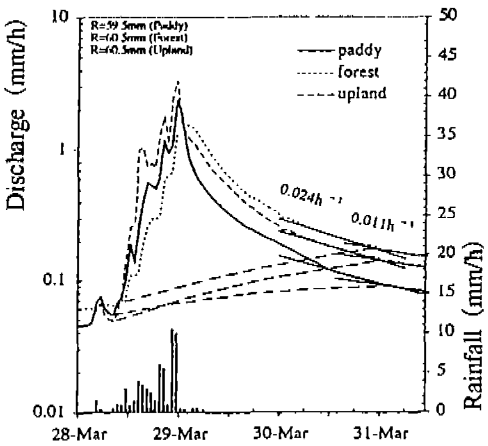

Fig.7 Comparison of storm hydrographs
(Source: L.Hong, 1998)

4.2 Storm runoff and long term runoff

Differences in soil properties change the runoff processes in catchments. In Fig.7, hourly hydrographs of the three experimental catchment are shown. It can be seen that the response of storm runoff in the upland field catchment is the quickest and the concentration time of peak discharge is the shortest among the three catchment; Meanwhile, the response in the paddy filed catchment is quicker than that in the forest catchment. As a result, the volume of peak discharge from the upland field catchment is about 3 times and that from the paddy field catchment is about 1.5 times as much as the volume from the forest catchment. Such changes in peak discharge are caused by the change in infiltration capacity and in concentration time. The lower infiltration rate in the upland filed or paddy field increases the effective rainfall for peak discharge and the higher density of drainage channel decreases the concentration time.

In Fig.8, a comparison of long term runoff between the terraced paddy field and the forest catchment. General observation of this figure shows that the discharge in irrigation seasons is quite different while the low flow discharge from both catchments is similar in non-irrigation seasons. Especially, the discharge from the paddy field catchment is greatly fluctuated in irrigation seasons. This may be due to the water management in paddy fields by farmers in the terraced paddy field catchment. The greater discharge in storms has been already explained.

5 RUNOFF ANALYSIS BY A LUMPED PARAMETRIC MODEL

As stated in previous sections, the differences in land use change hydrologic cycle in the catchments such as evapotranspiration, storm runoff and long term runoff. In this chapter, a lumped parametric model will be

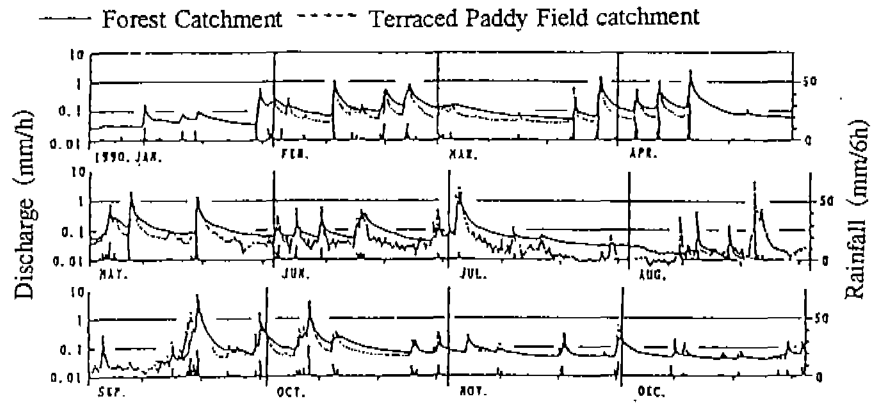

Fig.8 Comparison of long term discharge between the forest and the terraced paddy field catchment

applied to understand the hydrologic cycle in each catchment.

5.1 Structure of the model

Outline of the model is schematically shown in Fig.9. Some of rainfall is intercepted by vegetation and reaches to the ground surface as rain drop and stem flow, while some reaches directly to the surface. The rain water partially flows out on the slope as surface runoff and partially infiltrates into soil to supply moisture or percolate to lower soil layer. In the lower soil layer, the rain water is stored to be drained out as subsurface runoff or groundwater runoff. Evapotranspiration occurs from the surface of vegetation and soil. The model consists of some submodels as follows.

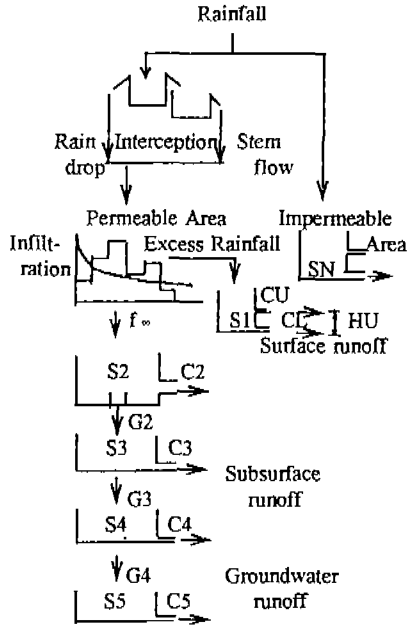

Fig.9 Basic Structure of the model

5.1.1 Interception submodel

For interception, a model which had been developed by Fukushima et al. (1986) was applied. As shown in Fig.9, the model consists of two tanks which represent a canopy and a stem of trees, respectively.

5.1.2 Runoff submodels

Inputted rain water to a tank from the upper layer is stored in and some of the water flows out as surface, subsurface or groundwater runoff. Other part of the water flows down to the lower layer at a constant rate, Gi. The equations for calculation are as follows;

$$dSi/dt = Si - Qi - Gi + Gi_{-1} \quad (1\text{-}1)$$

$$Qi = Ci \cdot S\ i \quad (1\text{-}2)$$

where, Si is storage in a tank, Qi is discharge from the tank, Gi is flow down to a lower layer and is constant, and Ci is a runoff coefficient.

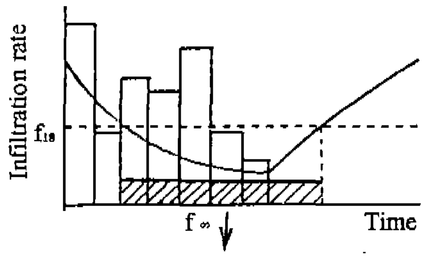

Fig.10 Change of infiltration rate

5.1.3 Infiltration submodel

Infiltration plays an important role on distribution of rain water at the surface of soil. In the model, Horton's equation was used to calculate the rate of infiltration into the soil. It is represented by the equation;

$$f(t) = f_\infty + (f_0 - f_\infty)\ exp\ (-\alpha\ t) \quad (2)$$

where, f(t) is an infiltration rate at a given time, f_∞ is a final rate, f_0 is an initial rate and α is a constant.

Infiltration begins at some rate f_0 and exponentially decreases during a storm. It was defined in the model that percolation to a lower soil layer from a surface layer begins at the rate f_∞ when the infiltration rate decreases to the rate f_{18}, which means the rate at soil moisture condition of pF1.8, or the condition of capacity. On no rainy time, the infiltration rate increases due to soil moisture loss by evapotranspiration or percolation to lower soil. The percolation continues until the infiltration rate gradually increases to reach the rate f_{18}. The decrease and increase of the rate is schematically shown in Fig.10.

In order to calculate an actual rate of infiltration at any time, it is necessary to modify the equation as it represent a potential rate of infiltration. The process of decreasing infiltration rate can be classified into two cases as follows.

① Rainfall intensity r(t) $\geqq$ Infiltration rate f(t)

In this case, the actual infiltration rate can be calculated by Eq.1. As the time step of hour was adopted for the calculation, the rate at a next time step is given by the equation;

$$f(t_{i}+1) = f_\infty + [f(t_i) - f_\infty]\ exp\ (-\alpha) \quad (3)$$

Then, rainfall more than infiltration becomes excess rainfall, which occurs surface runoff.

② Rainfall intensity $r(t) <$ Infiltration rate $f(t)$

In this case, the actual infiltration rate at a next time step cannot be given by Eq.(3). It is because a budget condition between the infiltrated water and rainfall is not satisfied. In the case, it is necessary to determine a time interval Δt, so as to satisfy the budget equation. The time interval is calculated by the equation;

$$\int_{t1}^{t1+\Delta t} [f_\infty + (f_0 - f_\infty) \exp(-\alpha t)]\, dt = R_1 \tag{4-1}$$

$$f_\infty \cdot \Delta t - [f(t_1) - f_\infty][\exp(-\alpha \cdot \Delta t) - 1]/\alpha = R_1 \tag{4-2}$$

Then, actual rate at the next time-step t_2 can be calculated by the equation;

$$f_2(t_2) = f(t_1 + \Delta t) = f_\infty + [f(t_1) - f_\infty] \exp(-\alpha \cdot \Delta t) \tag{5}$$

Evapotranspiration from the soil and percolation to lower soil layer increase the infiltration rate. The procedure of calculation to increase the rate is similar to one for the case 2. In this case, we replace Δt in Eq. (4-1) by $-\Delta t$ and R_1 by Et+Inf. Then, we obtain the equation;

$$\int_{t1-\Delta t}^{t1} [f_\infty + (f_0 - f_\infty) \exp(-\alpha t)]\, dt = Et + Inf \tag{6}$$

where, $Inf = 0$, if $f(t) > f_{1s}$

$Inf = f_\infty$, if $f(t) \leqq f_{1s}$

The infiltration rate increases until it reaches a maximum rate, f_{max}. The maximum rate is the rate in the condition where soil moisture of surface layer is dried up. If the maximum soil moisture which can be hold in the surface layer is defined as SM_{max}, the relationship between f_{max} and SM_{max} is given by the equation;

$$SM_{max} = \int_0^\infty [f_\infty + (f_{max} - f_\infty) \exp(-\alpha t)]\, dt - \int_{ns}^\infty f_\infty\, dt \tag{7}$$

Solving the equation for f_{max}, we obtain a value of f_{max}.

5.1.4 Treatment of evapotranspiration

Daily actual evapotranspiration Et_i is estimated by the equation;

$$Et_i = Ep_i \cdot CE_m \tag{8}$$

where, Ep_i is the potential evaporation and CE_m is a monthly ratio of actual evapotranspiration to potential evaporation, whose value was determined by water balance method.

5.2 Application of the model to the experimental catchments

Different types of the lumped parametric model were applied to the experimental catchments, considering the differences in drainage system and water management in them.

5.2.1 Application to the forest catchment

In application to the forest catchment, the whole area was treated as only one system by the model shown in Fig.9. The model was applied in some hydrologic years. The model parameters were determined so as to minimize the relative error between observed and calculated discharge by a mathematical optimization procedure. (Kobayashil, 1976)

A comparison of daily hydrographs is, shown in Fig.11. It is found that the good agreement between the observed and calculated discharge was obtained .

5.2.2 Application to the upland field catchment

In the upland field catchment, there are two types of land use, forest and upland field. Therefore, the catchment was modeled by two system as shown in Fig.12. After discharge from each system was calculated and summed, the total discharge was compared with the observed one. On the optimization of the model

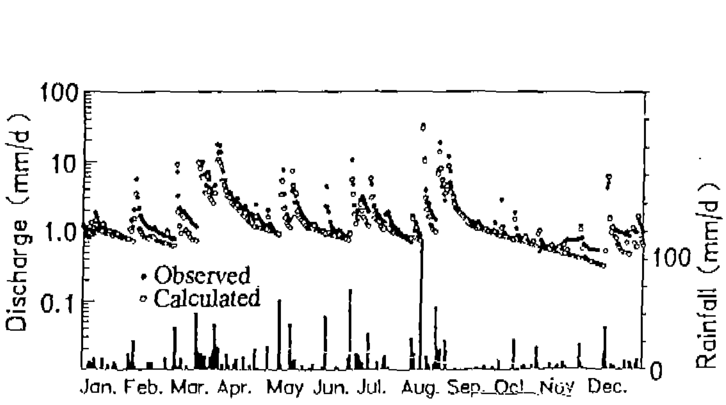

Fig. 11 Comparison of observed and calculated hydrographs in the forest catchment.

parameters, it was supposed that the values of parameters for the forest area were same as those of the forest catchment and the values were determined only for the upland field area.

A comparison of daily hydrographs is shown in Fig.13. It is found that the good agreement between the observed and calculated discharge was obtained

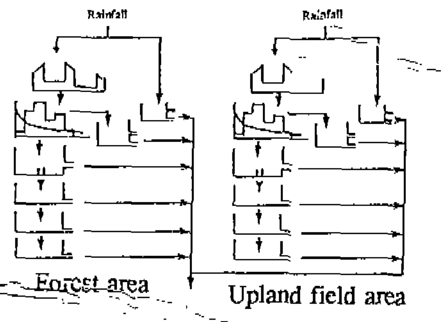

Fig.12 Model for the upland filed catchment

5.2.3 Application to the *terraced paddy field catchment*

The catchment includes the terraced paddy fields and farmers use the stream flow for irrigation. Therefore, the catchment was modeled by two system as shown in Fig.14. In irrigation seasons, the discharge from the forest area is inputted into the paddy field system while the discharge flows out directly in non-irrigation seasons. The observed discharge was compared with the calculated discharge from the paddy field area in irrigation seasons and with the calculated total discharge from the forest and paddy field area.

A comparison of daily hydrographs is shown in Fig 15. Despite of complex water management and drainage system, good agreement between the observed and calculated discharge was obtained.

5.3 Discussions

Judging from the results in previous sections, it is considered that the model represents the actual hydrologic processes in the catchments. Therefore, the values of model parameters and annual amounts of runoff components which were calculated by the model were compared among the catchments.

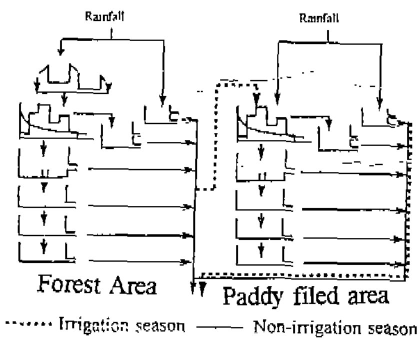

Fig.14 Model for the paddy filed catchment

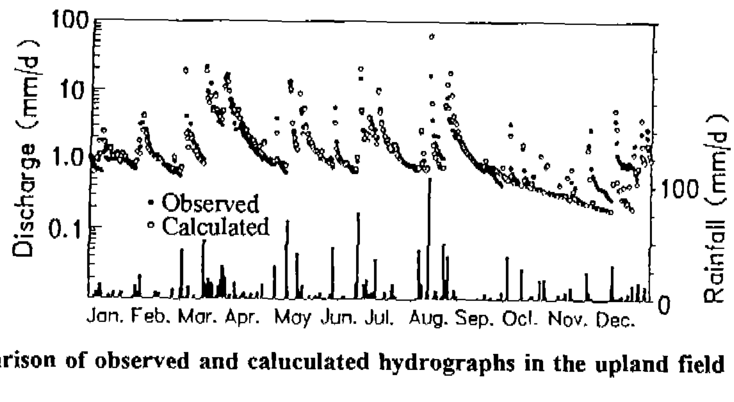

Fig. 13 Comparison of observed and caluculated hydrographs in the upland field catchment.

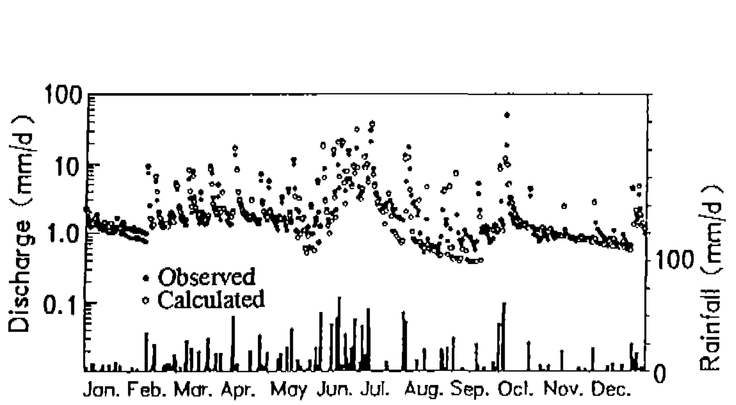

Fig. 15 Comparison of observed and caluculated hydrographs in the paddy filed catchment.

Table 3 Comparison of values of some parameters among the catchments

	Forest area	Upland filed area	Paddy filed area
Final rate of infiltration : f_{1s} (mm/h)	3.9	1.7	0.04
Height of the upper hole : HU (mm)	87.4	6.2	6.6
Runoff coefficient of the upper hole : CU (mm/h)	0.18	0.27	0.11
Runoff coefficient of the lower hole : CL (mm/h)	0.15	0.18	0.11

Table 4 Comparison of percentage of runoff components to annual discharge among the catchments

	Forest	Upland filed	Paddy filed
Surface runoff	20 %	35	52
Subsurface runoff	24	28	11
Groundwater runoff	56	37	37

As the model parameters have relationships each other, it may not be so reasonable to compare the values of parameters. However, some parameters reflected the properties of hydrologic cycle in the catchments. Table 3 shows the comparison of values which were determined. As shown in this table, the final rate of infiltration of the forest area is the highest and that of the paddy field area is the lowest. This reflects the differences in observed infiltration rate in the catchments, which have been stated in Chapter 3.

Consideration of the differences in values of parameter related to surface runoff suggests that the surface runoff from the forest catchment may be less than those from other catchments. Table 4 shows the percentage of surface, subsurface and groundwater runoff to total annual discharge. It is obvious that the surface runoff in the terraced paddy field catchment is the greatest among them. It is because almost of stream flow from the forest area is used in the paddy fields in irrigation season and because the infiltration rate in the fields is very small. Furthermore, it is suggested that the change in land use from forest to upland field has also a relatively great effect on surface runoff.

6 Conclusion

In this paper, the properties of hydrologic cycle in three experimental catchments, which are a forest, a reclaimed upland field and a terraced paddy field catchment, were compared and different types of a lumped parametric model were applied to understand the hydrologic cycle in the catchments.

The comparison of hydrologic properties showed that the differences in land use have great influences on the soil properties of surface layer, which cause changes in hydrologic processes such as evapotranspiration and storm runoff et.al. By the runoff analysis models, good agreements between observed and calculated discharge from the catchments were obtained and it was found that the differences in values of optimized model parameters and water budget components reflect those in hydrologic among them. As the results, it is suggested that the differences in land use and water management will change hydrologic cycle, especially the hydrologic processes on surface layer.

The research is not so sufficient to understand perfectly the effects of differences in land use on hydrologic cycle and more detail observation, investigation and analysis will be desired in future for management and conservation of water resource.

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