

On the Regional Characteristics of Actual Evapotranspiration
Derived from Landsat MSS and Elevation Data

Satoshi UCHIDA
Science Information Processing Center
University of Tsukuba
Ibaraki 305, JAPAN

Takashi HOSHI
Institute of Information Sciences and Electronics
University of Tsukuba
Ibaraki 305, JAPAN

Abstract

The system to estimate actual evapotranspiration (ET) over wide area has been developed. The method of estimation is based on modified Penman's method and utilized Landsat MSS, elevation and ground observed meteorological data. The distinctive feature of this system is that this system estimates ET not by directly using spectral data but by combining empirical parameters. Therefore once landuse data is produced from Landsat MSS data, various climatic condition can be applied to calculation. To examine the regional characteristics of ET, several watershed areas are selected in Japan. Then both of local characteristics of landuse and topography and regional characteristics of climate are found to be equally influencing the amount of ET. Moreover the calculation in case of occurring landuse conversion according to land grading are executed. Its result has given the possibility to parameterize the amount of ET using a few parameters, that is the regional averaged value of albedo and/or soil heat flux constant.

Introduction

Evapotranspiration (ET) is one of the water circulating processes on the earth, which implies the release of water vapor from the surface into the air. ET consists of evaporation and transpiration, the latter is the vaporization process through botanical organ. The amount of ET is controlled by not only radiant condition such as inputting short-wave radiation but also physical characteristics of the surface. Therefore when we try to estimate the amount of ET over wide area, the information of land cover distribution will be needed.

Various methods have been adopted for measuring or estimating ET. For measurement of ET, the eddy correlation method is reliable on the point that this method measures directly the latent heat flux near the surface. However this method lacks the accurate measurement of water vapor at the present and also has disadvantage to limit spatial representation. In relation to estimation of ET, the water budget method or the energy budget method have been frequently adopted. Both methods are based on the complementary relationship of budget equation, that is considerable components except ET or the latent heat flux component in the budget equation should be given. Only these methods may bring the residual error.

Remote sensing data, which is taken by the platforms as satellites or aircrafts, has the advantage of its simultaneity and homogeneity over wide area. Therefore some investigations using remote sensing data have been attempted to estimate ET over wide area (e.g. Soer(1980), Kotoda et al.(1984), Klaassen and Berg(1985), Nieuwenhuis et al.(1985), Rambal et al.(1985), Taconet et al.(1986), Kawashima(1986)). Most of them have adopted the energy budget equation to estimate ET. There has been two different types of estimating ET using remote sensing data. One is to use directly observed thermal or radiative characteristics for estimating ET, and another is to classify first land cover categories according to spectral characteristics of remote sensing data, and then to estimate ET using empirical parameters of each category supplemented by ground observed meteorological elements. The latter is suitable to estimate ET for a long period because the spectral characteristics of land cover changes regularly with seasons considering the corresponding landuse.

Authors has been developing the estimation system of areal ET based on Kotoda's formula(Kotoda(1986)). His idea is to adopt modified Penman's model and to use empirical parameters of albedo and soil heat flux constant relating to landuse classified from Landsat MSS data. Authors have employed elevation data, which is needed to calculate short-wave radiation flux, from Digital National Land Information of Japan. Then the system has a potential to estimate ET for arbitrary area in Japan(Hoshi et al.(1987), Hoshi and Uchida(1987), Uchida and Hoshi(1987)). The reliability of estimation is at least better than the estimation by the water budget method and its discussion will be refered in the text.

The objective of this paper is to examine the regional characteristics of ET using the system mentioned above. So several watershed areas located in Japan are selected as study areas. Then authors try to gain rational relationship between the amount of ET and topographic and/or spectral characteristics of the areas. Also authors execute some calculation under the condition that landuse conversion is occurred according to land suitability.

Systems for estimating regional evapotranspiration

The system is equipped to estimate monthly value of ET for the range up to 512 lines by 500 columns. Calculation is executed at every grid point of which the size corresponds to the size of geometrically corrected pixel of Landsat MSS image data. Therefore the maximum area size to be calculated at one time has an order of thousand square kilometers. In order to execute calculation of ET using this system, it needs Landsat MSS, elevation data and ground observed meteorological elements like temperature, precipitation, wind speed, vapor pressure and sunshine duration. Our center (Science Information Processing Center, University of Tsukuba) has collected more than one hundred Landsat MSS scenes covering almost area of Japan. Also the elevation data adopted here covers the whole area of Japan with the mesh size of 7.5" in latitude by 11.25" in longitude. For meteorological data, AMeDAS (Automated Meteorological Data Acquisition System) is established and operated at about 17km mesh in Japan, then the meteorological elements except for vapor pressure are given by these stations. The value of vapor pressure can be found at meteorological observatories which are located at least one point in each prefecture. In the system each meteorological element is regressed linearly with height for giving the value at every grid point. Then we are to be able to calculate monthly value of ET for arbitrary area in Japan.

The procedure for estimating ET consists of largely three parts, which are

preparing procedure, executing calculation program and analysis of output result. In the preparing procedure Landsat MSS data is classified into land cover type and then into one of landuse categories of which albedo and soil heat flux constant are empirically given. In the second procedure, elevation data is interpolated and fitted to the same grid of classified landuse data and meteorological values at every grid point are calculated from this elevation value.

The flow of calculating ET is shown in Fig.1. In this figure calculation is performed from top to down. The distinctive feature of this method from Penman's method is that this method adopts the conversion factor f_0 from Penman's potential ET ($E_p = E_e + E_v$) to actual ET (E_{ac}). The coefficients of conversion factor are determined by comparing with the obtained values of weighing lysimeter at Tsukuba (Kotoda(1986)). The additional constraint, that is f_0 cannot exceed one, are later adopted by authors. The reason of adoption is that this method has evidently overestimated the amount of ET in case of having heavy precipitation without the constraint and that the constraint coincides with the complementary relationship reported by Morton(1983) and Otsuki et al(1984ab).

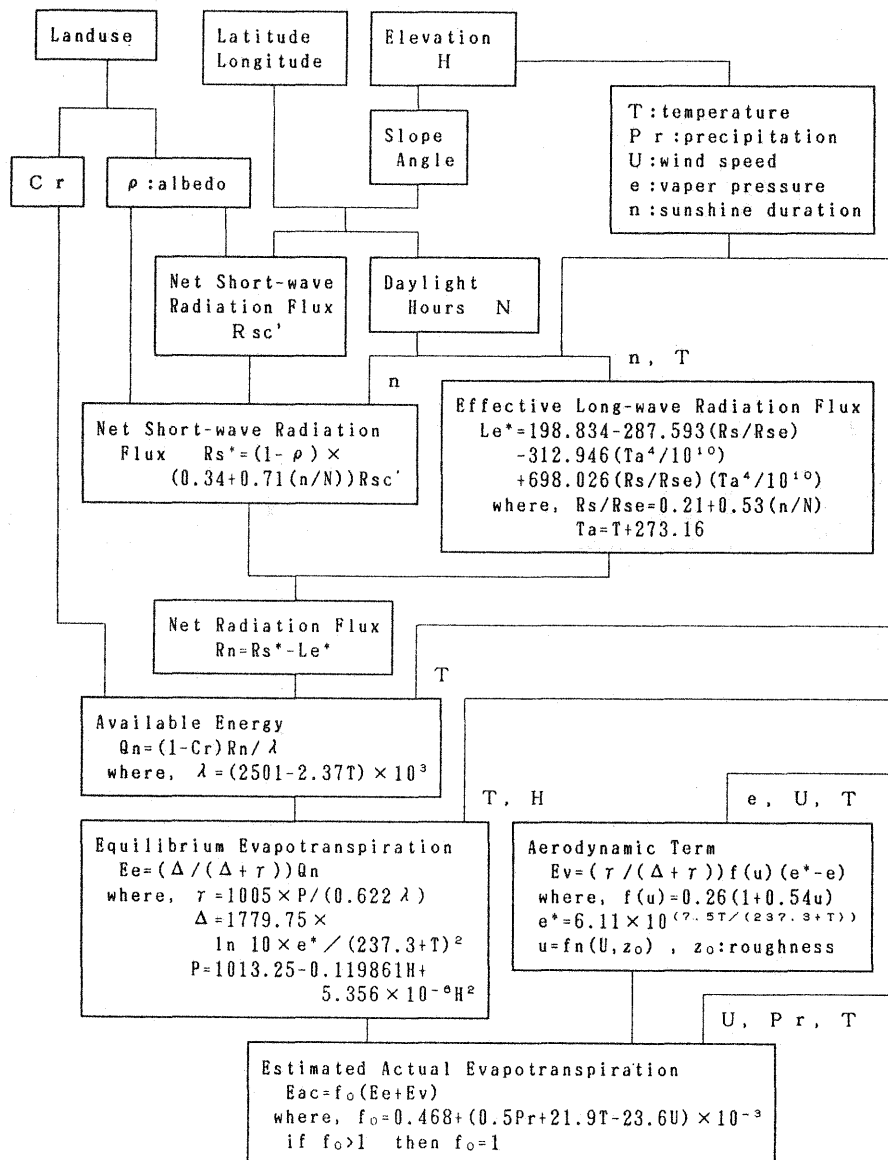


Fig.1 Flow of calculating actual evapotranspiration

The accuracy of estimation is fairly good especially for summer months as discussed later. However for winter months the estimated amount tends to be underestimated. Nevertheless we might evaluate that this system is usefully applicable to examine the temporal and spatial characteristics of ET, since the amount of ET in winter months are small enough comparing with that in summer months.

Description of the study area

Estimation of ET has performed about selected watershed areas, which are Ishi, Kizu, Warashina and Kokai river basins. Their location is shown in Fig.2 and all of them are located in the middle part of Japan. Their climatic condition resembles each other. The difference to be noted is that temperature tends to decrease eastward and the amount of precipitation in Warashina is larger than that in other areas. There exists a major rainy season from June to July for all areas, only its end comes earlier at more western area. So the depression of the amount of pan evaporation is clearly indicated only in June for Yonago and Shionomisaki observatories and in June and July for Tokyo observatory. Such a feature of difference is found, however the total amount of pan evaporation is similar as mentioned in the next chapter.

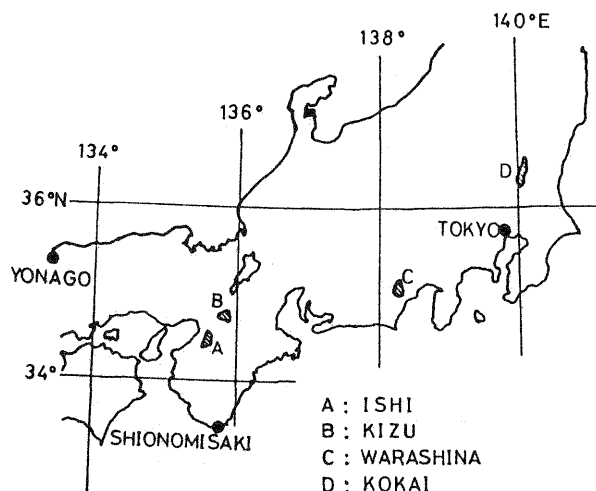


Fig.2 Location of study area

Table 1 Composition ratio (%) of classified landuse of study areas

Area Name	ISHI	KIZU	WARASHINA	KOKAI
Area Size(km ²)	215.2	103.0	112.2	205.0
Open Water	0.08	9.33	0.00	0.50
City Settlement	0.88	4.03	0.00	0.09
Forest(ever green)	8.54	8.94	0.04	10.63
Forest(deciduous)	32.31	18.57	58.47	23.27
Orchard	17.40	9.54	3.78	15.57
MulberryField etc.	6.04	5.83	2.62	26.07
Grassland etc.	7.59	2.08	30.82	1.98
Paddy Field	3.71	2.65	0.17	4.30
Vegetable Field	11.25	28.20	0.91	11.55
Bare Soil	5.27	7.80	1.00	5.79
Not Classified	1.81	1.39	0.00	0.27
	3.99	1.63	1.59	0.00
Original Data				
Mission	LANDSAT3	LANDSAT3	LANDSAT2	LANDSAT2
Path-Row	118-36	118-36	116-36	115-35
Date	1980.4.3	1980.4.3	1979.5.22	1979.5.21

Table 2 Topographical characteristics of study areas (unit:%)

(a) Elevation

(m)	ISHI	KIZU	WARASHINA	KOKAI
1400-	-	-	0.29	-
1200-1400	-	-	1.89	-
1000-1200	0.41	-	3.03	-
800-1000	3.19	-	11.42	-
600-800	11.02	-	25.08	-
400-600	17.47	0.61	30.30	0.15
200-400	26.91	6.64	24.18	5.19
0-200	41.01	92.75	3.81	94.66

(b) Slope Angle

(deg)	ISHI	KIZU	WARASHINA	KOKAI
30 -	0.95	0.00	7.73	0.00
25 - 30	3.09	0.08	17.13	0.05
20 - 25	7.73	0.52	26.64	0.37
15 - 20	13.58	2.06	22.43	1.35
10 - 15	18.18	5.39	14.88	4.44
5 - 10	22.73	21.69	8.44	14.97
0 - 5	33.74	70.27	2.74	78.82

(c) Slope Direction

	ISHI	KIZU	WARASHINA	KOKAI
Flat	0.23	0.75	0.00	1.21
N	17.37	13.41	9.18	10.10
NE	12.51	12.77	12.03	8.67
E	11.38	14.73	13.98	12.59
SE	6.81	10.24	14.11	8.42
S	5.89	10.51	14.33	12.45
SW	10.83	11.40	13.16	15.15
W	16.36	13.09	12.67	19.37
NW	18.63	13.11	10.55	12.04

The composition ratio of landuse categories, which are classified from Landsat MSS data, is represented in Table 1. This table also shows the size of areas and the information of original data. It is difficult to classify into different vegetation categories among such as ever green forest, deciduous forest, orchard, mulberry field and vegetable field from Landsat MSS data taken at a specific time. Therefore this classification has a possibility to contain some errors. However from this table, we can generally say the state of landuse about each area. Especially it is interesting to notice the difference of composition ratio about urban, forest and arable land arranged among classified components.

The state of landuse should be related with topographical condition. Table 2 shows the topographical characteristics of each area. Then each area is roughly characterized as followings.

Ishi: It mixes steep and gentle slopes with the direction of north exceeding. Forest remains about a half of area and the rest portion has been well developed as suburban area.

Kizu: It represents almost flat and a little hilly area. Paddy field exceeds but urbanization is also advanced with some extent.

Warashina: It is represented of steep mountaneous area with the direction of south exceeding. Forest dominates other categories and urbanized area is scarcely found.

Kokai: It represents flat and a little hilly area like Kizu. A certain extent of urbanization is also found. The difference of landuse from Kizu is that paddy field is not exceeded.

Results

Calculated results of ET are summarized in Table 3. In this table annual values of ET and precipitation averaged from 1979 to 1984 are represented with their standard deviation. Averaged values of E_p/E_{pan} and E_{ac}/E_{pan} are also represented in the table, only these values are calculated by the accumulated values from April to November as annual value because of lack of data about pan evaporation in winter months. Pan evaporation data obtained by using pan with 120cm in diameter is collected at Yonago, Shionomisaki and Tokyo in this study. And the corresponding value of pan evaporation with each area applies to averaged value of Yonago and Shionomisaki(YS) for Ishi and Kizu area, averaged value of Shionomisaki and Tokyo(ST) for Warashina area and value of Tokyo(T) for Kokai area, respectively. This might not cause considerable errors, because averaged annual values (from April to November) of pan evaporation does not largely change by stations. In this case the amount of YS, ST and T is 703.00mm, 719.62mm and 717.87mm, respectively.

Table 3 describes the tendency of decreasing E_{ac} with locating eastward. this is considered to be caused mainly by the difference of temperature all the year. On the other hand the difference of precipitation affect the amount of E_{ac} not so much. The reason of this appearance is that months having large variance of precipitation are allocated in June to September when the conversion factor f_0 is almost one without much precipitation. It is a little questionable to discuss the absolute value of E_p/E_{pan} or E_{ac}/E_{pan} among all areas, since the value of pan evaporation does not represent the value of study areas. However it is interesting of showing the similar tendency of regional variation of E_{ac}/E_{pan} to E_{ac} . The difference of values between Ishi and Kizu should be caused by the difference of state of landuse and topography. Then the factors of influencing the characteristics of ET are to be composed of the state with regional and local scale similarly.

Table 3 Estimated annual ET and the ratio against pan evaporation

	ISHI	KIZU	WARASHINA	KOKAI
E_{ac} (mm)	684.90	660.30	612.11	599.56
σ	21.86	16.60	10.09	25.60
P(mm)	1395.35	1358.90	2957.27	1250.84
σ	223.32	190.50	630.73	209.69
E_p/E_{pan}	0.994	0.876	0.798	0.820
σ	0.031	0.024	0.039	0.053
E_{ac}/E_{pan}	0.864	0.836	0.748	0.736
σ	0.035	0.024	0.027	0.049

note) E_{ac} : averaged annual actual evapotranspiration
P: averaged annual precipitation
 E_p : Penman's potential evapotranspiration
 E_{pan} : Pan evapotranspiration
 E_p/E_{pan} , E_{ac}/E_{pan} are calculated by the accumulated value from April to November as annual value

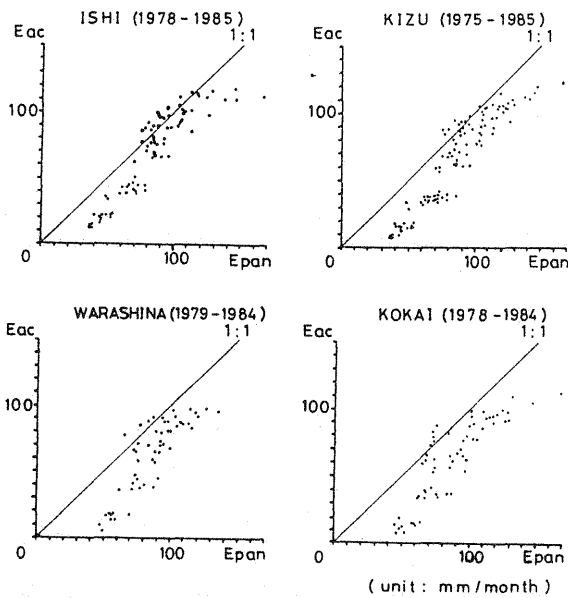


Fig.3 Scattergram between estimated actual ET (E_{ac}) and observed pan evaporation (E_{pan})

Fig.3 represents the comparison between actual ET (E_{ac}) and pan evaporation (E_{pan}) for examining the reliability of estimation. From this figure the tendency to increase the ratio of E_{ac}/E_{pan} until about 80mm of E_{ac} and then to decrease the ratio with increasing E_{pan} is evidently described in all areas. The ratio represents reasonable number in comparison with empirical values reported by Kaneko(1973) and Kayane(1980) except for the case of winter months when the ratio seems to be a little small. The correlation coefficient between monthly values of E_{ac} and E_{pan} against yearly variation also proves the reliability of estimation. The correlation coefficient in summer months are high enough to make sure of their correlation, for example the values are 0.900, 0.935 and 0.944 for June, July and August, respectively, in case of Kokai area. However other months often show less correlation.

It has been often adopted the water budget method to estimate ET. Here authors also execute the budget calculation using observed runoff data, precipitation and estimated actual ET. Fig.4 shows the change of residual component, that is the component of subtracting runoff and ET from precipitation. In this figure the value of each month represents three months running mean value for eliminating the effect of time lag between precipitation and runoff. The residual components of each area change almost periodically by year except

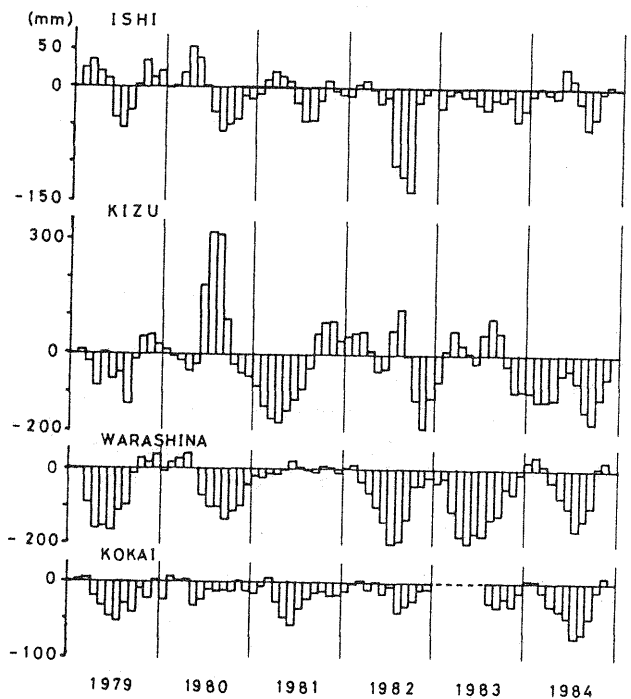


Fig.4 Change of monthly value of residual component of water budget equation (precipitation-runoff-ET)

for Kizu area where the study area is selected as intermediate area between two runoff stations. This feature of variation has been expected, however the total budget for a year or even for a longer period could not be suited to zero. Two major reasons will be pointed out about this discord. One is the lack of information discounted here, for example ground water, and another is the observational or estimating error of each component. Anyway the estimation method of ET adopted here is to be superior than the water budget method.

Next authors examine the effect of landuse conversion on the amount of ET for the case of Warashina and Kokai area. For this purpose landuse conversion table is set based on topographic condition (Table 4). This conversion table is reasonable compared with land grading for agricultural development in Japan. This table tells that the stage of development would progress according to the type number increase. Therefore the state of landuse at the present should be basically allocated between type one to four.

Fig.5 shows the calculated results for the case of occurring landuse conversion with climatic condition in 1984 according to the conversion listed in Table 4. Both of Warashina and Kokai describe that the amount of ET would continuously decrease with development progressing, only the decreasing rate among landuse conversion types is different each other. This difference is mainly caused by the difference of topographic condition. As mentioned before, the state of landuse at the present should be allocated in the lines of one to four. For Warashina area, the state of landuse at the present seems to be a similar value of type two and type three for Kokai area.

Table 4 Landuse conversion based on topographic condition

Type	Slope Angle (deg)			
	0 - 5	5 - 15	15 - 25	25 -
1	Forest(e.gr.)	Forest(e.gr.)	Forest(e.gr.)	Forest(e.gr.)
2	Paddy Field	Mulberry Field etc.	Forest(e.gr.)	Forest(e.gr.)
3	Paddy Field	Settlement	Orchard	Forest(e.gr.)
4	Settlement	Settlement	Orchard	Bare Soil

note) e.gr. : ever green

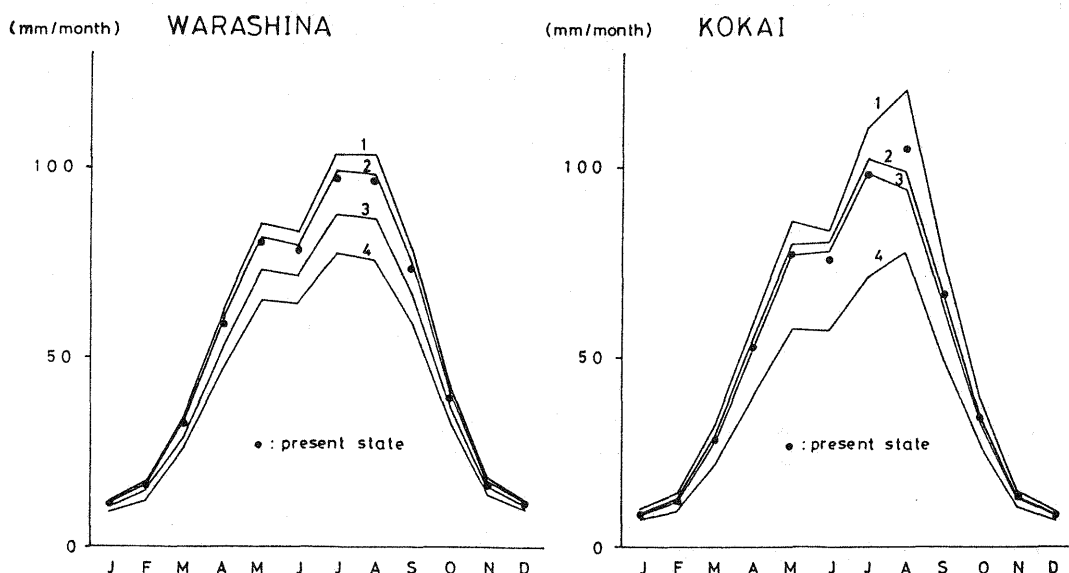


Fig.5 Monthly evapotranspiration (1984) calculated for the case of landuse conversion (conversion type ; see Table 4)

Table 5 Annually averaged value of albedo (ρ) and soil heat flux constant (C_r) after landuse conversion

Conversion Type	WARASHINA		KOKAI	
	ρ	C_r	ρ	C_r
1	0.1083	0.0400	0.1083	0.0400
2	0.1235	0.0712	0.1433	0.1323
3	0.1665	0.1513	0.1595	0.1605
4	0.2164	0.2207	0.2476	0.2972
Present State	0.1311	0.0854	0.1549	0.1283

note) conversion type ; see Table 4

To see the formulation represented in Fig.1, it might be approximated the value of ET using albedo and soil heat flux constant. Then it would be possible to characterize each area using these parameters. Table 5 shows annually averaged value of albedo and soil heat flux constant for Warashina and Kokai area. From this table we might also notice the rough allocation of present state under landuse condition.

Again to see the formulation, the simple equation as $E_{ac}=a\rho C_r+b\rho+cC_r+d$ where a,b,c,d is constant, might be set for first approximation. When this equation is resolved concerning yearly value for each area, we get the following numbers.

a=3206.36, b=-2567.47, c=-112.45, d=918.88 for Warashina.

a=-1247.84, b=33.65, c=-533.98, d=678.46 for Kokai.

As we can see in Table 5, the order of ρ and C_r is the same then we have found that the weighing of each parameter characterize the amount of ET for areas. For example component of C_r is adequately smaller than that of ρ for Warashina area and on the contrary for Kokai area component of ρ is sufficiently smaller. This tendency is not substantially distorted by climatic condition because similar tendency have been found for the case of calculation in 1980 when it was extremely cooler in summer than standard climate.

Conclusions

Through the calculation of this paper, we again evaluate the reliability of the estimation system introduced here. Some problems must be solved for improvement, for example the underestimation in winter months. Nevertheless it is useful to discuss about the values in summer months or annual values. Also it should be evaluated the applicability to various fields.

Estimates values of ET for several study areas in Japan represent the tendency of decreasing with locating eastward although the value of pan evaporation does not largely vary from region to region. This is mainly caused by the difference of temperature not by the difference of precipitation. Besides the climatic condition, topographic and landuse condition substantially influence the amount of ET.

Landuse conversion which has been generally occurred before brings the decrease of ET. It would be possible to evaluate the environment of the specific area at the present from the point of view of hydrology using calculation like this. Also it is valuable on water resource problems to forecast quantitatively the state of water circulation in the future.

It is possible to parameterize the amount of ET using albedo and soil heat flux constant. The parameters and their combinations are probable indicator for

representing landuse and topographic condition in short.

In this paper the analysis has not been satisfactory to find the definite relationship of the amount of ET against the amount of pan evaporation which represents the climatic condition, topographic and landuse conditions. However some ideas examined here are expected to produce fruit for considering hydrological environment in the near future. Problems are focused on the point that the calculating experiment will be accumulated for the cases of partly fixed condition until the satisfactory relationship is attained.

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