Estimation of Water Balance based on Satellite Data in the Korean Peninsula

Shin, Sha Chul* and Sawamoto Masaki**

ABSTRACT : Quantifying water balance components is crucial to understanding the basic hydrology and hydrochemistry. An importance of water balance studies has been emphasized from the need to grasp the actual condition of water resources and environmental changes including climatic changes. This paper proposes a method for evaluating water balance components based on the vegetation monitor using remote sensing data. Here, the evapotranspiration model adopts a direct method by using NDVI(Normalized Difference Vegetation Index) calculated from NOAA/AVHRR data and a detailed description of water balance by using the evapotranspiration over the Korean Peninsula. In the study, areal distribution data sets of water balance components are produced using NDVI and a simplified water balance model. This method enables one to discuss the hydrological problems for North Korea where insufficient meteorological and hydrological data exist. The results obtained indicate the specific regional features on water inventory and fluctuation in water balance.

1. Introduction

Water is one of the most precious natural resources and now water management problems represent a key area of applied science concerned with the current worldwide economic and ecological situations. The imbalance between water demands and natural supplies in space and time is a common problem in most regions. It is generally found that periods of the highest precipitation do not coincide with periods of maximum water demands.

Legates and Mather(1992) suggested that climatic water-budget bookkeeping technique has been successfully employed over the years to provide quantitative information applicable to a wide variety of hydroclimatic problems. Another global field of water balance was derived by Willmott and Rowe(1985) and Mintz and Walker(1993).

Accurate quantitative knowledge of the components of hydrologic cycle such as precipitation,

* Water Resources Research Institute, KOWACO, Taejon, Korea
* * Department of Civil Engineering, Tohoku University, Sendai, Japan.

evapotranspiration, soil moisture, runoff, etc., is of basic importance in assessment of water resources. Although evapotranspiration is one of the most important factors in water balance and water resources planning, it is very difficult to estimate actual evapotranspiration by consideration of regional characteristics of topography or landuse. But, evapotranspiration data sets are still required as stated above for water resources analysis. Here, a direct method for estimating actual evapotranspiration is proposed using NDVI(Normalized Difference Vegetation Index) calculated from NOAA/AVHRR data, and detailed distributions of water balance will be evaluated by using evapotranspiration data sets over the Korean Peninsula. Figure 1 illustrates the employed approach for water balance application.

The study area is the Korean Peninsula extending over the area of 220,848k㎡2. The average annual precipitation of Korea is 1,274mm, roughly 1.3 times of the global average. Although this seems abundant, the average annual rainfall per capita is 3,000m3, one eleventh of the global average. Furthermore, two thirds of Korea's annual precipitation occurs during the flood period from June to August and is almost discharged directly to the sea in the form of flood.

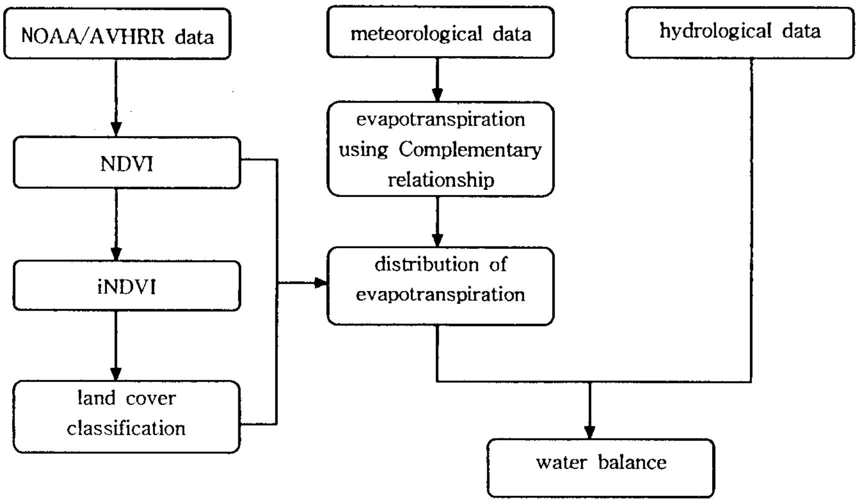

Fig. 1 Flowchart of employed approach for water balance application

2. Land surface distribution of evapotranspiration

2. 1 Vegetation monitoring

NOAA/AVHRR data have been used extensively for the large area of vegetation monotoring. Typically, the spectral bands used for this purpose have been the channel 1 visible band (0.58 to 0.68μm) and the channel 2 near-infrared band (0.73 to 1.10μm). Various mathematical combinations of the NOAA/AVHRR channel 1 and 2 data have been found to be sensitive indicators of the presence and condition of green vegetation. These mathematical quantities are thus referred to as the Normalized Difference Vegetation Index(e. g., Justice et al., 1985 ; Tucker et al. , 1985a,b ; Townshend and Justice, 1986 ; Benedetti et al. 1994). This index is computed from the equation

$$NDVI = \frac{Ch.2 - Ch.1}{Ch.2 + Ch.1} \tag{1}$$

where Ch.1 and Ch.2 represent data from NOAA/AVHRR channel 1 and 2, preferably expressed in terms of radiance or reflectance. Vegetated areas will generally yield high values for NDVI because of their relatively high near-infrared reflectance and low visible reflectance. In contrast, clouds, water, and snow have larger visible reflectance than near-infrared reflectance. Thus, these features yield negative index values. Rock and bare soil areas have similar reflectances in the two bands and result in NDVI near zero.

Also, iNDVI(integrated NDVI) has been utilized to know the total amount of NDVI during any period. This is defined as

$$iNDVI = \frac{\Sigma(NDVI_j \times d_j)}{\Sigma d_j} \tag{2}$$

where $NDVI_j$ represents the NDVI of the jth period of duration d_j days.

NOAA/AVHRR data used in this study are for the period of April to November 1989, excluding that of winter affected by the snow cover. In this section, a simple land cover classification method is introduced, based on the vegetation condition obtained from satellite data. Since each category has its own characteristics for vegetation, a classification method is developed using the quantity and seasonal variations of vegetation. The application of this method enables one to classify the land cover in the Korean Peninsula and to obtain information for that in North Korea. This method will be useful for rough classification of land cover over a very large area. Detailed methodology for this method will not be described here, but Shin and Sawamoto(1995) and Shin et al(1996) provide further information.

2. 2 Evapotranspiraion model

In hydrological studies such as water balance calculations, a knowlege of evapotranspiration at the scale of a basin or a region is indispensable. Therefore, evapotranspiration is fundamental to water resources planning, water supply management and irrigation or drainage of agricultural lands. In spite of its importance, monthly, seasonal and annual fields of evapotranspiration data sets for large areas are even less well known. Because of difficulty in direct measurements, evapotranspiration is estimated using empirical /semi-empirical methods.

Remote sensing provides a possible means to estimate the distribution of actual evapotranspiration over a wide area in connection with regional characteristics of vegetation and landuse. Factors controlling evapotranspiration from the ground are air temperature, humidity, wind, radiation, soil moisture and so on. Vegetation directly influences evapotranspiration, therefore we can expect a high correlation between the evapotranspiration and the vegetation. It may be considered that evapotranspiration flux is large when the value of NDVI is high. Firstly, the relationship between NDVI and evapotranspiration is determined for each land cover category for five basins in Korea. Multiple regression analysis is used to determine coefficients between NDVI and evapotranspiration, such as

$$E = \frac{1}{P} \sum_{i=1}^{n} e_i \, p_i \tag{3}$$

where E is the actual average evapotranspiration(mm /mon), P is the total number of pixels, e_i is the typical evapotranspiration in ith range of NDVI, P_i is the number of pixels in the ith range of NDVI, and n is the number of range.

In order to carry out this regression analysis, actual evapotranspiration is required. In this study, the complementary relationship suggested by Brutsaert and Stricker(1979) is selected to calculate actual evapotranspiration. Sets of E use evapotranspiration obtained by complementary relationship, and P, p_i are counted from NOAA images. If sets of regression coefficients e_i can be calculated, we can estimate the distribution of evapotranspiration from the NDVI, and the total evapotranpiration over a wide area. Here, the distribution of evapotranspiration can be obtained in more detail if the number of the range n is large. However, it has been known that the best result is obtained for n=4(Shin and Sawamoto, 1995). The relationships between NDVI and evapotranspiration can be estimated for the five basins of Korea by the regression analysis. The relationships between NDVI and evapotranspiration are indicated in Figure 2.

Next, we can obtain linear relations to estimate actual evapotranspiration with only one parameter by extension of the relationship between NDVI and evapotranspiration for the five basins. The areal distribution of evapotranspiration for the year 1989 is shown in Figure 3. This figure shows that evapotranspiration for the forest areas is high whilst it is low for the urban areas. Figure 4 shows evapotranspiration for each land cover condition for the year 1989.

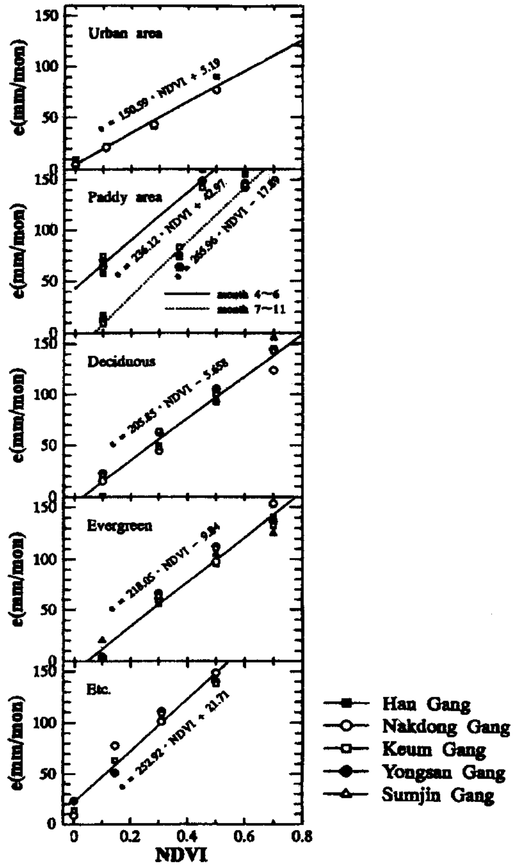

Fig. 2 Relationship between NDVI and evapotranspiration

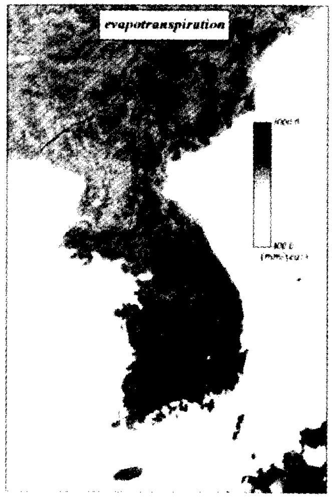

Fig. 3 Distribution of evapotranspiration(1989)

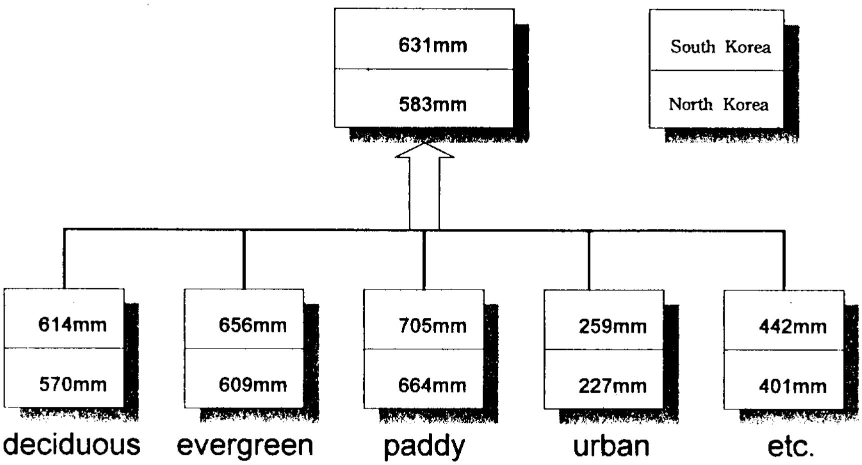

Fig. 4 Comparison of evapotranspiration for the Korean Peninsula

3. Runoff Analysis for Main River Basins in North Korea

3. 1 Tank Model

Runoff characteristics differ depending on types of land utilization and conditions of water use. Tank model which is proposed by Sugawara(1972) is basically composed of 4 tanks laid vertically in series. The model adopted in this study is well known as an excellent model because this model includes the mechanism of rainfall loss. However the decision of optimum parameters is a very difficult problem for the application of runoff analysis.

In this paper, the problem of searching for the parameters is substituted by the problem of function minimization, and analyzed, using Powell's conjugated direction method(1964), which is well-known as a high efficient method for analyzing the problem of function minization without constraint.

3. 2 Estimation of Monthly Discharge for Main River Basins in North Korea

The four-cascade Tank model adopted in this study is shown in Figure 5. The unknown parameters were identified by Powell's conjugated direction method. However, observed flow rates were not able to be obtained in the region of North Korea. Therefore the parameters determined from the basins of South Korea were used for estimating runoff in the region of North Korea.

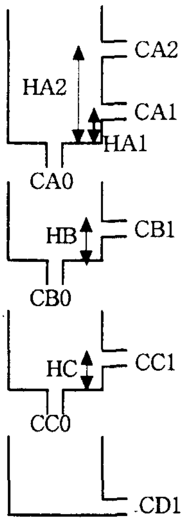

Fig. 5 Structure of four-cascade Tank Model

First monthly runoffs in the 5 main river basins of South Korea were estimated using the Tank model. And reliable stations were selected as those which were situated in the most remote downstream and were not affected by the tidal effect.

To obtain the parameters to be able to apply for the basins of North Korea, the variation of parameters doesn't have to be too large and the means of parameter was selected.

Most of the monthly runoff volume is controlled by the first and the second tanks. In other words, the third and the fourth tanks little affect the precision of runoff volume. Therefore parameters of the first and the second tanks are fixed to suitable values and parameters of the third and the fourth tanks were identified. In that manner, parameters of the first and the second tanks were identified using the recognized parameters of the third and the fourth tanks. The parameters of Tank Model obtained by repetition of this way are shown in table 1.

Monthly runoff of the 5 river basins of North Korea was estimated using the mean parameter of the Han river basin which was considered to be similar to that of North Korea in geographical and hydrological conditions. Figure 6 shows the result between the runoff(Qc_1) estimated from the mean parameter of the Han river basin and that(Qc_2) estimated from the mean parameter of the 5 river basins of South Korea. The lateral outlet parameters of the first and the second tanks show that mean parameters of the Han river basin were larger than that of the 5 river basins of South Korea. As the mean parameters of the Han river basin were used, the runoff was estimated as largely 20%. As the result, when the tank parameters of the Han river basin are used, we have to accept 20% errors.

Table 1 Optimized Tank model parameter for 5 basins

	CA1	CA2	CA0	HA1	HA2	CB1	CB0	HB	CC1	CC0	HC	CD1
Han river	0.663	0.247	0.041	25.64	33.93	0.102	0.0069	29.94	0.0129	0.0199	46.59	0.00006
Nakdong river	0.467	0.166	0.064	39.49	56.11	0.083	0.0219	43.15	0.0145	0.0050	56.54	0.00025
Keum river	0.295	0.256	0.091	10.85	32.63	0.034	0.0095	29.87	0.0017	0.0013	41.95	0.00099
Yongsan river	0.570	0.225	0.103	39.56	52.90	0.018	0.0499	86.79	0.0151	0.0666	14.52	0.00233
Sumjin river	0.674	0.158	0.059	36.22	49.30	0.090	0.0181	57.51	0.0453	0.0266	59.63	0.00006

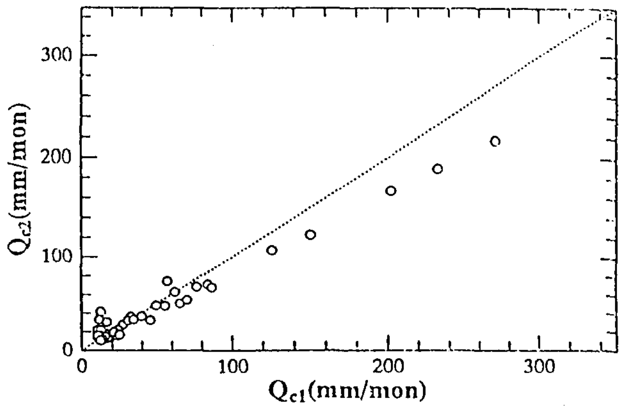

Fig. 6 Comparison of monthly runoff volume

(Qc_1 : using the Tank parameters for the Han river basin

Qc_2 : using the Tank parameters for 5 river basin)

4. Water Balance

4.1 Water Balance for the Main River Basins

The water balance equation can be written as follows

$$P = Q + E \pm \Delta S \tag{4}$$

where P, Q, E and S are the rates of precipitation, runoff, evapotranspiration and storage, respectively. The evaluation of change in storage depends on the period over which the water balance is made. On the annual basis, the time at which the balance is effected is chosen so that the water stored in the ground and on the surface is approximately the same each year and thus in the equation, $\Delta S=0$. Therefore, the annual water balance is given by the following equation :

$$P = Q + E \tag{5}$$

Figure 7 shows the water balance in the Korean peninsula in 1989. For South Korea, the evapotranspiration from the land surface is around 42% of the precipitation. The remainder can be considered to be runoff around 56% of the precipitation. However, for North Korea, the evapotranspiration from the land surface is above 50% of the precipitation. Accordingly, a part of evapotransiration is very important for North Korea's water balance.

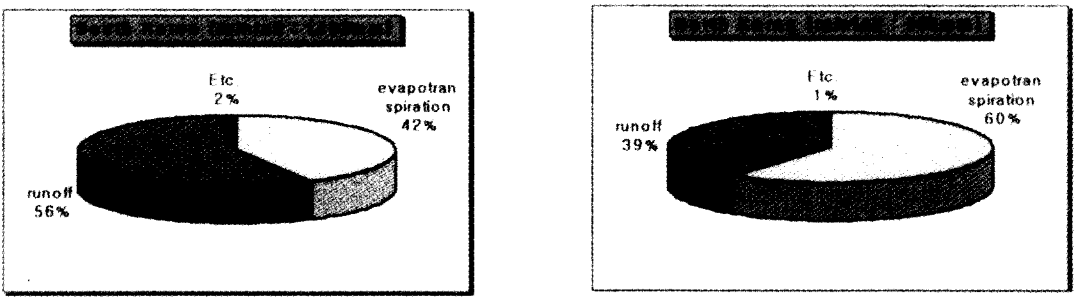

Fig. 7. Water Balance in the Korean Peninsula(1989)

4.2 Distribution of Water Balance

Water balance models were introduced originally to evaluate the importance of different hydrologic parameters under a variety of hydrologic conditions. This technique is very simple and uses long-term average monthly precipitation, evapotranspiration, soil and vegetation characteristics. Therefore it is applicable in those parts that are monitored poorly and can indicate seasonal trends in rainfall, evapotranspiration, soil moisture, irrigation need, and runoff. Since its introduction, the water balance approach has become one of the most versatile and widely used tools for the environmental and hydrological analysis.

A comparison of water supply with the climatic demand for water brings the information on the amount of water stored under various conditions. The water deficit(D) was defined as the difference between the climatic water demand and the actual water loss, and the water surplus (S) as the excess of moisture beyond what plants need when the soil capillaries are recharged with water. Water deficit is the amount of water that must be supplied by the irrigation to keep vegetation growing at an optimum rate. On the other hand, surplus is the moisture that will ultimately percolate to the water table and be lost as stream flow (Legates and Mather 1992). The surplus includes both surface and subsurface runoffs. The water surplus and deficit on the corresponding grid were determined as follows.

$$S_i = P_i - E_i \tag{6}$$
$$D_i = PE_i - P_i \tag{7}$$

where S_i is the water surplus(mm/year), D_i is the water deficit(mm/year), P_i is the precipitation(mm/year), E_i is the actual evapotranspiration(mm/year), and PE_i is the potential evapotranspiration(mm/year).

Figure 8 shows the water surplus distribution calculated by the above equation. Maximum water surplus, when annual computations are used, occurs in the southern region, concurrent with the band of the highest precipitation. Distribution of water deficit is generally the opposite of deficit.

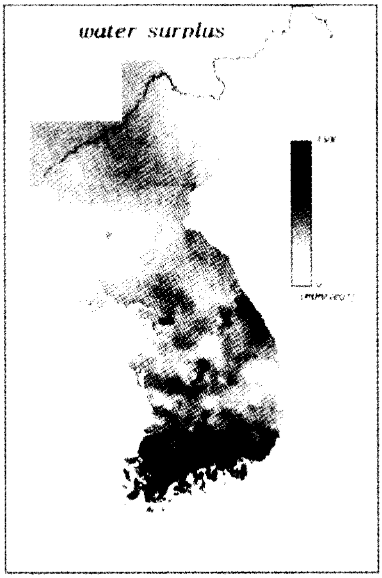

Fig. 8. Distribution of Water Surplus(1989)

Humidity index is used for hydrometeorological investigation by Shahin(1985), and it is calculated using potential evapotranspiration.

$$I_{mi} = \frac{100(S_i - 0.6D_i)}{PE_i} \tag{8}$$

where I_{mi}, S_i, and D_i are the humidity index, surplus and deficit at any pixel, respectively. Figure 9 shows distribution of moisture index for the year 1989, and types of climates corresponding to I_{mi} value show in Table 2. Southern parts of the Korean Peninsula have a very high moisture index value, whilst it is low for the northern part. However, the average moisture index for the Korean Peninsula in 1989 is 91, and it corresponds to the humid condition.

Table 2 Types of climates correspond to I_m value

Type	I_m
Perhumid	100 and above
Humid	20 to 100
Moist sub-humid	0 to 20
Dry sub-humid	-20 to 0
Semi-arid	-40 to -20
Arid	-100 to -40

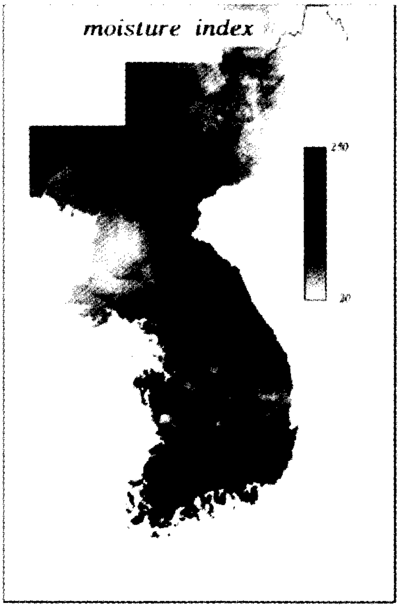

Fig. 9 Distribution of moisture index(1989)

5. Estimation of Runoff Ratio

Knowing the runoff ratio in an area is useful for estimating water resources. Since the runoff amount at any point is unknown, this is estimated indirectly, using the water balance equation. But the change of storage at the point is unknown, too. For that reason, we use a method that changes of storage will be assumed as zero by correction of precipitation, then the change of storage would be ignored during the long-term water balance. But, because rainy and dry seasons are relatively obvious in Korea, we can consider that the change of storage would be very small during only one year when the selection of the water year lies from one dry season to another dry season. Annual precipitation is corrected, using the following equations.

$$P_{ri} = C_p \cdot p_i \tag{9}$$

$$C_p = \frac{\sum_{j=1}^{12} (Q_j + E_j)}{\sum_{j=1}^{12} P_j} \tag{10}$$

where P_{ri} is a corrected precipitation pixel, P_j an observed monthly precipitation, P_i a pure precipitation pixel, C_p, a correction factor, Q_j, observed monthly runoff, and E_j a monthly average evapotranspiration.

The C_p is calculated as about 10%, and is very small. Therefore the amount is collected uniformly with the annual precipation. Eventually, the runoff ratio at any pixel is estimated from the following relations.

$$R_{ri} = \frac{Q_i}{P_i} = \frac{P_i - E_i \pm \Delta S_i}{P_i} = \frac{P_{ri} - E_i}{P_i} \tag{11}$$

The distribution of runoff ratio for the year 1989 is shown in Figure 10. From this result, we can readily understand the regional characteristics of runoff for each land cover condition. An average runoff ratio in the Korean Peninsula for the year 1989 is estimated as about 0.48.

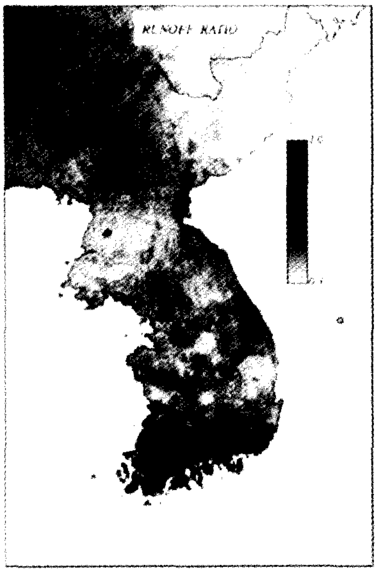

Fig. 10 Distribution of Runoff Ratio(1989)

6. Discussion and conclusion

This study presents an alternative approach for estimating land surface evapotranspiration and water balance based on remote sensing techniques. Although there are more complex parameterizations of the hydrological components of land-atmosphere interactions than are incorporated in this model, the comparison of runoff is of interest because it has implications for future water resources and indicates possible areas of improvement in model parameterizations of surface processes.

The results suggest that there is a possibility to assess the changes of hydrologic quantities in the past and the future by adopting remote sensing. For estimating the accuracy of the developed data sets, it is necessary to compare a number of observation data which have the same spatial resolution and are distributed widely. Unfortunately, those observation data sets were not available at present.

A great advantage of this model is that it can be applied to an ungauged area, for instance North Korea, because it requires the only precipation data. Other information has been derived by acquistion of evapotranspiration information directly from satellite data. The method is applicable to other countries after the suitable calibration of relationships between NDVI and evapotranspiration. However Applications of this method require attention in a poor vegetation area.

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