Verification of an NDVI-evapotranspiration model using a single layer model

HIROAKI WATANABE¹, SO KAZAMA² & MASAKI SAWAMOTO¹
¹Department of Civil Engineering, Graduate School of Engineering, Tohoku University, Aoba 06, Aramaki, Aoba, Sendai, Miyagi Prefecture 980-8579, Japan
watanabe@kaigan.civil.tohoku.ac.jp
²Graduate School of Environmental Studies, Tohoku University, Aoba 06, Aramaki, Aoba, Sendai, Miyagi Prefecture 980-8579, Japan

Abstract To establish a method for estimating evapotranspiration from NDVI data, cloud free images were compiled by a new algorithm using a temporally varying function and land use data. The NDVI data set was used for the estimation of evapotranspiration, and the estimated flux was compared with the estimation of a single layer model. The comparison shows that the single layer model produces less evapotranspiration than the NDVI method based on water balance. The distribution patterns of evapotranspiration estimated by the two methods were quite similar, indicating that the NDVI method is effective in estimating evapotranspiration.

Key words cloud-free image; evapotranspiration; GIS; NDVI; remote sensing

INTRODUCTION

Evapotranspiration is the general term for the water transportation process from the ground surface to the atmosphere. Since evaporation and transpiration are indistinguishable they are treated together. The copious energy flux on the earth surface is transferred by the latent heat contained in the water vapour in the atmosphere. However, the accuracy is very uncertain for evapotranspiration. The water balance method, the eddy correlation method, etc. are former evapotranspiration estimation methods. The water balance method cannot give the distribution of evapotranspiration in a basin. However, the eddy correlation method cannot give evapotranspiration for a wide area, in spite of the good modelling of a local phenomenon.

This study challenges the estimation of actual evapotranspiration using remote sensing technology, and a correlation between vegetation and evapotranspiration. Vegetation activity is evaluated using NDVI (Normalized Difference Vegetation Index) calculated from NOAA (National Ocean and Atmospheric Administration) satellite data. To verify the physical property of the statistical NDVI method, the flux estimated by NDVI is compared with the single layer model as a physical method. The purpose of this study is development of an accurate model estimating the evapotranspiration distribution of a wide area by comparing both methods.

STUDY BASIN

The study basin is the Natori River basin, which is located in the north part of Japan. Its headwaters begin in the Zao mountain range as shown in Fig. 1. It discharges
through the Sendai plain and drains into Sendai Bay. The basin area is 939 km² (mountainous area is 675 km², plain area is 245 km², and water body is 20 km²) and main flow channel length is 55 km. The basin has various land uses such as urban area, paddy field region, and forest region. Up- and mid-stream regions are almost covered with forests.

**DATASET**

We have used JAILDAS (JApan Image DatabaSe, JAIDAS) which is made from the images of NOAA/AVHRR. Based on GIS, elevation and land use distribution data in the Natori River basin are derived. The land use classification of this study is shown in Table 1. The meteorological data at Sendai and Nikkawa are obtained from the AMeDAS (Automated Meteorological Data Acquisition System) for one of the heat balance methods, the single layer model. To estimate wind velocity distribution, wind velocity data at Sasaya (580 m elevation) was provided by the Japan Highway Public Corp.

<table>
<thead>
<tr>
<th>GIS classification</th>
<th>Land use classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>No 1</td>
<td>Paddy field</td>
</tr>
<tr>
<td>No 2</td>
<td>Crops field</td>
</tr>
<tr>
<td>No 3</td>
<td>Orchard</td>
</tr>
<tr>
<td>No 4 &amp; No 5 &amp; No 6</td>
<td>Forest</td>
</tr>
<tr>
<td>No 7–No 10</td>
<td>City</td>
</tr>
<tr>
<td>No 11–No 15</td>
<td>Water body</td>
</tr>
</tbody>
</table>

GIS classification: 1, paddy field; 2, crops field; 3, orchard; 4, timber field; 5, forest; 6, waste land; 7, building cover (A); 8, building cover (B); 9, traffic zone; 10, other sites; 11, inland water; 12, river (A); 13, river (B); 14, coastal area; 15, sea water body.
CALCULATION OF NDVI

NDVI (Normalized Difference Vegetation Index), used as an index for the evaluation of the vegetation condition, has been calculated by the following equation (1) from the Channel 1 (visible wavelength: 0.72–1.10 µm) and Channel 2 (near infrared wavelength: 0.58–0.68 µm) of JAIDAS.

\[
\text{NDVI} \% = \frac{\text{Ch.2} - \text{Ch.1}}{\text{Ch.2} + \text{Ch.1}} \times 100
\] (1)

Chlorophyll in vegetation absorbs visible rays and reflects near-infrared rays. It is known that the difference in both wavelengths expresses vegetation mass and that NDVI is therefore proportional to a leaf density in each pixel.

Sometimes NDVI data is covered with clouds, particularly over upstream regions. Clouds decrease the NDVI value relative to the actual one. To solve this problem, cloud-free NDVI data in time series were made from the following procedure. At first, maximum NDVI on each pixel during a month is extracted to obtain the maximum NDVI distribution. Secondly, maximum NDVIs on each land use are obtained. And a regressed function with high order in time series is calculated for each land use during one year. We call this the maximum function. We can obtain maximum seasonal NDVI variation for each land use from this function. The maximum function for forest is shown in Fig. 2.

To express seasonal NDVI variation for each pixel in the Natori River basin, the maximum function was used according to the land use in each pixel. If land use was paddy field in a certain pixel, NDVI data of each month on the pixel is compared with the maximum function for paddy field. The smallest difference month \( M_{\text{min}} \) between NDVI and the maximum function is referred to the time series function of NDVI on the pixel as shown in the equation (2):

\[
F(x,y,i,t) = F_{\text{max}}(i) \times \frac{\text{NDVI}(x,y,i,M_{\text{min}})}{F_{\text{max}}(i,M_{\text{min}})}
\] (2)

Fig. 2 The maximum function on forest (2001). The black points show maximum NDVI of each month. The black curved line shows the maximum function. The maximum function expresses the seasonal variation characteristic of NDVI.
where $F$, $i$, $t$, $x$, $y$, $F_{\text{max}}$, and $M_{\text{min}}$, are NDVI varying function, land use classification, month (from April to November, 2001), abscissa in the Natori River basin, ordinate, the maximum function and smallest difference month between the maximum function and NDVI data. NDVI varying functions on all pixels were derived using the same process. Cloud-free NDVI data in time series over the Natori River basin were obtained using these methodologies. Figure 3 shows an original image of NDVI in July, 2001. Figure 4 shows the improved NDVI image estimated by NDVI varying function in July, 2001. Figure 4 has completely removed the influence of clouds upstream, as shown in Fig. 3.

![Fig. 3 The original image of NDVI in July, 2001.](image1)

![Fig. 4 Cloud-free NDVI image in July, 2001 estimated by the NDVI varying function.](image2)
METHODS

Estimation of evapotranspiration using NDVI

Evapotranspiration flux is affected by various factors such as temperature, land surface temperature, sunshine duration, humidity, wind velocity and soil water. These factors are dominant for regional vegetation, which also affects the evapotranspiration.

Evapotranspiration and its spatial distribution in the Natori River basin were estimated using the relationship between NDVI and evapotranspiration, which has been obtained in the Kamafusa dam basin by Tada et al. (Fig. 5). Figure 5 represents the proportional relationship between evapotranspiration and NDVI. Tada et al. obtained this relationship using the water balance in the Kamafusa dam basin. However, evapotranspiration from paddy fields does not depend on NDVI. It is generally known that the radiation method can estimate evapotranspiration from paddy fields. This method utilizes the characteristic on the paddy surface, which always has saturated water vapour pressure from water stored. Therefore solar radiation and temperature can derive potential evapotranspiration.

Estimation of evapotranspiration using single layer model

The single layer model, as a physical method with meteorological data from AMeDAS (2001), also estimates evapotranspiration to verify the validity of evapotranspiration estimated by NDVI. Firstly, equation (3) and equation (4) are substituted in equation (5), and arbitrary surface temperature $T_e$ is obtained by the successive approximation. $T_e$ is substituted in equation (3) and monthly evapotranspiration is estimated. Some parameters in the equations are referred to general values on each land use. Solar radiation $S_l$ and specific humidity $q$ are uniform in the study basin. Long wave radiation $L_l$ is estimated from day length, latitude and longitude. Wind velocity distribution (30 m above ground surface) is important input data used in the single layer model and interpolated using three wind velocity measurement stations (Sendai, Nikkawa, Sasaya) and obtained from equation (6) with elevation effect.

Fig. 5 Relationship between NDVI and evapotranspiration obtained from the water balance method in the Kamafusa dam basin.
Verification of an NDVI-evapotranspiration model using a single layer model

\[
E = \rho \beta C_h U [q_{\text{SAT}}(T_e) - q] \quad (3)
\]

\[
H = c_p \rho C_h U (T_e - T) \quad (4)
\]

\[
(1 - \text{ref})S \downarrow + L \downarrow = \sigma T_e^4 + LE + H \quad (5)
\]

\[
U = \frac{u_*}{\kappa} \ln \frac{z-d}{z_0} \quad (6)
\]

\(E\), evapotranspiration (kg m\(^{-2}\) s\(^{-1}\)); \(\rho\), air density (kg m\(^{-3}\)); \(\beta\), evaporation efficiency (dimensionless); \(C_h\), bulk transport coefficient (dimensionless); \(U\), wind velocity (m s\(^{-1}\)); \(q_{\text{SAT}}\), saturated specific humidity (dimensionless); \(q\), specific humidity (dimensionless); \(H\): sensible heat flux (w m\(^{-2}\)); \(c_p\), isopiestic specific heat for air (J kg\(^{-1}\) K\(^{-1}\)); \(T_e\), surface temperature (K); \(T\), atmospheric temperature (K); \(\text{ref}\), albedo (dimensionless); \(S\downarrow\), solar radiation (w m\(^{-2}\)); \(L\downarrow\), long wave radiation (w m\(^{-2}\)); \(\sigma\), Stefan-Boltzmann constant (5.67 \times 10^{-8} \text{w m}^{-2} \text{K}^{-4}); \(l\), latent heat for water (J kg\(^{-1}\)); \(u_*\), friction speed (m s\(^{-1}\)); \(\kappa\), Karman constant (0.4, dimensionless); \(z\), observation height (m); \(z_0\), roughness length (m); \(d\), zero-plane displacement (m).

RESULTS OF COMPARISON AND CONSIDERATION

Two evapotranspiration fluxes estimated by the NDVI method (Fig. 6) and the single layer model (Fig. 7) are similar in the city area. Evapotranspiration estimated by the NDVI method is over estimated by the single layer model over other areas of the study basin. This result is the same one year later. NDVI method based on water balance has more total basin wide evapotranspiration than the single layer model each month.

![Fig. 6 Distribution of evapotranspiration estimated by NDVI method in July, 2001.](image-url)
To compare distribution patterns, normalization of evapotranspiration is calculated by dividing by average evapotranspiration of each method. Figure 8 and Fig. 9 show similar distribution patterns.

Figure 10 shows a correlation between evapotranspiration estimated by the NDVI method and the single layer model. A gradient of the approximated-line of >1 also results, as mentioned in the previous section. However, the distribution pattern is quite
Similar. Since the NDVI method estimates total basin wide evapotranspiration from water balance, the amount of this method is believable. Therefore the physical property and accuracy of the NDVI method have been verified from a similar distribution pattern.
CONCLUSIONS

This study successfully shows the development of the method using NDVI on an arbitrary time and point. The estimation method by NDVI shows the validity from comparison with single layer model. This method using remote sensing technology is an easy and practical method which does not need many meteorological data like former methods.

REFERENCES