Integration of remote sensing with a soil water balance simulation model (SWATRE)

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Abstract
A method has been developed for the automatical mapping of evapotranspiration from digitally taken reflection- and thermal images. This method has been tested in combination with conventional methods in a remote sensing study project performed in the eastern part of The Netherlands. For this project different remote sensing flights were performed in the summer of 1982 and 1983. The images acquired after a very dry period were especially relevant to demonstrate that an important improvement of the hydrological description of an area could be achieved by combining the remote sensing approach with conventional methods.

1. Introduction
Information about regional evapotranspiration of crops is important for an optimal water management in agriculture and for the determination of the effect of man-made changes in the overall hydrological situation. Remote sensing can be very helpful in obtaining the necessary information (Heilman et al., 1976; Soer, 1980), although only the situation at one particular moment, c.q. time of overflight, is obtained. With the so-called SWATRE soil water simulation model for local conditions the use of water by agricultural crops can be simulated during the entire growing season (Feddes et al., 1978; Belmans et al., 1983). Since 1981 the applicability of Multi Spectral Scanning (MSS) techniques has been tested, in combination with the SWATRE approach, in a regional study project of an area (East Gelderland) in the eastern part of The Netherlands (Fig. 1). Crop temperatures derived from heat images can be transformed into daily evapotranspiration values with surface energy balance models (Jackson et al., 1977; Soer, 1980 and Hatfield et al., 1984). Jackson et al. proposed an empirical relation between midday surface-air temperature differences and actual daily evapotranspiration.

FIG.1 Location of the study area.
Nieuwenhuis et al. (1985) proposed some modifications to the method of Jackson. With the modified method differences in radiation temperature of a certain crop as derived from heat images can be directly transformed into differences in evapotranspiration.

The presently developed linear relationship between crop temperature and daily evapotranspiration is crop dependent. Therefore mapping of the thermographic evapotranspiration values was combined with automatic crop classification. Crop classification was performed by means of reflection images taken with a multi spectral scanner.

In the present study especially the effect of groundwater extractions on the water supply of agricultural crops has been emphasized.

2. Theory

2.1. Instantaneous crop temperature and evapotranspiration

The temperature of objects at the earth surface is determined by the instantaneous equilibrium between gains and losses of energy. At the earth surface net radiation $R_n$ equals the sum of latent heat flux into the air $LE$, sensible heat flux into the air $H$ and heat flux into the soil $G$:

$$R_n = LE + H + G \text{ (W m}^{-2}\text{)}$$  \hspace{1cm} (1)

where $L$ is the latent heat of vaporization (J kg$^{-1}$) and $E$ the evapotranspiration flux (kg m$^{-2}$ s$^{-1}$).

The term $R_n$ can be split up in a net short wave and a net long wave radiation term:

$$R_n = (1 - \alpha)R_s + e(R_\lambda - \sigma T_c^4) \text{ (W m}^{-2}\text{)}$$  \hspace{1cm} (2)

where $\alpha$ is the surface reflection coefficient, $R_s$ the incoming short wave radiation flux (W m$^{-2}$), $e$ the emission coefficient, $R_\lambda$ the long wave sky radiation flux (W m$^{-2}$), $\sigma$ the constant of Stefan Boltzmann (5.67.10$^{-8}$ W m$^{-2}$ K$^{-4}$) and $T_c$ the crop surface temperature (K).

When the crop is well-supplied with water, the net radiation energy is mainly used as latent heat for vaporization. When the latent heat flux decreases, the surface temperature increases, resulting in a rise of the sensible heat flux $H$. Considering the transport of heat from the crop surface with temperature $T_a$ (K) to a certain height $z_{ref}$ (m) with air temperature $T_a$ (K) the transport equation can be expressed as:

$$H = -\rho C_p \frac{(T_a - T_c)}{r_{ah}} \text{ (W m}^{-2}\text{)}$$  \hspace{1cm} (3)

where $\rho$ is the density of moist air (kg m$^{-3}$), $C_p$ the specific heat of moist air (J kg$^{-1}$ K$^{-1}$) and $r_{ah}$ the turbulent diffusion resistance for heat transport (s m$^{-1}$) from the crop surface to $z = z_{ref}$.

Combining the eqs (1), (2) and (3) the relation between latent heat flux $LE$ and surface temperature $T_c$ can be found (Brown and Rosenberg, 1973 and Stone and Horton, 1974):

$$LE = \rho C_p \frac{(T_a - T_c)}{r_{ah}} + (1 - \alpha)R_s + e(R_\lambda - \sigma T_c^4) - G \text{ (W m}^{-2}\text{)}$$  \hspace{1cm} (4)

From eq. (4) it can be seen that $LE$ depends on a number of meteorological and crop surface parameters. For a certain regional area, $T_c$ can be remotely sensed by thermal infrared line scanning. When $T_a$, $r_{ah}$, $\alpha$, $R_s$, $e$, $R_\lambda$ and $G$ are known (or estimated) $LE$ can be computed.

The resistance $r_{ah}$ depends on wind velocity $u$, roughness of the crop surface $z$, and atmospheric stability (Dyer, 1967 and Webb, 1970).

For clear sky conditions $T_a$, $R_s$, $R_\lambda$ and $u$ can be taken constant over a
certain area. This means that standard meteorological measurements can be used. The parameter $a$, has to be determined from field measurements or from reflection images. With more indirect procedures $e$ and $z_0$ can also be estimated by combining field observations with interpretation of reflection images.

2.2. Relation between instantaneous crop temperature and 24 hour evapotranspiration rate

For the translation of instantaneous to daily values Soer (1977) developed the TERGRA-model. However, interpretation of thermal images with the aid of the TERGRA-model is rather complicated because of the large number of input parameters that are required.

Jackson et al. (1977) related midday surface-air temperature differences linearly to 24 hour evapotranspiration and net radiation values. To estimate the slope of this relationship a crop-dependent analytical expression has been derived by Seguin and Itier (1983).

Nieuwenhuis et al. (1985) proposed to replace the surface-air temperature difference by the temperature difference $(T_c - T_c^*)$ that exists between the crop that is transpiring under the actual restriction of the soil moisture condition and that transpiring under optimal soil moisture conditions. The net radiation term was replaced by the 24 hour potential evapotranspiration rate of the crop. With these adjustments they obtained:

$$\frac{LE_{24}^{p}}{LE_{24}^{24}} = 1 - B^r (T_c - T_c^*)_i$$  \hspace{1cm} (5)$$

where $LE_{24}^{24}$ and $LE_{24}^{p}$ are respectively the actual and potential 24 hour evapotranspiration rate (mm day$^{-1}$), $B^r$ (K$^{-1}$) is a calibration constant and the subscript $i$ indicates instantaneous values. By means of eq. (5) differences in radiation temperature of a certain crop derived from thermal images can be directly transformed into reductions in evapotranspiration.

From TERGRA-model calculations Thunnissen (1985) found that $B^r$ can be described by a linear function of the wind velocity ($u$) at a height of 2.0 m above ground surface:

$$B^r = a + b \cdot u$$  \hspace{1cm} (K$^{-1}$)$$

Values for the regression coefficients $a$ and $b$ are given in Table 1 for different type of crops and crop heights.

For agrohydrological purposes heat images are usually taken on clear days in the summer period. It was found that for such days eqs (5) and (6) can be applied for the meteorological conditions prevailing in The Netherlands.

<table>
<thead>
<tr>
<th>Crop</th>
<th>$H$ (cm)</th>
<th>$a$ (K$^{-1}$)</th>
<th>$b$ (K$^{-1}$m$^{-1}$s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grass</td>
<td>&lt;15</td>
<td>0.050</td>
<td>0.010</td>
</tr>
<tr>
<td>Grass</td>
<td>&gt;15</td>
<td>0.050</td>
<td>0.017</td>
</tr>
<tr>
<td>Potatoes</td>
<td>60</td>
<td>0.050</td>
<td>0.023</td>
</tr>
<tr>
<td>Sugar beet</td>
<td>60</td>
<td>0.050</td>
<td>0.023</td>
</tr>
<tr>
<td>Cereals</td>
<td>100</td>
<td>0.090</td>
<td>0.030</td>
</tr>
<tr>
<td>Maize</td>
<td>200</td>
<td>0.100</td>
<td>0.047</td>
</tr>
</tbody>
</table>

TABLE 1—Values for the coefficients $a$ and $b$ in eq. (6) for a number of crops with crop height $H$ (after: Thunnissen, 1985).
2.3. Simulation of the water balance of a cropped soil with the SWATRE-model

Remotely sensed images characterize the conditions at one time. For several agrohydrological applications, however, determination of cumulative effects in time on the total crop yield is required. As an example one can think of the effects of groundwater extraction for domestic purposes on the growing conditions of grassland and arable crops. The amount of water available for transpiration strongly influences dry matter production.

With a model such as SWATRE (Feddes et al., 1978 and Belmans et al., 1983) the use of water by agricultural crops can be simulated during the entire growing season. SWATRE is a transient one-dimensional finite-difference soil-water-root uptake model, that applies a simple sink term and different types of boundary conditions at the bottom of the system. When the soil system remains unsaturated, one of three bottom boundary conditions can be used, namely pressure head, zero flux or free drainage. When the lower part of the system remains saturated, one can give either the groundwater level or the flux through the bottom of the system as input. In the latter case the groundwater level is computed. At the top of the system, 24 hour data on rainfall, potential soil evaporation and potential transpiration are needed.

The SWATRE-model can be sued to simulate actual transpiration, hence it can be used to investigate how far the moisture conditions at particular times are representative for the entire growing season.

3. Description of the study area and remote sensing flights

The study area covers about 36 km² and is situated in the eastern part of The Netherlands around the pumping station 't Klooster (Fig. 1). Most of the study area is covered by grassland, but the cultivation of maize becomes more and more important.

The area is geohydrologically characterized by a coarse sandy aquifer overlying a more or less impermeable layer of fine silty sand at a depth of about 35 m. The most important soil types in the study area are the Typic Hapludands (Gleyic Podzols, about 45%), the Typic Humaquepts (Humic Gleysols, about 20%) and the Plaggepts (Plaggen soils, about 20%). The soils show differences in drainage class resulting from small variations in elevation and soil texture (fine sand and loamy fine sand). In The Netherlands on soil maps the drainage classes are indicated as so-called groundwater table classes (Table 2). Each class is a combination of a mean highest groundwater table (winter situation) and a mean lowest groundwater table (summer situation). In the study area classes III till VII are found.

In 1982 and 1983 a number of remote sensing flights were performed in the eastern part of The Netherlands. Digital reflection and heat images were taken with a Daedalus digital scanner (DS1240/1260) by Eurosense (The Hague), simultaneously with false colour photographs. Especially the images taken after a relatively dry period show important information about the regional hydrological situation. Results are presented from a flight performed on 30 July 1982 at a height of about 3000 m resulting in a pixel size of about 7.5 x 7.5 m.

| Table 2—Drainage classes indicated on soil maps in The Netherlands. |
|-----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| I               | II              | IIIa           | III             | IV             | V              | VI             | VII            |
| MHG             | -               | <20            | <40             | >40            | <40            | 40-80          | 80-140         |
| MLG             | <50             | 50-80          | 80-120          | 80-120         | >120           | >120           | >160           |

MHG = Mean Highest Groundwater depth (cm - groundsurface)
MLG = Mean Lowest Groundwater depth (cm - groundsurface)
4. Applied methods

The image processing was performed on the remote sensing data handling system (RESEDA) of the National Aerospace Laboratory (NLR) in Amsterdam. A crop map was composed from the reflection bands 5 (0.55-0.60 um), 7 (0.65-0.69 um) and 9 (0.80-0.89 um) by applying a more or less standard supervised classification procedure. The classification result was checked with field measurements and was compared with results obtained by interpretation of the simultaneously taken false colour photographs. It was found that a distinction between tall grassland and maize was impossible with standard classification procedures. Therefore it was decided to improve the classification result interactively by indicating all the maize plots on the videoscreen of the data handling system in order to obtain a reliable crop map.

Depending on the height, grassland was divided into three classes by applying the Vegetation Index (VI), which is defined as (Tucker, 1977):

$$VI = \frac{(IR - R)}{(IR + R)}$$

(7)

For IR and R the radiation intensities in respectively wavelength band 9 and 7 have been applied. The relation between the Vegetation Index and the crop height has been determined by measuring on flight days the crop height on several plots. It was found that about 90% of the considered plots was correctly classified.

With eqs (5) and (6) for maize, middle high (5-15 cm) and tall (>15 cm) grassland the heat image was automatically converted into a map with estimates of relative 24 hour evapotranspiration rates.

With the SWATRE-model (Feddes et al., 1978 and Belmans et al., 1983) the water balance terms were simulated during the entire growing season with actual weather data of that particular year and for three typical soil types present in the study area. For 30 July 1982 results obtained with the SWATRE-model have been compared with the remote sensing approach.

5. Results and discussion

5.1. Interpretation of the evapotranspiration map

The evapotranspiration map of the study area composed from the reflection and heat images of 30 July 1982 is presented in Fig. 2.

Because of irrigation by means of sprinkling irregularly distributed over the area, plots are present with crops well supplied with water. On these plots crops are more or less potentially transpiring (dark in Fig. 2).

Under natural conditions crop evapotranspiration depends on the moisture availability in the root zone, which is determined by:

- the depth of the root zone;
- the available moisture capacity in the root zone;
- the hydraulic conductivity of the subsoil;
- the groundwater level during the growing season.

The first three factors are mainly dependent on the soil properties. By comparing the evapotranspiration map with the available soil map the occurrence of drought could be explained for several soil types (Nieuwenhuis, 1985).

As phreatic groundwater is extracted by the pumping station 't Klooster (indicated with a 'P' in Fig. 2) the groundwater level and therefore the occurrence of drought damage is influenced by the groundwater extraction in the shown area. Around the centre of the extraction a more or less conical depression of the groundwater table occurs. The isoline indicating a 10 cm drawdown according to calculations reported by De Laat and Awater (1978) is also shown in Fig. 2.
The evapotranspiration of crops has been studied in relation to the distance from the centre of the groundwater extraction. As crop evapotranspiration depends on soil type and groundwater level a systematic analysis has been performed for each soil type and each groundwater table class separately. Fig. 3a and b show two typical results.

Fig. 3a shows that the evapotranspiration rate for grassland on a Typic Haplaquod soil in combination with a relatively high groundwater table under natural conditions, decreases in the direction of the centre of the extraction. Natural conditions are defined as the situation without groundwater extraction. At distances of more than 1300 m from the centre of the extraction the drawdown of the groundwater table is negligible and because of sufficient water supply by capillary rise from groundwater crops are transpiring potentially.

Fig. 3b shows a quite different result. For maize on a Typic Haplaquod soil with a relatively deep groundwater table the evapotranspiration rate is very low and independent on the distance from the centre of the extraction. This means that under these circumstances even without lowering of the groundwater table the water delivery to the root zone by means of capillary rise can be neglected.

5.2 Calculations with the SWATRE-model

Calculations with the SWATRE-model were performed to obtain information about the effect of a lowering of the groundwater table on the total crop yield.

Evapotranspiration was simulated during the entire growing season of 1982 for grass and maize grown on a Typic Haplaquod soil with groundwater table class V. In the calculations measured groundwater depths were taken for
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FIG. 3 Relative 24 hr evapotranspiration rate ($\frac{LE_{24}}{LE_P}$) on 30 July 1982 derived from the evapotranspiration map shown in Fig. 2 for (a) grass on Typic Hapludult soil with drainage class V and (b) for maize on the same soil with drainage class VI depending on the distance to the centre of the groundwater extraction. Drainage classes are given in Table 2 (after: Thunnissen, 1984).

situations without extraction. Moreover, model calculations were performed assuming a constant drawdown during the entire growing season. Fig. 4 shows that for the growing season of 1982 the cumulative effect of a lowering of the groundwater table can amount to 15% for grass and 20% for maize.

Except cumulative effects for 30 July 1982 also the effect of a lowering of the groundwater table on crop daily evapotranspiration was studied. Fig. 5a and b show respectively the results for grass on a Typic Hapludult soil with drainage class V and maize on the same soil with drainage class VI.

In a dry period the water supply of crops depends on suppletion from groundwater by means of capillary rise. The effect of a lowering of the groundwater table could be serious if a relatively shallow groundwater table is present under natural conditions (Fig. 5a). For a relatively deep groundwater table crop evapotranspiration of maize is even under natural conditions very low on 30 July 1982 and the effect of a lowering of the groundwater table is than limited (Fig. 5b).

FIG. 4 Ratio of cumulative actual to potential 24 hr evapotranspiration over the entire growing season of 1982 ($\Sigma \frac{LE_{24}}{LE_P}$) for grass and maize on Typic Hapludult soil with drainage class V (see Table 2) depending on groundwater table drawdown (after: Thunnissen, 1984).
5.3. Comparison of remote sensing results with SWATRE-model calculations

According to the remote sensing approach crop evapotranspiration strongly decreases on 30 July 1982 in the direction of the centre of the extraction in case of shallow groundwater tables under natural conditions. This is shown in Fig. 3a. Fig. 3a shows that also according to SWATRE-model calculations for the concerning conditions crop evapotranspiration strongly decreases with lowering of the groundwater table.

Also for relatively deep groundwater tables under natural conditions both results show good agreement (Fig. 3b and 5b). If no suppletion from groundwater occurs crop evapotranspiration is very low on 30 July 1982 and a lowering of the groundwater table has no perceptible influence on crop evapotranspiration.

For specific locations, where the groundwater level was measured, crop evapotranspiration was simulated with the SWATRE-model during the entire growing season of 1982. For 30 July 1982 model results have been compared with results obtained with the remote sensing approach. Table 3 shows some examples. For Typic Haplaquod and Typic Humaquept soils results are in good agreement. For Plaggept soil, however, crop evapotranspiration is overestimated by the SWATRE-model in relation to the remote sensing approach. The model results are determined by the applied soil physical properties. Probably for Plaggept soil an overestimation of crop water supply occurs with the applied properties. In general results obtained with the SWATRE-model are in good agreement with the remote sensing approach.

![FIG.5](image)

**FIG. 5** Relative 24 hr evapotranspiration rate ($\frac{LE_{24}}{LE_{24}}$) on 30 July 1982 for (a) grass on Typic Haplaquod soil with drainage class V and (b) for maize on the same soil with drainage class VI depending on groundwater table drawdown. Drainage classes are given in Table 2 (after: Thunnissen, 1984).

6. Conclusions

With remote sensing detailed information about the regional distribution of evapotranspiration on flight days is obtained. With agrohydrological simulation models like SWATRE for a restricted number of locations crop evapotranspiration can be simulated during the entire growing season. For the explanation of drought patters on the evapotranspiration map determined with remote sensing, such model calculations are indispensable.

Moreover, with model calculations effects of certain drought periods during the growing season on total crop yield can be determined. It can be concluded that an important improvement of the hydrological description of an area can be achieved by combining SWATRE-model calculations with remote sensing.
TABLE 3—Relative 24-hour evapotranspiration rates ($LE^{24}/LE^{24}$) for 30 July 1982 according to the remote sensing approach and calculated with the SWATRE-model for 14 grassland plots and 3 different soil types (after: Thunnissen, 1984).

<table>
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<th>Soil type</th>
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<th>SWATRE-model</th>
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<td>1. Typic Haplaquods</td>
<td>85</td>
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</tr>
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<td>2. Typic Haplaquods</td>
<td>&lt;30</td>
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</tr>
<tr>
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</tr>
<tr>
<td>4. Typic Haplaquods</td>
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</tr>
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<td>5. Typic Haplaquods</td>
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<td>6. Typic Haplaquods</td>
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References


