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Remote sensing in the water management practice

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Introduction

The concept of water management implies that optimality (or improvement) is achieved by attuning water delivery or withdrawal to local requirements and constraints. Water management is, however, intrinsically non-local, since water resources are being managed for an area within which both requirements and constraints are actually variable. It appears, therefore, that the quantitative determination of requirements and constraints is essential for solving any water management problem. The ideal determination method should not smooth out the actual variability in space and time.

In principle two classes of methods can be applied to determine the required variables. First, estimation methods (models) involving the calculation of the variables with other data, such as calculation of water requirements by simulating soil-water flow on the basis of soil hydrological properties and weather observations. Second, direct observation of areal patterns of the variables by means of remote sensing.

Models have the advantage that evolution in time can accurately be described, but they are limited in that actual field conditions have to be schematized. This implies establishing grid cells and estimating the required input values for each grid cell. Since remote sensing gives information in terms of patterns, it has the potential to help in establishing the grid cells.

In this paper we describe the application of some remote sensing techniques in water management case studies. Special attention will be given to illustrate the place of remote sensing in relation with conventional hydrological methods.

Applications

In this section three case studies will be described briefly to illustrate the usefulness of remote sensing for water management. There are important conceptual and practical aspects relating to the required spatial detail in each water management problem. The three case studies are arranged in a sequence of increasing length scale and of increasing picture element size.

Case study 1. Remote sensing in water management in a humid region with intensive land-use

Practical framework

For an optimal water management in agriculture and for the determination of the effect of man-made changes in the overall hydrological situation (e.g. groundwater extractions, improvement of the drainage system and soil improvement) information about regional evapotranspiration is important. To determine crop water use under varying conditions usually field measurements and agro-hydrological simulation models are applied.

Collection of field data is laborious and the results obtained depend strongly on the schematization in the applied model. With remote sensing detailed information about the variability of hydrological and soil physical characteristics can be obtained. Therefore, the applicability of remote sensing techniques in water management problems has been investigated in different research projects.

Approach

To describe the hydrological situation in a certain area two approaches can be applied. First, simulation of the water flow in the soil–plant–atmosphere system with a quasi three-dimensional regional agro-hydrological simulation model like GELGAM (de Laat & Awater, 1978; de Laat, 1980). The applicability of a regional model depends strongly on the size of the grid cell and the choice of the plant parameters and soil physical characteristics (schematization of the model).

Second, application of remote sensing in combination with a one-dimensional agro-hydrological simulation model like SWATRE (Thunnissen, 1984a; Nieuwenhuis, 1985). A method has been developed to map evapotranspiration from digitally taken reflection and thermal images (Soer, 1980; Thunnissen, 1984b; Nieuwenhuis et al., 1985). Such a map provides information about the occurrence and pattern of drought damage. However, only information about crop stress conditions at flight days is obtained. For the explanation of the occurrence of drought damage and for the translation into seasonal effects the SWATRE model (Feddes et al., 1978; Belmans et al., 1983) is applied. With this model crop water use can be simulated for certain locations during the entire growing season depending on soil physical characteristics and the prevailing weather conditions.

Results and conclusions

In the framework of a remote sensing study project performed in an area in the eastern part of the Netherlands remote sensing has been applied in combination with conventional methods. The verification of evapotranspiration values calculated with hydrological simulation models appeared possible (Thunnissen, 1984a). Fig. 1 shows an evapotranspiration map obtained with digitally taken reflection and thermal images. The figure demonstrates that large variations in evapotranspiration occur within a grid cell applied in the model GELGAM. Model calculations provide mean values for each grid cell. With remote sensing information is obtained about the deviations that may occur. This gives an insight in the meaning of results ob-

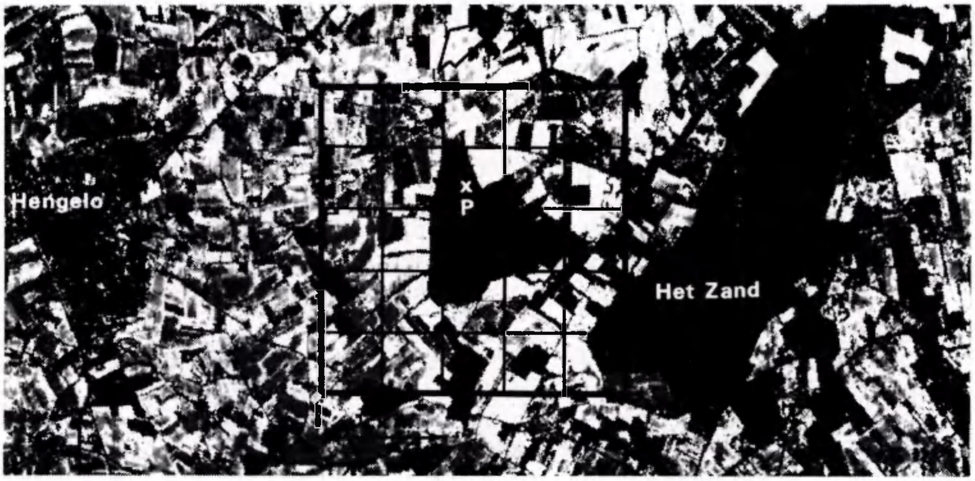

Fig. 1. Evapotranspiration map of the study area situated around the pumping station 't Klooster (P). The map is composed from reflection and heat images taken on 30 July 1982 at 12.00 MET. The grid applied in the GELGAM-model has been indicated. Crop evapotranspiration decreases from potential (dark grey) till a level of about 30% of the potential one (white). Black areas are not classified.

tained with a regional hydrological simulation model.

The variations in evapotranspiration visible in Fig. 1 are caused by variations in crop and soil type, and local drainage conditions. Within the research area several farmers apply sprinkling irrigation and at the pumping station 't Klooster phreatic groundwater is extracted. The effects of the groundwater extractions were investigated in a systematic analysis of evapotranspiration of cropped plots for each soil type and drainage class (Fig. 2).

The description of the hydrological conditions and their changes in an area for water management purposes can thus be greatly improved by combining remote sensing with hydrological model calculations.

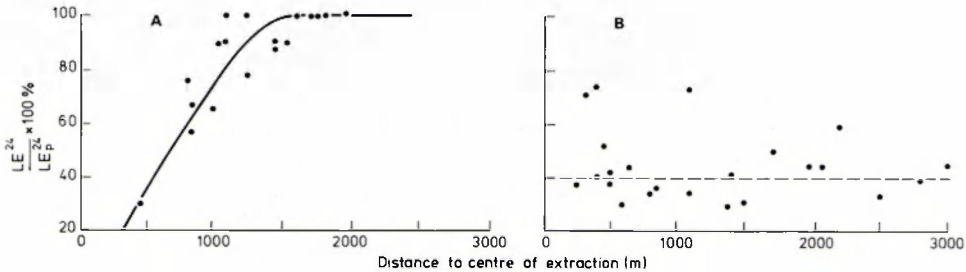

Fig. 2. Relative 24-h evapotranspiration rate (LE^{24}/LE_p^{24}) on 30 July 1982 derived from the evapotranspiration map shown in Fig. 1. A: grass on Typic Haplaquod soil with drainage class V. B: maize on the same soil with drainage class VI (depending on the distance to the centre of the groundwater extraction).

Case study 2. Remote sensing in the evaluation and improvement of irrigation water use

Practical framework

Gross allocation of irrigation water far exceeds actual net crop water requirements. Water is often allocated to deliver everybody's fair share of the available resource, i.e. proportionally to the irrigated area. Furthermore, information on actual crop water requirements is either scarce or not available. This applies especially to the extent of the actually irrigated area. Overirrigation is then a solution to guarantee reliability of water deliveries and to comply with traditional laws dealing with water allocation.

In the past twenty years, however, a clear picture has been drawn about overirrigation. Gross water diversion is limited in that soon a stage will be reached where tail-end users do not receive enough water. Moreover, the huge and uncontrolled water losses within the irrigation system induce serious waterlogging and salinization.

Approach

An enormous amount of literature deals with the optimization and improvement of irrigation water use (Bottrall, 1985; Rees & Hamlin, 1985; Smith, 1985). An especially debated issue is whether priority should be given to either social and economical aspects or to the 'technicalities' of water management. Here the somewhat restricted view is taken that the main goal is the delivery of the actually required water at the farms' inlet with a minimum difference between gross water diversion and net delivery.

The first step is to measure the performance of an irrigation infrastructure and of its parts. Standard definitions of irrigation efficiencies have been given by Bos (1985). To measure these efficiencies one has to measure stream-flow at canal inlet and actual crop water requirements; both quantities have to be transformed into volumetric units. Crop water requirements can be calculated per unit area with meteorological data, while the actually irrigated area has to be determined to obtain the requirements in terms of volume.

A different definition of irrigation efficiencies has been applied by Menenti et al. (1985). This definition involves an equivalent water depth, d, defined as the ratio of volumes to irrigated area, V/A. Since the definition makes water quantities relating to different parts of an irrigation system comparable with each other, it is quite helpful in establishing the proper sampling strategy to evaluate the areal variability of irrigation efficiencies. Moreover, as shown by Menenti et al. (1985), this definition straightforwardly suggests a procedure to set up a numerical model to mimic the functioning of the irrigation system. The kernel of this model is a water balance equation written for a particular node of the irrigation network:

$$d_i = \Sigma_j d_{ij} \tag{1}$$

where d_i is the equivalent water depth reaching the node i and d_{ij} the equivalent water depths leaving the node i. By applying the definition of d, Eq. 1 reads:

$$V_i/A_i = \Sigma_j (V_{ij}/A_{ij}) \tag{2}$$

This equation shows that an accurate determination of the actually irrigated area of each scheme unit U_j is essential for: accurate determination of irrigation efficiencies, accuracy of model results, and proper water allocation.

It is essential, independent of the procedure presented above, to use up-to-date maps of the actually irrigated area. Determination of actual crop area by means of field inquiries may not be feasible, as for example mentioned by R. Gommes (personal communication) in relation with crop monitoring in Tanzania.

The urgent need for an operational and reliable method to map crops and irri-

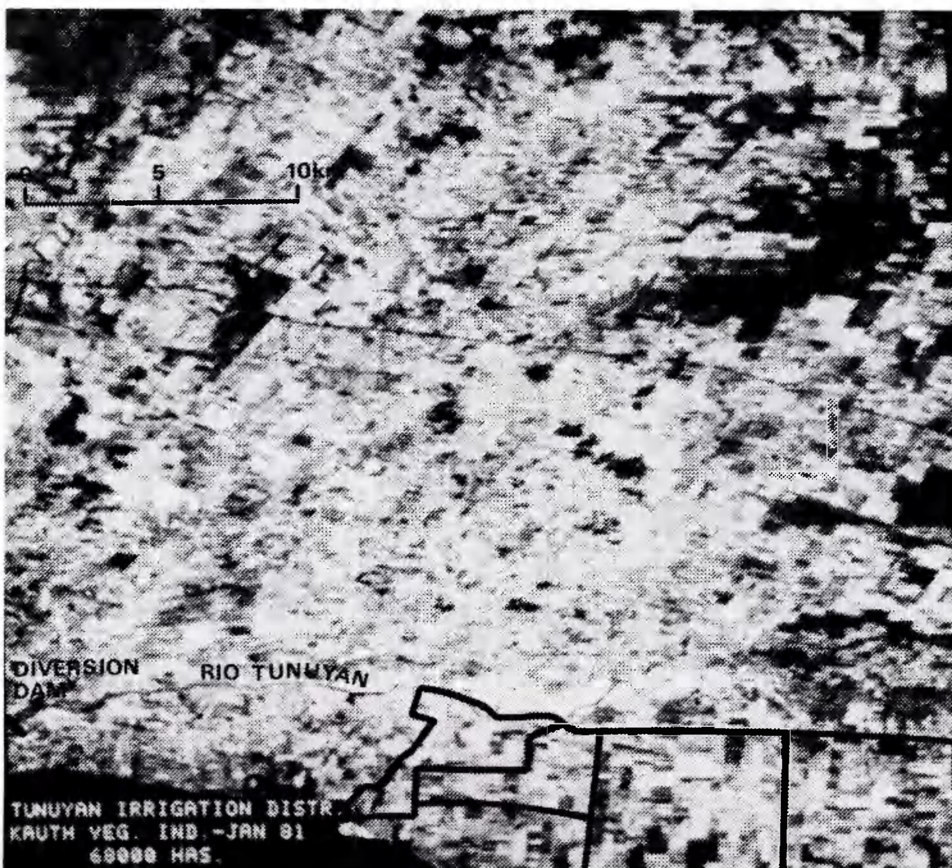

Fig. 3. Map of the Kauth Green Vegetation Index, as calculated from a LANDSAT-MSS image; Rio Tunuyán irrigation district; 15 January 1981. Irrigated land is light gray to white; unirrigated land is black to dark gray; the size of a grid cell applied in the model of Menenti et al. (1985) is indicated.

gated area is further demonstrated by two other studies. An inquiry on irrigation water use in the Po plain (Bernardi et al., 1985) showed that only 2 out of 547 irrigation districts could deliver data of total crop area. In the irrigation districts of Mendoza, Argentina, water is being allocated on the basis of the area holding water rights; these figures are outdated (L. Chambouleyron, personal communication), as also indicated by the ratio of actually paid to due water rights.

Mapping of irrigated area by means of LANDSAT-type satellite data is an accurate (5-10 % accuracy; Heller & Johnson, 1979) and cost-effective approach. Especially in arid areas, such as Mendoza in Argentina, mapping of actually irrigated areas is straightforward (Menenti et al., 1985). Furthermore, the relatively low frequency of cloudy days guarantees a higher re-visit frequency.

Results and conclusions

The image of the Greenness Vegetation Index for the Rio Tunuyán irrigation district in Mendoza (Fig. 3) shows the discrepancy between areas holding water rights and areas actually irrigated. Even in the sections of the irrigation district, located close to the diversion dam, patches of land that is not irrigated can be seen. In these sections the area holding water rights is 100 % of the total.

Table 1 illustrates how LANDSAT images taken on different dates during the growing season (multitemporal analysis) can be applied to identify crops. Of particular interest is the difference between vineyard, vineyard with grass and vineyard with olive trees. These results indicate that there is a clear potential for discrimination of different intercropping patterns.

The presented results show the capability of remote sensing by satellites in obtaining data on irrigated area and crop type. This information is essential to assess the performance of irrigation schemes and to mimic and to improve water allocation by means of models.

Table 1. Values of the ratio (%) of reflectances in the near-infrared spectral range (0.8-1.1 μm, MSS 7) to the red reflectance (0.6-0.7 μm, MSS 5); LANDSAT Multi Spectral Scanner (MSS) measurements; Mendoza, Argentina.

Crop	(MSS 7/MSS 5)		
	28 August 1984	27 February 1985	15 March 1985
Onion	69	89	82
Vine	73	140	125
Lucerne	121	143	158
Olive trees	105	122	96
Vineyard with grass	155	150	107
Vineyard with olive trees	79	128	114
Fruit trees	67	113	113
Rangeland	69	66	61

Case study 3. Remote sensing in mapping of groundwater losses by evaporation in deserts

Practical framework

Agricultural development in deserts is taking place by extracting groundwater. Current recharge of underground reservoirs is probably negligible. By comparing groundwater extraction with total groundwater storage, it is shown that the issue is not groundwater depletion, but accurate long-term prediction of water table drawdown (Menenti, 1986). The assessment of the impact of newly established irrigated areas is intrinsically regional in character. Groundwater consumption in the irrigated areas may be a factor 100 to 1000 larger than local rainfall (Menenti, 1984). This is offset if a small fraction of land is occupied by irrigated crops. The West Libya aquifer system, for example, occupies 800 000 km^2, with the irrigated area being 100 km^2 only (Menenti, 1984; Pizzi & Sartori, 1984)

Along with groundwater extraction, evaporation of groundwater occurs in depressions where the water table is shallow. These losses by evaporation are comparable with the extracted amounts, or even larger. This implies that long-term planning of groundwater development to supply irrigated agriculture requires the regional determination of actual evaporation of groundwater.

Approach

Actual evaporation can be obtained as the latent heat flux term in the surface energy balance. The underlying theoretical aspects have been presented before, together with an example of application (Menenti, 1984).

In deserts, large variations of surface reflectance occur, thus implying a large areal variability of the available radiant energy (net radiation). Furthermore, especially in the areas where the water table is at shallow depths, layered soils are present. These soils are characterized by a large variability of thermal and hydrological soil properties. This results in a large areal variability of surface temperature (Nieuwenhuis & Menenti, 1986). Surface reflectance, α_0, and surface temperature, T_0, will, therefore, provide essential information on the surface energy balance. The latent heat flux, LE, changes when either α_0 or T_0 or both change, so there is an opportunity to calculate LE from α_0 and T_0.

Formally the concepts presented above can be summarized in considering the energy balance equation as an estimator f_1 that relates the six variables α_0, R_{sw}, T_a, T_0, r_a and G_0 to LE:

$$\{\alpha_0, R_{sw}, T_a, T_0, r_a, G_0\} \xrightarrow{f_1} \{\mathrm{LE}\} \quad (3)$$

where T_{sw} is the shortwave solar radiation, T_a air temperature, r_a the mean turbulent transfer resistance and G_0 the heat flux in the soil. Out of these variables α_0 and T_0 can be measured with remote sensing, so a simplified estimator f_2 is established:

$$\{\alpha_0, T_0\} \xrightarrow{f_2} \{\mathrm{LE}\} \quad (4)$$

The remaining variables have to be measured or estimated. The scope of this approach depends on the linearity of f_2 and on the sensitivity of LE to variations in the remaining variables.

Actual evaporation is surveyed by mapping the latent heat flux term with surface reflectance and surface temperature measurements done by means of radiometers on-board meteorological and earth observation satellites. Supplementary ground measurements are performed to obtain the variables which cannot be measured in this way.

Results and conclusions

In Fig. 4 a cross-section of an LE image is given. This cross-section correctly accounts for the evaporation being negligible in the dunes and on the rocks. Furthermore a decrease in evaporation from the wetter southern boundary to the drier northern boundary of the playas is seen.

An important advantage of satellite measurements is that the entire study area can be covered at a reasonable cost. The usual approach to calculate actual evapotranspiration on behalf of hydrological studies is by identifying and mapping landuse units, calculating the specific actual evaporation of each unit and, finally, obtaining total evaporation. This may be misleading as is shown in the following example.

In Table 2 two estimations of total actual evaporation in the Wadi Ash Shati (Libya) are compared. In the study performed by Aquater (1980) the area of playas was established prior to the calculation of evaporation by means of LANDSAT imagery interpretation and knowledge of morphology. The air-borne survey performed by Aquater included just a part of the playa area, and only this part of the playas was used to estimate the groundwater losses. The method applied by Menen-

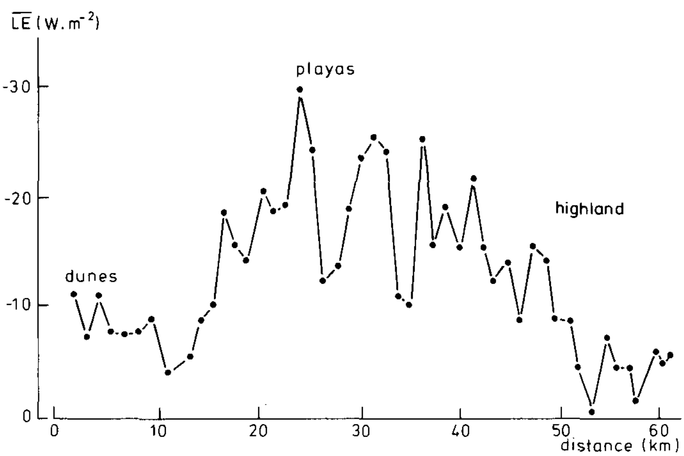

Fig. 4. Cross section of an image depicting the areal pattern of the mean latent heat flux (LE) as calculated by combining satellite and ground reference measurements. The Heat Capacity Mapping Mission data used were collected on 16 and 18 September 1978 (after Menenti, 1984).

Table 2. Comparison of two studies on evaporation losses from the playas in the Wadi Ash Shati basin in Libya.

Source	Area of evaporation (km^2)	Evaporation ($mm\ a^{-1}$)	Evaporation losses ($m^3\ a^{-1}$)
Menenti (1984)	3800	220	8.5×10^8
Aquater (1980)	194	400	0.8×10^8

ti (1984) was based on images taken by the Heat Capacity Mapping Mission satellite. The measurements in this case covered a much larger area and mapping of LE within this area makes preliminary assumptions regarding the land-use units relevant for the calculation of actual evaporation unnecessary.

The presented results show that hydrological applications of satellite remote sensing are quite apt to deal with the intrinsically regional character of groundwater management in deserts. Especially when finite-elements simulation models are applied, mapping of actual evaporation is useful in establishing shape and size of the elements.

Conclusions and perspectives

Operational applications of remote sensing in water management

In future the application of remote sensing to water management will be enhanced by the standardization of data analysis techniques. A typical example is mapping of land-use and of crop types. Here the issue is not the feasibility of the remote sensing technique, but its cost-effectiveness in the framework of a practical application, such as irrigation water management. Remote sensing measurements clearly are cost-effective when they can directly be fed into current management procedures. If organizational and technological improvements are needed, for instance in an irrigation district, it is very difficult to assess the cost-effectiveness of the newly available information.

More specifically one has to establish for each type of water management application a trade-off between:
a) the required performance of a water management system, with the marginal cost increasing with performance; and
b) the cost of a particular remote sensing application, of which the cost increases with decreasing picture element size.
The choice of this trade-off is further complicated by the difficulty of relating performance to benefit in monetary terms.

Since it is impossible to solve theoretically the issues mentioned above, the detailed operational aspects of remote sensing applications will have to be defined by a stepwise approach through case studies.

Theoretical versus experimental research in remote sensing

Strictly speaking, remote sensing is an indirect technique since radiances are measured rather than the variables needed for applications. It is, therefore, necessary to establish and validate schematic descriptions (models) of earth surface processes to relate the remotely measured radiances to the variables needed for a specific application.

Much effort has been dedicated in the past to develop theoretical models for the analysis of remote sensing measurements. Sophisticated theoretical models, however, can hardly be applied in practice, because of excessive data requirements. The general approach to overcome this problem is by tentatively establishing simplified models and then validating them by means of experiments.

Experimental research at field-plot scale, however, is only a partial remedy, since it relates to oversimplified natural conditions. To develop practically useful remote sensing techniques, more complex situations, i.e. case studies, have to be dealt with. Field plot experiments will remain useful to demonstrate the sensitivity of the remotely measured radiances to individual changes in surface processes.

In the near future priority in experimental remote sensing research is likely to be given to the case studies. Shortcomings of simplified models will become apparent and will eventually be solved by studying complex natural conditions.

Remote sensing applications in the Netherlands

In the Netherlands we have to deal with intensively used agricultural land. Conflicting interests often occur between agriculture, nature and public water supply. For decision making regional simulation models are used. Validation of model calculations and determination of spatial variability is difficult and time-consuming with conventional methods. Remote sensing with aeroplanes is very promising in this context. It can provide detailed information at flight days about land-use and crop water supply. This information is relevant in establishing a compromise between the different interests.

The application of aeroplane and satellite remote sensing in practice will depend on the availability of useful and payable images. For the time being application of remotely sensed scanner images in humid regions with intensive land-use as in the Netherlands will mainly depend on remote sensing images taken from aeroplanes. As such images are rather expensive remote sensing can only be cost-effective if images are used for more purposes, such as drought damage detection, determination of crop water use, and mapping of vegetation and soil.

Remote sensing applications in developing countries

Remote sensing is often presented as a quick-fix solution to improve water resource management in developing countries. We have already emphasized that much remains to be done to streamline and expand current remote sensing applications. An additional complication with remote sensing applications in developing countries is the local infrastructure and scientific environment. One has to establish the best possible compromise between the practical aspects specific of each technique, the scientifically established limits of models and the capability of local infrastructure to accommodate the techniques.

Much pressure is being put on the remote sensing community to fully develop the operational potential of the technique. To reach the operational stage in a shorter time, especially with respect to developing countries, the transfer of know-how will have to be combined with the case-study type of experimental research.

After the great optimism in the first 10-years of remote sensing research, the coming years will be devoted to gradually attuning the techniques to the physical aspects of earth surface processes and to the practical constraints set by existing water management systems.

In the near future remote sensing will become an essential component of water management in developing countries. The trade-off mentioned above between performance and data collection will tilt on the remote sensing side, because hydrological data are usually scarce and the performance of water management systems is often unsatisfactory. The increased information made available through remote sensing will allow improvements in performance at relatively low marginal costs.

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