Thermal satellite scenes in modelling soil humidity for single event modelling of wind erosion

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Abstract— **Soil moisture remains one of the most important indices influencing soil resistance to the shear forces of dropping and flowing water or blowing wind. Physically based models as well as experiments at various spatial and time scales confirm that firmly. There is however a major obstacle in wide utilization of soil moisture information in wide-area erosion intensity monitoring - the availability of reliable data sources. The research described in that paper is aimed at finding a reliable methodology for the estimation of current moisture of the topsoil, which can be than used to estimate potential or actual erosion rates at given erosive factors' intensity and duration. Thermal satellite imagery was chosen as source of data for soil humidity. Algorithms were developed for combining scenes from different satellites were developed aiming at achieving maximum temporal and spatial resolution of the output data. A NDTI model for transforming the thermal band images into soil humidity rasters were developed basing upon thermal inertial model. The models were validated with manual on ground measurements of soil humidity using high accuracy TDR soil moisture meter, revealing relatively good fit of the developed models with correlation coefficient at the level of R^2=0,41. A simple wind erosion model was chosen to demonstrate the usage of the soil moisture data overlaid with soil and land use maps. However the method of estimating the temporal soil moisture has a bigger application potential, eg. in single event soil erosion models, plant water deficit estimations and defense.**

I. Introduction

Soil moisture remains one of the most important indices influencing soil resistance to the shear forces of dropping and flowing water or blowing wind. Physically based models [12] as well as experiments at various spatial and time scales confirm that firmly. The results of our experimental research, performed in controlled micro-plot conditions, show high correlations between soil humidity in its upper layer and the rates of both wind [16] and water erosion [17]. There is however a major obstacle in wide utilization of soil moisture information in wide-area erosion intensity monitoring - the availability of reliable data sources. In case of Poland, similarly to whole Northern Europe, where soil cover tends to be highly variable due to the spatial diversity of post-glacial soil substrates, measuring soil moisture physically is not a realistic option, especially as interpolation methods are not reliable enough considering low density soil moisture monitoring stations not covering a representative set of soil units. The monitoring of the dynamics of soil moisture induced by precipitation remains equally difficult. While the average distance between meteorological stations within Poland national weather monitoring grid is ca 70km, the size of an average storm cloud remains at the level of few kilometers, hence using a simple linear interpolation of even geostatistics do not provide results reliable enough for the soil moisture to be effectively modelled based upon the climatic water balance or other models of water balance. The potential solution for wide-area and relatively frequent monitoring of soil moisture remains satellite imagery. This paper will present an exercise of modelling soil moisture content based upon thermal satellite images and its use in the modeling of single event events of wind erosion.

II. Soil moisture model for thermal satellite imagery

A. Available models

The models suitable for the estimation of soil humidity basing upon the thermal satellite images can be divided into two groups:

1. Thermal balance models utilizing the effect of stronger warming of areas with water deficit in soil caused by limited real evapo-transpiration (transpiration has cooling effect on the surface);
2. Thermal inertial models basing upon the fact, that wet areas warm up and cool down slower than dry areas, because of the water's large heat capacity, which corresponds to the daily amplitude of temperature being inversely proportional to soil humidity.

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For the thermal balance models the starting point of the equations is the thermal balance of the surface of crop cover as a consequence of the energy conservation principle in a time unit. These models can be divided into two categories differing in the representation of surface as one or two layer models [10]. In the one-layer models the surface of plant and soil is treated as a single uniform layer. Two-layer models the temperature of soil and plant cover is separated into two surfaces, dependent from each other.

In the one-layer category the most popular models are [10]: SEBS (Surface Energy Balance System) [13], SEBAL (Surface Energy Balance Algorithm for Land) [3, 4] and METRIC (Mapping EvapoTranspiration at high Resolution with Internalized Calibration) [1].

In the realm of two-layer models the most widely used models are [10]: TSEB - Two Source Energy Balance [5, 8], ALEXI – Atmosphere-Land EXchange Inverse [2] and DisALEXI – Disaggregated ALEXI [6, 9].

A separated group of models related to the thermal balance model, but based upon empirical observations are models based upon a cloud of points within a coordinate system of two axes: one is surface temperature (Ts) or its function and second is a vegetation index, eg. most frequently used NDVI (Normalized Difference Vegetation Index). Among this group, the most popular models are: triangular model (Ts/NDVI), NDTI (Normalized Difference Temperature Index), SWSI (Crop Water Stress Index) and S-SEBI (Simplified Surface Energy Balance Index (chart of Ts/albedo) [11].

Thermal inertial models are not that frequently used as thermal balance models. Their application as explanatory models for thermal satellite scenes has one large disadvantage. The models assess the dynamics of temperature change in two time intervals in a single day, eg. day and night, which is very hard to achieve in existing satellite systems, which have either frequent reacquisition time and low resolution or high resolution and long return time (see tab. I for free data source options).

TABLE I. SOURCES OF FREE SATELLITE IMAGES IN THERMAL BAND

Satellite	Sensor	Spectral resolution Number of TIR bands, wavelengths	Spatial resolution [m]	Temporal resolution [days]
Terra	ASTER	5 (8,5-11,6 μm)	90	16 on demand
Terra, Aqua	MODIS	16 (3,7-14,4 μm)	1000	2 (day and night) automatic
Landsat 8	TIRS	1 (10,3-12,5μm)	100	16 automatic
Landsat 7	ETM+	1 (10,4-12,2μm)	60 (od 31.05.2013 partially corrupted – 22% of a scene)	
NOAA	AVHRR/3	2/3 (3,5-12,5 μm)	4000	2 (day and night)
ENVISAT	AATSR	3 (3,7-12 μm)	1000	2 (day and night)
Meteosat 8, 9, 10	SEVIRI	8 (3,5-14,4 μm)	3000	0,01

As the combination of high spatial and temporal resolutions and in practice not possible to achieve in a single thermal satellite product an algorithm of combining scenes of high spatial and low temporal resolutions with ones with high temporal and low spatial resolutions. The refining algorithm bases upon a comparative analyses with archive and current precise scenes as reference and correction layers, the agricultural-soil map as the reference for spatial variability of soils' hydrological features and current low spatial resolution but frequent scenes.

B. *Validation of the scene combination algorithm*

The algorithm for the estimation of current soil humidity was validated on a sample are of Bystra river catchment in South-Eastern Poland. 23 locations for soil sampling were chosen: 12 on ploughland, 6 on grasslands, 1 on abandoned land and 5 in the forests. Urban areas , waters and water wastelands were not considered.

Soils investigated are: sands, loams, silts, rocks and organic peat.

The validation was done through comparison of soil humidity, measured with a TDR sensor with values predicted by the NDTI model applied on thermal satellite scenes disaggregated with the refining algorithm. The validation revealed relatively good fit between models and observed soil moisture values, where R^2 = 0,41 while there were no data filtering applied on extreme values. The results for satellite scenes are still higher than for the simple profiling soil moisture sensors widely used in practice eg. for irrigation management.

III. APPLICATION OF SATELLITE DERIVED SOIL MOISTURE DATA IN THE ESTIMATION OF EROSION INTENSITY

One single event was chosen as an example.

The calculations are basing upon empirical models developed in controlled conditions of simulated wind. The inputs were:

- Soil moisture layer based derived form a desegregated thermal scenes of MODIS;
- Soil texture derived from agricultural soil map 1:25000 and linked with the IUNG database of reference soil samples;
- Land use structure derived from a LANDSAT 7TM scene;
- Wind occurrence were derived from IUNG meteorological stations in Pulawy, Rogalow and Palikije.

Very simple model was chosen for this example. The equation for wind erosion in threshold wind speed was assessed using equation [17]:

$$D = 19{,}73 + 0{,}241998 \bullet Fp - 1{,}211924 \bullet W + 39{,}11221 + 0{,}1 \bullet Fp + 55{,}32836 \bullet W \quad (1)$$

where:

D-deflation [g•h•m -2];

Fp- content of sand fraction in soil [%];

W- initial soil humidity [%].

Soil agricultural map and land use map derived from Landsat 8 were used as a reference for the spatial distribution of sand content in soils and locations of land not being ploughed, which is excluded from the study. The event of March 2013 was chosen, where winds of 8m/s were blowing for 2,5 hours.

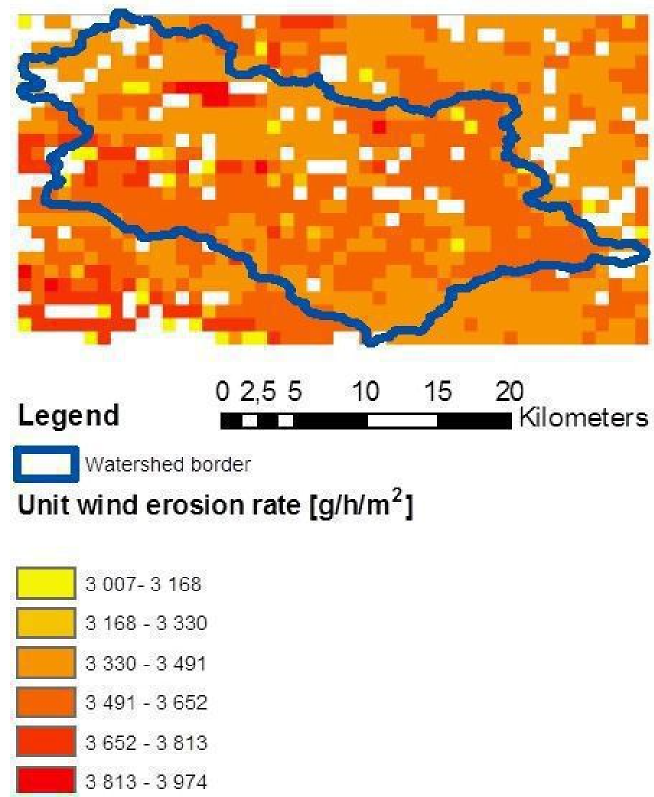

Figure 1. Unit deflation rates on agricultural ploughed land for the event on March 17th 2013

IV. CONCLUSIONS

The NDTI model to transform thermal satellite bands into the spatial datasets of soil humidity has underwent initial validation, revealing relatively high R square at the level of 0,41. The algorithm for combining various sources of thermal scenes into a source for NDTI calculation increases the spatial and temporal resolution of the data sources.

The method for remote estimation of current soil moisture has potentially a wide range of applications, going beyond the example wind erosion rate calculations. Many single event models addressing erosion and geomorphology [12, 14] utilize soil moisture information, which is usually hardly available for wider geographical extents. Another possible domains, where the algorithms of NDTI me be of use use are agriculture (calculation of plant water deficit) [7] and defence (estimating terrain trafficability through calculation of soil bearing capacity for military vehicles) [15].

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