AN APPROACH TO DYNAMIC TRAFFICABILITY MAPPING AS A COMPONENT OF BATTLE MANAGEMENT SYSTEMS

Rafal Wawer, Eugeniusz Nowocien, Artur Lopatka

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Trafficability remains a key issue for operations in the battlefield. The majority of published works focus on either terrain trafficability or on vehicle mobility over terrain. Vehicle mobility, which focuses on the dynamics of track-wheel-terrain interactions (Shoop 2001, p. 69), predicts either a vehicle's performance on various terrains (Zheng-Dong, Perkins 1999; Sullivan, Anderson 2003, p. 45) or estimates the consequences of the vehicle's passage over terrain. Terrain trafficability focuses on the ability of the terrain to sustain the transport of military vehicles (e.g. Field Manual FM 5-430-00-1, 1994; Slocum et al. 2003).

A detailed and thorough analysis of a terrain's ability to sustain military transport facilitates decision making at the operational level, both in selecting the optimal path for one's own troops, as well as for predicting the movements of the enemy. The manual methods of estimating existing soil trafficability (Field Manual FM 5-430-00-1, 1994) are time consuming, provide imprecise results, depend strongly on the experience of the officer in the field conducting the analysis, and finally carry the risk of revealing the potential transport path to the opponent

In 2002 extensive research was undertaken in order to develop a methodology for the rapid development of up to date trafficability maps to be used at the operational level, and a set of base maps, which could be used at strategic level.

The output had to fit the following criteria:

- Every vehicle type used in the Polish Military Forces should be covered by the study;
- The influence of meteorological phenomena on trafficability should be clearly defined;
- The algorithms should incorporate the database of military vehicles;
- Trafficability must be unambiguously defined, and be based on soil humidity data;
- Trafficability should be assessable even without the data of immediate soil humidity.

A Method for Determining Soil Trafficability at the Strategic Level

Country-wide agricultural soil maps were used as the main reference for soil cover. The spatial dataset was created by digitizing the traditional soil maps, which had been created by the Institute of Soil Science and Plant Cultivation - State Research Institute during its country-wide soil classification and mapping endeavour in the 1960's and 1970's. The mapping resulted in the creation of 1:5000 soil maps, which covered the entire country. The soil map is supplemented by a spatially georeferenced database of reference soil profiles, and is characterized by numerous variables reflecting texture (measured in the lab using hydrometric methods), soil type, habitat, location in landscape, slope, hydrological features, etc. From the 1:5000 map, the 1:25,000, 1:100,000 and 1:500,000 soil maps of Poland were created. As of 2002 the largest scale of the soil maps available that had been digitized into a spatial GIS dataset was the 1:100,000 soil map. That particular scale range is obviously not suitable for tactical operations, which is why the first aim of the study was to create maps at the strategic planning level, and to prepare the algorithms for the tactical level.

To achieve the goal of assessing the soil bearing capacity to sustain military vehicles, several experiments and measurements had to be carried out. There is a wide range of data on mechanical soil properties that is available from many sources, and industry normative standards, especially those concerning road building, are also applicable. However, the differences between the definitions of the agricultural and geotechnical soil classifications were too large to directly apply the mechanical properties of the agricultural soil maps to the soil texture classes. It was necessary to carry out several additional laboratory and field experiments in order to assign physical and mechanical indices to the soil textural units.

The threshold values of a soil state's limits in relation to its bearing capacity and the ability to sustain overland transport were investigated. Based on the Polish industry standards we measured (the methods were compatible with the EN ISO 14688-1:2002 i EN ISO 14688-2:2004 norms, but Polish soil geotechnical classification were used):

- The bulk and particle density of the soil using direct weight methods;
- The primary and secondary deformation module according to the Polish industry standard BN-64/8931-02;
- The natural soil humidity, using a FP/M sensor at 5 different depths: 0.3–1.5 m every 0.3 m;
- The optimal soil humidity, meant as a value of the maximal compaction of the soil skeleton, according to the Polish industry standard PN-88/B-04481;
- The passive capillarity, based on two phenomena: water adhesion and the superficial tension of water;
- The compaction ability of soil under static and dynamic loads;
- Indirect soil cohesion, providing categorization into 4 classes: loose soils and 3 classes of cohesive soils, based on the plasticity indicator;
- The soil state humidity thresholds, according to the Polish industry standard PN-B-02480:1986:
    - The fluidity threshold, based on standard experiments carried out using the Casagrande apparatus according to the Polish industry standard PN-88/B-04481;
    - The plasticity threshold, based on a standard rolling test;

The soil state thresholds were then used to calculate the degree of plasticity I_L:

$$I_L = (w_n - w_P) \cdot (w_L - w_P)^{-1}$$

where:
w_n – natural humidity;
w_P – plasticity threshold;
w_L – fluidity threshold.

Describing the physical state of the soil (Wilun 1987, p. 260) (Fig. 1):

- compact: $I_L < 0$ and $w_n \leq w_S$;
- semi-compact: $I_L < 0.$ and $w_S < wn \leq wp$;
- hard-plastic: $0 < I_L \leq 0.25$;
- soft-plastic: $0.50 < I_L \leq 1.00$;
- fluid: $I_L > 1.00$, or $w_n > w_L$.

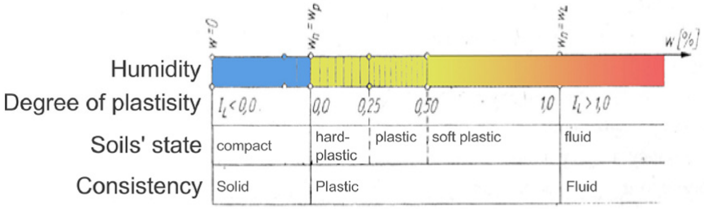

Figure 1. Soil state physical thresholds depending on soil humidity.

Field research was used to ground truth the laboratory results. The experiments were based on three typical military vehicle groups:

1. Overland passenger vehicles and vans with a front axle load of 0.55 Mg up to 4.6 Mg and a rear axle load from 0.57 Mg to 8.2 Mg;
2. Heavy transport vehicles with a front axle load of 1.05 Mg to 6.0 Mg and a rear axle load of 1.4 Mg to 2x8.0 Mg;
3. Fighting vehicles (armoured transport, battle infantry vehicles, and tanks) with a mass of 9.7 Mg to 46 Mg, and a ground pressure of 0.045 MPa to 0.09 MPa.

The algorithm for trafficability that was developed as a result of the laboratory and field research was based on three main criteria:

1. Soil texture and soil humidity;
2. Terrain relief;
3. The type of vehicle.

Terrain relief, which is characterized by the terrain slope was derived from the military DEM of Poland.

The trafficability of a soil depends on its current physical state, which is a product of its humidity. At the time of the study there were no wide-ranging datasets, which could serve as a source for estimating existing soil humidity. Hence a general description of the weather conditions in the form of climatic seasons was used. This reflected the typical distribution of rain and evapotranspiration throughout the year for the climatic conditions of Poland.

The decision support algorithm utilizes datasets that are relatively static spatially, with only one of them being dynamic and highly variable in time – soil humidity. The algorithm determines the current features of the mechanical properties of both loose and cohesive soils. In loose soils, humidity influences the compaction rates and the bulk density, whereas in cohesive soils it determines their physical state (solid, plastic or fluid). This is described by the thresholds of plasticity and fluidity, which in physical terms means the volumetric water content, wherein the soil transforms between the states of solid, plastic and fluid. An additional indicator derived from the humidity thresholds is the degree of plasticity, which describes the absolute state of soil consistency.

Methods for Determining Existing Soil Moisture for Tactical Operations

Determining existing soil moisture is a key aspect of the analysis of terrain trafficability for military vehicles. If the game of chess can be used as a metaphor, then a soil map and the terrain may be seen as something akin to a chessboard, and the vehicles are the pieces, each with their own unique battle abilities, but it is the current soil humidity that defines the moves of the pieces. For this research we chose three basic methods:

1. Direct measurement in the field using a manual TDR soil humidity sensor (humidity measured at two depths: 0.3 m and 0.6 m) or an array of wireless sensors with a geo-location feature, distributed across the operation area with e.g. drones or artillery shells;
2. Modelling of soil water balance based on climatic water balance derived from the infrastructure of weather stations;
3. Indirect measurement using remote sensing techniques, in particular freely available LANDSSAT scenes, ERS radar with resolution not lower than 30 m.

Modelling soil humidity

There are many models and decision support systems that are pertinent to estimates of immediate soil humidity and that can be used to model environmental indices (nutrient leaching, erosion rates). These are widely used for agriculture, especially when it is necessary to make a decision in regards to supplementing irrigation. The simplest, and the least demanding models in terms of data are those that are based on the climatic water balance, which is the difference between the inflow and outflow of water from the soil pedon (Arnold *et al.* 1990, p. 230):

$$SW_t = SW_0 + \sum_{i=1}^{t} (R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw}),$$

where:

SW_{t} – the temporal water content of the soil [mm H_2O];

SW_{0} – the water content of the soil at the starting point [mm H_2O];

t – time [days];

R_{day} – the amount of precipitation in a day [mm H_2O];

Q_{surf} – the amount of superficial runoff in a day [mm H_2O];

E_{a} – the amount of evapo-transpiration in a day [mm H_2O];

w_{seep} – vertical percolation in a day [mm H_2O];

Q_{gw} – horizontal subsurface runoff in a day [mm H_2O].

Precipitation and initial soil humidity are the only measurable variables for these kind of models. Runoff can be easily determined by modelling the current soil humidity and terrain slope of each of the soil texture classes. The remaining variables for percolation and subsurface outflow depend strongly on the terrain relief and the composition of the deeper soil horizons, hence the results expose high uncertainty.

Modern models are able to forecast soil humidity based on advanced weather forecasting models, e.g. ENORASIS. This is the best option for estimating soil humidity over larger areas.

Deriving immediate soil moisture from satellite thermal bands

An estimation of the soil moisture is a crucial factor in creating a correct and timely assessment of existing soil trafficability. There is, however, one major impediment to using soil moisture information to ascertain trafficability for a wide area – the poor availability of reliable data sources. In the case of Poland, which is similar to all of Northern Europe, the soil cover tends to be highly variable due to the spatial diversity of post-glacial soil substrates, and physically measuring the soil moisture is not a realistic option, especially as the interpolation methods are not reliable enough, and the low density soil moisture monitoring stations do not cover a representative set of soil units. Monitoring the dynamics of soil moisture induced by precipitation is equally difficult. While the average distance between meteorological stations within the Polish national weather monitoring grid is ca 70 km, the size of an average storm cloud is usually only a few kilometres, so simply using a basic linear interpolation (even geostatistical methods) will not provide reliable enough results for the soil moisture to be effectively modelled based on the climatic water balance, or provide accurate results for any other models of water balance. Therefore, satellite imagery is the only potential solution that would allow for the relatively frequent monitoring of a broad area.

The suitable models for estimating soil humidity based on thermal satellite images can be divided into two groups:

1. Thermal balance models that utilize the effect of stronger warming of areas with a water deficit in the soil that is due to limited real evapo-transpiration (transpiration has a cooling effect on the surface);

2. Thermal inertial models which are based on the fact that wet areas warm up and cool down more slowly than dry areas, due to the high thermal mass of water, and which correspond to the daily amplitude of temperature being inversely proportional to soil humidity.

For the thermal balance models, the starting point of the equations is the thermal balance of the surface of the crop cover as a consequence of the energy conservation principle in unit time. These models can be divided into the categories of one layer models, and two layer models, with each of the two categories differing in their representation of the surface. (Petropoulos 2014) In the one-layer models the surface of plant and soil surface is treated as a single uniform layer. In the two-layer models the temperature of soil and plant cover is separated into two surfaces, which are dependent on each other.

In the one-layer category the most popular models are (Petropoulos 2014): the SEBS = Surface Energy Balance System (Su Z 2002), the SEBAL = Surface Energy Balance Algorithm for Land (Bastiaanssen *et al.* 1998a, 1998b) and the METRIC = Mapping EvapoTranspiration at high Resolution with Internalized Calibration (Allen *et al.* 2007).

The most widely used two-layer models are: (Petropoulos 2014): the TSEB = Two Source Energy Balance (Norman *et al.* 1995, French 2002), the ALEXI = Atmosphere-Land EXchange Inverse (Anderson *et al.* 1997) and the DisALEXI = Disaggregated ALEXI (Kustas *et al.* 2003, Norman *et al.* 2003).

A separate group of models related to the thermal balance model, but which are also based on empirical observations, are those that make use of point clouds within a coordinate system of two axes: one being surface temperature (Ts) or its function, and the second being the vegetation index. Of these, one of the most frequently used is the NDVI (Normalized Difference Vegetation Index). Also among this group, the most popular models are: the triangular model (Ts/NDVI), the NDTI (Normalized Difference Temperature Index), the SWSI (Crop Water Stress Index), and the S-SEBI (Simplified Surface Energy Balance Index (chart of Ts/albedo) (Roerink *et. al.* 2000).

Thermal inertia models are not as frequently used as thermal balance models. Their application as explanatory models for thermal satellite images has one big disadvantage. The models assess the dynamics of temperature change at two time intervals within a single day, e.g. day and night, something which is very hard to achieve using the existing satellite systems, as these have either a frequent reacquisition time and low resolution, or high resolution and a long return time (see Tab. 1 for free data source options).

In practice it is not possible to have both high spatial and temporal resolutions within a single thermal satellite product, and an algorithm for combining scenes of high spatial and low temporal resolution with high temporal and low spatial resolution should be used. The refining algorithm is based on a comparative analysis with archive and current, precise scenes as reference, and correction layers, the agricultural-soil map as the reference for spatial variability of soil hydrological features, and the current low spatial resolution with frequent scenes.

Table 1. 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 (10.3–12.5 μm)	100	16 automatic
Landsat 7	ETM+	1 (10.4–12.2 μm)	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

The algorithm used to estimate current soil humidity was validated through a sampling of the Bystra river catchment in South-Eastern Poland. Soil samples were taken from 23 different locations: 12 were from arable land, 6 were from grassland (TUZ), 1 was from an abandoned piece of land, and 5 were from the forest (Ls). Urban areas (Tz), waters (W) and water wastelands (WN) were not considered (Fig. 2).

Soils pl-pgmp are sands; gs, glp, gs and gc are loams; pli, plz and l are silty soils; s is rock; torf is organic peat.

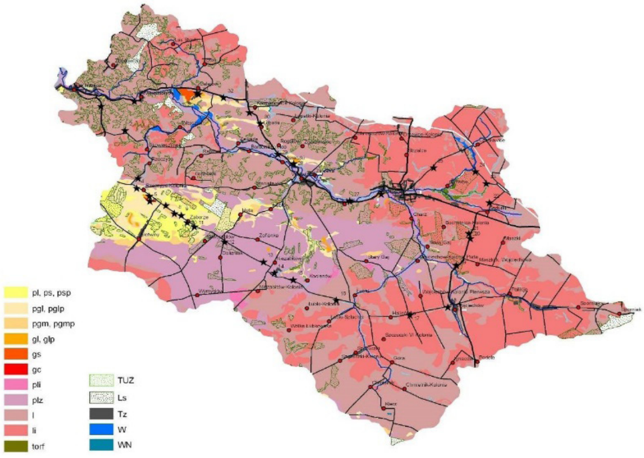

Figure 2. The location of validation points in the Bystra catchment, considering soil cover and land use

The data was validated by comparing the soil humidity, which had been measured with a TDR sensor, with the value predicted by the NDTI model after it was applied to thermal satellite images that had been disaggregated with the refining algorithm. The validation revealed a relatively good fit between the models and the observed soil moisture values, where $R^2 = 0.41$, and no data filtering was applied to the extreme values. The results gathered from the satellite images are still better than those that could be gathered from the simple profiling soil moisture sensors, which are widely utilized, e.g. for irrigation management.

Conclusions

Accurate estimation of soil moisture is a crucial factor in making correct and timely assessments of immediate soil trafficability. As there are no spatial data sources showing soil humidity available for large areas, adaptation of remote sensing methods based on widely accessible satellite images seems to be the easiest and most reliable method for estimating the temporal water content in soils. By using an agricultural soil map with defined soil texture classes as a background, soil humidity can be estimated.

Thermal bands were chosen as the most promising source of spatial information. Two kinds of models were developed: models for the estimation of current soil moisture and models for the disaggregation of satellite images coming from different satellites differing both in terms of spatial resolution and re-acquisition time. An initial validation revealed the R square ratio at the level of 0.41, which is satisfactory when the early stage of the model's development is taken into consideration; however, if it is to be used for actual military operations, then the model still needs fine-tuning and more research is required to improve its estimations.

The current algorithm for estimating soil trafficability for military vehicles is a dynamic and interoperable solution and can be integrated as a component of any battle management system. The algorithm's trafficability prediction may be vastly improved via the use of drones equipped with high resolution thermal optical sensors and may be integrated with online weather prediction services to provide 3-day forecasts for terrain trafficability.

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Introduction of Authors

RAFAL WAWER (Dr. engineer), Researcher, Department of Soil Science and Land Protection, Institute of Soil Science and Plant Cultivation, State Research Institute, Pulawy, Poland.

EUGENIUSZ NOWOCIEN, Researcher, Department of Soil Science and Land Protection, Institute of Soil Science and Plant Cultivation, State Research Institute, Pulawy, Poland.

ARTUR LOPATKA, Researcher, Department of Soil Science and Land Protection, Institute of Soil Science and Plant Cultivation, State Research Institute, Pulawy, Poland.