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# CORRELATIONS BETWEEN TOPOGRAPHIC WETNESS INDEX AND SOIL MOISTURE IN THE PANNONIAN REGION OF CROATIA

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**ABSTRACT:**

The study investigates the relationship between variations of topographic wetness indices, resampled digital elevation model (DEM) resolutions and soil moisture in Croatia's Pannonian region during all seasons. It delves into the spatial distribution of soil moisture, vital for various sectors including agriculture, forestry, ecology, and military. Utilizing topographic wetness index (TWI), the research focuses on resampling high-resolution DEM into coarser resolutions and flow-routing methods concerning in-situ soil moisture measurements. It encompasses the Kaznica River catchment area, characterized by diverse topography and soil types, including fine-grained automorphic and hydromorphic clays. The study extensively conducts field measurements, evaluating soil moisture at various depths (1, 15, 30, and 45cm) across all seasons, cross-referenced with meteorological data. Through an examination of six runoff algorithms and six spatial resolutions, it concludes that the optimal TWI resolution for correlation with soil moisture is 150m at a 30cm soil depth. However, it stresses the necessity of calibrations for precise soil depth, cell resolutions and season. The shallowest soil depth has the lowest correlation coefficients in all periods, while the highest coefficients were achieved in period with the highest soil moisture values. Recognizing the complexity of factors influencing soil moisture, it recommends the integration of additional data sources like remote sensing, other geomorphological indexes, and detailed land cover analysis to enhance the accuracy of predictions.

**Key-words:** *Topographic Wetness Index, Soil wetness, Loess, Digital Elevation Model, Raster cell resolution.*

## 1. INTRODUCTION

Understanding the spatial distribution of soil moisture is one of the fundamental factors for successful management in agriculture, forestry, ecology, and military activities. Land topography significantly influences hydrographic conditions by affecting the spatial distribution of soil moisture, where groundwater runoff typically follows the terrain (Seibert et al., 1997; Rodhe & Seibert, 1999). The hydrographic properties of an area are predetermined by the geological substrate, physical and chemical soil properties, vegetation cover, human activities, as well as climatic and topographic factors. Topography is sometimes the only available data source to predict soil moisture. DEM enables the modelling of land topography (Li & McCarty, 2019), upon which the TWI (also referred to as the compound topographic index) has been developed by Beven & Kirkby (1979) as a component of the runoff model known as TOPMODEL. According to Beven & Kirkby (1979) TWI can be expressed as follows:

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$$\boldsymbol{TWI = ln\left(\frac{a}{tan\,\beta}\right)} \tag{1}$$

where:

$a$ - contributing catchment area (the cumulative upslope area draining through a cell divided by the contour width), usually named as specific catchment area (SCA),

$\beta$ - the local slope.

The SCA represents how prone a location is to receive water from the upslope area, while the local slope characterizes its tendency to drain or evacuate water (Gruber & Peckham, 2009). Therefore, this index acts as a relative indicator of the prolonged soil moisture availability at a specific location within the landscape, maintaining steady-state and spatially consistent characteristics. The TWI is specifically used in humid regions, and it measures the precise locations where lower values signify elevated ridges, while higher values signify the presence of stream channels, lakes, and ponds (Martin, 2017). The accuracy of TWI depends on several parameters, such as the accuracy of input DEM, methods for calculating terrain slope, the size of the studied area, and the size of the raster cell. On the other hand, soil moisture is defined by various factors such as insolation, slope, slope orientation, physical and chemical soil properties, precipitation, soil temperature, evaporation, transpiration, ground cover and groundwater level.

The TWI is usually calculated from gridded elevation data. Different algorithms are used for these calculations. The main differences lie in how the accumulated upslope area is routed downwards, the representation of creeks, and which measure of slope is used. Moore *et al.*, (1991), Wilson & Gallant (2000), Gruber & Peckham (2009), and numerous articles in the 'Hydrological Processes' journal series describe fundamental input parameters, including flow directions and slope computation. These authors delve into diverse flow algorithms, including single flow direction (SFD), multiple-neighbour flow direction (MFD), implications of various contributing areas and considerations of flow width. Nowadays, different variations of algorithms, each with its own approach to calculating flow direction, accumulation, and the subsequent computation of TWI, can be found in off-the-shelf GIS software like SAGA GIS, GRASS GIS, Whitebox GAT, ArcGIS, and ENVI.

As Buchanan et al., (2014) points out the two most common approaches of soil moisture prediction involve: (i) often complex, distributed watershed models that numerically simulate the physical processes governing soil water dynamics or (ii) more simple terrain-based indices based on topography and sometimes soil properties. TWI and other static indices have limitations in predicting soil moisture (Riihimäki et al., 2021), and widespread validation through field observations supporting TWI-based predictions of landscape-scale soil moisture patterns on a large scale is uncommon. Several publications have presented calibrations of parameters and recommendations for improving TWI based on field measurements (Burt & Butcher, 1985; Zhang & Montgomery, 1994; Nyberg, 1996; Crave & Gascuel-Odoux, 1997; Seibert *et al.*, 1997; Schmidt & Persson, 2003; Güntner et al., 2004; Western et al., 2004; Sørensen et al., 2006; Ma et al., 2010; Tague et al., 2010; Ågren et al., 2014; Buchanan et al., 2014; Kopecký et al., 2021; Riihimäki et al., 2021). These studies encourage careful evaluation of algorithms and DEM resolutions when using TWI as a proxy for soil moisture. Field observations revealed a broad spectrum of correlation strengths between parameters (Burt & Butcher, 1985; Nyberg, 1996; Schmidt & Persson, 2003; Western *et al.*, 2004; Sørensen *et al.*, 2006; Tague *et al.*, 2010).

All research findings emphasize the critical need for a highly accurate DEM in studies. However, the optimal TWI grid resolution varies significantly, depending on scale and landscape characteristics. As an example, various recommended resolutions include: 2 m (Riihimäki et al., 2021), 10 m (Zhang & Montgomery, 1994), 24 m (Ågren et al., 2014). Similarly, Seibert et al. (1997), Güntner et al. (2004), and Kopecký et al. (2021) underscore the significance of algorithms as a crucial element for achieving improved outcomes.

The use of TWI for soil moisture prediction holds significant potential across various applications. It allows for the prediction of numerous environmental facets linked to soil, including spatial scale effects on hydrological processes. Additionally, it aids in delineating hydrological flow pathways for geochemical modelling and characterizing biological processes like annual net primary production, vegetation patterns, forest site quality, and soil pH (Sørensen et al., 2006).

Our research is focused on predicting vehicle cross country mobility where many geographical factors influence vehicle mobility (Heštera & Pahernik, 2018). Soil bearing capacity is one of the fundamental factors of vehicle mobility that has been explored by many authors, among whom it is necessary to highlight Frankenstein & Koenig (2004), Priddy et al. (2012), Rybansky (2015) and Dasch et al. (2016). Due the importance of soil moisture, TWI takes a significant part in vehicle mobility predictions and map production (Kokkila, 2002; Gumoś 2005; Pahernik et al., 2006, Hohmann *et al.*, 2013; Dasch *et al.*, 2016; Nazish Khan et al., 2021). Onwards Heštera (2021) established strong correlation links between TWI, soil moisture, and Cone Index.

This work is not focused on the development of TWI per se, but rather on determining the suitable resample degree of high-quality DEMs resolution for a SCA, during seasons, and *in-situ* measurement of soil moisture at specific soil depths, using various drainage algorithms. This research aims to enhance current understanding of vehicle terrain trafficability, seeking more precise information regarding soil moisture based on parameter relationships and measured values within the research area. Moreover, the findings could be extended to encompass a wider area within the Pannonian region of Croatia, where soils share similar characteristics.

## 2. STUDY AREA

The research area covers the catchment area of the Kaznica River (117.6 km$^2$), located in the eastern part of the Republic of Croatia, specifically in the central part of Slavonia (**Fig. 1**). The surface layer is dominated by Quaternary deposits (loess) of Pleistocene age and young alluvial deposits of Holocene age (Bognar, 1978) (**Fig. 2e**). In geomorphological terms, the area (elevation ranging from 95 m to 263 m, with mean 141 m) can be divided into three distinct units, namely, the loess plateau, the hills of Krndija and Dilj, and the terrace lowlands. According to Gravellius (1914), this watershed has a compactness index of 1.56, which refers to a basin that is very regular or compact in shape. Based on the classification according to the method of soil water level (Husnjak, 2014), this area contains automorphic and hydromorphic soils (**Fig. 2b**). Soils are mildly developed with deep pedon (eolian and suffusion origin) and according to USCS soil type they can be classified as fine-grained soils (Heštera, 2020; Heštera et al., 2023). The length of the watershed is 21.6 km and tributaries of the Kaznica River (part of the Sava River basin) are characterized by numerous longer and shorter intermittent stream valleys of erosion-derasion type, which do not have permanent sources and therefore dry up during the summer. The hilly areas are covered with forests, while the valley and loess plateau are mostly converted into agricultural land (**Fig. 2d**). According to the Köppen climate classification, the climate of this area is marked as "Cfwbx" (Zaninović et al., 2008).

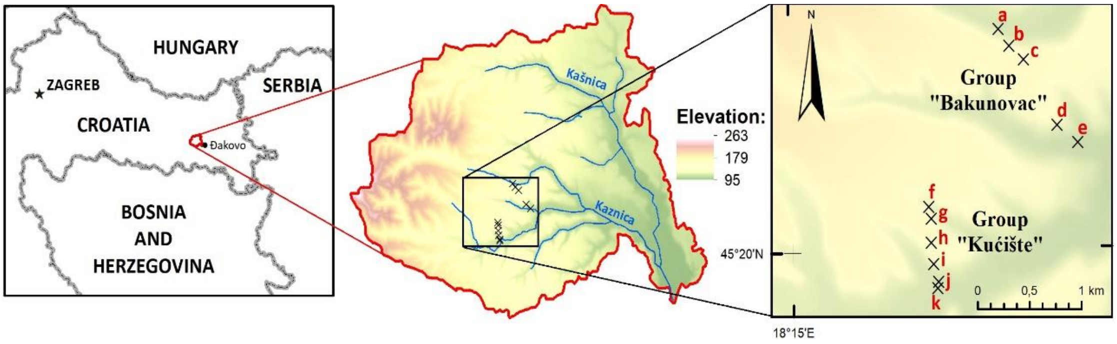

**Fig. 1.** Research area with soil moisture measurement locations.

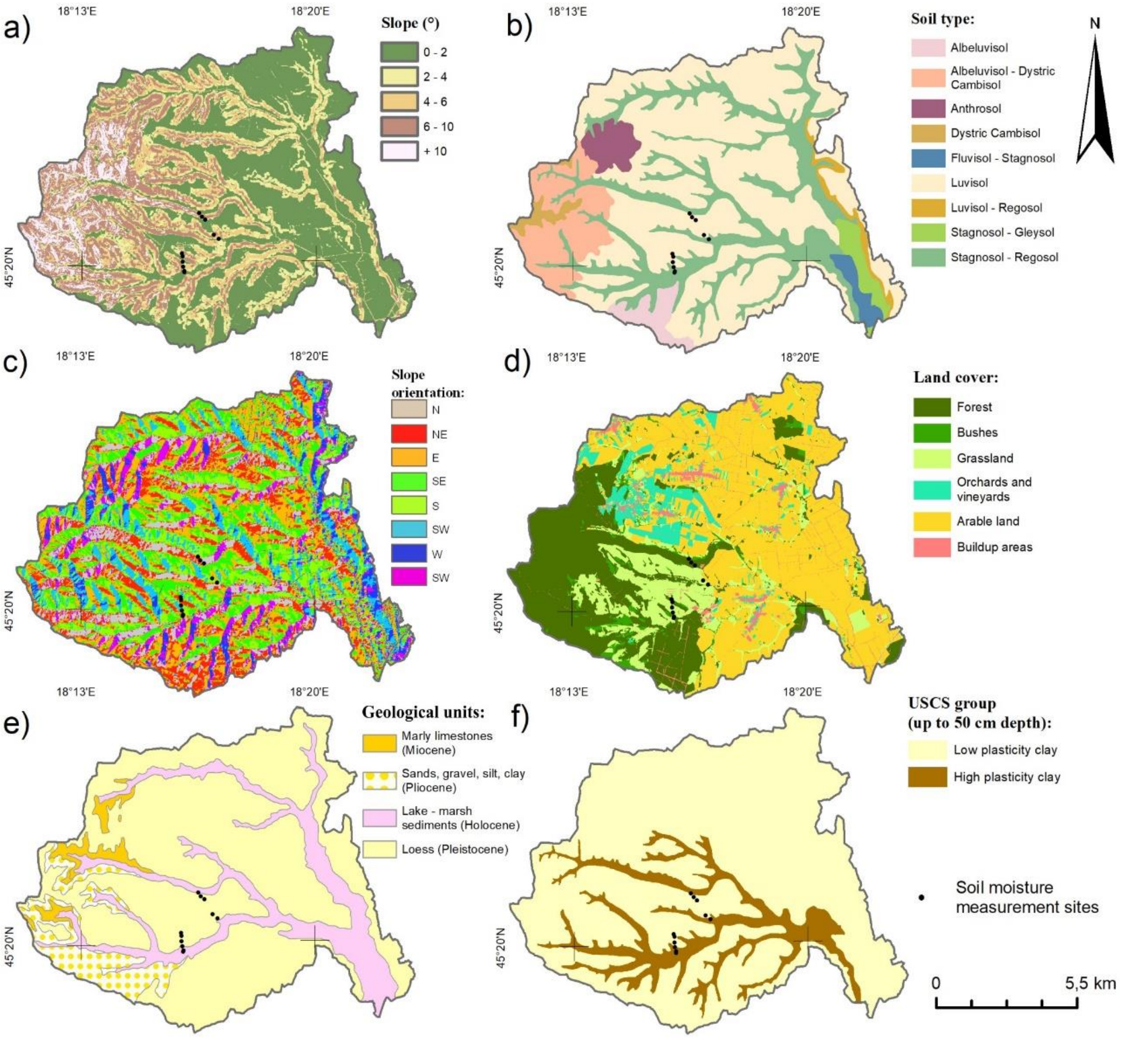

**Fig. 2.** Research area: a) terrain slope, b) pedological map, c) slope orientation, d) land cover, e) geological map, and f) USCS soil group.

## 3. DATA AND METHODS

### 3.1. Soil moisture measurements

It should be noted that, in addition to measuring soil moisture, simultaneous measurements of cone index, soil temperature, and soil shear strength were conducted (Heštera, 2021) for the purpose of researching vehicle cross country mobility. These measurements were based on the idea of using selected locations as representative samples of the entire research area. To this end, locations with heterogeneous physical and geographical characteristics were chosen (**Fig. 2**, **Table 1**). During locations selection process, there were certain limiting and conditional factors:

i) Locations had to be on public land, not on private property.
ii) Locations had to be shielded from "external" influences.
iii) Locations had to be within the boundaries of the military training ground "Gašinci".

iv) The measurements at the locations should not disrupt other activities on the military training ground; therefore, locations on the outskirts of the training ground were selected.

A total of 7 five-day measurements (a total of 35 days) were conducted at 11 locations, at 4 soil depths (a total of 1540 individual measurements) during year 2019. Soil moisture measurements were performed using the "ML3 ThetaProbe" soil moisture probe. Probe measures soil moisture content based on the conductivity of current between four metal needles inserted into the soil. The results are within a resolution of ±1% volumetric water content in the soil (User Manual for the ML3 ThetaProbe, 2013). During its use, the probe was connected to the housing of the digital cone penetrometer "Penetrologger" from Eijkelkamp, which recorded the measurement results. Data preparation for further analysis was conducted in the "PenetroViewer 6.08" software.

Soil moisture measurements were carried out at depths of 1 cm, 15 cm, 30 cm, and 45 cm (**Fig. 2**). Holes for soil moisture measurement were manually drilled to the specified reference depths. The measurement site covered an area of 20 m$^2$, to avoid the possibility of previous sample boreholes affecting the results of future samples, a new borehole was made for each sample within a radius of 2.5 meters from the defined coordinates. The selection of measurement times was based on representative climatic periods throughout the year 2019 (Jones et al., 2005). Two sets of five-day measurements were conducted during climatological winter (February 25 - March 1 and December 16 - December 20), spring (March 11 - March 15 and April 30 - May 4), and autumn (November 15 - November 19 and November 25 - November 29), and one five-day measurement during summer (August 26 - August 30). The locations were divided into the "Bakunovac" and "Kućište" groups. The measurements at each group (6 locations each) took between 2.5 to 3 hours. Initially, measurements were planned for and conducted at 12 locations, but one location in the "Bakunovac" group was excluded due to significant parameter deviations. Therefore, the analysis included a total of 11 locations. The daily measurement schedule was designed such that measurements in the "Bakunovac" group began at 8:00 AM, and in the "Kućište" group at 3:00 PM.

**Table 1.**

**Physical-geographical characteristics of sampled locations.**

| Location ID | Slope (°) | Soil type (World Reference Base for Soil Resources) | Slope orientation | Land cover | Altitude (m) | Catchment area (km$^2$)* |
|---|---|---|---|---|---|---|
| a | 5.7 | Luvisol | NE (24°) | Forest | 122 | 0.23 |
| b | 8.2 | Luvisol | N (20°) | Forest | 133.5 | 0.15 |
| c | 2 | Luvisol | NE (41°) | Forest | 143 | 0.11 |
| d | 4 | Luvisol | S (175°) | Grassland | 130.3 | 0.17 |
| e | 2 | Stagnosol - Regosol | SE (157°) | Grassland | 114.5 | 0.06 |
| f | 2 | Stagnosol - Regosol | E (78°) | Forest | 130 | 14.4 |
| g | 5.6 | Luvisol | NE (46°) | Bushes | 135.6 | 0.12 |
| h | 2.7 | Luvisol | S (182°) | Grassland | 142.1 | 0.04 |
| i | 6.4 | Luvisol | SW (211°) | Grassland | 129 | 0.17 |
| j | 2.5 | Stagnosol - Regosol | S (188°) | Grassland | 119.1 | 0.15 |
| k | 0.8 | Stagnosol - Regosol | W (262°) | Forest | 118 | 590.43 |

**Areas are calculated on TWI with a 30 m resolution using the DETINF method.*

### 3.2. Digital elevation model

The DEM was generated using ArcPro 2.9.1 software. The utilized data were (HTRS96/TM coordinate system) part of the CRONO GIP project (Croatian-Norwegian geoinformation project), which collected input elevation data from aerial imagery at a scale of 1:20,000 and other sources (there are no publicly available LIDAR data). A detailed description of the specifications for creation, methods, accuracy, and allowable deviations when creating the DEM can be found in Državna geodetska uprava (2004) and Šimek et al. (2018). The accuracies of the terrain slope at various resolution levels generated from the subject dataset in the research area are presented in Heštera (2021, p. 149).

Based on the original vector data, a Terrain dataset was created. During the creation of the Terrain dataset, the following parameters were defined for generating the basic DEM with a cell resolution of 1 m:

i) Mass points: trigonometric points, benchmarks, and elevation points
ii) Hard lines: roads, pathways, railways, above-ground structures, culverts, shorelines, narrow rivers, narrow channels, streams, and watercourses, linear watercourse features, embankments, and walls
iii) Soft lines: contour lines, ridges, and valleys
iv) Soft clip: the boundary of the research area.

### 3.3. Methods

Before creating the TWI layers at different spatial resolutions and using different runoff algorithm methodologies, input DEM layers were grided from high 1 m resolution DEM. ArcPro 2.9.1 software and the Aggregate tool was used to create layers with different spatial (meter) resolutions (30, 60, 90, 120, 150, and 180), using the mean function in the calculations. The origin (snap) of all raster's was referenced to the lowest resolution raster (180 m) for consistency in grid boundary overlaps (D'Avello et al., 2016). These raster cell sizes (varying by 30 m) were chosen to maintain consistency in the overlap of the grid, thus the maximum raster resolution is 30 m.

In the Whitebox GAT program, the Breach tool was used to breach potential obstacles with settings for lengths up to 200 m and a maximum cut depth of 2 m to remove obstacles, such as bridges, even in the lowest resolution raster. The remaining depressions in the raster were filled using the Fill Depressions tool (Wang & Liu, 2006). SAGA GIS (ver. 7.8.0) TWI (One Step) tool was used to compare runoff algorithms/methods. We chose the most used methods from relevant scientific literature for calculating the SCA. We examined flow distribution algorithms which can be divided into two main categories: SFD and MFD. We tested two SFD algorithms: Deterministic 8 (D8) (O'Callaghan & Mark, 1984) and Rho 8 (RHO8) (Fairfield & Leymarie, 1991) and 4 MFD alogoritms: Braunschweiger Reliefmodell (BRAUNS) (Bauer et al., 1985), Multiple Flow Direction (MFD) (Freeman, 1991), Deterministic Infinity (DETINF) (Tarboton, 1997), Triangular Multiple Flow Direction (MULTRI) (Seibert & McGlynn, 2007) and Multiple Flow Direction based on Maximum Downslope Gradient (MAXGRAD) (Qin et al., 2011).

Using the methods described above, layers of different resolutions and runoff algorithms (a total of 36) were created, and TWI values were spatially associated with the corresponding field locations through spatial analysis. During the spatial analysis, the measured locations always fell within separate cells, because the spacing between sampling points was greater than 180 meters. Correlative factors related to soil moisture were created at the individual daily level and then averaged over the five-day measurement period. Further data processing was carried out in Microsoft Excel, where correlative relationships were compared between cell size, runoff algorithm, soil moisture at four different depths, and soil moisture measurement period.

## 4. RESULTS

**Fig. 3** illustrates the average results of five-day soil moisture measurements at four different depths in the soil. A common characteristic of almost all depth profiles at all locations throughout the year (except in summer) is that moisture decreases with depth. The measurements conducted in the spring recorded the highest soil moisture levels. When summing up the results of all the five-day average measurement results, the period from April 30 to May 4 showed the highest soil moisture levels. In the results of daily measurements, clear amplitude changes were observed only at locations with loess substrates, while on alluvium, the changes were more uniform and less intense.

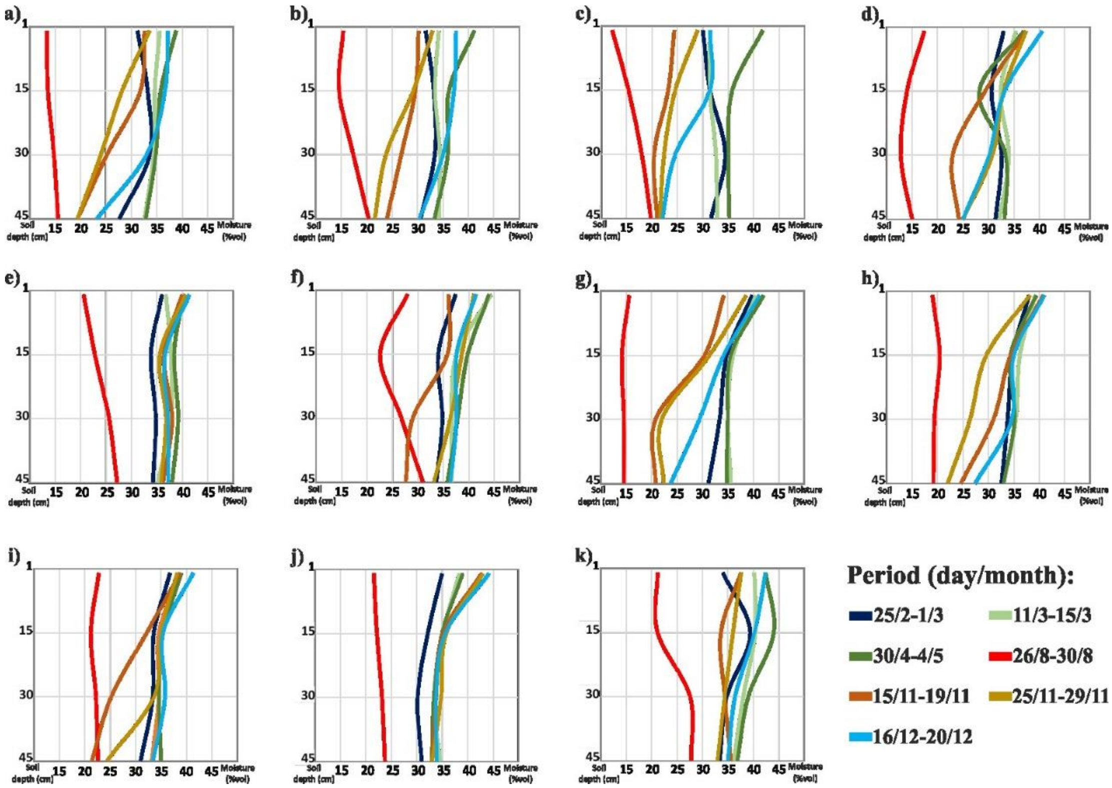

**Fig. 3.** Average values of daily soil moisture measurements by locations (**Fig. 1**) in selected periods in 2019**.**

Daily, weekly, or monthly changes in soil moisture content at different depths depend on numerous factors, with the most significant influences being the amount of rainfall and air temperature. The measured values shown in **Fig. 4** are from the Đakovo measurement station, which is in the immediate vicinity of the research area (2 km to the east).

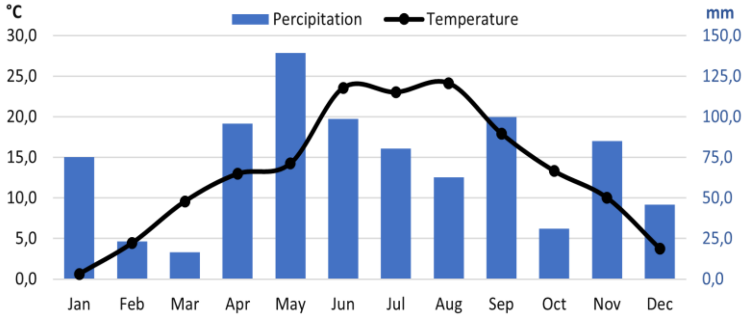

**Fig. 4.** Average monthly precipitation and air temperature in 2019 at weather station Đakovo (*data provided by Croatian Meteorological and Hydrological Service*).

From **Fig. 4**, it is evident that higher soil moisture levels during winter and spring periods are the result of a combination of lower temperatures (0.6-4.4°C) (resulting low evaporation) during winter and significant rainfall during spring (251 mm). On the other hand, lower soil moisture levels during summer and autumn are due to highest summer temperatures (23.0-24.1°C) which cause drying of the measured soil horizons, and the recorded rainfall (216 mm) during autumn was insufficient for significant water infiltration into the soil.

The created TWI layers, observed from the perspective of cell resolution changes, show (**Fig. 5**) that the index amplitudes decrease as the resolution decreases. Comparing the results of the 6 observed algorithms, no significant differences were found.

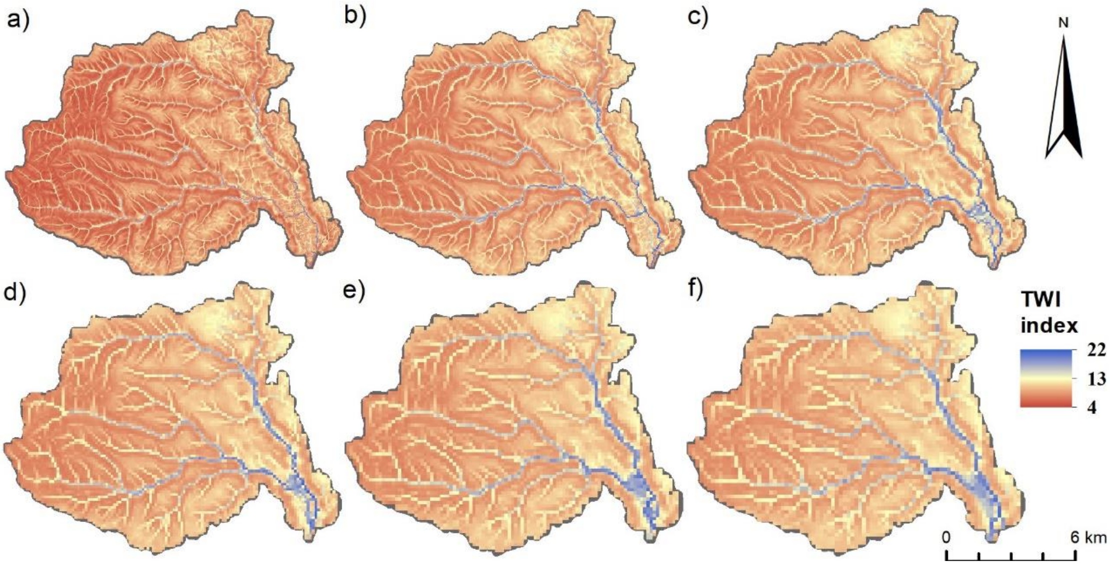

**Fig. 5.** TWI values (MFD algorithm as example) in different raster cell resolution (m): a) 30, b) 60, c) 90, d) 120, e) 150, f)180.

The correlation analysis between cell resolution and other observed parameters is presented in **Fig. 6**. The overall result indicates that the optimal cell size is 150 m ($\bar{x}$ ρ = 0.65). Only the resolution of 180 m (**Fig. 6c**) surpasses this resolution during periods of lower soil moisture (November and December), while the 90 m resolution proved to be the best during periods of the highest soil moisture.

Among the observed algorithms (**Fig. 7**), the highest average correlation coefficient ($\bar{x}$ ρ = 0.59) was achieved by the MFD algorithm. It is important to note the very small amplitude of the obtained results for all compared algorithms, which is ρ = 0.026.

The highest amplitude of the compared parameters is observed in soil moisture with respect to depth (**Fig. 8**), where the depth of 1 cm stands out and has the lowest $\bar{x}$ ρ = 0.41, while the highest $\bar{x}$ ρ = 0.66 is at a depth of 45 cm. When comparing raster resolution and soil depth, the best individual result (ρ = 0.74) was obtained at a depth of 30 cm and a raster resolution of 150 m (**Fig. 8b**). The best result in terms of measurement period was obtained during March at a depth of 15 cm (**Fig. 8c**).

Comparing measurement periods (**Fig. 9**), the highest average result with $\bar{x}$ ρ = 0.68 was obtained in March, while the initial measurement in November had the lowest result with ρ = 0.51.

When comparing other parameters with measurement periods, it's important to highlight that the highest correlation coefficient was recorded with a 150 m resolution during February (ρ = 0.77), while for the other periods, the most suitable cell resolution varies. The shallowest soil depth has the lowest correlation coefficients in all periods, while the highest coefficients were achieved during measurements in March compared to other periods of the year. In periods with the lowest soil moisture content (November and December), the lowest correlation coefficients were recorded (ρ = 0.51-0.54).

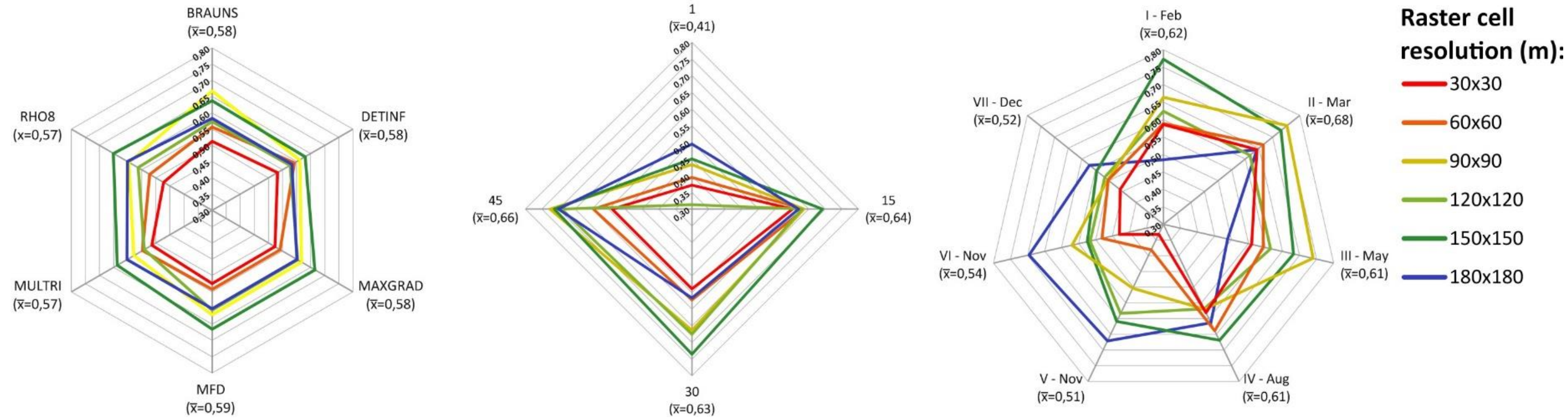

Fig. 6. Correlative relationships (ρ) between raster cell resolutions and TWI algorithm, soil moisture at different depths and different soil moisture measurement periods.

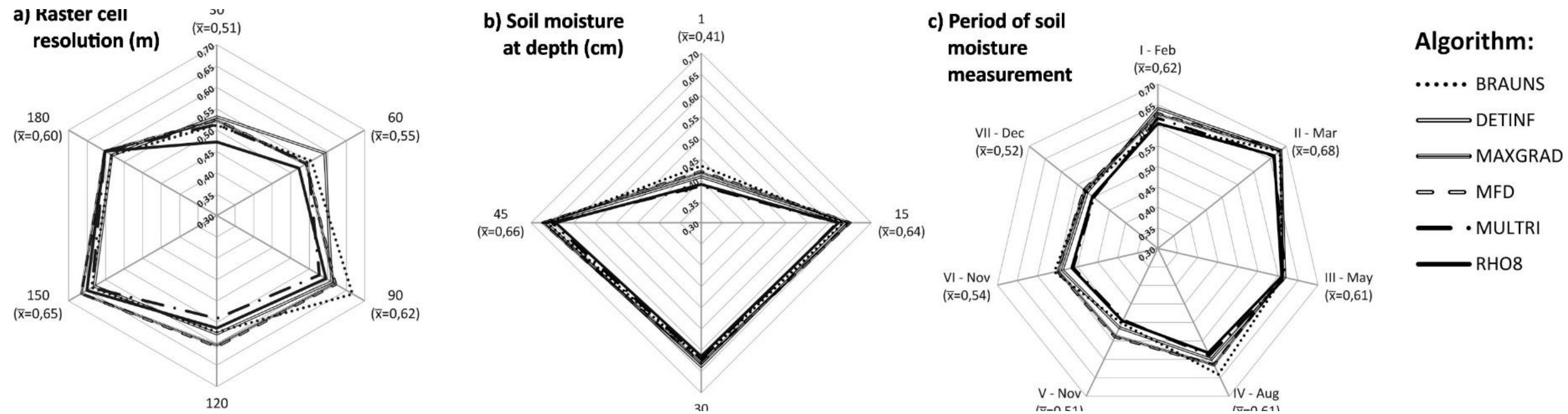

Fig. 7. Correlative relationships (ρ) between TWI algorithm and raster cell resolutions, soil moisture at different depths and different soil moisture measurement periods.

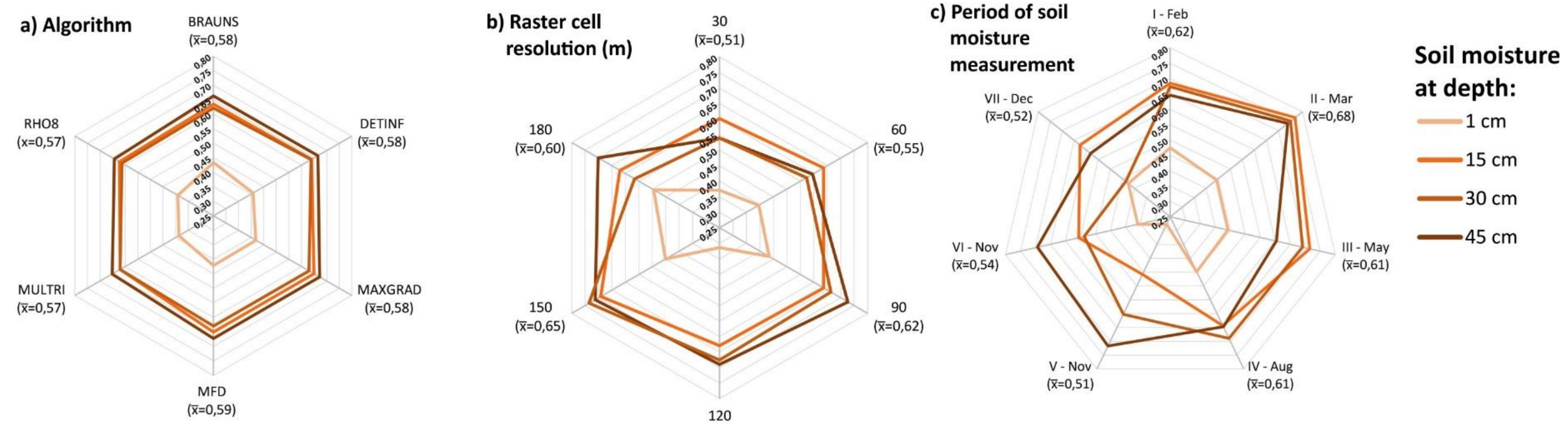

Fig. 8. Correlative relationships (ρ) between soil moisture at different depths and TWI algorithm, raster cell resolutions and different soil moisture measurement periods.

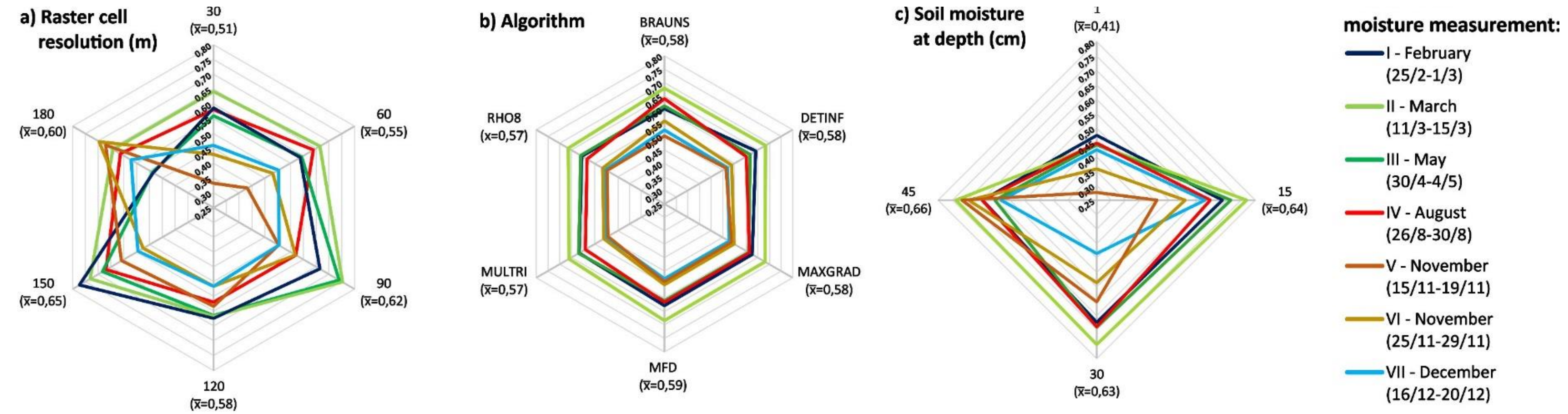

Fig. 9. Correlative relationships (ρ) between different soil moisture measurement periods and raster cell resolution, TWI algorithm and soil moisture at different depths.

## 5. DISCUSSION

We were interested in determining the optimal method for creating TWI in combination with cell size, for vehicle trafficability purposes. Specifically, we sought to find the most suitable combination of cell size and TWI creation method for a specific soil depth. The obtained result would also allow for predicting soil moisture based on measured values in the research area. Given that the results vary throughout the seasons, there is the possibility of variability in the most suitable combinations of raster, depth, and TWI method. The most accurate results would be obtained through continuous measurements over multiple years. Additionally, there is a challenge when dealing with different types of substrates where the measurement locations are located, as they have varying properties related to transpiration, evapotranspiration, vegetation, location exposure, terrain slope, albedo, and more.

We consider that by choosing specific locations with diverse characteristics, we were able to attain a representation that spans the entirety of the research area. Certainly, incorporating more measurement sites would enhance comprehension and yield improved results. Further research would require the introduction of additional corrective factors. For instance, the land cover could be evaluated through remote sensing based on the normalized difference vegetation index (NDVI). In combination with air temperature measurements, measuring insolation on different slopes' exposures would contribute to a more accurate determination of soil drying rates. Precise data on the depth and changes in the water table level would lead to a more accurate definition of TWI, especially in flat areas. Results also vary due to changes in meteorological conditions (temperature, precipitation, cloud cover, insolation, wind) within the selected five-day reference measurement period. It's important to note that there were no significant changes in weather conditions during all measurement periods, particularly in terms of precipitation occurrence. It should be noted that the impact of meteorological conditions decreases with increasing soil depth and the variability of external factors' impact is inversely proportional to the depth of the soil. The nature of loess, its permeability, and the terrain's complexity significantly impact measurement accuracy. The scattering of results can also be attributed to the "nature of loess" and its sporadic permeability in the cracks of unconsolidated vertical layers.

In flatter landscapes, larger cell sizes may be adequate, whereas in rough or highly varied terrains, smaller cell sizes may be essential to accurately capture the intricacies of the landscape. The importance lies in the observation that lower TWI resolutions yielded stronger correlation coefficients. This outcome is likely due to the smoothing effect of lower resolutions in TWI calculations, which helps mitigate data irregularities and noise. This smoothing process contributes to a more generalized comprehension of the landscape's wetness patterns. Conversely, higher resolutions could detect minor or localized features, adding more variability to the calculations. This surplus detail might overly emphasize specific terrain elements, potentially distorting the overall wetness index.

## 6. CONCLUSIONS

The cell resolution impacts the TWI index, with higher resolutions displaying more pronounced index amplitudes. The measurements have shown that considering the entire year, the best resolution is with an overall average correlation coefficient of 150 m, though 180 m performed well during periods of lower soil moisture. However, the measurements have highlighted the importance of conducting calibrations—specifically, a separate analysis of TWI parameters—to determine the most accurate resolution and algorithm for a particular soil depth in each unique scenario. Therefore, it should be emphasized that there is no universal TWI; rather, there is only the least inaccurate one. The MFD algorithm showed the highest average correlation ($\rho = 0.57$) considering cell size, seasons, and moisture in all soil depths. However, the choice of algorithm did not significantly affect the results. Soil depth of 30 cm with a 150 m resolution yielded the strongest correlation ($\rho = 0.77$). Due to the higher exposure of the upper soil layer to various external influences TWI provided the lowest results for soil moisture at a depth of 1 cm compared to greater soil depths (15 cm, 30 cm and 45 cm).

Soil moisture correlations varied across seasons, indicating the need for continuous, multi-year measurements. The relationship between meteorological conditions and soil moisture was observed, with weather impacting shallower soil depths more significantly than deeper layers. Variability in substrates, terrain, and external factors like weather conditions poses challenges in accurately predicting soil moisture. Further research could incorporate corrective factors like land cover evaluation, insolation, and water table level changes to refine TWI determination and better predict soil moisture. In conclusion, it should be emphasized that only in-situ soil moisture measurements enable a better definition of TWI parameters, turning it into an excellent indicator of soil moisture and vehicle trafficability. This enables a broader perspective and contributes to higher-quality planning and easier decision-making for experts in various fields and interests, such as the military.

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