Complex assessment of soil moisture conditions in the Rákos stream catchment

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FINAL REPORT

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1. Introduction

Understanding and timely monitoring of the dynamics of soil moisture is not only critical for agricultural production, but also for nature conservation and the general welfare of the population. The frequency of agricultural and meteorological droughts is expected to rise (Cisneros et al., 2014), even in areas with potential increase in summer precipitation, due to increased evapotranspiration rates (Wong et al., 2011). These effects are likely to significantly influence future crop yields (Wang et al. 2017). As well presented by the droughts of 2022, all these vital systems are affected by water scarcity, and such extreme meteorological conditions are more likely to occur (Lakatos et al., 2014). Therefore, the establishment of cost-effective and accurate soil monitoring systems is required as a significant part of our water management system.

Recent advances in Earth Observation technologies, UAV applications and computational capacity have provided us with an abundance of available data and methodologies to address these issues. However, the limitations in field observations have proven to be a restriction in the application of these methods, particularly at a small catchment or field level.

The aim of our project was to establish a methodology to monitor soil moisture dynamics at the Rákos stream catchment in Central Hungary, and develop methodologies to provide spatially explicit soil moisture estimation.

2. Materials and Methods

Study area

The Rákos stream is a tributary of the Danube River, with a total catchment area of 185 km^2, out of which 88km^2 is within the administrative boundaries of Budapest. Its location, manageable size and variations in topography and land cover make the area ideal as a test area for the proposed study. The stream has been previously studied by the faculty of MATE (formerly Szent István University) (Halász et al., 2007). Figure 1 presents the location and land cover of the catchment area. As the lower part of the catchment is primarily dominated by urban areas, the focus of our research was on the upper part of the watershed.

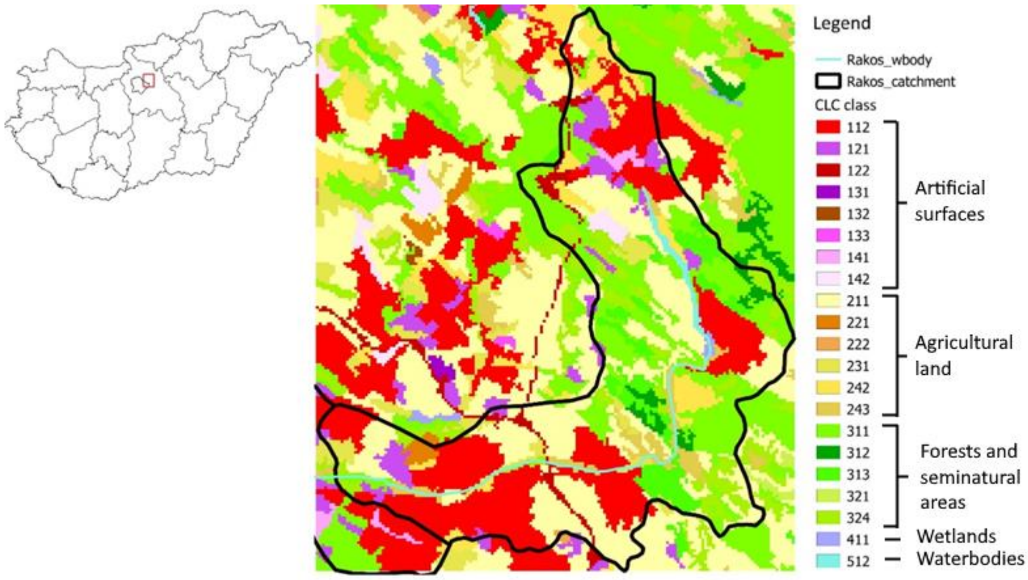

Figure 1. Land cover of the area based on the 2018 CORINE Land Cover dataset

Data sources and collection

In the project we established multi-level soil moisture monitoring system. Monitoring was primarily founded on the utilization of a Diviner 2000 (Sentek Sensor Technologies, Australia) capacitive soil moisture probe, which enabled us to repeatedly monitor volumetric soil water content (SWC) in several layers of the soil profile. Monitoring tubes for the Diviner 2000 have been continuously established (and re-established, when needed) during the project timeline. Monitoring tubes have been established at two main sites at MATE's experimental farms within the catchment, in Gödöllő, as well as two additional sites in suburban gardens in Budapest.

Besides occasional measurements in the soil profiles, two selected sites have been equipped with permanent probes at 10, 20, 40, 70 and 100 cm depths, for calibration and continuous monitoring, recording every 15 minutes. Prior to field establishment, we performed laboratory calibration of the continuous soil moisture probes (Decagon [METER] 5TM). One site was located in Gödöllő, another one in Budapest, at the lower section of the study area.

As the installation of permanent monitoring tubes for the Diviner 2000 probe was met by significant resistance by the land owners, in order to improve spatial coverage, we have utilized the handheld sensor FieldScout 300 TDR (Spectrum Technologies, Aurora, IL, USA) to observe spatial variations of topsoil SWC in the Rákos catchment. Monitoring was carried out in a campaign-based system, where one day would cover all, or most accessible points.

Figure 2 presents the location of the monitoring points along the catchment. The collected soil moisture information was used to calibrate and validate the applied modeling methods.

Climate time series have been obtained from the Meteorological Data Repository of the Hungarian Meteorological Service (OMSZ). Soil physical parameters (field capacity, permanent wilting point and saturation) have been downloaded from the EU-SoilHydroGrids ver1.0 dataset, while soil texture information was derived from the DOSoReMI.hu initiative (Pásztor et al. 2015).

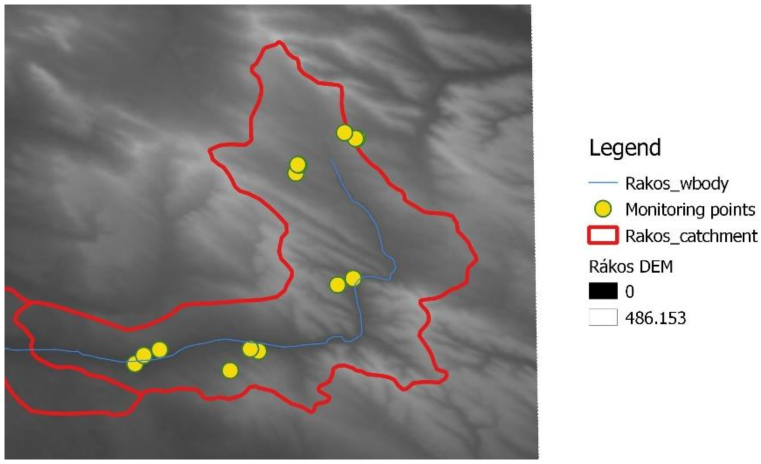

Figure 2. Topography and **m**onitoring point locations along the catchment,

Modeling – the AquaCrop approach

Our primary approach for spatially explicit estimation of soil moisture was the raster-based application of the AquaCrop Model. As the current verions of AquaCrop are only supporting vector-base application, we have developed a methodology utilizing the R programming environment.

Spatial data processing was primarily carried out using QGIS and SAGA GIS software, with additional processing in R. In order to allow a user-friendly approach, three R functions have been developed (see figure 3) and grouped together as an R package. The functions allow the user to run the plug-in version of AquaCrop on a raster dataset, and receive raster-based time-series output in NetCDF format. Detailed methodology has been published in Deganutti De Barros et al. (2022).

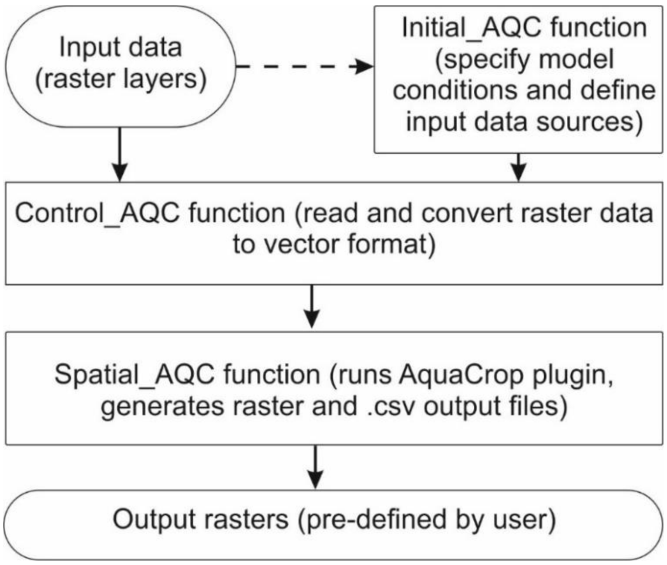

Figure 3. Workflow of the developed R methodology,

Modeling – the HYDRUS-1D approach

As our application of the AquaCrop model was primarily suitable only for agricultural lands, we have decided to explore another model for a more general approach. However, raster-based application of the HYDRUS-1D model was not feasible, and therefore, another approach has been developed. As calibration and validation points have been scarce in certain regions of the catchment, in order to boost kriging performance, we have decided to adopt a combined approach, utilizing virtual points (see figure 4). These points have been defined using Conditional Latin Hypercube Sampling, taking into account the slope, soil texture, land use and topsoil organic material. On the selected locations, the HYDRUS-1D model was applied, with input variables derived from the spatial data layers. Selected points have also been included in field monitoring to provide calibration/validation for the model application.

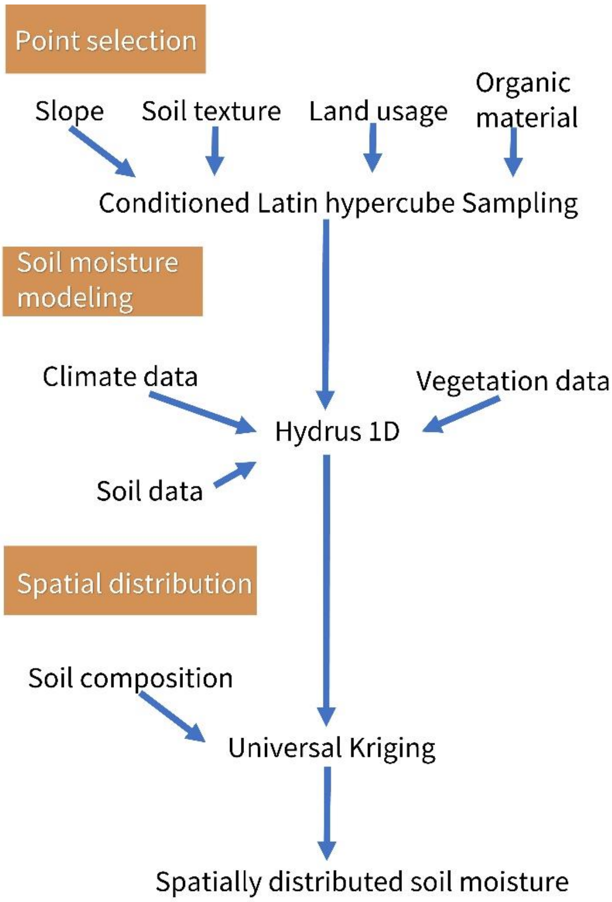

Figure 4. Workflow of the HYDRUS-based approach,

Evaluation of the Normalized Difference Moisture Index for soil moisture prediction

Satellite data has been primarily assessed through the utilization of the Normalized Difference Vegetation Index (NDVI) and the Normalized Difference Moisture Index (NDMI), based on Sentinel-2 data. While our results have indicated that NDVI correlated well with estimated biomass, we have decided to focus on the NDMI as it was assumed to be more strongly related to soil moisture content (Wilson & Sader, 2002). For NDMI evaluation 95 valid images have been used from February, 2020 to August, 2022. NDMI data has been matched with relevant soil moisture monitoring data and evaluated. Evaluation of the results has been primarily carried out through analysis of correlation in MS Excel.

3. Results

Application of the AquaCrop model

The developed R package has proved to be suitable for the spatially explicit application of the AquaCrop model. Figure 5 presents the 100 x 100 m resolution map of the yearly outputs for 2020, with a distinct run of AquaCrop for each cell, demonstrating the method's capabilities.

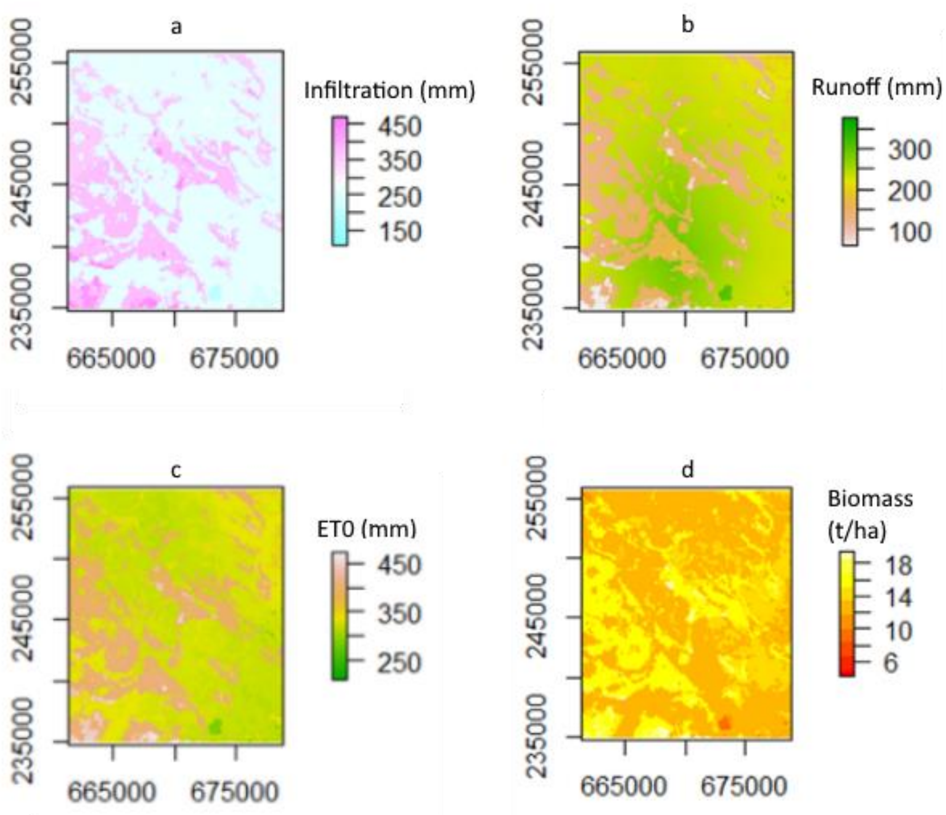

Figure 5. Yearly output of the AquaCrop model for the study area at a 100 x 100 m resolution for 2020,

While the above maps present the yearly output, a major advantage of our method is that it is possible to extract daily values for the whole grid, as presented in figure 6.

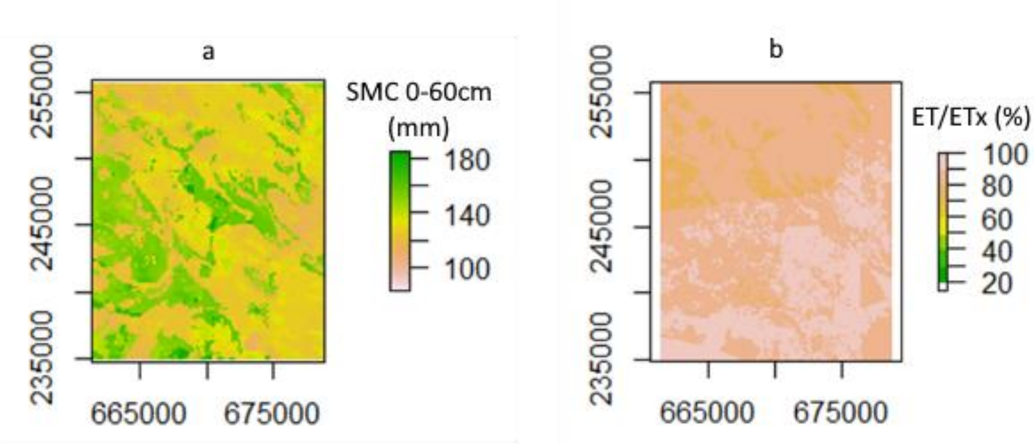

Figure 6. Spatial variation maps of daily water content for the rooting zone (6.a.) and percentage of relative evapotranspiration (6.b.) for the 10th of September 2020. (Projection: EPSG:23700)

Comparison of model output has demonstrated a good fit of estimated crop biomass with NDVI-based estimates for wheat (figure 7). However, we have found that the same was not true for canopy cover (CC %) as there was a visible break in the data, around the end of tillering for wheat. Once the time series has been split to two periods (emergence/tillering and erect growth), the correlation has improved significantly (figure 8).

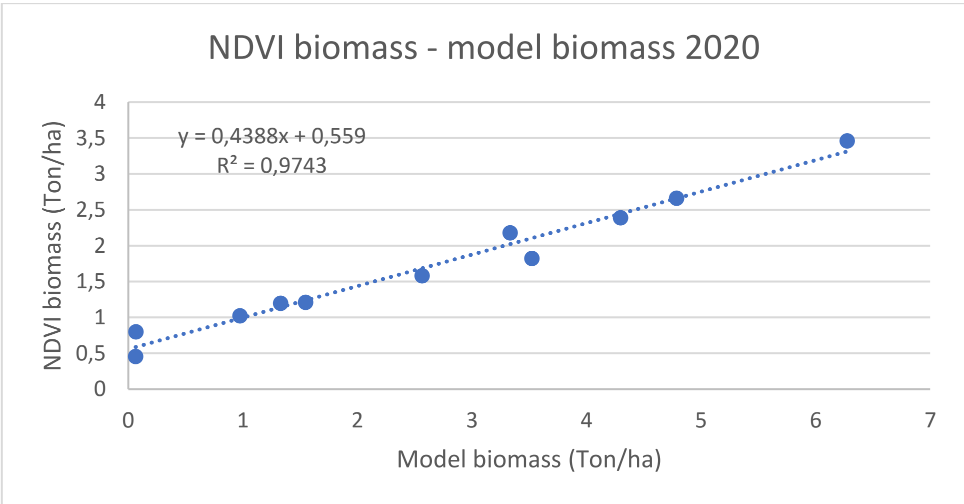

Figure 7. Comparison between NDVI biomass and modeled biomass for winter wheat in 2020.

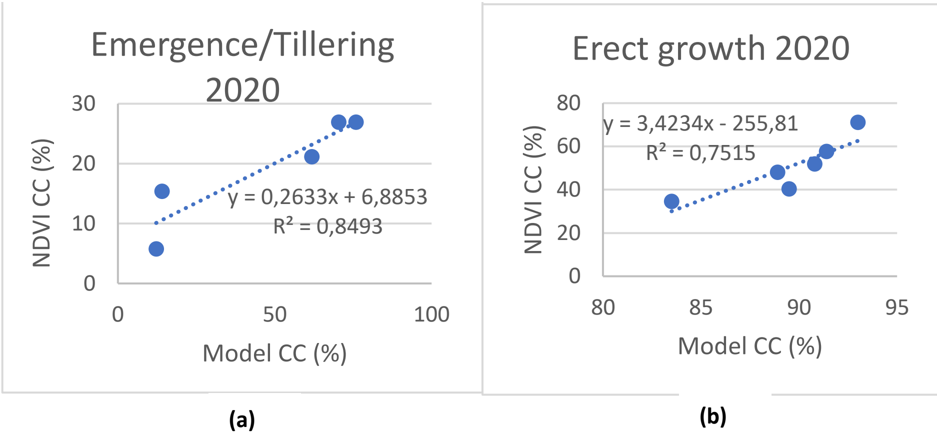

Figure 8. Comparison between NDVI and model-based canopy cover for emergence/tillering (a) and erect growth (b), winter wheat, 2020

In order to test the applicability of the method outside of the study area, we have compared soil moisture estimates for an experimental site (Sándor et al. 2020) in Martonvásár, Hungary (figure 9). The results indicated that AquacCrop has systematically overestimated the soil moisture content, albeit the two graphs were generally following the same trends.

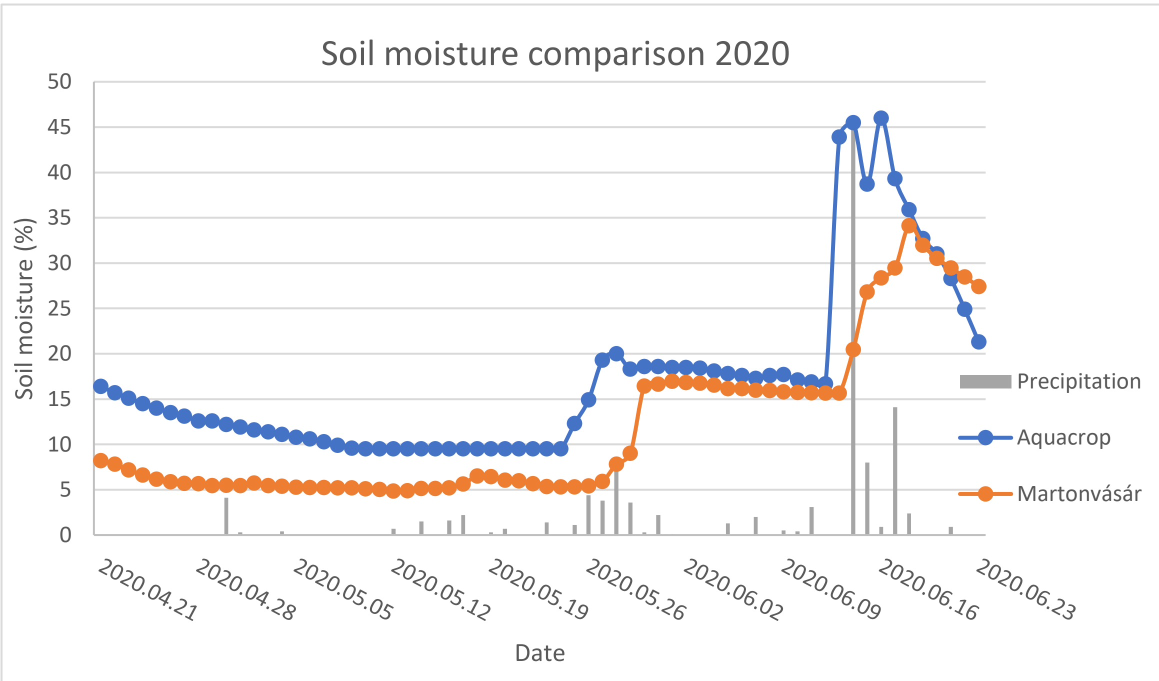

Figure 9. Comparison between modeled soil moisture and measure soil moisture in Martonvásar for 2020.

Application of the HYDRUS-1D model

The application of the HYDRUS-1D model showed that on-sire monitoring generally measured higher SWC values, while the model was following the same trends, but with significantly less amplitude (figure 10).

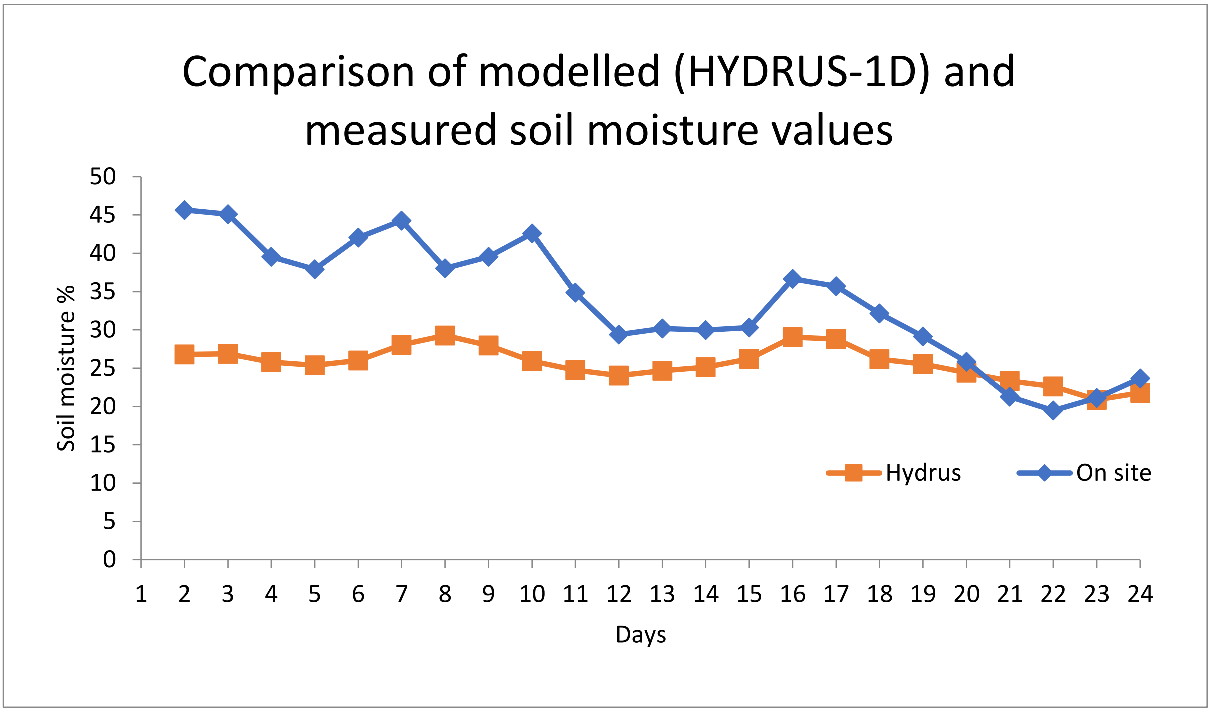

Figure 10. Comparison between modeled soil moisture and measured soil moisture in Martonvásar for 2020.

Utilizing the virtual points simulated by HYDRUS-1D for the kriging process, we were able to derive spatially explicit soil moisture maps. However, due to the uneven distribution of the points, the estimated variance of the results was still very high in certain regions (figure 11).

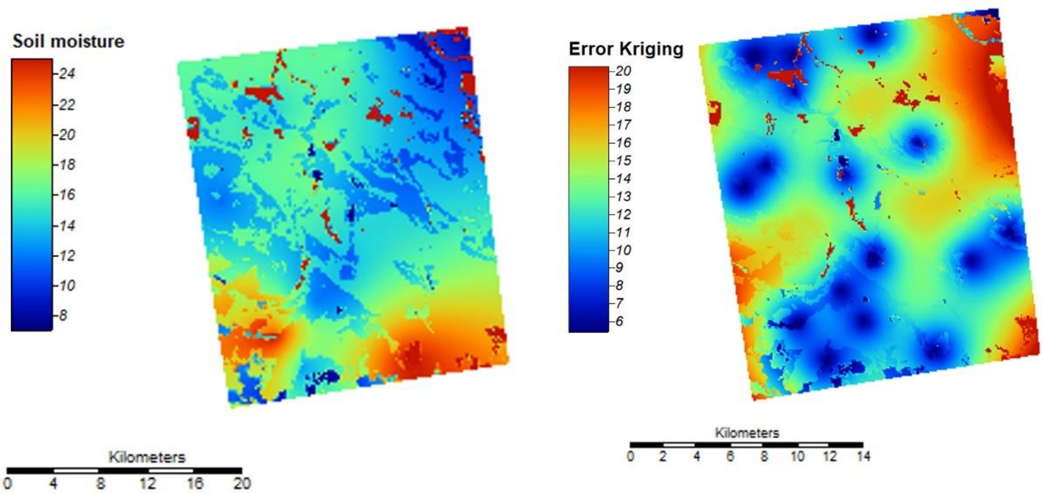

Figure 11. Soil moisture map for 0-30 cm (left) and kriging variance (right) for the Rákos catchment area

Evaluation of NDMI and soil moisture

The NDMI time-series have been collected. Figure 12 presents the minimum, maximum and mean values for the total study area, also presenting the effect of the drought of 2022.

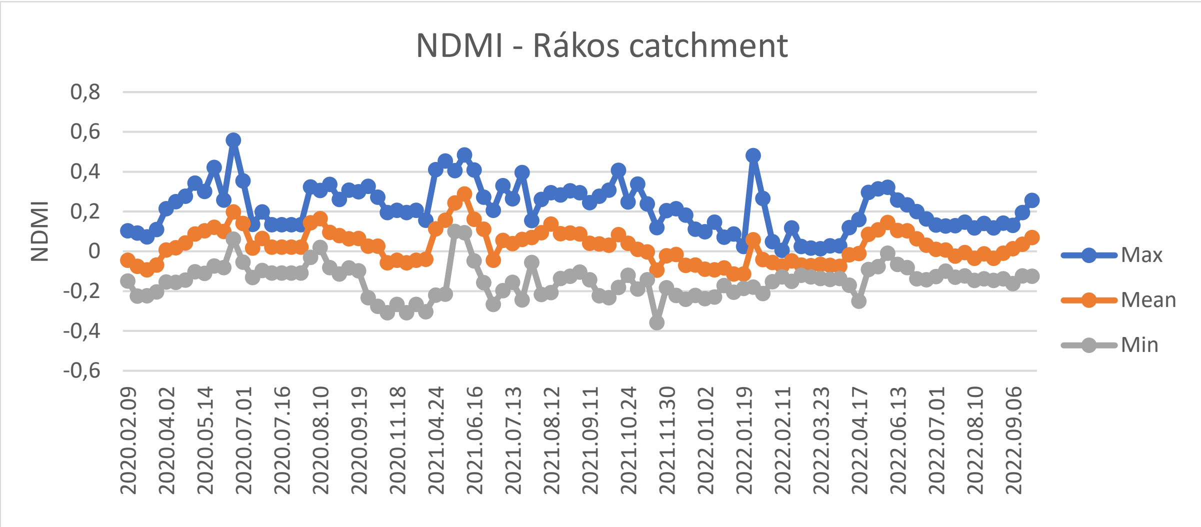

Figure 12. Time series of NDMI local minimum, maximum and mean.

Upon comparison of the local mean NDMI and SWC values for the experimental site in Gödöllő, we can observe a general correlation at most soil depths (figure 13 presents an example at 30 cm depth), with the exception of 40 cm (see table 1). Interestingly, this corresponds with the depth of a locally typical compacted layer in the soil (figure 14).

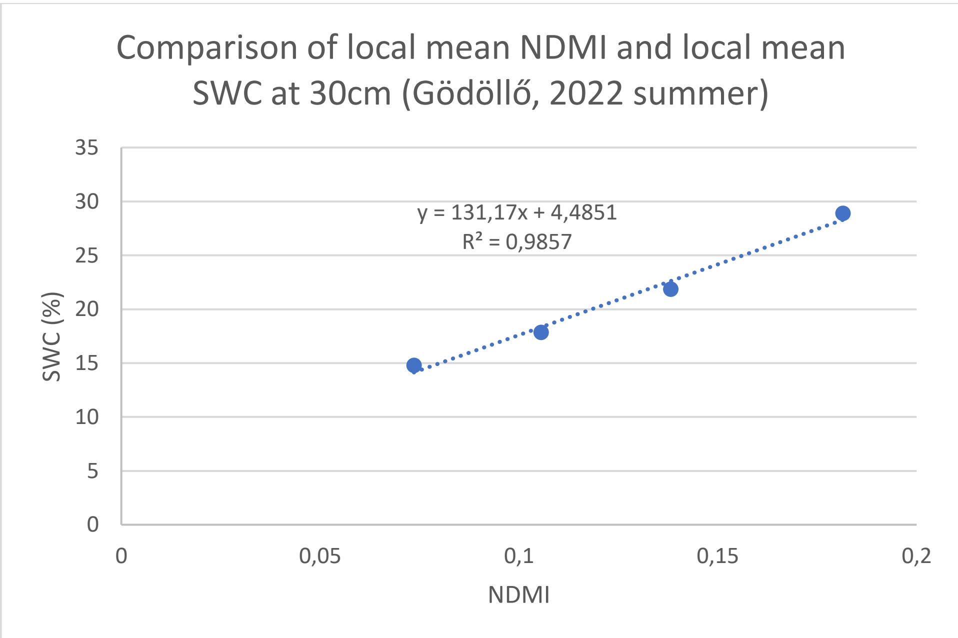

Figure 13. Correlation between local mean NDMI and local mean SWC at 30 cm.

Table 1. R^2 values for NDMI mean and SWC at different depths.

Depth	R^2
10cm	0,719
20cm	0,9518
30cm	0,9857
40cm	0,0796
50cm	0,8703
60cm	0,8878

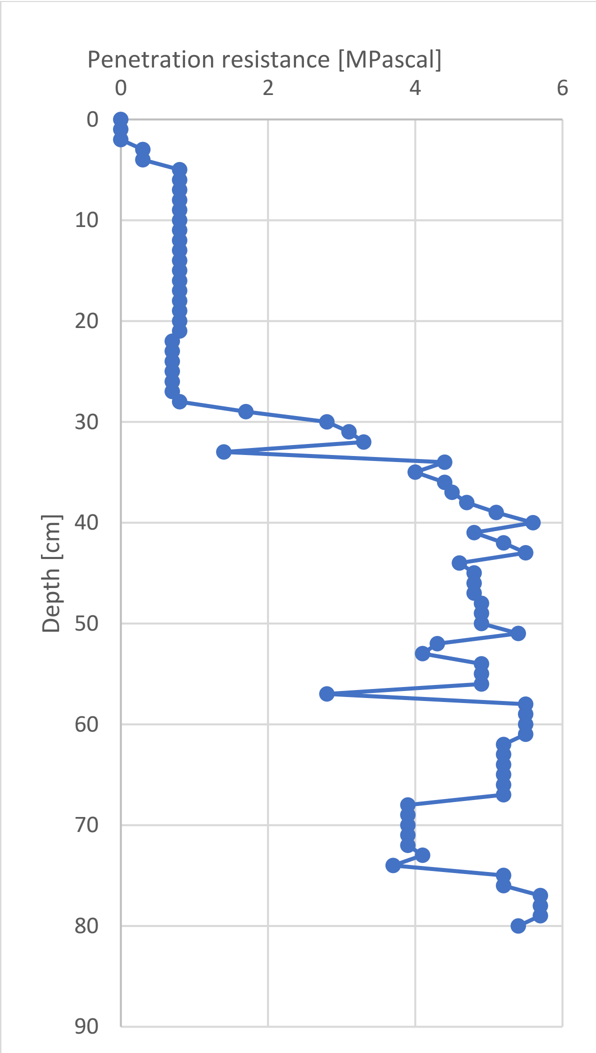

Figure 14. Depth distribution of penetration resistance at the experimental site in Gödöllő (Alrahaife et al. 2022)

4. Conclusions

Utilizing the established soil moisture monitoring network, we were able to calibrate/evaluate the applied methodologies for spatially explicit prediction of SWC.

The developed methodology for the raster-based application of the AquaCrop model has proven to be effective. During the evaluation we have also discovered that the model estimates and NDVI-based estimates develop differently over time and we have identified a break around the end of tilling.

We have also developed a HYDRUS-1D based methodology utilizing universal kriging for spatial inference. However, our results have indicated that for arable land, the AquaCrop based method is probably more suitable as it is easier and more reliable. On the other hand, for areas with dominantly non-arable land cover, the HYDRUS-based approach might be feasible after further calibration.

We have found that NDMI values derived from satellite products correlate well with volumetric soil moisture content, down to at least 60 cm depth. This indicates that the NDMI products can be utilized in further applications, particularly as an environmental covariate for kriging during the HYDRUS-1D-based approach. However, it has also been observed that the reliability of the NDMI for such estimates might be dependent on soil conditions, and therefore, such effects should also be explored before widespread application of the proposed methodology.

Both developed methodologies are suitable for continuous, spatially explicit estimation of SWC at multiple depths of the soil profile. However, it is evident that in order for such a network to become operational, a larger concentration of monitoring points is required.

While farm level operational application of the derived methodology wasn't expected as a result from the project, MATE Nonprofit Ltd. (operating a number of the sampling sites) has expressed an interest in continuing collaboration with the project team for further advancement of the methodology.

Further development of the methodology will focus on the establishment of an online server for the provision of daily estimates, and the continuous improvement of the established system up until the operational level, to benefit local farmers.

5. The project's achievements in light of the original objectives

Objective 1. To assess and compare the feasibility of EO techniques for soil moisture monitoring.

Our initial assessments have revealed that direct observation of soil moisture with remote sensing techniques would not be feasible once crop cover is present. Therefore, we have decided to focus on relevant vegetation indices (NDVI, NDMI). We have presented that the NDMI correlates reasonably well with soil moisture content even below the soil surface, therefore it can be utilized in the future as an effective environmental covariate for spatial inference of soil moisture content.

Objective 2. To establish a multi-level soil moisture monitoring system

We have established a multi-level soil moisture monitoring system in the Rákos stream area. While connection to farmers has proven to be difficult, we were able to establish a core network of ground points and have developed a methodology based on modeling to provide reasonable estimates in data scarce locations. The system will be further developed in the future to support local farmers.

Objective 3. To develop a methodology for optimal combination of EO data, hydrological modelling, digital mapping and field validation for economically feasible monitoring of water content in the soil profile with focus on the root zone.

We have developed two methodologies for the spatial monitoring and modeling of soil moisture content in the study area. Our first approach (application of the AquaCrop model) has proven to be applicable for soil moisture assessment, with also being suitable for crop biomass estimation. Our second approach (HYDRUS-1D based modeling and geostatistical application) proved to be very promising, likely more suitable for soil moisture assessment, but lacking some of the crop related features of the first approach. A combined application and evaluation of these methods is still to be implemented utilizing post-drought data from 2022.

Objective 4. To assess soil water dynamics within the Rákos stream catchment.

The applied methodologies are both suitable for spatial assessment of soil moisture dynamics in the Rákos stream catchment. However, due to the severe drought of 2022, the final connection between soil moisture dynamics and surface runoff could not have been studied sufficiently.

6. Publication activities

In the first year of the project, we were focusing on planning and reviewing existing literature. A poster was presented, outlining the general aims and concept of the project at the bi-annual conference of the Hungarian Soil Science Society (Waltner et al. 2018).

The first peer-reviewed manuscript of the project was focusing on the study are and changes in its land use, published in Hungarian in Tájökológiai Lapok (Q4) (Saeidi et al. 2019b). Following, we have presented a poster at the GEOMATES conference, analyzing the relationship between land use and geomorphometric parameters within the study area (Saeidi et al. 2019a) Based on the results of the ongoing work, we have presented preliminary results associated with the project in international conferences in 2020. Some results associated with field work was presented in Szilágyi et al. (2020) and Geleto et al. (2020). Further results of the analysis of the topographic wetness index and vegetation indices was presened in Almashrequi et al. (2020), while the initial concept of the raster-based application of the AquaCrop model was presented in Minoarimanana et al. (2020).
An improved version of the AquaCrop-based approach, focusing on wate footprint calculation was presented at an international conference in 2021 (Deganutti De Barros et al. 2021). Results of the project have been presented at international conferences in 2022, including comparison of field survays and UAV-based estimates of topography (Alrahaife et al. 2022), comparison of the AquaCrop and HYDRUS-1D models (Deganutti De Barros et al. 2022) and vegetation dynamics in the Rákos catchment (Kaldybayeva et al. 2022). Another small study was presented focusing on the effects of land use and landcover on the water qualiry of the Rákos catchment (Saeidi et al. 2022) A poster presentation at the 2022 World Congress of Soil Science presented the initial concept of the HYDRUS-1D based geostatistical estimation of soil moisture content (Deganutti De Barros et al. 2022). As a key output from the project, results of the raster-based application of the AquaCrop model have been published in Plants (Q1, IF: 4,658) (Deganutti De Barros et al. 2022c). Additional publications from the project results are expected in the near future, a manuscript to the journal Időjárás (Q4, IF: 0,896) is currently under major revision and is expected to be published in 2023.

7. Main changes in the course and budget of the study

The project has suffered from numerous obstacles and setbacks througout its timeline.

- Public procurement procedures and their changes have hindered the acquisition of key equipment in the first two years of the project.
- Structural and administrative changes in the host institution (The merging of Szent István University with other institutions, later the change to Hungarian University of Agriculture and Life Sciences) have all proven to have affected the project.
- The global COVID-19 pandemic and the resulting restrictions have made effective field work impossible for a while, later extremely difficult.
- Several pieces of equipment (UAV, soil moisture probes, penetrologger, computers) have malfunctioned during the project and repair has proven to be challenging at times, particularly during the pandemic.
- UAV flights have been severely limited due to flight restrictions and changes in the legal framework governing UAV flights.

As a result of the above mentioned issues, the project has been extended for a 5th year, however, the drought of 2022 have severely limited the range of the observed soil moisture dynamics, particularly when the monitoring would have been at its peak.

The overall budget of the project hasn't changed. Reallocation of the budget has primarily affected the travel and personal costs. As the pandemic has made travel options extremely limited, the budget has been adjusted to better compensate the participating members of the research team, particularly as positions and salaries have significantly changed over the 5 years of the project lifetime.

Acknowledgements

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