Temporal and spatial variability of soil hydraulic properties with implications on soil moisture simulations and irrigation scheduling

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M.Feki, G.Ravazzani, M.Mancini

Politecnico di Milano, DICA, Milano, Italy (*contact*: mouna.feki@polimi.it)

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Introduction

The increase in consumption of water resources, combined with climate change impacts, calls for new sources of water supply and/or different managements of available resources in agriculture. One way to increase the quality and quantity of agricultural production is using modern technology to make farms more "intelligent", the so-called "precision agriculture" also known as 'smart farming'. To this aim hydrological models play crucial role for their ability to simulate water movement from soil surface to groundwater and to predict onset of stress condition. The models accuracy when implemented for this aim is very important. Right decisions are taken based on right data while uncertain data leads to unreliable results and thus inadequate decisions. Many uncertainties are limiting the implementation of these models for irrigation scheduling due to: meteorological data, field measurements and the formulation of some processes such as infiltration, evapotranspiration…etc. Typically, soils to be characterized, exhibit large variations in space and time as well during the cropping cycle, due to biological processes and agricultural management practices: tillage, irrigation, fertilization and harvest. Soil properties are subjected to diverse physical and chemical changes that lead to a non-stability in terms of water and chemical movements within the soil and to the groundwater as well. The knowledge of the soil properties variability is highly recommended to define the water stress thresholds based on which the decision to irrigate is taken. The aim of this study is to assess the variability of soil hydraulic properties over a cropping cycle and their effect on soil moisture simulations and irrigation scheduling. To investigate soil properties variations, both measurements in the field and laboratory tests on both undisturbed and disturbed collected samples were performed. VADOSONE Model was implemented as tools to assess the efficiency of the irrigation schedule. Performed simulations allowed to evaluate the irrigation schedule of maize field in the Po Valley-Northern Italy. Temporal and spatial variations of soil properties have been implemented instead of the constant ones to compare their impact on simulated water status thus on the evaluation of previously implemented irrigation schedule.

Material and methods

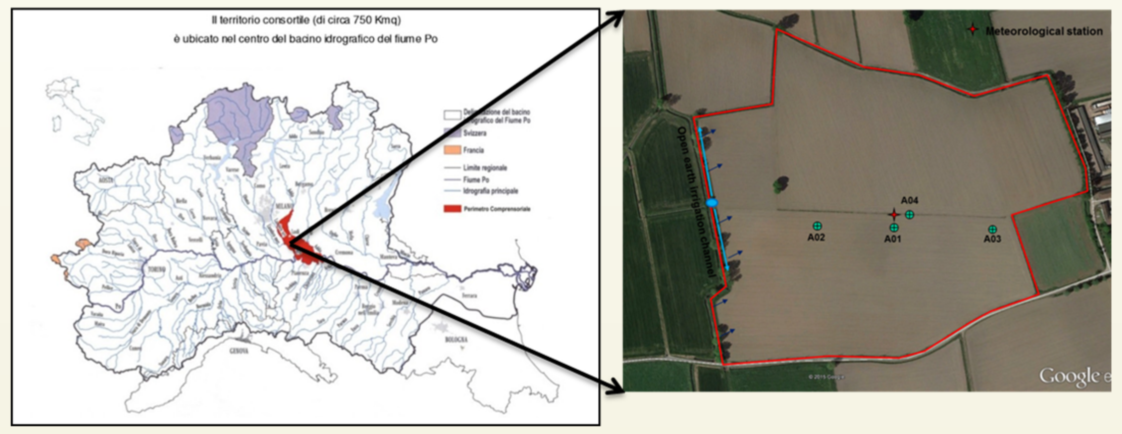


Figure .1 study site Sampling points location

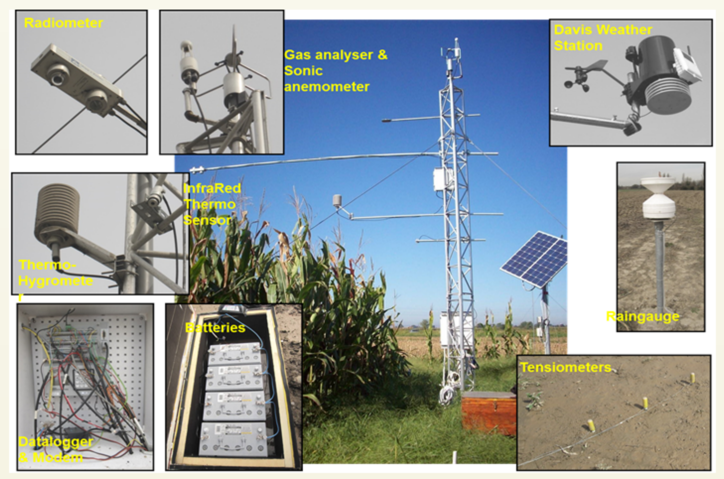


Figure .2 Field monitoring: Eddy covariance and soil moisture probes

Table 1. Main characteristics of the study site

Max temperature	35.48°C
Min temperature	8.75°C
Mean temperature	22.33°C
Cum Rainfall of the monitoring period	195 mm
Sowing date	08/04/2015-09/04/2015
Harvest date	15/09/2015
Irrigations	30/06/2015-14/07/2015

The study site is a maize field (45°13'31.70" N, 9°36'26.82 E) located in Northern Italy-Lombardy region. This field belongs to the Consortium of Muzza Bassa Lodigiana. This site is a surface irrigated field that covers an area of 6ha. Experimental measurements were carried out from 21 April 2015 to 16 September 2015. This site was taken as case study of the SEGUICI project, aimed at experimenting soil moisture forecast for irrigation scheduling.

Soil sampling

During several field campaigns soil samples were collected at different points (A01, A02, A03 and A04), at different soil depths (Top soil, 20cm and 40cm). We limited our soil parameter monitoring to the first 40 cm of the soil, since the top soil in more susceptible to variability due to agronomic practices then deeper layers. For each soil sample we carried out several tests to measure the hydraulic conductivity, soil water retention curve parameters, bulk density , particle size distribution and organic matter content. The selection of sampling points aimed at assessing the spatial variability of soil properties). The point A04 was selected from an uncultivated part of the field, for more than 8 years, in order to assess the effect of agronomic practices on soil properties as compared with other sampling points located within the maize cultivated part for more than 25 years. .

Table 2.Sampling campaigns

1st campaign	2 weeks after sowing 30/04/2015
2nd campaign	Fully developed crop after irrigation 08/07/2015
3RD campaign	After harvest 25/09/2015

Model simulations

To assess the effect of spatial and temporal variability of soil properties water movement within the soil profile was simulated. Soil moisture simulations were carried out using VADOZONE model , developed at Politecnico di Milano. This physically based model uses Richards equation for the simulation of 1D water flow.
A common way of characterizing unsaturated flow is Richards' equation (Richards, 1931).
A general version of this equation is

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial Z}\left[K\left(\frac{\partial h}{\partial z} + 1\right)\right]$$

Where θ is the volumetric water content, h is the pressure head (L) , Z is the soil depth (L), K is the hydraulic conductivity (LT^{-1}) and t is the time (T). Richard's equation was solved following Ross (2003) Fast solution. Several simulations were performed, as presented in table 3, with different sets of soil hydraulic parameters

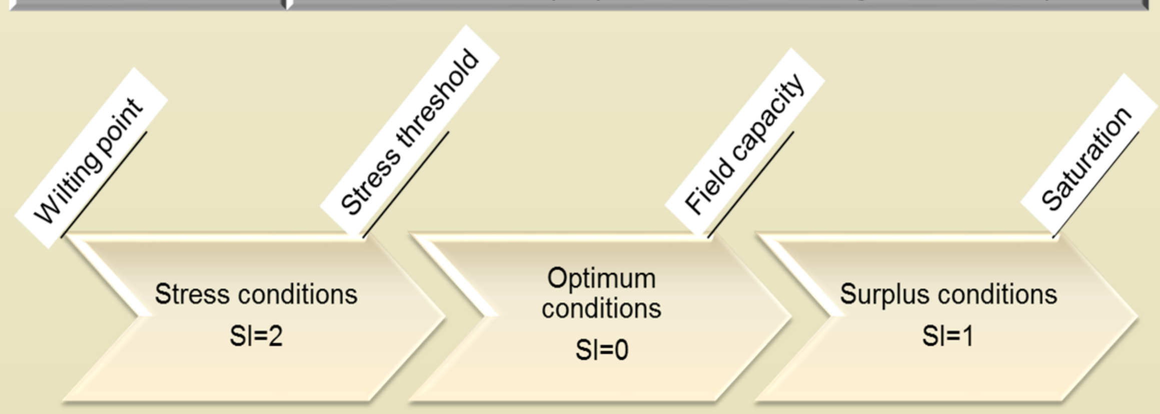
Table 3. Performed simulations

SIMULATION	Details
S1	Soil properties from first campaign with homogeneous soil profile
S2	Soil properties from first campaign with heterogeneous soil profile
S3	Values from second campaign with homogeneous soil profile
S4	Values from second campaign with heterogeneous soil profile
S5	Time variable soil properties with homogeneous soil profile
S6	Time variable soil properties with heterogeneous soil profile

At an hourly time step a stress index (SI) is calculated. The evaluation of the stress conditions is carried out according to a fixed stress and surplus thresholds. The surplus conditions corresponds to situations where the water content is higher or equals to the field capacity and this situation is identified by a stress index equals to 1.Instead, the stress threshold was calculated according to the following equation:

$$\textbf{Stress Threshold} = \theta_{FC} - p \times (\theta_{FC} - \theta_{WP})$$

Where θ_{FC} is the water content at field capacity and θ_{WP} is the water content at the wilting point. P is the allowable depletion. The value of P ranges between 0 and 1 that depends on climatic conditions and the crop. For water content values between field capacity and stress threshold, the stress index is equal to 0 that corresponds to optimum conditions for roots water extraction. While when the soil moisture is lower than the stress threshold the stress index is equal to 2.



Results and discussions

It has been proven from the performed measurements that soil properties, in particular near the surface, are subjected to temporal variation during the cropping cycle that can be due to many factors : drying/wetting cycles, fertilization , roots development, irrigation, tillage and harvest. The time variability affected more the cropped part of the field. The saturated hydraulic conductivity is a sensitive parameter to temporal changes. This parameter is required as input for many ecological, environmental and agricultural models and this variation should be taken into consideration. Comparing spatial and temporal variations of measured soil properties showed that temporal changes are greater.

Soil moisture simulations

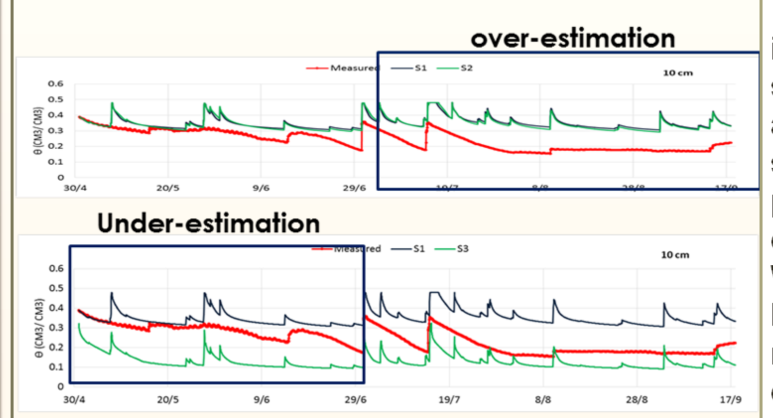


Figure .3 Soil moisture simulations VS measurements with constant soil properties

Results of S1 and S2 show that taking into consideration time constant set of soil parameters that were measured at the beginning of the cropping season overestimates soil moisture in particular under fully developed crop conditions.
While for S3 and S4, where soil hydraulic properties measured in the middle of the cropping season were considered as constants for the entire simulation period, tend to underestimate soil moisture during the first half of the cropping cycle.

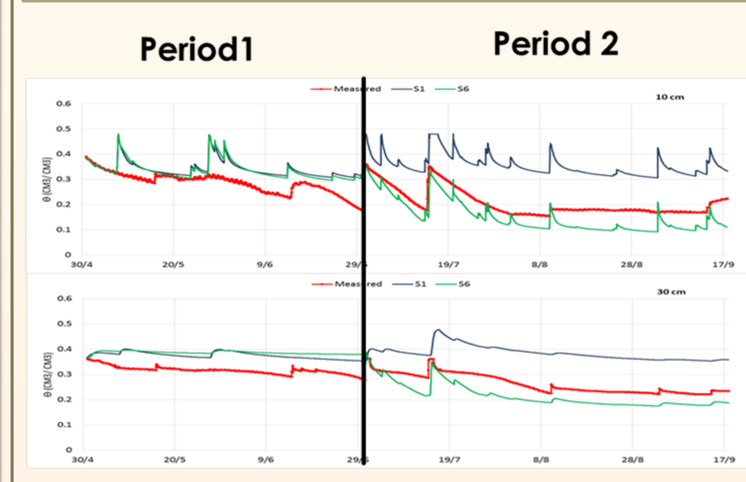


Figure .4 Soil moisture simulations VS simulations with time variable soil properties

Soil moisture simulations were carried out with time variable soil hydraulic properties. The simulation period was divided into two periods: the measurements of the first campaign were used as first set and the measurements of the second campaign were used as second set used as inputs for the second period. The vertical black line represents the time when the second set of soil hydraulic parameters measured in the middle of the cropping cycle have been introduced.

Although there is a small disagreement between simulations and measurements, S6 yielded the best result. This confirms that taking into consideration the temporal variability together with the vertical heterogeneity of soil properties yielded a significant improvement of simulation quality.
In order to assess the effect of this spatial variability on soil moisture simulations, soil properties were interpolated inverse distance weighting and used as inputs for spatially distributed simulations. Results presented in the maps of surface soil moisture shows the spatial variability of soil moisture at field scale at three different days during the 2015 cropping season. The simulation results using data from the first field campaign are presented in the figure 5-a and results of simulations based on data from the second field campaign are presented in the figure 5--b. Though simulated under the same forcing and for the same dates, soil moisture simulations yielded different results. Simulations showed as well the soil moisture distribution within the study field was heterogeneous

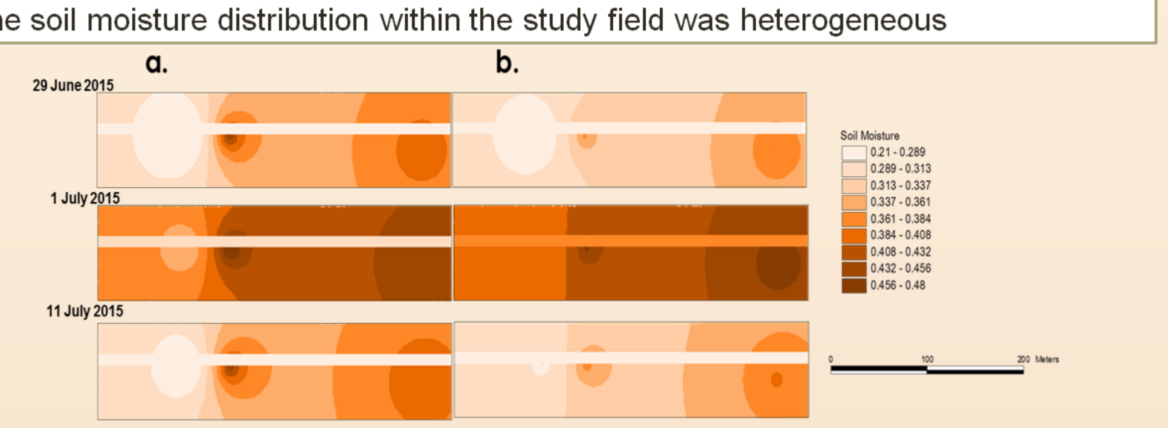


Figure.5 Spatial distribution and temporal variation of soil water content (a. soil data from the first measuring campaign, b. soil data from the second measuring campaign) .

Irrigation scheduling

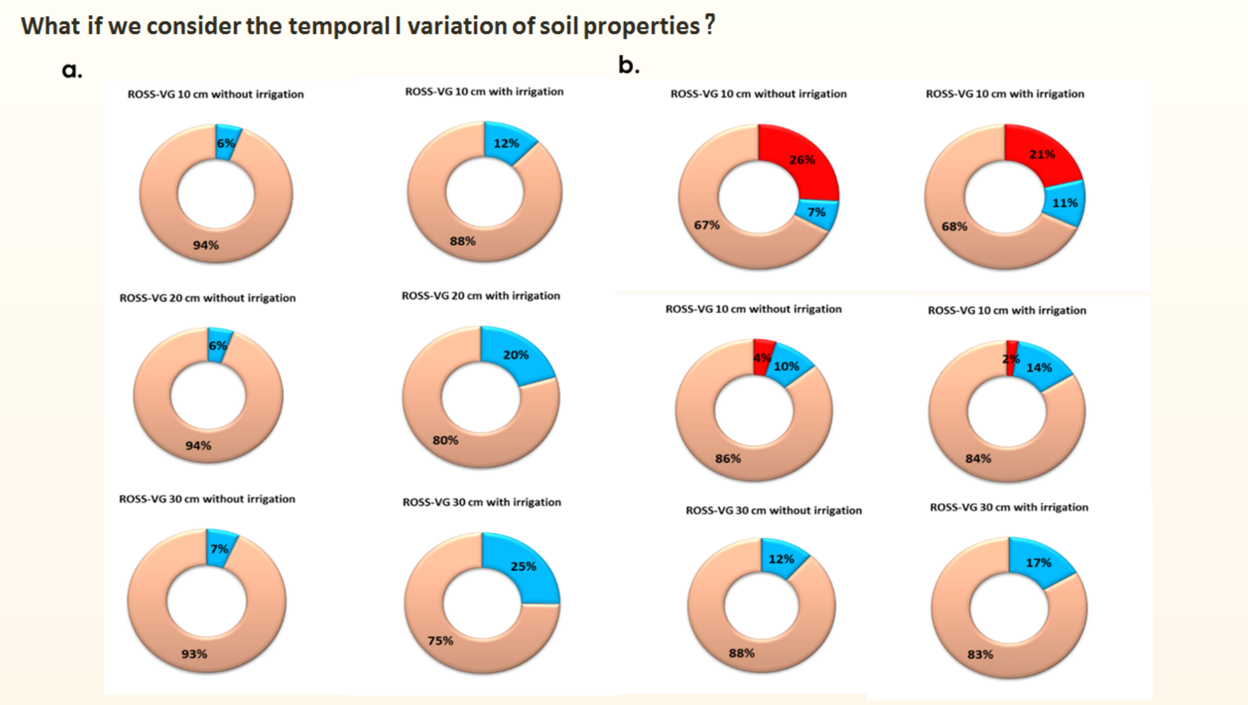


Figure .6 Percentages of stress, surplus and optimum conditions during the 2015 growing season with and without irrigation a. without time variable soil hydraulic properties b. with time variable soil hydraulic properties

The first simulation was carried out with constant set of soil parameters. Considering the stress index at different soil layers, more surplus conditions were observed in deeper soil at 30 cm than 10 cm and 20 cm layers under irrigation. So according to these results no irrigation was required at all since during the whole cropping season no stress conditions were observed.
When temporally variable soil hydraulic properties together with temporally variable stress and surplus thresholds were considered, stress conditions were observed in contrary to previous results.

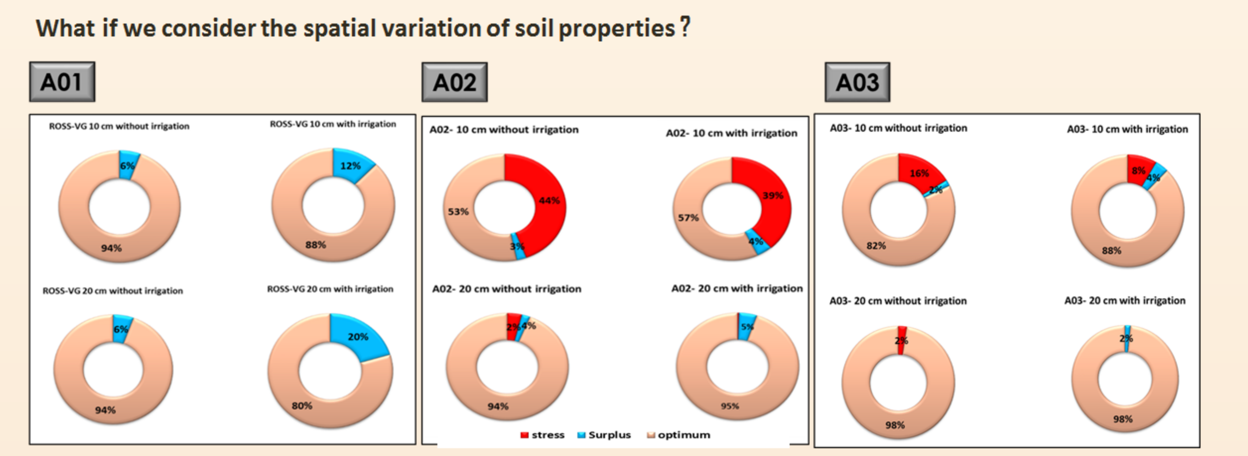


Figure .7 Percentages of stress, surplus and optimum conditions with and without irrigation without time variable soil hydraulic properties

The percentages of occurrence of stress, surplus and optimum conditions at the different sampling points of the field were different. As observed at A01, no stress was recorded even without irrigation and stress appeared only when the second set of soil parameters was introduced. On the contrary to the results of assessment of the stress index at A01, the stress appeared at A02 and A03 even when the first set of soil hydraulic properties was introduced. Considering or not the temporal variability of soil hydraulic properties, the irrigation didn't reduce efficiently the stress while it developed more surplus for both A02 and A03. These results confirm that the use of local simulations can lead to inadequate evaluation results or decisions if used to schedule future irrigations.

Conclusions

The main use of dynamic simulations of soil moisture is for irrigation water management purposes. Knowing the soil water content at a given time step allows to evaluate if the available water allows to meet the evaporative demand or not.. Results of this study illustrated the importance of considering time and space variable soil properties while modeling soil water movement. Yet constrained by the effort and cost required to monitor these changes, soil hydraulic properties variability in time and space should be further investigated. This will help for a better planning of cropping practices. A stress index has been suggested as an indicator used to evaluate the soil water conditions. At each time step a stress index was calculated. It has been proved that accounting or not for time and spatial variation of soil properties yielded different results of the evaluation of irrigation scheduling. Neglecting the time variation of stress thresholds during the cropping season can lead to erroneous decisions. According to the results of this study, accounting for spatial distribution of soil water status is crucial since soil hydraulic properties are subjected to spatial variability even at small scales. If the monitoring and modeling are carried out locally in the field, the selected location to carry out these activities should be adequately chosen in order to be representative for the entire field.