Soil moisture simulations for a sustainable irrigation management

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Abstract: Accurate estimations of crop water requirements accounting for spatial heterogeneous soil properties are recognized as a major contribution towards a sustainable agricultural irrigation management. Crop-specific irrigation demand estimations may be improved by physics-based soil moisture models, although spatially distributed soil moisture simulations strongly rely on profound assessments of the model accuracy and applicability under open-field conditions. Hence, this study aims to investigate simulated root-zone soil moisture dynamics on a variably irrigated potato field provided by the HYDRUS-1D model and its suitability for irrigation management purposes in terms of input parameter requirements and applicability on larger, heterogeneous sites. All simulations were highly accurate (RMSE = 0.018 m^3 m^{-3}), when compared to in-situ measurements, but varied stronger in topsoil than in subsoil layers. A pixel-based approach using aggregated soil properties, phenological characteristics and meteorological conditions enables appropriate trade-offs between simulation accuracy and the parameterization effort and applicability in irrigation management.

Keywords: HYDRUS-1D, plant available water, irrigation decision support systems, gun sprinkler irrigation, potato production

1 Introduction

Increasing competition for freshwater resources are major concerns for agricultural authorities worldwide. The development of adaptation strategies is indispensable for a sustainable and demand-driven irrigation management [Fa21]. The potato crop (*Solanum Tuberosum* L.), in particular, requires additional water for securing the optimum soil water budgets. Location-specific variances of the crop water demand often lead to a limited accuracy of crop water demand estimations on larger and heterogeneous sites [AS23]. Spatial variances in soil hydraulic properties, in particular, contribute to a reduced crop water productivity [BS17]. Physics-based soil moisture models may increase the accuracy of estimated crop water demands with regard to spatial and temporal variances [YHH19].

The HYDRUS-1D model [ŠGŠ05], for instance, is a well-known tool for simulating soil moisture dynamics within the unsaturated soil profile by using a mechanistic solution of the Richards equation via coupling a multi-layer soil moisture scheme with a single-layer canopy scheme. Several approaches have been suggested for improving agricultural

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irrigation management, or for increasing the simulation and prediction ability of soil moisture dynamics, solute transport and crop growth [Sh18]. An often-proposed approach aims towards the coupling of the HYDRUS-1D model with crop models or empirical hydrological models [Tu21; Wa21], but increases the parameterization requirements and hence the applicability of physics-based models in practical irrigation management.

Moreover, the applicability of the HYDRUS-1D model for spatial distributed crop water balance estimations under open-field conditions strongly depends on (i) profound model accuracy and performance assessments under open-field conditions, and (ii) the availability of spatial and depth-distributed soil hydraulic properties, phenological characteristics, and meteorological conditions [Te20].

Hence, this study aims towards a novel investigation of the accuracy of root-zone (0 cm - 60 cm) soil moisture simulations, provided by the HYDRUS-1D model on a variably irrigated potato field under open-field conditions. The results of this study may serve for future in-depth assessments of the farm level model applicability in terms of data requirements. An innovative, pixel-based approach is discussed for location-specific irrigation demand estimations of the potato crop.

2 Material and Methods

A field experiment was conducted under open-field conditions from May to September 2022 on a loamy-sandy (814 g kg^{-1} sand, 166 g kg^{-1} silt, 20 g kg^{-1} clay) potato field in Mecklenburg-Western Pomerania, Germany (35 ha, 53°56'29" N, 13°14'40" E, Fig. 1).

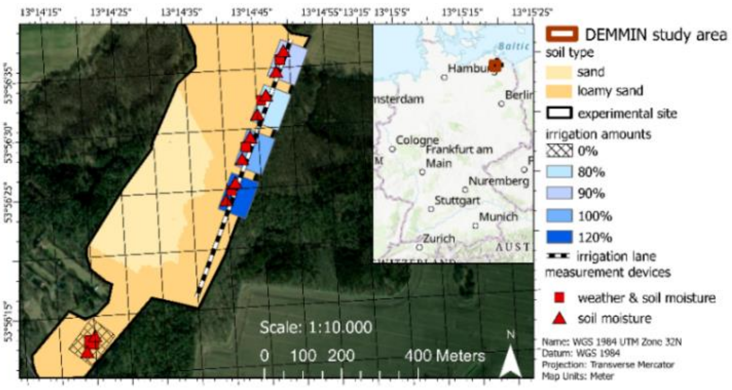

Fig. 1: Study site and experimental design. Four differently irrigated test plots (each 172 m x 72 m) were installed in 2022 on a homogeneous loamy sandy potato site

Four test plots (172 m x 72 m each) were installed within one gun sprinkler irrigation lane. Irrigation was scheduled iteratively each irrigation day by the local farmer. Each test plot was irrigated with one irrigation amount: the common irrigation of the local farmer

(100 %), two deficit irrigation amounts (80 %, 90 %), and one abundant irrigation amount (120 %). The total irrigation amounts were: 121 mm (80 %), 126 mm (90 %), 133 mm (100 %), 152 mm (120 %). Agrometeorological conditions were observed in each test plot using smart weather sensors (Arable Mark 2, Arable Labs, Inc., Princeton, NJ, USA). Root-zone (0 cm - 60 cm, in 10 cm increments) soil moisture was observed in triplicate per test plot using 60 cm Sentek Drill&Drop profile probes. The irrigation system was controlled in-field using 7-min GPS based speed and location data, which were used to derive location specific (4.5 m per point, 10 datasets per soil moisture probe) irrigation amounts. These location specific data enabled the consideration of spatial and temporal variances in the irrigation amounts due to technical properties of the utilized irrigation system and ensured the highest possible accuracy of irrigation amounts for soil moisture simulations under open-field conditions.

The HYDRUS-1D [ŠGŠ05] model was used for simulating daily depth-distributed (0 cm - 60 cm, in 10 cm increments) soil moisture dynamics at each location of a soil moisture probe. The "van Genuchten-Mualem" relationship between soil moisture and pressure head [Ge80; Mu76] was applied for solving the Richards equation. The sink term in the Richards equation accounting for root water uptake was solved using atmospheric boundary conditions accounting for the crop specific evapotranspiration rates based on in-situ measured meteorological conditions. The profile depth was set to 80 cm, discretized into four layers (0 cm - 10 cm, 10 cm - 20 cm, 20 cm - 30 cm, 30 cm - 80 cm), with a freely draining boundary condition (Fig. 2).

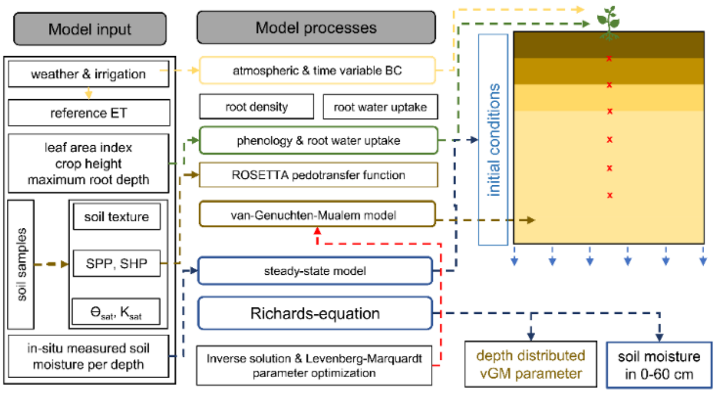

Fig. 2: Flow diagram for depth-distributed (red points) soil moisture simulations

The required van Genuchten-Mualem parameters (α, n, residual water content) were estimated using the integrated ROSETTA pedotransfer function [SLG01], based on laboratory determined water content at saturation and at permanent wilting point and soil textural classes. The maximum rooting depth of the potato crop was set to 60 cm, and root water uptake was assumed to decrease with water stress [FKZ78]. All simulations were calibrated using an inverse parameter optimization-based model solution and validated via in-situ measured soil moisture dynamics using the root mean square error (RMSE), the mean absolute error (MAE), and the coefficient of determination (R^2).

3 Results and Discussion

Simulated soil moisture dynamics were in good agreement with in-situ measurements (RMSE = 0.018 m^3 m^{-3}, MAE = 0.014 m^3 m^{-3}, R^2 = 0.645, for all irrigation amounts, Tab. 1). Significant differences in the accuracy between different soil depths were found for the RMSE ($p = 0.003$) between 20 cm depth and all other depths and for the MAE ($p < 0.001$) between 10 cm, 20 cm and 60 cm, and all other depths. The R^2 was significantly ($p < 0.001$) highest in 60 cm depth and lowest in 30 cm depth. The model accuracy may further be increased by controlled experimental conditions, which, however, contradict to model assessments under open-field conditions. These open-field conditions are of particular importance for deriving adaptation strategies in agricultural practice [Li16]. In this study, the use of in-situ derived irrigation amounts ensured the highest possible accuracy of simulated soil moisture dynamics with varying irrigation amounts.

soil depth	RMSE (m^3 m^{-3})	MAE (m^3 m^{-3})	R^2 (-)
10	0.019 a	0.014 b	0.618 ab
20	0.014 b	0.012 b	0.640 b
30	0.020 a	0.018 a	0.581 a
40	0.020 a	0.018 a	0.631 b
50	0.018 a	0.017 a	0.661 b
60	0.016 ab	0.015 b	0.741 c

Tab. 1: Model performance metrics (Root mean square error, RMSE (m^3 m^{-3}), mean absolute error, MAE (m^3 m^{-3}), and coefficient of determination, R^2). Lower-case letters indicate statistically significant differences metrics between different soil depths

Less accurate results in the topsoil (0 cm - 30 cm) may be due to the effects of evapotranspiration, precipitation and irrigation and due to a temporally and spatially erratic root water uptake of potato crops during early growth stages [Qi14]. Potato ridging may have altered the soil hydraulic properties and the two-dimensional features of water flow dynamics in a potato ridge [St08], indicated by significantly less accurate simulations in 30 cm and 40 cm depth. The effects of wetting front dynamics were accurately simulated. The average deviations between in-situ measured and simulated soil moisture content after an irrigation event were -0.026 m^3 m^{-3}, 0.008 m^3 m^{-3}, -0.004 m^3 m^{-3}, -0.016 m^3 m^{-3}, -0.022 m^3 m^{-3}, and -0.013 m^3 m^{-3}, for each depth (0 cm - 60 cm) separately.

The HYDRUS-1D model is generally considered to provide an increased accuracy of simulated crop water demands, when compared to evapotranspiration-based models [Gu20]. It is hence often recommended for irrigation management purposes, despite its increased parameterization requirements [La23]. A more straightforward parameterization, contrarily, usually prevents accurate and spatially distributed crop water demand estimations, especially under open-field conditions [LL18]. Trade-offs between the required accuracy of crop water demand estimations for a sustainable irrigation management and the increased parameterization effort of physics-based models are indispensable for the practical applicability of physics-based soil moisture models. Novel approaches are required for an automatic integration of spatially distributed soil hydraulic properties, atmospheric boundary conditions, and phenological characteristics [YHH19].

4 Conclusions and Perspectives

In this study, depth-distributed soil moisture simulations were conducted on variably irrigated potato field using the HYDRUS-1D model. The accuracy of simulated soil moisture dynamics in comparison with in-situ measurements indicated a high suitability of the HYDRUS-1D model for improving crop water demand estimations in practical irrigation management. Such accuracy assessments at varying irrigation amounts and under open-field conditions are of particular importance for assessing the implementation of physics-based models (e.g., HYDRUS-1D) into easy-to-adopt irrigation decision support systems. The necessity of depth-distributed soil hydraulic properties and van Genuchten-Mualem parameters in physics-based models is a major limitation for spatial distributed estimations of root-zone soil moisture. Despite novel technologies (e.g., remote sensing data) and open-data repositories, these data requirements often inhibit a simple application of comprehensive modeling approaches in agricultural practice.

Forthcoming, an innovative pixel-based application of the HYDRUS-1D model is implemented for a spatially distributed farm-level crop water demand estimation. Specific intra-site specific areas with homogeneous soil conditions derived from validated soil base maps are used for the delineation of irrigation management zones. Spatially distributed agrometeorological conditions are implemented by freely available data repositories by the German Meteorological Service. Crop-specific root water uptake-rates are simulated via the integration of remotely sensed phenological characteristics. All simulations are applied on a spatial resolution of 50 m x 50 m, accounting for trade-offs between the required accuracy of simulated soil moisture dynamics, the parameterization effort and the accuracy of water application using gun sprinkler irrigation systems under open-field conditions. These approaches may serve as potential measures for improving agricultural irrigation management towards a demand-driven water supply and for implementing distributed soil moisture simulations into easy-to-use irrigation decision support systems.

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