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Modelling Moisture Dynamics of Agricultural Steppe Soils in the Greater Caucasus

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Abstract. *The aim of the work is to study the dynamics of moisture and the process of moisture infiltration in grey-brown ordinary plowed soil under conditions of natural moisture, after precipitation. The relevance of this research problem is also determined by the progressive degradation of the soil cover, its intensive exploitation, the deterioration of the water and nutrient regime of agricultural soils, erosion, desertification, and salinization. Accurate information on the water regime of steppe zone soils is crucial for maintaining their biological productivity. The modeling data correlates well with experimental data on changes in soil moisture, which will allow for future forecasts and hydromeliorative calculations. The main hydrological parameters of the soil (approximation parameters of the main hydrophysical characteristic) of the agricultural landscape soils were obtained using Rosetta Lite pedotransfer functions in the RETC program, using data on particle size distribution, density, porosity, minimum water capacity, wilting point, and yield point moisture content. It was found that the α parameter (the reciprocal of the capillary air entry pressure during soil drying) is significantly lower in the upper arable horizon than in the denser B and C horizons, which is typical for soils subject to tillage. Moisture chronoisopleths were constructed in the Surfer program, clearly reflecting changes in the moisture status of the soil horizons of the arable steppe during and after rainfall. It has been established that, as early as the third day after precipitation and with the initial moisture level in the upper arable horizon, the pressure in all soil layers equalizes. In the absence of a pressure gradient, the downward flow of moisture between horizons virtually ceases.*

Keywords: *capillary-sorption pressure, hydrological and hydrophysical characteristics, soil humidity, pedotransfer functions, modeling, vegetation*

Introduction

Moisture monitoring is a critical factor in crop yield management and adaptation to dry periods. Studying these processes in soils or assessing the impact of tillage operations helps prevent water stress in crops. The processes of water entry into the soil, its subsequent retention and distribution are an important component of the regime of any soil and are significantly determined by the physical properties of the soil – density, porosity, particle size distribution (Bunyatova et al., 2025; Gahramanova et al., 2026; Hasanova & Mammadova, 2023).

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In the dry steppe soils, where atmospheric moisture is practically the only source of water, the process of water absorption and its subsequent redistribution in the soil unsaturated with moisture is of particular interest – infiltration, which divides precipitation on the earth's surface into surface runoff and water entering the soil profile. In Azerbaijan, effective management of irrigation and soil agrophysical properties is critical to protecting crops from precipitation shortages. Automatic weather stations and specialized sensors are used to more accurately calculate water consumption and monitor moisture dynamics (Hasanova et al., 2026; Hasanova Baba-zade et al., 2026; Ismayilov et al., 2025; Ismayilova et al., 2025a).

The primary quantitative characteristic of soil water-holding capacity is the fundamental hydrophysical characteristic the relationship between the capillary-sorption pressure of moisture (Pk-s) and moisture content. Vertical moisture movement in unsaturated steppe soils is characterized by the hydraulic conductivity function the relationship between the coefficient of hydraulic conductivity (Kvl) and Pk-s. The HYDRUS 1D model allows for the calculation and modeling of moisture transfer processes in soils, taking into account their physicochemical and hydrophysical properties (Ismayilova et al., 2025b; Mammadova et al., 2025a; Makki et al., 2025). Using specialized hydrophysical experimental software, HYDRUS 1D accounts for the influence of soil structure on its hydraulic properties and enables the accurate calculation of moisture transfer processes in soils (Mirzezadeh et al., 2025; Mammadova et al., 2026a).

Materials and Methods

Field and laboratory studies were conducted using standard methods. Field moisture was determined using the thermostat-weight method (GOST 5180-84), soil bulk density was determined using the cutting ring method, and solid phase density was determined pycnometrically (Mammadova et al., 2025b). The soil granulometric composition was determined using the Kachinsky pipette method. Total porosity was determined as the ratio of the bulk density of the soil to the density of its solid phase (Mammadova et al., 2026b). The minimum water capacity (LWC) in the field was determined 24 hours after the completion of the flooding experiments for water permeability, the wilting point moisture content (WP) of plants was determined using the potting miniature method (seedlings) according to GOST 28268-89, the liquid limit (SL) was determined according to GOST 5180-84, using a balancing cone, and the maximum hygroscopicity (MH) of the soil was determined by saturating the soil with vaporous moisture according to GOST 28268-89 (Mirzezadeh & Mammadova, 2026; Nasirova et al., 2025).

The subjects of this study were gray-brown ordinary soils of agricultural landscapes on deluvial loamy-gravelly deposits. The basin floor is a vast, gently rolling plain, the topography of which is complicated by the channels of river tributaries. Currently, the soil cover of the basin floor consists mainly of almost completely plowed soils (Mazhar et al., 2025; Madnee et al., 2025). The average annual precipitation in the basin is 450–600 mm, with most of it falling between May and July, during which time the moisture coefficient is 0.7–0.8.

The key to achieving a good harvest in steppe agricultural landscapes is creating optimal moisture and heat conditions in the soil profile. This hydrothermal regime ensures adequate plant nutrition and influences their growth and development. In summer, when moisture is insufficient, cereal crops fail to establish tillers and lag in growth. In such cases, the primary agricultural practices should be aimed at creating moisture reserves in the soil through hydrological reclamation. However, this approach is impossible without knowledge of the basic hydrological properties of the cultivated soils (Ramazanova et al., 2026; Shukurov et al., 2025; Sadigov et al., 2025). The agricultural landscape in question occupies a leveled, topographically uniform area and is represented by a plot of arable land under oat crops. To approximate the main hydrophysical characteristics of agrocenoses, the Van

Genuchten equation, currently the most widely used in global soil science, was used. Soil particle size distribution parameters, adjusted to the FAO International Soil Classification System, were used, along with density data, HB (TH33 in Hydrus 1D), and VZ (TH1500). When calculating the approximation parameters of the main hydrophysical characteristic in the RETC program, additional parameters were specified for more accurate curve construction: the PT indicator – soil moisture in this state corresponds to a pressure of pF = 2.17, as well as the MG indicator, corresponding to pF = 4.5. Modeling of vertical moisture transfer in the basin soils was carried out in HYDRUS-1D for a 7-day period, consisting of no precipitation on the first day, followed by two days of rain with varying intensity, and then four days of virtually no precipitation (Sadigov et al., 2026; Verdiyeva et al., 2025).

Soil moisture samples were collected on the evening of July 10; in triplicate, several days before sampling (July 6 and the morning of July 10) it rained, and the upper arable horizon was noticeably wetter than the underlying soil layers. The moisture content of the A arable horizon was 26% (0.279 cm^3/cm^3), the B horizon – 18.5% (0.211 cm^3/cm^3), and the C horizon – 15% (0.176 cm^3/cm^3). Over the next two days (July 12 and 13), rain fell, with precipitation amounts of 18 and 7 mm. On July 14 and 15, only 0.5 mm of precipitation fell. There was no precipitation on the last two days of the study period, July 16 and 17. A second moisture sample was taken four days after the rain, on July 17 (before the evening rain). To model soil moisture movement during the study period, five periods differing in precipitation amounts were defined in the Time Variable Boundary Condition. Under conditions of high humidity and cool daytime temperatures, evapotranspiration will not significantly influence moisture dynamics in the upper horizon.

For the initial and final conditions, we adopted a potential transpiration value of 0.12 mm/day. To account for water uptake by plant roots, the Root Water Uptake option was selected in the Main process, and the appropriate root uptake parameters for a given crop were entered from the built-in database in The Root Water Uptake Parameters. The "Corn – vegetative period" was selected, during which optimal water uptake by oat roots (between P_{opt} and P2 pressures) occurs within a soil water pressure range of -25 to -500 cmH_2O, which corresponds to the initial natural conditions of water content (and pressure) in the studied steppes on the study dates. Chronoisopleths of soil moisture were plotted using Surfer. Using the Soil Profile – Graphical Editor, when plotting the distribution of root systems at depths of 0–15 (or 0–20) cm, the root density was set to a constant value, decreasing linearly throughout the profile depth (Nasirova et al., 2026; Verdiyeva et al., 2026).

Results and Discussion

The bulk density of the soil under study increases with depth, while the texture of the lower horizon is finer than that of the upper and middle horizons. The wilting point moisture content can also be determined by calculation, multiplying the maximum hygroscopicity of the soil under study by factors ranging from 1.3 to 1.6. For example, a factor of 1.35 is used for wheat. The wilting point moisture content values we obtained using the seedling method (according to GOST 28268-89) correlate with the maximum hygroscopicity index within ranges from 1.2 to 1.48. According to the study results, the maximum values of water-holding capacity and residual moisture are characteristic of the upper humus arable horizon, while the minimum values are characteristic of the parent material. A similar pattern was previously observed in leached soils. Using additional soil-hydrological data (expressed in % moisture) to calculate the approximation parameters of the main hydrophysical characteristic of the plowed depression soils significantly adjusted the shape of the resulting water-holding curve. When calculating the approximation parameters of the main hydrophysical characteristic, taking into account the wilting point, maximum hygroscopicity, and yield point, the saturation moisture content, residual moisture content, α, and n values changed significantly, especially in the upper soil horizon. The A arable horizon showed a very low α value the reciprocal of the air entry pressure into large capillaries as the soil dries immediately after saturation. The air entry pressure into large capillaries itself graphically corresponds to the location of the first inflection in the curve of the main hydrophysical characteristic: when the soil moisture pressure is close to 0 and begins to decrease as the soil dries, soil moisture content does not change immediately. Initially, only a change in the curvature of the capillary meniscus occurs, after which some of the large capillaries empty and air enters. It is believed that soil cultivation methods influence its physicochemical properties and key soil-hydrological characteristics: for example, the α value is significantly lower in soils that are constantly subject to plowing than in soils in natural landscapes. Scientists have found that the α value in soils cultivated without moldboard cultivation ($\alpha = 0.0227$) is higher than in traditionally tilled soils ($\alpha = 0.0187$).

Our previous studies also showed that in soils that are not subject to annual tillage (under hayfields), the α value is significantly higher than in soils under oats. To simulate the dynamics of moisture in Hydrus 1D, the initial soil moisture pressure was set for each horizon (without a smooth decrease) in the graphical editor under Initial conditions, corresponding to the initial moisture content: 450 cm H_2O in the upper arable horizon, 600 cm H_2O in the B horizon, and 900 cm H_2O in the lower horizon. The soil moisture pressure was determined based on the curves of the main hydrophysical characteristics obtained in the RETC program and the measured moisture content at the time of sampling. Since the precipitation rate of 1.8 cm/day is significantly lower than the filtration coefficient in the arable horizon (88 cm/day), complete saturation of the soil with moisture (to the level of $\theta s = 0.459$) cannot occur under natural steppe conditions. The moisture content in ordinary chestnut soils after precipitation of 18+7 mm was 0.316 cm^3/cm^3, or 30%, which is slightly below the level of the least water capacity (0.35 cm^3/cm^3, or 33%). The underlying layers (B and C horizons), under conditions of periodic moistening of the upper horizon, gradually become saturated with moisture; downward moisture outflow from the A to B and further to the C horizon occurs even during periods of no precipitation.

However, the high density of the B and C horizons prevents rapid moisture penetration into them. Water loss from the upper horizon, under conditions of high atmospheric humidity and insignificant evapotranspiration (but taking into account root moisture consumption), occurs gradually. At the end of the period under consideration, the pressure in all soil layers is practically equalized and the downward flow of moisture from the upper horizon to the lower ones practically ceases on the 7^{th} day (Fig. 2a). On the first day of the experiment, July 11, when there was no precipitation, the moisture content in the upper soil horizon decreased due to root water consumption, transpiration, and downward moisture flow. The latter was reflected in an increase in moisture content in the B and C horizons and a gradual vertical equalization of soil moisture pressure (Fig. 2b). After rain on July 12 (18 mm), the moisture content in all soil horizons increased significantly. The second rain (7 mm) on July 13 did not lead to a significant increase in moisture content in the upper A horizon – the moisture moved deeper into the soil profile (Fig. 1a and 1b).

Over the next two days, the moisture content in the upper arable horizon decreased due to root water consumption and downward moisture flow, and the B and C horizons continued to become moist. However, by the 7^{th} day of the experiment, the pressure in all soil layers equalizes; in the absence of a difference in pressure, the downward flow of moisture between horizons ceases, and the moisture content begins to gradually decrease not only in the A horizon, but also in the B and C horizons as a result of root consumption and the evapotranspiration process. Moisture penetration between the upper loosened and less dense arable horizons is hindered, in part due to the higher density of the B horizon. The high moisture capacity of the upper loose arable horizon does not ensure optimal water management throughout the entire soil layer. The difference in soil water pressure levels out fairly quickly, and further moisture saturation of the B and C horizons slows, although differences in moisture content remain noticeable. Moisture exchange between the B and C horizons occurs fairly uniformly. When comparing moisture data obtained experimentally and using HYDRUS 1D modeling, the results were found to be consistent, with small discrepancies (less than 5%). The model slightly underestimates moisture content in the A and B horizons, which may be due to an overestimate of moisture loss due to transpiration (in the A horizon). The discrepancy in the data may also be due to the hysteresis effect of the main hydrophysical characteristic, which was not taken into account in the modeling. It is known that, at the same moisture pressure, the moisture content of the main hydrophysical characteristic obtained during drying will be higher than during wetting. This may be why the actual moisture content of the soil, which gradually loses moisture during drying, turned out to be slightly higher than the calculated value.

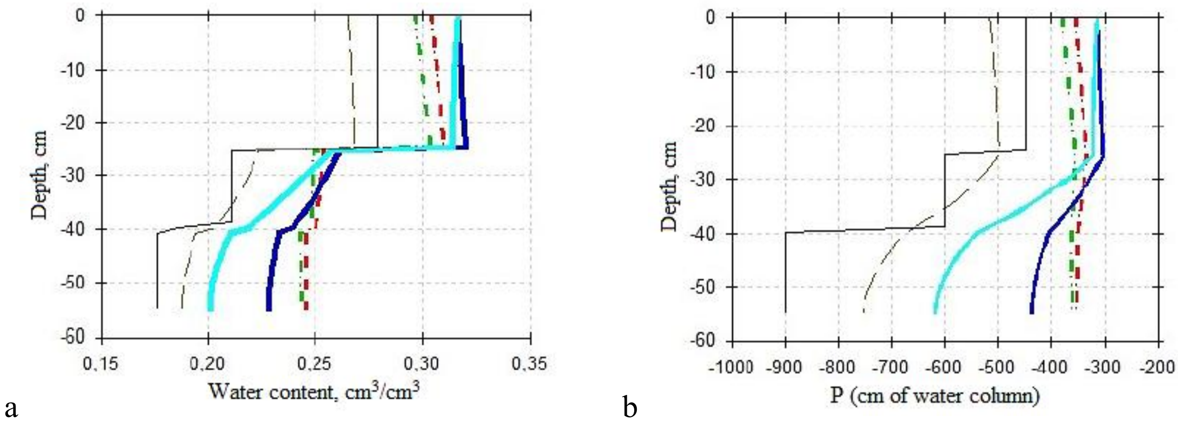

Figure 1

Dynamics of volumetric moisture: a) and moisture pressure; b) in a plowed field under oat crops in July 2024 under conditions of natural atmospheric moisture, after 25 mm of precipitation

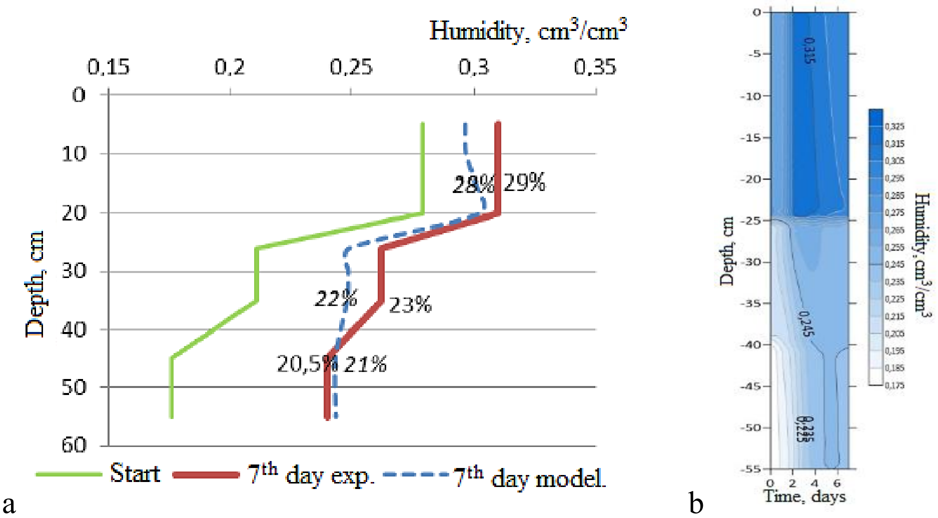

Figure 2

Actual and estimated moisture content of steppe soil horizons (a); Chronoisopleths of soil moisture in plowed steppe (based on the results of soil moisture movement modeling in Hydrus 1D) (b)

Note. By authors in July 10 and 17, 2024

Conclusion

Using the pedotransfer functions of the RETC program, hydrological parameters of the upper arable soils of steppe agrolandscapes were obtained and analyzed. It was found that the approximation parameter of the main hydrophysical characteristic of the A horizon – the α index (the reciprocal of the air inlet pressure) – is significantly lower in the upper horizon, which is constantly exposed to plowing, than in the B and C horizons. Using Hydrus 1D, soil moisture dynamics were modeled under natural moisture conditions over a 7-day summer period. It was found that the high moisture capacity of one upper arable horizon under oat crops does not ensure an optimal water regime for the entire soil layer. The resulting modeled moisture dynamics parameters for ordinary gray-brown soils were in good agreement with experimental soil moisture data, with the discrepancy being within 5%. It is possible that the reason for the discrepancy in the data is the hysteresis effect of the main hydrophysical characteristic, which was not taken into account in the modeling, and the actual moisture level in the gradually drying soil is slightly higher than the calculated one. Good water permeability of the upper arable horizon does not necessarily mean optimal water conditions for the entire soil layer.

Declaration of Competing Interests

The authors declare that they have no competing interests. T.H. is an Editor of the journal, and G.M. is a member of the Editorial Board. Neither T.H. nor G.M. was involved in the editorial evaluation or publication decision concerning this manuscript.

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