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Automatic system for moisture regime observation in the unsaturated zone of the loess complex

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Резюме. Настоящата статия е посветена на целта и напредъка на дейностите, предприети в рамките на проекта ДФНИ-Е 02/4. Целта на проекта е да се определи количествено водният поток през ненаситената зона на льосовия комплекс, който е широко разпространен в Северна България. В резултат на значителна изменчивост на валежите и изпарение, потока на влага променя посоката от низходяща към възходяща. Този процес ще бъде моделиран с помощта на HYDRUS-1D, а полевите данни са необходими, за да се осигурят както параметри, така и времеви серии за калибриране на модела. В резултат на този процес в кратък времеви мащаб, воднобалансовите елементи могат да бъдат оценени от гледна точка на сезонни и многогодишни вариации.

В рамките на проекта са организирани два експериментални участъка: в Североизточната и в Северозападната част на страната. В тази статия подробно описание е дадено само за първия участък (в близост до град Русе). Оборудването на експерименталните участъци се състои от метеостанция с допълнителни сензори, разположени на три нива под земята (тензиометри и датчици за съдържание на почвената влага). Всички данни от измерванията могат да бъдат видени и изтеглени от определен уебсайт в реално време. Досега системата показва стабилна работа и логични стойности на данните. На втория етап на проекта получените резултати ще бъдат анализирани и моделирани.

Ключови думи: льос, ненаситена среда, воден баланс, подхранване на подземните води

Abstract. This paper is devoted to the objective and progress of the activities undertaken in the frames of the project DFNI-E02/4. The aim of the project is to quantify water flow within the unsaturated zone of the loess complex, which is widespread in North Bulgaria. With respect to substantial variability of precipitation and evaporation, water fluxes change their direction from downward to upward. This process will be modeled using the HYDRUS-1D software. The field data are necessary to provide both soil hydraulic parameters and time-series for calibration of the model. As a result of the modeling process, components of the water balance could be shown at large time scales - seasonal and multiannual variations.

In the frames of the project two experimental sites were established: in Northeast and in Northwest of the country. In this paper, the detailed description is given only for the first site (near to the city Ruse). The equipment of experimental sites consists of a meteorological station with additional sensors installed at three levels below the ground (tensiometers and sensors for soil moisture content). All the data from the sensors can be seen and downloaded from a particular web site in real time. Up to now, the time-series show a stable work of the system and consistent values of the data. During the second stage of the project, the collected data will be analyzed and modeled.

Keywords: loess, unsaturated medium, water balance, groundwater recharge

Introduction

Water is a valuable yet limited resource. As a part of hydrologic cycle, it is influenced by climate variability. In view of the tendencies for more frequent droughts in Bulgaria, there is a concern for a possible increase in water shortages. Groundwater resources become increasingly important in a changing climate scenario, taking into account that aquifers may store large amounts of water and are less prone to evaporation (Sukhija, 2008). Population in many rural areas of Bulgaria relies on groundwater as their primary source of drinking water.

The groundwater recharge is defined as "the residual flux of water added to the saturated zone, resulting from evaporative, transpiration and runoff losses of precipitation", and it is "a sensitive function of various climatic factors, local geology, topography, and land use" (Dragoni, Sukhija, 2008).

Widespread loess sediments with a typically deep unsaturated zone are a specific feature of North Bulgaria. Different methods were applied in Northern Bulgaria to evaluate groundwater recharge, including hydrograph separation techniques (Spasov, 1966, 1969), groundwater level fluctuations method (Spasov, 2012), soil water balance studies (Orehova et al., 2012, Vasileva, Orehova, 2015), and lysimeter studies in the Karaboaz lowland (Diankov, 2015).

The obtained results provide common features and spatial variations in this large area. Up to now no detailed studies were conducted to assess the groundwater recharge variability with respect to changing precipitation inputs within the loess cover in Northern Bulgaria. Fertile chernozems are developed on the top of the loess complex, and this area is important for agricultural activity. On the other hand, a relatively low permeability of loess along with a deep unsaturated zone favored the location of the Nuclear Power Plant near Kozloduy.

In general, water flux occurs as a diffuse infiltration through the unsaturated zone. This process may be modeled using the HYDRUS-1D software (Šimůnek et al., 2008). The field data are necessary to provide both the soil hydraulic parameters and time-series for calibration of the model. As a result of the modeling process, various components of the water balance can be evaluated at time scales of seasonal and multiannual variations.

In the frames of the project DFNI-E02/4 supported by the Bulgarian Fund for scientific research, two automatic weather stations, each coupled with a system for observation of the soil moisture regime, have been installed within a typical plain terrain of the loess complex in North Bulgaria. An experimental site № 1 is located near the city of Ruse and an experimental site № 2 in the town of Kozloduy. In this paper, a special attention is paid to the site № 1.

During the first stage of the project, the main task is the installation of the equipment at two study sites, along with sensors. The obtained time-series will be used to model unsaturated flow in the loess complex.

In the short term, the task of the study is to observe and present the dynamics of water flow, i.e., the real movement of moisture in the unsaturated zone at certain depths as a result of the water entry at the land surface. Thus, meteorological data at the same site are necessary. As a result of this process, in the longer time scale, the components of the water balance will display seasonal and multi-annual variations with respect to climate variability.

The purpose of this paper is to describe the concept of the ongoing research with a specific attention to the study site, project equipment and first results. Although in the frames of the project, two experimental sites were equipped, a specific attention is paid in this manuscript only to the study site № 1 in the Ruse city. Future steps for data processing and modeling are briefly described.

The Danubian plain and characterization of the loess complex

The Danubian plain is located in North Bulgaria. The loess complex occupies about 13% of the territory of the country (about 14 000 km^2), and the major part of it is developed within the Danubian plain – about 12 000 km^2. The loess here is mainly of the aeolian origin, the transfer of the silty material being from north and northeast.

The largest thickness of the loess cover is along the Danube River where it varies from 40-50 up to 100 m. Up to seven "paleosols" (fossil soils), intercalate respectively up to eight loess horizons, denoted as L1 to L8, listed by their position from top to bottom (Evstatiev, Evlogiev, 2008). The number of these fossil soils decreases from north to south where they join in a single soil complex several meters thick in the most southern part of the loess province (Evlogiev, 2006).

In general, the loess complex within the Danubian plain is under typical unsaturated conditions. Locally, the so-called "hanging valleys" are found – these small gullies are periodically watered and hence temporal perched aquifers are formed below them, usually on the fossil soil located between the L3 and L4 horizons. In urban areas, water losses from damaged pipes are common, and then technogenic perched aquifers may be formed, usually above the L1 and L2 horizons.

From hydrogeological point of view, the loess complex can be divided into three horizons (Minkov, 1968):

- upper horizon (with a thickness of 3 to 5 m) where water content shows seasonal variations;
- medium horizon (with a thickness of 5 to 30 m) with weak fluctuations in soil moisture;
- bottom horizon (a zone of the capillary rise), which is connected to groundwater in the gravel layer that underlies the loess complex. The height of the capillary rise varies, but could be up to 2.5 m.

Loess is a collapsible soil, and the respective deformation processes are registered in the city of Ruse, mainly related to the human impact, such as water losses from pipes (Evstatiev, Antonov, 2005).

The climate in Northern Bulgaria is temperate, with cold winters and hot summers. Mean annual precipitation near the Danube River is about 450–500 mm a^{-1} (Koleva, Peneva, 1990). Maximum rainfalls occur in May and June, and minimum rainfalls are in February. The precipitation sum during the cold half of the year is about 40% of the annual sum. The snow cover in the Danubian plain is not stable, it lasts usually less than 100 days.

The soils overlaying the loess are mainly fertile chernozems and the major land use is for agricultural activities. The soil texture within the loess complex varies from sandy loess to clayey loess, depending on the horizontal and vertical location. The hydraulic conductivity varies from 1.0 – 2.5 m d^{-1} (sandy loess) to <0.1 m d^{-1} (clayey loess) according to Minkov, Evstatiev (1962).

In addition, the soil hydraulic parameters of the loess complex near Kozloduy, Northwestern Bulgaria, were determined by Antonov et al. (2012). The methods included laboratory tests of undisturbed samples, and in situ borehole infiltration tests. Soil hydraulic properties were evaluated by means of an inverse optimization technique provided by HYDRUS-2D.

Project concept and objective

The ongoing project DFNI-E02/4 (2015-2016) entitled "Application of up-to-date methods and technologies for evaluation of the groundwater recharge related to future climate change in Bulgaria, with emphasis on the vadose zone" and with a project leader Assoc. Prof. Tatiana Orehova is supported by the Bulgarian Fund for Scientific Research. The overall goal of this project is to observe and model water flow in the unsaturated zone at two study sites located in Northern Bulgaria. For this purpose, two experimental sites were established in Ruse and Kozloduy. A weather station were installed at each site. Additionally, sensors (both for soil moisture and pressure head) were installed in the undisturbed vertical soil profile at different depths.

Coupling of data from the meteorological station and soil sensors is essential for the project. Time-series from the meteorological station and soil sensors are necessary input data for the assessment and modeling of water flow in the unsaturated zone under different weather and soil conditions. Water fluxes in the loess cover are due to changing weather conditions mostly upward and downward. Therefore, a one-dimensional program for water flow modeling, such as the HYDRUS-1D code, is a suitable tool to quantify the respective fluxes that form water balance on the land surface.

Groundwater recharge is defined as downward flow of water reaching the water table (de Vries, Simmers, 2002). Potential groundwater recharge is defined as water that percolates beyond the root zone. Low-permeable horizons within the loess complex may impede groundwater recharge.

Generally, the thick loess cover restricts downward infiltration of water and thus reduces groundwater recharge of the underlying gravel aquifer, which occurs more likely under lesser thickness of the loess complex.

Gathering long-time series data from the parallel measurements of the soil moisture and pressure head within the undisturbed loess horizon would allow estimation of soil hydraulic parameters of the loess in situ. In addition, such equipment of the experimental sites that provides monitoring of the soil moisture regime at different depths down to 2 meters below the surface is innovative as there are no other published studies on such topic till December, 2015.

As the project focuses on the processes in the unsaturated zone with respect to changing weather conditions, the locations of the two experimental sites were chosen in the North-Western and North-Eastern Bulgaria as the main atmospheric fronts differ there.

Location of the experimental sites

The study site № 1 is located in Northeast Bulgaria close to the Danube River and west of the Ruse city, within the Geotechnical Research Station of the Geological institute at the high river bank. The terrain is flat, and the loess deposits are approximately 30 m thick. The structure of the loess complex is presented in Fig. 1.

The study site № 2 is located in the Kozloduy town (Northwest Bulgaria), near to the office of „Kozloduy NPP - New Power", Ltd.

Project equipment

According to the project goals the monitoring program includes standard meteorological observations: air temperature and humidity, precipitation amount, wind speed, and solar radiation. In addition, sensors for matrix water potential and sensors for soil moisture were installed at three depths, namely 0.55, 1.00, and 1.50 m at experimental site № 1 (Fig. 1) and 1.0, 1.5, and 2.0 m at experimental site № 2. Particular elements of the meteo-station are as follows: a wind speed sensor produced by THIES CLIMA; a solar radiation sensor (pyranometer) - PYR Decagon; a sensor for air temperature and relative humidity with solar radiation shield - E+E Elektronik; a professional rain gauge – PRONAMIC; a sensor for soil moisture content 10HS – Decagon; a tensiometer MPS-6 – Decagon. The whole station is operated by the GPRS Datalogger produced by ADCON. The technical specifications of particular sensors are shown in Table 1.

According to the aim of the project, a special attention was paid to the sensors placed in the ground and to the operating device – the data logger. The advantage of the tensiometer MPS-6 consists of the dramatically improved accuracy in comparison with the pre-existing types of sensors, a long-lasting body with salts insensitivity, i.e., the sensor is accurate in salty environments, with no recalibration required and with an excellent range of measurements.

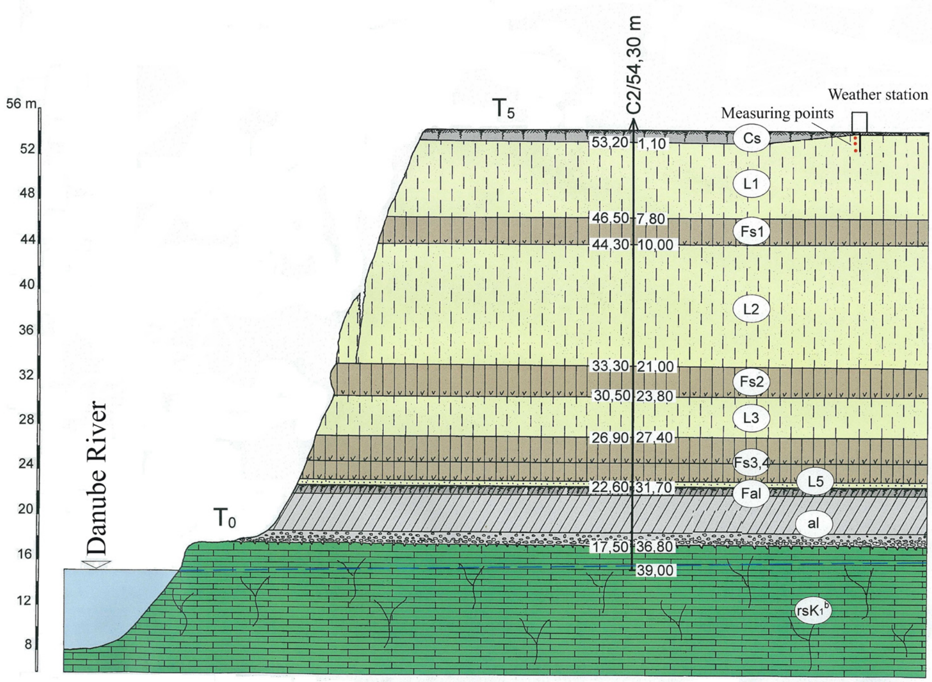

Fig. 1. A cross-section of the loess complex at the experimental site, the Ruse city (Evlogiev, 2015)
Фиг. 1. Профил през льосовия комплекс при експерименталната площадка, гр. Русе (Evlogiev, 2015)

The soil moisture sensor 10HS allows accurate measurements of water content in a large volume of influence with minimal salinity and textural effects. The data logger is an autonomous device powered by a solar panel. It operates all the above-mentioned sensors and transfers the discrete measurements (at a certain time step) in a 24/7 format via wireless connection (GPRS) to a specific web site. Practically, the data logger together with the sensors form an automatic system for observing the moisture regime. In addition, it is possible to change the time interval step on any time length due to the small file size of the transferred data.

Table 1. Main technical specifications of the installed sensors
Таблица 1. Основни технически спецификации на инсталираните сензори

Sensor, **type**	Type of measurement, units	Accuracy	Resolution	Range	Measurement time
Matrix water potential sensor, **MPS-6**	Pressure head (matrix potential), kPa	±(10% + 2 kPa) from -9 to -100 kPa	0.1 kPa	-9 to -100000 kPa	150 ms
	Temperature, °C	± 1°C	0.1°C	-40° to 60°C	150 ms
Soil moisture sensor, **10HS**	Volumetric water content, %	Apparent Dielectric Permittivity, ε_a: ±0.5 from ε_a of 2 to 10; ±2.5 from ε_a of 10 to 50	ε_a: 0.1 from εa of 1 to 30; 0.2 from εa of 30 to 50 VWC: 0.0008 $m^3 m^{-3}$ (0.08% VWC) in mineral soils from 0 to 0.50 $m^3 m^{-3}$ (0-50% VWC)	ε_a: 1 (air) to 50 VWC: Calibration dependant; up to 0 - 57% VWC with polynomial equation	10 ms
Solar radiation sensor, **PYR**	The solar radiation flux from a field of view of 180 degrees, W m^{-2}	± 5%	N/A	380 - 1120 nm* (*spectral range) 0 to 1750 W m^{-2}	N/A
Small wind transmitter sensor, **4.3515.50**	Wind speed, m s^{-1}	±0.5 m s^{-1}	0.4 m (wind run)	0.5 - 40 m s^{-1}	N/A
Rain and precipitation gauge, **Rain-O-Matic Professional**	Precipitation, mm	+/- 2%	1 mm	self-emptying tipping bucket	less than 300 ms
OEM humidity and temperature transmitter, **EE060**	Temperature, °C	±0.3°C at 20°C	0.1°C at 25°C	-40°C to 60°C	N/A
	Relative humidity, %	± 2.5% at 20°C	0.5% RH at 20°C	0 to 100% RH between 0° and 50°C	N/A

First results and future steps

A general view of the experimental site pit is shown in Figure 2. In order to keep the soil profile at natural (i.e., undisturbed) conditions, a special digging technique was used. The loess was excavated manually and stored apart at different places according to the depth of digging. Then a pair of sensors (for moisture content and water potential) were installed starting in the lower part up to the upper part of the profile. The distance between both sensors was chosen such so that they would not interact electrically with each other and still represent “a point” measurement. The tight placement of each sensor into the undisturbed complex was done by using the technique explained in the operation manuals. As it was noted above the depths were 1.5, 1.0 and 0.55 meters. The strict vertical strip location of the three “points” was followed well (Fig. 2).

Fig. 2. An experimental site pit with three measuring points
Фиг. 2. Шурф на експерименталната площадка с трите измервателни позиции

The meteorological sensor units and the data logger were then placed above ground. Once the system started transferring data from the experimental site to the Internet, the pit was carefully backfilled untill pre-existing natural conditions were reached.

As it was set in the aim of the project, all the data from the sensors could be seen and downloaded from a particular web site in a real time. In that sense, "a real time" is a period between the data transfer (by the data logger) to the web site, and thus it varies from 5 to 55 min (there was one exception of about 3 hours) depending on the local Internet speed.

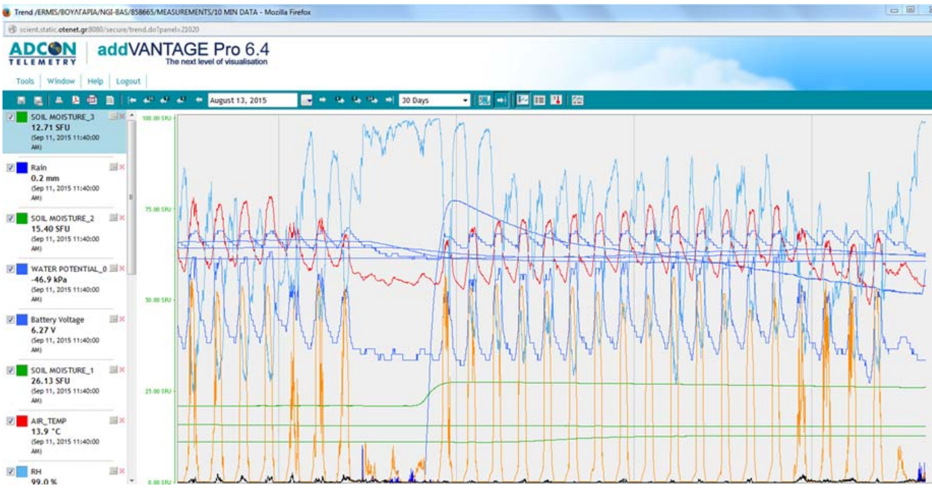

Fig. 3. A screenshot of the project web site showing all measurements in the graphical mode for a given time period
Фиг. 3. Снимка от интернет сайта на проекта показващ в графичен режим всички измервания за определен интервал от време

The measurements themselves are limited to milliseconds, with the exception of the rain precipitation gauges. A display of selected results at the web site is shown at Fig. 3.

The system started working in the middle of August. Two distinct periods could be distinguished till the middle of December, especially in the soil moisture regime observations. During the first period (from the middle of August till the end of October), the soil moisture and matrix water pressure sensors responded adequately to the dry weather, i.e., recording a slow decrease or constant values of water contents and hence a slow increase or constant values of soil water pressures. During the second period (from the beginning of November till the middle of December), due to intense precipitation, the underground sensors started working much more intensively following the precipitation input.

The following activities will be performed as future steps, based on year-round data collection:

(*i*) data processing in order to couple the results of the soil moisture dynamics and the matrix water potential;

(*ii*) evaluation of the water balance elements, including evapotranspiration;

(*iii*) evaluation of downward fluxes (groundwater recharge);

(*iv*) modeling of unsaturated flow, i.e., implementation of the observed data into the HYDRUS-1D code.

Conclusion

In the framework of the project supported by the Bulgarian Fund for Scientific Research, an automatic system for moisture regime observation was installed at two experimental sites located on the unsaturated loess complex. Each system includes a weather station, sensors for measuring soil water contents, and tensiometers, all operated by a GPRS data logger. The four months exploration period in Ruse shows a stable functioning of the system and consistent values of the time-series data. The installed equipment will provide input information in order to quantify water fluxes within the studied area.

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