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Estimation of evapotranspiration rate by using the Penman–Monteith and Hargreaves formulas for the loess in Northeast Bulgaria complex with HYDRUS-1D

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Abstract. Loess and loess-like sediments cover approximately 13% of the Bulgarian territory, mainly within the Danubian plain. From the Danube River to the Fore-Balkan, the loess soils form a loess complex where its depth varies from 50–60 meters in the north to few meters in the south, respectively. Widespread loess sediments possess a specific feature: they typically form deep unsaturated zones. Quantification of the near surface water balance is extremely important for evaluating land-atmosphere interactions, and the impact of land-use change on the subsurface flow and the evapotranspiration rate is an essential term in this quantification. In the frames of a scientific project, an automatic weather station was installed in a typical plain terrain of the loess complex in Northeast Bulgaria, recording meteorological data from September 2015 to February 2017.

This study provides a mathematical description of processes (*i.e.*, Penman-Monteith and Hargreaves Methods) used to estimate daily evapotranspiration rates implemented into the numerical model HYDRUS-1D, as well as a respective rate investigation of months with and without intensive rainfalls. Overall results indicate that using the Hargreaves formula for evaluation of the potential evapotranspiration leads to overestimation between 10% and 20%, respectively for a "wet" and "dry" month.

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Keywords: evapotranspiration, unsaturated medium, computer modeling.

INTRODUCTION

The loess complex occupies about 13% of the territory of Bulgaria (about 14,000 km^2), and the major part of it is developed within the Danubian plain about 12,000 km^2. The largest thickness of the loess cover is along the Danube River, where it varies from 40–50 m up to 100 m and decreases in southern direction (Minkov, 1968; Evlogiev, 2006). Widespread loess sediments with a typically deep unsaturated zone are a specific feature of North Bulgaria (Minkov, 1968).

On the other hand, no detailed studies have so far been conducted to assess the groundwater recharge variability with respect to changing precipitation inputs within the loess cover in North Bulgaria. Fertile chernozems are developed on the top of the loess complex, and this area is important for agricultural activity. In addition, a relatively low permeability of loess, along with a deep unsaturated zone, favors the location of the Nuclear Power Plant near Kozloduy (Stoyanov, 2009). In general, water flux occurs as a diffuse infiltration through the unsaturated zone. This process may be modeled, using the modern computer programs for water flow modeling in variably-saturated media. In connection with this, field data are necessary in order to provide time-series for evaluation and calibration of the model. As a result of the modeling process, various components of the water balance can be evaluated at time scales of daily, monthly, seasonal and multiannual variations.

Water balance modeling is one of the few available tools that can be used to predict groundwater recharge, which is critical for assessing water resources and aquifer vulnerability to contamination. Quantification of the near-surface water balance is extremely important for evaluating land–atmosphere interactions, and the impact of climate change and land-use change on the subsurface flow (Šimůnek, 2015) and evapotranspiration rate is an essential term in this quantification.

In the frames of a scientific project supported by the Bulgarian Fund for Scientific Research, an automatic weather station was installed in a typical plain terrain of the loess complex in Northeastern Bulgaria (so-called experimental site), recording meteorological data from September 2015 to February 2017.

The study provides a mathematical description of processes implemented into the numerical model HYDRUS-1D, especially for those used to estimate daily evapotranspiration rates, as well as to investigate months with and without intensive rainfalls (*i.e.*, March and July 2016).

MATERIAL AND METHODS

Natural setting and site apparatuses

The experimental site is located in Northeast Bulgaria, close to the Danube River and west of the city of Ruse at the high river bank. The climate is temperate and, in March of the particular year of the study, the total amount of rainfall was somewhat abundant (65.6 mm), which is 13% of the average annual precipitation (AAP) for this area. In contrast, in July the amount of rainfall was only 2.6% from the AAP. The terrain is flat, and the loess deposits are approximately 30 m thick. The particular elements of the meteo-station are: 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 Rain-OMatic Professional. The whole station is operated by the GPRS data logger produced by ADCON Telemetry (Fig. 1). The recording interval was set to 20 min for the period September 2015–February 2017. All data were transferred online. The exact specifications of the equipment are described in detail by Antonov *et al*. (2015).

Code and Model description

The program HYDRUS-1D numerically resolves the advection-dispersion equation on the basis of the solution of the partial differential equation of Richards and incorporates several modules for solute transport, CO_2 transport, root-water uptake, etc. For the evaluation of potential evapotranspiration, HYDRUS-1D incorporates two often used methods or formulas, namely the Penman-Monteith Method and Hargreaves Method (Leterme *et al*., 2012).

Fig. 1. General overview of the weather station at the study site.

Hargreaves equation

For determination of the potential evapotranspiration ET_p over the investigated area, the Hargreaves Formula (Hargreaves, 1994) integrated in HYDRUS-1D (Šimůnek *et al.*, 2008) was used for each day of March and July, given by:

$$ET_p = 0.0023 R_a \left(T_m + 17.8\right)\sqrt{TR},$$

where R_a is the extraterrestrial radiation in the same units as ET_p [*e.g.*, mm/d or J/(m^{2}s)], T_m is the daily mean air temperature, computed as an average of the maximum and minimum air temperatures [°C], *TR* is the temperature range between the mean daily maximum and minimum air temperatures [°C]. The extraterrestrial radiation can be calculated as follows:

$$R_a = \frac{G_{sc}}{\pi} d_r \left(\omega_s \sin\varphi \sin\delta + \cos\varphi \cos\delta \sin\omega_s\right),$$

where G_{sc} is the solar constant [J/(m^{2}s)] (1360 W/m^2); φ is the site latitude [rad]; ω_s is the sunset hour angle [rad]; d_r is the inverse relative distance Earth–Sun [-]; and δ is the solar declination [rad]. The last three variables are calculated as follows:

$$\omega_s = \arccos\left(-\tan\varphi \tan\delta\right)$$

$$d_r = 1 + 0.033 \cos\left(\frac{2\pi}{365} J\right)$$

$$\delta = 0.409 \sin\left(\frac{2\pi}{365} J - 1.39\right),$$

where *J* is the number of the day in the year [-].

Penman-Monteith Combination equation

By defining the reference evapotranspiration (ET_0) as the rate of evapotranspiration from a hypothetic crop with an assumed crop height of 12 cm, a fixed canopy resistance of 70 s/m and an albedo of 0.23, closely resembling the evapotranspiration from an extensive surface of green grass of uniform height, actively growing, completely shading the ground and not short of water, the estimation of ET_0 can be determined with the combination formula based on the Penman-Monteith approach (Allen *et al.*, 1998; Šimůnek *et al.*, 2008). When combining the aerodynamic and radiation terms, the combination formula can be written as:

$$ET_0 = \frac{0.408\Delta\left(R_n - G\right) + \gamma \frac{900}{T+273} U_2 \left(e_a - e_d\right)}{\Delta + \gamma\left(1 + 0.34 U_2\right)},$$

where ET_0 is the reference crop evapotranspiration [mm/d]; R_n is the net radiation at crop surface [MJ/(m^{2}d)]; *G* is the soil heat flux [MJ/(m^{2}d)]; *T* is the average temperature [°C]; U_2 is the wind speed measured at 2 m height [m/s]; ($e_a - e_d$) is the vapor pressure deficit [kPa]; Δ is the slope vapor pressure curve [kPa/°C]; γ is the psychrometric constant [kPa/°C]; and 900 is the conversion factor.

Modeling schematization

For the purpose of our investigation, a vertical profile model is elaborated for the study site. One-dimensional model is proposed. The schematization is in accordance with the field observation data, using information about the sediment layers' depth with the respective five hydraulic parameters for the first 0.55-cm loess layer determined by pedotransfer function analysis of the grain-size distribution curve (Schaap and Leij, 1998; Schaap *et al.*, 2001). The initial condition is set equal to the examined *in situ* pressure head (Antonov *et al.*, 2018). The bottom boundary condition is set to free drainage condition and the upper boundary condition represents the number of time-variable boundary records (*e.g.*, the precipitation records for March and July taken from Tables 1, 2).

RESULTS AND DISCUSSION

In March, according to the Penman-Monteith formula, the evapotranspiration rate varies from 0.3 mm/d to 4.6 mm/d. For the Hargreaves formula, the same period shows ET_p rate from 0.6 mm/d to 4.1 mm/d (Fig. 2). In general, both plots represent similar tendencies during the month but not exact values of the results. Exact or similar values (with a difference of 0.1 mm/d) of the evapotranspiration rates are observed when the ET_p process is increasing (*e.g.*, on the 3rd, 6th, 14th, 17th, 21st and 26th of March, although such tendency cannot be seen from the 27th to the 31st of March, when the Hargreaves calculations determine strictly increasing rate from 2.4 mm/d to 4.1 mm/d, and the Penman-Monteith ones determine an oscillating pattern in the range of 1.8–4.6 mm/d). In case of summation of the daily ET_p rates for the whole month, the Penman-Monteith and Hargreaves formulas produce values of 57.6 mm/month and 64.4 mm/month, respectively. Thus, there is an overestimation of the rate if the latter formula is used, although the overestimation is about 10%. Similar result has been observed during a comparative analysis of reference evapotranspiration research in central Serbia (Alexandris, 2008).

Table 1

Meteo data for March 2016 used in the Penman-Monteith and Hargreaves Formulas

Month, year	March, 2016									
Date	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
Day in the year [DOY]	61	62	63	64	65	66	67	68	69	70
Precipitation [cm/d]	0.06	0.02	0.00	1.58	0.30	0.00	0.00	0.04	0.40	0.46
Air temperature, min [°C]	10.4	6.0	3.0	5.2	4.8	2.5	6.9	8.6	9.2	7.1
Air temperature, max [°C]	20.5	15.6	17.7	9.0	14.9	20.4	21.7	19.1	11.3	10.1
Net radiation [MJ/(m^2d)]	7.49	9.46	9.45	1.72	11.67	12.45	6.66	11.43	2.18	1.37
Wind speed [km/d]	7.62	11.52	18.06	11.58	8.88	9.72	19.68	7.62	7.56	18.12
Humidity [%]	72.93	81.56	80.91	96.40	84.84	72.58	63.30	75.52	94.52	94.98
Date	11th	12th	13th	14th	15th	16th	17th	18th	19th	20th
Day in the year [DOY]	71	72	73	74	75	76	77	78	79	80
Precipitation [cm/d]	0.14	0.04	0.2	0.04	0.00	0.00	0.00	0.00	0.06	0.06
Air temperature, min [°C]	6.2	5.5	4.7	2.1	–0.2	0.3	–2.3	0.4	1.3	0.9
Air temperature, max [°C]	7.4	8.7	9.7	9.5	9.2	9.2	13.6	16.4	15.0	12.7
Net radiation [MJ/(m^2d)]	1.54	2.45	4.24	8.67	6.42	5.47	12.60	12.60	9.57	10.12
Wind speed [km/d]	11.94	1.14	4.20	41.94	2.22	1.80	9.48	9.48	19.38	7.32
Humidity [%]	99.80	95.90	91.31	67.89	66.65	69.04	72.12	72.12	69.42	81.15
Date	21th	22nd	23th	24th	25th	26th	27th	28th	29th	30th/31st
Day in the year	81	82	83	84	85	86	87	88	89	90/91
Precipitation [cm/d]	0.00	1.08	0.38	1.40	0.30	0.00	0.00	0.00	0.00	0.00/0.00
Air temperature, min [°C]	1.1	7.2	6.0	4.7	2.6	2.2	2.7	3.4	3.8	6.4/7.4
Air temperature, max [°C]	19.3	10.6	10.9	9.8	7.7	14.1	14.2	17.2	17.9	23.2/25.4
Net radiation [MJ/(m^2d)]	12.23	2.34	2.29	1.81	3.96	12.60	8.60	15.68	7.35	16.65/17.00
Wind speed [km/d]	10.38	6.78	16.44	1.68	1.38	5.16	7.64	6.48	8.28	6.84/8.22
Humidity [%]	70.26	95.31	92.68	99.12	93.62	78.03	79.09	72.54	74.80	68.38/60.07

On the other hand, during the dry weather conditions of July, the rates' patterns are different (Fig. 3). In accordance to the Penman-Monteith formula, the evapotranspiration rate varies from 3 mm/d to 6.6 mm/d. Using the Hargreaves formula, the same period shows ET_p rate from 5.3 mm/d to 7.7 mm/d. Thus, the variations of the evapotranspiration rate values do not coincide, except on

Table 2
Meteo data for July 2016 used in the Penman-Monteith and Hargreaves Formulas

Month, year	July, 2016									
Date	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
Day in the year [DOY]	183	184	185	186	187	188	189	190	191	192
Precipitation [cm/d]	0.00	1.06	0.00	0.20	0.00	0.00	0.04	0.00	0.00	0.00
Air temperature, min [°C]	19.3	19.6	19.6	18.2	17.5	15.2	16.9	14.9	15.3	17.5
Air temperature, max [°C]	34.9	34.9	34.3	30.7	30.3	33.6	31.5	30.6	32.8	32.4
Net radiation [MJ/(m^{2}d)]	12.88	16.86	17.64	9.56	17.74	19.80	18.58	19.49	18.64	18.66
Wind speed [km/d]	6.12	78.00	36.06	44.10	52.14	16.56	30.48	54.12	15.30	22.20
Humidity [%]	78.81	76.38	81.50	88.06	71.27	66.49	69.74	63.84	66.08	62.74
Date	11th	12th	13th	14th	15th	16th	17th	18th	19th	20th
Day in the year [DOY]	193	194	195	196	197	198	199	200	201	202
Precipitation [cm/d]	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00
Air temperature, min [°C]	15.9	16.1	16.0	17.7	20.1	19.2	18.9	17.0	17.4	17.4
Air temperature, max [°C]	33.3	35.6	35.9	36.9	35.1	35.3	32.1	31.0	30.7	29.3
Net radiation [MJ/(m^{2}d)]	19.19	19.85	19.68	18.75	14.34	16.87	19.37	11.44	13.72	12.81
Wind speed [km/d]	67.56	37.50	25.56	120.54	90.84	176.76	129.30	144.36	68.22	23.16
Humidity [%]	62.83	59.46	66.73	66.93	67.91	59.22	68.01	66.55	62.79	62.30
Date	21th	22nd	23th	24th	25th	26th	27th	28th	29th	30th/31st
Day in the year [DOY]	203	204	205	206	207	208	209	210	211	212/213
Precipitation [cm/d]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00/0.00
Air temperature, min [°C]	16.0	15.7	17.1	19.7	18.5	17.4	19.0	17.4	17.0	18.0/19.3
Air temperature, max [°C]	32.1	35.2	35.7	35.8	35.3	34.7	34.9	35.4	38.5	36.9/37.2
Net radiation [MJ/(m^{2}d)]	17.58	18.30	17.16	18.64	18.31	15.92	17.56	17.29	18.03	14.89/17.07
Wind speed [km/d]	14.16	33.60	14.52	98.16	168.30	124.74	153.48	115.86	15.6	7.56/8.34
Humidity [%]	65.56	62.43	63.23	58.84	58.60	59.56	59.44	62.41	58.88	65.24/61.60

the 8th and 25th of July. In general, the plot of the Hargreaves rate calculations is shifted upwards the Penman-Monteith one, which has much less amplitude. Therefore, in July, the overestimation of the Hargreaves formula is much more pronounced (206.6 mm/month) than data obtained by the Penman-Monteith formula (173.1 mm/month). In fact, there is a double increase in the overestimation values on a monthly basis, from 10% (March) to almost 20% (July).

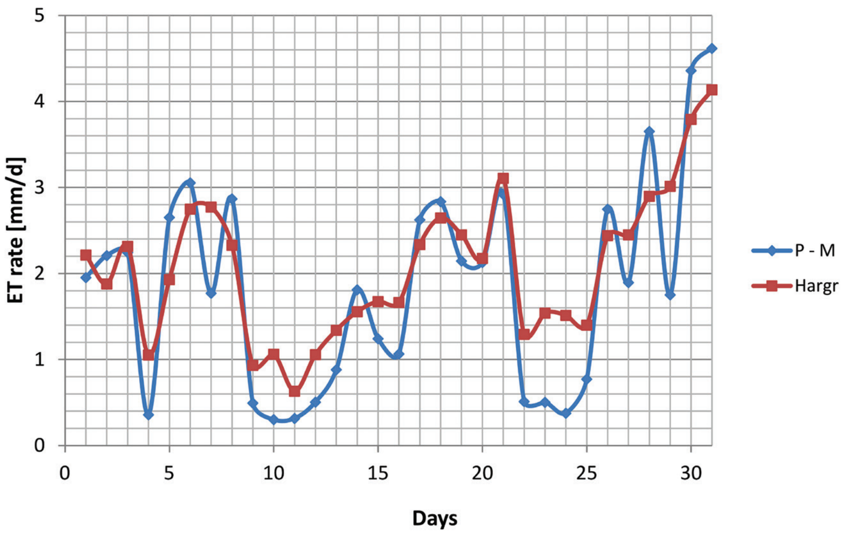

Fig. 2. Calculated evapotranspiration rates in March according to the Penman-Monteith (blue graph) and Hargreaves (red graph) formulas.

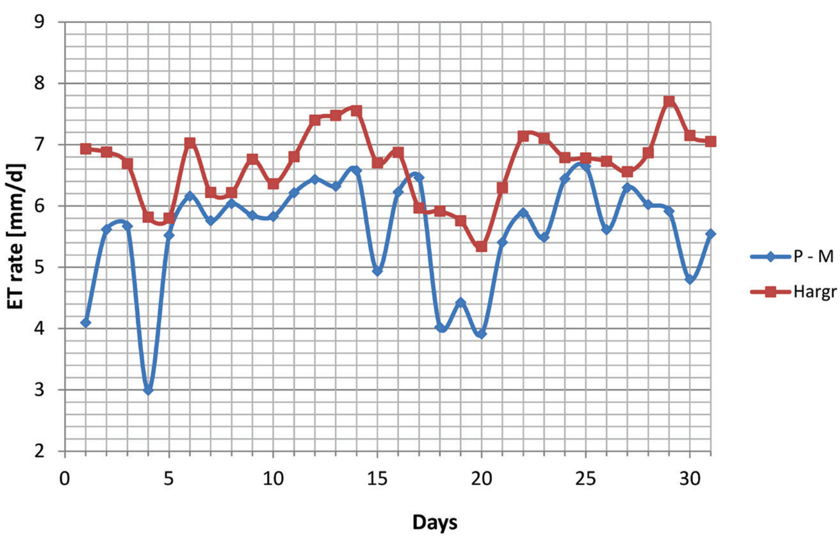

Fig. 3. Calculated evapotranspiration rates in July according to the Penman-Monteith (blue graph) and Hargreaves (red graph) formulas.

CONCLUSION

The aim of the study was to provide information of the potential evapotranspiration rates in Northeast Bulgaria in connection to the loess complex water flow and recharge estimations. Overall results indicate that the use of the Hargreaves formula for evaluation of the ET_0 leads to an overestimation between 10% and 20%, respectively for the "wet" and "dry" month. Therefore, for precise water balance studies in a short period, especially in the summer season (hot weather without rainfalls), it is recommended to use the Penman-Monteith formula. In spring (and autumn), with alternating rainy and dry days, using the Hargreaves formula is permissible, as the error is equal to or less than 10%.

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REFERENCES

Alexandris, S., Stricevic, R., Petkovic, S. 2008. Comparative analysis of reference evapotranspiration from the surface of rainfed grass in central Serbia, calculated by six empirical methods against the Penman-Monteith formula. *European Water* 21/22, 17–28.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M. 1998. *Crop evapotranspiration – guidelines for computing crop water requirements*. FAO Irrigation and Drainage Paper 56, Food and Agriculture Organization, Rome, 300 pp. (http://www.fao.org/docrep/x0490e/x0490e00.htm).

Antonov, D., Orehova, T., Gerginov, P., Kolev, S. 2018. Seasonal changes of the soil-water potential in loess deposits, Northeastern Bulgaria case. *Review of the Bulgarian Geological Society* 79 (3), 133–134.

Evlogiev, Y. 2006. *The Pleistocene and the Holocene in the Danubian Plain*. DSc Thesis, Geological Institute, Bulgarian Academy of Sciences, Sofia, 263 pp. (in Bulgarian; unpublished).

Hargreaves, G.H. 1994. Defining and using reference evapotranspiration. *Journal of Irrigation and Drainage Engineering* 120 (6), 1132–1139.

Leterme, B., Mallants, D., Jacques, D. 2012. Sensitivity of groundwater recharge using climatic analogues and HYDRUS-1Dd. *Hydrological Earth System Science* 16, 2485–2497.

Minkov, M. 1968. *The Loess in North Bulgaria. A Complex Study*. Publishing House of the Bulgarian Academy of Sciences, Sofia, 202 pp. (in Bulgarian, with French, Russian and English abstracts).

Mualem, Y. 1976. A new model for predicting the hydraulic conductivity of unsaturated porous media. *Water Resources Research* 12, 513–522.

Schaap, M.G., Leij, F.J. 1998. Using Neural Networks to predict soil water retention and soil hydraulic conductivity. *Soil and Tillage Research* 47, 37–42.

Schaap, M.G., Leij, F.J., van Genuchten, M.T. 2001. ROSETTA: a computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions. *Journal of Hydrology* 251, 163–176.

Šimůnek, J. 2015. Estimating groundwater recharge using HYDRUS-1D. *Engineering Geology and Hydrogeology* 29, 25–36.

Šimůnek, J., Šejna, M., Saito, H., Sakai, M., van Genuchten, M.T. 2008. *The Hydrus-1D Software Package for Simulating the Movement of Water, Heat, and Multiple Solutes in Variably Saturated Media. Version 4.0.* HYDRUS Software Series 3, Riverside California, Department of Environmental Sciences, University of California Riverside, 315 pp.

Stoyanov, N.T. 2009. Prognostication of mass-transport of radionuclides in the loess complex in the region of NPS "Kozloduy". *Annual of the University of Mining and Geology* 52 (1), 159–164 (in Bulgarian, with English abstract).

van Genuchten, M.T. 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society of America Journal* 44, 892–898.