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Estimation of groundwater recharge by flow in vadose zone simulation at the watershed with different landscapes and soil profiles

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Резюме. Основната цел на настоящото изследване е оценка на дифузното подхранване на подземните води посредством моделиране на водния баланс на земната повърхност и в ненаситената зона. За оценка на подхранване на подземните води за водосбора в близост до град Воронеж (Централна Русия) въз основа на дългосрочни метеорологични данни с дневна стъпка, бе използван компютърен код HYDRUS-1D (Šimůnek et al., 2008; Šimůnek et al., 2009). Климатът на този район се характеризира с относително дълъг зимен период, затова данните за валежите не могат да бъдат използвани директно в HYDRUS като атмосферно гранично условие. Тези данни трябва да бъдат предварително обработени за да се вземат под внимание процесите на формиране на снежната покривка, снеготопене, изпарение от сняг и растителна покривка, както и замразяване и размразяване на почвата. За тази цел бе използвана специална програма SurfBal (Grinevskiy, Pozdniakov, 2010; Grinevskiy, Pozdniakov, 2011) – код за предварителна обработка на данни моделиращ воден и енергиен баланси на земната повърхност, който генерира данни за горните гранични условия на HYDRUS-1D.

Така на първия етап на симулацията SurfBal изчислява (въз основа на дневни стойности на валежите, температурата и влажността на въздуха) воден и енергиен баланс, в това число: интерцепция, изпарение от повърхността на листната маса и от сняг, натрупване на сняг, уплътняване на снежната покривка и нейното топене, замразяване на горния слой на почвата и повърхностен отток, както и първоначалните потенциални стойности на изпарение, транспирация и инфилтрация на вода в почвата. Тези резултати са входните данни за следващия етап на моделиране на ненаситения поток с HYDRUS-1D, включително с отчитане на всмукване на влага от корени на растенията.

За целите на изследването в пределите на изучавания водосбор бяха подбрани три типични участъка с различни параметри на почвата и ненаситената зона. Почвите в двата участъка са чернозем върху песъчливо-глинеста основа, а в третия участък почвата е песъчлива върху пясък. За всички участъци подземните води залягаха на дълбочина повече от 10 m. Резултатите от моделиране на водния баланс и подхранването на подземни води с използване на SurfBal и HYDRUS-1D за различни ландшафти и почви в изучавания водосбор показаха силната зависимост на годишното подхранване и характера на неговите дългосрочни вариации от типа на горния почвен слой и основните параметри на почвата. Най-големите стойности на подхранването са получени за песъчливи почви върху песъчливия профил, а най-малките – за профила от чернозем с дебелина 2 m.

Ключови думи: подхранване на подземни води, чернозем, влагопренос в ненаситена среда, воден баланс, моделиране

Abstract. The main purpose of this investigation is the evaluation of the diffusive groundwater recharge by using point-scale simulation of surface and subsurface water balance. The well-known package HYDRUS-1D (Šimůnek et al., 2008; Šimůnek et al., 2009) was used for groundwater recharge estimations based on long term meteorological data with daily resolution for the watershed in vicinity of Voronezh city, Russia. The climate of this region is characterized by a relatively long winter period, thus initial meteorological data such as precipitation cannot be used directly as the atmospheric boundary condition in HYDRUS. This data must be preprocessed to take snow accumulation and snow melting, evaporation from snow and vegetation cover, and soil freezing-defrosting processes into account. For this purpose, SurfBal (Grinevskiy, Pozdniakov, 2010; Grinevskiy, Pozdniakov, 2011), a special preprocessing code for simulating surface and top soil water energy balances and generating upper boundary conditions for HYDRUS-1D was used.

Thus at the first stage of the simulation the SurfBal calculates (based on daily values of precipitation, air temperature and humidity) the surface water and energy balance including: interception by canopy, surface (leaf and snow) evaporation, snow accumulation, consolidation of snowpack and its melting, top soil freezing status and surface runoff, as well as initial potential values of evaporation, transpiration and water inflow to soil. These results are the input values for the next stage of simulation the unsaturated flow with root water uptake using HYDRUS-1D.

For the field study, the three typical sites with different vadose zone parameters and top soils were selected. The top soils at two sites were chernozem soil on the sandy loam, while at the third site the topsoil is sandy soils on sands. The groundwater level depth at all sites is more than 10 m. The results of water balance and groundwater recharge simulations using SurfBal and HYDRUS-1D under various landscapes and soil cover for the studied watershed showed the strong dependence of annual recharge and its long-term variation from types of topsoil and underlying soil parameters. The largest recharge values were obtained for sandy soils on sand profile, and the smallest values were obtained for the profile with 2 m thick chernozem.

Keywords: groundwater recharge, chernozem, flux in the vadose zone, water balance, simulation

Introduction

Groundwater recharge forms available water resources of shallow aquifers and plays important role in the context of water management. Assessing recharge rate is one of the most challenging issues in groundwater investigations even for current climate conditions. Potential climate change impact on groundwater recharge is the subject of intensive study of geohydrological community (Crosbie et al., 2010; 2013, Ng et al., 2010, Beigi, Tsai, 2015) and others. In the context of global climate change, the historical data on recharge change could be used to understand the effects of climatic variability on groundwater resources and to make projection for the future in connection with climate scenarios, but such data related with experimental recharge measurement sets are unavailable. Estimation of groundwater recharge for specific soil, vegetation, and climate conditions can be done with using physically based soil-water balance models, i.e. vadose zone water balance simulation based on Darcian flow in saturated-unsaturated domain of water that comes from soil surface after surface precipitation transformation. For the point scale simulation, the HYDRUS-1D model (Šimůnek et al., 2008; Šimůnek et al., 2009) is very appropriate code for such simulations, and it has been used for such an application in different climatic conditions (Lu et al., 2011; Wang et al., 2009; Grinevskiy, Pozdniakov, 2009, Grinevskiy, Pozdniakov, 2011, as some examples). The simulation with the HYDRUS-1D for reanalysis of influence of observed scale of meteorological condition variation on the recharge time and space variation can be a tool for estimating the future climate change impact on shallow groundwater resources. Thus, the objective of this paper is simulation of groundwater recharge using climatic records for few past decades to understand the formation of mean recharge and its variation during past decades under different landscape and soil profile within a single watershed.

The climate of the Central European part of Russia changes from boreal and sub-boreal to cold semiarid and is characterized by large inter-annual and interdecadal variability in precipitation and temperature, which provides opportunities to examine the response of groundwater recharge to changes in meteorological conditions with using reanalysis on physically based models like HYRDUS-1D.

Climatic conditions in boreal, sub-boreal and cold, semi-arid climate regions that affect the groundwater recharge are as follows:

- the total precipitation exceeds or is equal to total potential evapotranspiration, so the dryness (aridity) index is more than one or it is about one;
- the winter season with temperatures below zero causes a high amount of solid precipitation accumulated in snow cover;
- winter thaws are usually very short and rare, and the upper part of the soil is frozen, so the water seepage into the soil is negligible during winter season;
- the snow melting period is usually short and intensive, which causes the high volume of snowmelt runoff.

All these features result in special variable upper boundary meteorological and flow conditions for unsaturated flow simulations using HYDRUS-1D. Thus the program code SurfBal (Grinevskiy, Pozdniakov, 2010; Grinevskiy, Pozdniakov, 2011) was developed to simulate the processes of precipitation and heat energy transformations on the land surface in order to generate the upper boundary meteorological conditions for HYDRUS.

The simulation tools

Simulation process consists of two stages. The input meteorological variables: precipitation, air temperature, solar radiation and air humidity stored on the daily base for the whole period of simulation are used by the SurfBal code. On the first stage the code SurfBal calculates the surface water balance including: interception by canopy, surface (leaf and snow) evaporation, snow accumulation, consolidation of snowpack and its melting, and surface runoff, as well as initial potential values of evaporation, transpiration and water inflow to soil. These results are the input values for the next stage of simulation the unsaturated flow with root water uptake using the package HYDRUS-1D.

The SurfBal integrates with daily time step the next water budget equation at the surface:

$$\frac{dV}{dt} = P - E_{LS} - S - v_p; \quad V = V_s + V_l; \, E_{ls} = E_l + E_s \qquad (1)$$

where V – total volume of water accumulated, V_L and V_S - volume of water accumulated on vegetation and in snowpack respectively, P - precipitation rate, E_{LS} - total surface evaporation including evaporation from leafs (E_L) and snow cover (E_S), S - surface runoff, V_p - potential infiltration into soil profile.

The interception of liquid precipitation by the canopy P_L when total intercepted water is less than maximum storage P_{max}, depends on daily value of leaf area index LAI and water retention constant K_L equals 0.2 mm (Liang et al., 1994):

$$P_L^i = \Lambda^i \left[1 - \exp\left(\frac{P^i}{\Lambda^i} \right) \right], \quad \Lambda^i = P_{\max}^i - V_L^i; \; P_{\max}^i = K_L LAI^i \qquad (2)$$

Thus, the daily changes of water volume ΔV_L accumulated on leafs depend on interception as well as leaf evaporation E_L:

$$\Delta V_L^i = V_L^i - V_L^{i-1} = P_L^i - E_L^i \tag{3}$$

which is proportional to potential evapotranspiration ET^0 (Liang et al, 1994):

$$E_L^i = ET_i^0 \left(\frac{V_L^i}{P_{\max}^i} \right)^{2/3} \tag{4}$$

Daily values of potential evapotranspiration ET^0 are calculated by using minimal and maximum air temperature, net solar radiation, air humidity data, status of land cover by vegetation and (optionally) wind speed with selecting one of the next well described in literature ET^0 models: Priestley–Taylor, Penman–Monteith (Allen et al., 1998) or Shuttleworth–Wallace (Shuttleworth, Wallace, 1985).

The modified model of Gelfan and Kuchment (Kuchment, Gelfan, 1996) is used to calculate snow depth dynamics and the release of melting water at the soil surface. Dynamics of the snow depth H at the surface is simulated by depth-averaged equations for the snow state, considered as a three-phase system that includes solid phase ice with the density ρ_i, water with density ρ_w, and void space. The model takes into account accumulation of snow during precipitation when air temperature T <0, snowmelt, snow metamorphism, sublimation, refreezing of melting water, and its flow to the soil surface through snowpack:

$$\begin{aligned} \frac{dH}{dt} &= \left[P_s \chi_0 - \left(L + E_S \right) \chi I^{-1} \right] - V_p \\ \frac{d}{dt}\left(IH \right) &= \chi \left(P_s - L - E_S + S_i \right) \\ \frac{d}{dt}\left(\theta H \right) &= \left(P_r + L - v_s - E_L - S_i \right) \end{aligned} \tag{5}$$

where I and θ are parts of ice and water in snow volume, $\chi_0 = \rho_w \rho_{s0}^{-1}; \chi = \rho_w \rho_i^{-1}$, P_s and P_r are snowfall and rainfall rates respectively, and S_i is the rate of refreezing of melt water for T<0, which is calculated as:

$$S_i = K_i \sqrt{|T|} \tag{6}$$

where $K_i \approx 4.5$ [mm deg$^{-0.5}$ day^{-1}] is the empirical coefficient of water-ice phase transformations.

The total sublimation of ice ES and evaporation of liquid water EW from snowpack depends on potential evapotranspiration ET^0

$$E_S^i + E_L^i = \begin{cases} \beta^i \, ET_i^0 \text{ ,when } V_S^i > \beta^i ET_i^0 \\ V_S^i \text{ , when } V_S^i < \beta^i ET_i^0 \end{cases} ; \beta^i = \exp(-0.45 LAI^i) \tag{7}$$

V_ρ is the snowpack self-compression rate due to its weight:

$$V_p = 0.5 K_v \rho_s H^2 \exp(\beta_1 T - \beta_2 \rho_s) \tag{8}$$

where β_1 and β_2 are empirical calibration parameters.

The current snow density is:

$$\rho_s = \frac{\rho_i I + \rho_w \theta}{H} \tag{9}$$

and fresh snow density ρ_{s0} is the function of air temperature:

$$\rho_{s0} = \begin{cases} \rho_{\min}; T < T_{\min} \\ \rho_{\min} + (\rho_{\max} - \rho_{\min}) \dfrac{T - T_{\min}}{|T_{\min}|}; T_{\min} \le T < 0; \\ \rho_{\max}; T \ge 0 \end{cases} \tag{10}$$

The snow melting rate L depends on the temperature and the current snow density ρ_s with the empirical coefficient of snow melting K_s:

$$L = \begin{cases} 0; T < 0 \\ K_s \rho_s T; T \ge 0 \end{cases} \tag{11}$$

The release rate of melting water to the soil surface v_s due to gravity-dominated flow of water through the unsaturated snowpack (Gray et al., 2001):

$$v_s = \begin{cases} K_f \bar{\theta}^{3.5}; \bar{\theta} = \dfrac{\theta - \theta_{\max}}{1 - I - \theta_{\max}}; \theta \ge \theta_{\max} \\ 0; \theta < \theta_{\max} \end{cases} \tag{12}$$

Solution of system (5-10) gives ΔV_L – daily changes of water volumes, accumulated in snow and snow water rate release soil surface v_s that is equal to value of v^i_p for i-th day with snow cover.

The well-known curve number method (USDA, 1985) is used for calculations of daily surface runoff. When T<0, daily curve number value CN depends on thawed or frozen status of topsoil (Schroeder et al., 1993). For the calculation of the soil status, the model for approximate numerical calculation of the soil freezing depth (Gusev, 1985) was incorporated into SurfBal.

Thus, solution of Eqs. (1-13) with daily time step gives a value of v^i_p for i-th day, which is passed to HYDRUS-1D as the upper boundary condition:

$$v_p^i = P^i - \Delta V_S - \Delta V_L - S^i - E_S^i - E_L^i \tag{13}$$

Because potential evapotranspiration ET^0 characterizes total available water losses to atmosphere due to energy limits of the landscape, the remaining daily part of ET^0, except for losses by snow E_S and leaf E_L evaporation, can be estimated:

$$ET_p^0 = ET^0 - E_S - E_L \qquad (14)$$

This value is the limit for potential soil evaporation E_p^0 and potential plant transpiration TR_p^0 and can be divided as:

$$E_p^0 = \beta ET_p^0; TR_p^0 = (1-\beta) ET_p^0; \beta = \exp(-0.45 LAI^i) \qquad (15)$$

The results of SurfBal calculations - daily values of inflow and potential evaporation, and transpiration rates TR^0_p - describe upper boundary conditions for the soil profile and are passed to HYDRUS-1D as the atmospheric boundary condition. The calculated by SurfBal surface runoff *S* and additional runoff that can be generated later by HYDRUS-1D are used for future analysis of precipitation transformation.

Site description and data parametrization

The investigated area is located to south-east from Voronezh city, on the left bank of the Don River, in the south-west part of Oksko-Donskaya plain. The left bank of the Don River between mouths of the Voronezh River and the Hvorostan River is a bit hilly plain with gentle landforms. Main of these landform types are: river valleys with terraces, watersheds crossed by ravines and combes. The shallow subsurface deposits are alluvial and fluvioglacial formations. The prevailing type of topsoil is ordinary chernozem with the thickness up to 2 meters. In addition, sandy soils can be met on terraces and fluvioglacial formations.

The climate of the area is characterized by hot and dry summer and moderately cold winter with steady snow cover and well expressed transitional seasons. To characterize the meteorological conditions of the studied area and subsequent simulation of precipitation transformation with SurfBal, a 47-year continuous daily series of meteorological data from Voronezh meteorological station was collected. The absolute minimum of air temperature reaches -38^{0}C, absolute maximum is +41^{0}C. Average annual temperature makes +5.4^{0}C. The average annual precipitation is 558-672 mm. Average maximum snow depth is 20-28 cm. Average snow water equivalent is 40-45 mm.

In the investigated territory the Hvorostan River watershed was studied, and three pilot sites within this watershed with different landscape conditions and structure of vadose zone were chosen for field investigations. The soil samples were taken from the studied profiles for lab study. The soil texture of investigated sites is presented in Table 1.

Table 1. Soil textures at the study sites
Таблица 1. Механичен състав на почвите в изследваните участъци

Site	Depth from surface	Soil texture
	m	-
Field	0.00 - 0.68	chernozem - silt loam
	0.68 - 1.00	sandy loam
Forest	0.00 - 0.50	sandy soil
	0.50 - 0.70	sand
River valley	0.00 - 1.70	chernozem - silt loam

Particle size distribution, physical and water-physical properties of the selected samples were defined in laboratory. The results are presented in Table 2.

Table 2. Water-physical and physical properties of studied soils
Таблица 2. Водно-физични и физични свойства на изследваните почви

Sites	Depth	Soil texture	Total (wet) soil density, ρ	Gravimetric water content, W	Dry bulk density, ρ_d	Soil particle density, ρ_s	Porosity, n	Upper plastic limit, W_{up}	Lower plastic limit, W_{lp}	Maximum hygroscopicity, W_{mh}	Soil water content at the field capacity, FC
	m	-	g cm^{-3}	g g^{-1}	g cm^{-3}	g cm^{-3}	-	-	-	-	-
Field	0.00 - 0.13	chernozem	0.94	0.12	0.84	2.52	0.67	0.43	0.29	0.07	0.13
	0.13 - 0.20	chernozem	1.18	0.12	1.05	2.52	0.58	0.51	0.34	0.09	0.37
	0.20 - 1.00	sandy loam	1.65	0.12	1.47	2.70	0.45	-	-	-	0.44
Forest	0.0-0.13	sandy soil	1.49	0.01	1.48	2.65	0.44	-	-	0.01	0.37
	0.13 - 0.30	sandy loam	1.66	0.01	1.64	2.70	0.39	-	-	0.01	0.33
	0.30 - 1.00	sand	1.61	0.01	1.59	2.65	0.40	-	-	-	0.39
River valley	0.00 - 0.13	chernozem	0.93	0.15	0.81	2.52	0.68	0.43	0.28	0.07	0.13

For HYDRUS-1D simulation, van Genuchten parameters (θ_r, θ_s, α, n) were obtained using the RETC code (van Genuchten et al., 1991). This code gives an opportunity to fit the water retention curves using points with known values of volumetric water contain θ and suction h (absolute value of negative pressure head). For the reference points we adopted Voronin's energy concept (Voronin, 1984; Shein et al., 2012) that gives the relation between gravimetric water content W and lg(h) for special reference points. The mentioned above reference points according to the concept are given below:

1. Maximum water capacity or porosity, $porosity \rightarrow \lg(h, cm) = 0$

2. Upper Plastic limit, $W_{nm} \rightarrow \lg(h, cm) = 2.17$

3. Lowest water content, $W_{lc} \rightarrow \lg(h, cm) = 2.17 + W_{lc}$

4. Lower Plastic limit, $W_{lp} \rightarrow \lg(h, cm) = 2.17 + 3W_{lp}$

5. Maximum hygroscopicity, $W_{mh} \rightarrow \lg(h, cm) = 4.45$

Thus, the main hydrophysical characteristic (i.e. the soil water retention) was restored using the defined physical and water physical properties of soils. Van Genuchten parameters (θ_r, θ_s, α, n) of chernozems were obtained by RETC code using the lowest-square method. Van Genuchten parameters (θ_r, θ_s, α, n) for sand and sandy loam soils were obtained by well-known code ROSETTA (Schaap et al., 2001) using data on particle size distribution and bulk density. The hydraulic conductivity for sandy and sandy soils was obtained in the lab using falling head test. Hydraulic conductivity for chernozems was taken 0.2 m/day according to data of field tests of the same chernozems in Kamennaya Steppe area of Voronezh region (Shein et al., 2012). The results of estimating van Genuchten parameters are shown in Table 3.

Table 3. Van Genuchten parameters used for HYDRUS-1D simulation
Таблица 3. Параметри на van Genuchten, използвани за моделирането с HYDRUS-1D

Site	Soil texture	Depth	Residual water content, θ_r	Saturated water content, θ_s	Empirical parameter, α	Empirical parameter, n	Saturated hydraulic conductivity, K_s
	-	m	-	-	m^{-1}	-	m day^{-1}
Field	chernozem	0.0 - 0.1	0.07	0.67	0.020	1.40	0.2
	chernozem	0.1 - 0.7	0.09	0.58	0.006	1.42	0.2
	sandy loam	0.7 - 6.0	0.04	0.38	3.320	1.46	0.6
River valley	chernozem	0.0 - 2.0	0.07	0.68	0.019	1.42	0.2
	sandy loam	2.0 - 6.0	0.04	0.38	3.320	1.46	0.6
Forest	sandy soil	0.0 - 0.1	0.05	0.39	2.000	3.83	10.0
	sandy soil	0.1 - 0.5	0.05	0.34	3.310	3.39	6.0
	sand	0.5 - 6.0	0.05	0.36	3.620	3.23	5.0

A 47-year continuous series of daily meteorological data from Voronezh meteorological station including maximum, minimum and average temperature, amount of precipitation, relative air humidity and net solar radiation were used to characterize meteorological conditions of studied area. Main input parameters of the surface water balance model are presented in Table 4.

Table 4. Main input parameters of SurfBal model
Таблица 4. Основни входни параметри на модела SurfBal

Parameter	Field area	Forest area	River valley area
LAI, min-max	0.01 – 2.00	3 - 4	0.01 - 2.00
Snow melting rate, K_s [cm^4 deg^{-1} g^{-1} day^{-1}]	1.90		
Snow self-consolidation coefficient [g cm^{-4} day^{-1}]	0.24		
Curve number for runoff calculation	93		
Method of Potential ET calculation	Shuttleworth – Wallace		

The snow melting rate and snow self-consolidation coefficient presented in Table 4 were selected by calibration based on comparison of the mean annual daily snow cover thickness with actual data. An example of comparison of model and actual snow cover thickness is presented in Figure 1.

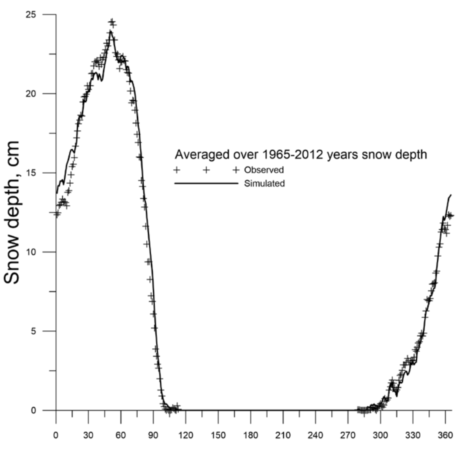

Fig. 1. Observed and simulated mean annual daily snow depth values (in cm) averaged over 47 years
Фиг. 1. Наблюдавана и моделирана среднодневна височина на снежната покривка (в cm), осреднена за 47 години

Simulation results

Using the previously described simulation process consisting of two stages, the 47 years (starting from the year 1966) of SurfBal and HYDRUS-1D simulation for each site was performed.

For the Hydrus-1D simulation, the depth of the soil profile for all sites was taken 6 m (Table 3). In connection with the fact that in all three areas the natural depth of groundwater level is more than 10 meters, the lower boundary condition was set as Free Drainage boundary (Šimůnek et al., 2008). The Feddes's model (Šimůnek et al., 2008) was chosen for simulation of root water uptake dependence from soil water status. The Feddes's model parameters were selected from the library of these parameters incorporated into HYDRUS-1D model for pasture (river valley), for grass (field) and for trees (forest). The initial conditions were taken as the constant pressure head. For the forest site this head was set at -1 m, for river valley site at -8.75 m, and for field site at -3.5 m. The selection of these values was done by preliminary simulation and estimation the mean pressure variation for the each site.

The groundwater recharge was taken equal to the downward water flux through the lower boundary of the modeled soil profile. By averaging of the recharge values over time, the mean annual groundwater recharge value was obtained for each area (Table 5).

Table 5. Mean annual groundwater recharge values of the study sites
Таблица 5. Средни стойности на годишното подхранване на подземните води за изследваните участъци

Site	Mean annual recharge, [mm yr^{-1}]	Coefficient of variation of annual recharge
Field	15	0.36
Forest	130	0.95
River valley	0.07	0.20

Maximum groundwater recharge value is obtained in forest area ($3.57*10^{-04}$ m d^{-1} or 130 mm yr^{-1}), average value – in/for field area ($4.15*10^{-05}$ m d^{-1} or 15 mm yr^{-1}), and the minimum value – for area in river valley ($1.79*10^{-07}$ m d^{-1} or 0.07 mm yr^{-1}).

Figure 2 shows the correlation of obtained for 47 years simulated recharge with observed annual precipitation. One can see from this figure that visible correlation exists only for the site with the largest annual recharge.

Figure 3 shows the simulated time series of recharge and dryness index, i.e. ratio of annual precipitation to potential evapotranspiration versus time. This figure shows quick response on the changes from year to year of dryness index only for the site with the largest annual recharge, while the other sites do now show visible response of recharge on the change of dryness index.

Figure 4 shows the relatively strong correlation between groundwater recharge at the forest site and dryness index of previous year. This correlation is larger than the correlation of recharge and dryness index for the current year. For the other sites such correlations are insignificant. Figures 3 and 4 confirm that only at the forest site the recharge is sensitive to year-on-year changes of dryness index.

Figure 5 shows the autocorrelation function calculated for the simulated annual recharge series. One can see from this figure that for recharge formed at chernozem top soils the autocorrelation is significant. This slow decreasing of autocorrelation indicates the important role of water retention effect within simulated soil profile on temporal change of recharge. This water retention compensates change of dryness from year to year.

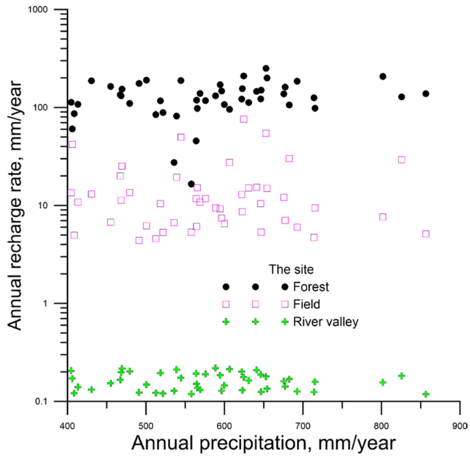

Fig. 2. Mean simulated annual recharge rate versus precipitation
Фиг. 2. Връзка между моделирани стойности на годишно подхранване на подземните води и валежната сума

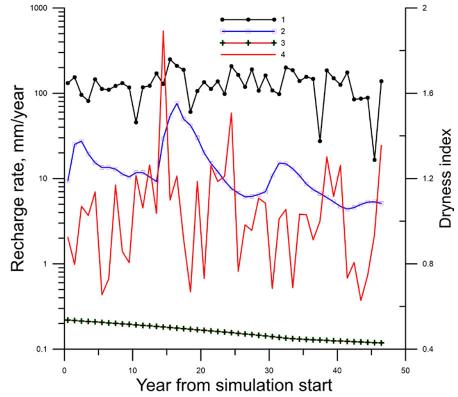

Fig. 3. Simulated series of the annual recharge rate
Фиг. 3. Редица на моделирани стойности на годишното подхранване на подземните води

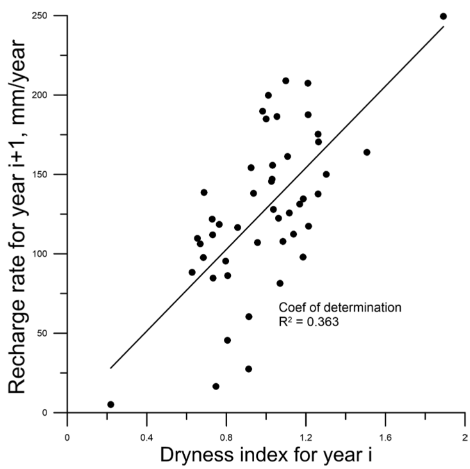

Fig. 4. Correlation between annual recharge at the forest site and dryness index of previous year
Фиг. 4. Корелация между годишното подхранване на подземните води за участъка в горски масив и индекса на сухота за предходната година

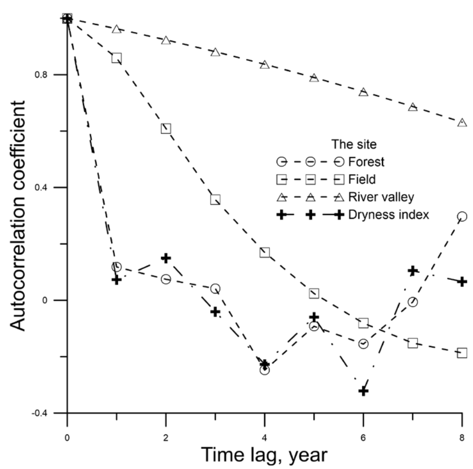

Fig. 5. Autocorrelation functions calculated for the simulated annual recharge series
Фиг. 5. Автокорелационни зависимости изчислени на база на моделираното годишно подхранване за отделните участъци

For the sandy soils the correlation of recharge for adjacent years, i.e. the correlation for time lag equal to one year, is very small. The autocorrelation for this site is very similar to the autocorrelation of dryness index. Thus for this site the temporal change of recharge is governed by temporal variations of annual dryness index.

Conclusions

The maximum groundwater recharge value was obtained in forest area on sandy soils ($3.57*10^{-04}$ m d^{-1} or 130 mm yr^{-1}), the average value was obtained on field area ($4.15*10^{-05}$ m d^{-1} or 15 mm yr^{-1}), and the minimum value was on area in river valley ($1.79*10^{-07}$ m d^{-1} or 0.07 mm yr^{-1}). Such a large scale of recharge changes from site to site within one watershed related to the top soil properties. The possible explanation of this result is as follows.

The obtained minimum groundwater recharge value is due to better water-retention properties of chernozem and greater thickness of the chernozem layer, while the maximum value is due to poorer water-retention properties of sandy soil and its lower thickness. Due to the same temperature and net radiation, the potential ET is the similar for each site, and availability of water for transpiration and evaporation is controlled by water retention properties of the upper 1-2 meters zones. That is why the melted water infiltrated in spring in chernozem profile remains in top soil up to beginning of the growing season and is used by plants and soil evaporation, while at the sandy soil this water moves downward and forms recharge. This explanation agrees with the results shown in Figures 2 and 3.

In the terms of future climate change, the obtained results show relatively large coefficient of variation of the simulated annual groundwater recharge. These coefficients shown in Table 5 are larger than the typical coefficient of variation for precipitation (0.18) or potential *ET* (0.09) in the studied area. Autocorrelation analysis of simulated recharge series shows important role of the soil water retention parameters for temporal changes of recharge. For the chernozem profile, high water retention compensates the effect of dryness temporal variability on recharge variability. For the sandy soil profile with low water retention, the dryness index variability is the main factor controlling recharge variability from year to year.

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