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ORIGINAL ARTICLE

Hydrology models approach to estimation of the groundwater recharge: case study in the Bulgarian Danube watershed

Olga Nitcheva[1]

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Abstract

The groundwater (GW) makes an important part of a region runoff. GW bodies playing the role of accumulating reservoirs regulate the GW discharge enabling the river flow to have more uniform long-term distribution. Along with other important advantages, the GW offers the users stable water abstraction rate independent from the recharge rate. The GW recharge quantification belongs to the uneasy tasks in the water resource management. Applying the conventional methods needs multiyear observation records of the variation of the groundwater body (GWB) characteristics. The employment of hydrology models avoids that necessity but requires great amount of data related to the soil hydraulic properties, the land topography and cover of the GWB watershed and long-term records of the climatic effects. The paper presents an introduction of the mathematical model CLM3 into the GW recharge estimation problem. It is a complex and advanced model with adequate interpretation of the water-related processes in the soil and on the land surface under atmospheric effects. The input is available from NCEP/NCAR reanalysis atmosphere data and the International Geosphere-Biosphere Program (IGBP) data base. The model is applied to GW recharge assessment of the Bulgarian Danube district for the year 2013. The obtained monthly and yearly total district values and the areal distribution of the infiltration intensity are matched to the existing field observation-based estimates. The study shows that the CLM3 model approach leads to encouraging results. The method comes very useful with GWB lacking regime observation data as well as for GW recharge prognostic assessments under climatic scenarios.

Keywords Groundwater recharge · CLM3 model groundwater recharge estimation

Introduction

In flat regions of the world, the ground water recharge (GWR) makes an essential part of the water resource. This is a process occurring on the surface and in the subsurface environment. Beside the soil water retention and transport properties, the GWR strongly depends on the meteorological processes and effects of the region. Unlike the surface waters, its direct measurement is practically impossible. For that reason up to the present time, various approaches to quantitative assessment of the GWR have been developed. Depending on the available information, they can principally be divided into two groups—indirect methods, based on the existing records of the GWB behavior, and direct methods facing their genesis as function of the existing long-term data series of climatic factors and water retention and transport properties of the soil profile and surface cover. The second approach is primarily realized by hydrology models. This paper presents the results from a study showing the possibility of a sophisticated model of the type like the CLM3 for attaining satisfactory evaluation of the groundwater recharge, especially when vast territories are concerned.

Practical aspects and theoretical fundamentals for groundwater recharge evaluation

Groundwater bodies (GWB) are as a rule fed mainly from the atmosphere and from the rivers in periods of high waters as well. Such periods in the rivers of the Bulgarian Danube watershed are short so that the main source for their recharge remains the precipitation. On the other hand, the GWB discharge into the rivers and thus they form their baseflow. Some part of the GWB water is pumped out for water use.

✉ Olga Nitcheva
olgani@imbm.bas.bg

[1] Institute of Mechanics at the Bulgarian Academy of Sciences (BAS), "Acad. Bonchev" 4 Str., Sofia, Bulgaria

Depending on the rate of the discharge and that of recharge, the GWB retains the water for significant periods of time and thereby they serve as GW reservoirs regulating annually and very often multi-annually the infiltrated atmospheric water. This quality of them and their availability all over the country land, away from rivers and surface reservoirs, also their less vulnerability to pollution (Döll and Fiedler 2008) make the GWB very convenient and easily attainable water source.

Ultimately, the utilization of the GW resources is at the expense of the surface runoff from the watershed. This could less relate to some deep GWB in flat areas with very slow outflow rate where practically the water abstraction mainly forms their discharge. This fact and the discussed above seasonal and mostly multi-annual character of the GW regulation make it necessary to formulate what part of the GW resource could in reality be abstracted and used, how and for what time period it should be evaluated.

The GW resource logically must be the annual water volume which could be abstracted and sustainably used for a long time period, i.e., it should be renewed during that period. It is usually assumed to be equal to the long-term average groundwater recharge. It makes the maximum amount of sustainably used groundwater resources (Xu and Beekman 2003; Döll and Fiedler 2008). This assumption involves the entire GW component of the whole territory runoff. In reality except for GWB with negligible natural outflow, the abstraction of the total GW recharge in the most cases is not possible even physically. Practically GW use ought to be limited in certain measures because their overexploitation can diminish the rivers baseflow to ecologically inadmissible levels (Tai-cheol et al. 2005).

It appears that it is necessary to assess the part of the GW body recharge which can reasonably be pumped out. This can be approximately estimated by computing in discrete time steps, may be 1 month, the GW reservoir long-term balance accounting for the recharge, the water abstraction minus the return waters and the discharge. The possible annual amount of the abstraction with high reliability should be estimated in the way described above, satisfying at the same time the observance of the base flow ecological minimum. The calculation is similar to surface water reservoirs dimensioning and users' reliability assessment. As to the author's knowledge, hardly such a calculation so far has been done or discussed. It is complicated by the dependence of the discharge on the GW water level, which makes necessary the possession of long period records of measured GW levels and corresponding baseflow values. Methodologically, it could be developed and applied to regions where the GW is intensively used playing, at the same time, important role for the maintenance of the river's ecological regime. Most often, the possible long-term abstraction is approximately assessed in a much simpler way by extracting the necessary annual water volume for maintaining the ecologically minimal river discharge from the long-term annual GWB recharge.

From the above commentaries, it becomes clear that the estimation of the GW recharge is aimed at the assessment of the possible annual quantity of water which could be abstracted with the necessary reliability during a long period without exhausting the GW reservoir. That quantity must be calculated on the basis of the average annual GW recharge in a long enough multiyear evaluation period. The latter length could be selected according to the available data and their statistical significance. The multiyear assessment period also to a great extent eliminates the influence of the errors due to the approximate evaluation methods and data scarcity and bias.

The most difficult problem with the GW is the evaluation of their recharge. The uncertainty and approximate character of this issue is recognized in the literature by many authors dealing with it (Lee et al. 2007; Yeh et al. 2007; Xu and Beekman 2003; Kommadath 2000). This is so because it depends on many not-easy-for-measurement, collection and numerical assessment natural factors such as GWB type and location, soil type, texture, moisture-specific yield, transport properties, land cover vegetation and slope, irrigation practices, evapotranspiration and the climatic effects such as precipitation, air temperature and humidity, soil surface insolation, and wind velocity. Key problem and difficulty here consist in the necessity of providing the above-cited data, measured and recorded along multiannual periods. Another very difficult problem is the mathematical simulation and quantitative assessment of the physical processes of water movement through soil and other geological media until reaching the GWB. Therefore, the GW recharge evaluation despite the sophistication of the computation methods remains an action with rather approximate results. Hardly, any of the existing methods makes an exception.

Presently, two main groups of methods are used for the solution of this problem. The first of them is based on the knowledge of the GWB characteristics linked with the discharging river baseflow or spring discharge behaviour recorded during multiannual periods (Spasov 1966; Spasov and Pavlova 2015; Antonov and Danchev 1980; NIMH 2012).

The second approach makes use of the existing meteorological, soil moisture and runoff data records and soil moisture properties. To this approach belong the soil water balance method and the inverse modelling technique. The latter method is based on calibrated model simulating the transient water movement in the saturated zone in an iterative trial and error procedure until the model response is sufficiently close to that of the real system (Kommadath 2000).

With the second approach, very important are the soil specific yield and vadose and saturated zone moisture properties, land vegetation and climatic data. The inverse modelling method accuracy is narrowly linked with the precision of the soil hydraulic characteristics determination (Ebrahimi et al. 2016). Often these two approaches are used together for achieving more reliable results (Lee et al. 2007; Kommadath 2000).

The following more important shortcomings can be noted about the above-described methods. With them it is difficult to account for the water abstraction from the GWB, water deviations from the recipient river and irrigation losses because usually they are not properly recorded. They do not consider the re-infiltration from the recipient rivers in cases of high waters. Their application needs good knowledge about the GWB size, location and discharge recipients. But their most important deficiency is their impossibility to be used for prediction of the GW recharge considering scenarios of future changes of the climatic factors. In addition, they are not suitable for GW recharge assessments of vast territories comprising many GWB.

The above-mentioned methods are known as conventional ones. They have been developed and used since the second half of the last century.

Lately, into the practice for GW recharge assessment entered the employment of models using the meteorological impacts as GW recharge-defining factor. An early step to distributed model application for soil moisture and groundwater recharge assessment for 1.6 km^2 pasture area is exposed by Zhang et al. (1999). Xu and Beekman (2003) reported the application of models establishing the relationships between rainfall, abstraction and water level fluctuations. Lumped conceptual rainfall-runoff model called DAWAST for estimation of groundwater recharge of 6.75 km^2 using the instrument of the water balance concept of the unsaturated and saturated layers was developed and reported by Tai-cheol et al. (2005). The field data about the groundwater level and stream flow rate were used to validate the model. Two well-known hydrologic models SWAP and EARTH have been applied (Gebreyohannes 2008) for GW recharge assessment in low plains of the Netherlands based on data records for the period 1973–1992. Special attention deserves the reported by Döll and Fiedler (2008) estimation of the global-scale average for the period 1960–1990 diffuse groundwater recharge by the most recent version of the WaterGAP Global Hydrology Model (WGHM). The estimate was obtained using two state-of-the-art global datasets of gridded observed precipitation. The model is spatially distributed with a spatial resolution of 0.5° × 0.5° and daily time step for the temporal variables. The daily groundwater recharge is computed as part of the total runoff from the land using a heuristic approach. Based on qualitative knowledge about different characteristic influence on partitioning the total runoff into surface one and groundwater as relief, soil texture, hydrogeology and others, the GW recharge is obtained as a product of number of coefficients. The model WGHM was tuned against observed long-term average river discharge at 1235 gauging stations to adjust the precipitation partitioning into evapotranspiration and runoff. The study gives interesting global-scale estimates of the average GW recharge in different regions of the world.

The next step to introduction of mathematical models into GW and soil moisture assessment field is the utilisation of improved hydrological models (Niu et al. 2007; de Roo et al. 2012; Pagliero et al. 2014; Pistocchi et al. 2015; Karabulut et al. 2016; Trichakis et al. 2017). The current development of complex hydrological models includes adequate simulation not only of the surface runoff formation and evaporation but also of the processes of water infiltration and transport through the soil-unsaturated zone. The latter means mathematical simulation of the processes commanding the water movement through that zone until reaching the GW table. This approach does not need GWB behaviour records but a great amount of data related to the soil hydraulic properties, land surface water retaining, runoff and evaporation factors and long-term records of the climatic effects. These data are commonly used in the agriculture and other areas of the human practice as well, which makes them not so difficult for provision.

The model used in this study is the Community Land Model version 3.0 (CLM3). It is the Land Surface Scheme of the Community Earth System Model and the Community Atmosphere Model developed in the USA National Center for Atmospheric Research (NCAR) (Oleson et al. 2004, 2008; Bonan et al. 2002).

The model computes the water and energy exchange between the soil surface and the atmosphere on the basis of calculation of the water cycle and heat transfer through the soil profile. The processes are assumed one-dimensional in the vertical direction. The heat transfer model follows the laws of the theory of heat conduction and mass transfer.

CLM model calculates the water balance between the precipitation, runoff, evapotranspiration and infiltration through the soil layer. Parameterization of the runoff is based on the TOPMODEL (Beven and Kirkby 1979), where fractional saturated area and fractional unsaturated area based on the groundwater level are introduced. In the case of a saturated area, the soil surface is saturated and precipitation that falls over that area runs off immediately and it is converted into surface runoff. The evaporation and evapotranspiration are calculated by the Monin–Obukhov similarity theory.

The moisture transfer model considers a soil layer with maximum 3.43 m thickness. Its spatial heterogeneity is accounted for by presenting the soil layer as made of joining to each other vertical columns with varying water and heat transport properties. The column cross-section coincides with the computation mesh elements. The mesh in this study is made of 5 × 5 km elements (columns) when covering the earth surface and of 2° × 2° ones for interpolation of the atmospheric effects. The soil layer with active water and heat transfer processes is regarded as made of ten sub-layers with different thickness and physical properties.

The vertical water transfer through the soil is presented by the mass conservation law (Oleson et al. 2004):

$$\frac{\partial \theta(h)}{\partial t} = -\frac{\partial q}{\partial z} - e(h, z) \tag{1}$$

where $\theta(h)$ is the volumetric soil moisture (mm^3 water/mm^3 soil), t is the time (s), z is the height above the soil column bottom level (mm), q is the water flow in the soil (mm/s) (upward is the positive direction), $e(h,z)$ is the water leaving the soil through evaporation or vegetation root uptake (s^{-1}) and h is the soil water pressure head (mm).

Darcy law applied to substitute q in Eq. (1) brings to the Richards equation (Richards 1931),

$$\frac{\partial \theta}{\partial h}\frac{\partial h}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z} + 1\right)\right] - e(h, z) \tag{2}$$

The non-linear partial differential equation of second-order Eq. (2) governs the vertical movement of the water forced downward by the gravitation and upward by root uptake and evaporation. It depends on the wetness of the medium. The soil hydro-physical properties—the moisture retention θ (h) and the hydraulic conductivity $K(h)$ depend on the moisture retained in the soil. The types of empirical formulae that exist for their estimation are—those of van Genuchten and Mualem (1980) and the simpler ones of Clapp and Hornberger (Clapp and Hornberger 1978; Cosby et al. 1984). The CLM model uses the soil characteristics calculated by the second type of formulae. An investigation on the accuracy of the both approaches made by laboratory and field measurements of the author (Nitcheva and Kazandjiev 2013) shows practically not important differences and the applicability of both of them.

The Eq. (2) is solved numerically by dividing the soil column into ten horizontal layers with boundary condition of the infiltration flux into the top soil layer and gravitational drainage at the bottom of the soil column (specified here as the hydraulic conductivity K of the tenth soil layer). In case of high rainfall, when the soil profile gets saturated and the surface excess water does not run off, the flux boundary condition switches to a pressure head boundary condition.

The initial conditions for temperature and moisture distribution in the soil profile can be set by the user or be accepted the CLM model default initialization—uniform soil temperature of 283 K and volumetric water content 0.3 mm^3/mm^3 in all ten soil layers with no snow and canopy water.

The atmospheric forcing is imposed through the time-dependent parameters of the wind, specific humidity, pressure, air temperature, solar radiation and precipitation. Soil and plant information need setting of soil texture (% of sand and % of clay), soil color and vegetation parameters (monthly leaf LAI and stem SAI indices).

The one-dimensional Eq. (2) is integrated by the method of finite differences. The solution to the time variable uses explicit scheme assuming 3 h time step in the discussed study. This enables the linearization of the equation evaluation at every step $\theta(h)$ and $K(h)$ by the Clapp and Hornberger formulae.

The model veracity is investigated in model intercomparison studies—Project for Intercomparison of Land Surface Parametrization Schemes (PILPS) and Global Soil Wetness Project (GSWP) (Dirmeyer et al. 1999; Guo and Dirmeyer 2006). The validity of its physical—mathematical approach to phenomenon and the numerical solution accuracy should not be disputable. The degree of its approximation when modeling the recharge of vast areas depends above all on the input data. First of all, this relates to the atmospheric effects data. They should be reliable and the mesh discretisation be detailed enough to interpolate satisfactory the atmospheric forcing values assigned to its nodes. This is above all important for the precipitation (Sahoo et al. 2008). Next come the soil-hydraulic properties and land cover type data. They are specific for every cell of the computation mesh. The hydraulic properties as $\theta(h)$ and $K(h)$ are specific for every sub-layer of the soil column. The number of the necessary data of the discussed type obviously is great and their provision is a difficult and responsible job. Their correction through calibration of the model for the concrete case study is a way for increasing its reliability. An attempt in this direction has been performed by the author in comparing the model results to satellite-obtained soil moisture data (Nitcheva et al. 2017).

Altogether, the model accuracy refinement is an intricate job and could be carried out when the method is established as the main tool for estimation of the GWB recharge. In such a process, the model sensitivity from the deviation of the numerous types of data could be investigated and fixed too. The purpose of this study is to demonstrate the possibility of application of the model to the problem of GWB recharge realistic estimation and of course to show ways for its accuracy improvement.

The main advantage of the discussed model compared to other hydrological models is above all the detailed and realistic description of the water flow transport through the unsaturated zone by detailed mathematical description. They account not only for the gravity but also for the porous and capillary uplift forces. The latter depends on the degree of the soil wetness.

The model is applied to assessment of the recharge of the Bulgarian Danube watershed GWB during the year 2013. The task target is a consideration of the plausibility of the model employment for long-term GW recharge estimation over large territories. The target achievement is important from two main aspects. First, the utilisation of the model facilitates the GW recharge estimation simply because once loaded with the necessary soil and geographical data every next use needs input of the new atmospheric forcing only. Second, it enables the assessments of the consequences for the GW ensuing from future climate changes under different scenarios.

Bulgarian Danube watershed GWB description

Bulgaria is a mountainous country and the water needs for irrigation and domestic water supply are mainly satisfied by regulation in many reservoir surface water. The groundwater serves as basic water source in flat regions, where water supply systems from surface sources are not easily available. Many settlements including big towns such as Plovdiv in South Bulgaria and Pleven in North Bulgaria and many others depend on groundwater resources. The groundwater is an important water source for the population in the region of the Bulgarian Danube watershed and particularly in its East part called Ludogorie.

For the most of the settlements in this part of Bulgaria building of surface water supply systems is rather problematic and not economically justified, while for Ludogorie region—North Bulgarian Arch (Fig. 2) it is too difficult. Hence, along the necessity for preservation of the quality it is important to have always good knowledge about the quantity and resource capacity of the groundwater in this area.

The Bulgarian Danube watershed occupies the greater part of the North Bulgaria (Fig. 1). Its area is about 47,235 km^2. The northern part is flat while to the south the relief becomes hilly of mean elevation 400 m. The plane from South is barred by the Balkan mountain chain with an average height of 900 m. The climate is moderately continental. In the flat northern part, the precipitation is between 500 and 600 mm/a, while in the southern hilly part it is between 650 and 700 mm/a with maximums in late spring and early summer.

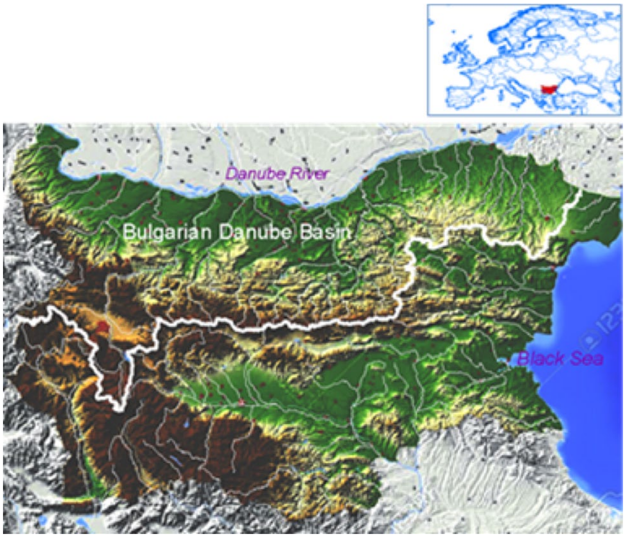

Fig. 1 Bulgarian Danube watershed

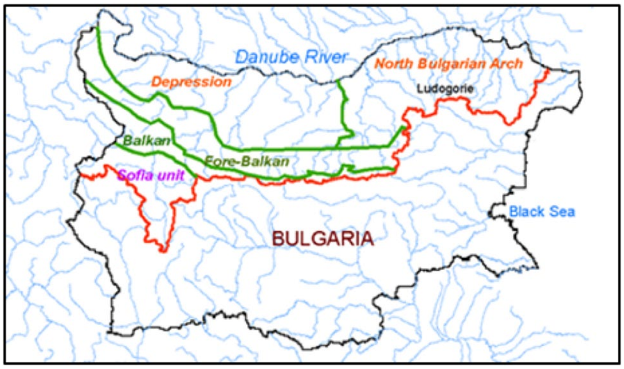

Fig. 2 Bulgarian Danube basin hydrogeological zones

The region has a complex geological structure. It is developed on the stable Moesian Platform (part of the Eurasian plate) and on the Balkan zone (part of the Alpine-Himalayan orogenic belt). Compared to the other three Bulgarian districts for river basin management it is the richest of groundwater. Precondition for this is the conserved from strong tectonic destructions mantle cover of the Moesian platform, where in the several hundreds to 2–3 thousands-m-thick Mesozoic sediments there exist big reservoirs of fresh and mineralized groundwater. The relief is even, the geological layers are stratified (parallel) and covered by loess (60–100 m). The porous and karst aquifers prevail (Santourdjian and Spasov 2000). The North mountainous part of the region is crossed by faults and folds, the fissured groundwater are widespread (Orehova et al. 2009).

The general direction of the groundwater flow is towards the Danube. The Danube region can be divided into five hydrogeological zones, which have specific hydrodynamic characteristics (Fig. 2). In the southern and central part of the North Bulgarian arch elevation in the limestone sediments formed are extensive karst fissure two-story located aquifers. In this part of the country, there is no permanent surface run off. The waters of the temporary arising streams enter the karst beds and transforms into groundwater flows. For this reason, here the groundwater is the only source for water supply. In the North West Bulgaria located is the broad Lom artesian basin (Depression—Fig. 2) with two significant aquifers—Pontian and Sarmatian. The Pontian level is in sandy layers and contains pore water, while the Sarmatian is made of different sediment rocks wherefore its waters are of fissure–karst–pore mixed types. The Sarmatian aquifer spreads to the whole North West Bulgaria. Its waters give the origin of great number of springs and recharge the rivers along their whole length. Most of the springs are captured for local water supply.

The mountain karst is rather developed in the Fore Balkan region with rich water karst basins formed in the limestone and dolomites in the middle. The discharge of the region is performed through big karst springs, but water discharge is very unevenly distributed during the year—big flow in the winter–spring period and much smaller in the summer–autumn one. Although the Bulgarian bank of the Danube is high, there are ten stretches known as Danube lowlands. In the alluvial deposits, abundant aquifers with very good filtration properties are formed. So far, from the practice, it is established that the river recharge along the Danube lowlands are of the order 300–500 l/s/km. All comparatively big towns such as Vidin, Lom, Oriahovo, Svishtov, Ruse and Silistra are supplied with water from the Danube lowlands.

It is estimated that the Danube basin management district disposes with considerable operating resources of groundwater. The river terraces with very good filtration properties and considerable withdrawal from river waters by the water intake facilities remain as basic and easily accessible sources for fresh waters. In North East Bulgaria, the main sources for water supply are the lower Triassic Jurassic Creaceous and Malm Valangnian aquifers. The karst waters in the mountainous part of the district represent significant resource but have very unsteady regime.

The present usage of the groundwater in the district is difficult to be established with precision. It is approximately estimated by different information sources to be around 13.5 m^3/s or 425×10^6 m^3/a, primarily meant for domestic supply where it is not done by surface waters (Santourdjian and Spasov 2000). The usage for irrigation purposes is very limited because of the unjustified high price of the water abstraction. This situation could be altered in not far future considering the expected climate changes leading to decrease of the surface waters and the increase of the demand for food production worldwide caused by the population growth.

In the Bulgarian Danube watershed distinguished are 50 GW bodies situated in six geological layers in different depths and partly overlaying each other (Fig. 3). There are monthly records of about 36 well level fluctuation and

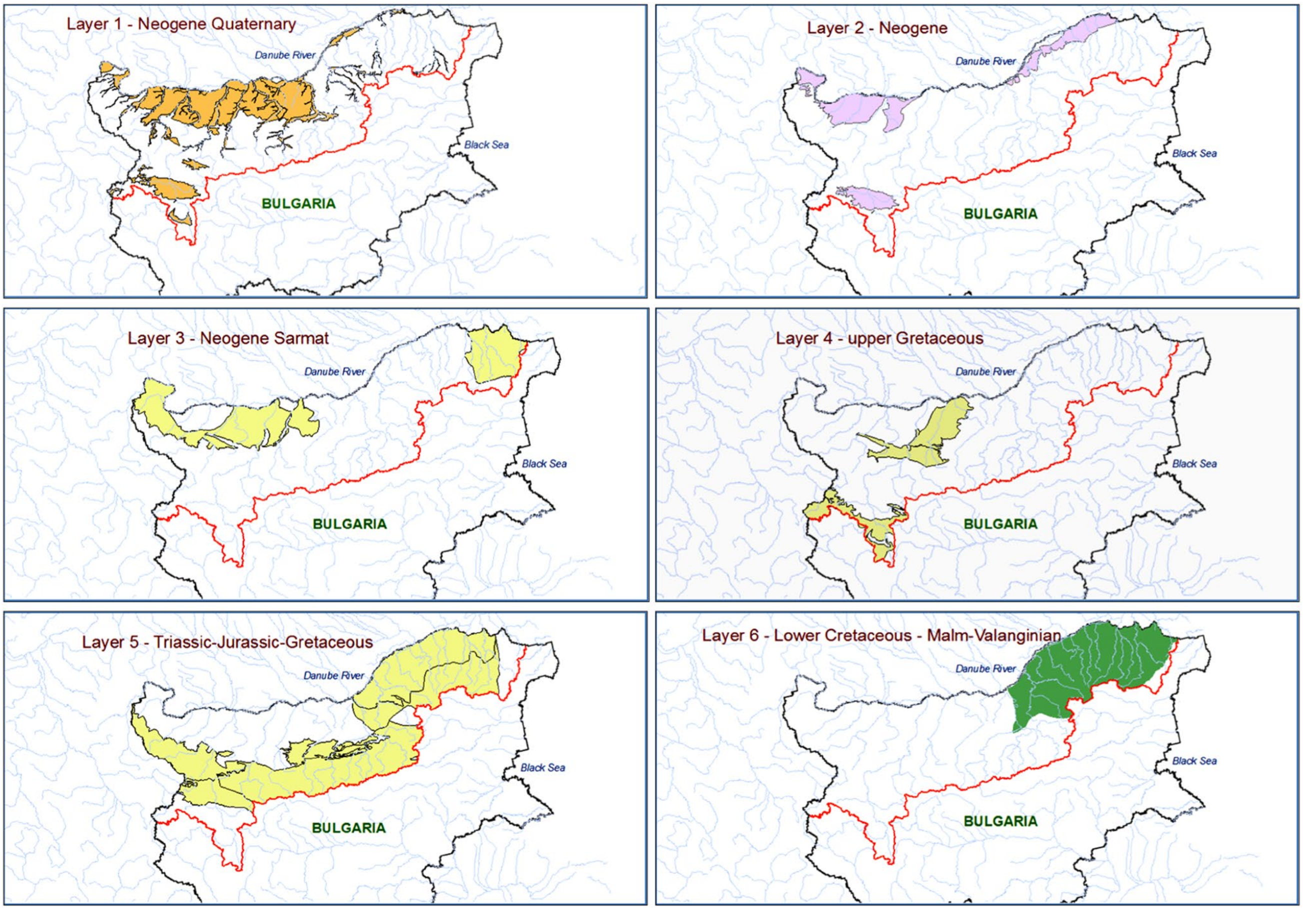

Fig. 3 Bulgarian Danube watershed GWB geological layers situation

of 13 spring discharge variation, gathered during different multiannual periods.

In 2012, the National Institute of Meteorology and Hydrology (NIMH), ordered by the Ministry of Environment and Water (MEW) of Bulgaria, elaborated methodology for assessment of the GW resources of Bulgaria (NIMH 2012). It included description of some of the conventional methods discussed in paragraph 2 applicable for most of the country GWB and respectively preparation on their basis of computation programs in Excel. Serving the MEW needs NIMH perform an assessment of the country water resources for the period 1981–2013 including the GW recharge in l/s for all GWB. The latter is summarized for the whole country and for the four river-management districts as well. The information is published on the MEW site (http://www.moew.government.bg/?page_id=24269) (MEW 2013, 2015).

According to that information source, given in 10^6 m^3, the interesting to the paper topic information in averaged for the period 1981–2013 annual values looks as follows:

For the whole country: precipitation—70,865 (638 mm/m^2), evapotranspiration—54,681, runoff (without Danube) 16,184, GW recharge—5408, GW abstraction resource—4650.

For the Danube river management district only: precipitation—27,245 (580 mm/m^2), evapotranspiration—22,021, runoff (without Danube) 5224, GW recharge—2558, GW abstraction resource—2344.

The GW resource possible for abstraction is estimated as the difference between the total GW recharge and the volume necessary for ecologically minimum discharge of the draining rivers.

Aiming at model result verification purposes, the author has prepared a GIS map of the averaged for the period 1981–2013 value of the recharge intensity of all GWB watersheds in the Danube region based on data published in the MEW site in the Web. It was evaluated by division of the MEW shown groundwater body mean annual recharge in l/s to the watershed area. The intensity on areas with overlaying groundwater bodies is calculated by superposition.

Having in mind the way the map is worked out (the plotted intensities are recharge values averaged over areas ranging from several dozens to thousands km^2) and the approximate character of the GWB recharge calculation it cannot be expected great accuracy of the detailed areal distribution of the recharge intensity. The latter of the ten lowland GWB along the Danube includes the infiltrated water from the river which can amount to more than 150×10^6 m^3/a. This makes the calculation for the mentioned GWB intensity much greater than it is in reality. The ones shown on the map intensities in average are lower than real ones because the recharge areas of many groundwater bodies are less than their watersheds. According to the MEW estimates, the infiltration area of the district, recharging the GWB, amounts to 26,000 km^2 from the total 47,235 km^2. It is obtained by extracting the urbanized and industrial areas, lakes, territories without GWB and other impermeable areas from the last figure. The map is based on estimations using observational data and regardless the above pointed out discrepancies because of a lack of more trustworthy documents it can be used for various GWB related assessments.

GW recharge assessment by the Community Land Model

The model CLM3 is applied to the evaluation of GW recharge of the whole Bulgarian Danube watershed during 2013. No longer than 1 year simulation period is assumed because of the significant difficulties in the input of the huge massifs of the numerous atmospheric data. The year 2013 is characteristic with having country annual precipitation 638 mm nearly the same as the average precipitation for the period 1981–2013. The mean annual precipitation for the same period for the Danube plain region is equal to 580 mm, quite close to the annual precipitation for 2013—583 mm. It is obtained as averaged values of the precipitation measured in eight observation stations, situated in eight main towns in the region. The mountainous part of the district is not accounted for in this assessment, which suggests that the real precipitation is greater than 583 mm.

As the purpose of the modeling is to show the possibility of realistic estimation of the GW recharge by the model CLM3, its results should be compared to data obtained by other methods based on field observations and measurements. In the of case such data are the above-presented values of the GW recharge estimates for the period 1981–2013 with nearly the same average precipitation as one of 2013. Such comparison will be to a great extent indicative because the main factor for GW recharge is the precipitation amount. The other climatic effects as air temperature and humidity, wind velocity, solar radiation etc., cannot vary in a measure to influence significantly the water infiltration process. The difference in the precipitation areal distribution in 2013 from the average one of the long-term period can cause differences in the recharge of separate GWB estimated by the two approaches, but the overall estimates will not be much affected.

Regarded is the territory of the above-described Bulgarian Danube watershed. The resolution (cells) of the distributed soil surface mesh is assumed with dimensions 5 × 5 km. To every cell water movement and transformation related properties assigned are values specific for its topography, land cover vegetation and soil profile.

The meteorological input is supplied in this study from NASA atmosphere NCEP/NCAR Reanalysis data [US National Centre for Environmental Prediction (NCEP) and the US National Centre for Atmospheric Research (NCAR)], gathered by different methods and tools for weather observations all over the world. (Kalney et al. 1996). The climatic data as air temperature, air pressure and humidity, solar radiation, wind speed, precipitation with 1 day time step are applied to the nodes of computational grid with cells 200 × 200 km and are continuously distributed within the cell. The mean annual precipitation on the Bulgarian Danube watershed for 2013 computed by the model meteorological input is 664 mm, very close to the MEW estimation as mean for the time period 1981–2013.

The soil characteristics and land cover data for every grid cell with resolution 5 × 5 km are taken from the International Geosphere–Biosphere Programme (IGBP) data base.

The simulation period starts two months before the beginning of the study period on 1 November 2012, to avoid the influence of the assumed initial soil moisture distribution on the simulation results. The soil infiltration capacity is controlled by soil properties and soil moisture within the top soil layers (Li et al. 2011).

The model soil layer thickness is 3.43 m divided into ten sub-layers. The computation is performed with 3 h time step. The water amount calculated as filtrated below the vegetation root zone, with assumed maximum thickness 1 m, is considered as potential groundwater recharge. The model obtained potential recharge intensity monthly values for 2013, average for the whole area, are shown on Table 1. In the table, the potential recharge intensity is called infiltration because it converts into groundwater recharge only on a part of the watershed.

The results shown on Table 1 bring to the following conclusions. The evaluated district territory mean annual infiltration intensity in percentage of the annual precipitation is within the normal ranges for such a value for geographical regions with similar topographic and climatic conditions. The monthly distribution of the infiltration quantities responds to the expectations considering the precipitation amount and the temperature level. In the cold and rainy seasons, the filtration moves downward forced by the gravitation, while in the warm season the water moves upward under the capillary uplift forces. Only in June there is an exception because of the very strong rain.

The shown infiltration turns into potential GW recharge only on the 26,000 km^2 of the whole district estimated by the MEW as actual recharge area. If so, the total annual recharge for 2013 on the Bulgarian Danube basin can be evaluated as equal to $26{,}000 \times 10^6 \times 0.0997 = 2592 \times 10^6$ m^3. This figure is too close to the recharge amount of 2558×10^6 m^3 estimated by the MEW as long-term GW recharge for the Bulgarian Danube basin district. As a matter of fact, the real recharge is higher because the calculated value does not include waters re-infiltrated from the rivers and above all from the Danube. At the same time, it should not be neglected the fact that the model input annual precipitation of 664 mm is 14% greater than the MEW estimated for the period 1981–2013 long-term precipitation of 580 mm.

The calculated by the model infiltration intensity is an averaged value over every grid cell. On their basis a GIS map (De Jager and Vogt 2010) of the territorial distribution of the infiltration intensity during the considered year throughout the Bulgarian Danube basin has been prepared. It is shown on Fig. 5. The map is compared to the map on Fig. 4, which similarly shows the distributed recharge intensity on the district territory caused by approximately equal annual precipitation. Nevertheless, they differ substantially considering the rather approximate way of producing the map on Fig. 4. The map on Fig. 4 gives a generalized picture of the district GW recharge intensity territorial distribution, calculated by dividing the real GWB recharge volume to its entire watershed area, while the values of the map on Fig. 5 are computed over detailed mesh cells with area as small as 25 km^2.

In spite of all noted above differences, the both maps display great similarity in the recharge intensity values as well as in their territorial distribution. This is very evident when the Figs. 4 and 5 are shown in colors. It is seen on the two maps that the east part of the district has twice and even more GW recharge potential than the rest of it. The large South Fore Balkan region is shown on both the maps with very scarce GW recharge capacity. The infiltration intensity values on both figures are of the same order except for the Danube lowland GWB. Because of the infiltration from Danube the intensity of the field data-based map is much higher.

The above discussed comparison between the two maps, produced by different methods and data sources, convinces

Table 1 X

Months	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	2013
Rain (mm)	17.7	46.7	31	43.5	62.2	184	81	22.3	19.6	41	37.4	5.7	592
Snow (mm)	33.3	7.5	0.33							0.01	18	12.8	71.9
Total precipitation (mm)	51	54.2	31.3	43.5	62.2	184	81	22.3	19.6	41.0	55.4	12.4	663.9
Infiltration (mm)	8	22.4	14.1	4.7	− 10.1	67.3	− 14.7	− 29.3	− 9.2	13.3	24.9	8.3	99.7
Infiltration/precipitation (%)	15.7	41.4	45.0	10.8		36.6				32.3	44.9	44.9	15.0

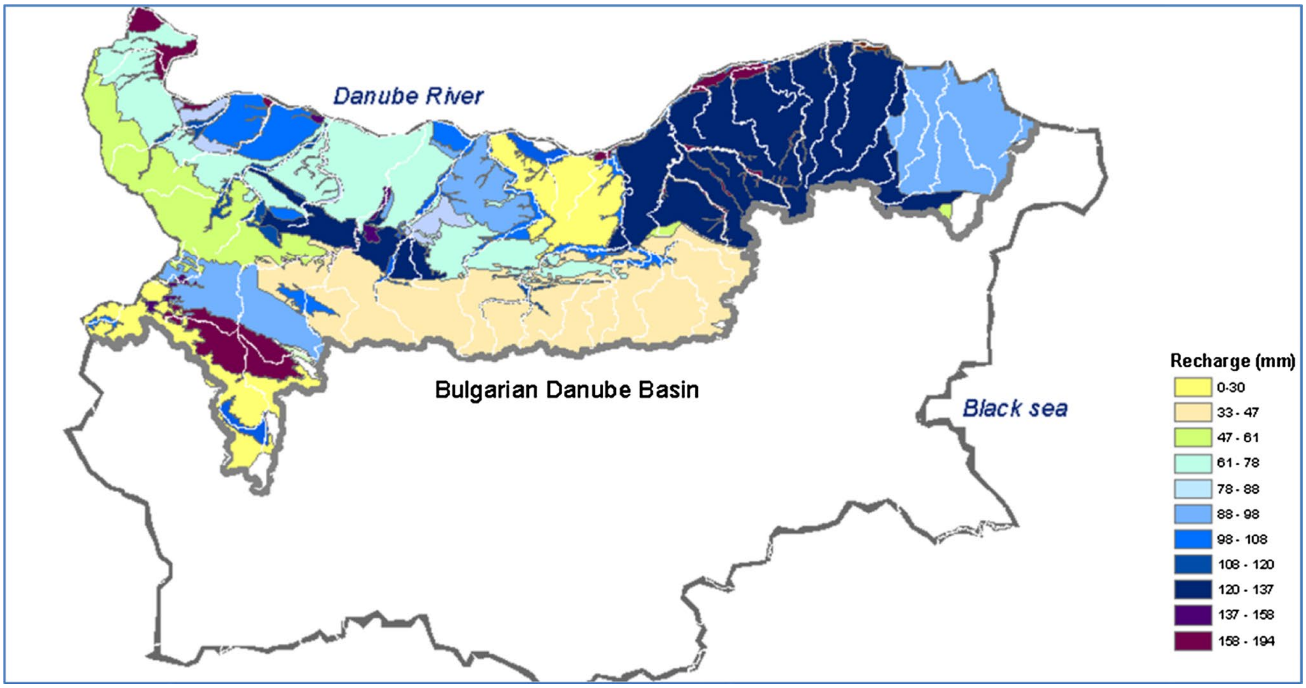

Fig. 4 Map of the averaged for the period 1981–2013 recharge intensity of GWB watersheds in the Bulgarian Danube Basin based on the MEW data

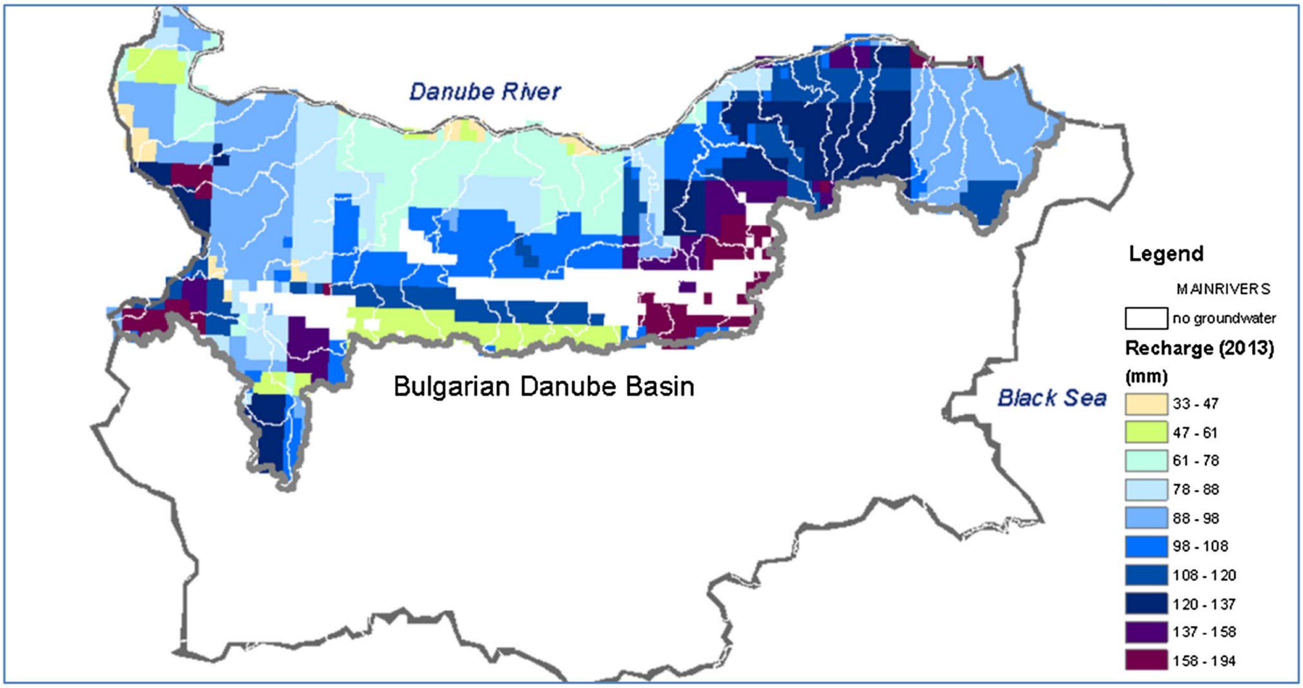

Fig. 5 Map of the territorial distribution of the model calculated infiltration intensity during 2013 in the Bulgarian Danube Basin

the possibility of the model CLM3 to well simulate the soil-moisture infiltration processes and also considering the infiltration below the 1 m root zone water as potential recharge is realistic. The other very important conclusion is that the great amount of the model input concerning the land surface, soil hydraulic properties and climatic effects is

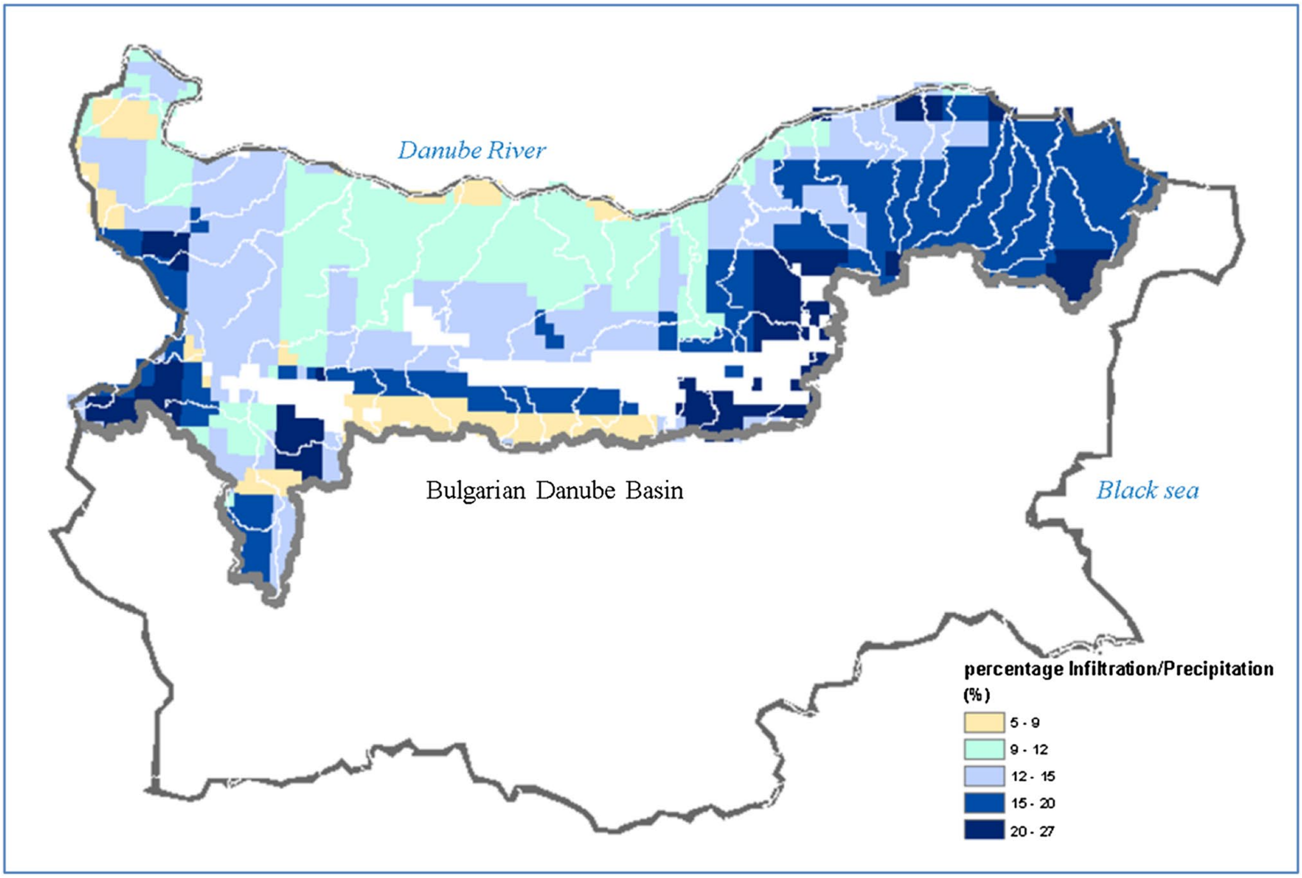

Fig. 6 Map of the percent ratio between the modeled infiltration and precipitation in 2013 on the Bulgarian Danube basin territory

representative for the studied territory on a whole. Through the method of back analysis of a single GWB, it is possible that further calibration of soil and land cover datasets of selected grid cells and areas.

As confirmation of the results shown on Fig. 5 a GIS map of the percent ratio between the infiltration and precipitation in 2013 is prepared and shown on Fig. 6. This ratio varies from 5 to 27%. The biggest are the values in the east part of the region.

Conclusions

The CLM3 model approach to the task of GW recharge assessment is possible when the needed enormous amount of soil characteristics, land surface and vegetation cover data and long-term climatic data are available. The results from CLM3 model simulation of the soil moisture transport processes on the Bulgarian Danube district territory during 2013, the calculation on their basis of the total GW annual recharge amount and the territorial distribution of the computed infiltration intensity are rather encouraging in respect to the possibility through the employed model to achieve reliable practical assessments important for the water resources management field.

The hydrology models and in particular the CLM3 approach has two main advantages. It makes possible the assessments of the resources of GWB lacking long-term observation data of their regime. It is also the only instrument for prediction assessments of the GW recharge response to climate changes under given scenarios.

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