

COMMENT 1: *The manuscript presents a modified version of the large-scale karst recharge model VarKarst. The here presented model (V2Karst V1.0) replaces the simplified evapotranspiration (ET) component (empirical Priestley-Taylor equation) by the physical based Penman-Monteith equation (for potential evapotranspiration). The authors also include a separate calculation of the different evaporation processes in order to use the model for climate and land cover change impact studies. The model extension increases the number of parameters. The general functioning as well as the influence of the new parameters are tested by applying the new model to four study sites, different in climate and vegetation. The manuscript is a novel extension of previous work published by the research group. The conceptual description and the numerical adaptation of the processes are sound. The results of the model application on the four test sites prove the general functioning of the new model. However, the manuscript also has weak points, which are mainly related to the presentation of the method and the results. The manuscript can easily be shortened by 10-20% without losing important information. The presentation of the results needs to be improved, especially since it is difficult to distinguish between observed values and modeled results. My detailed comments are listed below.*

REPLY 1: We wish to thank the Reviewer for appreciating the novelty and soundness of our work and for the detailed comments, especially regarding the karst aspect of our work.

We realise that the manuscript is rather long in parts, and we will shorten our revised version.

We will also clarify the distinction between observed and simulated values. In brief, the parameter estimation approach (Sect. 4.1) uses measurements of weather variables to force the model and measurements of model output to define the soft rules. The global sensitivity analysis (Sect 4.2) uses measurements of weather variables to force the model, but no measurements of model output. Finally, the virtual experiments (Sect 4.3) do not use any measurements. In the revised version of the manuscript, we will clarify the point by changing the sentence that introduces the method section p16 L8-12, for instance as: “To test the plausibility of V2Karst realisations at FLUXNET sites, we estimate the model parameters by constraining model simulations with actual ET and soil moisture observations (Sect. 4.1), and we perform two sensitivity analyses using measured data to force the model (Sect. 4.2), and synthetic forcing data and land cover change scenarios (Sect. 4.3).”

Part of the confusion regarding the distinction between observed and simulated values may also come from the fact that Figure 6 includes a lot of information. We will simplify Figure 6 by removing the yellow and green lines corresponding to the two additional estimates of measured evapotranspiration (no correction and residual correction) and report the additional information on these two quantities in our supplementary material. These two additional estimates of evapotranspiration were not directly used in applying the soft rules but were only used to assess the uncertainty in latent heat measurements. Likewise, we will shorten the paragraph on the assessment of uncertainty in latent heat measurements (Sect 3.2 p15 L26-p16 L6), to improve readability.

MAIN COMMENTS

COMMENT 2: *The purpose of V2Karst V1.0 is to predict recharge in karst regions. The authors mention that “a large part of the groundwater recharge occurs as concentrated and fast flow in large apertures and the other part as diffuse and slow flow in the matrix (Hartmann and Baker, 2017).” Especially concentrated recharge, e.g. fast infiltration into sinkholes, can be considered as a short-term process and is entirely uncoupled from soil and/or vegetation properties (overland flow -> percolation).*

I assume that your model, calculating the water balance, underestimates the recharge in karst regions dominated by concentrated recharge. Do you think your model is able to equally represent both recharge processes?

REPLY 2: We agree with the need for representing concentrated recharge processes. In karst systems, infiltration and recharge can be slow and diffuse in the matrix and fast and concentrated in large conduits or fissures that act as preferential flow pathways. Lateral flow at the surface and in the epikarst is an important mechanism that concentrates the infiltrating water into the preferential flow pathways (Jeannin and Grasso, 1997; Williams, 1983, 2008). In particular, the epikarst plays a role of temporary storage that can redistribute fast and concentrated recharge (Williams, 1983, 2008). Figure R1.c below provides a conceptual model of the soil and epikarst processes of a real karst system.

V2karst's representation of concentrated and diffuse infiltration and recharge, which is the same as in the VarKarst model (Hartmann et al., 2015), follows this conceptual model (Figure R1.a). V2karst represents the spatial variability of subsurface properties observed in karst systems by dividing each model simulation unit into a number of vertical compartments that have different soil and epikarst properties. Parameters for each model compartment (soil and epikarst storage capacities and epikarst outflow coefficient) are estimated using a distribution function. The daily water balance is explicitly evaluated for each model vertical compartment. Additionally, when a given compartment saturates (both soil and epikarst stores), its saturation excess generates a surface lateral flow to the next unsaturated compartments that have higher storage capacities and higher permeabilities. In this representation, surface and subsurface lateral flow are thus lumped together. Conceptually, in V2Karst, the direct contribution of precipitation to infiltration and recharge can be associated with diffuse infiltration and recharge, while the contribution of lateral flow can be associated with concentrated infiltration and recharge. Hence, the V2karst structure allows to account for the interplay between diffuse and concentrated infiltration and recharge processes.

The representation of karst processes in V2Karst and VarKarst is based on a previous karst model developed for applications at the local scale introduced in Hartmann et al. (2012). The structure of this previous models explicitly represents lateral flow both at the surface and in the epikarst, in agreement with understanding of the flow mechanisms in the epikarst (e.g. Williams, 1983, 2008). It was tested using hydrodynamic and hydrochemical information at stalactite drips in a karstic cave in Hartmann et al. (2012). However, simplifications have been introduced for applications at the large-scale, given the limited information available to constrain the additional parameters required in the previous karst model to represent lateral flow in the epikarst.

We are aware of the fact that, in V2Karst's and VarKarst's representation, concentrated recharge is not entirely uncoupled from the soil and vegetation properties as it is observed in real karst systems. However, a previous study by Hartmann et al. (2017) compared simulated recharge with VarKarst and independent estimates of recharge and showed that there was no systematic bias in the simulations (Figure R2 below). Moreover, the study by Hartmann et al. (2017) showed that recharge values simulated with VarKarst were significantly higher than recharge values simulated with models that do not include karst processes (Figure R2 below).

As stated in REPLY 9, we will briefly explain how diffuse and concentrated recharge is represented in VarKarst and V2karst p6 L12.

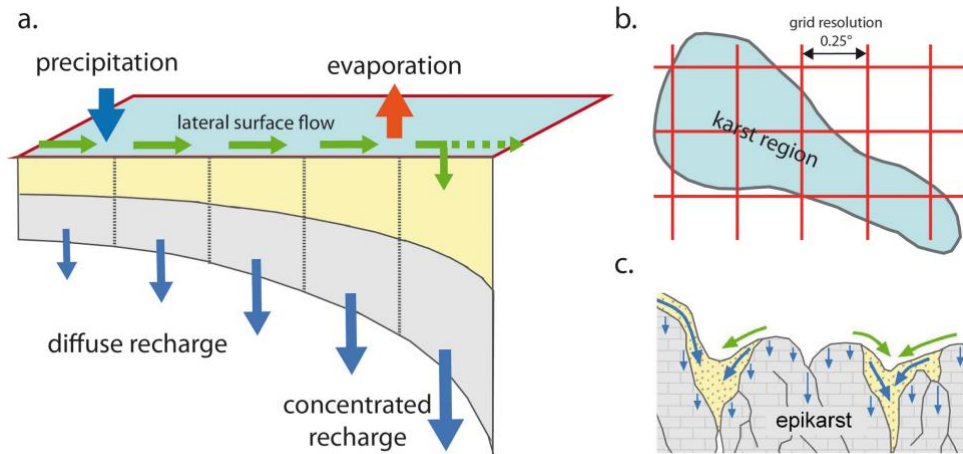


Figure R1. (a) Schematic description of the VarKarst model for one model grid cell including the soil (yellow) and epikarst storages (grey) and the simulated fluxes, (b) its gridded discretization over karst regions and (c) the subsurface heterogeneity that its structure represents for each grid cell. Figure taken from Hartmann et al. (2015, Figure 1)

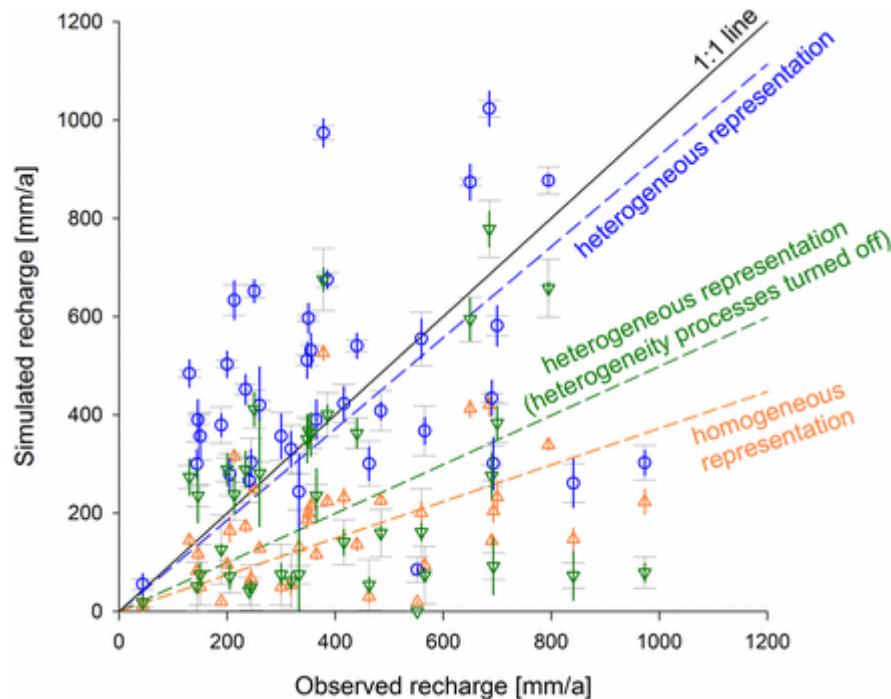


Figure R2. Comparison of simulated and observed recharge. **In blue are reported values simulated with the VarKarst model (heterogeneous representation)**, in yellow values simulated with the PCR-GLOBWB model (homogeneous representation, i.e. absence of karst processes in the model representation), and in green the Varkarst model with subsurface heterogeneity processes turned off. Whiskers indicate the simulation uncertainty (1 SD) for simulations with VarKarst. **No statistical difference (5% significance level) was found between simulations with Varkarst and the observations.** mm/a, millimeters per year.

Figure taken from Hartmann et al. (2017, Figure 2)

COMMENT 3: *I am aware of the fact that the manuscript is focused on the implementation and the testing of the new evapotranspiration component. Since soil layers in karst regions can be thin or even totally absent the authors should consider this fact in the interpretation of the results.*

REPLY 3: Large differences in soil depth can indeed be observed across different karst landscapes. To apply the VarKarst model over Europe and the Mediterranean, Hartmann et al. (2015) have identified four main karst landscapes with different soil depths and degrees of karstification based on climate and topography (Humid, Mountain, Mediterranean and Desert landscapes). Different values of the parameter V_{soi} (mean soil water capacity) have been applied in the different landscapes. In particular, very small values of V_{soi} have been used in arid areas (i.e. desert landscape in Hartmann et al. (2015)), where soils tend to be very thin.

We are also aware of the fact that soils may be absent in some karst areas (e.g. karren field in high mountain areas, see e.g. Hartmann et al. (2014a)), and that these areas may consequently produce very high recharge amounts. The model does not account for the fact that the soil may be absent and always includes a soil layer, although the soil layer can be very thin and therefore can have a limited impact on recharge. This assumption seems reasonable given the large extent of the simulation units for large-scale applications ($0.25^\circ \times 0.25^\circ$ or $0.5^\circ \times 0.5^\circ$ cell in previous applications). In fact, we can assume that soil layers can always be found in such large simulation units. However, for model applications at high resolutions, we recognise the fact that an explicit consideration of bare rock regions should be included in the model.

We will briefly discuss this point in Sect. 6.3 that discusses the application of V2karst over large domains.

COMMENT 4: *The manuscript lacks a description/characterization of the four karst regions (e.g. by describing dominant karst features or by the interpretation of spring hydrographs).*

REPLY 4: In this study, we focus on groundwater recharge, which is a key component of the water balance. Recharge characterises the amount of renewable groundwater, and therefore the amount of groundwater available to human consumption and ecosystems (e.g. Scanlon et al., 2006; Döll and Fiedler, 2008; Wada et al., 2012). We do not model groundwater flow and storage nor spring discharge. Therefore, to test the model, we focus on datasets that can be related to the fluxes and states simulated by V2Karst, i.e. soil moisture and evapotranspiration as in Hartmann et al. (2015). No datasets providing time series of recharge are available. We do not use spring hydrographs, because spring discharge depends on groundwater routing and is not commensurate with groundwater recharge. Spring discharge measurements were used to extensively test a previous versions of the VarKarst model including groundwater storage and routing to the spring, at different locations in Europe and the Mediterranean (Hartmann et al., 2013a, 2013b, 2014b).

Table B1 describes the four sites, and more specifically the soil depth and bedrock. We have realised that we have exchanged the name of the two French sites in Table B1 (Puéchabon is actually the French 2 site and Font-Blanche the French 1 site) and we will correct this mistake in the revised version of the manuscript. We did not add more details on the sites in the main text to limit the length of the manuscript.

COMMENT 5: *In general, a differentiation between different karst systems and therefore the wide variety of hydraulic properties dominating the recharge pattern (see above) is missing here.*

REPLY 5: A large variability in hydraulic properties and in recharge patterns can indeed be observed across karst systems (e.g. Klimchouk and Ford, 2000; Hartmann et al., 2014a). For applications over large-scale domain, Hartmann et al. (2015) identified four typical karst landscapes with different hydraulic properties, based on climate and topography (as mentioned in REPLY 3). This simplified classification of the simulation domain in four landscapes was introduced to enable large-scale applications of the model.

In Sect. 6.3 (discussion of V2karst large-scale application), we will better highlight the fact that future large-scale applications of V2Karst will need to account for the variability observed across karst systems, for instance using a simplified classification as in Hartmann et al. (2015).

COMMENT 6: *As already mentioned, the current manuscript is too long and needs to be shortened:*

- 1)** *(Almost) every section starts with a short introduction on the section. Most of them are redundant.*
- 2)** *The authors use wordy descriptions instead of clear words for describing their work. Is a “virtual experiment with synthetic data to assess the sensitivity” (Page 1, Line 19) not simply a “sensitivity analysis”?*
- 3)** *Discussion chapter: Consists of sentences/paragraphs, which can be defined as general knowledge (e.g. Page 26. Line 16; Page 26, Line 24) or which should be familiar by the readers of the journal (e.g. Page 28, Line 12).*

REPLY 6: We thank the Reviewer for suggesting how to shorten the manuscript and we reply below to the three points raised by the Reviewer.

1) We will revise the introductions of the sections to make them more informative (see REPLY 1) and we will remove them where appropriate (p4 L13-15, p20 L3-5 and p23 L17-19).

2) The virtual experiments are indeed sensitivity analyses. However, an important aspect is that we used synthetic data, which has been done only in few studies (e.g. the studies reported p18 L20-29). The reason for using synthetic data is that it allows to explore conditions beyond what was historically observed, and it is therefore useful to better understand potential impact of changes in climate. It also permits unequivocal attribution of changes in model output to changes in model inputs.

Therefore, we think that it is important to mention that we used synthetic data p1 L19. However, as discussed in REPLY 7, we will clarify this part of the abstract. We will also check for wordy descriptions in the manuscript and revise them where appropriate.

3) We agree that the discussion section can be shortened and clarified and more specifically at the places indicated by the Reviewer.

We will clarify the discussion of the virtual experiments (Sect. 6.2). Firstly, the virtual experiments confirm that the model behaves reasonably, since it shows sensitivities to both precipitation (overall amount and temporal distribution) and land cover, in agreement with previous studies and general understanding. Secondly, the virtual experiments allow to unequivocally and quantitatively characterise the relationship between simulated recharge and both precipitation (overall mean and temporal distribution) and land cover. Therefore, virtual

experiments are a complementary approach to model applications using site-specific data to assess the impact of climate and land cover changes on simulated recharge.

We will revise the discussion on large-scale application of the model (Sect. 6.3) and we will clarify in particular the points mentioned in REPLY 3 and 5.

SECONDARY COMMENTS

COMMENT 7: - *Page 1, Line 21: ". . . and they suggest that simulated recharge is sensitive to both precipitation (overall amount and temporal distribution) and land cover. " Is this one of the main results of your work and is it really a new finding?*

REPLY 7: We agree that we need to reformulate this sentence. We refer to REPLY 6 for a clarification of the objectives of the virtual experiments.

We will replace the sentences p1 L19-24 ("Then, we use virtual experiments with synthetic data to assess the sensitivity of simulated recharge to precipitation characteristics and land cover. Results reveal how both vegetation and soil parameters control the model behaviour, and they suggest that simulated recharge is sensitive to both precipitation - overall amount and temporal distribution- and land cover") for instance by: "Then, virtual experiments with synthetic data confirms that the model has sensible sensitivities to precipitation (overall amount and temporal distribution) and land cover in light of previous studies In addition, results allow to quantify the relationship between changes in simulated recharge and changes in precipitation and land cover characteristics."

COMMENT 8:

- *Page 2, Line 30: The sentence is difficult to understand.*

- *Page 4, Line 17: Please, rephrase the long sentence (and consider deleting the first part of the sentence).*

REPLY 8: We will reformulate these two sentences.

COMMENT 9: *Page 6, Line 12: Could you please add a bit more information on how diffuse and concentrated recharge is considered by the model.*

REPLY 9: We refer to REPLY 2 for a detailed explanation of the conceptualisation of recharge processes in V2Karst and we will add a brief explanation on this p6 L12.

COMMENT 10: *Page 12, Line 12/13/14: Please, consider using SI-Units.*

REPLY 10: We have adopted these units because they are typically used in the evapotranspiration literature (e.g. Allen et al., 1998; Shuttleworth, 1993, 2012).

The revised version of the manuscript will include the unit of net radiation (R_n [$\text{MJ}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$]) which is missing.

COMMENT 11: *Page 13 Seasonality of vegetation: Are you using the same seasonality on every study site irrespective of the local climate and vegetation type?*

REPLY 11: Typically, in hydrological models, vegetation seasonality is represented using different schemes with different levels of complexity or is neglected completely (Table A3). We chose to implement a simple representation (piecewise linear function). In this way, we can test the impact of vegetation seasonality by assessing the sensitivity of recharge to the seasonality parameter LAI_{min}. We applied the same function at all sites, but we used different values of the seasonality parameter LAI_{min} as indicated in Table 3. The timings of the four phases reported in Eq. (14) are appropriate for study sites that are located in the northern hemisphere and that have natural vegetation.

We will add a sentence p13 to clarify the fact that the timings of the four phases of the seasonality model should be adapted to the application domain.

COMMENT 12:

- Page 15, Line 4: *Please consider splitting the sentence.*

- Equation 17/18: *Please remove the units from the equation and mention both parameters in the text, e.g. “1. Each, bow [mmmonth1], a corrected value that assumes that latent heat ($\delta \cdot IR \cdot \delta \cdot IR \cdot y$ [MJ.m⁻².month⁻¹]) and sensible heat ($\delta \cdot IR \cdot z$ [MJ.m⁻².month⁻¹]) have similar errors (referred to as Bowen ratio estimate):*

- Page 17, Line 29: *Please, rephrase the sentence.*

- Page 24, Line 4: *Please, rephrase the sentence.*

REPLY 12: We will apply these changes in the revised version of the manuscript.

COMMENT 13: *Figure 4: The Figure presents the results in a confusing way and some of the values exceed the constrained parameter ranges according to Table 3.*

REPLY 13: We realise that the plot we used – a parallel coordinate plot – is not familiar to all readers in earth sciences. A parallel coordinate plot is a two-dimensional plot that allows to visualise a multidimensional space (here the space of the model parameters and outputs). In Figure 4, each line represents a combination of model parameters values (normalised) and the corresponding model output values (normalised). Parallel coordinate plots are increasingly used (e.g. Inselberg, 2009; Kasprzyk et al., 2013; Pianosi et al., 2017), and are implemented for instance in the Matlab Statistics and Machine Learning Toolbox (function “parallelcoords”) and in the SAFE toolbox for sensitivity analysis we utilised in our paper (Pianosi et al., 2015).

Initially, we sampled the parameter space within wide ranges (Table 2), and we applied a priori information on parameter ranges (Table 3) only in rule 5. Therefore, prior to application of rule 5, parameter values can exceed the ranges of Table 3 (yellow, light blue, green and dark blue lines in Figure 4). Instead, posterior to application of rule 5, all parameter values should be within the ranges of Table 3 (red lined in Figure 4).

The Reviewer may be referring to the fact that some red lines slightly exceed the black vertical lines in Figure 4. This is a plotting issue and it will be corrected in the revised version of the manuscript.

MINOR COMMENTS AND TYPOGRAPHICAL ERRORS

COMMENT 14: *Please, use a consistent citation style.*

REPLY 14: We will check the citation style throughout the manuscript.

COMMENT 15: *Please, use a consistent style for figure references. Two different versions exist: Fig. and Figure.*

REPLY 15: We will replace 'Figure' by 'Fig.' p6 L22, p6 L28, p14 L14 so that the referencing of the figures is consistent with guidelines of GMD available at (https://www.geoscientific-model-development.net/for_authors/manuscript_preparation.html): *The abbreviation "Fig." should be used when it appears in running text and should be followed by a number unless it comes at the beginning of a sentence, e.g.: "The results are depicted in Fig. 5. Figure 9 reveals that..."*.

COMMENT 16:

- Units -> *Replace the dots by multiplication sign or even better delete them.*
- Page 2, Line 2: *. . .world. . .*
- Page 2, Line 2: *For instance, . . .*
- Page 5, Line 4: *. . . (Hartmann et al., 2015). This . . . (space missing)*
- Page 5, Line 33: *. . . to represent. . .*
- Page 7, Line 13: *. . . the following formulas . . .*
- Page 12, Line 13: *. . . is the psychrometric constant, . . .*
- Page 15, Line 18: *. . . data processing are reported . . .*
- Page 20, Line 18: *red lines -> the a priori information are indicated by black lines in Figure 4!*
- Page 29, Line 14: *We, therefore, . . .*
- Figure 5, Line 4: *. . . percentage of Eact . . .*
- Figure 6: Line 5: *Blue . . .*
- Figure 9: Line 4: *remove the open bracket*

REPLY 16: The revised version of the manuscript will include these corrections.

References to support our reply to the Reviewer

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