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Hydrology and
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Discussions

Interactive comment on "Modelling the hydrological interactions between a fissured granite aquifer and a valley mire in the Massif Central, France" *by* Arnaud Duranel et al.

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We thank Anonymous Referee #2 for stating that our research question and case study are interesting and that our field measurement campaign that provided the data for model calibration and validation was comprehensive. We believe that we can significantly improve the paper by accounting for the referee's comments and suggestions.

General comment

Rather than testing a range of competing theoretical conceptualisations of our geological model as proposed by Referee #1 (a valid but entirely different approach), we chose

to use the most plausible conceptualisation based on the data available, while making reasonable simplifying assumptions to account for constraints associated with practical computing times and the risk of over-parameterisation. We fully agree with Referee #2 that a detailed description of how we built the conceptual model is required. An in-depth description is available in Duranel (2015) which is cited and is available online (https://discovery.ucl.ac.uk/id/eprint/1472054/1/Duranel_PhDthesisADuranel2015.pdf). Indeed, a whole chapter of this PhD thesis is devoted to the geological model which was built using a large dataset derived from multiple sources (existing unpublished data, data we collected as part of the project, and published literature and technical reports mainly in French).

In the original version of the paper we provided a concise description of the geology of the site and the geological model, considering that, since the geological model is described in the above publication, we should instead focus on the hydrological model and its results. Including more information on the geological model is certainly possible but will clearly make the paper a little longer. We believe that this will be necessary to respond to the referee's comments and would improve the paper. Therefore, we propose to revise Section 2.2 ("Geological model") of the paper to include 1) a new figure showing the two most informative Electrical Resistivity Tomography transects which were instrumental in defining the geological model; 2) as specifically requested by Referee #2, a new figure showing the results of previous drillings by the uranium mining company; and 3) a description and interpretation of the results obtained from the ERT survey and the geological drillings. The location of the two selected ERT transects and, as requested by Referee #2, the drillings, will be shown on an updated version of Figure 1 of the original version of the paper. We estimate that the proposed changes will add approximately two pages to the manuscript. Drafts of the proposed additional figures showing two selected ERT transects and the geological drillings are shown in Figure 1 and Figure 2 of this reply, respectively. Please note that their captions refer to Figure 1 of the original version of the paper.

Figure 1 of this reply shows the presence of conductive material underneath much more resistive material on the hilltops and slopes of the catchment. The transition between these layers is abrupt and its altitude is largest beneath hilltops. The depth of the transition is larger beneath steep slopes, and on all transects it intersects the surface topography in the valley precisely where the wetland boundary is located (taking into account the ERT positional accuracy). The only location where conductive material was recorded above resistive material is on one hilltop (visible on the left-hand side of transect a). This was interpreted as demonstrating that most of the material investigated corresponds to the densely fissured layer of a truncated granite weathering profile. The interface between resistive and conductive material was assumed to correspond to the groundwater table (the exfiltration of which led to the formation of the wetland). The increase in resistivity with depth at the very bottom of transect b) at a depth of around 55m below ground level was interpreted as a decrease in fissure density (and therefore bulk porosity), and a transition towards unweathered granite. The superficial conductive material on the hilltop was assumed to be (probably unsaturated) saprolite, which is more conductive than the fissured granite layer due to its larger clay and water contents. The configuration was not seen anywhere else within the study area, leading to the conclusion that on most hilltops and hillslopes the majority of saprolite has been eroded away and the combined thickness of the soil, periglacial deposits and remaining in-situ saprolite is too small (less than a metre) to be detected. There is no indication of the presence of a substantial saprolite layer in the valley bottom beneath the wetland, however the complete saturation of the profile may make the distinction between fissured granite and saprolite impossible in this area. Figure 2 of this reply shows that the granite is weathered to highly weathered, with dense fissuration leading to low or variable core recovery percentages, to a depth of 15-65m. A substantial saprolite layer ("grus") is present in five out of seven locations. This is seemingly at odds with the apparent absence of saprolite beneath the wetland on the ERT transects located further downstream. However it should be noted that the geological drillings are not representative of the entire catchment as they were undertaken within a small area along uranium-rich mineralised faults of tectonic origin, which may have led to a more pronounced weathering locally. Our interpretation of the ERT and geological data agrees with the current understanding of granite weathering processes, granite landscape geomorphology and granite hydrogeology in the Massif Central in general and in the Monts d'Ambazac specifically (Desire-Marchand and Klein, 1986; Dewandel et al., 2006; Godard et al., 2001; Klein, 1978; Klein et al., 1990; Mauroux et al., 2009).

An important conclusion of the ERT survey is that the wetland appears to be hydrologically connected to, and most likely dependent on, a groundwater body within the fissured granite layer. Periglacial deposits and in-situ saprolite are patchy, and very shallow where present. Pedological pits on hillslopes and hilltops showed that soil texture is loamy-sandy to sandy-gravelly, and drainage is always good. Given these observations, we are of the opinion that, as raised by Referee #1, the "possibility that within the same layer parameters for the whole catchment there is combination of soil layers with regionally higher k and granite fissures with lower k" (which would imply that the soil layer plays a much larger role in lateral flow towards the wetland) is relatively small.

We developed our conceptual geological model taking into account the insights described above, and made the simplifying assumptions that:

- saturated flow occurs mostly in the fissured granite zone and in the peat;

- soil, saprolite and periglacial deposits can be neglected as far as saturated flow is concerned (but note that they are accounted for when modelling unsaturated flow);

- the hydrologically active fissured granite zone is 55m deep, follows the surface topography, and has homogeneous properties throughout.

Our computational model reflects these assumptions. Referee #2 is correct in stating that "the saturated zone of the model comprises of two computational layers. At peatlands the layer was 1) the peat as top layer and 2) fissured granite below; at mineral soils 3) 2 meter thick layer on top and 4) fissured granite below. [...] all of the layer structures 2-4 had the same parameters (e.g. hydraulic conductivity). Given that there were some soil on top of the granite at least locally, all of the geological information outside the peat layer are within the parameters of layers 2-4." This indeed means soils (but also periglacial formations and the saprolite layer) are, for the reasons explained above, neglected as far as saturated flow is concerned. In revising the paper, we will make this important information much clearer justifying the assumptions with reference to the available geological information. We will also discuss more clearly the possible uncertainties considering the model structure as recommended by Referee #2.

Whilst we acknowledge that our conceptual and computational models, like any scientific model, are simplifications of reality, our results show that they are sufficiently accurate to reproduce observed water levels in a large number of piezometers, observed stream discharge at four locations distributed throughout the catchment upstream and downstream of the mire, and, importantly, the observed distribution of mire habitats (including along the narrow valley downstream and in the small sub-basins located upstream of and 30m above the main mire extent where no groundwater table depth data were available for calibration). We therefore conclude that they are appropriately accurate to reproduce the dominant hydrological characteristics of the mire and its catchment and to quantify its long-term water balance.

Specific comments:

"Is figure 9 needed in addition to figure 8?" Whilst Figure 8 gives the water balance terms in absolute terms, Figure 9 provides the proportional contribution of the three main sources of water to the mire. It highlights that, in proportion, the contribution of groundwater increases during the driest months. We feel this finding is important to better understand the eco-hydrology of this type of mire. This feature of our results cannot be as easily seen from Figure 8, which shows that, in absolute terms, groundwater inflow decreases during the driest months. Nevertheless, in response to this comment from Referee #2, we propose to move Figure 9 to the Supplement when revising the

paper thereby still demonstrating this finding but avoiding the potential repetition of similar figures.

Figures 10 and 11. We believe that Figure 11 is interesting in showing the progressive decline in the seepage rate from winter to late summer, and the almost perfect agreement between areas where seepage still occurs in September and the mire extent. We do, however, also acknowledge that the figure takes a large amount of space. Therefore we propose to move it to the Supplement. In revising the manuscript, we will follow the recommendations of Referee #2 and produce a new figure replacing Figures 10 and 11 in the main paper. As recommended, this figure will show the mean groundwater table depth, and the mean seepage rates in the driest and wettest months. Figure 3 of this reply provides a draft of the proposed new figure.

"Figure 12 is not opening up easily for the reader." We do believe that it is important to provide the time-series of hydrological data describing the wetland hydrology and used in the following analysis, in particular to demonstrate average hydrological condition in the wetland and to provide opportunities for comparison with other wetland systems. However, we acknowledge that we could provide some more discussion of this figure when it is first introduced. As recommended by Referee #2, in the revised paper, we propose to add vertical dashed lines marking a few points of interest on Figure 12, and to discuss these in the text. These lines will highlight the unusually low and high summer groundwater tables in 2005 and 2007, respectively. We will discuss these in view of the relatively high inter-annual variability of precipitation. We will also revise the background grid lines and improve their visibility to make it easier to relate patterns in the time-series to specific years.

Detailed comments:

"Page 4, line 29-30: Where are these boreholes on the map?" As described above, in revising the paper we will indicate the location of the boreholes on Figure 1.

"Page 16, line 20: Is the word evacuated the correct term?" In the revised paper we will replace “they are quickly evacuated as saturation excess runoff” with “they quickly leave the wetland as saturation excess runoff”.

"Figure 5. text. Explain what are the a-h standing for?" We are grateful to Referee #2 for pinpointing this missing text. The correct caption for Figure 5 should have been: “Observed mire boundary based on botanical (Durepaire and Guerbaa, 2008) and pedological (Duranel, 2015) criteria and the predicted mire distribution based on model results (simulated 2001–2013 mean groundwater table depth higher than 0.166 m below ground level). (a)-(h): refer to Section 3.1 for further explanation.”

"Figure 13 text: explain abbreviations in x- and y-axes." Similarly, the correct caption for Figure 13 should have been: “Smooth terms of the final generalised additive model of simulated monthly mean groundwater table depth on the response scale. The curve shows the fitted value of the response, conditional upon the other explanatory variables being held at their sample mean. The shaded area is the approximate 95 % confidence interval. The time-series used are simulated spatially-averaged monthly means in the peat soil domain for the period 2001–2013: groundwater table depth (GWT), groundwater table depth in the preceding month (GWTm-1), upward saturated flow from the lower computational layer (SZ.up), actual evapotranspiration (ET) and precipitation (RR).” We apologise for these oversights, which will be corrected in the revised paper.

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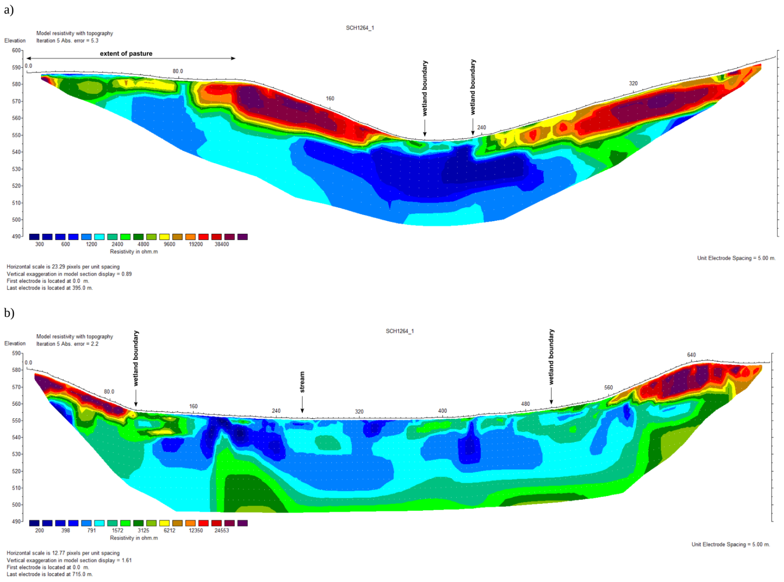

Fig. 1. Selected Electrical Tomography Resistivity transects across the study site. The transect locations are shown on Figure 1.

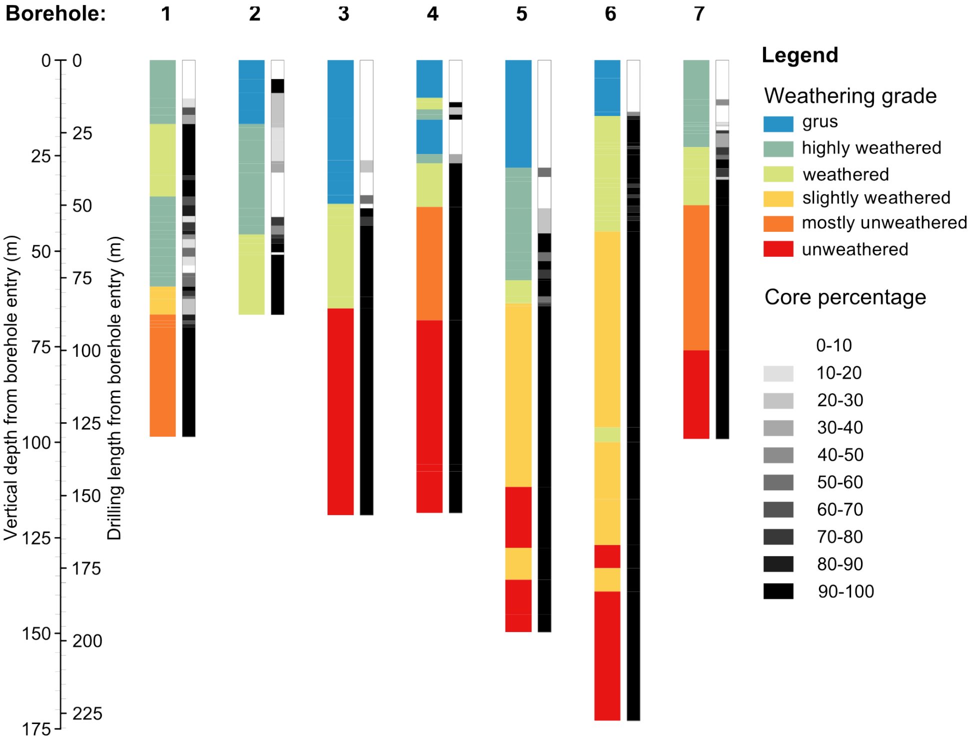

Fig. 2. Geological drillings by the Commissariat à l'Energie Atomique, showing the granite weathering grade and the core recovery percentage. The drilling locations are shown on Figure 1.

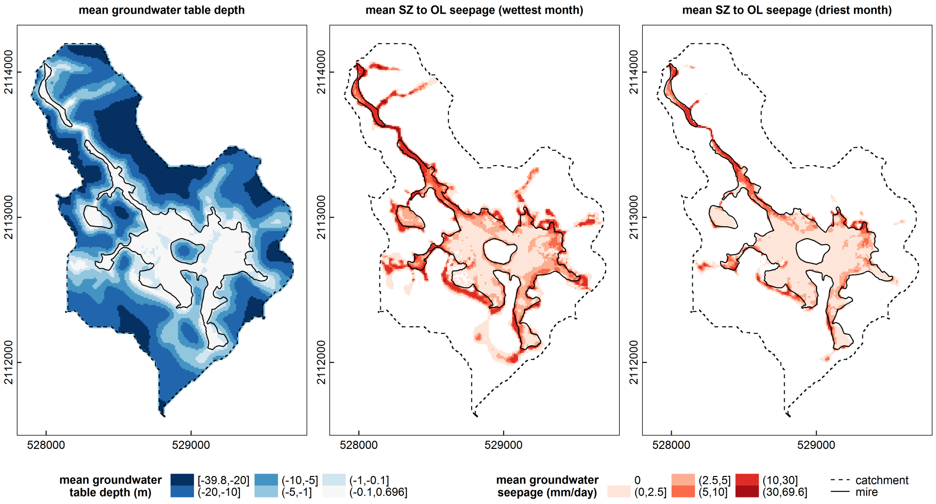

Fig. 3. Simulated mean annual groundwater table depth and seepage rates in the wettest (January) and driest (September) months (2001–2013).