Reply (in blue) to « RC2: 'Comment on hess-2023-152', Anonymous Referee #2, 18 Sep 2023 (https://doi.org/10.5194/hess-2023-152-RC2) » (*in italic*)

General remarks

The paper deals with a relevant topic. It is well written, straight to the point and interesting for both the specialists and the less experienced audience. For these reasons I recommend minor revisions, that mostly concern the description of the aquifer properties of the Luxembourg Sandstone Formation. As a matter of fact, sedimentary, diagenetic, structural and geomorphological (i.e. diffuse karstification) properties have been too poorly described, sometimes in a misleading way. I suggest to revise deeply section 2, removing the misleading sentences, introducing the most relevant hydrostratigraphic and hydrogeological features and completing/updating the references to the most relevant papers. This will make more convincing the discussion and conclusion sections, permitting to establish reliable comparisons between the modelling results and the heterogeneity and anisotropy of the real world aquifer.

We thank Referee #2 for a thorough review of our research work. We greatly appreciated her/his positive feedback and welcomed all the valuable advice given to improve our manuscript. Please find in this document our responses to Referee #2's comments and how we plan to address them in a revised version of this manuscript.

Specific remarks

Section 2.1

The part of this section dedicated to the geological properties of the Luxembourg Sandstone is definitely too poorly informative and insufficient to characterize the heterogeneity and the anisotropy of the aquifer under investigation. It also contains some incorrect statements (see the following remarks). Please update the references about the formation, that are incomplete and in some cases outdated. The most relevant stratigraphic, sedimentological, compositional and diagenetic properties should be mentioned to describe shortly how they control the modes and paths of groundwater flow through the porous/fractured/karstic medium. The superimposed structural pattern of faults and fractures should be also introduced to mention how it contributes to the duality of groundwater circulation (fissured - porous rocks) that You assess. In its present from the description of fractures is almost useless. The presence of widespread karst features, reported by some literature, should be mentioned and commented, also considering the impact of these features on the "dual" circulation system (is it really dual?). In addition, the presence of aquitards within the aquifer group should be introduced before the discussion section. In its present form this section conveys the wrong idea of an almost homogeneous and isotropic sandstone body, with uniform facies/hydrostratigraphic properties through space, that is not the case. It should also be mentioned which members, i.e. which aquifer systems within the group, and at which sites have been sampled and studied. This latter part totally relies on the technical notes by public agencies, that do not permit to figure out the geometry of the aquifers composing the group, of the compartments within them and of their recharge areas. As a matter of fact, the identification of the groundwater bodies that You are studying is not sufficiently clear to the reader and reliable. As You state in Your discussion section, the integration of Your modeling results with the knowledge on aquifer geometry and physical behavior would lead to "more accurately represent the multi-scale complexity of the Luxembourg Sandstone bedrock aquifer". So why don't You start by incorporating a very short synthesis of the most relevant hydrostratigraphic knowledge, in terms of heterogeneity and anisotropy of the rocks and identification of the major groundwater bodies within them in Your paper?

We thank Referee #2 for these constructive comments on Section 2.1. We agree that some aspects of the Luxembourg Sandstone are not accurately enough depicted or missing in our description, which may lead to a wrong understanding of the aquifer's context. The section will be modified accordingly in the revised version of the manuscript.

Line 102: no need to indicate SiO2 and CaC03, just state "quartz" and "calcite"

In the revised version of the manuscript, "SiO_2" and "$CaCO_3$'' will be removed.

Line 103: really the Luxembourg Sandstone is just a calcite-cemented pure quartzarenite (see for instance Berners, 1983)? is the average bulk chemical composition relevant to describe aquifer heterogeneity? The Luxembourg sandstone is an outstanding example of how diagenesis determined the poro-perm properties under control of the composition of the framework grains and the changes of texture and sedimentary structures (i.e. facies associations).

We thank Referee #2 for this insightful comment. This will be considered when revising the Luxembourg Sandstone description.

Line 103: please replace the reference to the unpublished PhD thesis with the reference to Van Den Brill and Swennen (2009), or at least quote also the published paper.

We thank Referee #2 for this advice. This will be considered in the revised version of the article.

Line 104: what do You mean by "… crossed by beds of sandy marls"? Are these beds neptunian dykes? Please describe the stratigraphy of the formation properly: there are marly units separating sandstone bedsests, facies and compositional changes (framework grains, cements, matrixes) occur through the sandstone divisions, many bedsets are almost limestones, owing to primary composition and diagenetic replacement, so karst features are widespread in some bodies at some sites (see for instance Meus and Willems, 2021). Do You really would describe this formation as a "uniform" unit? On the contrary it is highly heterogeneous and anisotropic, that implies relevant bearings on Your experiments.

We thank Referee #2 for this pertinent advice. This will be considered when revising the Luxembourg Sandstone description.

Line 115: Meus and Willems (2021) is missing in the reference list

We thank Referee #2 for pointing out this mistake. The full reference will be added to the reference list in the revised version of the manuscript.

Line 131: considering the regional geology, are You pretty sure that recharge occurs only through the outcrop area of the Formation?

Correct. The outcrop area of the Luxembourg Sandstone constitutes the main, but not the only, aquifer recharge zone (i.e., additional secondary recharge components exist, e.g., leakages from the overlying Strassen formation, connexions through faults with other geological layers). This will be accounted for when revising the Luxembourg Sandstone description.

Fig.1 is almost useless to describe aquifer architecture and heterogeneity. Stratigraphic logs introducing the general features of the formation should be added.

We thank Referee #2 for this advice. A stratigraphic log introducing the general features of the Luxembourg sandstone will replace or complement Figure 1 in the revised version of this article.

Fig.2 is very difficult to read. The geological attributes are hidden by the elevation map of the formation base (please specify m "above sea level" in the color scale). The legend of the geological features is obscure (alluvial materials? What do You mean? Quaternary? Which formations are involved?). Where do we read these features? Where are represented the fault/fracture systems? Which hydrogeological features are shown? The sampled springs are sparse at different settings. Which units of the Formation have been sampled? All belong *to the same sandbar systems? Are some springs located in the limestone (karstified) units? Are there marlstone beds (aquitards) at some locations?*

We thank Referee #2 for raising here readability/accuracy issues with Figure 2. These aspects will be considered in the revised version of the manuscript.

<u>Section 2.2</u>

Fig.3. This is a very general and unrealistic conceptual picture of the Luxembourg Sandstone Aquifer. It is portrayed as a uniform, homogeneous and isotropic medium, without bedding planes associated to litho-textural variations. Fractures are not drawn (the reader must assume two orthogonal vertical sets everywhere). "Slow infiltration through matrix" is declared in the unsaturated zone, with black lines maybe indicating strange infiltration paths (if I understand the picture) that would never permit the percolating water to reach the saturated zone. Moreover, what is the matrix? In the karstic aquifers, matrix is sometimes intended as the impervious rock with no circulation, that instead occurs through conduits, caves and fractures. In the list of "some numbers" You declare up to 40% porosity, so this would not be a matrix, neither from the lithological/sedimentological point of view (it would be a mudrock) nor from the hydrological point of view. In addition, it looks a little bit strange the use of the conceptual image of a carbonate karstic aquifer, without considering the karstic features of Your specific setting. I strongly suggest to redraw a realistic conceptual model of Your aquifer, with the true stratigraphic, lithotextural, structural and geomorphological features and inserting the plausible location of the clusters of springs You sampled. Please note that I am not asking for a more detailed or accurate picture, I just would like to see a very simple and general model showing the most relevant features of Your aquifer group.

As proposed by Referee #2, we will strive to draw a simpler/general but more realistic hydrogeological conceptual diagram in the revised version of the manuscript.

<u>Section 3.1</u>

Lines 176-177: this statement should have been supported by the description of the conceptual model of the Luxembourg Sandstone in Chapter 2, that is unfortunately largely insufficient. Moreover, this assumption should be site-specific in such a large aquifer group as the one You are dealing with.

This statement will be supported by the revised Section 2.

Line 190: Fig.2 does not explain the hydrogeological setting of the 32 sampled springs. Do they share the same recharge area, geological and hydrological conditions? Do the same approach apply to all the sampled springs? You rightly mention the hydrochemical and hydrogeological and exploitation variability among them, that should be better described and accounted for in Your approach.

As mentioned previously in our response to Referee #2's comments, Figure 2 will be modified to be more readable. The revised figure will also indicate more precisely which sampled spring belong to which recharge area. Referee #2 asks also here if "the same approach apply to all the sampled springs?", but unfortunately, we have not been able to understand what this refers to.

Lines 200 and following: which data on average thickness and presence/absence of surface soils did You use? Which data for evapotranspiration?

We assume that Referee #2 is referring here to "lines 220 and following" and asks for clarification about the approach used to assess effective precipitation. As mentioned in the manuscript (see lines 218-223 & 300-303), we followed the Thornthwaite method (1948). Perhaps our explanation is not clear enough for the reader and we will rephrase it in the revised version of our article.

The Thornthwaite method is essentially a water balance of the rootzone performing monthly book-keeping of precipitation, evapotranspiration and soil moisture. Deep infiltration below the root zone (i.e., effective precipitation) occurs only when field capacity is exceeded (i.e, the maximum water-holding capacity). The Thornthwaite method (1948) comes with an empirical potential evapotranspiration formula using only monthly mean air temperature as input. Although this approach is empirical and could be considered outdated, the Thornthwaite method is still widely accepted and used in several disciplines, especially in hydrogeology for estimating aquifer recharge (e.g., Lanini et al., 2016; Mammoliti et al., 2021).

As already mentioned in our response letter to Referee #1's comments, the maximum water-holding capacity set to 100 mm in our study is an overall mean value derived from laboratory measurements carried out on samples taken from several soil pits and is usually used for soils overlying the Luxembourg Sandstones (Hissler et al., 2015; Hissler and Gourdol, 2015). As asked by Referee #2, it is worth noting that soil pits indicate soils 40 to 100 cm thick (average 83 cm).

Lines 245-250: an effort to estimate the aquifers volumes in order to obtain some independent numbers to evaluate the estimates of groundwater volumes would make this study a little more linked to the real world.

We agree with Referee #2 that it would have been nice to rely on direct data that would have made it possible to assess the volumes of groundwater stored in the aquifer in a different independent way. For instance, measurements of the water table level in boreholes could have made it possible to estimate the volumes of water stored in the saturated zone of the aquifer. Unfortunately, as mentioned in lines 148-149, hydrogeological drillings in the Luxembourg Sandstone are too sparse and poorly distributed (one can also see the "Hydrogeological drillings" layer in the Luxembourg platform for governmental geodata and service https://map.geoportail.lu/). For instance, only one borehole is in the KRD recharge area and none in the KRG, M, P and D ones (excluding shallow exploratory boreholes drilled in the very near vicinity of spring catchment facilities). However, it is worth noting that Farlin et al (2013a) indicate a saturated thickness of about 10 m at the level of the observation borehole in the KRD sector, which is consistent with the average numbers we assessed in our study (see Fig. 8).

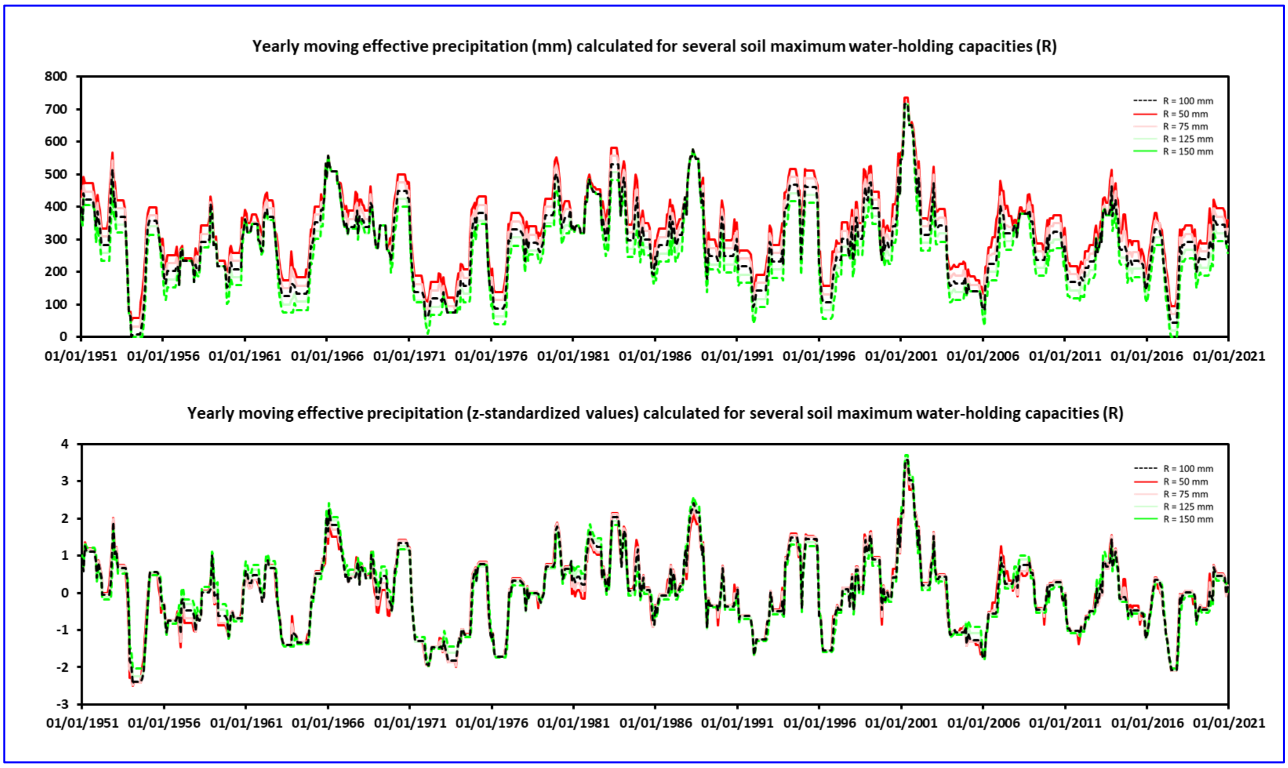
Section 3.2

Lines 289 – 290: here You refer to the current use of effective infiltration in karst aquifers after literature, but since this statement You did not consider the Luxembourg sandstone a karst aquifer. This issue must be addressed properly in section 2 where You should definitely characterize the aquifer group under investigation as karstified or not.

We thank Referee #2 for this comment. The karstification degree of the Luxembourg Sandstone (which is overall relatively poor despite the presence of karstic features) will be described in the revised Section 2.

Lines 296-297: this assumption, in my opinion, is unrealistic and makes poorly reliable the use of effective infiltration.

Referee #2 disagrees here with our decision to consider the effective precipitation homogeneous for the entire study area, but without explaining why. As argued, the spatial extension of our study area is relatively restricted. This allows us to assume that the spatial variability of the precipitation input signal is rather small (especially since precipitation is effective mainly in winter, a period during which the spatial variability of precipitation fields is particularly low in comparison to convective summer rainfall event; one can also see the work of Pfister et al. (2017) describing the spatial variability of the precipitation as rather homogeneous over a region otherwise even wider containing our study area). In addition, recharge area mean elevations of the different groups of springs are very close to each other (see Table 1), which makes it possible to consider similar temperatures from one area to another. Perhaps Referee #2 does not agree with our hypothesis because thinking that the soil type/cover variability would induce too much heterogeneity in the effective precipitation input signal. If so, here again we think that our assumption is reasonable. As element of justification, the figure hereafter documents the yearly moving effective precipitation computed for a maximum water-holding capacity varying from 50 to 150 mm (which allows to some extent the soil variability to be mimicked). It is true that the maximum water-holding capacity value impacts the effective precipitation amount (the smaller the maximum water-holding capacity, the higher the effective precipitation; see the upper panel of the figure), but this does not impact the temporal variability of the signal (see the lower panel of the figure) which is finally the most important for the cross-correlation analysis performed in our study.

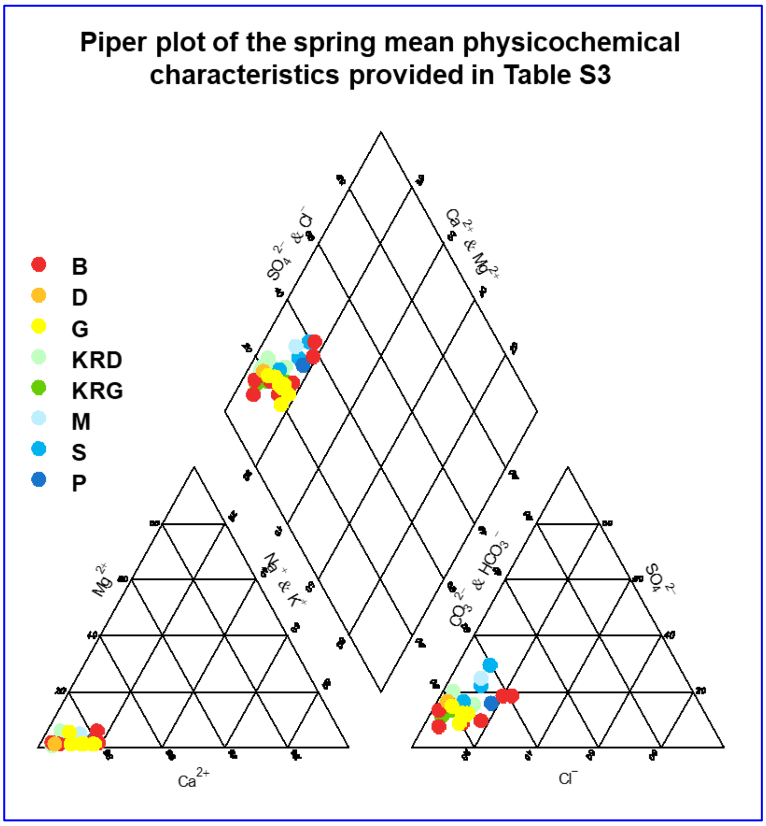


Line 311: I suggest to make explicit the abbreviations at least at their first appearance (MRT)

Note that the MRT abbreviation is already introduced in the manuscript line 276.

Lines 323-324: might You consider the opportunity of inserting the Piper plots to better visualize and characterize the eventual variability of hydrochemical facies? At line 329 You state that the "… the spatial variability of the hydrochemistry … is stable over time… ", implicitly admitting that this variability do exist and might be clarified by these very simple and traditional plots.

We have already tested the potential added value of a Piper diagram (which allows to distinguish the major types of water based on major ions relative composition), but we concluded that this type of representation would not be the best option for documenting the hydrochemical variability in our study. Indeed, the springs of Luxembourg City, although exhibiting an inter-spring hydrochemical variability, are all characterized with the same $CaHCO_3$ facies and are therefore represented very close to each other in a Piper plot (see figure hereafter).



Section 4

Lines 348 – 350: the recharge areas of the spring groups are not sufficiently described and commented by the previous sections and by Fig.2 that are based on the 1939 geological maps and on local RGD technical notes, that make it very difficult to obtain a reliable idea of the groundwater bodies and hydrogeological basins involved by the study.

See our responses to Referee #2's comments about Section 2, Figures 2 and 3, and Line 190.

Section 5

Through all the discussion section, several different properties of the real aquifer are mentioned for comparisons with the modelling results and the assessment of uncertainty (real sandstone thickness, vadose/saturated zone ratio, modes and times of transit through the vadose and saturated zones of the dual porous/fractured aquifer without considering the karst features, presence of local or widespread confining layers and internal compartments in the aquifer group, areas and lengths of the recharge regions and paths, hydrochemical properties and so on). In most cases You claim that these comparisons support the results, but most of these properties have been introduced and considered in a very rough and generic way, sometimes not truly coincident with the real world. In addition, You formerly used many of the same properties to take or to validate decisions, so introducing some circularity in Your line of reasoning. As a matter of fact, this generic use of a poorly presented knowledge on the aquifer group does not really support the results, on the contrary highlighting to the reader the distance between knowledge on the real-world aquifer heterogeneity and anisotropy and the presented modeling results. An example is given by the last part of the section (from line 552 to the end) where the obvious anisotropy of this kind of aquifers, that is portrayed by hundreds of papers of the current hydrostratigraphic literature, is introduced and discussed very roughly. Over these lines the Authors look to discover this property (that is shared by all the bedded aquifers) at this point of the paper (see also lines 590-592 in the Conclusions), arguing that this physical property might be better understood, so it should be studied in order to set up an integrated model (hydrostratigraphic, hydrogeological, *hydrochemical, let’s say in 4D), that incorporates the tritium based LPM approach nicely proposed in this paper. So, why the Authors did not use all the existing literature on the Luxembourg sandstone aquifer group to make tight comparisons between the real world and their modelling results? How nice would have been to show that the well-known anisotropy of the bedded aquifer is mirrored by the computed anisotropy of water velocity through the vadose and saturated zones?*

We thank Referee #2 for these constructive comments. Echoing the revision of Section 2 (which will notably introduce the anisotropy of the bedded aquifers to which the Luxembourg Sandstone belongs), it is worth noting that several parts of the Section 5 Discussion will be rewritten in the revised version of the manuscript.

Lines 475 – 476: I agree that presuming stationarity for groundwater is less critical than for stream water, but this does not mean that steady-state might be assumed safely for a heterogeneous, mixed karstic/fractured/porous aquifer group like the Luxembourg sandstone.

As Referee #2 concedes, presuming stationarity for groundwater is in general less critical than for stream water. Including a statement mentioning it is thus reasonable in our opinion, and we would therefore prefer to keep our sentence as is.

References used in our response to Referee #2 that were not already cited in the manuscript:

Hissler, C., Gourdol, L., Juilleret, J., Marx, S., Leydet, L., and Flammang, F. : Pedotransfer functions for predicting soil hydrological characteristics in Luxembourg: literature review and reliability tests for predicting the soil maximum water-holding capacity (Fonctions de pédotransfert pour la prédiction des caractéristiques hydriques des sols au Luxembourg : analyse bibliographique et premiers tests de fiabilité pour la prédiction de la réserve utilisable maximale des sols), Report drafted on behalf of the Administration des services techniques de l’agriculture (in French), 2015.

Hissler, C. and Gourdol, L.: Assessment of soil maximum water-holding capacity in Luxembourg at national scale: a first estimate based on recent datasets (Évaluation de la réserve utile maximale en eau des sols au Luxembourg à l’échelle nationale : une première estimation basée sur des jeux de données récents), Report drafted on behalf of the Administration de la gestion de l’eau (in French), 2015.

Lanini, S., Caballero, Y., Seguin, J.J., and Maréchal, J.C.: ESPERE – A Multiple-Method Microsoft Excel Application for Estimating Aquifer Recharge, Groundwater, 54, 155-156, doi.org/10.1111/gwat.12390, 2016.

Mammoliti, E., Fronzi, D., Mancini, A., Valigi, D., and Tazioli, A.: WaterbalANce, a WebApp for Thornthwaite – Mather Water Balance Computation: Comparison of Applications in Two European Watersheds, Hydrology, 8, 34, doi.org/10.3390/hydrology8010034, 2021.

Meus, P. and Willems, L.: Tracer tests to infer the drainage of the multiple porosity aquifer of Luxembourg Sandstone (Grand-Duchy of Luxembourg): implications for drinking water protection, Hydrogeology Journal, 29, 461–480, doi.org /10.1007/s10040-020-02274-z, 2021.

Pfister, L., Martínez-Carreras, N., Hissler, C., Klaus, J., Carrer, G.E., Stewart, M.K., and McDonnell, J.J.: Bedrock geology controls on catchment storage, mixing, and release: A comparative analysis of 16 nested catchments, Hydrological Processes,31, 1828–1845. doi.org/10.1002/hyp.11134, 2017.