POLITECNICO DI MILANO

**DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING**

Piazza Leonardo da Vinci, 32 I-20133, MILANO (Italy)

27th February 2024

**Re: Response to Comments of Reviewer #1 -** *A Comprehensive Framework for Stochastic Calibration and Sensitivity Analysis of Large-Scale Groundwater Models* Submission to *Hydrology and Earth System Sciences*

We appreciate the efforts the Reviewer has invested in our manuscript. Following is an itemized list of the comments together with our response to each. Comments are listed in black italic font and our responses in blue font. Proposed revisions to the original text are in red fonts.

Sincerely,

Andrea Manzoni, Giovanni Michele Porta, Laura Guadagnini, Alberto Guadagnini, Monica Riva

general comments:

*The topic of the manuscript is of high relevance for the management of large aquifer systems. The presented approach provides a very suitable methodology to develop a groundwater model with predictive potential for a complex heterogeneous large-scale groundwater system. Such a model supports the understanding of the system dynamics and enables to identify parameters impacting diverse system responses. For the first time stochastic calibration and informed global sensitivity analysis are used to calibrate the groundwater model of the main aquifer system in the Po River watershed. The potential of the presented methodology is well concluded.*

We thank the Reviewer for the thorough evaluation and positive feedbacks on our manuscript. We appreciate the recognition of the relevance of our work and modeling approach in the context of management of large aquifer systems. We will carefully address the suggested revisions to further improve the quality of the manuscript.

*The manuscript is well structured and well readable. The title clearly reflects the contents of the paper. The abstract provides a concise and complete summary. The scientific methods and assumptions are valid and clearly outlined.*

*The authors give proper credit to related work and clearly indicate their own contribution. The number and quality of references appropriate.*

*I recommend the publication only after the revisions described below.*

specific comments:

In the following I would like to recommend several revisions in order to improve the manuscript.

**Comment #1:**

*The lateral extent and the base of the groundwater system should be described more clearly (l. 180/181). This should cover a more detailed the description of the interfaces with the sub-basins (l. 212/213) particularly the vertical distribution inflow boundary condition (l. 219). Furthermore, the basic geologic concept behind the vertical discretization is missing.*

**Answer #1:**

We thank the Reviewer for the valuable comment. We have taken steps to address the suggestions to enhance the quality and clarity of the large-scale groundwater model setup.

Details about the geometry of the groundwater system are accessible through the geological databases maintained by regional environmental authorities and listed in the original manuscript. We rely on location of boundaries and bottom of the modeled geometry that have been determined by local authorities, who integrated information from geological studies performed in the area. To enrich the information pertaining to the geometry, in the revised manuscript we will include additional details from some studies where the estimated location of the boundaries and of the base of the aquifer system within the study area are discussed. We will also expand on the description of the interfaces with the sub-basins focusing on the vertical distribution of the inflow boundary condition. We will also revise the manuscript to include a detailed explanation of the main concepts underpinning the vertical discretization employed in the numerical flow model.

We will incorporate the following modifications and additions to the revised manuscript in Section 3.2.

"The architecture of the subsurface system is assessed by curating information embedded in datasets from three distinct local authorities. In this sense, we obtain an original integration of data stemming from the hydrostratigraphic survey of Emilia-Romagna (Regione Emilia-Romagna, 1998), as well as from the regional water protection plans of the Lombardia (Regione Lombardia, 2016) and Piemonte (Regione Piemonte, 2022) Regions. These studies provide information on the lateral extent and the bottom surface of the depositional group that includes the groundwater system. This information has been obtained by local authorities upon integration of information from geological studies performed in the area. The evolution of the sedimentary basin, as controlled by geodinamic and climatological factors, is characterized by an overall regressive trend from Pliocene open marine facies to Quaternary marginal marine and alluvial deposits (Ricci Lucchi et al., 1982; Regione Emilia–Romagna and ENI, 1998; Regione Lombardia and ENI - Divisione AGIP, 2002). The aquifer system is characterized by a dense network of deep faults that influence the overall depth of the aquifers (Carcano and Piccin 2001), driving the variability of the groundwater system thickness from a few meters (close to the foothills) to more than 300 m (in the central and eastern portions of the plain). A continuous portion of essentially impermeable material can be found below the base surface.

…

Inflow takes place through the vertical surface that extends from the ground surface to the aquifer base along the lateral extent of the aquifer system. Since such lateral surface is typically characterized by a limited depth (only a few meters), lateral inflow is distributed uniformly across portions of lateral surface associated with each sub-domain.

...

This study employs a vertical discretization of the numerical grid that favors a balance between computational efficiency and the vertical distribution of geomaterials provided by the study of Manzoni et al. (2023). In this context, the vertical discretization is then finest closer to the surface, where thinner geomaterial layers are documented, consistent the higher geological data density therein. Thus, the surface grid is then extruded along the vertical direction to create layers whose thickness increases with depth according to the following criteria: … “

Added references

Carcano, C., Piccin. A.: Geologia degli acquiferi Padani della Regione Lombardia Regione Lombardia, Eni Divisione Agip, https://www.cartografia.regione.lombardia.it/metadata/acquiferi/doc/, 2001.

Regione Emilia-Romagna, ENI-AGIP, 1998. Riserve idriche sotterranee della Regione Emilia-Romagna. S.EL.CA, Firenze.

Regione Lombardia, ENI-AGIP, 2002. Geologia degli acquiferi padani della Regione Lombardia. S.EL.CA, Firenze.

Ricci Lucchi F, Colalongo ML, Cremonini G, Gasperi G, Iaccarino S, Papani G, et al. Evoluzione

sedimentaria e paleogeografica del margine appenninico (Sedimentary and palaeogeographic evolution of the Apenninic margin). Guida alla geologia del margine appenninico padano. Guide geologiche regionali, Soc. Geol. Ital.; 1982. p. 17–46.

**Comment #2:**

*In lines 265/266 a reference to the formulas where the targets of the calibration kc and rq might be added.*

**Answer #2:**

We thank the Reviewer for the comment. We will modify the manuscript as follows to improve clarity (see also answer to comment #6 of Reviewer #2).

"where, $\overline{h_l}$ and $h_l$ denote observed and estimated hydraulic head at well $l$, respectively. Estimation of permeability of each geomaterial ($k_c$ in Eq. 3) and of the correction coefficient ($r_q$ in Eq. 4) entails minimizing Eq. (6) (i.e., considering all available hydraulic head data, $N_{h_b}$)."

**Comment #3:**

*It is not clearly described whether the proportion of geomaterials, Fig. S1, is an a priori information or the result of calibration. As this is an important information anyway Fig. S1 should be included in the manuscript and not part of the supplementary material. In order to support the descriptions in l. 351 (and similar descriptions), it would be helpful to have a figure with the distribution of the geomaterials available.*

**Answer #3:**

We agree that including Figure S1 in the main body of the manuscript would enhance clarity. Additionally, a clear explanation of the origin of the information will be added in Section 3.2. We also add to the figure some information taken from the study of Manzoni et al. (2023) showing the geomaterial distribution upon which calculation of $f_{c,i}$ is grounded. The revised text now reads:

"Here, $N_i$ denotes the number of cells associated with the hydrostratigraphic model of Manzoni et al. (2023) that are included in the $i$-th cell of our simulation grid and $P_{c,j}$ is the probability that the $c$-th category (or geomaterial) be assigned to cell $j$ of the above mentioned hydrostratigraphic model. Figures 3a depicts the percentage of simulation grid cells associated with given (color-coded) ranges of values for $f_{c,i}$ cross each geomaterial category. Figure 3b illustrates the spatial distribution of the most probable geomaterial category within the Po River basin, as obtained by Manzoni et al. (2023). We then assess the permeability of the $i$-th cell of the numerical grid as

$$\bar{k}_i = \sum_c^{N_c} f_{c,i}\, k_c \qquad \text{with } N_c = 6 \tag{3}$$

where $k_c$ is the permeability of the $c$-th category. Values of $k_c$ are estimated through model calibration, while $f_{c,i}$ is provided as prior information (see Manzoni et al., 2023). Details regarding model calibration are illustrated in Sect. 3.3."

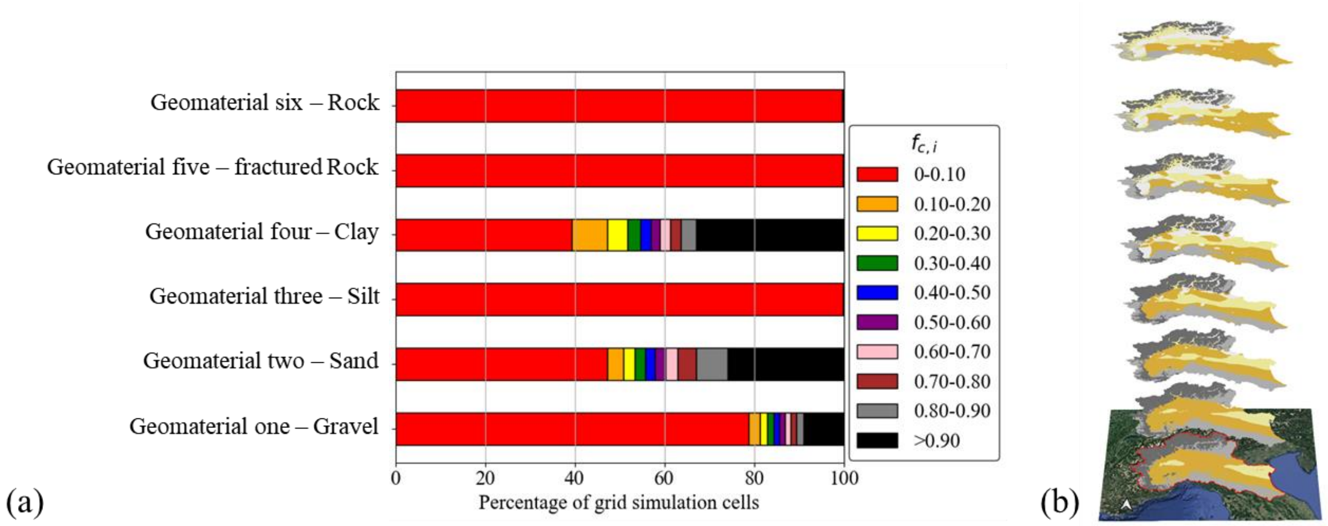



**Figure 3: (a) Percentage of grid cells characterized by given ranges of values of $f_{c,i}$ (Eq. 2); (b) Spatial distribution of modal categories obtained by Manzoni et al. (2023). Planar maps are selected at 5, 10, 25, 50, 100, 150, 200, and 350 m below ground surface.**

…

"This finding is attributed to the fact that the simulation grid cells with the highest proportion of geomaterial five can be found in the mountainous areas and near the foothills (see Fig. 3b), which are close to the boundary where an inflow boundary condition is applied."

**Comment #4:**

*The concept behind the combination of the information in Fig. 4 is not really clear. Why are Fig. 4a and 4b combined with 4c and 4d? The information in Fig 4a might not really be important for the purpose of the manuscript. Fig 4b might be improved if the difference between simulate and observed heads are provided instead of the observed heads only. In Fig 4d the dark grey and dark red areas could not easily be distinguished as described in l. 359.*

**Answer #4:**

We understand the concern about the clarity of the combination of information in Figure 4. We will revise Figure 4 to improve readability and interpretation. Figure 4 will include a frequency distribution of the difference between simulated and observed heads, as suggested by the Reviewer. Furthermore, we will reorganize the material in the original Figure 4 into two figures, i.e., Figures 4 and 5. We will increase the color saturation of the image in Figure 4c and 4d to make the colors more distinguishable. The revised figures are included in the following.

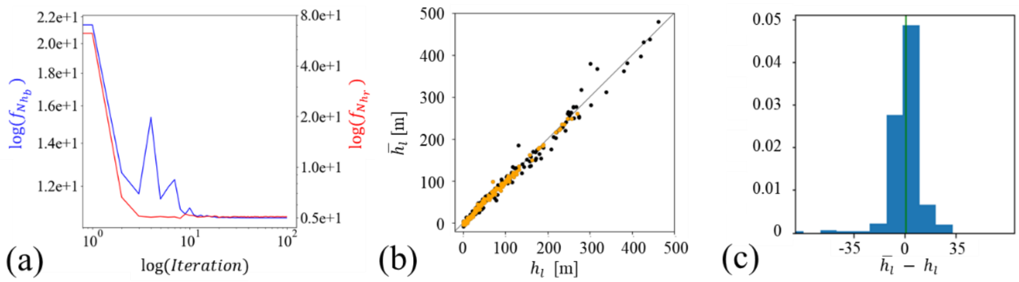



**Figure 4: (a) Convergence analysis of $f_{N_b}$ and $f_{N_r}$ (Eq. 6); (b) observed versus simulated hydraulic heads (head values associated with the $N_{h_r}$ wells located close to the rivers are depicted in orange); (c) normalized frequency distribution of differences between observed and simulate hydraulic heads.**

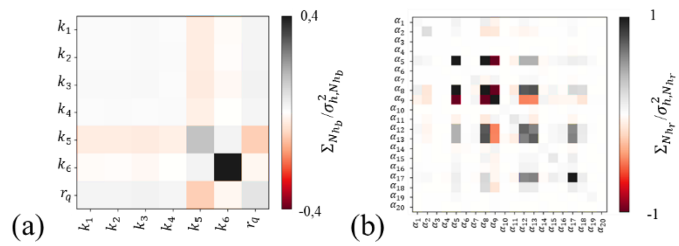



**Figure 5: Covariance matrix of parameter estimates related to (a) Eq. (6) and (b) Eq. (7).**

**Comment #5:**

*The concept behind the combination of the information in Fig. 5 is not really clear. The description of Fig 5a, l. 372-380, is too coarse. The definition of the macro areas is not clearly motivated. There are more areas related to the several macro areas as described. In Fig 5b it does not become clear what the colour distribution in the represents. The comparison described in l. 367-369 does not really become clear from Fig. 5c.*

**Answer #5:**

We will include a general description of Figure 5 that elucidates the combination of the maps and graphs herein included. Additionally, we will revise the description in lines 372-380 of the original manuscript to provide a more detailed explanation. We will then ensure that the motivation behind the definition of these macro areas is clearly articulated to enhance readability.

To assist the Reviewer, we show below (Figure R.1) a graph of the frequency distribution of log-permeability values (vertical axis not in log scale, as opposed to the original Figure 5) to support the concept behind the identification of strongly homogeneous large volumes of the domain associated with the highest peaks in the frequency distribution of permeability values.

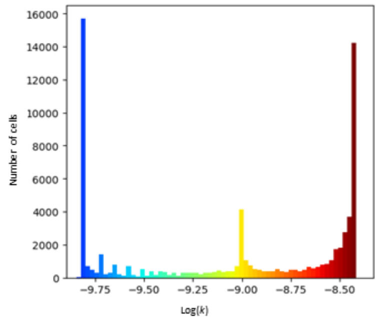


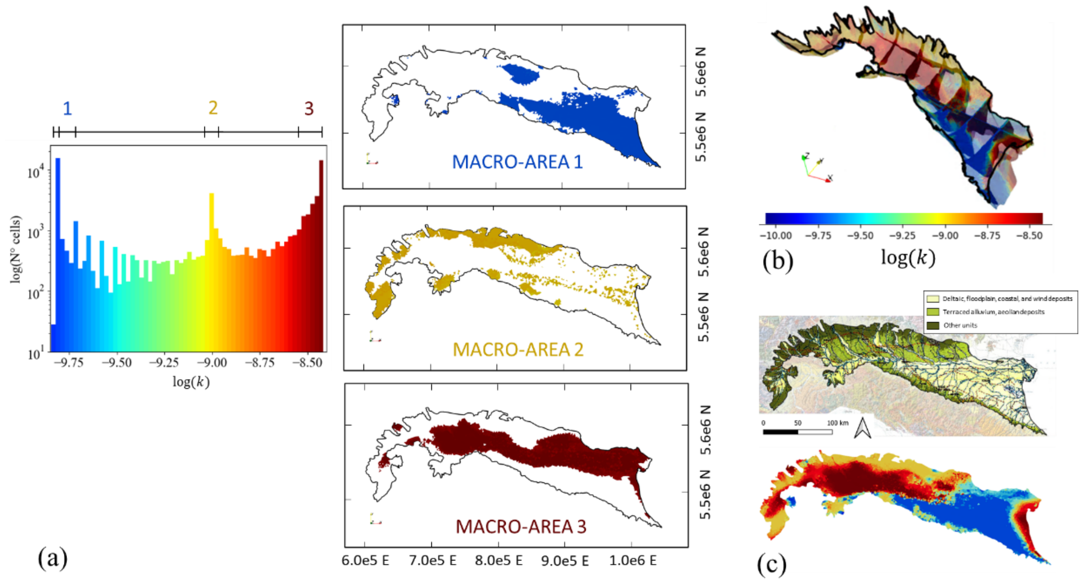

Figure R.1: Frequency distribution of natural logarithm of permeability, log(*k*) (*k* expressed in $m^2$).

We will revisit Figure 5c to enhance clarity of the comparison described in lines 367-369 of the original manuscript. In the following we add a proposal of revised text for the interest portion of the manuscript.

"Figure 5 offers an overview of the spatial distribution and vertical variation of permeability values (*k*) across the subsurface domain. Figure 5a depicts the frequency distribution of the estimated *k* values. These results reveal three dominant modes (or peaks) in the distribution. These are characterized by a frequency that is one order of magnitude higher with respect to the rest of the *k* values. This element suggests that the subsurface domain can be conceptualized as comprising three main macro-areas, each of these being characterized by (mostly) homogeneous spatial distributions of permeability values.

The spatial distribution of these macro area is consistent with the distribution of the three main sediment types indicated in the Italian Geological Map (Compagnoni et al., 2004) within the Po Plain (see Fig. 5c). Figure 5a provides an appraisal of the spatial distribution of the three macro-areas by means of envelopes obtained through projection of their otherwise three-dimensional shape onto a two-dimensional plane. This visualization is complemented by Fig. 5b, which depicts a qualitative representation of the vertical distribution of log(*k*) along selected cross-sections (vertical exaggeration of 200). Access to a detailed grid of the three-dimensional distribution of *k* is available through the code and data repository (https://doi.org/10.5281/zenodo.10697654).

The first macro-area, associated with the lowest permeability values within the modeled domain, generally corresponds to the south-eastern portion of the alluvial plain (Adriatic sector). Here, finer and less permeable sediments constitute the main features associated with geological deposition processes. The second macro-area is primarily located near the northern and western boundary, adjacent to the Alpine foothill areas, and is characterized by intermediate permeability values. Additional smaller areas with conditions similar to the Alpine foothills can be identified in the foothill areas of the Apennines. Note that, according to Éupolis Lombardia (2016), the planar area adjacent to the foothills in the Lombardia Region is very heterogeneous and features a series of highly permeable layers interspersed with less permeable layers. This is consistent with the intermediate range of permeability values obtained within our large-scale domain through model calibration. The third macro-area is characterized by high permeability values. It spans the entire depth of the system in the central-southern portion of the plain while it does not reach the surface in the northeastern part of the domain. This area is influenced by the deposits formed by the presence of the Po River.




**Comment #6:**

*Fig. 6 might be reorganized as different information, v and h, is combined. It does not become clear why different cross section are used in Fig 6 and Fig. 5.*

**Answer #6:**

We thank the Reviewer for the suggestion regarding the organization of Figure 6. We will reconsider the layout of the figure to improve the communication of the combined information on different variables. Additionally, we will modify Figure 5b (see answer to comment 4 above) to include the same vertical cross-sections used in Figure 6.

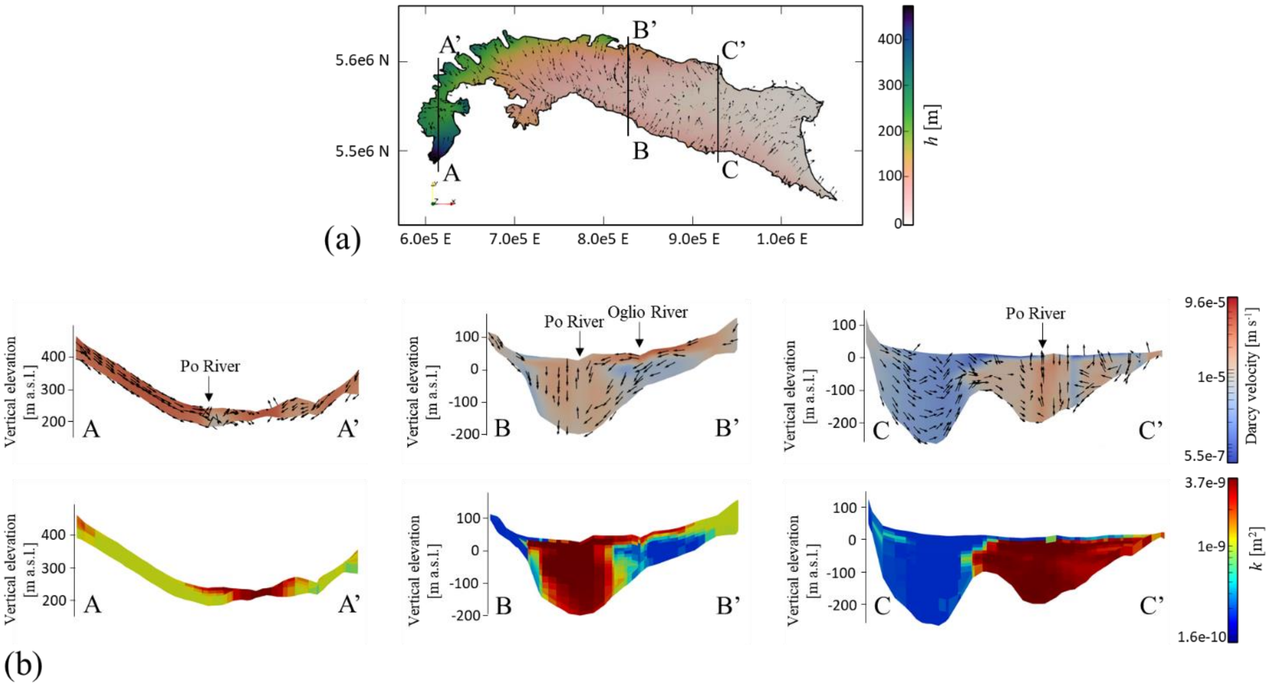



**Figure 1: Groundwater flow model outputs: (a) hydraulic head and distribution of groundwater fluxes across the top layer of the model; (b) magnitude and direction of groundwater flux and permeability distribution along cross-sections A-A', B-B', and C-C' (vertical exaggeration = 200).**

**Comment #7:**

*In order to emphasis the importance of the 3d approach it might be useful to describe the Morris indices for all model layers, especially the lower ones. If helpful an additional figure might be provided which might be added as supplementary material.*

**Answer #7:**

We agree that including a representation in a format that allows for a better understanding of the vertical distribution of Morris' indices can enhance the quality of the manuscript. We will add an accessible grid that contains 10 cross section into the data repository. We will modify the original manuscript to highlight the availability of these data in the open access data repository in Section 4.3 as follows.

"It is worth noting that all Morris indices display only modest variability along the vertical direction. The complete three-dimensional spatial distribution of $\mu^*_{\theta_p}$ and a grid containing 10 cross-sections highlighting our findings about the vertical variability of Morris indexes can be accessed in an open-source Visualization Toolkit (VTK) format for structured grids (Schroeder et al., 2006). These data are available in the code and data repository (https://doi.org/10.5281/zenodo.10697654)."

**Comment #8:**

*Fig. S2 might be included in the manuscript eventually in combination with Fig. 8 as this is an important result of the study.*

**Answer #8:**

Regarding the placement of Figure S2: We have opted to leave it in the supplementary material due to concerns about the paper density and length. We will of course abide by the Editor's decision on this matter.

**Comment #9:**

*A reference for the Penman-Monteith model should be added (l. 157) if this not covered by the reference 'Allen et al. (1998)'.*

**Answer #9:**

We will adjust the manuscript to enhance clarity as follows:

"For the evaluation of the actual evapotranspiration, $ET$, potential evapotranspiration is first computed by (*i*) making use of the model provided by Hargreaves and Samani (1985) in non-irrigated regions and (*ii*) combining the Penman-Monteith model with the correction crop coefficient in cultivated areas (consistent with Allen et al., 1998)."

technical corrections:

**Comment #10:**

*The sizes of the following figures should be increased. The names of the rivers should be readable in Fig. 1. The cross sections in Fig. 5b are not clearly visible. The sediment types in Fig. 5c are not clearly visible and a corresponding legend is missing. Details in the graphs in Fig. 6 are only hardly visible.*

**Answer #10:**

We will implement the suggestion of the Reviewer to improve quality of figures. We will increase the river name sizes in Figure 1. Vertical exaggeration of Figure 5b will be doubled and the prospective will be changed. We will increase the color exposure for Figure 5c. We will also modify Figure 6 according to comment 6 above, thus reducing redundancy and increasing image dimensions (see modified images at the answer of comments #5 and #6 above).

**Comment #11:**

*The formula '$Qs = rqR'sSs$' should treated as separate equation (l. 214). The further equations should be renumbered then.*

**Answer #11:**

We will implement the suggestion of the Reviewer to improve the clarity of the manuscript as follows.

$$Q_s = r_q R'_s S_s, \qquad (4)$$

**Comment #12:**

*Within Fig 8 the number '6.5e5' is printed.*

**Answer #12:**

We will correct this oversight and apologize for the inconvenience.