Final Response : Technical note: HydroModPy – a Python toolbox for deploying catchment-scale shallow groundwater models

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Referee comments on "Technical note: HydroModPy – a Python toolbox for deploying catchment-scale shallow groundwater models" by A. Gauvain et al., Hydrology and Earth System Sciences Discussions., https://egusphere.copernicus.org/preprints/2026/egusphere-2026-868/.

Thank you for your review. Referee comments are shown in black, and our point-by-point responses are provided in blue italics.

1 RC1: "Comment on egusphere-2026-868", Anonymous Referee 1, 18 Apr 2026

GENERAL COMMENTS

Gauvain et al. introduce a highly useful toolbox for groundwater modelling that is sure to appeal to readers of HESS. Based on established tools, the toolbox integrates them effectively and reproducibly. The explanations are clear and it is illustrated with a practical example.

We thank the reviewer for this positive assessment of the manuscript.

In my view, the main limitation of the current version is the type of aquifer systems that can be simulated: 'unconfined shallow aquifers where hydrogeological boundaries roughly correspond to topographic divides' (L82-83) 'where the water table lies close to the surface and topography strongly influences goundwater flow dynamics' (L113). In my experience, aquifer systems do not align with the boundaries of surface catchments as often as one might expect, and the issue of boundary conditions is often a key challenge in hydrogeology. When I consider which of my models this tool could be applied to, I ultimately cannot think of so many examples. It would certainly be an advantage to incorporate the way in which geology shapes aquifer systems. In this sense, I am not entirely convinced by the idea that the tool 'bridge[s] the gap between detailed site-specific studies and regional-scale hydrogeological assessments' (L355-356, see also L383-384) — at least when considering aquifer systems at a regional level (e.g. multi-layered systems).

Indeed, the present scope is mainly limited to shallow, unconfined, and topography-controlled systems. Nonetheless, HydroModPy includes an optional buffer-based domain extension to capture possible groundwater flow between neighboring catchments, as well as the ability to manually import watershed boundaries using shapefiles.

We also clarified this in the text (L355-356 and L383-384) to avoid overstatement and to better reflect the current scope:

L355-356 : "This systematic implementation demonstrates HydroModPy's scalability across catchment sizes within its targeted scope of shallow, unconfined, and topography-controlled groundwater systems, providing a standardized and efficient framework for comparative analyses using widely accessible datasets."

L383-384: "This approach offers a scalable solution for comparative hydrogeological analysis across multiple catchments, within the current scope of shallow unconfined aquifers where topographic divides approximate hydrogeological boundaries. It is worth noting that HydroModPy supports a buffer-based domain extension to capture potential inter-catchment groundwater exchanges, and model boundaries can also be defined manually via shapefiles to accommodate cases where surface and groundwater divides diverge."

Nevertheless, the authors put forward many promising prospects, which will surely be attractive to numerous modellers. In the meantime, I think it would be useful to release the current version. While reading through it, I had a number of minor queries and comments, which I have set out below as I went through the text. These in no way call into question its publication in HESS. You will also find a few technical comments.

Thank you for this comment. We have addressed all minor and technical comments below with corresponding revisions in the manuscript.

SPECIFIC COMMENTS

L67-74: This paragraph seems a little idealised to me. In my experience as a developer, there is never a perfect 'magic box', and you always have to write some code to adapt it to your specific situation. Proof of this lies in the wide range of initiatives mentioned.

We agree, and our goal is not to present HydroModPy as a perfect solution, but rather as a useful toolbox that can be used to build a groundwater model with a high degree of automation and reproducibility, while still allowing for user adaptation and customization. We modified this paragraph:

"Although numerous tools have been developed to address specific aspects of hydrogeological modeling, often with varying levels of complexity and scope, their integration into a coherent workflow frequently requires substantial user intervention. In practice, users often need to develop custom scripts and interfaces to connect model domain extraction, model setup, code coupling, model execution, deployment across multiple sites, and FAIR-compliant data management. While this flexibility allows adaptation to diverse applications, it can also increase workflow complexity and hinder reproducibility, portability, and large-scale deployment."

L73: Similarly, it is always easy and smart to refer to the critical zone, but while this type of groundwater tool may be useful for educating the community, I don't see exactly how it currently 'bridges the gap' and 'promotes collaboration' between hydrogeologists and other communities within the critical zone.

Thank you for this comment. The possibility of creating a groundwater model with HydroModPy can indeed facilitate collaboration with other Critical Zone communities by providing a common framework for integrating groundwater processes into broader Critical Zone studies. We modified this paragraph as follows:

"This highlights the need for an integrated and adaptable toolbox that can bring these concepts together within a coherent workflow. Rather than a generic solution, such a framework should combine a high degree of automation and reproducibility with the possibility for user adaptation to site-specific data, assumptions, and objectives. In practice, this type of tool can support interdisciplinary Critical Zone studies by providing reproducible scripts, explicit model settings and metadata, and standardized outputs that can be readily exchanged with other disciplinary tools and workflows. This does not remove all disciplinary barriers by itself, but it provides a common technical basis that can facilitate collaboration between hydrogeologists and other Critical Zone communities (Gaillardet et al., 2018; Wang et al., 2025; Staudinger et al., 2019)."

L78-80 'patterns of seepage areas can be used to represent the dynamics of the hydrographic network' & L200-204: However, if I understand correctly, this capacity only applies to baseflow, right?

Yes, the flow representation primarily reflects baseflow-driven groundwater exfiltration and associated seepage dynamics. We modified this sentence as follows:

"Thanks to the spatio-temporal simulation of groundwater flow and hydraulic heads, groundwater discharge zones naturally emerge, allowing for studying the dynamics of baseflow."

L97 'for calibration': The next four steps make no mention of calibration.

Thank you. Following your comment and the comment of reviewer #2, we revised the workflow description to explicitly include calibration as a key step, and we updated the corresponding figure 1 to reflect this.

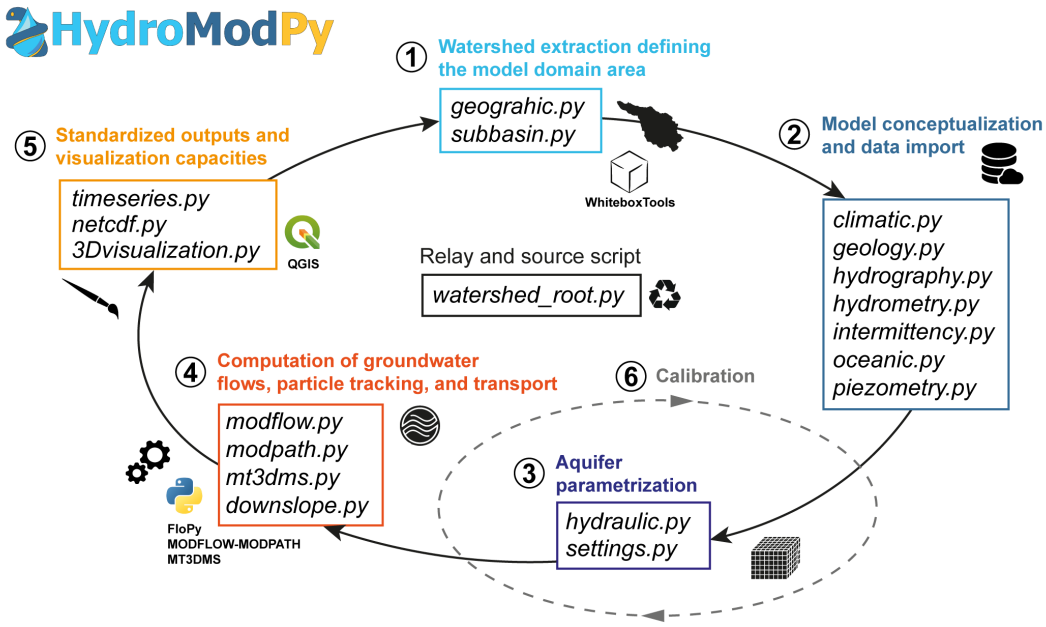

Figure 1. *Workflow of HydroModPy, illustrating the organization and interconnection of Python scripts within the toolbox across five main stages: (1) watershed extraction defining the model domain area from digital elevation models and outlet coordinates, (2) model conceptualization and data import, including climatic forcing, hydrographic networks, and observational datasets for calibration, (3) aquifer parameterization, specifying hydraulic properties, geometry, and boundary conditions, (4) computation of groundwater flows using MODFLOW-NWT via FloPy, with optional particle tracking (MODPATH) and transport simulations (MT3DMS), (5) standardized outputs and visualization, exporting results in geospatial formats (GeoTIFF, shapefile, NetCDF, VTK) and providing 2D/3D visualization tools for interactive exploration and analysis, and (6) comparison of outputs and data for calibration.*

L133 'DEM resolution': Is this the best possible resolution for the model? Can it be adjusted?

In this version of HydroModPy, the DEM resolution is the same as the model grid resolution. We are currently working on allowing independent DEM and model grid resolutions, which will provide more flexibility. We added a sentence in the discussion:

"Another planned development is to dissociate the model grid resolution from the resolution of the input DEM. In the current version, the DEM resolution defines the model grid, whereas future versions aim to allow these two resolutions to be specified independently, providing greater flexibility to balance topographic detail, model design, and computational cost."

L136 'by an ocean/sea/lake/river': Or any other lateral aquifer?

We agree and have rephrased this sentence.

"Nevertheless, constant hydraulic head can be imposed at prescribed domain limits to represent boundary conditions imposed by an ocean, sea, lake, river, or by lateral groundwater inflows from adjacent aquifer systems."

L155 'with the aquifer base specified at a given elevation': Is it a single value, or can it vary across the space? One might wish to interpolate contour lines for the aquifer bottom, which are sometimes available.

It can be either a single value or spatially variable. We clarified that the aquifer base can be prescribed as a raster/elevation field over space:

"The model thickness may be defined as constant, assuming an aquifer base parallel to the topography with a uniform depth, or as spatially variable, with the aquifer base prescribed either as a single elevation value or as a spatially distributed elevation field (e.g., raster)."

L158 'can be assumed uniform and isotropic across the entire model domain. but heterogeneity' & L160-161 'vertical heterogeneity' 'through anisotropy': 'Heterogeneity' and 'anisotropy' are two distinct concepts.

Thank you, we agree. We corrected the wording to clearly distinguish spatial heterogeneity from anisotropy, and removed the ambiguous sentence:

"Vertical variability of hydraulic properties can be represented as a function of depth or stratigraphic layering, for example through an exponential decay of K, Sy, and Ss with depth (Figure 2e). Anisotropy is treated separately as directional differences in conductivity (e.g., $K_h \neq K_v$)."

L160 'defining parameter zones based on geological maps or user-specified units': Could a stochastic approach be used instead?

Yes, stochastic approaches are possible and relevant. This is a future extension for parameter uncertainty and heterogeneity representation.

L165-166 'MODFLOW-2005': The current version of Modflow is Modflow 6. There are plans to upgrade to the new version (L413-414). Will this include the Particle Tracking (PRT) Model of Modflow 6 (vs MODPATH) and its Groundwater Transport (GWT) Model (vs MT3DMS) (L184-187)?

Thank you. We mentioned in Section 4.2 that migration to MODFLOW 6 is ongoing and that the integration of MF6-native modules (including PRT/GWT) is part of the planned roadmap, while current stable workflows rely on MODPATH/MT3DMS.

L186: Is it single- or multi-species solute transport? Does it cover basic chemical reactions?

In the current version, transport is implemented with MT3DMS. At this stage, we are able to simulate the advection, dispersion, and diffusion of a single chemical species (for example, NO3 in the example provided in the documentation). We can also enable zero-order or first-order reactions. In addition, the application allows users to specify heterogeneous concentration inputs and chemical degradation in the 3D model. We clarified this as follows:

"Solute transport is implemented using the MT3DMS (mt3dms.py) suite (Bedekar et al., 2016), enabling simulation of single-species transport with advection, dispersion, and diffusion. Basic reaction processes are supported through zero-order and first-order degradation kinetics (e.g., for conservative or moderately reactive solutes such as nitrate). Heterogeneous initial concentration distributions can be specified. More advanced reactive transport and multi-species configurations are envisioned as future extensions."

L172-173 'the storage coefficient corresponds to the vertically integrated specific yield': I don't think the specific yield needs to be vertically integrated, since it has the same dimension as the storage coefficient (unlike the specific storage) and there can only be one unconfined layer.

We agree and corrected this statement:

"For a unconfined (resp. confined) layer, the storage coefficient corresponds to the specific yield (S_y) (resp. vertically integrated specific storage S_s)."

Code 1: Wouldn't it be better to calibrate the hydraulic conductivity and the specific yield together rather than separately?

We used sequential calibration (following this recent paper: https://doi.org/10.1002/hyp.15167) because the calibration methods are based on steady and transient simulations, which are more sensitive to hydraulic conductivity and specific yield, respectively. However, we agree that a joint calibration approach could be more efficient and we are currently working on implementing this in HydroModPy.

L254-255 'how HydroModPy can be systematically employed to set up, simulate, calibrate, and analyze hydrogeological models across multiple catchments': Does such systematic work risk overlooking hydrogeological features, such as surface formations or faults?

We agree that this is a risk. In our approach, we primarily focus on the effective hydraulic properties of the aquifer, taking into account potential heterogeneities at the catchment scale. Nevertheless, study sites can also be constrained using site-specific knowledge (geology, structures, faults), and future versions of HydroModPy will allow the integration of such features when data are available, notably by adapting the model grid and parameterization to capture key hydrogeological controls. We modified this sentence:

"The objective is to illustrate how HydroModPy can be systematically employed to set up, simulate, calibrate, and analyze hydrogeological models across multiple catchments, with calibration primarily targeting catchment-scale effective hydraulic properties."

L319: Shouldn't we adjust the spatial resolution according to the size of the catchment area (see L313-314)?

We agree that it is a good idea to adapt the spatial resolution to catchment size and complexity. In this example, however, we wanted to show the capability of HydroModPy to deploy groundwater models from a regional DEM, and we chose to keep the same resolution across all catchments for comparability. In future versions, we will allow resolution adjustments by separating the DEM resolution from the model grid resolution.

L345 'to assess the simulation results': Sorry to stay on the basics, but what about hydraulic heads?

In this example, we focused on the representation of seepage areas (hydrographic patterns) and streamflow dynamics. Seepage areas are directly related to hydraulic heads, which are therefore implicitly considered in the analysis. We agree that hydraulic heads are not compared with well measurements in this example (https://doi.org/10.1016/j.jhydrol.2026.135118 and https://doi.org/10.1016/j.jhydrol.2024.131859). We chose to focus on seepage areas and streamflow because these data are more widely available for deployment across multiple catchments.

L353 'across diverse hydrological conditions, catchment scales, and topographies': Can we say that the hydrological conditions and topography really do vary between catchments in the Armorican Massif?

Thank you. We moderated this sentence to avoid overstatement and now describe variability more cautiously within the Armorican Massif context:

"Consistently high model performance across the range of hydrological settings, catchment sizes, and topographic contexts represented within the Armorican Massif dataset confirms the reliability of the simplified conceptual framework and automated calibration methodology."

L378 'across diverse [...] topographical, and geological settings': The same. All of them are crystalline basement aquifers, and their hydraulic conductivities are very similar (L379-380).

Agreed. We have revised this sentence as follows:

"First, the automated workflow successfully calibrated all models with consistent performance metrics (NSE_{log} > 0.75), demonstrating robust convergence across a range of catchment sizes (7–526 km^2) within a relatively homogeneous crystalline basement context. The calibrated effective hydraulic conductivity values (1.75×10^{-5} to $2.79 \times 10^{-4}, \mathrm{m.s^{-1}}$) are relatively similar among catchments, which is consistent with the shared geological setting and with values reported in the literature for crystalline basement aquifers (Lachassagne et al., 2021)."

L360: Cite Gleeson et al. 2011 (see Figure 1) for calibrated regional-scale hydrogeologic models. doi:10.1029/2010GL045565

Thank you for this reference. We added Gleeson et al. (2011) at the relevant location.

L385 'to integrate multiple data sources': Assuming they are indeed available for all catchments.

Absolutely. A user check is required to ensure that the necessary data sources are available for the catchments of interest. We clarified this point in the text:

"Third, HydroModPy's ability to integrate multiple data sources, when these datasets are available for the catchments of interest, substantially reduces the time and technical barriers typically encountered in catchment-scale groundwater modeling. In practice, successful integration still depends on the user verifying data availability, completeness, and quality for each study site."

L394-395: It all depends on how the recharge is calculated. In fact, this key parameter is not calculated within this modelling framework, but specified as an input instead, which could be seen as a limitation (but it is being resolved, L420-421).

We agree, recharge is currently an external forcing in the presented setup (obtained from an independent land surface model), and we now better explain ongoing coupling work to improve internal consistency of recharge estimates.

L395 'Similarly'; 'default assumption of homogeneous effective hydraulic properties'; L398 'assumption of spatially uniform recharge': These default options, which can be overridden (see L401-405), are not as significant as the other limitations.

Agreed. We have rephrased this part as follows:

"Additional, more easily addressable limitations include the default assumption of homogeneous effective hydraulic properties within each catchment which may fail to capture the heterogeneity typical of geological contacts or stratified aquifers. The instantaneous surface routing scheme neglects key processes influencing surface – subsurface interactions, such as reinfiltration. Finally, the assumption of spatially uniform recharge cannot capture variations in precipitation, evapotranspiration, land cover, or land use-factors that must be considered when addressing specific scientific questions and hydrological challenges."

L414-420 'additional tools' 'multiple groundwater flow solvers' 'other open-source codes': I'm not sure exactly what these additional tools are.

We agree that this sentence is vague. The main objective of HydroModPy is to provide a flexible framework that can integrate various groundwater flow solvers (e.g., MODFLOW, HS1D) and other tools like recharge estimation models (HELP, GR4J). We clarified this in the text by providing specific examples of the types of tools and solvers that are planned for integration in future versions.

L423 'will allow': Does the integration of land surface models work effectively? Or is it still a work in progress?

It is still a work in progress. We revised this to: "Currently two land surface models are under implementation in HydroModPy"

L425-427: a 'non-iterative approach' means 'feedback mechanisms' are not fully resolved?

Thank you for this comment. We removed: ", using a non-iterative approach"

L429-430 'we aim to extend HydroModPy's applicability to a broader range of hydrological contexts': That's fine, but it will mean straying from HydroModPy's core philosophy.

We agree with this caution. However, the philosophy of HydroModPy may depend on the intended application and hydrological context.

L436 'for piezometry and climate data': It is somewhat unfortunate that the example given in Section 3.2 does not make use of either groundwater levels or climate data.

Good point. As we mentioned in a previous response, the example focuses on streamflow and seepage area patterns because these data are more widely available across multiple catchments. We chose to highlight HydroModPy's ability to deploy and calibrate groundwater models across multiple catchments, and we wanted to use a consistent set of data for all catchments.

Section 4.3: In terms of teaching, the tool offers a wide range of features. But to what extent could this type of tool also be used for synthetic modelling?

Thank you for this comment. Although HydroModPy is primarily designed for real-world applications, it can also be used for synthetic modeling by allowing users to create idealized scenarios and test specific hypotheses.

TECHNICAL CORRECTIONS

L4-5: I suggest adding 'tools' as a word is missing in 'The current version integrates well-established geospatial tools, such as Whitebox Tools'.

Corrected, "tools" was added in the abstract sentence.

L29 'pressures.'; L129 'study site.': Remove the punctuation mark.

Corrected, the extra punctuation marks were removed.

L41-44 'and the ability to explore the sensitivity and uncertainty of model parameters.': The end of this sentence seems incomplete.

Thank you, the incomplete sentence was rewritten and completed.

L84: level ('water table' (without level) on its own might also work).

Corrected. We revised the wording to "water table level" (or "water table" where most appropriate).

Figure 1 (2) 'hydrography.py': Appears twice.

Corrected. The duplicate occurrence of "hydrography.py" in Figure 1 was removed.

Figure 2 (a): No matter how much I zoom in, I can't see the 'pink-highlighted' area. Is it just the pink colour on the map?

Thank you. We improved the figure styling and caption wording so the highlighted area is clearly visible.

Figure 2 (e) 'exponential decay with depth': Link this to $1/\alpha$.

Agreed. We now explicitly link the exponential decay formulation to the $1/\alpha$ scale parameter.

Figure 2 (f–i) 'watertable depth': water table depth.

Corrected to "water table depth".

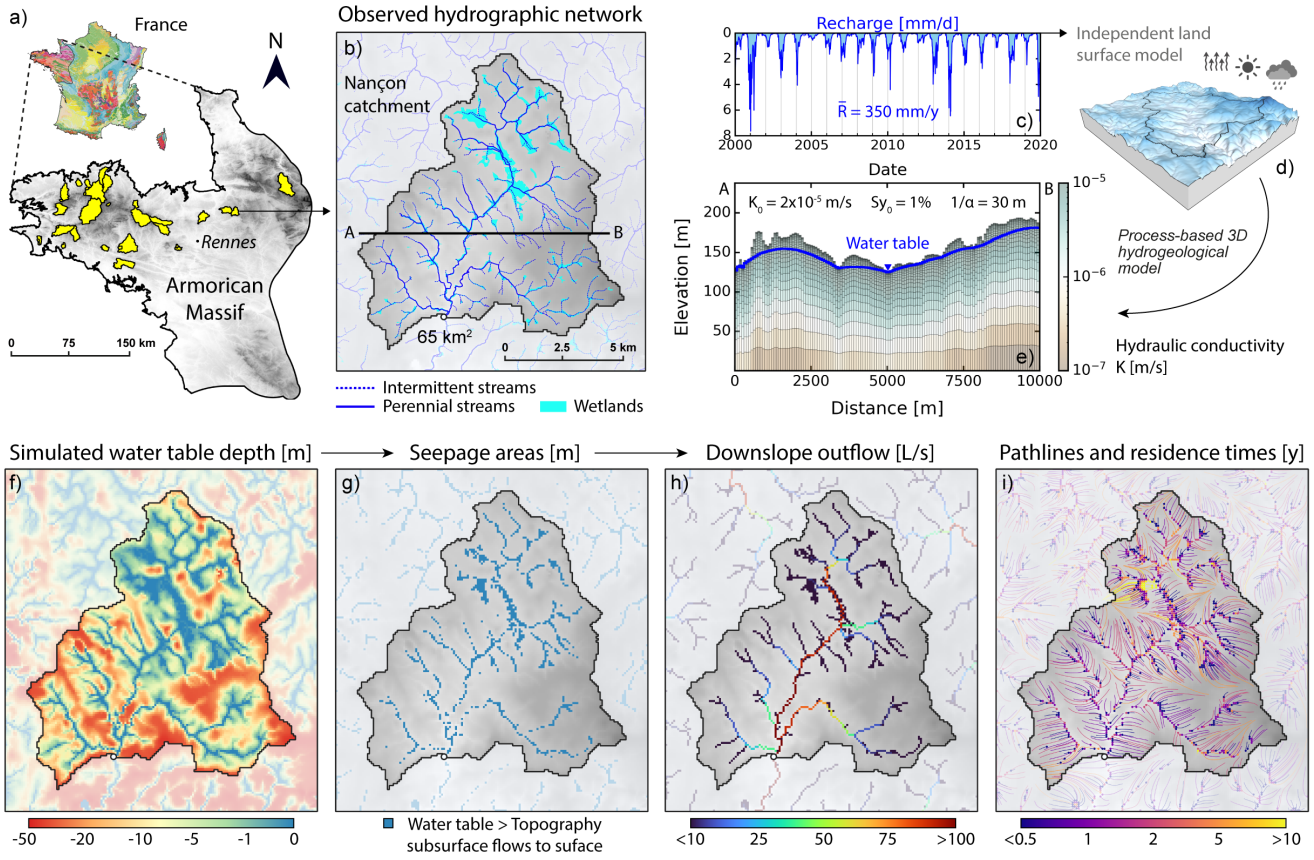

Figure 2. *HydroModPy modeling steps illustrated for the Nançon catchment, Brittany (France). (a) Extraction of the watershed from a regional DEM, located to the west of the Geological Map of France. (b) Clip data based on the watershed extent. (c) Recharge time series provided from an independent land surface model. (d) 3D diagram illustrating the model conceptualization and parameterization based on data available and assumptions. (e) The cross-section (A-B) illustrates the vertical grid discretization and the resulting water table. The parameters include an exponential decay $1/\alpha$ with depth from the maximum hydraulic conductivity K_0 and specific yield Sy_0 (%) in the first layer. (f–i) 2D map top-view visualization displaying spatial data and model results in steady state across the study area (left to right): water table depth, seepage areas, accumulated outflow, pathlines, and residence times.*

L158-159 ’but heterogeneity of these parameters can be easily implemented specified using geological maps or user-defined zones.’: To be removed.

Done. The redundant sentence was removed.

L186: And advection.

Corrected. Advection is now explicitly mentioned in the transport description.

L205-206: visualization (with a ’z’).

Corrected to American spelling (“visualization”) for consistency throughout the manuscript.

L210-212 ’This includes the topography and model grid, water table elevations and depths, seepage areas, and the associated accumulated surface flow.’: Repeated twice.

Corrected. The duplicated sentence in this section was removed.

L206 & L216: Standardise the writing of ’vedo’.

Corrected. We standardized the library name as “vedo” throughout the text.

Figure 3: knickpoints

Corrected.

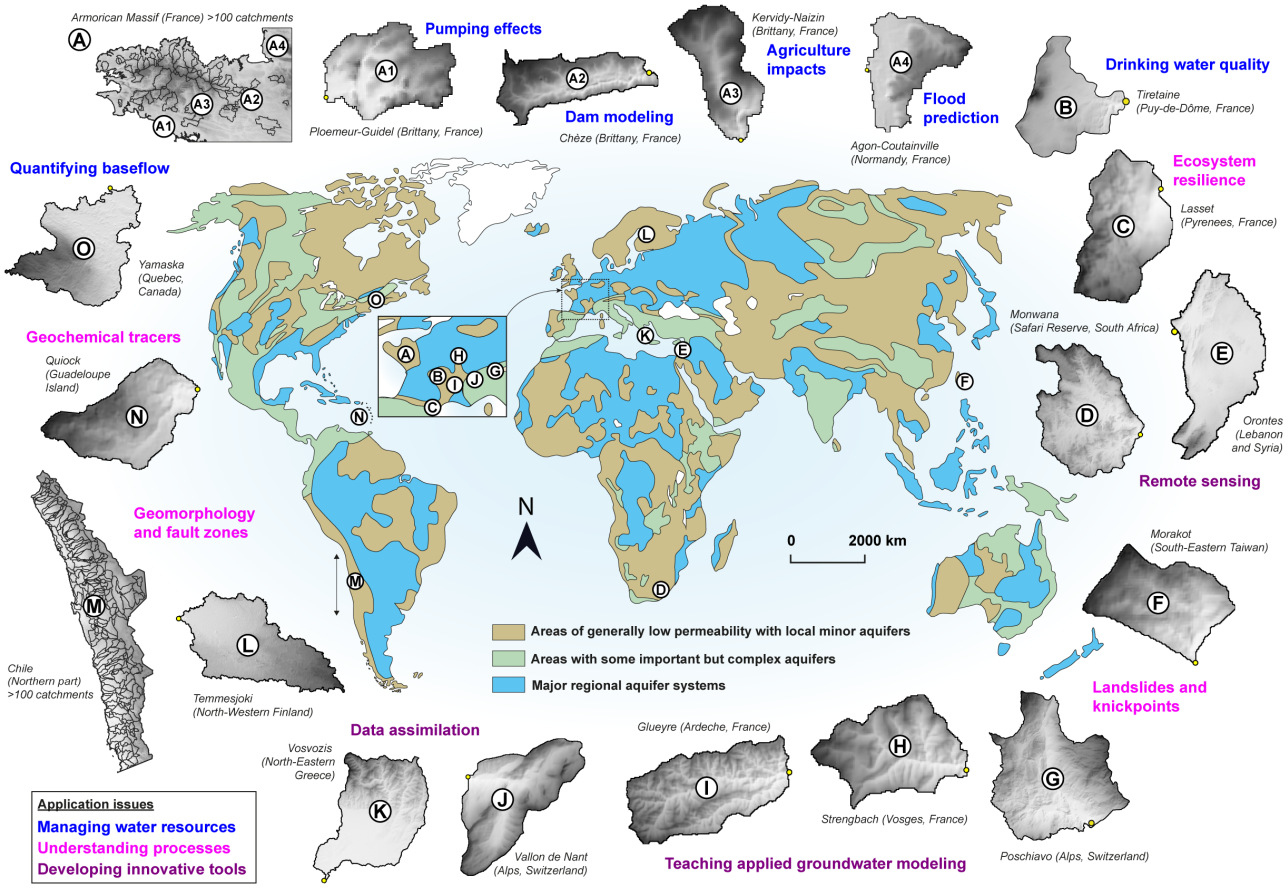

Figure 3. *Worldwide application sites of HydroModPy. Simplified global groundwater resources map (Duscher et al., 2015), modified from Taylor et al. (2013) and originally obtained from Struckmeier et al. (2008). Catchments are grouped into three main application fields: water resources management, process understanding, and tool development. Since HydroModPy primarily focuses on subsurface–surface interactions, all catchments are located in areas of generally low permeability with shallow, local, minor aquifers (brown areas on the world map). Extensive applications of HydroModPy have been carried out in France (A) and Chile (M) across multiple catchments.*

L220 'on the hydrogeological map IHME1500 (Duscher et al., 2015): The references given in the caption for Figure 3 are different 'Simplified global groundwater resources map, modified from Taylor et al. (2013) and originally obtained from Struckmeier et al. (2008)'

Thank you. We harmonized the Figure 3 source references so they are consistent between text and caption.

L305: What do you mean by '3.2.3'?

That's a mistake. We've removed it.

L322 'the mesh grid sizes range from 2,800 to 207,152 cells': the number of grid cells ranges from 2,800 to 207,152

Corrected as suggested ("the number of grid cells ranges from 2,800 to 207,152").

L323 'weathered or fractured': Is that incompatible?

They are not incompatible; they can coexist. We clarified the wording to "weathered and/or fractured" to avoid confusion.

L324 'in the Armorican Massif region': in the Armorican Massif

Corrected to "in the Armorican Massif".

L334 'while DOS represents the inverse': represents the reverse

Corrected to "represents the reverse".

L342 'a simulation': a transient simulation over the 3-year period?

Yes. We clarified that this refers to a transient simulation over the 3-year period.

L359 (and elsewhere): I don't think the units should be written in italics (don't use LaTeX's math mode); to be checked with HESS

Thank you. We revised unit formatting to match journal conventions and avoided unnecessary italic math formatting for units where required.

L361 'measurements. Dewandel et al. (2021)': measurements (Dewandel et al., 2021).

Corrected to "measurements (Dewandel et al., 2021)".

L363 'simulations': Is the plural form correct?

Yes. Corrected.

L421 'both': two

Corrected: "both" was replaced by "two".

L843: Fix the DOI 'https://doi.org/10.1007/S42452-022-05082-0'

Corrected. The DOI was fixed to https://doi.org/10.1007/S42452-022-05082-0.

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