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Response to reviewers and editor

HESS revision

airGRteaching: an open-source tool for teaching hydrological modeling with R

Reviewers' comments are in italics. Previous responses from the online discussion are in blue. New responses after revision are in red.

Response to Editor

Editor decision: Publish subject to minor revisions (further review by editor)

thank you for your replies to the comments published during the Interactive Discussion phase. Please, submit at your earliest convenience the revised manuscript that will be checked by the Editor.

Please, incorporate suggestions according to your replies, and prepare a list of changes made to the revised version of the manuscript.

After further analysis of data, the airGRdatasets R package has been updated (version 0.2.1; Delaigue et al., 2023). Therefore, the table 2 and the figures 3 & 4 have been updated in the manuscript. In the airGRdatasets package and in the article, the A341020001 & V121401001 catchments have been replaced by A273011002 and V123521001, respectively. In addition, due to a misordering, catchments with IDs F, G, and H have been reordered in the table 2, and the figure 4 has been corrected accordingly.

Statistics of the figure 4 have been recomputed over the available daily time series in the airGRdatasets package (i.e. from 1999-01-01 to 2018-12-31; and a year is considered to have less than 10 % of missing streamflow values to be accounted for in statistics), and not anymore over the entire available period (often longer), which varies from a station to another. The caption has been corrected accordingly.

Table 2 modifications.

	Station code	ID	Station Name	Area (km²)	Hydrological regime
~~1~~	~~A341020001~~	~~A~~	~~the Zorn at Saverne [Schinderthal]~~	~~184~~	~~Pluvial~~
1	A273011002	A	the Bruche at Russ [Wisches]	224	Pluvial
2	A605102001	B	the Meurthe at Saint-Dié-des-Vosges	371	Pluvial
3	B222001001	C	the Meuse at Saint-Mihiel	2543	Pluvial
4	E540031001	D	the Canche at Brimeux	917	Groundwater
5	E645651001	E	the Nièvre at Étoile	270	Groundwater
~~6~~	~~H010002001~~	~~F~~	~~the Seine at Plaines-Saint-Lange~~	~~686~~	~~Pluvial~~
6	F439000101	F	the Loing at Épisy	3917	Pluvial
~~7~~	~~H120101001~~	~~G~~	~~the Aube at Bar-sur-Aube~~	~~1298~~	~~Pluvial~~
7	H010002001	G	the Seine at Plaines-Saint-Lange	687	Pluvial
~~8~~	~~F439000101~~	~~H~~	~~the Loing at Épisy~~	~~3917~~	~~Pluvial~~
8	H120101001	H	the Aube at Bar-sur-Aube	1298	Pluvial
9	H622101001	I	the Aisne at Givry	2888	Pluvial
10	J171171001	J	the Trieux at Saint-Péver - Pont Locminé	184	Pluvial
11	J421191001	K	the Odet at Ergué-Gabéric - Treodet	203	Pluvial
12	K134181001	L	the Arroux at Rigny-sur-Arroux	2271	Pluvial
13	K265401001	M	the Couze Pavin at Saint-Floret	216	Pluvial
14	K731261001	N	the Indre at Saint-Cyran-du-Jambot	1707	Pluvial
~~15~~	~~V121401001~~	~~O~~	~~the Fier at Dingy-Saint-Clair~~	~~224~~	~~Nival-Pluvial~~
15	V123521001	O	the Ire at Doussard	25	Nival-Pluvial
16	X031001001	P	the Durance at Embrun [La Clapière] - DREAL PACA	2283	Nival
17	X045401001	Q	the Ubaye at Lauzet-Ubaye [Roche-Rousse] - DREAL PACA	943	Nival
18	Y643401001	R	the Esteron at Broc [La Clave]	442	Mediterranean
19	Y862000101	S	the Taravo at Zigliara [Pont d'Abra]	332	Mediterranean

Reference:

Delaigue, O., Brigode, P. and Thirel, G.(2023). airGRdatasets: Hydro-Meteorological Catchments Datasets for the 'airGR' Packages. R package version 0.2.1, doi: 10.57745/3SPJ4B, URL: https://CRAN.R-project.org/package=airGRdataset

Response to RC1

Thank you very much for your review. We provide below some complements to answer the reviewer's remarks, and we also would like to use the open review feature to ask for more details regarding one of the reviewer's remarks.

Q1: *The manuscript presents a contribution to the hydrology teaching task and in general to the water education context, I suppose at the university level. Overall the airGRteaching appears an interesting approach for the purpose: it is a versatile tool able to model streamflow data at different time scale, integrating different hydrological processes, it has a nice and attractive graphical interface* *and seems to have a good module to interact with the model component and model parameters (par 3.1.1.) in order to explore their relevance in the modlling phase. I found not really detailed the calibration and validation module.*

A1: We recognize that we did not detail too much the calibration algorithm in the manuscript. The main reason for that is that this algorithm does not belong to airGRteaching, but to airGR, and this algorithm was described into further details in Coron et al. (2017), section 2.3.

Two distinct steps are included in the procedure:

1. a systematic inspection of the parameters space is performed to determine the most likely zone of convergence. This is done either by direct grid-screening or by constrained sampling based on empirical parameter databases;

2. a steepest descent local search procedure is carried out to find an estimate of the optimum parameter set.

We will present these two steps in the revised version of the manuscript.

These new elements have been added in section 3.2.2 “Automatic calibration”.

Q2: *I see from figure 9 that it would be possible for the student to graphically realize what is the impact of parameter calibration in terms of relevant hydrological processes (snowmelt effect in figure 9), but other model features would be interesting to be explored in my opinion. As an example it could be instructive and informative for a student to learn and maybe visually catch how an hydrograph would be shaped by a range of value of given parameter (eg. an ensamble of shapes of the recession limbs for an ensamble of catchment delay time) and perhaps have a real time exploration of the assessment of the goodness of fit .*

A2: We are a bit puzzled by the comment regarding how the hydrograph is shaped by different values of model parameters, since what the reviewer asks seems to be already provided in Figure 6 for the catchment delay (and in Figures 5 and 7 for two other parameters). Could the reviewer precise the demand? In the absence of explicit feedback from the reviewer, we made no changes.

Regarding the “real time exploration of the assessment of the goodness of fit”, we did not provide such a visualization in airGRteaching, because the calibration process of GR models is very fast (circa 0.4 second for a calibration of GR4J on a 10-year period, see Coron et al., 2017, Table B.3). This does not permit a convenient real-time visualization. Instead, we provide an a posteriori visualization in airGRteaching, which is introduced in Figure A.5 in the submitted manuscript.

Q3: *1) In the abstract (line 5) such as at page 4 line 21, I would suggest the authors to introduce what the GR models (class of models) are, maybe with some basic references. I know that sometime later in the paper a good review of the literature is provided, but I believe some basic reference should be given when introducing the GR models at the very start of the manuscript.*

A3: We will better introduce the GR models in the manuscript.

We added a few words in the abstract, but no references as this is not advised by the journal guidelines. We also completed a sentence at the end of the introduction, as suggested by the reviewer. However we did not go into further details, as sections 2.1 and 2.2 are dedicated to introducing the GR models.

Q4: *2) The legend and the caption in Figure 2 are not really clear to me. Should be improved.*

3) I found not really appropriate the example for "4 years of warm-up" period in figure 8. Probably it was mentioned just as an example, but maight be a bit unrealistic.

4) Also in Figure 12 the legend and the caption should be improved.

A4: Thank you for these comments. We will try to improve the legends and captions. Regarding the warm-up period, we will introduce a 1-year warm-up period on Figure 8, which is the warm-up default period in airGRteaching. We introduced a 1-year warm-up period on figure 8, instead of a 4-year period. We also updated consequently the appendix D4.

We also improved both the caption and the legend of Figure 12.

We provided further details to the caption of Figure 2. However, this figure does not contain any legend, so we did not make any modification here.

Reference:

Coron, L., Thirel, G., Delaigue, O., Perrin, C., and Andréassian, V.: The Suite of Lumped GR Hydrological Models in an R package, Environmental Modelling and Software, 94, 166–171, https://doi.org/10.1016/j.envsoft.2017.05.002, 2017.

Response to CC1

Thank you very much for your review. We provide below some complements to answer the reviewer's remarks, and we also would like to use the open review feature to ask for more details regarding one of the reviewer's remarks.

Q1: *I think every tool has limitations, there is no perfect tool. As this tool has been used for teaching in various places, I am wondering what the limitations of this tool are (from the students and the lecturer's perspective). In the future, if someone wants to develop a similar tool, which expectations such a tool should be (also from the students and lecturer's perspectives). I think adding a section describing limitations of this tool and the future outlook for such a tool would be interesting.*

A1: We thank the reviewer for this interesting comment. Identifying some of the potential limitation of the airGRteaching package and similar tools is definitely something that would benefit to the manuscript. Regarding the outlook of such a tool, we consider that the "5. Perspectives" section of the manuscript already responds to this proposition.

Consequently, we propose to modify the "5. Perspectives" section by adding elements concerning potential limitations of such a tool.

We renamed section 5 from "Perspectives" to "Limitations and perspectives", and divided it into two subsections section 5.1 "Limitations" (adding new elements) and section 5.2 "Perspectives", containing the requested elements.

Q2: *When I select „Mountainous" or „Lowland basins", there are some error messages (attached figure) appear in the GUI as well as in the Rstudio Console. I would be nice if the authors can fix this.*

A2: We recognize that the error message identified by the reviewer briefly appears when we change the selected basin. However, this message just appears temporarily and disappears within a tenth of second. This is due to the numerous interactions in the Shiny interface between the different panels. We did not manage to solve this issue so far, but we consider that this is not a problem at all, as this is temporary and does not provoke neither any false calculation nor any real crash of the interface.

If the reviewer was talking about another error message, we kindly ask him/her to describe the exact way to reproduce it, so that we can identify the problem.

Response to RC2

Thank you very much for your review. We provide below some answers to the reviewer's remarks.

Q1: *Introduction: The explanation is too less. May be the authors can provide more explanation.*

1.1: Needs to be improved.

1.3: Needs to be improved.

A1: We thank the reviewer for this comment. We believe that a 3-page introduction is a rather classical size for research articles. The reviewer's comment not being very specific, we lack of elements to understand what is wrong in the introduction and we cannot improve it.

Q2: *1.4: Needs more explanation on the importance of R in the hydrological sector. Currently, what are the model/calibration packages available in the R environment?*

A2: Several works we cited did emphasize the importance of R for hydrology. See e.g. Slater et al. (2019) for the complete hydrological workflow and Astagneau et al. (2021) for the specific case of hydrological modelling. We do not aim to do better than these recent papers containing a review of tools and applications of R in hydrology, but we will try to improve the explanations about why R is important for hydrologists.

Regarding the calibration tools available in R, we refer again to Astagneau et al. (2021), section 5.1.1, paragraph « Parameter estimation », which lists several tools enabling calibration, either in hydrological modelling R packages or in more general R packages.

Q3: *1.5: Needs more explanation on why this package is important?*

A3: We believe that the fact that barely no other options exist in R can already highlight the importance of this package. In addition, airGRteaching relies on the widely-used GR models (see e.g. Perrin et al., 2003, which presents one of these models, and was cited 977 times according to Scopus), and on the airGR package, which gained lots of interest over the past few years (see Coron et al., 2017, which presents the airGR package, and was cited 133 times, or the https://hydrogr.github.io/airGR/page_publications.html#Use_and_mention_of_airGR airGR webpage, which lists all known uses of or references to airGR). We will therefore try to emphasize the importance of the airGRteaching package.

Q4: *Section 3.2.2: What is the optimization function used for calibrating the model? Needs more explanation here.*

A4: We provide here the same answer as we provided to Reviewer 1.

We recognize that we did not detail too much the calibration algorithm in the manuscript. The main reason for that is that this algorithm does not belong to airGRteaching, but to airGR, and this algorithm was described into further details in Coron et al. (2017), section 2.3.
Two distinct steps are included in the procedure:

1. a systematic inspection of the parameters space is performed to determine the most likely zone of convergence. This is done either by direct grid-screening or by constrained sampling
   based on empirical parameter databases;
2. a steepest descent local search procedure is carried out to find an estimate of the optimum
   parameter set.

   We will present these two steps in the revised version of the manuscript.

   As mentioned in A1 to RC1, we added new elements in section 3.2.2 “Automatic calibration”.

References :

Coron, L., Thirel, G., Delaigue, O., Perrin, C., Andréassian, V., 2017: The Suite of Lumped GR Hydrological Models in an R package, *Environmental Modelling & Software*, 94, 166-171. doi: 10.1016/j.envsoft.2017.05.002.

Perrin, C., Michel, C., Andréassian, V., 2003. Improvement of a parsimonious model for streamflow simulation. *Journal of Hydrology*, 279 : 275-289. doi: 10.1016/S0022-1694(03)00225-7.

Response to EC1

We thank the editor for his positive feedback. We provide below some answers to the editor's remarks.

Q1: *In Section 5 on perspectives, I would ask for a short discussion on (existing, recognised) limitations when used this tool. Several interesting capabilities for diverse combinations are shown in this section (such as for gaming purposes), can you think of some tool's limitations to mention them in the text.*

A1: The editor is right, as most tools, `airGRteaching` has some limitations.

The first one is that so far only GR hydrological models are available in `airGRteaching`. Adding other models could be possible, but would require tremendous efforts (for instance, it would require the adding of a model scheme for each model, the interface could become less handy with models presenting over 10 parameters to optimise, and calibration would be far less rapid).

In addition, it is not possible for the user to build its own hydrological model by adding, for example, reservoirs (with different discharge functions) and unit hydrographs, to help understand each compartment of a model. Other limitations, and those are mentioned in section 2.3, are that `airGRteaching` offers only a limited set of modelling options, compared to `airGR`. This however could also be seen as a strength, as proposing too many options could be cumbersome on a user's perspective, and these limitations are therefore voluntary.

Finally, remote sensed data, other than meteo or hydro data, cannot be used in `airGRteaching` at the moment (see answer to Question 3). In addition, the effect land cover changes cannot directly be assets to `airGRteaching`.

We will rename section 5 as *Limitations and perspectives* and mention these limitations.

As mentioned in A1 to CC1, we renamed section 5 from "Perspectives" to "Limitations and perspectives", and divided it into two subsections section 5.1 "Limitations" (adding new elements) and section 5.2 "Perspectives".

Q2: *Could you add your opinion, to which of 23 unsolved problems in hydrology (UPHJ, https://www.tandfonline.com/doi/full/10.1080/02626667.2019.1620507) this tool might contribute?*

A2: This is an excellent suggestion. As such, the `airGRteaching` tool is not intended to be used to realise extended hydrological research studies, and therefore it does not aim to be used to contribute to the actual solving of any of the 23 UPHs. However, as it permits to teach

hydrology, to understand hydrological processes and to masterize hydrological modelling, we believe that `airGRteaching` could be used as a preliminary step in the solving of some UPHs. Namely, **UPH19** (*How can hydrological models be adapted to be able to extrapolate to changing conditions, including changing vegetation dynamics?*) and **UPH20** (*How can we disentangle and reduce model structural/parameter/input uncertainty in hydrological prediction?*), due to the many model parameter manipulations and calibration/evaluation exercises that `airGRteaching` proposes are good candidates. We also believe that this tool can contribute to UPH21 (*How can the (un)certainty in hydrological predictions be communicated to decision makers and the general public?*) as it has already been used by several decision makers managers in hydrological trainings. `airGRteaching` can be seen as a gateway to mastering `airGR` (Coron et al., 2017; Coron et al., 2023) and other `airGR`-dependent packages, and thus indirectly helping to solve other UPHs. This is notably the case for questions linked to usage, thanks to the `airGRiwrm` package (Dorchies et al., 2022) for Integrated Water Resources Management (**UPH22**: *What are the synergies and tradeoffs between societal goals related to water management (e.g. water-environment-energy-food-health)?* & **UPH23**: *What is the role of water in migration, urbanisation and the dynamics of human civilisations, and what are the implications for contemporary water management?* `airGRiwrm` could help to solve problems of spatial heterogeneity and change of scale (**UPH5:** *What causes spatial heterogeneity and homogeneity in runoff, evaporation, subsurface water and material fluxes (carbon and other nutrients, sediments), and in their sensitivity to their controls (e.g. snow fall regime, aridity, reaction coefficients)?* & **UPH6**: *What are the hydrologic laws at the catchment scale and how do they change with scale?*), because it simplifies the use of `airGR` in a semi-distributed mode. The `airGRdatassim` package (Piazzi et al., 2021; Piazzi & Delaigue, 2021), which enables data assimilation, could be link to questions of prediction uncertainty (**UPH20**).
These elements will be added in Section 5. We added them in section 5.2 “Perspectives”.

Q3: *Furthermore, some sentences about measurements (hydrometry, remote sensed data) and their importance (precision/error, frequency, ...) when using such tools as `airGRteaching` should be added to stress the need of proper model validation - if some wants to use data of his/her own and not using available `airGRdatasets` package.*

A3: Except from the online version of the graphical version interface, users can use their own meteo and hydro datasets, as mentioned at line 4 page 15, or at line 2 page 21. We will try to make it clearer in the revised version. We have completed the table 1 and improve the start of §2.4.3 to be more explicit.

Remote sensed data, other than meteo or hydro data, cannot be used in the `airGRteaching` at the moment. The use of the remote sensed data belong to `airGR` (see section 2.2 regarding snow satellite data) and constitutes only a potential perspective of the `airGRteaching` package, as mentioned in section 5. In addition, proper uncertainty exercises, apart from the calibration on different periods, do not belong so far to this tool, which we see as a simple way of starting hydrological modelling. However, the editor is right and these are important issues, which we believe they can be tackled with `airGR`. We will make that clearer in the revised version of the manuscript. We added these elements in the new section 5.1 “Limitations”.

Q4: *Last but not least, a comment how to use this tool in teaching can be added (also from your own experiences): during informal education for general public, as a part of graduate studies in natural sciences and engineering... reading the manuscript, the research/scientific flair is prevailing over educational/teaching one.*

A4: Among the four authors, two give a few dozens of hours of teaching every year, and one is an assistant professor.

We and colleagues have used `airGRteaching` to teach to four different audiences:

- graduate students (in geography and hydrology) and engineering students,
- engineers working in consulting firms,
- researchers,
- and the general public at science fair-type events.

Our experience with these different audiences has shown that `airGRteaching` is useful in helping **students** understand a variety of basic concepts: from the choice of an objective function, to the sensitivity of model simulations to individual parameters, the difference between model states and model parameters, the difference between automatic and manual calibration, and the informative and complementary value of a variety of plots. Projects that are more elaborate have been developed and are listed in section 4. For students, depending on the time allotted and their experience, we use the graphical interface with or without the use of computer code. For **researchers**, it is more a matter of introducing them specifically to GR models, and the interface is used as an introduction of the GR model structure. For **engineers working in consulting firms**, it's often somewhere in between, depending on their experience and their background. The GUI is frequently used to avoid being bogged down in problems of form and to concentrate exclusively on the underlying concepts of hydrological modeling. The simplified code version allows a smooth transition to the more complex `airGR` code. For the **general public**, the aim is usually to introduce them using the `airGRteaching` GUI to one of the fields of hydrology, to help them understand what a model is, and to raise their awareness of applications such as flood and low-flow forecasting, and global change.

We will comment on that in section 5. We added these elements in section 5.2 “Perspectives”.

References:

Coron, L., Delaigue, O., Thirel, G., Dorchies, D., Perrin, C. and Michel, C. (2023). airGR: Suite of GR Hydrological Models for Precipitation-Runoff Modelling. R package version 1.7.4, doi: 10.15454/EX11NA, URL: https://CRAN.R-project.org/package=airGR.

Coron, L., Thirel, G., Delaigue, O., Perrin, C. and Andréassian, V. (2017). The Suite of Lumped GR Hydrological Models in an R package, Environmental Modelling and Software, 94, 166–171, doi: 10.1016/j.envsoft.2017.05.002.

Dorchies, D, Delaigue, O. and Thirel G. (2022). airGRiwrm: 'airGR' Integrated Water Resource Management. R package version 0.6.1, doi: 10.15454/3CVD1I, URL: https://CRAN.R-project.org/package=airGRiwrm.

Piazzi, G. and Delaigue, O. (2021). airGRdatassim: Suite of Tools to Perform Ensemble-Based Data Assimilation in GR Hydrological Models. R package version 0.1.3, doi: 10.15454/WEYYVZ, URL: https://gitlab.irstea.fr/HYCAR-Hydro/airgrdatassim.

Piazzi, G., Thirel, G., Perrin, C. and Delaigue, O. (2021). Sequential data assimilation for streamflow forecasting: assessing the sensitivity to uncertinties and to updated variables of a conceptual hydrological model. Water Resources Research, 57, e2020WR028390, doi: 10.1029/2020WR028390.