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

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Abstract. Hydrological modeling is at the core of most studies related to water, especially for anticipating disasters, managing water resources, and planning adaptation strategies. Consequently, teaching hydrological modeling is an important, but difficult, matter. Teaching hydrological modeling requires appropriate software and teaching material (exercises, projects); however, although many hydrological modeling tools exist today, only a few are adapted to teaching purposes. In this article, we present the `airGRteaching` package, which is an open-source R package. The hydrological models that can be used in `airGRteaching` are the GR rainfall-runoff models, i.e., lumped processed-based models, allowing streamflows to be simulated, including the GR4J model. In this package, thanks to a graphical user interface and a limited number of functions, numerous hydrological modeling exercises representing a wide range of hydrological applications are proposed. To ease its use by students and teachers, the package contains several vignettes describing complete projects that can be proposed to investigate various topics such as streamflow reconstruction, hydrological forecasting, and assessment of climate change impact.

- water resources management for hydropower, irrigation, and drinking water (e.g., Neumann et al., 2018);

- low-flow forecasting, to better manage water resources and to ensure that environmental flows are respected (e.g., Nicolle et al., 2014);

- flood forecasting, to protect people and property, to evacuate inhabitants, and to plan the allocation of rescue forces with sufficient anticipation (e.g., Furusho et al., 2016);

- flood protection, to define areas that cannot be built or to design dikes or dams (e.g., Paquet et al., 2013);

- assessing climate change impact, to better anticipate future risks and design adaptation measures (e.g., Dorchies et al., 2014);

- assessing water resources in catchments (e.g., Brigode et al., 2019);

- testing hypotheses about catchment processes since not all fluxes are easily measurable (Clark et al., 2011).

The consequences and damage of extreme events (floods and droughts) are more limited when such events are better anticipated or managed. Hydrological science can also help to optimize profits in the hydropower sector (Cassagnole et al., 2021). In this context, hydrological models are key tools because they help to transform meteorological variables into hydrological variables.

1 Introduction

In order to anticipate and manage water conditions, outcomes of hydrological research are applied on a regular basis by water managers and stakeholders. These are aimed at addressing numerous challenges, such as the following:

1.1 On the need for (and relevance of) teaching hydrology using models

For many years, teaching hydrology has implied teaching hydrological modeling (Wagener and McIntyre, 2007). As a consequence, teaching hydrology can also imply programming, thereby raising the important issues of automatic calibration, sensitivity analysis (AghaKouchak and Habib, 2010; Knoben and Spieler, 2022), and also reproducibility in hydrology (Hutton et al., 2016). Given the advantages of applying hydrological models for the real-life cases listed above, there is a considerable interest in and need for models to teach hydrology. First, hydrological modeling is a daily task for numerous practitioners, and thus it is an art that needs to be understood and mastered by students. Moreover, models are key tools for understanding the hydrological cycle, the interactions between the processes involved, and how hydrological variables evolve. Lastly, models represent an efficient way of proposing "active learning" courses to students. Thus, the impact of using hydrological models with students while they are learning can be significant. Sanchez et al. (2016) showed that the use of a simple spreadsheet with real hydrological data had a significant and positive impact on the civil engineering curriculum. AghaKouchak and Habib (2010) also found significant learning gains for students using modeling tools in class. Nevertheless, the added value of using models in class is not automatic and straightforward. For example, Marshall et al. (2015) demonstrated that the same hydrological course offered using either (i) Microsoft Excel (Microsoft Corporation, 2019), (ii) MATLAB (2018), or (iii) the COMSOL Multiphysics software (Zimmerman, 2006) (https://www.comsol.com/, last access: 30 December 2022) made no significant difference in student performances. This result highlights the need to use tools tailored for teaching hydrology with models.

1.2 On the need for common tools for teaching hydrological (reproducible) modeling

Wagener and McIntyre (2007) and Merwade and Ruddell (2012) highlighted the large diversity of approaches available to teach hydrology. Hutton et al. (2016) argued for the need for reproducible computational hydrology, to teach version-controlled programming:

> A key step to change this culture is to ensure that computational science training (e.g., http://software-carpentry.org) is properly embedded within hydrological science curriculums, so that future generations of hydrologists have the skills to build readable, version controlled and unit-tested software (McConnell, 2004), allowing them to engage more fully in an open scientific community by reproducing and reusing each other's research outputs.

This moves toward reproducible hydrology (Hall et al., 2022) and leads to the emergence of experiments of virtual laboratories (Ceola et al., 2015; Tarboton et al., 2014), open-source software (Coron et al., 2017; Slater et al., 2019), and open datasets (Addor et al., 2017; Irving et al., 2018). What about open hydrological teaching?

1.3 A review of modeling tools designed for teaching hydrological modeling

The development of modeling tools dedicated to teaching hydrology began in the 1960s, with the pedagogic hydrological model `ABC` (Fiering, 1967; Kay et al., 1982; Burt and Butcher, 1986; Kirkby and Naden, 1988). Since the development of `ABC`, several software programs have been designed for teaching hydrology (see *HESS* Special Issue entitled "Hydrology education in a changing world", Seibert et al., 2013). Elshorbagy (2005) used a system dynamics approach based on the `STELLA` visual programming language (Richmond et al., 1985) for teaching watershed hydrology. Pérez-Sánchez et al. (2022) described the use of Microsoft Excel (Microsoft Corporation, 2019) spreadsheets for teaching hydrological modeling and for estimating climate change impacts in a postgraduate civil engineering master's degree. The `HBV` rainfall-runoff model has been used several times as a basis to develop an education-dedicated version: AghaKouchak and Habib (2010) and AghaKouchak et al. (2013) developed the `HBV-EDU` toolbox in MATLAB to teach hydrology and uncertainty estimation (https://fr.mathworks.com/matlabcentral/fileexchange/41395-hbv-edu-hydrologic-model?s_tid=FX_rc1_behav, last access: 30 December 2022), while Seibert and Vis (2012) created the `HBV-light` software. Mendez and Calvo-Valverde (2016) and Viglione and Parajka (2020) developed, respectively, `HBV-TEC` and `TUWmodel` within the R programming language (R Core Team, 2023), and several web applications designed for using HBV are available online (e.g., https://github.com/NikoZHAI/lumphydro, last access: 30 December 2022). This approach of simplifying an existing hydrological model for teaching purposes has been applied with `HBV` but also with other models such as `VIC` by Wi et al. (2017) with `VIC-ASSIST` (developed in MATLAB). The MATLAB-based `HMETS` model (Martel et al., 2017) (https://fr.mathworks.com/matlabcentral/fileexchange/48069-hmets-hydrological-model?s_tid=FX_rc1_behav, last access: 30 December 2022), initially developed for teaching, has proved to be efficient over a large sample of 320 catchments located in the contiguous United States.

Numerous solutions exist to teach hydrological modeling, but they all have their limitations (see Carriba Demange et al., 2022), such as being a "light version" of a model (e.g., `HBV-light`), having an inability to import one's own data (e.g., `TUWteaching`, https://webaapptuwmodel.shinyapps.io/TUWteaching/, last access: 30 December 2022), having an inability to access and modify the source code (e.g.,

RS MINERVE; García Hernández et al., 2020), having an inability to manually or automatically calibrate the model parameters (e.g., `HBV.IANIGLA`; Toum et al., 2021), or being based on proprietary programming language (e.g., `VIC-ASSIST` developed in MATLAB).

1.4 R, a language increasingly used by hydrologists, especially for modeling …

The open-source programming language R is one of the most widely used languages in the hydrological community. It offers many open-source libraries useful, for example, for retrieving hydro-meteorological data, performing spatial analysis, and analyzing hydrological statistics. The whole workflow undertaken in hydrological studies can be done with R (see Slater et al., 2019), which is very useful for practical reasons. The reader is asked to refer to Slater et al. (2019) for further details about the advantages of R for all the steps of the workflow and to the R Hydrology Task View (https://cran.r-project.org/web/views/Hydrology.html, last access: 1 August 2022, Zipper et al., 2022) for a complete list of R packages linked to hydrology. The choice of hydrological modeling R packages is particularly large (see Astagneau et al., 2021, for a recent review), providing a variety of solutions adapted to the diverse problems or case studies that can be encountered. Here again, the reader is referred to Astagneau et al. (2021) for further details about the packages and models available. In addition, R facilitates interdisciplinary work in the other fields of geosciences in which R is also used (e.g., Bezak et al., 2019, who use the `airGR` package, Coron et al., 2017, 2022, for hydrological modeling and the prediction of landslides). One of the strengths of R is its ability to incorporate geographic data and spatial analysis, such as in the use of the MODIS dataset, for example, for modeling of snow accumulation and melt (Riboust et al., 2019).

1.5 … but not yet for teaching, even if attempts are being made

A basic search with the keywords "educ*" and "teach*" (last check on 1 August 2022) in the R Hydrology Task View only returns a few packages that address teaching aspects of hydrology: `TUWmodel` (Viglione and Parajka, 2020), which contains a hydrological model that is proposed for educational purposes but does not contain actual exercises or an interface; `EcoHydRology` (Fuka et al., 2018), which is aimed at providing a flexible framework for hydrology-related staff, students, or researchers for basic exercises; and `airGRteaching` (Delaigue et al., 2018, 2023b), which is the topic of the present article.

`airGRteaching` relies on the widely used GR hydrological models, a family of rainfall-runoff models simulating streamflows that are usually used in lumped mode (i.e., running at the basin scale with aggregated input) and that were recently incorporated into an R package (`airGR`; Coron

et al., 2017, 2022). To provide teaching material, the `airGR` developers set up an add-on package dedicated to teaching hydrology, named "`airGRteaching`". This package contains a graphical user interface, simple functions, and hydrology exercises. Since then it has been used for teaching and for hands-on projects in various universities and engineering schools (see, for instance, a master's degree project using `airGRteaching`: Roux and Brigode, 2018).

Since `airGRteaching` relies on the widely used GR models (see, e.g., Perrin et al., 2003, which presents the widely known GR4J model) and on the `airGR` package, which has gained lots of interest over the past few years (see Coron et al., 2017, which presents the `airGR` package or the list of publications on the airGR website (https://hydrogr.github.io/airGR/page_publications.html#Use_and_mention_of_airGR, last access: 30 December 2022) that lists all known uses of or references to `airGR`), we believe that this tool can pave the way to developing new hydrology teaching initiatives, developing similar tools, and promoting hydrology to a more general audience.

In this paper, after introducing the general concepts taught in hydrology, we present the main features of the `airGRteaching` package and introduce several exercises using this package.

2 Description of `airGRteaching`

2.1 The rationale behind `airGRteaching`: a glance backward

The GR models were initially developed in the 1980s by Claude Michel and his colleagues at Cemagref (that recently became Irstea and then INRAE). The main objective was to design efficient models, starting from a simple structure and gradually adding complexity that proved useful for improving the model's predictive power (Michel, 1983). This approach prioritized predictive power over explanatory models (Shmueli, 2010), finding justification for this from results obtained using large data sets and not from predefined concepts. This led to the development of a family of models that are usually used in lumped mode (i.e., running at the basin scale with aggregated input).

To disseminate their models beyond the Fortran programming community, a long time ago, the developers of the GR models proposed Microsoft Excel spreadsheets containing hydrological models, namely, the GR1A, GR2M, and GR4J models, as well as the CemaNeige snow accumulation and melt model (see next section for a description of these models), accompanied by a dummy dataset (https://gitlab.irstea.fr/HYCAR-Hydro/ExcelGR, last access: 20 July 2023). The rationale behind this approach was dual: easily providing the GR models to external users (researchers and consultants from France and abroad) and illustrating the hydrological concepts to students with the models developed

in-house. The relatively high efficiency and low computational time requirements of these models made them easy to run with Microsoft Excel. In addition, the use of Excel macros enabled interactivity (e.g., the possibility to automatically update simulations when parameter values are modified by users), and graphs were predefined.

Later, the `airGR` R package was developed to propose additional GR models, and the `airGRteaching` R package was built as an add-on package of `airGR`. These tools are described in the next sections.

2.2 The GR models and the `airGR` package

To ease the implementation of the GR models, Coron et al. (2017, 2022) proposed the `airGR` package. Gathering seven hydrological models and one snow accumulation and melt model, `airGR` can be seen as a research tool, as an efficient way for its developers to share research results, and as a tool simple enough to be used by water managers. The hydrological models included in `airGR` differ in their complexity and time step, with a gradual increase in complexity as the time step decreases, and various application objectives:

- GR1A (Mouelhi, 2003; Mouelhi et al., 2006a) is an annual one-parameter model, used for water resources assessment (Baahmed et al., 2015; Kouassi et al., 2012). It consists of a single equation relating the annual streamflow to antecedent annual precipitation and potential evapotranspiration.

- GR2M (Mouelhi, 2003; Mouelhi et al., 2006b) is a monthly two-parameter model, used for water resources assessment and water regime modeling (Belarbi et al., 2017; Marchane et al., 2017). It consists of two stores: a production store used for calculating the part of rainfall transformed into discharge (effective rainfall) and a routing store used for distributing in time the effective rainfall toward the catchment outlet.

- GR4J (Perrin et al., 2003) is a daily four-parameter model, used for water resources assessment, flood and drought simulation, and forecasting and climate change impact (Chauveau et al., 2013). In addition to the GR2M components, it contains two unit hydrographs that refine the temporal distribution of effective rainfall.

- GR5J (Le Moine, 2008) is a daily five-parameter model, used for similar applications as GR4J. Compared to GR4J, GR5J contains only one unit hydrograph, and the intercatchment groundwater exchange function is slightly more general with two-way exchange fluxes between surface and regional groundwater.

- GR6J (Pushpalatha et al., 2011) is a daily six-parameter model, used for similar applications to GR4J and GR5J. Compared to GR5J, an additional exponential store improves the representation of low flows.

- GR4H (Mathevet, 2005) is an hourly four-parameter model, used for flood forecasting (Desclaux et al., 2018). Its structure is almost identical to that of GR4J.

- GR5H (Ficchì et al., 2019) is an hourly five-parameter model, mostly based on the GR5J model structure.

- CemaNeige (Valéry et al., 2014) is a daily two-parameter snow accumulation and melt model, used for snowy catchments. It consists of (i) a partition of precipitation into rainfall and snowfall upgraded with an extrapolation based on altitudinal gradients, (ii) a snow store that also represents the snow heat content, and (iii) a melt function. Optionally, satellite snow data can be used to calibrate an improved version of CemaNeige representing the snow water equivalent–snow cover area hysteresis relationship (Riboust et al., 2019).

- Semi-distribution is enabled for the aforementioned models (except GR1A), which are originally lumped, in order to represent spatially heterogeneous catchments. The streamflow simulated for upstream catchments is propagated downstream using a lag function (de Lavenne et al., 2019).

2.3 The `airGRteaching` perspective

`airGRteaching` embeds the main features of `airGR` and offers simplified ergonomics. It therefore uses its basic tools, meaning that all models implemented in `airGR` are available in `airGRteaching`. Since these models have relatively simple structures and few parameters, they can be more easily understood by novice users such as students. `airGRteaching` does not provide "simplified" versions of existing GR models. Thus, students are able to learn hydrological modeling from the same models that are used in practice, not from degraded versions.

To ease hands-on experience, the choice was made to reduce the number of functions to implement a complete modeling exercise (an `airGRteaching` function therefore embeds several `airGR` functions). In addition, the number of modeling options has been reduced, which limits the number of arguments to be specified for running a simulation and simplifies the associated documentation. All these choices allow users to focus on the main questions that beginners ask themselves when they start dealing with hydrological modeling.

2.4 `airGRteaching` features

`airGRteaching` contains only a few functions, which can be split into two groups:

1. a small set of functions to prepare data, to calibrate and run hydrological models, and to plot outputs, i.e., the basic functions needed to undertake a hydrological modeling study;

Table 1. `airGR` and `airGRteaching` features. (SCA: snow cover area; SWE: snow water equivalent; NSE: Nash–Sutcliffe efficiency, Nash and Sutcliffe, 1970; KGE: Kling–Gupta efficiency, Gupta et al., 2009; KGE': modified Kling–Gupta efficiency, Kling et al., 2012; RMSE: root-mean-square error).

	`airGRteaching` (GUI)	`airGRteaching` (code)	`airGR`
Datasets			
Example data	yes	yes	yes
User data	yes	yes	yes
Working environment			
Graphical user interface	yes	no	no
Use of programming	yes (one command)	yes (simplified)	yes (advanced)
Dynamic graphics outputs	yes	yes	no
Static graphic outputs	yes	yes	yes
Models			
Hourly GR models (+ CemaNeige)	no	yes	yes
Daily GR models (+ CemaNeige)	yes	yes	yes
Monthly GR models	yes	yes	yes
Yearly GR models	no	yes	yes
Semi-distributed version of models	no	no	yes
CemaNeige with hysteresis using SCA & SWE	no	no	yes
Warm-up period disabling	no	yes	yes
Choice of initialization of internal states	no	no	yes
Criteria and calibration			
NSE criterion	yes	yes	yes
KGE criterion	yes	yes	yes
KGE' criterion	no	yes	yes
RMSE criterion	no	yes	yes
Composite criteria (defined by the user)	no	no	yes
Calculation of criteria over discontinuous periods	no	no	yes
Full freedom of parameter value ranges	no	yes	yes
Adaptation of the calibration options	no	yes (simplified)	yes (advanced)
Other calibration algorithms (defined by the user)	no	no	yes

2. a function to launch a graphical user interface (GUI) to set up the hydrological models manually.

These two levels of use allow teachers to choose between different levels of technical difficulty. They can choose the most adapted use according to the time available for the exercises, the teaching objectives, and the students' skills.

To get started with the package, particular attention was given to the documentation. The user manual describes the implementation of functions precisely and succinctly and provides simple examples (https://cran.r-project.org/web/packages/airGRteaching/airGRteaching.pdf, last access: 30 December 2022). In addition, a website was created to explain how to use the different features step by step and to answer frequently asked questions (https://hydrogr.github.io/airGRteaching/, last access: 30 December 2022).

Table 1 summarizes the `airGRteaching` (and `airGR`) features.

2.4.1 Basic functions for undertaking a hydrological modeling study

The main steps required to undertake a hydrological modeling study can be performed with `airGRteaching` with the help of a few simple functions:

– *A data preparation function*, `PrepGR()`. With only three main arguments, namely, the hydrometeorological input data as a data frame or independent vector time series, the name of the rainfall-runoff model to run, and a Boolean indicating whether the `CemaNeige` snow model is activated, this function prepares all the necessary inputs in the correct format for the `airGRteaching` functions. If CemaNeige is activated, additional arguments are needed (e.g., catchment elevation distribution).

- *A calibration function*, `CalGR()`. With three main arguments, namely, the object produced by `PrepGR()`, the objective function name (i.e., which criterion is used to optimize the parameter values), and the calibration period start and end, this function calibrates the chosen GR model. If desired, a transformation of discharge can be chosen for the objective function calculation in order to give more weight to certain ranges of discharges (Santos et al., 2018), and a warm-up period can also be defined.

- *A simulation function*, `SimGR()`. With four main arguments, namely, the object produced by `PrepGR()`, the parameter values (output of `CalGR()` or defined by the user), the name of an efficiency criterion used to evaluate the simulation, and the simulation period start and end, this function runs the chosen GR model and assesses its performance. If desired, a transformation can be used for the criterion calculation, and a warm-up period can be defined.

- *Static and dynamic functions*, `plot()` and `dyplot()`. These functions take any of the objects produced by `PrepGR()`, `CalGR()`, and `SimGR()` as main arguments (to be chosen). Graph-tuning arguments are available but optional. The dynamic graphs show the observed and simulated discharge time series. The static graphs render a choice of graphs to be selected with the `which` argument. Dynamic graphs use the functionalities of the `dygraphs` package (Vanderkam et al., 2018).

Many graphical outputs are available (see Appendix A and B). Figure A1 provides a general overview of the precipitation and streamflow records to identify possible outliers and periods with missing data. Figure A2 adds the simulated streamflow to the previous graph in order to have an overall view of the calibrated model behavior and provides graphical diagnostic tools to check whether the simulated streamflow hydrograph fits the observed streamflow hydrograph. Figure A4 focuses on time series graphs (available in Fig. A2) and adds the potential evapotranspiration. Figure A3 focuses on the errors of the model compared to the observed streamflows. Figure A5 helps the concept of parameter optimization to be understood by displaying the tested parameter values and the correspondence with the value of the criterion chosen as objective function. In general, dynamic graphs (Figs. B1 and B2) help the values of time series to be read more precisely and to zoom in on a particular event for each of the two axes (some options are available, e.g., to add a rolling average or a time range selector).

2.4.2 The graphical user interface

Using the functionalities of the `shiny` package (Chang et al., 2022), the `airGRteaching` graphical user interface

(GUI) called with the `ShinyGR()` function allows one to use the GR models with no programming skills at all, thanks to an intuitive interface. The `ShinyGR()` function takes hydrometeorological data and the simulation period start and end as arguments. Additional arguments can be provided if snow is present. Data can be provided for several catchments, and the function offers the possibility to use different themes for the interface. The GR and CemaNeige models and the objective function are to be selected within the interface.

Figure 1 presents a commented example of the interface. Several intuitive elements can be found. On the left side are the following:

- "Choose a dataset" enables a dataset to be selected from those provided by the user to the function.

- "Choose a model" enables a model to be selected among the GR2M monthly model and the GR4J, GR5J, and GR6J daily models according to the time step of the datasets provided (models at other time steps are not included in the GUI) and to activate the CemaNeige snow accumulation and melt model for the daily models.

- "Parameter values" enables the parameters of the models to be modified. The parameters proposed are automatically adapted to the chosen model and the ranges are predefined. Changing any parameter value causes a real-time update of the plots and displayed scores (see below).

- "Automatic calibration" enables an automatic calibration to be performed by optimizing a chosen objective function (among the Nash–Sutcliffe efficiency (NSE) and the Kling–Gupta efficiency (KGE) and with a squared root, inverse, or no transformation of discharge).

The following options are at the top:

- "Choose a plot" enables the kind of plot that is displayed to be changed (see Fig. 2). Users can choose from the following.

  - "Flow time series" are dynamic plots of observed and simulated discharge as well as precipitation time series and discharge errors.

  - "Model performance" is an ensemble of static plots of observed and simulated discharge as well as precipitation time series and of annual regimes, flow duration curves, and a scatter plot between simulated and observed discharges.

  - "State variables" are dynamic plots that show the time series of GR model store levels as well as the time series of internal model fluxes.

  - "Model diagram" is a plot that can be dynamic and on the right shows the scheme of the chosen GR model and the dynamic evolution of all its fluxes with time and the related hydrometeorological data.
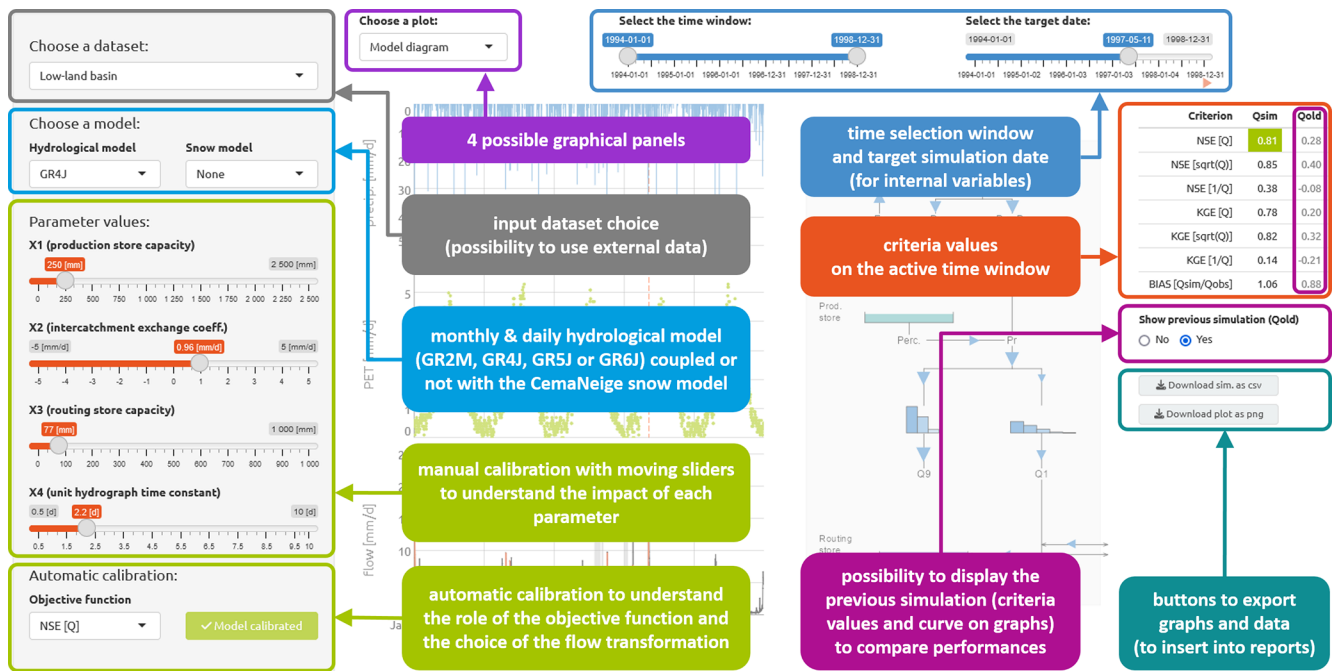
Figure 1. Overview of the `airGRteaching` GUI and identification of its main elements.

– "Select the time window" enables the user to zoom within the provided data period or to move the window using the sliders.

– "Select the target date" enables a specific date to be targeted (only for the "Model diagram" panel).

In the center, the plots are proposed by the "Choose a plot" panel.

On the right, the following are found:

– A table of criteria provides the values of seven performance criteria (NSE and KGE with use of squared root, inverse, or no transformation of discharge, in addition to the bias).

– Using the "Show previous simulation Qold" option, the previously obtained simulated time series appear on the plots provided in the center of the GUI as a dotted gray line. In addition, ticking this option makes criteria of this previous simulation appear in the criteria table introduced above. This option has no effect on the "Model performance" panel.

– Two buttons allow users to download the displayed plot in a PNG file format, which can be useful for a report for example (in order to ensure the tracking of the downloaded files, various information is automatically added to the file header: name of the dataset, name of the model, simulation period, and parameter values; see Appendix C), and the hydrometeorological data (including the simulation) in a CSV file format, to be used externally for further analysis or to be saved.

Figure 2 presents the airGRteaching GUI "Modeling" panels (a–d) and "Summary sheet" panels (e–f).

If R is not installed on the students' computers, it is possible to run the `airGRteaching` GUI online. Indeed, the graphical user interface is available at https://sunshine.inrae.fr/app/airGRteaching (last access: 20 July 2023) with demo datasets.

2.4.3 Data associated with `airGRteaching`

Users are free to use their own datasets, but the `airGRteaching` package benefits from the `airGRdatasets` package (Delaigue et al., 2023a), which contains a dataset of 19 different catchments located in France (Fig. 3 and Table 2). This dataset is a subset of the larger CAMELS-FR dataset (Delaigue et al., 2022) and has been assembled to include various French hydro-climatic regimes, with 12 rain-dominated catchments, 1 rain- and snow-dominated catchment, 2 snow-dominated catchments, 2 Mediterranean catchments, and 2 groundwater-dominated catchments. Figure 4 shows the main characteristics of the catchment set. Catchment area ranges from 25 to 3917 km^2, with half of the catchment set draining less than 686 km^2.

The dataset is composed of both static geomatic and physiographic catchment indices and hydro-climatic time series (solid and liquid precipitation, potential evapotranspiration, air temperature, and streamflow time series). The climatic time series have been extracted from the SAFRAN reanalysis (Vidal et al., 2010) and aggregated at the catchment scale, while streamflow series have been extracted using
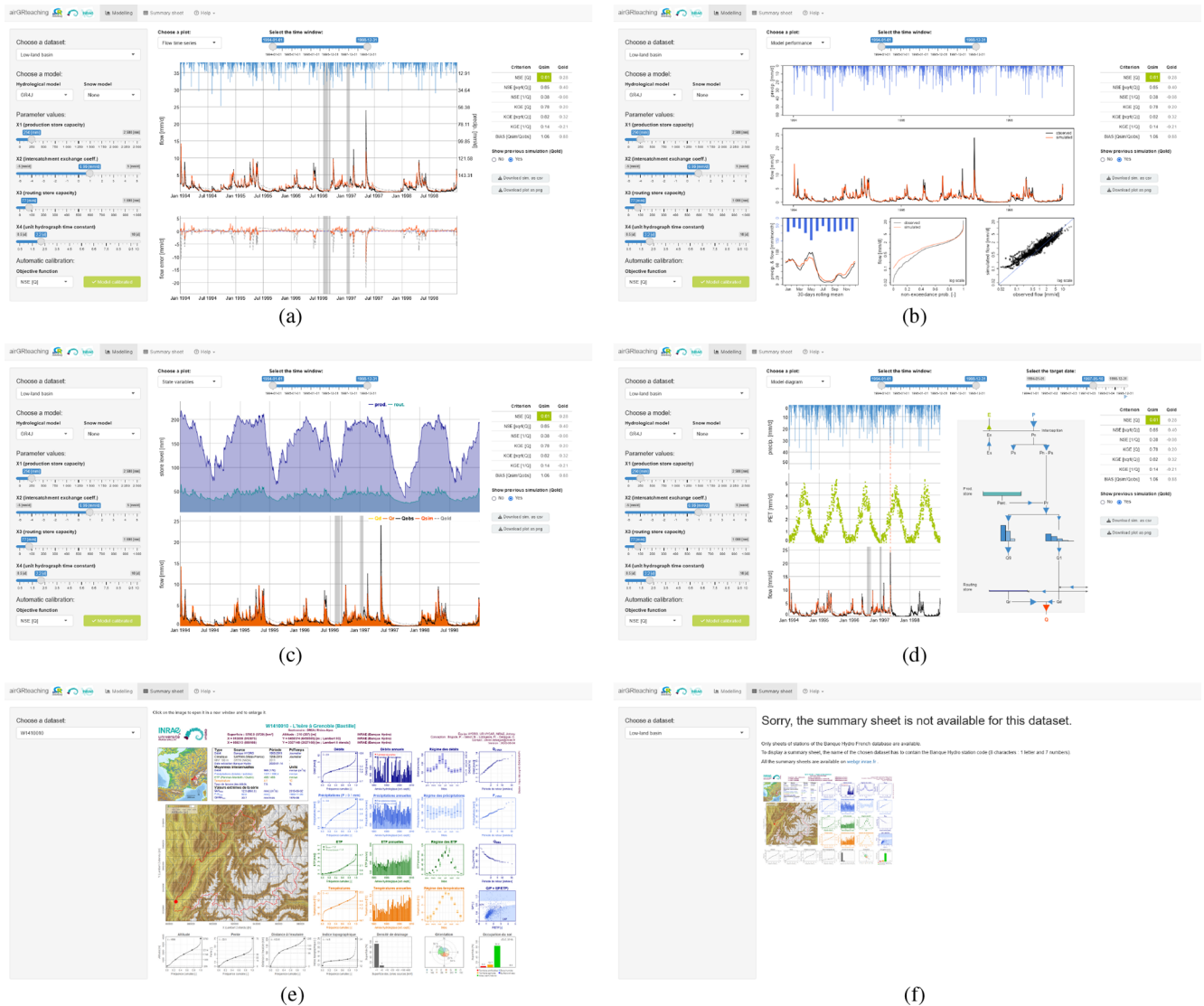
(a)

(b)

(c)

(d)

(e)

(f)

Figure 2. `airGRteaching` GUI "Modeling" panels **(a–d)** and "Summary sheet" panels **(e, f)** that can be reached through diverse clicking. In the following, the center column of the GUI is described for each possible panel; all other elements of the GUI were described in Fig. 1. **(a)** "Flow time series": precipitation, observed, and simulated hydrographs (top) and flow error time series (bottom). **(b)** "Model performance": precipitation (top), observed and simulated hydrographs (middle), simulated and observed regime hydrographs (bottom left), flow duration curves (bottom center), and a scatter plot between simulated and observed discharges (bottom right). **(c)** "State variables": time series of reservoir levels (top) and runoff components (bottom). **(d)** "Model diagram": time series (left) of precipitation, potential evapotranspiration, and simulated and observed flows (from top to bottom) and interactive model diagram (right; with updating of the flows, the size, and the level of the reservoirs). **(e)** Hydrometeorological and topographical characteristics of the selected catchment (Brigode et al., 2020, only available for French catchments). **(f)** Same as **(e)** when the catchment characteristics are not available.

the HydroPortail (https://hydro.eaufrance.fr/, last access: 30 December 2022). These hydro-climatic temporal series are available at the daily time step.

3 Teaching hydrology with `airGRteaching`

This section and the accompanying sections in the Appendix present tests based on the `airGRteaching` pack-

age and designed to illustrate rainfall-runoff modeling, model calibration, evaluation, and robustness in hydrological classes. These tests are also available as a vignette in the `airGRteaching` package: users can thus recreate all these illustrations using their own datasets.

Table 2. List of the 19 catchments in France included in the `airGRdatasets` package (ID: identification letters displayed in Fig. 3).

	Station code	ID	Station name	Area (km^2)	Hydrological regime
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	F439000101	F	the Loing at Épisy	3917	Pluvial
7	H010002001	G	the Seine at Plaines-Saint-Lange	686	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	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

Figure 3. Location of the 19 catchments in France included in the `airGRdatasets` package (map from the `airGRdatasets` package documentation: Delaigue et al., 2023a; using hydrometric station coordinates and catchment boundaries: Delaigue et al., 2022; river network: Lehner and Grill, 2013); DEM: GEBCO Bathymetric Compilation Group, 2021.

3.1 Understanding rainfall-runoff modeling

3.1.1 The role of model components and parameters

Rainfall-runoff models are composed of different components, e.g., reservoirs or unit hydrographs, whose behavior is defined by equations and parameters. Parameter estimation is a key step toward tailoring the models to a specific catchment. Understanding the role of model components and parameters is therefore an unavoidable preliminary step to performing hydrological modeling.

To illustrate the production and the routing parts of hydrological modeling that are present in any model, it is possible to use the different GR models included in `airGRteaching` and to produce rainfall-runoff transformations considering different model parameter values.

The GR4J model (Perrin et al., 2003) comprises a production store ($X1$ parameter), which determines the actual evapotranspiration and the net rainfall (see Appendix C4 for a GR4J flowchart). The routing of net rainfall is determined through two unit hydrographs ($X4$ parameter) and a routing store ($X3$ parameter). A final component, representing the intercatchment groundwater exchange, is determined by the $X2$ parameter.

As an example, the command lines in Appendix Listing D1 and Fig. 5 illustrate the role of the $X2$ parameter in the production part of the rainfall-runoff transformation, showing higher streamflow values simulated with higher $X2$ values, since higher $X2$ parameter values lead to more positive incoming water from groundwater. Moreover, Fig. 6 illustrates the role of the $X4$ parameter in the routing part of the
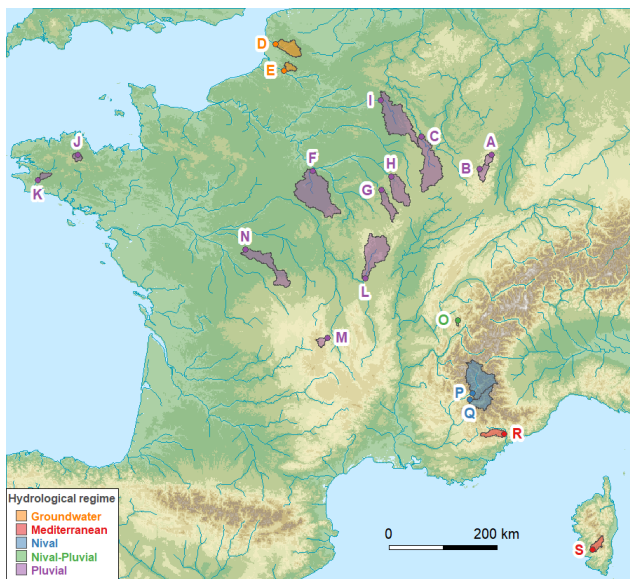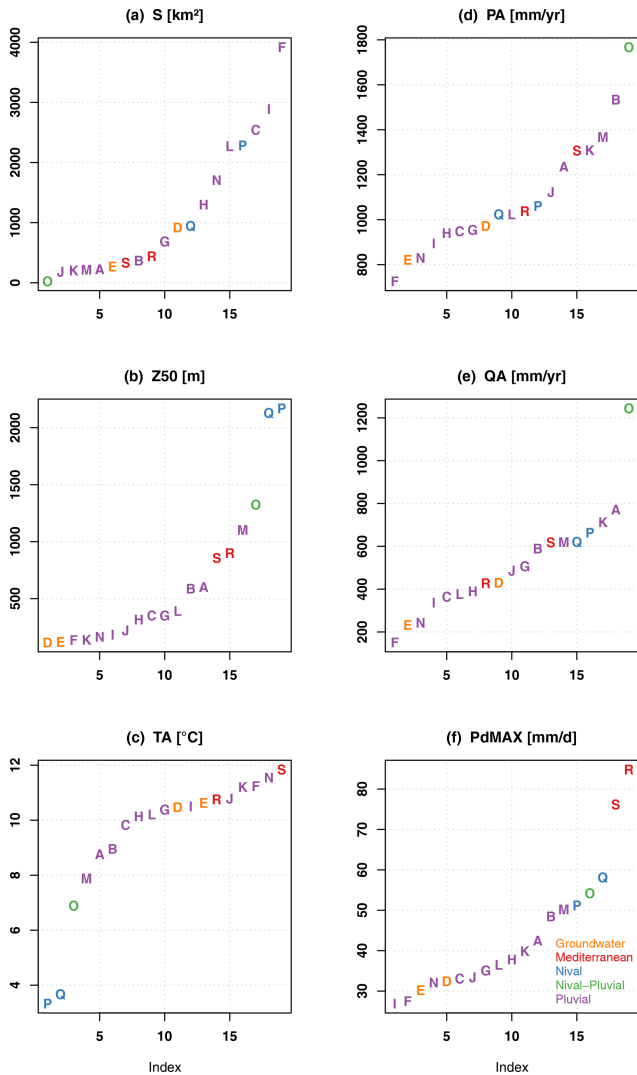
Figure 4. Distribution of the characteristics of the 19 catchments included in the `airGRdatasets` package. **(a)** "S", area (km^2); **(b)** "Z50", median altitude (m a.s.l.); **(c)** "TA", median of the mean annual air temperature (°C); **(d)** "PA", median of the annual precipitation (mm yr^{-1}); **(e)** "QA", median of the annual flow (mm yr^{-1}); and **(f)** "PdMAX", median of the maximum annual daily precipitation (mm/day), versus the catchment indexes. The statistics have been calculated over the available daily time series in the `airGRdatasets` package (i.e., from 1 January 1999 to 31 December 2018; only the years with less than 10 % of missing streamflow values have been considered).

rainfall-runoff transformation, with delayed flood peak values when considering higher $X4$ values (see command lines in Appendix Listing D2).

The relative importance of the production and routing functions depends on the time step considered for the rainfall-runoff simulation. The production process is more important for the larger time steps (e.g., month or year) since it controls the catchment water balance. This can be easily
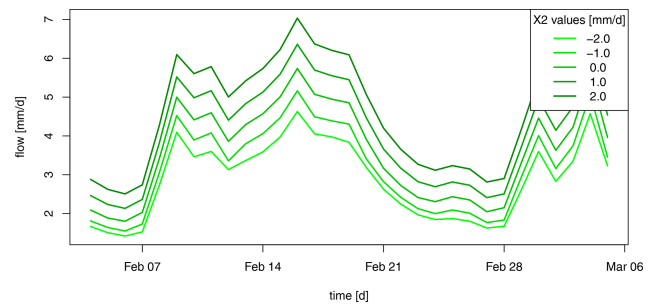
Figure 5. The role of the production component in GR4J illustrated by an example of flow simulation sensitivity to the $X2$ parameter values (groundwater exchange coefficient, mm d^{-1}).
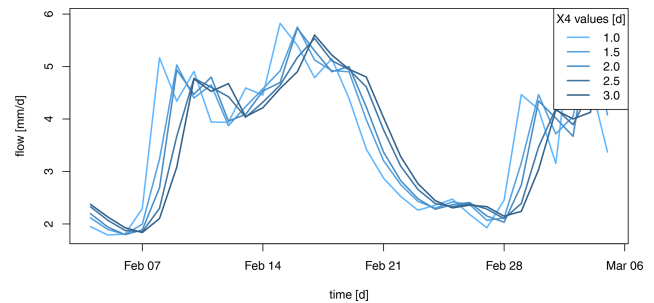
Figure 6. The role of the routing component in GR4J illustrated by an example of flow simulation sensitivity to the $X4$ parameter values (time base of unit hydrographs, in days).

illustrated by aggregating simulations performed at a daily time step to a yearly time step (see command lines in Appendix Listing D3). Figure 7 compares, at the annual time step, the GR4J daily simulations performed using different $X2$ parameter values with the simulations performed using different $X4$ parameter sets. We can observe that at the annual time step, the impact of considering different $X4$ parameter values is limited compared to the use of different $X2$ parameter values.

3.1.2 On the need to perform a model warm-up

Initial values of the model water storage must be specified at the beginning of a simulation. The way initial levels are defined can lead to potentially significant model errors. The most convenient way for modelers to initialize rainfall-runoff models is to perform a warm-up run of the model in order to limit the impact of this unknown.

This issue can be illustrated with `airGRteaching` by considering different warm-up period lengths (see command lines in Appendix Listing D4). Figure 8 illustrates a portion of the streamflow simulations obtained considering (i) no warm-up period, (ii) a 1-month warm-up period, and (iii) a 1-year warm-up period of the two GR4J stores. Figure 8 shows that the three simulations converge after a bit more than 5 months, reinforcing the necessity of perform-
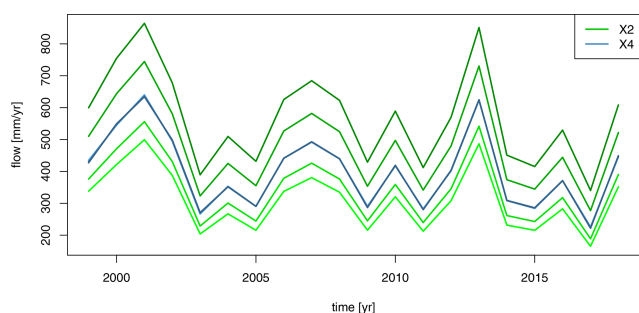
Figure 7. Comparison, at the annual time step, between GR4J daily simulations performed with different $X2$ parameter values (in green gradient) and simulations performed with different $X4$ parameter sets (in blue gradient).
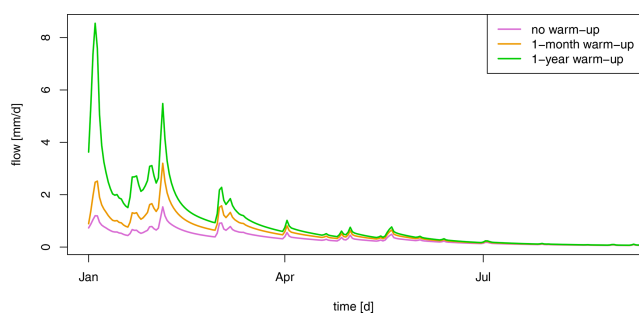

Figure 8. Example of streamflow simulations obtained considering no warm-up period (in purple), a 1-month warm-up period (in orange), and a 1-year warm-up period (in green) of the GR4J two stores.

ing a sufficiently long warm-up. Please note that by default, `airGRteaching` initializes the production and the routing stores at 30 % and 50 % of their capacity, respectively.

3.2   Model calibration, evaluation, and robustness

3.2.1   Manual calibration

In the `airGRteaching` GUI (see Fig. 2), it is possible to test different parameter sets of the GR rainfall-runoff models and to estimate the performance of each tested parameter set in order to perform a manual calibration. A classic way to do so through the `airGRteaching` GUI is to select a criterion as an objective function in the table showing the criteria values on the right, to activate the "Show previous simulations (Qold)", and to modify parameter values step by step until the simulation and criterion are satisfactory. This can also be done using the simple command-line functions (`PrepGR()` and `SimGR()`; see command lines in Appendix Listing D5).

3.2.2   Automatic calibration

Automatic calibration of model parameters is also possible in `airGRteaching` using the procedure described by

Michel (1991) and by considering one objective function such as NSE or KGE. To do so, there are two options in `airGRteaching`:

1. clicking on the automatic calibration button in the `airGRteaching` GUI;

2. using the simple `airGRteaching` command-line functions (`PrepGR()` and `CalGR()`; see command lines in Appendix Listing D6).

The calibration algorithm available in `airGRteaching` comes from `airGR` and is described in further detail in Coron et al. (2017, Sect. 2.3). Two distinct steps are included in the procedure:

1. A systematic inspection of the parameter 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. From the best parameter set of the previous step, a steepest-descent local search procedure is carried out to find an estimate of the optimum parameter set.

`airGRteaching` allows the second step of this procedure to be visualized (see command lines in Appendix Fig. A5).

3.2.3   How to evaluate model calibration

Different ways to evaluate the model calibration performance may be conceived using `airGRteaching`: evaluating criteria on the calibration period, examining the graphical summary of the calibration performance (`airGR::plot()`), and comparing simulated and observed streamflow temporal series, etc.

Analyzing simulated versus observed flow regimes is an informative indicator of model performance (see command lines in Appendix Listing D7). Figure 9 compares regimes in a mountainous catchment (located in the French Alps), while the flow simulation has been obtained with and without taking into account snow accumulation and melt. The regime comparison might be compelling for the students, hopefully leading them to use an additional snow accumulation and melt routine (such as CemaNeige, Valéry et al., 2014, available in `airGRteaching`).

3.2.4   Objective functions for model calibration

Oudin et al. (2006) and other authors showed the impact of using flow transformation in objective functions used for model calibration. It is possible, in `airGRteaching`, to apply different flow transformations to the objective function used for model parameter calibration (see command lines in Appendix Listing D8). Figure 10 compares the simulations performed considering GR4J parameter sets obtained
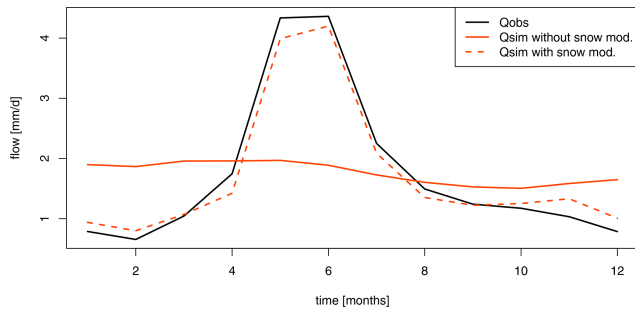
Figure 9. Example of flow regimes observed for a catchment located in the French Alps (in black) and flow regimes simulated by GR4J without considering snow accumulation and melting (solid red line) or when a snow accumulation and melting routine is used (dashed red line).
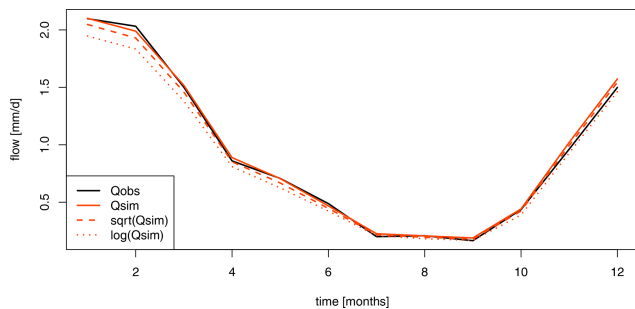

Figure 10. Example of observed flow regimes (in black) and flow simulations obtained when GR4J is calibrated on NSE calculated on untransformed flows (solid red line), NSE calculated on square-root-transformed flows (dashed red line), and NSE calculated on logarithmic-transformed flows (dotted red line).

after a calibration on (i) NSE calculated on natural flows (denoted as NSE_Q hereafter), (ii) NSE calculated on square-root-transformed flows (denoted as $\mathrm{NSE}_{\sqrt{Q}}$ hereafter), and (iii) NSE calculated on logarithmic-transformed flows (denoted as $\mathrm{NSE}_{\log Q}$ hereafter), emphasizing performance in high, mean, and low flows, respectively. Logically, we can observe that the model calibrated on NSE_Q performs better for high-flow periods, and the model calibrated on $\mathrm{NSE}_{\log Q}$ performs better for low-flow periods, while the model calibrated on $\mathrm{NSE}_{\sqrt{Q}}$ performs in between.

Similarly to the use of different flow transformations during model calibration, the `airGRteaching CalGR()` function allows us to test several objective functions such as NSE or KGE (see command lines in Appendix Listing D9).

3.2.5 Model evaluation and robustness

Split-sample tests, i.e., calibrating and evaluating a model on non-overlapping periods (Klemeš, 1986), is key for the assessment of model transferability in time, since in practice models are used outside their calibration conditions. Split-sample tests can be performed for model calibra-

Table 3. Example of differential split-sample results (KGE score) obtained for a given catchment.

Period	Calibration	Evaluation
Wet	0.974	0.836
Dry	0.962	0.886

tion and evaluation using both `CalGR()` and `SimGR()` `airGRteaching` functions, respectively (see command lines in Appendix Listing D10).

The differential split-sample test, also introduced by Klemeš (1986), consists in identifying two climatically contrasted periods in the available record and performing the split-sample test using these two periods. Table 3 presents the calibration and evaluation performance of the GR4J model obtained for two sub-periods, composed of the wettest and the driest hydrological years (based on the aridity index, i.e., the total annual precipitation divided by the total annual potential evapotranspiration; see command lines in Appendix Listing D11).

4 One step further: projects on flow reconstruction, forecasting, and climate change

The basic manipulations of the `airGRteaching` package illustrated in the previous sections can also be used in more comprehensive hydrological teaching projects, presented in a vignette format in the package (example in Fig. 11) available in both English and French. These three projects deal with flow reconstruction (i.e., producing simulated streamflow over periods for which records are missing), flow forecasting (i.e., anticipating streamflow conditions for days ahead from given initial conditions), and climate change applications (i.e., transforming climate projections into hydrological projections). These can be run as stand-alone projects with the dataset available in the `airGRdatasets` package or run on other catchments by importing the necessary hydroclimatic series.

1. *Streamflow reconstruction*. The Estéron at Broc catchment presents flow observation from 1999 to 2018 but also several missing data in 2004. This project aims to use the hydro-climatic series available and the GR2M model to reconstruct the missing flow data through rainfall-runoff simulation. The concepts addressed and the skills developed with this project are (i) parameter calibration (both manually and automatically) using an objective function and (ii) calibration–evaluation methodology.

2. *Low-flow forecasting*. This project aims to use the hydro-climatic data available for the Meuse at Saint-Mihiel catchment and the GR6J rainfall-runoff model

Model calibration

Manual calibration

In the **airGRteaching** GUI, it is possible to test different parameter sets of the GR rainfall-runoff models and to estimate the performance of each tested parameter set in order to perform a manual calibration. A classical way to do so through the **airGRteaching** GUI is to pick an objective function in the table showing the criteria values on the right, to activate the "Show previous simulations (Qold)" button, and to modify parameter values little by little until the simulation and the criterion are satisfactory.

Note that the manual calibration of model parameters is facilitated using the **airGRteaching** graphical user interface launched by the `ShinyGR()` function.

You can embed the following code in a loop (except the data processing step using `PrepGR()`). At each iteration you test a new parameter set and compute the corresponding criterion. This way you can find the "best" parameter set.

```
# Data processing for GR4J (with Q for calibration)
prep <- PrepGR(DatesR     = ts_obs$Date,
               Precip     = ts_obs$Ptot,
               PotEvap    = ts_obs$Evap,
               Qobs       = ts_obs$Qmmd,
               HydroModel = "GR4J",
               CemaNeige  = FALSE)

# Parameter set to test
i_param_gr4j <- c(X1 = 350, X2 = 0, X3 = 90, X4 = 1.4)

# Rainfall-runoff simulation on the calibration period
i_sim_manu <- SimGR(PrepGR  = prep,
                    Param   = param_gr4j,
                    WupPer  = c("1999-01-01", "2000-12-31"),
                    SimPer  = c("2001-01-01", "2010-12-31"),
                    EffCrit = "NSE",
                    verbose = TRUE)
```

```
## Crit. NSE[Q] = 0.6295
```

```
# Get the criterion value
GetCrit(i_sim_manu)
```

Automatic calibration

Automatic calibration of model parameters is also possible in **airGRteaching** using the procedure described by Michel (1991) and by considering one objective function such as NSE (Nash and Sutcliffe 1970) or KGE (Gupta et al. 2009). To do so, there are two options in airGRteaching:

1. clicking on the "Automatic calibration button" in the **airGRteaching** GUI;
2. using the simple **airGRteaching** command line functions (`PrepGR()` and `CalGR()`); see following commands.

```
# Calibration using NSE score
cal_auto <- CalGR(PrepGR  = prep,
                  CalCrit = "NSE",
                  WupPer  = c("1999-01-01", "2000-12-31"),
                  CalPer  = c("2001-01-01", "2010-12-31"))
```

```
## Grid-Screening in progress (0% 20% 40% 60% 80% 100%)
##   Screening completed (81 runs)
##       Param = 247.151,   -2.376,   83.096,    2.384
##       Crit. NSE[Q]     = 0.7372
## Steepest-descent local search in progress
##   Calibration completed (27 iterations, 281 runs)
##       Param = 242.257,   -0.888,   63.434,    5.126
##       Crit. NSE[Q]     = 0.9095
```

```
# Get parameter and criteria values at the end of the calibration step
GetParam(cal_auto)
```

```
## [1] 242.257207  -0.888106  63.434000   5.126126
```

```
GetCrit(cal_auto)
```

```
##   NSE[Q]
## 0.909467
```

Figure 11. Example of a vignette explaining how to perform both manual (left) and automatic (right) calibration of model parameters using the `airGRteaching` package.

to forecast the flows for the autumn of 2018, using (i) the last observed streamflow value, (ii) historical rainfall observations, and (iii) historical flow observations (see Fig. 12). The concepts addressed and the skills developed with this project are (i) the definition of climatology, (ii) flow forecasting, and (iii) flow assimilation.

3. *Impact of climate change on streamflow regime*. Using catchment-scale delta-change-derived future climate projections, this project aims at quantifying the impact of climate change on the flow regime of the Durance at Embrun catchment (see Fig. 13). The concepts addressed and the skills developed with this project are the (i) delta-change method, (ii) flow regime, (iii) bias correction, and (iv) impact of snow on the flow regime.

Users of the `airGRteaching` package may also produce their own exercises as `airGRteaching` vignettes, based on the three examples provided.

We believe that the proposed exercises and projects are a must if one wishes to learn hydrological modeling. They represent the core of many catchment-related studies.

5   Limitations and perspectives

5.1   Limitations

Like any tool, `airGRteaching` has its limitations. The first one is that so far only GR hydrological models have been available in `airGRteaching`. Adding other models is feasible, but to do so, they should be implemented to be compatible with the `airGR` framework (which contains the basic components for `airGRteaching`). While for the command-line use of `airGRteaching` (i.e., use of
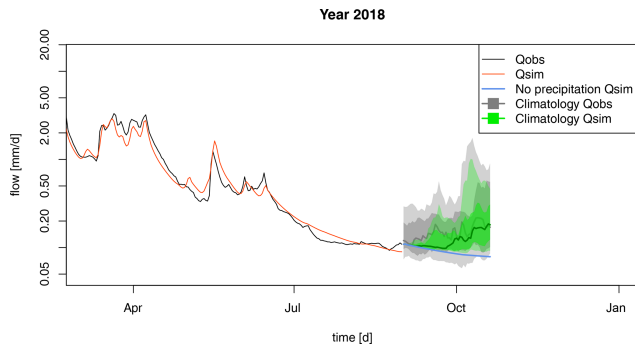
Figure 12. Final output of the `airGRteaching` "Low-flow forecasting" vignette: observed flow (in black), simulated flow (in red), and different forecast scenarios (in blue: simulated streamflow based on the pessimistic zero precipitation scenario; in gray: streamflow quantiles (10 %, 25 %, 50 %, 75 %, and 90 %) based on historical past flow observations; in green: simulated streamflow quantiles (10 %, 25 %, 50 %, 75 %, and 90 %) based on the precipitation climatology).
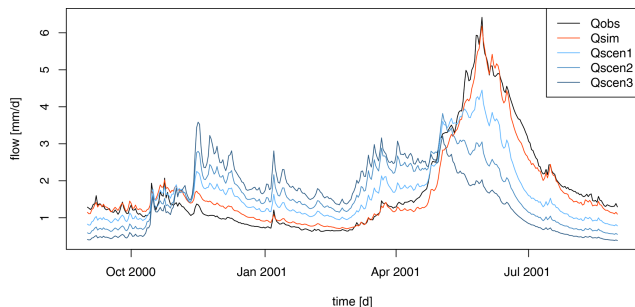

Figure 13. Final output of the `airGRteaching` "Impact of climate change on streamflow regime" vignette: flow regimes observed (in black), calibrated over the historical period (in red), and simulated using different climate change scenarios (in blue gradient).

the `PrepGR()`, `CalGR()`, and `SimGR()` functions), this should be easy to implement, the GUI implementation would require more 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 optimize, and calibration would be far less rapid).

In addition, it is not possible for the user to build their own hydrological model by adding, for example, reservoirs (e.g., with different discharge functions) and unit hydrographs, to help understand each compartment of a model. This is possible with the `RS MINERVE` software (García Hernández et al., 2020).

Other limitations, as mentioned in Sect. 2.3, are that `airGRteaching` only offers a limited set of modeling options, compared to `airGR`. This however could also be seen as a strength, as proposing too many options could be cumbersome from a user's perspective, and these limitations are therefore voluntary.

Remote sensing data, other than meteorological or hydrological data, cannot be used in `airGRteaching` at the moment. In addition, the effect of land cover changes cannot directly be an asset to `airGRteaching`, as is the case in some physically based models.

Finally, proper uncertainty exercises, apart from the calibration on different periods, have so far not been a part of this tool, which we see as a simple way of starting hydrological modeling. However, it is easy enough to add noise to the input data to assess input uncertainty. Uncertainty arising from model structure can only be studied by changing models (e.g., using GR4J and GR5J models). The uncertainty associated with parameter calibration methods cannot be tested, as only an optimization algorithm is provided (NB: other algorithms can be plugged into `airGR`). Finally, `airGRteaching` does not provide turnkey tools for visualizing uncertainty (e.g., error bars or envelopes on streamflow simulation).

5.2 Perspectives

Exercises linking hydrology with other disciplines and scientific communities could be developed by the coupling of the `airGRteaching` package with other numerical tools and models. First, using actual global (GCM) or regional (RCM) climate model outputs as rainfall-runoff model inputs would illustrate the impact of climate variability or emission scenarios on catchment hydrology, linking climatology and hydrology. In a similar way, streamflows produced by the `airGRteaching` package could be used as inputs to hydraulic models to produce flood maps in teaching projects involving both hydrological and hydraulic skills. Finally, coupling `airGRteaching` with models of water uses (e.g., water withdrawal models for drinking water or irrigation) would have interesting teaching applications. Another valuable perspective is to use remote sensing data to perform data assimilation for hydrological forecasting by recovering real-time meteorological (e.g., precipitation measured by rain gauges), hydrological (e.g., streamflow observed from gauging stations), or even satellite data (e.g., MODIS snow cover observations) and using these data as inputs of a rainfall-runoff model in the `airGRteaching` package, e.g., with the `airGRdatassim` package (Piazzi et al., 2021; Piazzi and Delaigue, 2021). Such applications would illustrate the added value of assimilating hydro-meteorological data for better modeling in hydrology. Other exercises could be centered around uncertainties, through coupling the airGRteaching package with sensitivity analysis methods.

Finally, the `airGRteaching` package could be used for the development of serious games devoted to hydro-meteorological applications, aiming, for example, to discuss the issues of making better decisions when considering probabilistic forecasts (Ramos et al., 2013).

The authors' experience with 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 Sect. 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 is 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.

The introduction to computer programming is ideal to teach these notions to students. If students are to take this tool into their own hands, they must gradually acquire the concepts without difficulty. It is therefore essential that this is done in a playful way so that they are not discarded. The use of a graphical interface allowing modeling notions to be acquired, while putting aside the programming aspects, allows the different problems to be separated: modeling on the one hand and programming on the other hand. As soon as they wish to go further in the understanding of their subject, students very quickly perceive the limitations that a graphical interface can represent (options too limited, etc.). In addition, use can quickly become daunting if tasks need to be repeated (for example, clicking a large number of times and in a well-defined order to reproduce the results on several datasets). Sometimes there is not enough time to learn programming, justifying the need to use simple tools.

As such, the `airGRteaching` tool is not intended to be used to realize 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 (unsolved problems in hydrology; Blöschl et al., 2019). However, as it is a tool to teach hydrology, to understand hydrological processes, and to master hydrological modeling, 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. 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 in hydrological training. `airGRteaching` can be seen as a gateway to mastering `airGR` and other `airGR`-dependent packages, thus indirectly helping to solve other UPHs. This is notably the case for questions UPH22 ("What are the synergies and tradeoffs between societal goals related to water management (e.g., water-environment-energy-food-health)?") and UPH23 ("What is the role of water in migration, urbanization, and the dynamics of human civilizations, and what are the implications for contemporary water management?"), linked to water usage, thanks to the `airGRiwrm` package (Dorchies et al., 2022), which allows water resources management to be integrated. This package could help to solve problems of spatial heterogeneity and change of scale, namely 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., snowfall regime, aridity, reaction coefficients)?") and 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, which enables data assimilation, could be linked to questions of prediction uncertainty, namely UPH20.

6 Conclusions

Teaching hydrological modeling requires hands-on experience with rainfall-runoff models. Dedicated tools need to be adapted to the skills of the students and users and preferably developed in an open-source programming language to ensure the reproducibility of the results. In this context, the `airGRteaching` R package has been developed as an add-on to the `airGR` package, which gathers several lumped rainfall-runoff models widely used by hydrological researchers and practitioners. `airGRteaching` contains a graphical user interface and allows teachers and students to import their own data and create their own exercises. A specific dataset of 19 different catchments in France is included in the add-on `airGRdatasets` package. This dataset is composed of hydro-climatic time series (solid and liquid precipitation, potential evapotranspiration, air temperature, and streamflow time series). Finally, three hydrological teaching projects are proposed aimed at (i) using a monthly rainfall-runoff model to reconstruct flow series, (ii) using a daily model to forecast low flows, and (iii) studying the impact of climate change on streamflow of a mountainous catchment. Thanks to its open nature, other projects may be added to the package by `airGRteaching` users, based on the dataset provided or other datasets.

Appendix A: Static plots produced by the package

In this appendix, we have used the time series of the X045401001 catchment (the Ubaye at Lauzet-Ubaye [Roche-Rousse] – DREAL PACA). The GR5J model, coupled to CemaNeige, was calibrated on the raw flows of the period from 1 January 2001 to 31 December 2004. The objective function used is the KGE.
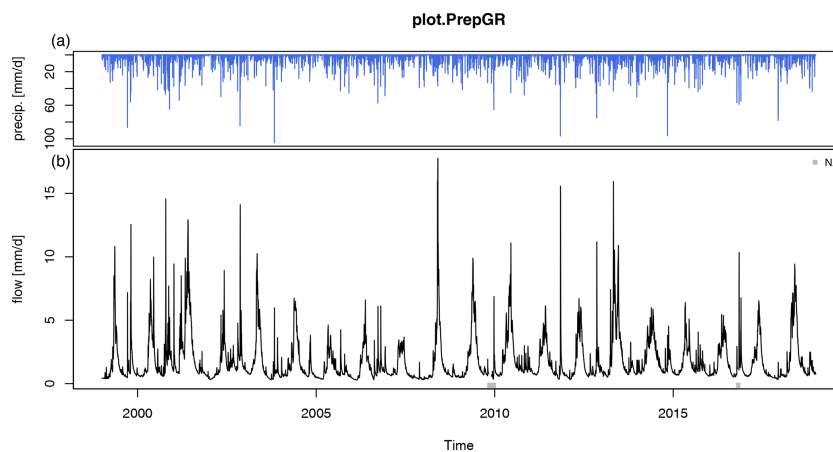

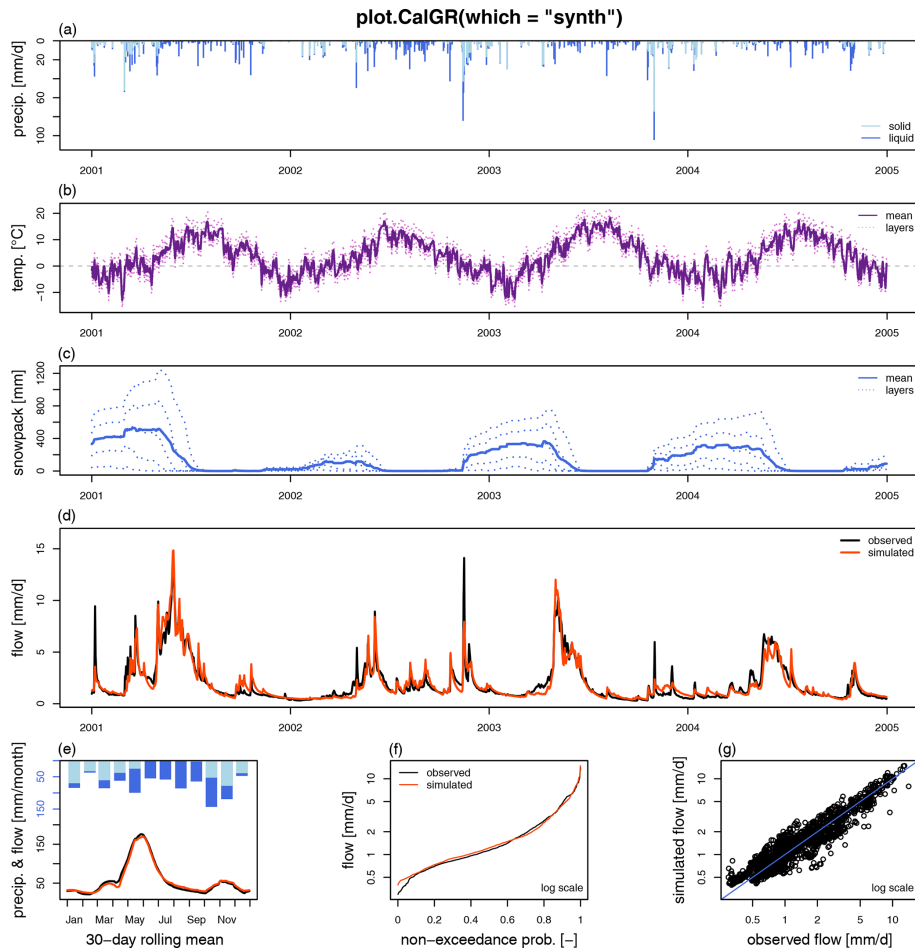**Figure A1.** Plot generated using the outputs of the `PrepGR()` function: **(a)** precipitation time series and **(b)** observed hydrograph.

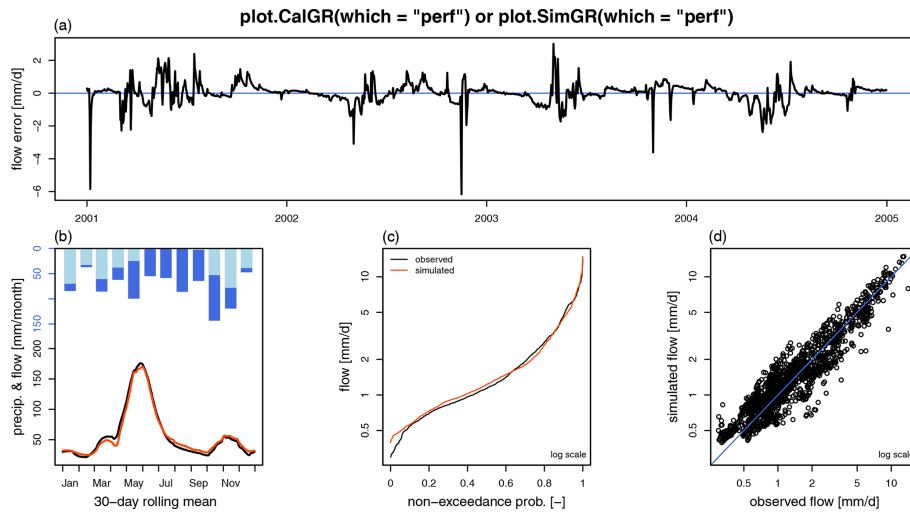**Figure A2.** Plot generated using the outputs of the `CalGR()` or the `SimGR()` functions, with the argument `which` = "synth" (synthesis; default value). From top to bottom and from left to right: **(a)** precipitation time series (liquid, and solid if CemaNeige is used), **(b)** temperature time series for each layer (if CemaNeige is used), **(c)** snowpack time series for each layer (if CemaNeige is used), **(d)** observed and simulated hydrographs, **(e)** monthly average precipitation (liquid, and solid if CemaNeige is used) and 30 d rolling mean of interannual mean daily streamflow, **(f)** observed and simulated flow duration curves, and **(g)** scatter plot between observed and simulated discharges. The hydrographs can also be plotted with a log scale.
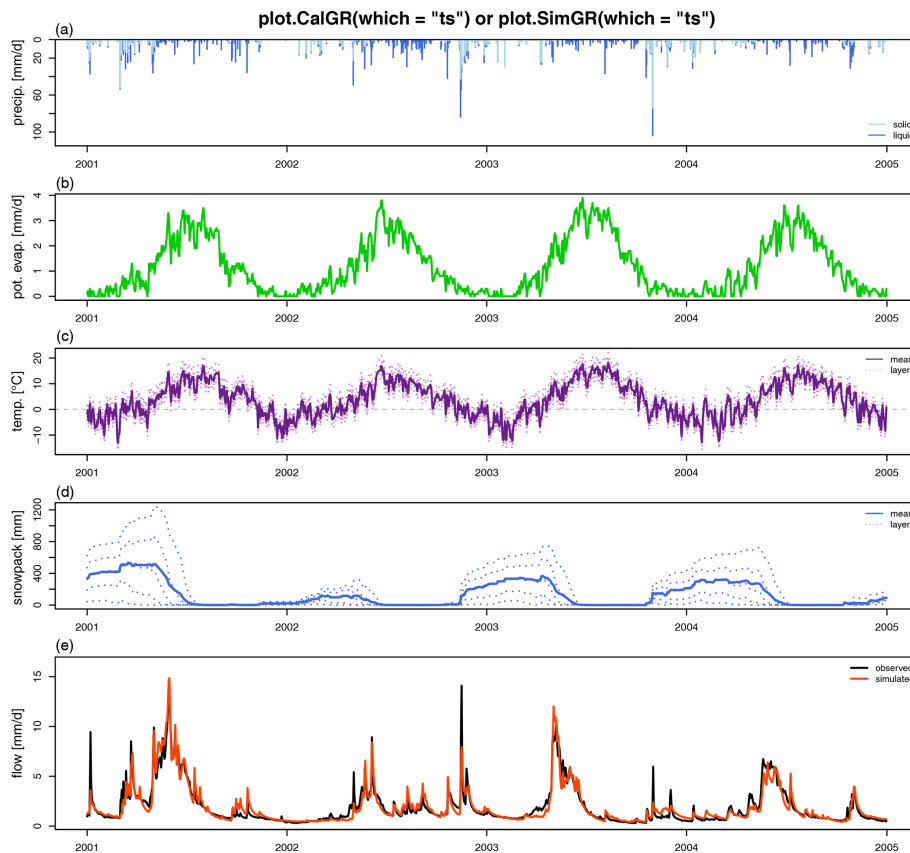
Figure A3. Plot generated using the outputs of the `CalGR()` or the `SimGR()` functions, with the argument `which = `"perf" (performance). From top to bottom and from left to right: **(a)** flow error (or residuals), **(b)** monthly average precipitation (liquid, and solid if CemaNeige is used) and 30 d rolling mean of interannual mean daily streamflow, **(c)** observed and simulated flow duration curves, and **(d)** scatter plot between observed and simulated streamflows. The flow error chart can also be plotted with a log scale.

Figure A4. Plot generated using the outputs of the `CalGR()` or the `SimGR()` functions, with the argument `which = `"ts" (time series). From top to bottom: **(a)** precipitation time series (liquid, and solid if CemaNeige is used), **(b)** potential evapotranspiration time series, **(c)** air temperature time series for each layer (if CemaNeige is used), **(d)** snowpack time series for each layer (if CemaNeige is used), and **(e)** observed and simulated hydrographs. The hydrographs can also be plotted with a log scale.
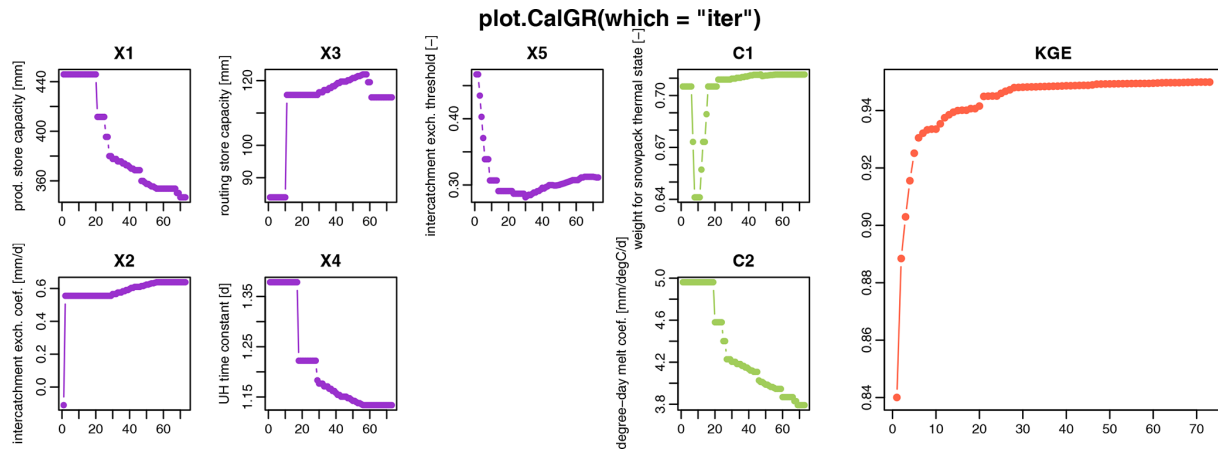
Figure A5. Plot generated using the outputs of the `CalGR()` function, with the argument `which = "iter"` (iterations). From left to right: evolution of parameters of the GR5J model (in purple) and CemaNeige model (in green) and of the efficiency criterion (in orange) during the iterations of the steepest-descent calibration step.

Appendix B: Dynamic plots returned by the package

In this appendix, we have used the time series of the X045401001 catchment (the Ubaye at Lauzet-Ubaye [Roche-Rousse] – DREAL PACA). The GR5J model, coupled to CemaNeige, was calibrated on the raw flows of the period from 1 January 2001 to 31 December 2004. The objective function used is the KGE.
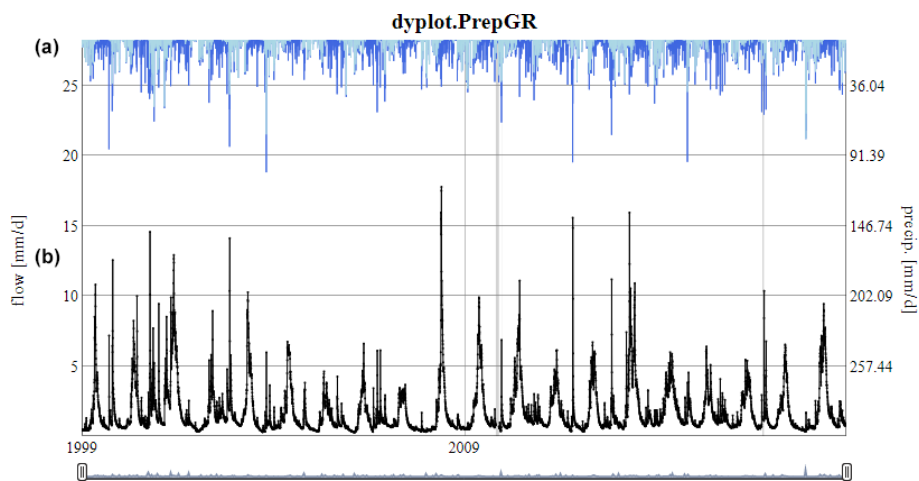
Figure B1. Dynamic plot generated using the outputs of the `PrepGR()` function: **(a)** precipitation time series (liquid, and solid if CemaNeige is used) and **(b)** observed hydrograph.
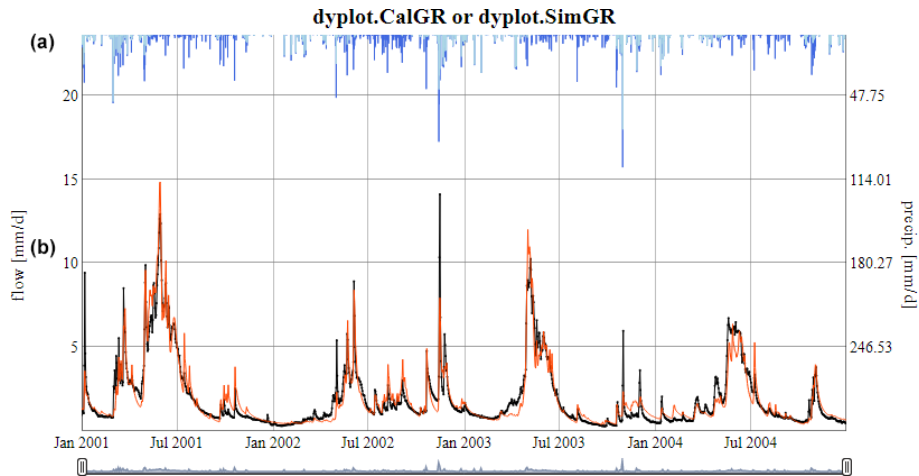
Figure B2. Dynamic plot generated using the outputs of the `CalGR()` or the `SimGR()` functions: **(a)** precipitation time series (liquid, and solid if CemaNeige is used) and **(b)** observed and simulated hydrographs.

Appendix C: Static plots downloaded from the `airGRteaching` GUI

In this appendix, we have used the time series of the X045401001 catchment (the Ubaye at Lauzet-Ubaye [Roche-Rousse] – DREAL PACA). The GR5J model, coupled to CemaNeige, was calibrated on the raw flows of the period from 1 January 2001 to 31 December 2004. The objective function used is the KGE.
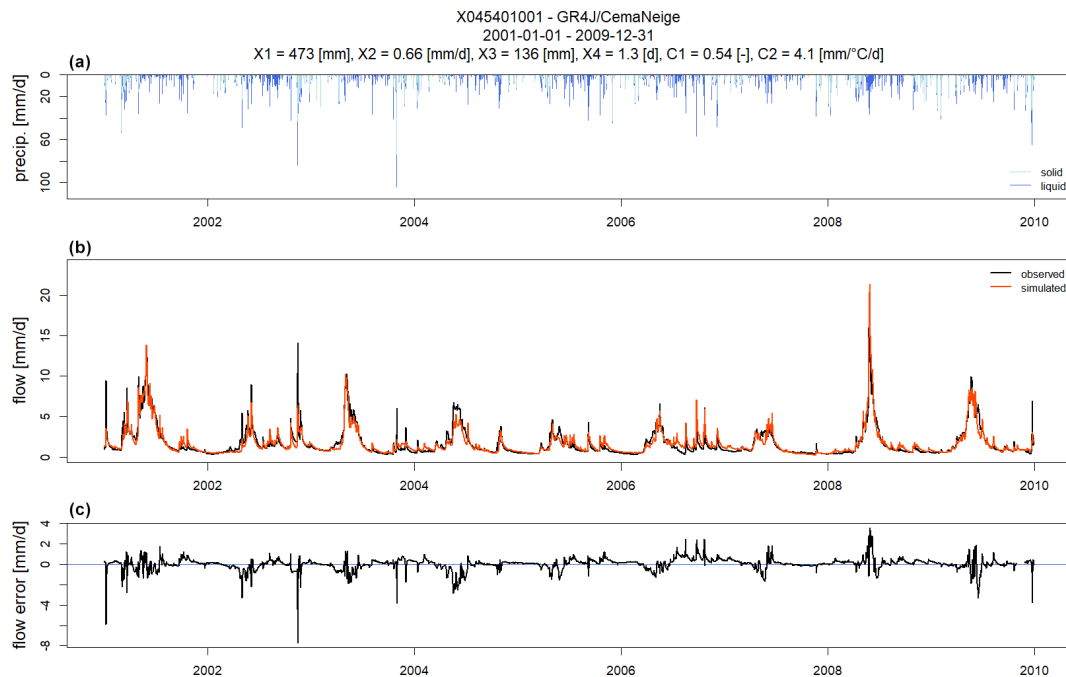

Figure C1. Static plot downloaded from the "Flow time series" tab of the GUI. From top to bottom: **(a)** monthly average precipitation (liquid, and solid if CemaNeige is used), **(b)** observed and simulated hydrographs, and **(c)** flow error time series.
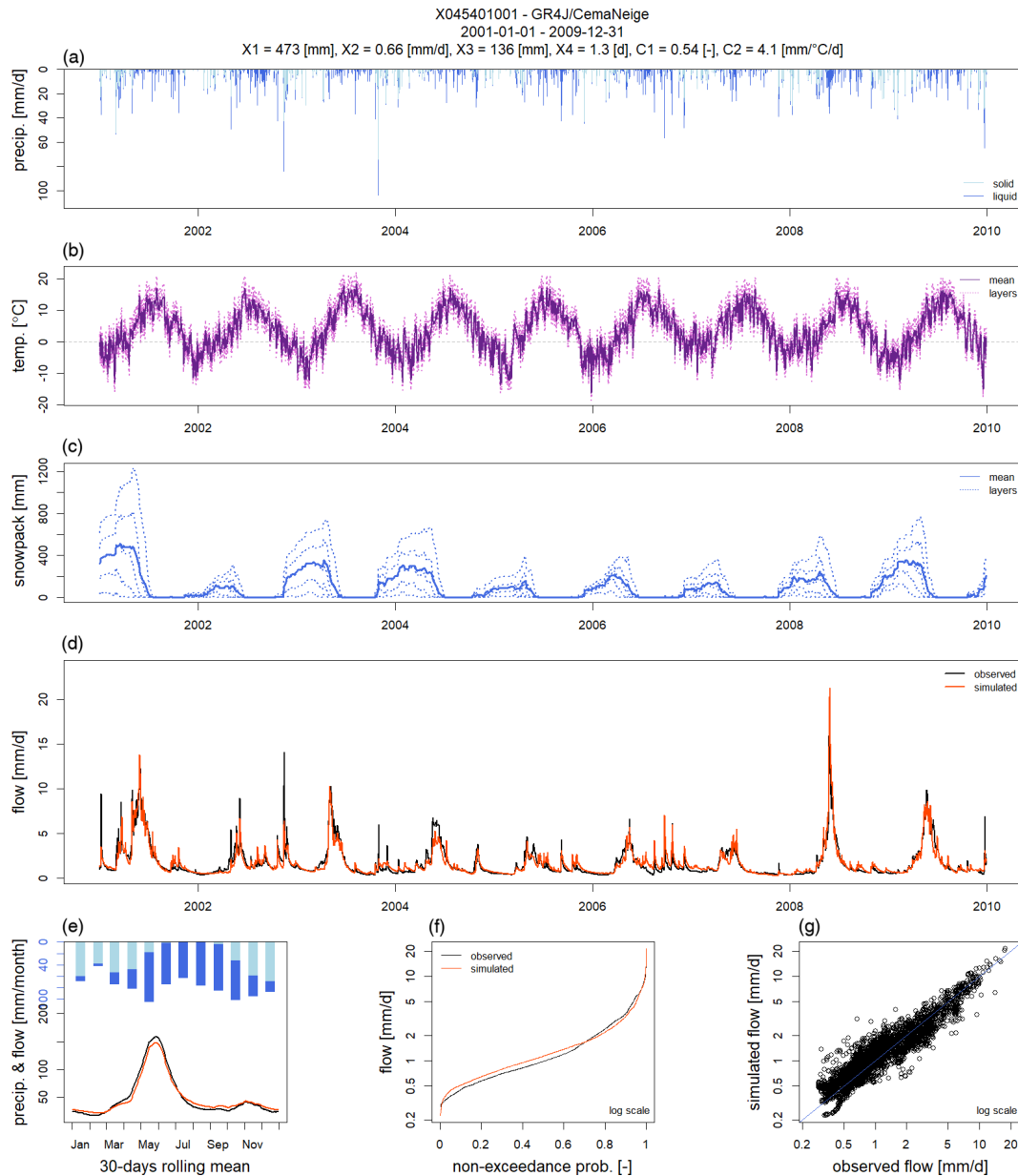
Figure C2. Static plot downloaded from the "Model performance" tab of the GUI. From top to bottom and from left to right: **(a)** precipitation time series (liquid, and solid if CemaNeige is used), **(b)** temperature time series for each layer (if CemaNeige is used), **(c)** snowpack time series for each layer (if CemaNeige is used), **(d)** observed and simulated hydrographs, **(e)** monthly average precipitation (liquid, and solid if CemaNeige is used) and 30 d rolling mean of interannual mean daily streamflow, **(f)** observed and simulated flow duration curves, and **(g)** scatter plot between observed and simulated discharges.
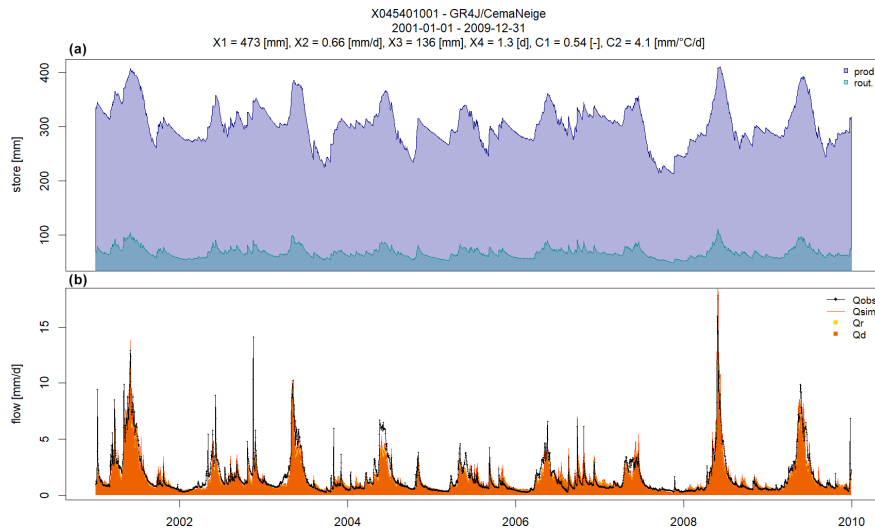
Figure C3. Static plot downloaded from the "State variables" tab of the GUI: **(a)** time series of store levels and **(b)** runoff components.
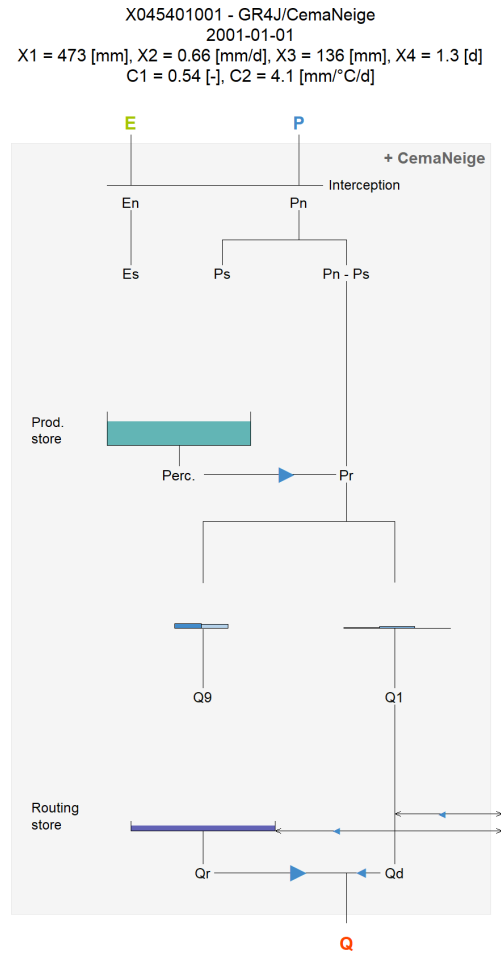

Figure C4. Static plot downloaded from the "Model diagram" tab of the GUI. Model diagram with adaptation of the arrows representing the different fluxes and of the maximal size and the level of the reservoirs according to the actual parameter values and to the values of all internal variables of the model.

Appendix D: "Teaching hydrology with airGRteaching" vignette command lines

```r
# Different X2 values around its median values (0 [mm/d])
param_x2 <- seq(from = -2, to = 2, by = 1)

# Combination of parameter values (X1, X3 and X4 are fixed; X2 changes)
param_gr4j <- expand.grid(X1 = 350,
                          X2 = param_x2,
                          X3 = 90,
                          X4 = 1.4)

# Streamflow simulations using parameter sets
sim_x2 <- apply(param_gr4j, MARGIN = 1, FUN = function(i_param_gr4j) {
  i_sim <- SimGR(PrepGR = prep_no_q,
                 Param = i_param_gr4j,
                 SimPer = per_sim,
                 verbose = FALSE)
  i_sim$OutputsModel$Qsim
})

# Graphical comparison
ind_zoom <- 400:430
col_param_x2 <- colorRampPalette(c("green1", "green4"))(ncol(sim_x2))
matplot(x = as.POSIXct(prep_no_q$InputsModel$DatesR[ind_zoom]),
        y = sim_x2[ind_zoom, ],
        xlab = "time [d]", ylab = "flow [mm/d]",
        type = "l", lty = 1, lwd = 2, col = col_param_x2)
legend("topright",
       legend = sprintf("% .1f", param_x2),
       lwd = 2, col = col_param_x2,
       title = "X2 values [mm/d]")
```

Listing D1. Role of the production component in GR4J.

```r
# Different X4 values around its median values (1.4 [d])
param_x4 <- seq(from = 1.0, to = 3.0, by = 0.5)

# Combination of parameter values (X1, X2 and X3 are fixed; X4 changes)
param_gr4j <- expand.grid(X1 = 350,
                          X2 = 0,
                          X3 = 90,
                          X4 = param_x4)

# Streamflow simulations using parameter sets
sim_x4 <- apply(param_gr4j, MARGIN = 1, FUN = function(i_param_gr4j) {
  i_sim <- SimGR(PrepGR = prep_no_q,
                 Param = i_param_gr4j,
                 SimPer = per_sim,
                 verbose = FALSE)
  i_sim$OutputsModel$Qsim
})

# Graphical comparison
ind_zoom <- 400:430
col_param_x4 <- colorRampPalette(c("steelblue1", "steelblue4"))(ncol(sim_x4))
matplot(x = as.POSIXct(prep_no_q$InputsModel$DatesR[ind_zoom]),
        y = sim_x4[ind_zoom, ],
        xlab = "time [d]", ylab = "flow [mm/d]",
        type = "l", lty = 1, lwd = 2, col = col_param_x4)
legend("topright",
       legend = sprintf("% .1f", param_x4),
       lwd = 2, col = col_param_x4,
       title = "X4 values [d]")
```

Listing D2. Role of the routing component in GR4J.

```r
# Aggregation of the simulated streamflow at the yearly time step
sim_x2_y <- cbind(DatesR = as.POSIXct(prep_no_q$InputsModel$DatesR),
                  as.data.frame(sim_x2))
sim_x2_y <- SeriesAggreg(x = sim_x2_y,
                         Format = "%Y",
                         ConvertFun = rep("sum", ncol(sim_x2_y) - 1))
sim_x4_y <- cbind(DatesR = as.POSIXct(prep_no_q$InputsModel$DatesR),
                  as.data.frame(sim_x4))
sim_x4_y <- SeriesAggreg(x = sim_x4_y,
                         Format = "%Y",
                         ConvertFun = rep("sum", ncol(sim_x4_y) - 1))

# Graphical comparison
matplot(x = sim_x2_y$DatesR, y = sim_x2_y[, -1],
        type = "l", lty = 1, lwd = 2, col = col_param_x2,
        xlab = "time [yr]", ylab = "flow [mm/yr]")
matlines(x = sim_x4_y$DatesR, y = sim_x4_y[, -1],
         type = "l", lty = 1, lwd = 2, col = col_param_x4)
legend("topright",
       legend = c("X2", "X4"),
       lwd = 2, col = c(median(col_param_x2), median(col_param_x4)))
```

Listing D3. Relative importance of the production and routing functions.

```r
# Warm-up and simulation periods
per_wup1m <- c("2002-12-01", "2002-12-31")
per_wup1y <- c("2002-01-01", "2002-12-31")
per_sim   <- c("2003-01-01", "2006-12-31")

# Parameter set
param_gr4j <- c(X1 = 350, X32 = 0, X3 = 90, X4 = 1.4)

# Simulation without warm-up period
sim_wup0d <- SimGR(PrepGR  = prep_no_q,
                   Param   = param_gr4j,
                   WupPer  = 0L,
                   SimPer  = per_sim)

# Simulation with a 1-month warm-up period
sim_wup1m <- SimGR(PrepGR  = prep_no_q,
                   Param   = param_gr4j,
                   WupPer  = per_wup1m,
                   SimPer  = per_sim)

# Simulation with a 1-year warm-up period
sim_wup1y <- SimGR(PrepGR  = prep_no_q,
                   Param   = param_gr4j,
                   WupPer  = per_wup1y,
                   SimPer  = per_sim)

# Graphical comparison
col_wup <- c("orchid", "orange2", "green3")
matplot(x = as.POSIXct(sim_wup0d$OutputsModel$DatesR),
        y = cbind(sim_wup0d$OutputsModel$Qsim,
                  sim_wup1m$OutputsModel$Qsim,
                  sim_wup1y$OutputsModel$Qsim),
        xlab = "time [d]", ylab = "flow [mm/d]",
        type = "l", lty = 1, lwd = 2, col = col_wup,
        xlim = as.POSIXct(x = c("2003-01-01", "2003-09-01"), tz = "UTC"))
legend("topright",
       legend = c("no warm-up", "1-month warm-up", "1-year warm-up"),
       col = col_wup, lwd = 2)
```

Listing D4. On the need to perform a model warm-up.

```r
# Data processing for GR4J (with Q for calibration)
prep <- PrepGR(DatesR    = ts_obs$Date,
               Precip    = ts_obs$Ptot,
               PotEvap   = ts_obs$Evap,
               Qobs      = ts_obs$Qmmd,
               HydroModel = "GR4J",
               CemaNeige  = FALSE)

# Parameter set to test
i_param_gr4j <- c(X1 = 350, X2 = 0, X3 = 90, X4 = 1.4)

# Rainfall-runoff simulation on the calibration period
i_sim_manu <- SimGR(PrepGR  = prep,
                    Param   = param_gr4j,
                    WupPer  = c("1999-01-01", "2000-12-31"),
                    SimPer  = c("2001-01-01", "2010-12-31"),
                    EffCrit = "NSE",
                    verbose = TRUE)

# Get the criterion value
GetCrit(i_sim_manu)

# Graphical assessment of the calibration performance
plot(i_sim_manu)
```

Listing D5. Manual calibration.

```r
# Calibration using NSE score
cal_auto <- CalGR(PrepGR  = prep,
                  CalCrit = "NSE",
                  WupPer  = c("1999-01-01", "2000-12-31"),
                  CalPer  = c("2001-01-01", "2010-12-31"))

# Get parameter and criteria values at the end of the calibration step
GetParam(cal_auto)
GetCrit(cal_auto)

# Graphical assessment of the calibration performance
plot(cal_auto)
```

Listing D6. Automatic calibration.

```r
# Catchment data loading
data("X031001001", package = "airGRdatasets")

# Observed daily time series
ts_obs <- X031001001$TS

# Catchment elevation distribution
hypso <- X031001001$Hypso

# Temporal subset
is_per <- ts_obs$Date >= as.POSIXct("1999-01-01", tz = "UTC") &
  ts_obs$Date <= as.POSIXct("2009-12-30", tz = "UTC")
ts_obs <- ts_obs[is_per, ]

# Data processing for GR4J (without snow module)
prep_snow_n <- PrepGR(DatesR    = ts_obs$Date,
                      Precip    = ts_obs$Ptot,
                      PotEvap   = ts_obs$Evap,
                      Qobs      = ts_obs$Qmmd,
                      HydroModel = "GR4J",
                      CemaNeige  = FALSE)

# Data processing for GR4J with snow module
prep_snow_y <- PrepGR(DatesR    = ts_obs$Date,
                      Precip    = ts_obs$Ptot,
                      PotEvap   = ts_obs$Evap,
                      Qobs      = ts_obs$Qmmd,
                      TempMean  = ts_obs$Temp,
                      ZInputs = median(hypso),
                      HypsoData = hypso,
                      NLayers = 5,
                      HydroModel = "GR4J",
                      CemaNeige  = TRUE)

# Calibration using NSE score (without snow module)
cal_snow_n <- CalGR(PrepGR  = prep_snow_n,
                    CalCrit = "NSE",
                    WupPer  = c("1999-01-01", "2000-12-31"),
                    CalPer  = c("2001-01-01", "2009-12-30"),
                    verbose = TRUE)

# Calibration using NSE score (with snow module)
cal_snow_y <- CalGR(PrepGR  = prep_snow_y,
                    CalCrit = "NSE",
                    WupPer  = c("1999-01-01", "2000-12-31"),
                    CalPer  = c("2001-01-01", "2009-12-30"),
                    verbose = TRUE)

# Combination of observed and simulated streamflow
tab_cal <- data.frame(Date       = cal_snow_n$OutputsModel$DatesR,
                      QObs        = cal_snow_n$Qobs,
                      Qsim_snow_n = cal_snow_n$OutputsModel$Qsim,
                      Qsim_snow_y = cal_snow_y$OutputsModel$Qsim)

# Computation of regime streamflow
tab_cal_reg <- SeriesAggreg(tab_cal,
                            Format = "%m",
                            ConvertFun = rep("mean", ncol(tab_cal) - 1))

# Graphical comparison between simulated and observed streamflow regimes
col_snow <- c("black", rep("orangered", 2))
lty_snow <- c(1, 1:2)
matplot(y = tab_cal_reg[, grep("^Q", colnames(tab_cal))],
        xlab = "time [months]", ylab = "flow [mm/d]",
        type = "l", lty = lty_snow, lwd = 2, col = col_snow)
legend("topright",
       legend = c("Qobs", "Qsim without snow mod.", "Qsim with snow mod."),
       lty = lty_snow, lwd = 2, col = col_snow)
```

Listing D7. Model evaluation.

```r
# Catchment data loading
data("B222001001", package = "airGRdatasets")
ts_obs <- B222001001$TS

# Data processing for GR4J (with Q for calibration)
prep <- PrepGR(DatesR    = ts_obs$Date,
               Precip    = ts_obs$Ptot,
               PotEvap   = ts_obs$Evap,
               Qobs      = ts_obs$Qmmd,
               HydroModel = "GR4J",
               CemaNeige = FALSE)

# Calibration using NSE score on raw Q
cal_raw <- CalGR(PrepGR  = prep,
                 CalCrit = "NSE",
                 transfo = "",
                 WupPer  = c("1999-01-01", "2001-12-31"),
                 CalPer  = c("2002-01-01", "2016-12-31"))

# Calibration using NSE score on sqrt(Q)
cal_sqrt <- CalGR(PrepGR  = prep,
                  CalCrit = "NSE",
                  transfo = "sqrt",
                  WupPer  = c("1999-01-01", "2001-12-31"),
                  CalPer  = c("2002-01-01", "2016-12-31"))

# Calibration using NSE score on log(Q)
cal_log <- CalGR(PrepGR  = prep,
                 CalCrit = "NSE",
                 transfo = "log",
                 WupPer  = c("1999-01-01", "2001-12-31"),
                 CalPer  = c("2002-01-01", "2016-12-31"))

# Combination of simulated streamflow
tab_sim_trsf <- data.frame(Date       = cal_raw$OutputsModel$DatesR,
                           QSIM_rawQ  = cal_raw$OutputsModel$Qsim,
                           QSIM_sqrtQ = cal_sqrt$OutputsModel$Qsim,
                           QSIM_logQ  = cal_log$OutputsModel$Qsim)
tab_sim_trsf <- merge(x = ts_obs[, c("Date", "Qmmd")],
                      y = tab_sim_trsf,
                      by = "Date",
                      all.y = TRUE)

# Computation of regime streamflow
tab_sim_reg <- SeriesAggreg(tab_sim_trsf,
                            Format = "%m",
                            ConvertFun = rep("mean", ncol(tab_sim_trsf) - 1))

# Graphical comparison between simulated and observed streamflow regimes
col_trsf <- c("black", rep("orangered", 3))
lty_trsf <- c(1, 1:3)
matplot(y = tab_sim_reg[, -1],
        xlab = "time [months]", ylab = "flow [mm/d]",
        type = "l", lty = lty_trsf, lwd = 2, col = col_trsf)
legend("bottomleft",
       legend = c("Qobs", "Qsim", "sqrt(Qsim)", "log(Qsim)"),
       lty = lty_trsf, lwd = 2, col = col_trsf)
```

Listing D8. Using flow transformation in objective functions.

```r
# Calibration using NSE score on Q
cal_nse <- CalGR(PrepGR  = prep,
                 CalCrit = "NSE",
                 transfo = "",
                 WupPer  = c("1999-01-01", "2001-12-31"),
                 CalPer  = c("2002-01-01", "2016-12-31"))

# Calibration using KGE score on Q
cal_kge <- CalGR(PrepGR  = prep,
                 CalCrit = "KGE",
                 transfo = "",
                 WupPer  = c("1999-01-01", "2001-12-31"),
                 CalPer  = c("2002-01-01", "2016-12-31"))

# Combination of observed and simulated streamflow
tab_crit <- data.frame(Date     = as.POSIXct(cal_nse$OutputsModel$DatesR),
                       Qobs     = cal_nse$Qobs,
                       Qsim_nse = cal_nse$OutputsModel$Qsim,
                       Qsim_kge = cal_kge$OutputsModel$Qsim)

# Graphical comparison
col_crit <- c("black", rep("orangered", 2))
lty_crit <- c(1, 1:2)
matplot(x = tab_crit$Date, y = tab_crit[, -1],
        xlab = "time [d]", ylab = "flow [mm/d]",
        type = "l", lty = lty_crit, lwd = 2, col = col_crit,
        xlim = as.POSIXct(x = c("2004-01-01", "2004-03-01"), tz = "UTC"))
legend("topleft",
       legend = c("Qobs", "Qsim NSE", "Qsim KGE"),
       lty = lty_crit, lwd = 2, col = col_crit)
```

Listing D9. Using different objective functions.

```r
# Calibration and evaluation sub-periods
per1_wup <- c("1999-01-01", "2001-12-31")
per1_sim <- c("2002-01-01", "2008-12-31")
per2_wup <- c("2009-01-01", "2011-12-31")
per2_sim <- c("2012-01-01", "2018-12-31")

# Calibration on per1 and per2
cal_per1 <- CalGR(PrepGR = prep,
                  CalCrit = "KGE",
                  transfo = "",
                  WupPer  = per1_wup,
                  CalPer  = per1_sim,
                  verbose = TRUE)
cal_per2 <- CalGR(PrepGR  = prep,
                  CalCrit = "KGE",
                  transfo = "",
                  WupPer  = per2_wup,
                  CalPer  = per2_sim,
                  verbose = TRUE)

# Get parameter values at the end of the calibration step
param_per1 <- GetParam(cal_per1)
param_per2 <- GetParam(cal_per2)

# Get criteria values at the end of the calibration step
crit_cal_per1 <- GetCrit(cal_per1)
crit_cal_per2 <- GetCrit(cal_per2)

# Evaluation over per1 and per2
eva_per1 <- SimGR(PrepGR  = prep,
                  Param   = param_per2,
                  WupPer  = per1_wup,
                  SimPer  = per1_sim,
                  EffCrit = "KGE",
                  verbose = TRUE)

eva_per2 <- SimGR(PrepGR  = prep,
                  Param   = param_per1,
                  WupPer  = per2_wup,
                  SimPer  = per2_sim,
                  EffCrit = "KGE",
                  verbose = TRUE)

# Get criteria values
crit_eva_per1 <- GetCrit(eva_per1)
crit_eva_per2 <- GetCrit(eva_per2)

# Cleveland dot plot of the criteria
dotchart(c(crit_eva_per1, crit_cal_per1, crit_eva_per2, crit_cal_per2),
         labels = c("eva (per1)", "cal (per1)", "eva (per2)", "cal (per2)"),
         groups = rep(1:2, each = 2),
         col = rep(c("darkred", "darkblue"), each = 2), pch = 19,
         xlab = "KGE [-]")
```

Listing D10. Split-sample test.

```r
# Estimation of annual aridity index (PE/P)
ts_obs_y <- SeriesAggreg(x = ts_obs[, c("Date", "Ptot", "Evap")],
                         Format = "%Y",
                         ConvertFun = c("sum", "sum"),
                         YearFirstMonth = 10)
ts_obs_y$Arid <- ts_obs_y$Evap / ts_obs_y$Ptot

# Identification of wetter and dryer hydrological years
barplot(height = ts_obs_y$Arid,
        names.arg = format(ts_obs_y$Date, format = "%Y"),
        xlab = "time [yr]", ylab = "aridity index [-]",
        col = "royalblue")

# Wet and dry periods
per_wet <- c("2016-10-01", "2017-09-30")
per_dry <- c("2000-10-01", "2001-09-30")

# Calibration over the wet and the dry periods
cal_wet <- CalGR(PrepGR  = prep,
                 CalCrit = "KGE",
                 CalPer  = per_wet,
                 verbose = TRUE)
cal_dry <- CalGR(PrepGR  = prep,
                 CalCrit = "KGE",
                 CalPer  = per_dry,
                 verbose = TRUE)

# Get parameter values at the end of the calibration step
param_dry <- GetParam(cal_dry)
param_wet <- GetParam(cal_wet)

# Get criteria values at the end of the calibration step
crit_cal_dry <- GetCrit(cal_dry)
crit_cal_wet <- GetCrit(cal_wet)

# Evaluation over the wet and the dry periods
eva_wet <- SimGR(PrepGR  = prep,
                 Param   = cal_dry,
                 SimPer  = per_wet,
                 EffCrit = "KGE",
                 verbose = TRUE)
eva_dry <- SimGR(PrepGR  = prep,
                 Param   = cal_wet,
                 SimPer  = per_dry,
                 EffCrit = "KGE",
                 verbose = TRUE)

# Get criteria values
crit_eva_dry <- GetCrit(eva_dry)
crit_eva_wet <- GetCrit(eva_wet)

# Cleveland dot plot of the criteria
dotchart(c(crit_eva_dry, crit_cal_dry, crit_eva_wet, crit_cal_wet),
         labels =  c("eva (dry)", "cal (dry)", "eva (wet)", "cal (wet)"),
         col = rep(c("darkorange", "deepskyblue3"), each = 2), pch = 19,
         xlab = "KGE [-]")
```

Listing D11. Differential split-sample test.

References

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