Reply to Elena Toth

We would like to thank Elena Toth for her very constructive comments on the manuscript and we are glad that she finds that the Technical Note may be of interest for the hydrological community. We agree with most of the comments and suggestions. We provide an answer to each comment and a potential roadmap to change the manuscript accordingly hereafter.

Comment:

In particular, I think that the attempt to keep apart but at the same include the differences due to the presence of the snow routines, make some sections much heavier and some tables much more difficult to read 'at a glance', and I would suggest considering to separate all the issues related to such routines (for the models that include it) in a dedicated section (or appendix).

Reply:

We believe that the snow routines are integral parts of the hydrological models, which instead of being named rainfall-runoff models should be named precipitation-runoff models, and that they can be very useful to users; snow-dominated basins and snow-impacted basins represent a large part of basins worldwide. For that reason, we built the manuscript with the feeling that discussing snow models in the text was necessary. However, we acknowledge that the description of the snow models might make the reading of the Technical Note a bit more difficult. This difficulty comes for its most part to the models themselves: snow models and rainfall-runoff models represent processes that happen at different time and space scales, making their spatial distribution and input variables, for instance, very different. We think that separating all the elements related to snow calculations from the other comparisons and keeping them in the body of the article would lengthen the article. For all the above reasons, we would prefer to keep the parts related to snow models as they are right now. However, if the associate editor also agrees on the fact that snow models should be presented differently, we would prefer to move most of the related content to the appendices for a better readability. We would keep Table 2 and the explanations of section 2.2 related to the snow routines (lines 113/114, line 149, lines 155/156 and lines 169/170) as they are right now, and add a cross-reference to the appendices. The snow-related section would be indexed as follows:

- Subsection A.1.1, dedicated to the description of the processes present in the snow models, with the explanations of section 3.1 related to the snow routines: lines 198 to 200, lines 212/213, lines 250/251, lines 265 to 267, lines 273/274, line 277, lines 284 to 289;

- Subsection A.1.2, dedicated to the spatial distribution of snow models, with the explanations of section 3.2.1 and Figure 2;

- Subsection A.1.3, dedicated to the requirements of snow models, with a Table for the requirements and outputs related to the snow routines, extracted from Table 4 (see Table A.2 below), and explanations of section 3.3 related to the snow routines: lines 376/377, lines 385/386, lines 392/393;

- Subsection A.2, dedicated to computation times when snow models are used, with the computation times of Figure 5 for the combination of hydrological models and snow routines and the related explanations of subsection 4.3.2: lines 615 to 617, lines 631 to 633.

We would keep the snow rectangles in Figure 1. The last column of Table 5 would also be moved to the appendices.

Table A.2: Requirements to run the snow routines and types of outputs made available by the related packages. P = precipitation; T = temperature; SR = shortwave radiation; hypso = hypsometric curve; TS = time series. Providing the hypsometric curve to the snow routines is not compulsory but it is strongly recommended when enabled by one of the packages.

Package	Model(s)	Inputs		Nb. of param.	Outputs		
		TS	Static		TS of internal fluxes	TS of store levels	Spatially distributed
airGR	CemaNeige	P; T	hypso	2	✓	✓	✓
HBV.IANIGLA	HBV	P; T		4	✓	✓	✗
hydromad	snow.sim	P; T		7	✓	✓	✗
sacsmaR	SNOW-17	P; T	hypso	10	✗	✗	✗
TUWmodel	HBV	P; T	hypso	5	✓	✓	✓
WALRUS	Degree-Day method or	P; T		0	✓	✓	✓
	Shortwave radiation method	P; T; SR		0	✓	✓	✓

Comment:

Introduction: Lines 39-61 may be substantially shortened

Reply:

We propose to remove lines 46 to 53 from "In spite of the growing availability" to "comprehensive and controlled protocols.".

Comment:

Section 2.1: I would have appreciated a wider list (acknowledging, of course, that it cannot be exhaustive) of the R-R models available in R that you have found in your search but have not been chosen (that is, not belonging to the conceptual continuous bucket-type).

Reply:

Thank you for this comment. We propose to add the following list of packages with the reasons why we chose not to include them in our analysis:

- The Ecohydmod package (Souza, 2017) implements an Ecohydrological model.

- The LWF-BROOK90 package (Schmidt-Walter et al., 2020) implements a physically-based land-surface hydrological model.

- The fuse package (Vitolo et al., 2016) proposes a large number of model structure configurations. It was considered that its main purpose was not to conduct a basic hydrological study but more to understand errors arising from hydrological models.

- The RHMS package (Arabzadeh and Araghinejad, 2019) implements several event-based hydrological models.

- The SWATmodel package (Fuka et al., 2014) implements a watershed hydrological transport model.

Comment:

Section 2.2: I would separate the different models in separate sub-sections (either numbered or just identified with a header), for a better 'indexing'

Reply:

Thank you for this suggestion. As some models are included in more than one package, we propose to separate the packages in different sub-sections rather than the models.

<u>Comment:</u>

I would move Table 2 in Section 3.2.1 (or, even better, in separate section/appendix, as suggested above).

<u>Reply:</u>

We think that it is more appropriate to put Table 2 before section 3.1.1 (or A.1.1), as we deal with the conceptual storages and fluxes related to the snow routines in this section.

<u>Comment:</u>

Section 3.1 The legend of Fig. 1 is tiny and, in order to better "read" the figure, I would suggest adding in the text at l. 198 a general description of the meaning of stores and transfers represented in Figure 1. And in the figure, I would add some symbols to the colours (S for snow inside the blue box, P for precipitation arrows, etc), especially needed for the bi-coloured boxes.

I would clarify in this section that details on the input data (input arrows) will be given in section 3.3 and Table 4.

Also here, I would add separate sub-section headers for the different models.

<u>Reply:</u>

We will try to improve the readability of Fig. 1 by increasing the size of the legend. We will move the explanations of the caption of Fig. 1 from "The root zone storage" to "on a single spatial unit." to lines 196/197 after "to ensure consistency.". We will also add the following sentence just after: "Details on the input data will be given in section 3.3 and Table 4.". However, we think that adding symbols would overload the diagrams. We will separate the explanations for the different models by adding sub-section headers.

<u>Comment:</u>

Section 3.2.1: It would be necessary to better clarify the differences between the spatial discretization needed by the snow routines (due to the influence of elevation) and the spatial distribution of the models in general (and again, if all the considerations on snow modelling may be moved in a following section/appendix, it would help in better following the main flow of the analysis)

<u>Reply:</u>

We acknowledge that more explanations are needed to clarify the differences between the spatial discretization needed by the snow routines and the spatial distribution of the hydrological models. We will try to make this point clearer in the revised manuscript. Depending on where the sections related to snow routines will be placed in the text, we propose to add the following sentences to section 3.2.1 or A.1.2 after line 303 and replacing lines 304/205: "The influence of snow processes on streamflow can vary with elevation, as snow accumulation and melt mainly depend on air temperature that usually decreases with elevation and precipitation that usually increases with elevation. For that reason, a spatial discretization within the catchment may be needed to better account for snow influence when modelling streamflow at the outlet of a catchment. Some packages propose a spatial discretization to account for the influence of snow processes on streamflow. Four configurations were found possible."

<u>Comment:</u>

Section 3.3 Table 4 has too many information and I find it confusing. Again, removing the information on the snow modules, now in the parentheses, would make the table much more readable. Otherwise, I would split it into two tables (one with time steps, input and #parameters and one with the outputs). I would also make two separate columns for the inputs (that is a very important issue for the practical use of the models), distinguishing the meteorological time-series from the static catchment properties (SA,

3

hypso, DEM, etc). In the text, separate (possibly again in sub-sections) the different issues that are discussed: outputs, inputs + number of parameters (since the availability of some static information on the catchment allows to set the values of some parameters), time steps.

Reply:

Thank you for this comment. We will separate Table 4 into two distinct tables. If the explanations related to snow routines are kept in the main body of our technical note, the two tables would become Table 4 and 5 as shown below. Otherwise, informations related to snow routines will be moved to section A.1.3.

Table 4: Requirements to run the models and associated numerical resolutions. D = daily; H = hourly; M = monthly; A = annual; FL = flexible; Num. res. = Numerical resolution; OS = operator splitting; Ana = analytic; Exp = explicit; Imp = implicit; P = precipitation; T = temperature; PET = potential evapotranspiration; DEM = digital elevation model; SA = subbasins area; hypso = hypsometric curve; TS = time series. Between parentheses: parameters or inputs of the corresponding snow routine. It is not compulsory to provide the snow routines with the hypsometric curve but it is strongly recommended when enabled by one of the packages. In this table, for the semi-distributed models, the parameters are considered uniform over the spatial units; in case they are considered distributed, the amount of parameters should be multiplied by the number of spatial units (i.e. HRUs, subbasins...).

Package	Model(s)	Time step(s)	Num. res.	OS	Inputs TS	Inputs Static	Nb. of param.
airGR	GR models	H; D; M; A	Ana	✓	P; PET; (T)	(hypso)	[1 ; 6] (+2)
dynatopmodel	Dynamic TOPMODEL	FL	Imp & Exp		P; PET;	DEM	8
HBV.IANIGLA	HBV	FL	Exp	✓	P; PET; (T)		[7 ; 9] (+4)
hydromad	GR4J	D	Ana	✓	P; PET		4
	IHACRES-CMD	FL	Ana	✓	P; PET; (T)		6 (+7)
	Sacramento	≥ H	Exp	✓	P; PET		13
sacsmaR	Sacramento	D	Exp	✓	P; PET; (T)	SA; (hypso)	13 (+10)
topmodel	TOPMODEL 1995	FL	Exp		P; PET	DEM	10
TUWmodel	Modified HBV	≤ D	Exp & Ana	✓	P; PET; (T)	(hypso)	10 (+5)
WALRUS	WALRUS	FL	Exp	✓	P; PET; (T)	soil type	3

Table 5: Model outputs made available by the packages. TS = time series; AET = actual evapotranspiration; RC = runoff components; ⌢: only some of the time series of runoff components, internal fluxes or store levels are provided. Between parentheses: outputs of the corresponding snow routine. All the packages return time series of discharge.

Package	Model(s)	TS of AET and TS of RC	TS of internal fluxes		TS of store levels	Spatially distributed	
airGR	GR models	✓	✓	(✓)	✓	✗	(✓)
dynatopmodel	Dynamic TOPMODEL	✓	⌢		✓	✓	
HBV.IANIGLA	HBV	✓	⌢	(✓)	✓	✗	(✗)
hydromad	GR4J	✓	⌢		✓	✗	
	IHACRES-CMD	✓	⌢	(✓)	✓	✗	(✗)
	Sacramento	✓	✗		✓	✗	
sacsmaR	Sacramento	✗	✗	(✗)	✗	✗	(✗)
topmodel	TOPMODEL 1995	✓	⌢		✗	✓	
TUWmodel	Modified HBV	✓	⌢	(✓)	✓	✓	(✓)
WALRUS	WALRUS	✓	✓		✓	✗	

We also propose to add the following sub-sections:

- 3.3.1 Inputs and number of adjustable parameters. This sub-section would gather: lines 360/361 from "Since" to "differ", lines 362/363 from "As data availability" to "requirements", lines 375 to 386 and lines 391 to 393 from "The two versions" to "snow considerations".

- 3.3.2 Time steps and numerical resolution of model equations. This sub-section would gather: "The packages allow operation of the models at different time steps and imply different types of numerical resolutions of model equations", sentences on numerical resolution (see the reply to Reviewer 1) "The different equations of a hydrological model can be solved using different techniques. The equations are usually solved analytically (the exact solution is determined by integrating the equation for a given time step), explicitly (the solution is approximated by its derivative at the beginning of the time step) or implicitly (the solution is approximated by its derivative at the end of the time step). When the resolution is analytical or explicit, the operator splitting technique is commonly applied to sequentially calculate processes such as evaporation, runoff and percolation (Santos et al., 2018). Numerical solution in hydrology can be seen as part of the mathematical model rather than software implementation, as it changes the results substantially" and lines 387 to 391 from "all the packages" to "some constraints".

- 3.3.3 Outputs. This sub-section would gather: lines 363 to 374 from "By making" to "by the packages" and lines 393 to 396 from "While few packages", to "TOPMODEL 1995".

Comment:

Section 4.1.1: it would be better if the text addressed separately each one of the functionalities (sub-sections): preprocessing, calibration, etc.

Reply:

We will separate the text into the following sub-sections:

- 4.1.1.1 Criteria. This sub-section would gather: lines 435 to 447 from "Weighted combinations" to "see Freer et al., 2004)"

- 4.1.1.2 Parameter estimation. This sub-section would gather: lines 477 to 454 from "Automatic calibration".

- 4.1.1.3 Plot function. This sub-section would gather: lines 455 to 466.

- 4.1.1.4 Graphical user interface. This sub-section would gather: lines 467 to 487.

Comment:

Section 4.1.2 may be substantially shortened, leaving just a few general comments. In fact, Table 6 is not really needed (the distinction of the meaning of different columns is not so sharp). And also Table 7 may be removed, especially since it presents information that may be updated any time, making it out-of-date.

Reply:

We disagree with this point. We think that Table 6 and 7 summarize important pieces of information for users. Information from Table 6 cannot be accessed by users before installing and manipulating the packages, while information from Table 7 can be difficult to find. Furthermore, it is one of the main points of our work that the documentation of the packages could be improved, which would broaden the use of the packages by making them more accessible to newcomers. From a user perspective, the lack of documentation is one of the limitations when using these packages. In order to make this point, we believe that this analysis must contain some elements of comparison. Also, the differences between the columns of Table 6 correspond to the different fields suggested by R when developing a package (see the example of Fig. 1 page 7 of this document).

Generate a network routing table

Description

Generates a network width table for a catchment. When passed to the run.dtm routine this will be used to route channel flows to the outlet during a Dynamic TOPMODEL run.

Usage

```
build_routing_table(dem, chans = NULL, outlet = NULL, breaks = 5,
  len.fun = flow.lens)
```

Arguments

dem	Elevation raster using a projected coordinate system (e.g UTM) and a regular grid spacing. Areas outside the catchment should be set to NA
chans	Optional raster of the same dimensions and resolution as the DEM. Non-zero cells in this raster are considered to contain a river channel. If not supplied then flowpaths from the entire catchment area are considered.
outlet	Index of cell or cells identified with the catchment outlet
breaks	Number of distance intervals
len.fun	For large rasters the flow.len function can be very slow and many paths fail to reach a single outlet cell. This applies a simple straight line distance to the outlet to obtain a rough approximation.

Details

Dynamic TOPMODEL routes channel flow to the outlet by a network-width approach (see Beven, 2012, pp. 97-97). A time-delay histogram is produced using the table. When any flow is distributed to the channel "unit" it is immediately redistributed across future time steps according to the proportions found in the histogram. These flows are then added to future outputs from the model.

Value

A two-column data.frame. Its first column is the average flow distance to the outlet, in m, the second the proportions of the catchment channel network within each distance category.

Author(s)

Peter Metcalfe

References

Beven, K. J. (2012). Rainfall-runoff modelling : the primer. Chichester, UK, Wiley-Blackwell.

Examples

Figure 1: Help page of the `build_routing_table` function included in the `dynatopmodel` package.

Comment:

Section 4.2 ll 548-554 may be moved in section 4.1.1 (in the functionalities section)? Fig 4 and text 554-583 should be moved after 4.3.1, since the 'user-function' boxes should be introduced first.

Reply: Thank you for this comment. We agree that lines 548-554 should be moved to section 4.1.1. We propose to move these lines to the new sub-section about parameter estimation functionalities. However, we think that Fig. 4 and lines 554 to 583 should stay in section 4.2 as it corresponds to the analysis of the connections between the functions of a package. Therefore, it intends to help users with their implementation of the hydrological workflow. Please note that Fig. 4 should have appeared one page before in the preprint. Also the term "dependency" in the legend of Fig. 4 will be replaced by "Legacy". We propose to add the definition of "user-function" at line 542 after "to run (Fig. 4)".

Comment:

I find Section 5 too long: I would suggest merging, reorganising and shortening the lines from 664 to 765 (last part of section 5.1 and sections 5.2 and 5.3). It is also important not mixing issues related to the additional functionalities with those related to the documentation. As a user, I believe one of the main obstacles in the use of some R-packages is the fact that the documentation is not modular enough, that is, it does not explain in an immediate way how to do only the specific thing you want to do. And,in this case, this would be for example just running the rainfall-runoff model, without any additional pre- or post- functionality, that I may prefer to carry out autonomously

Reply:

Thank you for this comment. We will consider shortening and reorganizing the discussion.

Comment:

Abstract: ll 6-7: I would clarify that some packages include more than one model and the same model may be included in more than one package.

Reply:

We believe that this information is not necessary in the abstract.

Comment:

I would move ll 33-38 (all languages), before ll 25-32 (R, that is one of the possible languages).

Reply:

Thank you for this suggestion. We propose the following modifications that also take the comments of the first reviewer into account: "Various types of hydrological models exist according to their assumptions on the representation of natural processes, space and time dependence (e.g. Clark et al., 2011; Beven, 2012; Clark et al., 2017). Various programming languages enable the use of these hydrological models. For example, some models are implemented in Python (e.g. EXP-HYDRO hydrological model, Patil and Stieglitz, 2014) or in Matlab with the MARRMoT toolbox (Knoben et al., 2019). A significant number of models like MIKE SHE (DHI, 2017) can only be operated through commercial software and platforms.

A large number of models can be found on the R platform, such as the HBV model (Bergström, 1976) or TOPMODEL (Beven and Kirby, 1979). The R language (R Core Team, 2020a) is an open source interpreted language. R was originally designed for statistics (as an open source implementation of the S language, Becker et al., 1988) but has since been employed

in many other scientific fields. The functionalities of the R language are contained in packages, some of which include features related to hydrology topics. The R language is reasonably easy to use and has been taking advantage of a growing community of users. A large range of documentation, tutorials, manuals and online discussion platforms are developed by the R-Hydro community, such as what the rOpenSci project (https://ropensci.org) develops or the many code examples available on Stack Overflow (https://stackoverflow.com). Also many short courses and workshops are regularly organised (e.g. the Using R in Hydrology short course at the EGU General Assembly). R can be used at each step required for a basic study in hydrology (the hydrological workflow steps, see Fig. 3 of Slater et al., 2019). Consequently, there has been an important increase in the growth and use of hydrological R packages (see Fig. 1 of Slater et al., 2019). Some of these packages are designed for hydrological modelling. In this study, we will restrict ourselves to the hydrological models that are available within the R environment."

Comment:

l. 68: I would not use "efficiency" here, to avoid misunderstanding with an assessment of the simulation performance.

Reply:

We agree. We propose the following modification: "The objective of this paper is to review the pros and cons of using hydrological models implemented as packages in the R environment and to compare and evaluate their applicability and usability."

Comment:

ll. 100-101: not clear.

Reply: We propose the following sentence: "We chose to exclude the packages that contain complex models without providing any function for data preparation or any explanatory document (e.g. SWATmodel, Fuka et al., 2014)."

Comment:

ll 189-194 may be replaced with just the list of references proposing similar diagrams, without explaining in what they differ from yours.

Reply:

We will remove the explanations on how these legends differ from the one we used. The explanations lines 188 to 195 from "This type of unified" to "from de Boer-Euser et al. (2017, Fig. 3)." would become: "This type of unified comparison was, for example, employed in the framework for understanding structural errors (FUSE, see Fig. 3 of Clark et al., 2008) to compare the structures of four models, or to present the forty models included in the MARRMoT toolbox (see Fig. 2 of Knoben et al., 2019). We selected a different approach for this analysis. The legend we used here was modified from de Boer-Euser et al. (2017, Fig. 3)."

Comment:

l 345: clarify the relation between the basin partition in elevation zones (snow routine) and in subbasins (see comment on snow appendix).

Reply:

We propose to replace "The discharge outputs from each zone are then summed up based on their relative area to the entire catchment" at line 346 by: "For example, a catchment can be divided into three subbasins, with one subbasin divided into five

elevation zones. The relative contribution of each spatial entity to the entire catchment is defined by the user with a weighting coefficient. The discharge outputs from each zone are then summed up using these coefficients."

Comment:

ll. 352-353: it may be highlighted that the higher flexibility of the spatial discretization of sacsmaR is obtained with a demanding pre-processing to be carried out outside of the package.

Reply:

We propose to add the following sentence at line 358: "Please note that the high level of spatial discretization enabled by some of the packages sometimes requires a demanding pre-processing to be carried out outside of the corresponding package (e.g. `sacsmaR`, see section 4 and Table 5)."

Comment:

l. 628: can you explain why the HBV.INANIGLA has lower times?

Reply:

We have not investigated the reasons that would explain the different CPU times. These reasons can be manifold and imply the choice of programming language, the model complexity, the code implementation and the method of numerical resolution among others.

References

Arabzadeh, R. and Araghinejad, S.: RHMS: Hydrologic Modelling System for R Users, URL https://CRAN.R-project.org/package=RHMS, R package version 1.6, 2019.

Fuka, D. R., Walter, M. T., Steenhuis, T. S., and Easton, Z. M.: SWATmodel: A multi-OS implementation of the TAMU SWAT model, URL https://CRAN.R-project.org/package=SWATmodel, R package version 0.5.9, 2014.

Schmidt-Walter, P., Trotsiuk, V., Meusburger, K., Zacios, M., and Meesenburg, H.: Advancing simulations of water fluxes, soil moisture and drought stress by using the LWF-Brook90 hydrological model in R, Agricultural and Forest Meteorology, 291, 108 023, https://doi.org/10.1016/j.agrformet.2020.108023, 2020.

Souza, R.: Ecohydmod: Ecohydrological Modelling, URL https://CRAN.R-project.org/package=Ecohydmod, R package version 1.0.0, 2017.

Vitolo, C., Wells, P., Dobias, M., and Buytaert, W.: fuse: An R package for ensemble Hydrological Modelling, The Journal of Open Source Software, 1, https://doi.org/10.21105/joss.00052, 2016.