GMD submission by Knoben et. al.

Modular Assessment of Rainfall-Runoff Models Toolbox (MARRMoT) v1.1: an open- source, extendable framework providing implementations of 46 conceptual hydrologic models as continuous state-space formulations

General response

We thank the editor and reviewers for their consideration of our manuscript and the obvious care with which the reviewers have scrutinized our work. Their comments are valuable and encouraging.

Their main points can be summarized as follows:

(1) Correspondence between MARRMoT models and original models is not sufficiently addressed;
(2) Table 1 should be appended to include additional information that specifies how we changed models from their original publication, and for what temporal resolution the models were originally intended;
(3) There is a possible mistake in the model smoothing code, resulting from a typing error in the source of the smoothing equation;
(4) There is an omission of code in the IHACRES model which is not explained in our documentation;
(5) There are various typing errors and sentences in need of clarification.

We discuss the reviewers' comments in the remainder of this document. Our responses are given in blue, and changes in the text are indicated in **bold** where relevant. Line numbers in our responses refer to the 'track changes' document.

We also fixed various spelling mistakes in the Supplementary Materials. These are not explicitly mentioned in the following comments.

The reviewers have highlighted one inaccuracy and one omission in the MARRMoT code. We have adapted the code following their recommendations and released MARRMoT version 1.1 which includes these changes. The manuscript title and DOI's have been updated to reflect this.

Kind regards,

On behalf of all co-authors,

Wouter Knoben

Reviewer 1 - P. Kraft

General Comments

(1) **Reviewer comment:** The authors have completed a great task: translating 46 model structures into a clean system, where equations and solver are separated and suitable to be used with an implicit solver scheme is a great accomplishment. I tried quite a while ago something similar for only a few models with CMF, which has a similar base structure as MARMMoT. I gave up to mimic existing models, since the abundant mixture of model code, flux equation and ad hoc solution schemes in existing models makes it extremely difficult and tiring to translate them into a clear set of ordinary differential equation. This translation of existing models into a common scheme is a new feature of MARMMoT that is not available for more abstract model building frameworks like SUPERFLEX, CMF and SUMMA.

Author response: Thank you for these kind words. To clarify, we created the MARRMoT models by only using model description papers or user manuals where papers where unavailable. We have not used any "original" model code to base our models on.

We note that reviewer comments 2 to 6 can all be related back to this point: we chose to base all MARRMoT models on written documentation only, not on existing computer code. Our reasons for doing this are as follows: (1) written documentation is traceable through the cited sources, which allows MARRMoT users to compare our documentation and code to the original work. (2) Computer code is often not available, which is a practical constraint on our ability to use existing code. (3) Multiple different versions of a certain models can be found (that still use the same name), with limited or no traceability or version control. This makes it difficult to decide which set of computer code can be considered the 'original' model. Therefore we rely on published documentation only.

We have introduced a new section 2.1 Scope (in response to reviewer comment 9), which includes the following clarification: P4 L 22: "**MARRMoT models are based on written documentation only, not on existing computer code. This choice is motivated by our aim to produce traceable code and by several practical concerns. The documentation we base our models on is traceable through our cited sources. Computer code of hydrologic models tends to be less traceable than their documentation: code might be unavailable, code might not be accompanied by a persistent identifier, or multiple versions of the same model (using the same model name) might be available which complicates finding the 'original' computer code. This is supported by various authors who developed the original models: "Today many versions of the HBV model exist, and new codes are constantly developed by different groups …" (Lindström et al., 1997) and " … TOPMODEL is not a single model structure […] but more a set of conceptual tools" (Beven et al., 1995).**"

(2) **Reviewer comment:** For this reason, I would be very happy to see this study published and I agree with the authors concerning the great potential of such a unified model collection for future studies. However, for future applications, the users must know how much the newly constructed models really resemble the original work. The authors state, that they needed to make assumptions, changed processing orders and smoothed discontinuities to make existing models fitting into the new structure, but the discussion about the effects of these changes in chapter 5.3.3 is shallow and not covered by data. If I use "m_37_hbv_15p_5s", how similar are the results compared with the original HBV-96?

Author response: We agree that section 5.3.3. does not contain any comparison of "original" models and our MARRMoT models but think our intent of this section might not have been sufficiently clear. We think that such a comparison is

impossible to make, because for many of our models no original code is available, and for other models too many different versions (all with the same model name) can be found online and at institutes. From personal experience, I have worked with three models that all claim to be (based on) HBV-96 but all three were certainly different. Hence we have not made any comparisons between MARRMoT models and other models inspired by the same original publication (more on this in response to the reviewers next paragraph). Instead, we intended section 5.3.3. as a caution against the assumption that our models are the same as other sets of code out there: our models will be different from any other model codes that are inspired by the same source material, and only by studying both the original papers and our MARRMoT implementation of such papers do we expect that users can fully understand why our code looks the way it does. This is currently covered in section 5.3.3:

P13 L5: "We strongly recommend readers to compare the original publication of each model with the version given in this toolbox, to place results from the MARRMoT models in a proper context of earlier work with these models."

We emphasized this caution in section 5.3.3., and the differences we introduced between original publications and MARRMoT models will hopefully be much clearer in the revised manuscript, where we now address these changes in Table 1 like the reviewers suggested. Changes to section 5.3.3.:

P13 L 7: **"We emphasize that our models are based on publications that describe existing models, not on existing computer code. Thus, we neither guarantee nor expect that our code performs exactly like the original version of each model's code (if indeed such a version exists and can be found and agreed upon for any given model). We hope that by making MARRMoT available as open source code, future studies can go beyond simply stating the model name without publishing any model code, and instead can refer to an open-source, traceable version of the model(s) used."**

We have further changed Figure 2, so that the header of the model column now reads "Original model that is the basis the MARRMoT implementation" instead of "Models".

(3) **Reviewer comment:** What kind of quality control did you use to ensure the correctness of the translation? From my experience with abstract model formulations in CMF even extremely small changes can lead to suprising strong changes of the overall behavior, therefore I deem a more detailed discussion on the effects needed for a better article.

Author response: We acknowledge that small changes in model structure or code can have large impacts on model behaviour. However, we also think that it is practically impossible to track down a version of each model where we can confidently claim that that bit of code is indeed the original code of that model. This is supported by various authors who developed the 'original' models, who state things such as "Today many versions of the HBV model exist, and new codes are constantly developed by different groups …" (Lindström et al., 1997) and " … TOPMODEL is not a single model structure […] but more a set of conceptual tools" (Beven et al., 1995). Moreover, even if it is possible to locate a version of each model that can be considered the true original, the code might not be available (any longer).

We currently provide a test case example of MARRMoT model performance (section 4 in the paper) but we believe that measuring this against a baseline of "original" models is unfortunately practically impossible. We have clarified that MARRMoT models are based on documentation only (not on computer code) in the caption of Table 1 and section 5.3.3, to clarify that we do not possess the necessary computer code for more in-depth comparison. We have also (briefly) summarized the discussion of this point in section 5.3.3 (see our response to comment 2). Changes to Table 1 caption:

P30: "Table 1: MARRMoT models. **Model IDs are used throughout this paper and the MARRMoT documentation. MARRMoT function names include a longer identifier that either refers to the name of the original model (e.g. m05_ihacres_7p_1s) or to the area of original application (e.g. m_01_collie1_1p_1s which was used in the Collie River basin). The column "Main changes" specifies structural changes between the MARRMoT model and the original model description (note that MARRMoT models are created solely based on the cited sources and not on any computer code). Not mentioned are cases where (i) model equations**

needed to be modified to account for the time step size at which the model is used; (ii) Ordinary Differential Equations were not given in the original source; (iii) cases where modelled processes were only described qualitatively in the original source, without equations; (iv) cases where model equations where smoothed in their MARRMoT implementations (these can be traced through the overview of flux equations in Supporting Materials S3)."

(4) **Reviewer comment:** The perfect solution would be to include a graph of RMSE (MARMMoT vs. original model result) for good parameter sets. If this requires too much work, I would at least expect such a comparison for 2 or 3 strongly changed models and for 1 or 2 lightly changed models in combination with an additional column in table 1, that indicate the deviation from the original model code for models.

Author response: We have adapted table 1 to include the changes we introduced between the MARRMoT version of each model and the description we base these models on (see our response to comment 3).

A full comparison of all MARRMoT models and their originals is indeed out of reach for the following reasons:

- As mentioned earlier (see our responses to comment 1-3), we have not used any computer code to create MARRMoT models for a variety of reasons. Finding the "official" version of all 46 MARRMoT models is practically impossible, which limits which MARRMoT models can be compared to "original" models;
- Several models can be freely downloaded but do not publicly share their source code. This allows us to compare the performance of these models with their MARRMoT equivalent, but still does not allow us to judge how well MARRMoT approximates the original documentation (i.e. the reviewer's concern is now applied to the downloaded model's code: we cannot be sure that the model's internal workings reflect its documentation);
- The fact that the numerical solving scheme used is not often mentioned in source documentation complicates this comparative analysis. A common solving scheme in hydrology is Explicit Euler, but we use an Implicit Euler scheme as the preferred option in MARRMoT. Even with the same model, using a different numerical approximation scheme will generally lead to different simulations. Because the scheme used in original models is generally not clarified, it is difficult to judge how similar we expect our MARRMoT model simulations to be to any simulations generated by "original" models.

To illustrate this point, we follow the reviewer's suggestion and compare a lightly changed model (MARRMoT m37, based on HBV-96) and a strongly changed model (MARRMoT m07, based on GR4J) with "official" alternatives (HBV Light and the R implementation of GR4J called airGR respectively). We've updated section 5.3.3. with three additional paragraphs and included a new Figure 4 that supports this comparison. Additions to 5.3.3:

P13 L 10: "We strongly recommend readers to compare the original publication of each model with the version given in this toolbox, to place results from the MARRMoT models in a proper context of earlier work with these models. **We emphasize that our models are based on publications that describe existing models, not on existing computer code. Thus, we neither guarantee nor expect that our code performs exactly like the original version of each model's code (if indeed such a version exists and can be found and agreed upon for any given model).**

To illustrate this point, we compare performance of MARRMoT model m07 (based on the GR4J model) with the R implementation of GR4J (part of the airGR package; Coron et al., 2017, 2019), and we compare MARRMoT model m37 (based on HBV-96) with HBV Light (Seibert and Vis, 2012). MARRMoT m07 is an example of a model that has changed significantly from the original source as a result of combining the original documentation (Perrin et al., 2003)

with a more recent state-space version of GR4J (Santos et al., 2018), while both MARRMoT m37 and HBV Light are similar to HBV-96. We thus expect larger deviations between simulations from MARRMoT m07 and airGR-GR4J than we expect between simulations from MARRMoT m37 and HBV-Light. In both cases, we selected 10000 parameter sets from MARRMoT's parameter ranges through Latin Hypercube sampling. In the case of GR4J, both MARRMoT and airGR versions use the same 4 parameters. In case of HBV, the MARRMoT version has several additional snow parameters and a capillary rise parameter, while HBV Light has various elevation and input correction factors. These have all been fixed at values that effectively disable their impact on model simulations. We then simulated 5 years of streamflow in the earlier described Hickory Creek using both versions of both models. For comparison purposes, we use the Kling-Gupta Efficiency (KGE; Gupta et al., 2009) to express the similarity between simulations and observations. Figure 4 shows the results of this comparison.

Figure 4a shows that for the best performing parameter set in our sample (in terms of KGE value), the hydrographs generated by MARRMoT m37 and HBV Light are relatively similar. Figures 4c-4e show a decomposition of KGE values into its three constitutive components, that express the linear correlation (KGE_r), the ratio of simulated and observed standard deviations (KGE_a) and the ratio of simulated and observed means (KGE_b) respectively. For a given parameter set, MARRMoT m37 and HBV Light generate simulations that are relatively similar (i.e. close to the 1:1 line). HBV Light tends to produce more variable flows than MARRMoT m37 does (high standard deviation and mean of simulated flows). The reason for this is difficult to investigate because although HBV Light is freely available, its source code is not. Differences between both models' equations and numerical approximation of these equations are likely explanations.

Figure 4b shows that for the best performing parameter set in our sample (in terms of KGE value), the hydrographs generated by MARRMoT m07 and airGR-GR4J are relatively different. Most notable, MARRMoT m07 recessions are much slower and higher than those from airGR-GR4J. Figures 4f-4h indicate that for parameter sets close to the optimal points (i.e. (0,0)), MARRMoT m07 and airGR-GR4J show similar performance. For parameter sets further away from the perfect simulation, MARRMoT m07 shows an increasing tendency to simulate more variable flows (higher standard deviation and mean components) than airGR-GR4J does. However, differences between MARRMoT m07 and airGR-GR4J are not unexpected because MARRMoT m07 also uses equations from state-space GR4J (Santos et al., 2018) and the models' equations are thus not identical.

Concluding, we emphasize again that MARRMoT models are based on existing publications only and not on computer code. Differences with other models using the same name are unavoidable. We hope that by making MARRMoT available as open source code, future studies can go beyond simply stating the model name without publishing any model code, and instead can refer to an open-source, traceable version of the model(s) used."

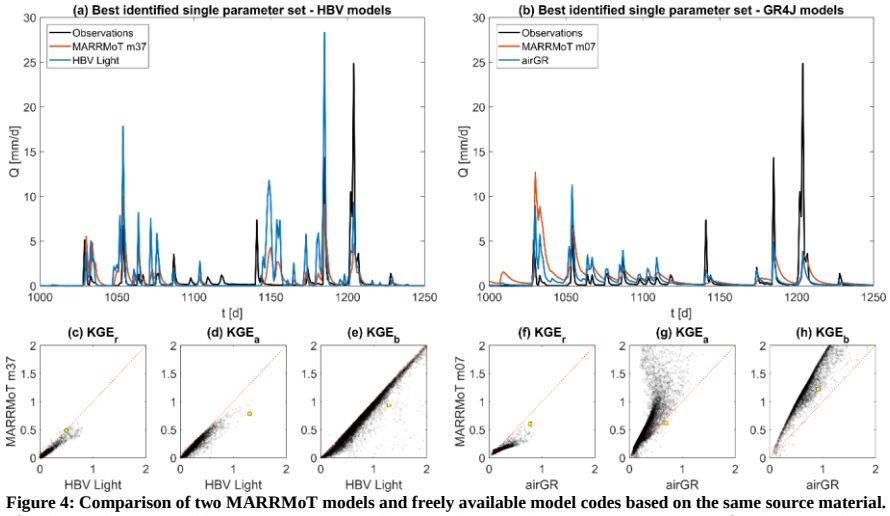

Figure 4: Comparison of two MARRMoT models and freely available model codes based on the same source material. (a) Close up of hydrographs generated by MARRMoT m37 and HBV Light using the same parameter values for their shared parameters. (b) Close up of hydrographs generated by MARRMoT m07 and airGR-GR4J using the same parameter values. (c-e) Constitutive components of the Kling-Gupta Efficiency (KGE) obtained by HBV Light and MARRMoT m37 for 10000 parameter sets in a single catchment. The yellow dot indicates the parameter set used to generate figure a. (f-h). Constitutive components of the KGE obtained by airGR-GR4J and MARRMoT m07 for 10000 parameter sets in a single catchment. The yellow dot indicates the parameter set used to generate figure b.

(5) **Reviewer comment:** Another concern that I have stems from the following: Deviations between equation implementations in code and their published version in "math" can easily differ – the authors suffered from this problem themselves. Hence I would be very interested if they found differences between model publication and implemented model code in their list of original models and how they dealt with such differences.

Author response: Unfortunately we cannot comment on this particular concern, because we did not use any existing computer code to inform MARRMoT modelling choices.

(6) **Reviewer comment:** And finally, what kind of quality control measures they took, to ensure that their implementation is in fact equivalent to the original implementation und does not differ strongly by new bugs or the correction quirks from the original model.

Author response: Because our MARRMoT code is only based on publications and not on examples of model code, no such quality control measures where possible. We cannot guarantee that no bugs are present in our framework. However, if bugs are present, our framework assures that each model that relies on the bugged element suffers from the same bug or quirk. This at least makes the comparison between models within MARRMoT fair. This is already mentioned as an important aspect of this work in the introduction:

P3 L30: "Due to the code being open source, transparency and repeatability of research is encouraged, additions to the framework are possible, and the community can find and correct any mistakes."

And also in section 3.1 (relevant section emphasised):
P8 L7 "Flux functions are kept separate from the model functions, and each model calls several flux functions as needed. This allows for consistency across models (if errors are present in any flux function, at least they are the same in all models), easy implementation of new flux equations and facilitation of studies that are specifically interested in differences between various mathematical equations that all represent the same flux or process."

Every model function has a built-in water balance check (output is reported on user request). This has been used to test each model's water balance accounting during development and no errors were found. We've included this information in section 3.2:
P8 L24: "**The model code as currently provided was extensively checked for water balance errors during development, using multiple parameter sets for each model, both randomly sampled and using all combinations of extreme values using MARRMoT's provided parameter ranges. These errors were generally in the order of 1E-12 or smaller, showing that the water balance is properly accounted for in each model.**"

Specific Comments

(7) **Reviewer comment,** P3 L 14: FARM does not fit into this listing, please remove

Author response: Agreed upon re-reading the paper, removed from the listing.

(8) **Reviewer comment,** P3 L 18: CMF falls for this comparison rather into the same category as SUPERFLEX, since you can build conceptual models as well as physical models and things in between. A reference for a "SUPERFLEX"-like usage of CMF is Jehn et al. 2018 https://doi.org/10.5194/hess-22-4565-2018

Author response: Thank you for this correction. We currently don't list any example applications of the cited model comparison frameworks but will re-visit Jehn et al (2018) in follow-up publications that use MARRMoT. Changes:
P3 L 17: "… models (e.g. **CMF**, SUPERFLEX), or …". Removed CMF from P3 L18.

(9) **Reviewer comment,** P3 L 32: The benefits of MARMMoT are explained a bit too enthusiastic – especially the "best practice" part about the solvers, in comparison to the discussion on that topic. I would also expect a clear note about the boundaries of MARMMoT's scope (eg. only lumped models, no internal ET calculation etc.)

Author response: This is fair. We have toned down the language somewhat ("best practices" are now "good practices") and added a new subsection to section 2 that outlines the scope and limitations of MARRMoT. Changes:
P1 L12: "several **good** practices **of model development**: …"
P3 L26: "… **good** practices for numerical model solving …"
P4 L9: "several other **good** practices for model development …"
P7 L2: "following the **good model development** practices outlined …"

P4 8: "… framework (Clark et al., 2008). **Section 2.1 gives a brief outline of the project scope and design philosophy.** MARRMoT follows several other **good** practices for model development which are briefly described **in sub-sections 2.2 to 2.5**.

2.1 Scope

MARRMoT's scope is limited to conceptual hydrological models and the code currently includes no spatial discretization of inputs or catchment response. Models are expected to be used in a lumped fashion, although users could create their own interface to use MARRMoT code to represent within-catchment variability using multiple lumped model structures. Required model inputs are standardized across all MARRMoT models and every model only requires time series of precipitation and potential evapotranspiration, and optionally of temperature (used by certain snow modules). Model outputs are equally standardized and provide time series of simulated flow and total evaporation fluxes, and optionally time series of model states and internal fluxes. The models are set up such that they can use a user-specified time step size (e.g. daily, hourly) which is currently effectively the temporal resolution of the forcing data. Models and flux equations internally account for this time step size, so that parameter values can use consistent units, regardless of the temporal resolution of the forcing data. The main goal of this set up is ease-of-use, so that it is straightforward to switch between different model structures within an experiment."

(10) **Reviewer comment,** P5 L 5: Implicit schemes can fail if the time step size is too large for the non-linear solver to converge. How does the solver in MARRMoT deal with this? Is there an internal dynamic time step?

Author response: The internal time step of each model is equal to the temporal resolution of the forcing data. A user can choose (inside each model function) to turn on a progress display and messages from the solver which will indicate whether such a problem has occurred. Adaptive sub-stepping can resolve this issue, but this is currently not implemented (see section 5.3.5. Possible extensions). We've updated the text to clarify this. Changes:
P5 L29: "Note that fixed time step size refers to the use of a single time step size throughout a simulation **(i.e. no adaptive sub-stepping is used; see section 5.3.5)** and does not prescribe the time step size **(e.g. hourly, daily)**."

(11) **Reviewer comment,** P5 eq. 2: The equation is wrong, must be changed to $Q_o = Q_i\left(1 - \phi(S, S_{max}, \rho_s, \varepsilon)\right)$ (see source code: eg. infiltration_3.m:21,23,25 interflow_11.m:23,25,27), otherwise the names inflow and outflow do not make sense. An adhoc implementation of this equation shows that the parameter $\varepsilon = 5$ does not prevent $S > S_{max}$. A longer discussion on that can be found at this gist: https://gist.github.com/philippkraft/aae02d23fbdad62f98a413ab04fe6d83

Author response: Thank you for this in-depth analysis. We agree with your assessment and have changed both the text in the manuscript and the smoothing code. We think this is a code change of sufficient magnitude to warrant a new release and have incremented MARRMoT's version number to 1.1. The code DOI's in the manuscript have been changed in response. Text changes:
P6 L11: $Q_o = Q_{in}\left(\mathbf{1} - \Phi(S, S_{max}, \rho_S, \varepsilon)\right)$

(12) **Reviewer comment,** P 11 L 7: Implicit solvers are usually error controlled. Which kind of tolerances (relative and absolute) are used in the solver? And how does the solver react, if a solution within the error boundaries is not found? I understand the text, that at least fsolve can return values with an unspecific error tolerance (I guess in situations where some convergence criteria are missed)

Author response: All solvers (*fzero*, *fsolve*, *lsqnonlin*) use default settings in our example workflows (default accuracy is 1E-6 mm function values, which equates to an accuracy of 1E-6 mm in our case), but users can easily choose other options if they wish. All solvers output a squared norm of residuals ("resnorm"), which is the value of the objective function at the solver-provided solution. The correct solution is found when resnorm = 0. MARRMoT contains basic error control in the form of user-specified tolerance ("resnorm_tolerance" in our workflow examples). If the "resnorm" of a given solution is larger than the user-specified tolerance, various actions can be triggered:

First, the model function uses a more robust solver (*lsqnonlin*) to see if that succeeds where the faster solver (*fzero* or *fsolve*, depending on number of stores) failed. This happens inside a sub-function called "rerunSolver". Next, within "rerunSolver" *lsqnonlin* attempts to solve the model equations at this time step for a user-specified number of times ("resnorm_maxiter" in our workflow examples). Each attempt is started from different initial guesses:
(1) zero storage values;
(2) very high storage values (beyond the store maximum) ;
(3) storage values where *fzero* or *fsolve* got stuck;
(4) storage values of the previous time step;
(5) maximum storage values (if provided);
(6) random storage values.

If no solution is found, the "rerunSolver" function outputs an error flag (which the user can check for) and uses the last found (non-optimal) solution.

We have updated the text in the manuscript with a general note on where to specify solver settings and updated the User Manual with a more in-depth description:
P12 L15: "**Note that settings for these root-finding methods are specified within each model file because certain settings are model-dependent. Progress display is disabled for all three functions (*fzero*, *fsolve*, *lsqnonlin*) by default but can be enabled by the user. The model-dependent Jacobian matrix is specified for *fsolve* and *lsqnonlin*. The maximum number of function evaluations is capped at 1000 for *lsqnonlin*. All other root-finding options are left at default Matlab values (see Matlab documentation of the root-finding methods for further details). Users are encouraged to experiment with these settings to find those that work for their specific problem.**"

User Manual, P17: **"The function "rerunSolver" will attempt to find new solutions for the current time step that are within the accuracy threshold specified in "solver.resnorm_tolerance". It does this up to "solver.resnorm_maxiter" times, and restarts the solving procedure from different initial guesses each time. This provides better chances of finding a solution with the requested accuracy.**
Currently, two optional output arguments of "rerunSolver" are unused. Output argument 2 provides the final value of "resnorm" which the user can request and check to see whether the accuracy specified in "solver.resnorm_tolerance" has been achieved. Alternatively, the user can request output argument 3 ("flag") which returns 0 if the function "rerunSolver" returned a sufficiently accurate solution. "flag" will return -1 if "rerunSolver" has not been able to find a sufficiently accurate solution."

(13) **Reviewer comment,** P 11 L 23: Since the comparability of the MARMMoT functions with the original model is the major feature of this study, I would expect a discussion on this topic that is deeper, completer and more explicit. See general comment.

Author response: Answered in responses to comments 2-6 above.

(14) **Reviewer comment,** Table 1: Add columns that indicate the type and level of deviation between the original source and the implementation in MARMMoT (eg. spatial generalization, change of solution order, introduction of smoothing functions, generalization of timestep, etc)

Author response: We have amended Table 1 quite significantly based on both reviewers' comments, and this change has been made. See pages 30 and 31 in the revised document.

Reviewer 2
Anonymous (Referee)
Received and published: 2 April 2019

(15) **Reviewer comment:** This is an interesting and well-written paper. It is a timely contribution to making available open, flexible and easy-to-use platforms for hydrological modelling. One strength and originality of the platform is the use of space-state model formulations and a well adapted solver. The Supporting material also gathers a wealth of information, very useful for young (and less young) modellers wishing to better understand models' behaviour. I have only a few minor comments detailed below. I advise publication after minor revision and I congratulate the authors for this impressive amount of work.

Author response: Thank you for these kind words. Please find answers to your detailed comments below.

Detailed comments

(16) **Reviewer comment,** P1, L4: Should not it be "state-space"? This aspect, which appears in the tittle, is not really discussed in the text. Maybe the authors could explain a bit more the implications of considering state-space formulations.

Author response: Thank you, state-space is indeed correct. Changed in the title. We've also added a clarification to the text to point out where state-space formulations are discussed (this discussion was already there, but not clearly labelled as such). Changes:
P5 L2: "First, MARRMoT uses a distinct separation of model equations **as state-space formulations** and the numerical approach used to solve these equations."

(17) **Reviewer comment,** P2, L5-8: A number of earlier papers had discussed the issue of modelling steps and may be cited if deemed useful (Refsgaard and Henriksen, 2004; Refsgaard et al., 2005; Scholten et al., 2007).

Author response: Thank you for these recommendations. We consider especially the first paper (Refsgaard and Henriksen, 2004) to be useful for our model development context and have included it as a reference. Changes:
P2 L8: "(e.g. Beven, 2012; Clark and Kavetski, 2010; Gupta et al., 2012; **Refsgaard and Henriksen, 2004**)"

(18) **Reviewer comment,** P4, L9: Move "(ODEs)" to line 15.

Author response: Agreed, changed (now on P5 L8 due to the new section 2.1).

(19) **Reviewer comment,** P7, L7-10: Is it possible with the tool to apply a model on a set of catchments? This would be useful in the perspective of model testing on large sample.

Author response: Yes, that would require only a simple loop that loads data for various catchments and sends this to the model(s). We have amended the text to clarify that there are no barriers to using MARRMoT in multiple catchments:
P8 L5: "**These examples can easily be adapted to work with multiple catchments if desired.**"

(20) **Reviewer comment,** P7, L30: I was surprised that PDM, which is widely applied in the UK and elsewhere, is not part of the platform.

Author response: The core of PDM is a certain set up of the soil moisture routine, which is currently included in MARRMoT as part of the HyMOD model (MARRMoT ID: 29). The nature of this project is such that it is practically impossible to include all models, but an interested user should be able to start with our HyMOD code and (with help from the User Manual) modify this model to more closely resemble PDM. The option to do this is currently described in the introduction, section 2, section 3 and section 5.3.5 (relevant sentences emphasised):

P3 L30: "Due to the code being open source, transparency and repeatability of research is encouraged, additions to the framework are possible, and the community can find and correct any mistakes."

P4 L7: "and (ii) add new options to the framework"

P8 L 17: "User Manual: This document helps a user set up MARRMoT for use in either Matlab or Octave, outlines the inner workings of the standardized models, provides several workflow examples and provides examples on how to create a new flux equation or model."

P14 L22: "The MARRMoT User Manual therefore provides detailed guidance on creating new model and flux functions, and the code's location and licensing on Github allows these new models to be shared freely. Extensions to the framework are thus possible and encouraged."

(21) **Reviewer comment,** P9, L1-11: Actually, these findings are not really new and corroborates past studies in the literature which could be cited.

Author response: This is true, we have added a sentence to clarify that these results are only meant to illustrate what can easily be done with our framework and are not intended to be taken as original findings. Changes:
P10 L6: "**Note that our findings in this test case are not new, but the** test case highlights the power of multi-model comparison frameworks:"

(22) **Reviewer comment,** P9, L26: The sentence was not fully clear for me.

Author response: We've added clarification to this sentence. Changes:

P10 L27 (please note that this change is part of the citation field and these changes somehow do not show with the standard 'track changes' mark-up): "Furthermore, this toolbox lowers the threshold for model comparison studies and can help to diminish "legacy" reasons for model application **(i.e. choosing to use a certain model for reasons other than the model's perceived appropriateness for the task at hand, such as convenience or past experience;** Addor and Melsen, 2019)."

(23) **Reviewer comment,** P12, L22: I am unsure that this would be straightforward. Adaptive time-stepping means that model parameters are not time dependent, which is not always the case (?).

Author response: MARRMoT already allows a user-specified time step size (e.g. daily, hourly). This ability should transfer directly to adaptive time-stepping. This is clarified in the new section 2.1. Changes (relevant section emphasized):
P3 L 11: **2.1 Scope**
MARRMoT's scope is limited to conceptual hydrological models and the code currently includes no spatial discretization of inputs or catchment response. Models are expected to be used in a lumped fashion, although users could create their own interface to use MARRMoT code in a semi-distributed way. Required model inputs are standardized across all MARRMoT models and every model only requires time series of precipitation and potential evapotranspiration, and optionally of temperature (used by certain snow modules). Model outputs are equally standardized and provide time series of simulated flow and total evaporation fluxes, and optionally time series of model states and internal fluxes. The models are set up such that they can use a user-specified time step size (e.g. daily, hourly) which is currently effectively the temporal resolution of the forcing data. Models and flux equations internally account for this time step size, so that parameter values can use consistent units, regardless of the temporal resolution of the forcing data. The main goal of this set up is ease-of-use, so that it is straightforward to switch between different model structures within an experiment."

(24) **Reviewer comment,** P23: The use of "unnamed" for many models is not informative. Could the authors give more explicit names, for example by using the first letters of the first author's name of the cited publications?

Author response: We have amended the header in this table to read "Original model name" to highlight that these are not intended as names of the MARRMoT models (we'd prefer those to be referred to by either their function name (column 3 of this table) – or their ID (column 1)). We've made the following change to the table caption to clarify this:
P30: "Table 1. MARRMoT models. **Model IDs are used throughout this paper and the MARRMoT documentation. MARRMoT function names include a longer identifier that either refers to the name of the original model (e.g. m05_ihacres_7p_1s) or to the area of original application (e.g. m_01_collie1_1p_1s which was used in the Collie River basin). […]**"

(25) **Reviewer comment,** P23: Many models are not using a snow module, but could actually be used with such a module. To which extent snowmelt modules existing in other models could be used with these models?

Author response: This is possible and should be fairly straightforward. The User Manual contains guidance on adapting existing models (and creating new ones). This is currently mentioned in Section 3, section 3.2 and section 5.3.5 (see also our response to comment 20).

(26) **Reviewer comment,** Supplementary material, S2: A few models (e.g. S1, S3, S6) were not initially developed for short time steps (daily or shorter, as mentioned in P5,L5 of the article) and may be not directly applicable at these time steps. Typically, I am unsure a bucket model alone would perform well on most catchments at the daily time step. Should not this be clarified somewhere? Maybe the information on the original model time step development could be added in Table 1.

Author response: We have amended Table 1 quite significantly based on both reviewers' comments, and this change has been made (P30).

(27) **Reviewer comment,** Supplementary material, S2: When reading this document, I found it would be useful to have a summary table for each model showing all model parameters together (symbol, meaning, unit). Some model descriptions are quite long and this table would ease the overview on model parameters. The authors may consider adding these tables, except if it is too much work.

Author response: Thank you for this suggestion. We have added the requested tables to each model description. These changes to the Supplementary Materials are too numerous to copy here.

(28) **Reviewer comment,** Supplementary material, S2: Some models (e.g. #25 or 40 and maybe others) compute net rainfall as the difference between raw rainfall and potential evapotranspiration. This is actually equivalent to having an interception store with null capacity. Therefore I think these models should appear as having an interception store in Fig. 2. This process may also appear in S3 as an interception process.

Author response: Currently this type of behaviour is already covered by our flux "interception_2". We have slightly changed the description of this flux in S3 to reflect that it can serve as both an abstract interception store (i.e. when a fixed amount is taken from incoming precipitation) and as a null capacity store (i.e. when a variable amount is taken from incoming precipitation based on current potential evapotranspiration values). Changes:
Supplementary P127: "Interception excess after an **absolute** amount is intercepted"

With regard to Figure 2, we have tried to keep our models as close to the original documentation as possible. In the source material for model 25, no mention is made of this effective rainfall representing interception. Therefore we do not think that we should assign this interpretation in Fig. 2 to our MARRMoT version (it might also represent surface depression storage or a form of precipitation bias correction). However, model 7 uses this same structure of effective P and the source documentation does mention that this represents interception with null capacity. We had erroneously not labelled this model as such in Fig. 2, which we have now corrected. Changes:
P25, Fig. 2: added an interception marker to model m07

(29) **Reviewer comment,** Supplementary material, S2.1: This bucket model is also often used to represent interception (with evaporation at the potential rate), not only soil moisture. But this is generally only a part of a model.

Author response: True, as evidenced by several other models that use this concept. Although such interception modules generally treat evaporation as occurring at the potential rate for all store depths, and the model in S2.1 uses a linearly decreasing evaporation ratio instead. Therefore we have decided not to mention this particular point in the description in section S2.1.

(30) Supplementary material, S2.5: line 8: "This"

Author response: Changed, thank you.

(31) **Reviewer comment,** Supplementary material, S2.5: The original IHACRES model includes a pure time delay, which is very useful for model applications on large catchments. Why was it removed here? I guess it would be useful also in other models which are not able to introduce a delay between rainfall and streamflow.

Author response: Our implementation of IHACRES was based on Figure 1 in Littlewood et al (1997) and sections 2.1.1 to 2.1.3. The pure time delay is only mentioned in the summary paragraph of section 2 (2.1.5). Removing this time delay from the MARRMoT model was no conscious choice, we simply didn't see this bit of information. We have made the following changes:

- Created a new Unit Hydrograph function: uh_8_delay, following your suggestions in the comment below
- We have changed our IHACRES model function (m05) as follows:
  - Included the new routing component (new parameter, new routing code, new water balance code)
  - Changed the name of this function from "m05_ihacres_6p_1s" to "**m05_ihacres_7p_1s"** to reflect the additional parameter
  - Tested this code to ensure no water balance errors have been introduced
- We have updated the IHACRES parameter range function
  - New name to reflect the additional parameter
  - New parameter range
- We have updated Figure 1 to reflect the increased number of parameters in our IHACRES version
- We have updated Table 1 in the User Manual to reflect the additional UH option
- We have created a new section 4.8 in the Supporting Materials that outlines the new UH option
- We have updated the model description in section S2.5
- We have updated Table S3 (which shows an overview of recommended parameter ranges in MARRMoT) to include the new time delay in IHACRES

To reflect this substantial change to the MARRMoT code, we have decided to increment the version number to v1.1.

(32) **Reviewer comment,** Supplementary material, S4: The pure time delay mentioned in the previous comment could be introduced as another option of unit hydrograph. Actually, it can be easily coded as a UH, which would have only two non-zero ordinates. If td is the time delay (it can be a real value, not necessarily an integer value), the two non-zero ordinates would be respectively td-int(td) and 1-td+int(td).

Author response: Thank you for specifying the required code. We have implemented this as "UH_8_delay".

(33) **Reviewer comment,** Supplementary material, S4,7: Why a question mark before "Moore and Bell"?

Author response: The question mark is the result of an error in referencing. Thanks for pointing this out. This is now corrected. Changes:
Supplements P145: "References E.g. MCRM (**Bell et al, 2001;** Moore and Bell, 2001)"

(34) **Reviewer comment,** P150: Not sure I fully understand the note on the filling parameter.

Author response: This parameter can be used to let the depression store in model 36 fill according to an exponential rate, where the shape of this exponential profile is decided by this parameter's value. However, literature applications of model 36 tend to set this parameter to 1, because no information is available on which plausible ranges of this parameter can be based. We've changed the text slightly to clarify this:

Supplements, P150: "Controls the **exponential rate** of depression store inflow flux but is usually set at 1 because no studies **are available that can be used to set plausible ranges**"

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Modular Assessment of Rainfall-Runoff Models Toolbox (MARRMoT) v1.~~0~~1: an open-source, extendable framework providing implementations of 46 conceptual hydrologic models as continuous ~~space-state~~state-space formulations

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Abstract. This paper presents the Modular Assessment of Rainfall-Runoff Models Toolbox (MARRMoT): a modular open-source toolbox containing documentation and model code for 46 existing conceptual hydrologic models. The toolbox is developed in Matlab and works with Octave. Models are implemented following several ~~best~~ good practices of model development: definition of model equations (the mathematical model) is kept separate from the numerical methods used to solve these equations (the numerical model) to generate clean code that is easy to adjust and debug; the Implicit Euler time-stepping scheme is provided as the default option to numerically approximate each model's Ordinary Differential Equations in a more robust way than (common) Explicit schemes would; threshold equations are smoothed to avoid discontinuities in the model's objective function space; and the model equations are solved simultaneously, avoiding physically unrealistic sequential solving of fluxes. Generalized parameter ranges are provided to assist with model inter-comparison studies. In addition to this paper and its Supporting Materials, a User Manual is provided together with several workflow scripts that show basic example applications of the toolbox. The toolbox and documentation are available from https://github.com/wknoben/MARRMoT (DOI: 10.5281/zenodo.~~2482542~~2677728). Our main scientific objective in developing this toolbox is to facilitate the inter-comparison of conceptual hydrological model structures which are in widespread use, in order to ultimately reduce the uncertainty in model structure selection.

1 Introduction

Rainfall-runoff modelling is useful to extrapolate our hydrologic understanding beyond measurement availability (Beven, 2009, 2012). We can challenge and improve our understanding of the way catchments function through model-based hypothesis testing (Beven, 2002; Clark et al., 2011; Fenicia et al., 2008b; Kirchner, 2006, 2016) and simulate the impact of changes in climatic conditions and catchment characteristics such as land use change (Bathurst et al., 2004; Ewen and Parkin, 1996; Klemeš, 1986; Peel and Blöschl, 2011; Seibert and van Meerveld, 2016; Wagener et al., 2010). Many different modelling

approaches are possible, ranging from lumped, empirical, deterministic bucket-style models to distributed, process-oriented, stochastic, 3D physics-based models (Beven, 2012). Each of these approaches has its own advantages and drawbacks, concerning the level of spatial detail, amount of model 'realism' in terms of processes represented, input data requirements and computational time. The toolbox presented in this paper uses deterministic, spatially lumped bucket-style models, also referred to as conceptual hydrological models. Note that this definition of a conceptual model is different from the definition used by authors discussing the modelling process, where the conceptual model is a step between having a mental, perceptual model of a catchment and the collection of equations referred to as a mathematical/procedural model (e.g. Beven, 2012; Clark and Kavetski, 2010; Gupta et al., 2012; Refsgaard and Henriksen, 2004).

Every application of a rainfall-runoff model is complicated by various aspects of uncertainty (e.g. Beven and Freer, 2001b; Pechlivanidis et al., 2011; Peel and Blöschl, 2011). Uncertainty is introduced during measurement of model input variables such as precipitation (e.g. Oudin et al., 2006) and temperature (e.g. Bárdossy and Singh, 2008) and derived variables such as potential evapotranspiration (e.g. Andréassian et al., 2004; Oudin et al., 2005, 2006). Uncertainty is also present in measurements against which model output is compared, such as streamflow (e.g. Di Baldassarre and Montanari, 2009; McMillan et al., 2010), water table depth (e.g. Freer et al., 2004) and water quality (e.g. McMillan et al., 2012). Values of model parameters can be uncertain due to dependency of 'optimal' parameter values on climatic conditions during model calibration (e.g. Coron et al., 2012; Fowler et al., 2016), due to the choice of calibration algorithm (Arsenault et al., 2014) or due to the performance metric used (e.g. Efstratiadis and Koutsoyiannis, 2010; Gupta et al., 2009). Finally, the choice of model structure (i.e. the collection of equations and their internal connections that make up the model) itself is uncertain (Andréassian et al., 2009; Coron et al., 2012; Van Esse et al., 2013; Fenicia et al., 2008a, 2014; Krueger et al., 2010). Currently, a wide variety of models are available. They may be different in spatial and temporal resolution, or include different processes, be deterministic or stochastic, might be based on top-down or bottom-up philosophies, or be different in some other way. This paper contributes to the investigation of model structure uncertainty of lumped, deterministic conceptual models. We hope to make progress towards answering a core question in hydrologic modelling: out of the overwhelming number of available models, which one is the most appropriate choice for a given catchment?

Conceptual models tend to have low data requirements (catchment-averaged forcing instead of spatially explicit) and are less computationally intensive than spatially explicit models. They are used in both scientific and operational settings (Perrin et al., 2001). A wide range of conceptual model structures exists, e.g. SACRAMENTO (Burnash, 1995; National Weather Service, 2005), TOPMODEL (Beven and Freer, 2001a), SIMHYD (Chiew et al., 2002), the TANK model (Sugawara, 1995) and many more, but there is no clear basis to choose between the different models (Beven, 2012). Models are different both in their internal structure (i.e. which storages are represented and how they are connected) and in their choice of flux equations (i.e. whether and how any given flux is quantified with a mathematical equation). Choosing the right model for a catchment where hydrological responses are measured is difficult because achieving a 'good' value on a performance metric is a necessary but not sufficient condition to determine whether a model produces the "right results for the right reasons" (Kirchner, 2006). Different model structures can achieve superficially similar performance metrics, but might reach this point by wildly different

internal dynamics (de Boer-Euser et al., 2017; Goswami and O'Connor, 2010; Perrin et al., 2001). Therefore, good simulation metrics do not necessarily tell us which model structure is more appropriate for this catchment. Choosing a suitable model structure where the catchment is ungauged is even more challenging. This model structure uncertainty is largely unquantified, even for existing models with a long legacy of 'successful' (often defined as having achieved a high value for some performance metric) applications. However, comparison of different models can be an expensive task if each model needs to be set up individually. Model inter-comparison studies are further complicated by the fact that documented computer code is unavailable for many model structures.

In recent years multi-model frameworks have received considerable attention. These provide a standardized framework in which several models are presented, or users can construct new models, or both. This reduces the time cost of a model comparison study, allows fair comparison of different model structures in a test case and allows the investigator to isolate choices in the model development process. Examples include the Modular Modelling System (MMS, Leavesley et al., 1996), the Rainfall-Runoff Modelling Toolbox (RRMT, Wagener et al., 2002), the Framework for Understanding Structural Errors (Clark et al., 2008), a fuzzy model selection framework (Bai et al., 2009), SUPERFLEX (Fenicia et al., 2011; Kavetski and Fenicia, 2011), the Catchment Modelling Framework (CMF, Kraft et al., 2011)~~, FARM (Euser et al., 2013)~~ and the Structure for Unifying Multiple Modelling Alternatives (SUMMA, Clark et al., 2015a, 2015b). These frameworks are either limited to a small number of existing models (e.g. MMS, RRMT), use a pre-defined internal organization of stores (FUSE), consist of generic model elements (i.e. stores, fluxes and lags) that are not easily recognizable as existing models (e.g. CMF, SUPERFLEX), or are more physics-based and thus difficult to use with conceptual models (e.g. ~~CMF,~~ SUMMA).~~.~~ Thus, despite these many existing frameworks, there is a need for a new framework that provides a user-friendly, standardized way to construct and compare existing, widely-used conceptual models, without constraining the allowed model architecture a priori.

This paper introduces the Modular Assessment of Rainfall-Runoff Models Toolbox (MARRMoT) to fill a gap in the current selection of multi-model frameworks. MARRMoT provides an open-source, easy-to-use, expandable framework that currently includes 46 different conceptual model formulations. This provides all the benefits of a multi-model framework: models are constructed in a modular fashion from separate flux equations, which allows easy modification of provided models and expansion of the framework with new models or fluxes; ~~best~~ good practices for numerical model solving are implemented as standard options; and all MARRMoT models require and provide standardized inputs and outputs. The large number of models in the framework will facilitate studies that lead to more generalizable conclusions about model and/or catchment functioning. This work also provides a pragmatic overview of the wide variety of different flux equations and model structures that are currently used, facilitating studies and discussion beyond direct model comparison. Due to the code being open source, transparency and repeatability of research is encouraged, additions to the framework are possible, and the community can find and correct any mistakes. Finally, MARRMoT is provided with extensive documentation about the models included, the conversion of flux equations to computer code, recommendations for generalized parameter ranges for model sensitivity

analysis and/or calibration, a User Manual explaining framework setup, functioning and use, and several example workflow scripts that allow use of the framework even with minimal programming experience.

2 MARRMoT design considerations

MARRMoT takes inspiration from earlier modular frameworks (e.g. FUSE (Clark et al., 2008), FLEX (Fenicia et al., 2011)) and uses modular code with individual flux equations as the basic building blocks. Multi-model frameworks benefit from modular implementation because this simplifies programming of the framework and makes it easier to (i) re-use components of a model in a different context, including cases where the same basic equation is used by multiple models; and (ii) add new options to the framework (Clark et al., 2008). Section 2.1 gives a brief outline of the project scope and design philosophy. MARRMoT follows several other ~~best~~ good practices for model development which are briefly described in ~~the following~~ sub-sections 2.2 to 2.5.

2.1 Scope

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MARRMoT's scope is limited to conceptual hydrological models and the code currently includes no spatial discretization of inputs or catchment response. Models are expected to be used in a lumped fashion, although users could create their own interface to use MARRMoT code to represent within-catchment variability using multiple lumped model structures. Required model inputs are standardized across all MARRMoT models and every model only requires time series of precipitation and potential evapotranspiration, and optionally of temperature (used by certain snow modules). Model outputs are equally standardized and provide time series of simulated flow and total evaporation fluxes, and optionally time series of model states and internal fluxes. The models are set up such that they can use a user-specified time step size (e.g. daily, hourly) which is currently effectively the temporal resolution of the forcing data. Models and flux equations internally account for this time step size, so that parameter values can use consistent units, regardless of the temporal resolution of the forcing data. The main goal of this set up is ease-of-use, so that it is straightforward to switch between different model structures within an experiment. MARRMoT models are based on written documentation only, not on existing computer code. This choice is motivated by our aim to produce traceable code and by several practical concerns. The documentation we base our models on is traceable through our cited sources. Computer code of hydrologic models tends to be less traceable than their documentation: code might be unavailable, code might not be accompanied by a persistent identifier, or multiple versions of the same model (using the same model name) might be available which complicates finding the 'original' computer code. This is supported by various authors who developed the original models: "Today many versions of the HBV model exist, and new codes are constantly developed by different groups …" (Lindström et al., 1997) and " … TOPMODEL is not a single model structure […] but more a set of conceptual tools" (Beven et al., 1995).

~~2.1~~2.2 Separation of model equations and equation solving

First, MARRMoT uses a distinct separation of model equations as state-space formulations ~~(ODEs)~~ and the numerical approach used to solve these equations. In the theoretical process of developing a new hydrological model, the modeller ideally goes through several distinct steps (e.g. Beven, 2012; Clark and Kavetski, 2010; Gupta et al., 2012). To start, the modeller develops a mental, *perceptual* model of catchment behaviour based on observations and/or other knowledge (i.e. expert opinion). Next, this model is simplified into an abstraction that shows the connection of the most important fluxes and storages (also termed a *conceptual* model, but this is a distinctly different meaning than when applied to a bucket-type hydrologic model). These relations are then formalized as Ordinary Differential Equations (ODEs) and their constitutive functions in a *mathematical* model. Finally, creating computer code to solve these equations sequentially as a time series is done with the *procedural* model. In practice however, these stages are often not distinct and tend to overlap (e.g. Kavetski et al., 2003), a process referred to as "ad hoc" modelling. Overlap of the *mathematical* and *procedural* model can lead to altered model behaviour and difficulty with parameter estimation (Clark and Kavetski, 2010; Kavetski and Clark, 2010; Kavetski et al., 2003). A clear separation between model equations and the code used to solve those equations gives computer code that is easier to understand and update with new time-stepping schemes or flux equations, relative to code where the model equations are interwoven with the numerical scheme.

~~2.2~~2.3 Robust numerical approximation of model equations

Second, MARRMoT gives the possibility to choose a numerical method to approximate the ODEs in discrete time steps. Currently, a fixed-step Implicit Euler method is recommended as default, and an Explicit Euler method is provided for result matching with previous studies. Many implementations of hydrologic models use the Explicit Euler method to approximate storage changes (Schoups et al., 2010; Singh and Woolhiser, 2002). The Explicit Euler method relies on storage values at the start of a time step to estimate flux sizes in the current time step: FLUX(t) = f(STORE(t-1)). This method is easy to implement and fast to compute, but has several disadvantages: it has low accuracy and only conditional stability, which can lead to large numerical errors and amplification of such errors under certain conditions (Clark and Kavetski, 2010; Kavetski and Clark, 2010; Schoups et al., 2010). Implicit methods such as Implicit Euler instead rely on an iterative procedure that relates flux size to storage at the end of a time step: FLUX(t) = f(STORE(t)). These methods require more intensive iterative computation, but avoid the aforementioned issues even when implemented with fixed time step sizes (Kavetski et al., 2006; Schoups et al., 2010). Higher-order numerical approximation methods are currently not provided in MARRMoT but can be included in a straightforward manner. Note that fixed time step size refers to the use of a single time step size throughout a simulation (~~e.g. hourly, daily~~i.e. no adaptive sub-stepping is used; see section 5.3.5)~~,~~ and does not prescribe the time step size (e.g. hourly, daily)~~.~~

~~2.3~~2.4 Smoothing of threshold discontinuities in model equations

Third, MARRMoT removes threshold discontinuities in model equations through logistic smoothing (Clark et al., 2008; Kavetski and Kuczera, 2007). Hydrologic processes are often characterized by thresholds, e.g. snowmelt starts when a certain temperature is exceeded, and saturation excess flow occurs when the soil is saturated. Introducing threshold behaviour into hydrologic models leads to discontinuities in the model's objective function, which can complicate parameter estimation when small changes in parameter values may lead to large changes in objective function value or in the gradient thereof (Kavetski and Kuczera, 2007). Smoothing model equations avoids these discontinuities but also involves a fundamental change to the model equations. Kavetski and Kuczera (2007) recommend logistic functions to smooth threshold equations that closely resemble the original threshold function but are continuous throughout the function's domain. MARRMoT smooths storage-based thresholds with a logistic function (Clark et al., 2008):

$$Q_o = Q_{in}\left(1 - \Phi(S, S_{max}, \rho_S, \varepsilon)\right) \quad (1)$$

$$\Phi(S, S_{max}, \rho_S, \varepsilon) = \frac{1}{1+e^{\frac{S - S_{max} - \omega\varepsilon}{\omega}}} \quad (2)$$

Where Q_o and Q_{in} are flux output and input respectively and $\phi(..)$ the smoothing operator. S and S_{max} are current and maximum storage respectively, ω represents the degree of smoothing according to $\omega = \rho_S S_{max}$, and ε is a coefficient that ensures that S does not exceed S_{max}. ρ_S and ε can be specified by the user, or used with default values of 0.01 and 5.00 respectively (Clark et al., 2008). Temperature-based thresholds are smoothed with a different logistic function (Kavetski and Kuczera, 2007):

$$P_S = P\Phi(T, T_t, \rho_T) \quad (3)$$

$$\Phi(T, T_0, \rho_T) = \frac{1}{1+e^{\frac{T - T_0}{\rho_T}}} \quad (4)$$

Where P_S is precipitation as snow, P incoming precipitation and $\phi(..)$ the smoothing operator. T and T_0 are the current and threshold temperatures respectively, and ρ_T is the smoothing parameter with default value 0.01.

~~2.4~~2.5 Simultaneous solving of model equations

Fourth, MARRMoT solves all model equations simultaneously rather than sequentially. Operator-splitting (OS) numerical approximations integrate fluxes sequentially and can be useful in cases such as large systems of partial differential equations, where computational speed would otherwise be a limiting factor (Fenicia et al., 2011). Sequential calculation of model fluxes is common practice in many hydrologic models (e.g. SACRAMENTO and GR4J) but this approach assumes that fluxes occur in a pre-determined order. It is preferable to integrate model fluxes simultaneously to avoid "physically unsatisfying assumption[s]" (Fenicia et al., 2011; Santos et al., 2018). MARRMoT follows this recommendation, barring certain cases where the model is divided into two distinct parts due to a delay function, in which case simultaneous solving of the first and second part of the model is impossible.

3 MARRMoT

MARRMoT provides Matlab code for 46 conceptual models following the ~~best~~ good model development practices outlined in Section 2. This section provides a summary of the framework because it is infeasible to discuss every individual model here. References to the Supporting Materials guide the interested reader to a more in-depth discussion of each model and its implementation in MARRMoT. In addition to this paper, the MARRMoT documentation includes the following:

- Supporting Material S2 - Model descriptions. This document contains descriptions of all 46 models in a standardized format. Each description includes a short introduction to the model, a list of parameters, a model schematic and a discussion of the ODEs and constitutive functions that describe the model's storage changes and fluxes.
- Supporting Material S3 - Flux equation code. This document contains an overview of the 105 different flux equations used in MARRMoT, and their implementation as computer code.
- Supporting Material S4 - Unit Hydrograph overview. This document contains an overview of the 7 different Unit Hydrograph routing schemes used in MARRMoT.
- Supporting Material S5 - Parameter ranges. This document contains an overview of recommended parameter ranges for the 46 models based on published literature about hydrologic process and model application studies. The ranges are standardized across models, so that similar processes use similar parameter ranges. Use of the recommended ranges is optional.
- User Manual: This document helps a user set up MARRMoT for use in either Matlab or Octave, outlines the inner workings of the standardized models, provides several workflow examples and provides examples on how to create a new flux equation or model.

3.1 General MARRMoT outline

Figure 1 shows the setup of the MARRMoT framework and what the framework requires (i.e. data, model options, etc.) and provides for a given modelling study. Each model has its own separate model function, which contains both the numerical implementation of the model (i.e. the ODEs and fluxes that make up this model, as given in Supporting Material S2, S3 and S4) and the necessary code to handle user input, run the model to produce a time series and generate output. The user is expected to provide the following inputs: time series of climate variables, initial values for each model store, choice of numerical integration method and settings for Matlab solvers, and values for each model parameter. Note that the solver selection relates to time-stepping numerics, not parameter selection / optimisation. Optionally, MARRMoT's provided parameter range guidance (Supporting Material S5**)** can inform the choice of parameter values. Parameter ranges have been standardized as much as possible across all models, such that similar processes use the same range of possible parameter values across models (e.g. this ensures that all models that have an interception component with a maximum capacity can use the same range, 0-5mm, for their respective interception capacity parameter). Each model generates a time series of total simulated flow and total simulated evaporation as default output. Optionally, users can request variables with time series of storages and

internal fluxes, as well as a summary of the main water balance components. The User Manual provides several workflow examples that showcase possible uses of MARRMoT: the examples cover (i) application of a single model, with a single parameter set to a single catchment, (ii) random parameter sampling from provided parameter ranges for a single model, (iii) application of three different models to a single catchment, and (iv) calibration of a single parameter set for a single model. These examples can easily be adapted to work with multiple catchments if desired.

The basic building blocks inside each model function are flux functions. Each flux function describes a single flux, for example evaporation from an interception store, water exchange between two soil moisture stores or baseflow from groundwater. Flux functions are kept separate from the model functions, and each model calls several flux functions as needed. This allows for consistency across models (if errors are present in any flux function, at least they are the same in all models), easy implementation of new flux equations and facilitation of studies that are specifically interested in differences between various mathematical equations that all represent the same flux or process. The inputs required, and output returned by each flux function varies. See Supporting Material S3 for a full overview of the mathematical functions used to represent fluxes in each model description, relevant constraints, numerical implementation of each flux in MARRMoT and a list of models that use each flux function). Various models use a Unit Hydrograph approach to delay flows within the model and/or simulate flow routing. See Supporting Material S4 for a full overview of Unit Hydrographs currently implemented in MARRMoT.

3.2 Summary of included models

Table 1 shows which models are currently implemented in MARRMoT and the main reference(s) for each. Some of the models have a long history of application, others are part of model comparison or development studies. MARRMoT development was not guided by a specific modelling objective (e.g. droughts, floods) and the current selection of model structures mainly aims for variety in the range of model structures. The User Manual provides guidance on changing and expanding the framework and, due to its open nature, these additions can be shared with the wider community. Each model is internally different from the others, either through using different configurations of stores and their connections, or through using different flux equations, or both. Models with sequential numbering (e.g. mopex1, mopex2) are part of the same study and tend to be similar but more elaborate as the number increases. Detailed model descriptions can be found in Supporting Material S2. The model code as currently provided was extensively checked for water balance errors during development, using multiple parameter sets for each model, both randomly sampled and using all combinations of extreme values using MARRMoT's provided parameter ranges. These errors were generally in the order of 1E-12 or smaller, showing that the water balance is properly accounted for in each model.

Figure 2 provides a summarized overview of the model differences, expressed through the number of stores, number of parameters and hydrological processes represented. Models use between 1 and 8 stores, and between 1 and 23 parameters. The number of parameters tends to increase with the number of stores, but exceptions exist. Most models' stores are used to track moisture availability (i.e. across all models 162 stores are used, 155 of which track moisture availability); deficit stores are much rarer (i.e. only 7 out of 162 stores are used to track moisture deficit). Soil moisture storage is the most commonly

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modelled concept, occurring in every model. Routing stores (e.g. "fast flow routing") are included in 18 models, groundwater stores in 13 models, snow storage in 12, interception in 10, unit hydrograph routing also in 10, surface depression storage in 2 and channel storage in 1 model. However, these numbers should not be seen as representative of all conceptual models, because our model overview is necessarily incomplete and some of our models are part of model development studies (where a model is modified until satisfactory performance is obtained). These studies skew the number of stores in certain categories.

4 46 model application test case

To demonstrate the potential of the framework, we calibrated all 46 MARRMoT models to flow observations at Hickory ~~Creak~~ Creek near Brownstown, Illinois (USGS ID: 05592575). This catchment was randomly selected from the CAMELS data set (Addor et al., 2017). The catchment is small with an area of approximately 115 km^2, located at 176 m.a.s.l. at latitude 38.9°. It has a strong seasonal cycle with temperatures varying between -20°C in extreme winters, up to nearly 30°C in summers. Average annual rainfall is approximately 1117mm, 6.4% of which occurs as snowfall. The runoff ratio is around 29% of precipitation. The flow regime is flashy (baseflow index is 0.18) and ephemeral (no flow is observed 18% of the time), High flows (95^{th} percentile flow is 3.7mm/d) are more common in winter and spring, while low flows (5^{th} percentile flow is 0mm/d) are more common in summer and autumn. Soils are a mixture of silt (60%), clay (24%) and sand (16%).

PET input was estimated using climate data included in CAMELS and the Priestley-Taylor method (Priestley and Taylor, 1972). Model calibration uses the time period 1989-1998, model evaluation uses the period 1999-2009. Initial states are found by iteratively running each model with data from the year 1989, until model states reach an equilibrium. The calibration algorithm is the Covariance Matrix Adaptation Evolution Strategy (CMA-ES, Hansen et al., 2003), using the Kling-Gupta Efficiency (Gupta et al., 2009) as the objective function. CMA-ES optimizes a single parameter set per model using MARRMoT's provided parameter ranges. Note that parameter optimization and sampling are currently not part of the provided tools but connecting MARRMoT to various calibration algorithms or Monte Carlo sampling strategies is straightforward (the User Manual provides several basic workflow examples).

Figure 3a shows KGE values during calibration and evaluation for each model. Each result is coloured to indicate the number of calibrated parameters. The number of model parameters seems unrelated to model performance and several models with higher numbers of parameters are outperformed by the simplest 1-parameter bucket model. After analysing the components present in most successful models (not shown), we can speculate that a saturation excess mechanism is key to achieve satisfactory calibration efficiency values in this catchment, and that this catchment's flashy behaviour could be related to rainfall events on soil with low available storage.

Figure 3b shows values for two common hydrologic signatures, calculated for time series of simulated flow by each model (blue/yellow dots, shade showing the KGE value during calibration) and for observations (red dot). These signatures are calculated for the calibration period. There is significant scatter around the observed signature values and models with "good" calibration efficiency (darker shades) are not necessarily closer to observed signature values than models with lower calibration

performance. From this we can conclude that even though certain model structures can achieve "high" values for a given objective function, there is no guarantee that the simulated flow series have the same statistical properties as the observed time series the models were calibrated against. Furthermore, this shows that a saturation-excess model can achieve high efficiency values, but that the full hydrologic behaviour in this catchment is likely more nuanced than a single runoff generation mechanism.

Note that our findings in this test case are not new, but ~~This~~this test case highlights the power of multi-model comparison frameworks: from two simple plots we have deduced a plausible important runoff mechanism in this catchment, found that this mechanism alone cannot satisfactorily explain the catchment's hydrologic behaviour, and that a higher number of model parameters does not necessarily result in more realistic or better performing models. Further investigation of the model structures and their performance could lead us to more insights about hydrologic behaviour and inter-model differences, but that is beyond the scope of this test case.

5 Discussion

5.1 Encouraging debate about reproducibility

Reproducibility of computational hydrology is rarely achieved, primarily because data and code are not regularly made available (Hutton et al., 2016). In the case of hydrologic models, this results in many different versions of the same model being in circulation, made either by different people with different interpretations of the original publication and/or including their own model variant. Without publicly available code, only stating a model's name in a study is insufficient for knowing which equations and numerical methods make up that particular instance of the model. Conclusions from any modelling study are thus conditional on a certain set of equations that are unknown to the reader, which makes generalizability of findings low. However, there is a trend in hydrology towards open and shareable research. Large-scale hydrologic datasets (e.g. CAMELS (Addor et al., 2017), CAMELS-CL (Alvarez-Garreton et al., 2018), GSIM (Do et al., 2018; Gudmundsson et al., 2018)) are commonly made available and certain journals already enforce better coding and sharing practices. Much work is being done on benchmarking data uncertainty (e.g. McMillan et al., 2012) and model performance (e.g. Seibert et al., 2018) which encourages objective conclusions about the strengths and weaknesses of any model and investigation. By making a multi-model toolbox based on various established models available as open source code, we hope to contribute to this trend of more transparent and reproducible science. Furthermore, this toolbox lowers the threshold for model comparison studies and can help to diminish "legacy" reasons for model application (i.e. choosing to use a certain model for reasons other than the model's perceived appropriateness for the task at hand, such as convenience or past experience; Addor and Melsen, 2019).

5.2 The state of conceptual hydrologic models

Our model overview (Supporting Material S2) and compilation of these models in a single framework allows unique lessons and insights into the current state of conceptual models (conditional on the sample of model structures we have selected).

The core of this selection of conceptual models is a soil moisture accounting (SMA) module. Every model includes some form of soil moisture store where moisture is kept and evaporated from. Despite this, surface processes, rather than those in the subsurface (both vadose and groundwater zones), tend to be modelled in the greatest detail. For example, intricate snow (e.g. Lindström et al., 1997; Schaefli et al., 2005), interception (e.g. Fukushima, 1988) and surface depression storage (e.g. Chiew and McMahon, 1994; Leavesley et al., 1983; Markstrom et al., 2015) conceptualizations exist among the models, but subsurface processes tend to be much more abstract. This is the same observation as made in Vinogradov et al. (2011). This is understandable because surface processes are easier to observe and formulate hypotheses about, but the subsurface is a crucial component in the water balance (as evidenced by the presence of a SMA component in every single model). A next step in conceptual modelling can be to explicitly formulate hypotheses of subsurface catchment configurations and testing these. For example, the 'fill-and-spill' hypothesis (Tromp-Van Meerveld and McDonnell, 2006) could be compared to more traditional subsurface conceptualizations such as linear reservoirs. Framing research as testing alternative hypotheses (Clark et al., 2011) and using modelling tools such as MARRMoT allows testing of these ideas in a controlled manner.

A striking difference exists among models that take evaporation from multiple stores. Certain models use the potential evapotranspiration (PET) rate to limit evaporation from each individual store (e.g. MODHYDROLOG (Chiew and McMahon, 1994), NAM (Nielsen and Hansen, 1973), HYCYMODEL (Fukushima, 1988)), whereas others use PET as the maximum that can be evaporated from all stores combined (e.g. ECHO (Schaefli et al., 2014), PRMS (Leavesley et al., 1983; Markstrom et al., 2015), CLASSIC (Crooks and Naden, 2007)). This can lead to situations where a model evaporates water at a net rate higher than PET. Depending on the way PET is estimated (see e.g. McMahon et al. (2013) for an overview of PET estimation methods) and which reference crop is used compared to the vegetation in the catchment being modelled, either assumption might be appropriate. Evaporation is a significant component of the water balance (McMahon et al., 2013) and a proper choice in any modelling effort is thus important.

Another difference is the distinction between process-aggregated and process-explicit models. Process-aggregated models (e.g. GR4J (Perrin et al., 2003), IHACRES (Croke and Jakeman, 2004; Littlewood et al., 1997)) do not attempt to model individual hydrologic processes but focus on the flows resulting from an aggregation of overall catchment behaviour. Process-explicit models (e.g. MODHYDROLOG (Chiew and McMahon, 1994), FLEX-Topo (Savenije, 2010)) explicitly include a variety of hydrologic processes deemed important for a certain modelling purpose. Process-aggregated models tend to have a small number of parameters which is preferable when calibrating a model to streamflow only. Process-explicit models are more intuitive when simulating changing conditions due to their explicit process representation, under the strong assumption that the model's parameters can be related to the real-world processes the model intends to simulate.

Summarizing, even within the subset of all hydrologic models, conceptual models exist in a wide variety of shapes and sizes. They are easy-to-use tools to test whether detailed findings from experimental catchments are applicable to many different catchment types world-wide. This approach combines the thorough understanding developed in well-monitored catchments with the ability to generalise conclusions through extensive testing of these findings in other places.

5.3 MARRMoT considerations

5.3.1 Reliance on imperfect methods

MARRMoT uses built-in Matlab root-finding methods to solve the ODE approximations on every time step. Currently, *fzero* is the default option for models with one store and *fsolve* is the default in multi-store models. *lsqnonlin* is used as a slower but more robust alternative if the former methods are not sufficiently accurate (compared to a user-specified accuracy tolerance). In most cases, this setup performs within acceptable bounds of accuracy. However, for special cases (e.g. very small maximum storage values), the root-finding method might return solutions that are outside the bounds of expected model behaviour (e.g. storages values below 0, storages higher than their maximum capacity or complex numbers), even if "realistic" solutions also exist. Additional constraints must be introduced into the flux equations to prevent this behaviour, because in a large-sample study these issues are difficult to troubleshoot if they occur during the sampling of several thousands of combinations of models and catchments. This involves a fundamental change to model equations necessitated by the use of these solvers. More robust solvers such as *lsqnonlin* allow specification of bounds to the solution space but are less computationally efficient. The current trade-off favours constraints implemented into the fluxes and default use of faster root-finding methods over the more elegant, but much slower, solution provided by *lsqnonlin.* Further optimization of the root-finding methods is considered outside the scope of this version of MARRMoT. Note that settings for these root-finding methods are specified within each model file because certain settings are model-dependent. Progress display is disabled for all three functions (*fzero*, *fsolve*, *lsqnonlin*) by default but can be enabled by the user. The model-dependent Jacobian matrix is specified for *fsolve* and *lsqnonlin*. The maximum number of function evaluations is capped at 1000 for *lsqnonlin*. All other root-finding options are left at default Matlab values (see Matlab documentation of the root-finding methods for further details). Users are encouraged to experiment with these settings to find those that work for their specific problem.

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5.3.2 Speed versus readability

Several considerations during MARRMoT design have been heavily influenced by readability and user-friendliness over computational efficiency. Implementing fluxes as anonymous functions rather than regular functions leads to reduced computational speed but increased clarity of the code.

Matlab was chosen out of similar concerns. Fortran or similar compiled language would grant significant speed-ups but reduce user-friendliness.

5.3.3 Correspondence between MARRMoT and original publications

During MARRMoT development, we have tried to stay close to the original publications that introduced the models. Differences are unavoidable however, due to our criteria of creating a uniform framework. Most changes have to do with spatial discretization, where we reduced the level of detail in a model to make all 46 models lumped.

For certain models (e.g. SACRAMENTO (Burnash, 1995; National Weather Service, 2005)) model code and numerical implementation are so interwoven that far-reaching changes were required to make these models fit into this generalized framework. For all models, it is likely that the use of the default Implicit Euler scheme will provide different results to previous studies that use the (much more common) Explicit Euler scheme. Furthermore, the smoothing of model equations will also cause differences to arise with previous studies. We strongly recommend readers to compare the original publication of each model with the version given in this toolbox, to place results from the MARRMoT models in a proper context of earlier work with these models. We emphasize that our models are based on publications that describe existing models, not on existing computer code. Thus, we neither guarantee nor expect that our code performs exactly like the original version of each model's code (if indeed such a version exists and can be found and agreed upon for any given model).

To illustrate this point, we compare performance of MARRMoT model m07 (based on the GR4J model) with the R implementation of GR4J (part of the airGR package; Coron et al., 2017, 2019), and we compare MARRMoT model m37 (based on HBV-96) with HBV Light (Seibert and Vis, 2012). MARRMoT m07 is an example of a model that has changed significantly from the original source as a result of combining the original documentation (Perrin et al., 2003) with a more recent state-space version of GR4J (Santos et al., 2018), while both MARRMoT m37 and HBV Light are similar to HBV-96. We thus expect larger deviations between simulations from MARRMoT m07 and airGR-GR4J than we expect between simulations from MARRMoT m37 and HBV-Light. In both cases, we selected 10000 parameter sets from MARRMoT's parameter ranges through Latin Hypercube sampling. In the case of GR4J, both MARRMoT and airGR versions use the same 4 parameters. In case of HBV, the MARRMoT version has several additional snow parameters and a capillary rise parameter, while HBV Light has various elevation and input correction factors. These have all been fixed at values that effectively disable their impact on model simulations. We then simulated 5 years of streamflow in the earlier described Hickory Creek using both versions of both models. For comparison purposes, we use the Kling-Gupta Efficiency (KGE; Gupta et al., 2009) to express the similarity between simulations and observations. Figure 4 shows the results of this comparison.

Figure 4a shows that for the best performing parameter set in our sample (in terms of KGE value), the hydrographs generated by MARRMoT m37 and HBV Light are relatively similar. Figures 4c-4e show a decomposition of KGE values into its three constitutive components, that express the linear correlation (KGE_a), the ratio of simulated and observed standard deviations (KGE_a) and the ratio of simulated and observed means (KGE_b) respectively. For a given parameter set, MARRMoT m37 and HBV Light generate simulations that are relatively similar (i.e. close to the 1:1 line). HBV Light tends to produce more variable flows than MARRMoT m37 does (high standard deviation and mean of simulated flows). The reason for this is difficult to investigate because although HBV Light is freely available, its source code is not. Differences between both models' equations and numerical approximation of these equations are likely explanations.

Figure 4b shows that for the best performing parameter set in our sample (in terms of KGE value), the hydrographs generated by MARRMoT m07 and airGR-GR4J are relatively different. Most notable, MARRMoT m07 recessions are much slower and higher than those from airGR-GR4J. Figures 4f-4h indicate that for parameter sets close to the optimal points (i.e. (0,0)), MARRMoT m07 and airGR-GR4J show similar performance. For parameter sets further away from the perfect simulation,

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MARRMoT m07 shows an increasing tendency to simulate more variable flows (higher standard deviation and mean components) than airGR-GR4J does. However, differences between MARRMoT m07 and airGR-GR4J are not unexpected because MARRMoT m07 also uses equations from state-space GR4J (Santos et al., 2018) and the models' equations are thus not identical.

Concluding, we emphasize again that MARRMoT models are based on existing publications only and not on computer code. Differences with other models using the same name are unavoidable. We hope that by making MARRMoT available as open source code, future studies can go beyond simply stating the model name without publishing any model code, and instead can refer to an open-source, traceable version of the model(s) used.

5.3.4 Parameter optimization and sampling

MARRMoT provides model code and recommended parameter ranges but does not include any parameter optimisation, parameter sampling or sensitivity analysis methods. This is a conscious choice because these methods continue to be developed and keeping a latest, state-of-the-art version of each packaged in the MARRMoT distribution is infeasible. We refer the reader to e.g. Arsenault et. al. (2014) for a recent discussion of various optimization methods, to e.g. Beven and Binley (2014) for a recent discussion of GLUE-based uncertainty analysis and to e.g. Pianosi et. al. (2015) for a recent publication of an open-source sensitivity analysis toolbox. Application of any of these methods with MARRMoT models is straightforward. The User Manual provides workflow examples for parameter sampling and parameter calibration, which can be used as a starting point to integrate parameter optimization, sampling or sensitivity analysis methods.

5.3.5 Possible extensions

Lists of contemporary relevant hydrologic models are hard to come by. Such a list would always be incomplete because new models and model variants continue to be developed. As such, there is no reason to assume that the current 46 models in MARRMoT showcase all possible lumped conceptual hydrologic models. Likewise, although MARRMoT includes a wide variety of flux equations, this list should not be assumed to be complete. The MARRMoT User Manual therefore provides detailed guidance on creating new model and flux functions, and the code's location and licensing on Github allows these new models to be shared freely. Extensions to the framework are thus possible and encouraged.

Currently lacking in the code is the possibility to use adaptive time stepping. Fixed-step Implicit Euler approximations are sufficiently accurate for most applications (Clark and Kavetski, 2010; Kavetski and Clark, 2010; Schoups et al., 2010) but adaptive time-stepping can provide additional benefits (Clark et al., 2008; Kavetski and Clark, 2011; Schoups et al., 2010). Our initial assessment is that it would be relatively straightforward to replace the current fixed-step time-stepping implementation with adaptive time-stepping (see e.g. Clark and Kavetski (2010) for further reading on adaptive time-stepping).

6 Conclusions

This paper introduces the Modular Assessment of Rainfall-Runoff Models Toolbox (MARRMoT). This modelling framework is based on a review of conceptual hydrologic models. Across these models, over 100 different flux equations and 7 different Unit Hydrographs (UHs) are used. These are implemented as separate functions and each model draws from this library to select the fluxes and UHs it needs. This results in standardized implementations of 46 unique, lumped model structures. The framework is implemented in Matlab, can be used in Octave, and is provided as open source software (https://github.com/wknoben/MARRMoT ; DOI: 10.5281/zenodo. 2677728~~2~~4825~~42~~). Requirements for running a model are simple: (i) time series of precipitation, potential evapotranspiration and optionally temperature, (ii) initial storage values, (iii) settings that specify the numerical integration method (currently provided are Implicit Euler (recommended) and Explicit Euler) and Matlab solver behaviour, and (iv) values for the model parameters (these can be sampled or optimized from parameter ranges provided as part of MARRMoT). MARRMoT comes with documentation that describes (i) each model and its equations, (ii) the conversion from model equations to computer code, (iii) the implementation of 7 different types of Unit Hydrographs, and (iv) the references used to inform standardized parameter ranges,. The User Manual provides guidance on navigating the Matlab functions in which each model is implemented, several examples of how the framework can be used (with workflow scripts that show the Matlab code required for these analyses), information on how to create new models or flux functions, and several small modifications that can speed up the model code by disabling certain output messages from Matlab's built-in solvers. The main purpose of MARRMoT is to enable multi-model comparison studies and objective testing of model hypotheses. Additional benefits can be gained from the framework's documentation, which provides an easy-to-navigate comparison of 46 unique conceptual hydrologic models. MARRMoT is provided to the community in the hopes that it will be useful and to encourage a growing trend of open and reproducible science.

7 Code availability and dependencies

MARRMoT is provided under the terms of the GNU General Public License version 3.0. MARRMoT code and User Manual can be downloaded from https://github.com/wknoben/MARRMoT (DOI: 10.5281/zenodo. 2677728~~2~~4825~~42~~). Additional documentation can be found in the Supplementary Materials to this paper. MARRMoT has been developed on Matlab version 9.2.0.538062 (R2017a), with the Optimization Toolbox Version 7.6 (R2017a). The Octave distribution has been tested with Octave 4.4.1 and requires the "optim" package. See the User Manual for some detail regarding running MARRMoT in Octave.

8 Author contribution

This work is part of WK's PhD project at the University of Bristol, supervised by RW and JF. WK, RW and JF developed the idea for this framework during discussions. This idea was further developed in discussions between WK, MP and KF, who ~~also~~ provided supervision during WK's visit to the University of Melbourne. WK collected and structured an overview of

available models, designed and coded the framework and wrote the original draft and final version of this manuscript and the framework documentation. KF and RW assisted with conceptualization and implementation of time step sizes in the framework. RW, JF, MP and KF reviewed and edited the manuscript and documentation drafts.

9 Competing interests

The authors declare they have no conflict of interest.

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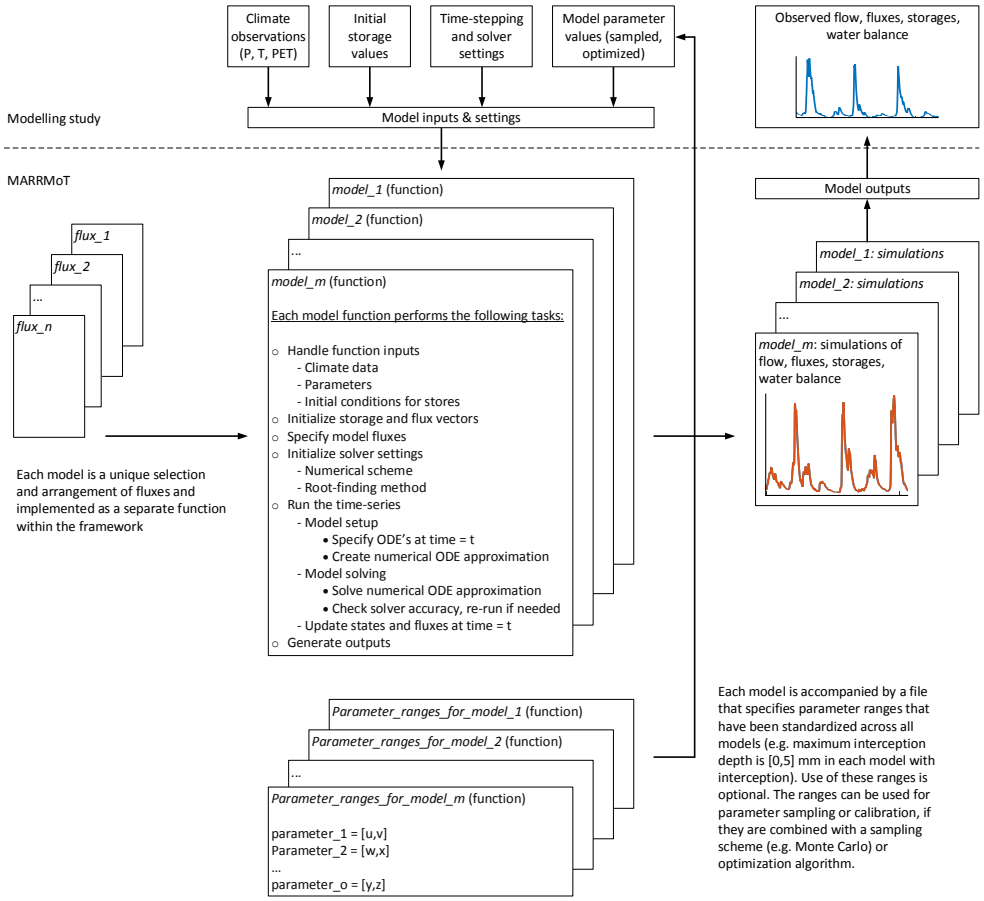
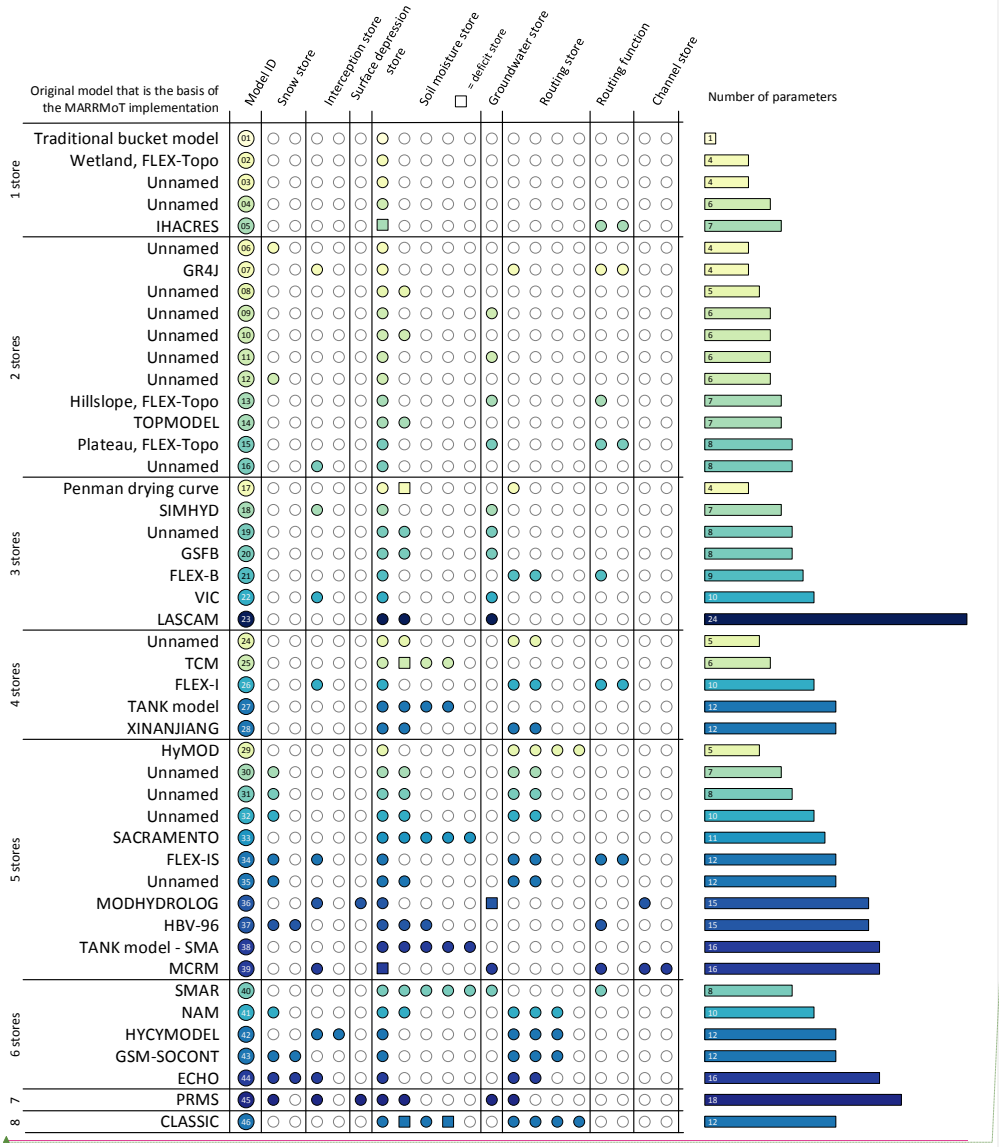


Figure 1: Schematic overview of the MARMMoT framework. MARRMoT provides 46 conceptual models implemented in a standardized way (part below the dotted line). Each model is a unique collection and arrangement of fluxes, but the code-wise setup of each model is the same. Inputs required to run a model are time series of climate variables, values for the model parameters (which can optionally be sampled or optimized using provided, standardized ranges), and initial conditions for each model store. The model returns time series of simulated flow, fluxes and storages and a summary of the simulated water balance.



Field Code Changed

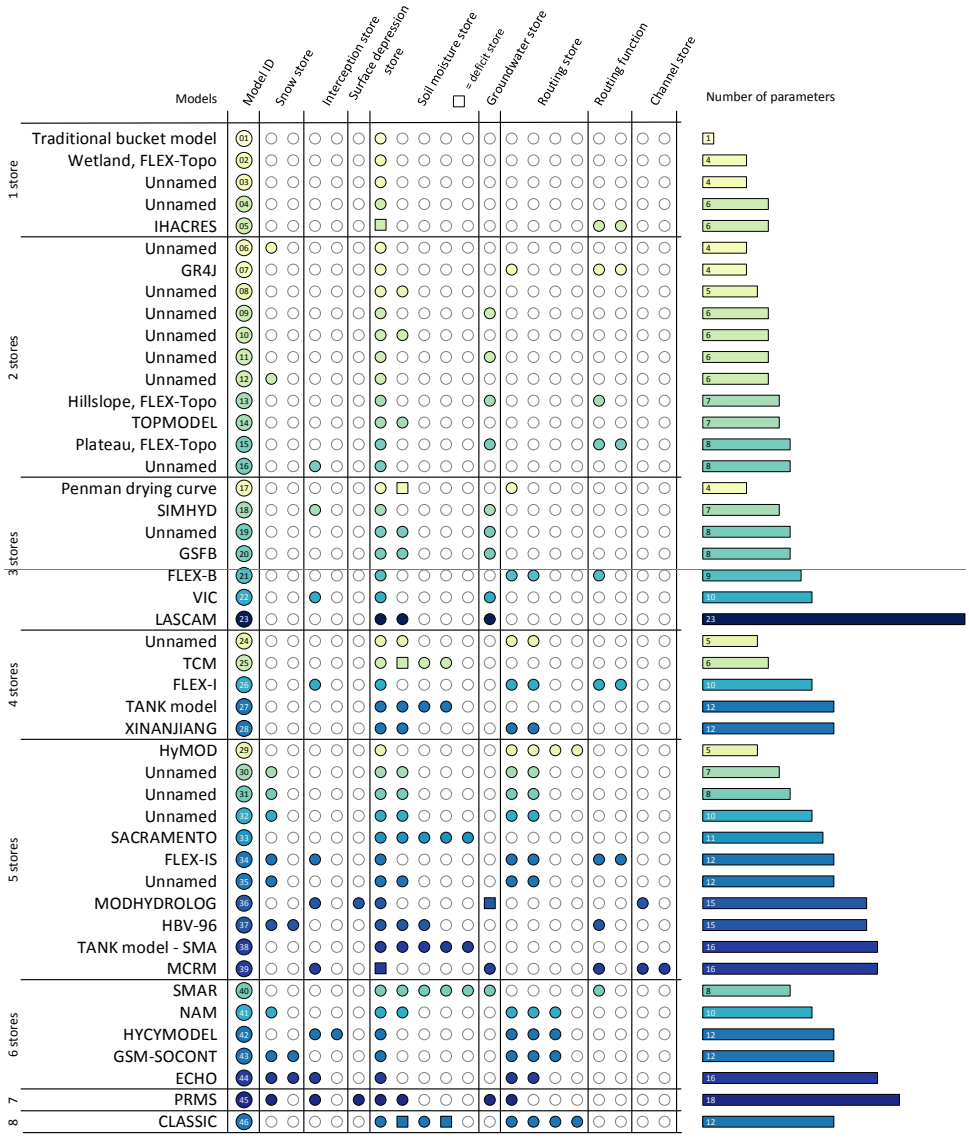

Models
Model ID
Snow store
Interception store
Surface depression store
Soil moisture store
= deficit store
Groundwater store
Routing store
Routing function
Channel store
Number of parameters
1 store
2 stores
3 stores
4 stores
5 stores
6 stores
7
8
Traditional bucket model
Wetland, FLEX-Topo
Unnamed
Unnamed
IHACRES
Unnamed
GR4J
Unnamed
Unnamed
Unnamed
Unnamed
Unnamed
Hillslope, FLEX-Topo
TOPMODEL
Plateau, FLEX-Topo
Unnamed
Penman drying curve
SIMHYD
Unnamed
GSFB
FLEX-B
VIC
LASCAM
Unnamed
TCM
FLEX-I
TANK model
XINANJIANG
HyMOD
Unnamed
Unnamed
Unnamed
SACRAMENTO
FLEX-IS
Unnamed
MODHYDROLOG
HBV-96
TANK model - SMA
MCRM
SMAR
NAM
HYCYMODEL
GSM-SOCONT
ECHO
PRMS
CLASSIC

Figure 2: Overview of MARRMoT models. Models are sorted vertically by number of stores (1 at the top, 8 at the bottom). The columns show broad categories of hydrologic process that can be represented by a model. Coloured circles indicate the model has a store dedicated to the representation of this hydrological process (squares indicate a deficit store). The bar plot on the right shows each model's number of parameters. Colouring refers to the number of parameters.

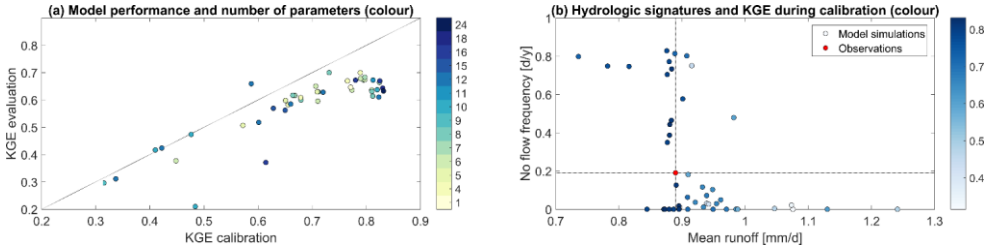


Figure 3: Example of MARRMoT application to Hickory Creek near Brownstown (USA). (a) model performance during calibration (1989-1998) and evaluation (1999-2009) periods. Each dot represents a single model and is coloured according to the model's number of calibrated parameters. (b) Comparison of simulated average flow and no-flow frequency signature values and observed values for those signatures (red dot bisected with lines).

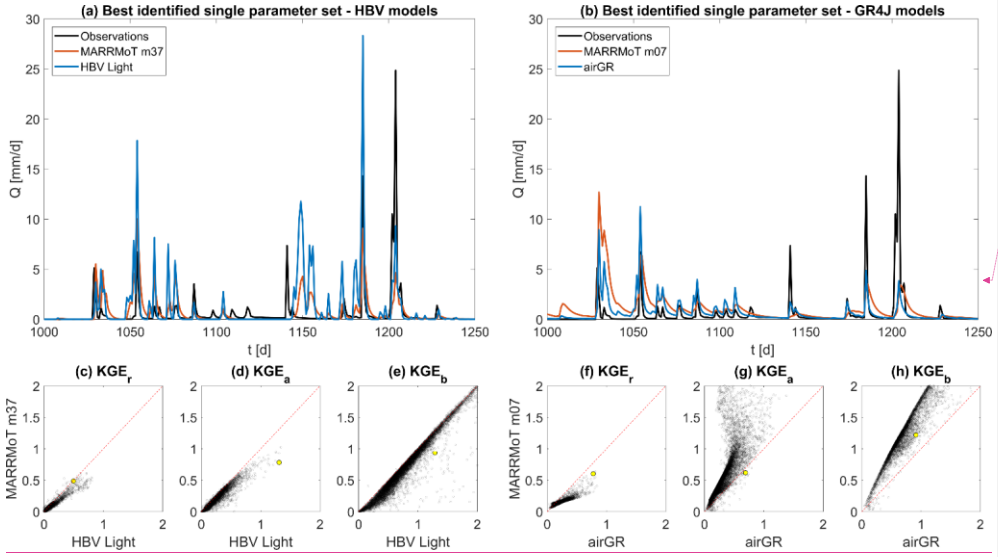


Figure 4: Comparison of two MARRMoT models and freely available model codes based on the same source material. (a) Close up of hydrographs generated by MARRMoT m37 and HBV Light using the same parameter values for their shared parameters. (b) Close up of hydrographs generated by MARRMoT m07 and airGR-GR4J using the same parameter values. (c-e) Constitutive components of the Kling-Gupta Efficiency (KGE) obtained by HBV Light and MARRMoT m37 for 10000 parameter sets in a single catchment. The yellow dot indicates the parameter set used to generate figure a. (f-h). Constitutive components of the KGE obtained by airGR-GR4J and MARRMoT m07 for 10000 parameter sets in a single catchment. The yellow dot indicates the parameter set used to generate figure b.

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Table 2: MARRMoT models. Model IDs are used throughout this paper and the MARRMoT documentation. MARRMoT function names include a longer identifier that either refers to the name of the original model (e.g. m05_ihacres_7p_1s) or to the area of original application (e.g. m_01_collie1_1p_1s which was used in the Collie River basin). The column "Main changes" specifies structural changes between the MARRMoT model and the original model description (note that MARRMoT models are created solely based on the cited sources and not on any computer code). Not mentioned are cases where (i) model equations needed to be modified to account for the time step size at which the model is used; (ii) Ordinary Differential Equations were not given in the original source; (iii) cases where modelled processes were only described qualitatively in the original source, without equations; (iv) cases where model equations where smoothed in their MARRMoT implementations (these can be traced through the overview of flux equations in Supporting Materials S3).

ID	Original model name	Original time step	Main reference(s)	MARRMoT function	Main changes
01	Traditional bucket model	Annual	(Jothityangkoon et al., 2001)	m_01_collie1_1p_1s	-
02	Wetland, FLEX-Topo	Daily	(Savenije, 2010)	m_02_wetland_4p_1s	Model intended to be used with hillslope and plateau in spatially explicit fashion.
03	Unnamed	Monthly	(Jothityangkoon et al., 2001)	m_03_collie2_4p_1s	-
04	Unnamed	Daily	(Atkinson et al., 2002)	m_04_newzealand1_6p_1s	Separated constitutive functions from numerical approximation.
05	IHACRES	6 min to monthly	(Croke and Jakeman, 2004; Littlewood et al., 1997)	m_05_ihacres_7p_1s	Original can use temperature as proxy for evaporation; here PET is always used. Separated constitutive functions from numerical approximation.
06	Unnamed	Monthly	(Eder et al., 2003)	m_06_alpine1_4p_2s	Separated constitutive functions from numerical approximation.
07	GR4J	Daily	(Perrin et al., 2003; Santos et al., 2018)	m_07_gr4j_4p_2s	Combines equations from Santos et al. (2018) with Unit Hydrographs of Perrin et al. (2003).
08	Unnamed	Daily to annual	(Bai et al., 2009)	m_08_us1_5p_2s	Only 1 configuration from several different ones used here. This configuration shows a concept not seen in many other models. Separated constitutive functions from numerical approximation.
09	Unnamed	Daily to annual	(Son and Sivapalan, 2007)	m_09_susannah1_6p_2s	No spatial discretization through multiple buckets used here.
10	Unnamed	Daily to annual	(Son and Sivapalan, 2007)	m_10_susannah2_6p_2s	No spatial discretization through multiple buckets used here.
11	Unnamed	Daily	(Jothityangkoon et al., 2001)	m_11_collie3_6p_2s	-
12	Unnamed	Daily	(Eder et al., 2003)	m_12_alpine2_6p_2s	Separated constitutive functions from numerical approximation.
13	Hillslope, FLEX-Topo	Daily	(Savenije, 2010)	m_13_hillslope_7p_2s	Model intended to be used with wetland and plateau in spatially explicit fashion.
14	TOPMODEL		(Beven et al., 1995; Clark et al., 2008)	m_14_topmodel_7p_2s	No spatial discretization. Only 1 out of many possible configurations used. Not based on topographic index values.

15	Plateau, FLEX-Topo	Daily	(Savenije, 2010)	m_15_plateau_8p_2s	Model intended to be used with hillslope and wetland in spatially explicit fashion.
16	Unnamed	Hourly	(Atkinson et al., 2002, 2003)	m_16_newzealand2_8p_2s	Porosity and soil depth simplified to a single soil moisture storage parameter. Separated constitutive functions from numerical approximation.
17	Penman drying curve	Daily	(Penman, 1950; Wagener et al., 2002)	m_17_penman_4p_3s	-
18	SIMHYD	Daily	(Chiew et al., 2002)	m_18_simhyd_7p_3s	Interception and soil moisture excess flows expressed through different functions.
19	Unnamed	Daily	(Farmer et al., 2003)	m_19_australia_8p_3s	Porosity and soil depth simplified to a single soil moisture storage parameter. Evaporation equations simplified. Separated constitutive functions from numerical approximation.
20	GSFB	Daily, but meant for monthly yield	(Nathan and McMahon, 1990; Ye et al., 1997)	m_20_gsfb_8p_3s	-
21	FLEX-B	Hourly	(Fenicia et al., 2008b)	m_21_flexb_9p_3s	-
22	VIC	Daily	(Clark et al., 2008; Liang et al., 1994)	m_22_vic_10p_3s	No spatial discretization of land types. No use of sensible and latent heat fluxes. Leaf-Area-Index approximated with sinusoidal function and calibration parameters.
23	LASCAM	Daily	(Sivapalan et al., 1996)	m_23_lascam_24p_3s	-
24	Unnamed	Daily	(Ye et al., 2012)	m_24_mopex1_5p_4s	Different formulation for storage excess flows used here.
25	TCM	Daily and event (15 min)	(Moore and Bell, 2001)	m_25_tcm_6p_4s	No spatial discretization in different hydrologic zones.
26	FLEX-I	Hourly	(Fenicia et al., 2008b)	m_26_flexi_10p_4s	-
27	TANK model	Hourly to daily	(Sugawara, 1979, 1995)	m_27_tank_12p_4s	-
28	XINANJIANG	Daily	(Zhao, 1992)	m_28_xinanjiang_12p_4s	No spatial discretization. Tension water represented through double instead of single parabolic curve.
29	HyMOD	Daily	(Boyle, 2001; Wagener et al., 2001)	m_29_hymod_5p_5s	-
30	Unnamed	Daily	(Ye et al., 2012)	m_30_mopex2_7p_5s	Different formulation for storage excess flows used here.
31	Unnamed	Daily	(Ye et al., 2012)	m_31_mopex3_8p_5s	Different formulation for storage excess flows used here.
32	Unnamed	Daily	(Ye et al., 2012)	m_32_mopex4_10p_5s	Different formulation for storage excess flows used here. Leaf-Area-Index approximated with sinusoidal function with calibrated parameters.
33	SACRAMENTO	Daily	(Burnash, 1995; National Weather Service, 2005)	m_33_sacramento_11p_5s	Various equations in the lower zone were changed to allow simultaneous calculation of all fluxes instead of the original forced sequential calculation.

34	FLEX-IS	Daily	(Fenicia et al., 2008b; Nijzink et al., 2016)	m_34_flexis_12p_5s	Different formulation of storage excess flows. Separated constitutive functions from numerical approximation.
35	Unnamed	Daily	(Ye et al., 2012)	m_35_mopex5_12p_5s	Different formulation for storage excess flows used here. Leaf-Area-Index approximated with sinusoidal function with calibrated parameters.
36	MODHYDROLOG	Daily	(Chiew, 1990; Chiew and McMahon, 1994)	m_36_modhydrolog_15p_5s	No spatial routing scheme.
37	HBV-96	Daily	(Lindström et al., 1997)	m_37_hbv_15p_5s	No spatial discretization. No precipitation and evaporation from lakes. No correction factors for climate inputs.
38	TANK model - SMA	Hourly to daily	(Sugawara, 1979, 1995)	m_38_tank2_16p_5s	-
39	MCRM	Daily	(Moore and Bell, 2001)	m_39_mcrm_16p_5s	Simplified evaporation and routing procedures.
40	SMAR	Hourly to daily	(O'Connell et al., 1970; Tan and O'Connor, 1996)	m_40_smar_8p_6s	Fixed number of upper stores instead of treating this as a calibration parameter.
41	NAM	Daily	(Nielsen and Hansen, 1973)	m_41_nam_10p_6s	Linear reservoirs used instead of routing functions.
42	HYCYMODEL	Hourly to daily	(Fukushima, 1988)	m_42_hycymodel_12p_6s	Assumption made about evaporation equation. Separated model equations from numerical approximation.
43	GSM-SOCONT	Daily	(Schaefli et al., 2005)	m_43_gsmsocont_12p_6s	No spatial discretization. No annual glacier calculations.
44	ECHO	Hourly to daily	(Schaefli et al., 2014)	m_44_echo_16p_6s	No spatial discretization. Soil moisture storage given in absolute terms instead of fractional terms.
45	PRMS	1 min to daily	(Leavesley et al., 1983; Markstrom et al., 2015)	m_45_prms_18p_7s	PET is a model input instead of calculated within the model. Simplified interception and snow modules. No spatial discretization.
46	CLASSIC	Daily	(Crooks and Naden, 2007)	m_46_classic_12p_8s	No spatial discretization. No arable soil component. Separated model equations from numerical approximation.

~~Table 1: MARRMoT models~~

ID	Name	Main reference(s)	MARRMoT function
01	Traditional bucket model	(Jothityangkoon et al., 2001)	m_01_collie1_1p_1s
02	Wetland, FLEX-Topo	(Savenije, 2010)	m_02_wetland_4p_1s
03	Unnamed	(Jothityangkoon et al., 2001)	m_03_collie2_4p_1s
04	Unnamed	(Atkinson et al., 2002)	m_04_newzealand1_6p_1s
05	IHACRES	(Croke and Jakeman, 2004; Littlewood et al., 1997)	m_05_ihacres_6p_1s
06	Unnamed	(Eder et al., 2003)	m_06_alpine1_4p_2s
07	GR4J	(Perrin et al., 2003; Santos et al., 2018)	m_07_gr4j_4p_2s
08	Unnamed	(Bai et al., 2009)	m_08_us1_5p_2s
09	Unnamed	(Son and Sivapalan, 2007)	m_09_susannah1_6p_2s
10	Unnamed	(Son and Sivapalan, 2007)	m_10_susannah2_6p_2s
11	Unnamed	(Jothityangkoon et al., 2001)	m_11_collie3_6p_2s
12	Unnamed	(Eder et al., 2003)	m_12_alpine2_6p_2s
13	Hillslope, FLEX-Topo	(Savenije, 2010)	m_13_hillslope_7p_2s
14	TOPMODEL	(Beven et al., 1995; Clark et al., 2008)	m_14_topmodel_7p_2s
15	Plateau, FLEX-Topo	(Savenije, 2010)	m_15_plateau_8p_2s
16	Unnamed	(Atkinson et al., 2002, 2003)	m_16_newzealand2_8p_2s
17	Penman drying curve	(Penman, 1950; Wagener et al., 2002)	m_17_penman_4p_3s
18	SIMHYD	(Chiew et al., 2002)	m_18_simhyd_7p_3s
19	Unnamed	(Farmer et al., 2003)	m_19_australia_8p_3s
20	GSFB	(Nathan and McMahon, 1990; Ye et al., 1997)	m_20_gsfb_8p_3s
21	FLEX-B	(Fenicia et al., 2008b)	m_21_flexb_9p_3s
22	VIC	(Clark et al., 2008; Liang et al., 1994)	m_22_vic_10p_3s

23	LASCAM	(Sivapalan et al., 1996)	m_23_lascam_24p_3s
24	Unnamed	(Ye et al., 2012)	m_24_mopex1_5p_4s
25	TCM	(Moore and Bell, 2001)	m_25_tcm_6p_4s
26	FLEX-I	(Fenicia et al., 2008b)	m_26_flexi_10p_4s
27	TANK model	(Sugawara, 1979, 1995)	m_27_tank_12p_4s
28	XINANJIANG	(Zhao, 1992)	m_28_xinanjiang_12p_4s
29	HyMOD	(Boyle, 2001; Wagener et al., 2001)	m_29_hymod_5p_5s
30	Unnamed	(Ye et al., 2012)	m_30_mopex2_7p_5s
31	Unnamed	(Ye et al., 2012)	m_31_mopex3_8p_5s
32	Unnamed	(Ye et al., 2012)	m_32_mopex4_10p_5s
33	SACRAMENTO	(Burnash, 1995; National Weather Service, 2005)	m_33_sacramento_11p_5s
34	FLEX-IS	(Fenicia et al., 2008b; Nijzink et al., 2016)	m_34_flexis_12p_5s
35	Unnamed	(Ye et al., 2012)	m_35_mopex5_12p_5s
36	MODHYDROLOG	(Chiew, 1990; Chiew and McMahon, 1994)	m_36_modhydrolog_15p_5s
37	HBV-96	(Lindström et al., 1997)	m_37_hbv_15p_5s
38	TANK model - SMA	(Sugawara, 1979, 1995)	m_38_tank2_16p_5s
39	MCRM	(Moore and Bell, 2001)	m_39_mcrm_16p_5s
40	SMAR	(O'Connell et al., 1970; Tan and O'Connor, 1996)	m_40_smar_8p_6s
41	NAM	(Nielsen and Hansen, 1973)	m_41_nam_10p_6s
42	HYCYMODEL	(Fukushima, 1988)	m_42_hycymodel_12p_6s
43	GSM-SOCONT	(Schaefli et al., 2005)	m_43_gsmsocont_12p_6s
44	ECHO	(Schaefli et al., 2014)	m_44_echo_16p_6s
45	PRMS	(Leavesley et al., 1983; Markstrom et al., 2015)	m_45_prms_18p_7s

~~46~~	~~CLASSIC~~	~~(Crooks and Naden, 2007)~~	~~m_46_classic_12p_8s~~