The emergence of community models in hydrology

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Context

Hydrological models (HMs) are essential tools to explore terrestrial water dynamics and to anticipate future hydrological events. Since their inception, HMs have been **developed in parallel by different institutions**. There is now a plethora of HMs, yet a relative absence of cross-model developments (code is almost never portable between models) and of guidance on model selection.

Furthermore, traditional HMs, developed over the last decades, **typically rely on a single model structure** (most processes are simulated by a single set of equations). This lack of modularity makes it difficult to i) understand differences between models, ii) run a large ensemble of models, iii) capture the spatial variability of hydrological processes and iv) develop and improve hydrological models in a **coordinated fashion across the community**.

Approach

We argue that these limitations can be overcome by modular modelling frameworks (MMFs), which are **master templates for model generation**. MMFs offer several options for each important modelling decision. They also allow users to **add functionalities when they are required**, by loading libraries developed and maintained by the community - this makes **multimodel frameworks good candidates to become community models** (slide 4).

Many MMFs exist (RAVEN, SUPERFLEX, MARRMoT, FUSE, SUMMA). Here we present recent FUSE developments designed to overcome the HMs limitations outlined above (slides 2), to foster **more reproducible, re-usable and collaborative research in hydrology** and enable more systematic model development and use (slide 3).

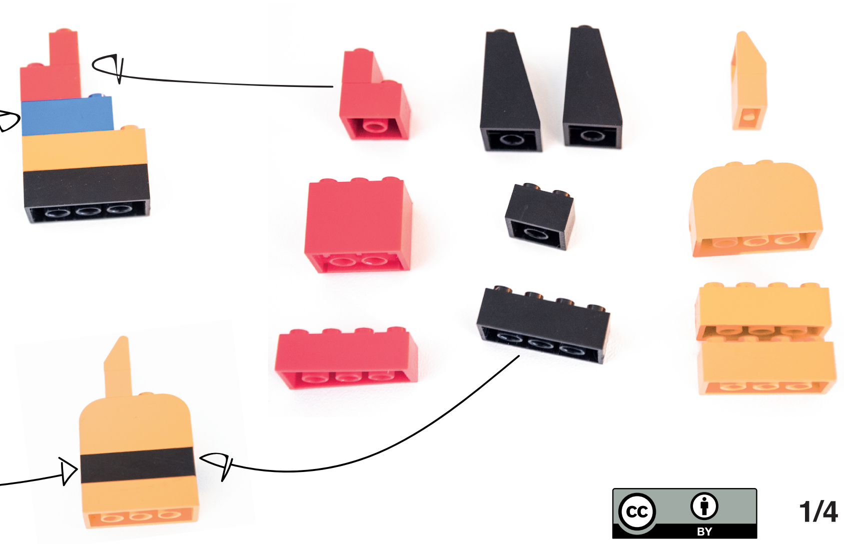
Differences between fixed-structure models and MMFs explained with Lego

Fixed-structure models

Each construction represents a **model**, each block represents a **module** (e.g. snow accumulation/melt, infiltration, baseflow generation).

The modules can be separated and recombined using MMFs to create new models

Modular modelling frameworks



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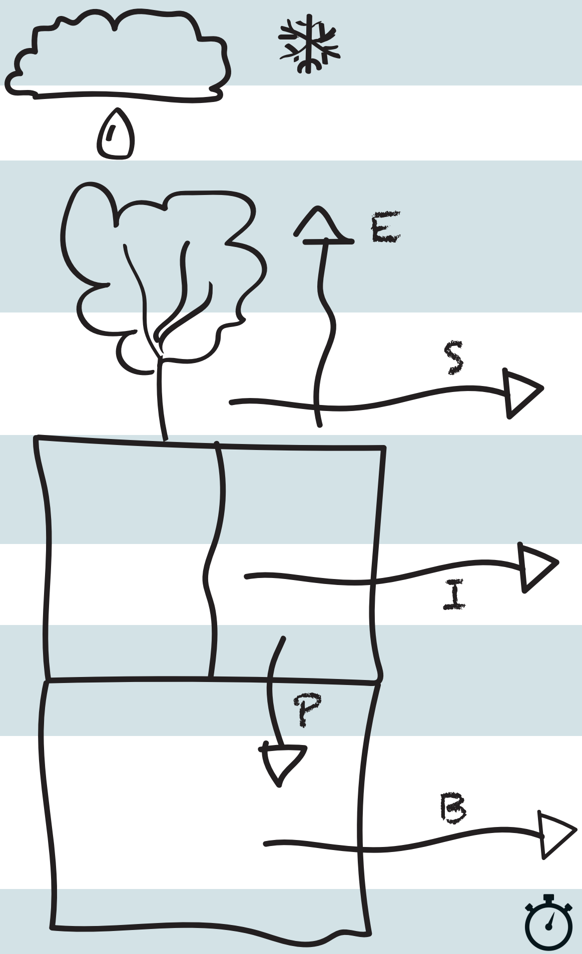
Fixed-structure models have a single option for most of their model decisions.
In contrast, the Framework for Understanding Structural Errors (FUSE) is a **multiple-choice model.**
FUSE was first released by Clark et al. (2008), FUSE2 (in prep.) improves its usabiltiy and efficiency over continenal domains.

These modules can be combined in many ways to i) conduct controlled experiments and ii) create and run an ensemble of models.

Hydrological processes (as seen by FUSE2)



Model decisions	FUSE options (modules)
1) snow	A) temperature index snow model
	B) no snow model
2) rainfall error	A) additive rainfall error
	B) multiplicative rainfall error
3) evaporation	A) sequential evaporation model
	B) root weighting
4) surface runoff	A) ARNO/Xzang/VIC parameterisation (upper zone control)
	B) PRMS variant (fraction of upper tension storage)
	C) TOPMODEL parameterisation
5) upper-layer architecture	A) upper layer broken up into tension and free storage
	B) tension storage sub-divided into recharge and excess
	C) upper layer defined by a single state variable
6) interflow	A) interflow
	B) no interflow
7) percolation	A) water from (field cap to sat) avail for percolation
	B) water from (wilt pt to sat) avail for percolation
	C) perc defined by moisture content in lower layer
8) lower-layer architecture and baseflow	A) tension reservoir plus two parallel tanks
	B) baseflow reservoir of unlimited size, frac rate
	C) baseflow reservoir of unlimited size, power recession
	D) baseflow reservoir of fixed size
9) time delay in runoff	A) routing use a Gamma distribution
	B) no routing

Clark et al., Framework for Understanding Structural Errors (FUSE): A modular framework to diagnose differences between hydrological models, Water Resour. Res., 44(12), doi:10.1029/2007WR006735, 2008.

Addor et al., FUSE2: a modular framework for controlled multi-model hydrological experiments, in prep. for GMD.

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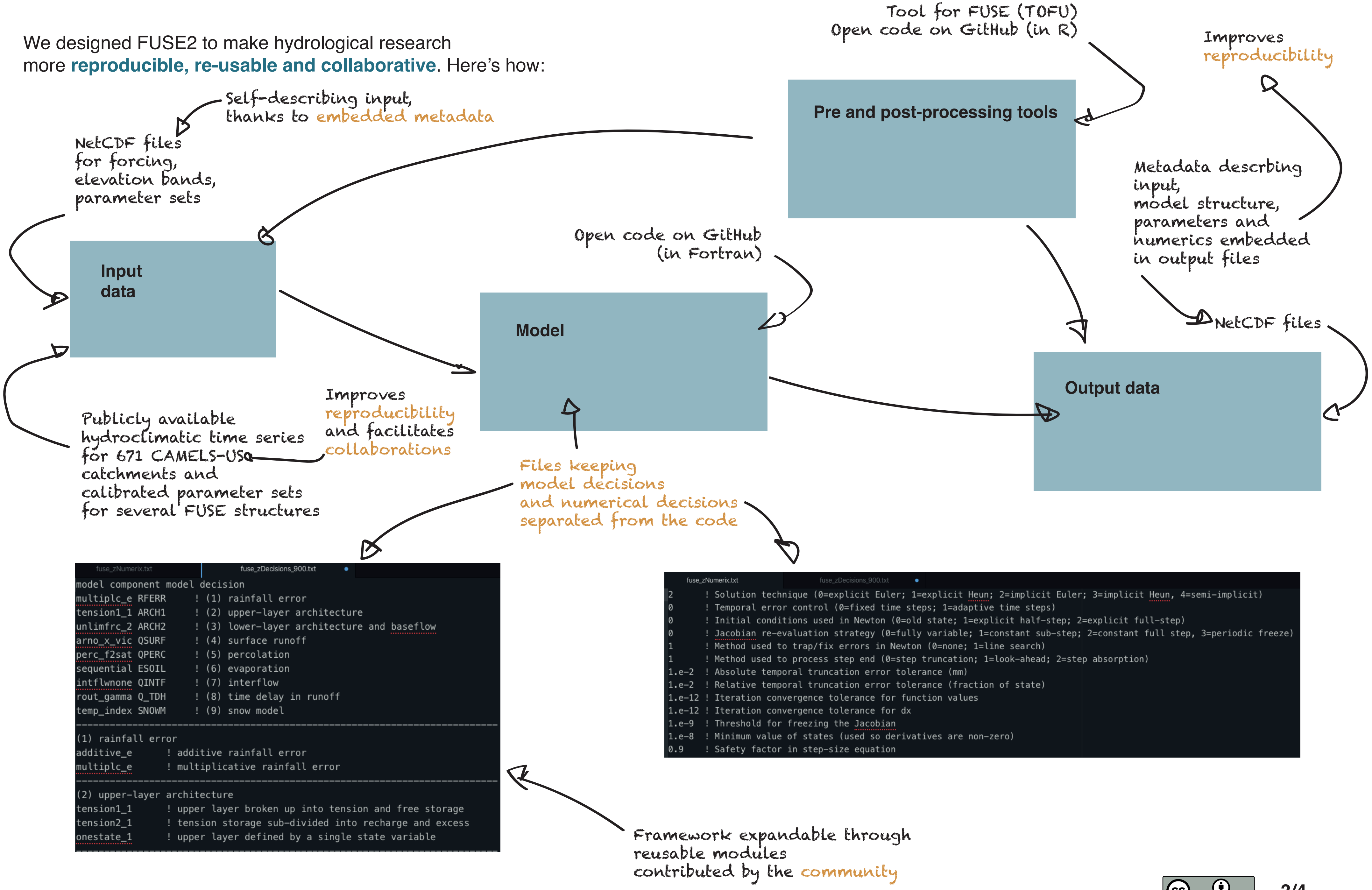
We designed FUSE2 to make hydrological research more **reproducible, re-usable and collaborative**. Here's how:

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model component model decision
multiplc_e RFERR     ! (1) rainfall error
tension1_1 ARCH1     ! (2) upper-layer architecture
unlimfrc_2 ARCH2     ! (3) lower-layer architecture and baseflow
arno_x_vic QSURF     ! (4) surface runoff
perc_f2sat QPERC     ! (5) percolation
sequential ESOIL     ! (6) evaporation
intflwnone QINTF     ! (7) interflow
rout_gamma Q_TDH     ! (8) time delay in runoff
temp_index SNOWM     ! (9) snow model
--------------------------------------------------------------------
(1) rainfall error
additive_e       ! additive rainfall error
multiplc_e       ! multiplicative rainfall error
--------------------------------------------------------------------
(2) upper-layer architecture
tension1_1       ! upper layer broken up into tension and free storage
tension2_1       ! tension storage sub-divided into recharge and excess
onestate_1       ! upper layer defined by a single state variable
```

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2      ! Solution technique (0=explicit Euler; 1=explicit Heun; 2=implicit Euler; 3=implicit Heun, 4=semi-implicit)
0      ! Temporal error control (0=fixed time steps; 1=adaptive time steps)
0      ! Initial conditions used in Newton (0=old state; 1=explicit half-step; 2=explicit full-step)
0      ! Jacobian re-evaluation strategy (0=fully variable; 1=constant sub-step; 2=constant full step, 3=periodic freeze)
1      ! Method used to trap/fix errors in Newton (0=none; 1=line search)
1      ! Method used to process step end (0=step truncation; 1=look-ahead; 2=step absorption)
1.e-2  ! Absolute temporal truncation error tolerance (mm)
1.e-2  ! Relative temporal truncation error tolerance (fraction of state)
1.e-12 ! Iteration convergence tolerance for function values
1.e-12 ! Iteration convergence tolerance for dx
1.e-9  ! Threshold for freezing the Jacobian
1.e-8  ! Minimum value of states (used so derivatives are non-zero)
0.9    ! Safety factor in step-size equation
```

We see modular modelling frameworks and multi-model frameworks emerging as community models. They are essential to overcome challenges met by traditional fixed-structure models (see below) and enable more reproducible, re-usable and collaborative research in hydrology.

A transition to improve reproducibility and foster team work

FIXED-STRUCTURE MODELS

(e.g. VIC, HBV)

Technical limitations of fixed-structure models → Consequences for hydrological research

i) understanding the reasons behind differences in simulations from different models is hard → i) challenging to trust and improve models if we know *which* models perform best, but not *why*

ii) running a large ensemble of models is impractical → ii) this limits our ability to draw from the pool of available hydrological knowledge and to account for structural uncertainty

iii) differences in processes across the landscape are accounted for by parameter tunig → iii) this forces us to adhere to the "one-structure fits all" paradigm

iv) the development of hydrological models is siloed → iv) developments cannot be shared among models, making model development inefficient

we keep reinventing the wheel

MODELLING FRAMEWORKS

(e.g. RAVEN, MARRMoT, FUSE, SUPERFLEX, SUMMA)

Solutions

i) modular modelling frame-work enable us to conduct controlled modelling experi-ments

ii) an ensemble of models can be generated using a single modelling framework

iii) multiple model structures can be compared to provide guidance on model selection

iv) model components can be shared across the community

load modules when you need them, make your modules available.

Challenges

modelling frameworks need more TLC

A - modular frameworks need more developed ecosystems (e.g. datasets, pre- and post-processing tools) and friendlier user interfaces

B - parameter estimation for a large ensemble of model structures is challenging

C - do we have a strategy to efficiently explore model space?

Addor and Melsen: Legacy, rather than adequacy, drives the selection of hydrological models, Water Resour. Res., 55(1), 378–390, doi:10.1029/2018WR022958, 2019.