UniFHy v0.1.1: A community modelling framework for the terrestrial water cycle in Python

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Abstract. Land surface, hydrological, and groundwater modelling communities all have expertise in simulating the hydrological processes at play in the land system, but these communities have largely remained distinct with limited collaboration between disciplines. In order to address key societal questions regarding the future availability of water resources and the intensity of extreme events such as floods and droughts in a changing climate, these communities must build on the strengths of one another. The development of a common modelling infrastructure, a framework, can contribute to stimulating cross-fertilisation between them. By allowing (parts of) their existing models to be coupled together, improved land system models can be built to better understand and simulate the terrestrial hydrological cycle. This paper presents a Python implementation of such a framework named the Unified Framework for Hydrology (`unifhy`). The framework aims to provide the technical infrastructure required to couple models, taking into account the specific needs of a land system model. Its conceptual design and technical capabilities are outlined first, before its usage and useful characteristics are demonstrated through case studies. The limitations of the current framework and necessary future developments are finally presented as a road map for later versions and/or other implementations of the framework.

1 Introduction

The Earth's atmosphere and land surface are deeply interconnected systems. Given this, hydrological knowledge is as critical to atmospheric scientists as meteorological knowledge is to hydrologists. ~~Land surface models~~ These interactions have long been represented in land surface models (Blyth et al., 2021). However, they have historically been developed as a lower boundary condition to atmospheric models which, to this day, partially explains the shortcomings in the representation of hydrological processes in land surface models. ~~Indeed~~In particular, the resolution of the land system coupled with the atmosphere has typically been too coarse to adequately represent the spatial structures of the dominant hydrological processes, while the focus on vertical exchanges between the land and the atmosphere has limited the development of the critical lateral redistribution of

water on and below the ground. To overcome these limitations, a modular representation of the terrestrial water cycle using interconnected modelling components would provide the flexibility required in the spatial discretisation of the land system while preserving the existing coupling approaches with atmospheric models. In addition, such modularity would contribute to developing and comparing alternative representations of the real-world land system and assessing their impacts on hydrological and atmospheric predictions alike.

The land surface modelling community has developed highly configurable models such as the Joint UK Land Environment Simulator (JULES) (Best et al., 2011; Clark et al., 2011), the Organising Carbon and Hydrology In Dynamic Ecosystems (OR-CHIDEE) model (Krinner et al., 2005), and the Community Land Model (Lawrence et al., 2019). However, these models do not allow different parts of the land system to be simulated at different explicit resolutions (except for the runoff routing), nor do they make it possible to substitute part of one model with another part from another model~~. The~~, which are crucial requirements to advance land surface modelling (Blyth et al., 2021). The Earth surface dynamics modelling community has developed coupling frameworks for the land system, e.g. Landlab ~~(Hobley et al., 2017)~~ (Hobley et al., 2017; Barnhart et al., 2020) can be used to develop modelling components complying with the Basic ~~Modelling~~ Model Interface (BMI) (Peckham et al., 2013; Hutton et al., 2020) that can be coupled using the Python Modelling Toolkit ~~(Hutton et al., 2021), although as yet none of the existing~~ (PyMT) (Hutton et al., 2021). However, these frameworks are primarily developed to address requirements of geomorphologists, therefore they do not consider the essential need for land surface models ~~above are built using such technologies.~~to be coupled with external models, e.g. atmospheric models, where the handling of time advancement and memory allocation of the land model need to be delegated to an external model.

The hydrological modelling community has also been developing frameworks to compare different physical processes and/or conceptualisations of the hydrological behaviour of a catchment. For example, FUSE (Clark et al., 2008), SUPERFLEX (Fenicia et al., 2011), and CMF (Kraft et al., 2011) provide bucket-style building blocks to develop integrated catchment models, while SUMMA (Clark et al., 2015) and Raven (Craig et al., 2020) allow the construction of physically-explicit hydrological models using process equations as the building blocks. However, refactoring existing land surface models using these frameworks is not trivial, and an intermediate level of modularity is required to simplify their refactoring. The Open Modelling Interface (OpenMI) has been developed to provide an international standard to link hydrological and hydraulic models as components. It has been implemented as a flexible approach for allowing models as components to be linked at runtime (Harpham et al., 2019). However, there is no standardised interface for linking components which impedes on their compatibility and continued reusability over time.

~~Such intermediate modularity is already a reality within the~~ The Earth system modelling community has also developed frameworks with intermediate modularity, where atmosphere, ocean, and land components together simulate the dynamics of the Earth system. The technologies used to combine such modelling components range from integrated coupling frameworks such as ESMF (Collins et al., 2005) or CPL7 (Craig et al., 2012), where existing modelling components require code refactoring to comply with a set of organising and interfacing requirements, to couplers such as OASIS-MCT (Valcke, 2013; Craig et al., 2017), or YAC (Hanke et al., 2016), where existing modelling components require minimal additions to expose their variables to the coupler. While these two families of frameworks vary in the level of intrusiveness into the existing code, they both offer

access to essential functionalities such as I/O, parallelism, flexible spatial discretisation, remapping, and so on. ~~This~~ In addition, the community has developed standardised interfaces between the components (see e.g. Polcher et al., 1998; Best et al., 2004). While this experience and these technologies ought to be exploited to build modular ~~frameworks to form a new generation of land system models~~ land system models, these frameworks do not consider the specific challenges in the land system and the hydrological cycle. In particular, linear interpolation applicable in the remapping in continua such as those of the atmosphere and of the ocean is problematic for the land continuum because of strong discontinuities on and below the ground. In addition, the spatial discretisations typically used in Earth System modelling frameworks lack meaning for the hydrological cycle. This is why a modular framework specific to the land system is required.

In this manuscript, a new framework for modelling the hydrological cycle in the land system is described, inspired by the intermediate modularity of existing Earth system modelling frameworks. It follows an integrated coupling philosophy featuring three framework components interconnected through standardised interfaces allowing new science components to be embedded into the framework with minimal refactorisation of their existing interfaces. Section 2 expands on its design principles and implementation details, Section 3 showcases usage of the framework, Section 4 details how to contribute to the framework with new science components, Section 5 demonstrates the capabilities of the framework on case studies, and finally Section 6 explores avenues for future developments.

2 Description of the framework

2.1 Modular water cycle blueprint

Given the dominant spatial structures and temporal scales of the processes involved in the terrestrial water cycle, and the interconnected nature of the land system with the atmosphere and the ocean, a modular blueprint featuring three framework components is chosen (see Figure 1): a surface layer component encapsulating the dynamics of moisture and energy exchanges between the atmosphere and the Earth's surface, which are amongst the fastest processes in the terrestrial water cycle and predominantly uni-directional (i.e. vertical); a subsurface component to address the movement of water through the soil down to the bedrock, which in comparison tends to be slower and truly tri-directional (i.e. lateral redistribution according to topographic and hydraulic head gradients, and vertical percolation/capillary rise/vegetation uptake); and an open water component for the movement of free water in contact with the atmosphere which is of intermediate speed and predominantly bi-directional along the surface of the Earth towards the seas and oceans. Despite this modularity, each component must be conservative with respect to the quantities in the continuity equations so that these are also conserved across the entire land system.

For existing modelling components to be coupled, outputs from one need to be mapped onto inputs for another: this requires a common bank of defined variables, i.e. an ontology, to guarantee that the output of one is semantically equivalent to the input of the other. Moreover, to maximise the chances of finding compatible models, this calls for a common interface between components that skilfully yet pragmatically subdivides the terrestrial water cycle continuum. Indeed, a compromise must be found between allowing flexibility in model construction and maximising the potential for existing models to be incorporated in the framework. This is why the degrees of freedom offered to the user are intentionally limited and a standard interface
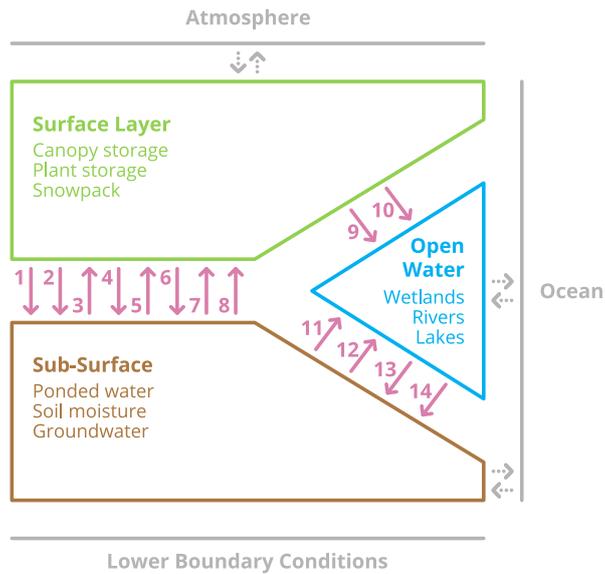
Figure 1. Schematic blueprint of the terrestrial water cycle featuring the three components 'Surface Layer', 'Sub-Surface', and 'Open Water', their transfers of information as numbered arrows (see Table 1), and their relationships with external models (atmosphere and ocean).

between the components of the framework is formulated. This interface is a set of prescribed transfers of information between each pair of components in the blueprint. For instance, the open water component is receiving (i.e. inward transfers) 'direct throughfall flux', 'water evaporation flux from open water', 'surface runoff flux delivered to rivers', and 'net subsurface flux to rivers', while it is sending (i.e. outward transfers) 'open water area fraction' and 'open water surface height' (see Figure 1 and Table 1). These interfaces define the relationship between the framework components. They were designed considering the existing structure of land surface models, namely JULES (Best et al., 2011; Clark et al., 2011) and ORCHIDEE (Krinner et al., 2005). The information transferred through the interface includes the fluxes necessary to fulfil the continuity equations across the entire land system, as well as the diagnostic quantities characterising the state of components which necessarily condition fluxes in other components.

2.2 Integrated coupling approach

A first implementation of this blueprint is developed in Python (Hallouin and Ellis, 2021) as an integrated coupling framework following an object oriented approach (see Figure 2 for a visual overview of the software architecture using the Unified Modelling Language (UML)). Object oriented programming is ideally suited to efficiently implement such modular software: the inheritance of the core functionalities of a framework component allows for code reuse in the constitution of the various subdivisions of the water cycle, and ultimately the development of community-based component contributions. In this framework, three `Component` objects are coupled together by a `Model` object and executed concurrently, so that the

Table 1. Prescribed interface variables defining what must be transferred between the framework components.

#	Name	Unit
1	canopy_liquid_throughfall_and_snow_melt_flux	$\mathrm{kg\,m^{-2}\,s^{-1}}$
2	transpiration_flux_from_root_uptake	$\mathrm{kg\,m^{-2}\,s^{-1}}$
3	soil_water_stress_for_transpiration	1
4	direct_water_evaporation_flux_from_soil	$\mathrm{kg\,m^{-2}\,s^{-1}}$
5	soil_water_stress_for_direct_soil_evaporation	1
6	water_evaporation_flux_from_standing_water	$\mathrm{kg\,m^{-2}\,s^{-1}}$
7	standing_water_area_fraction[*]	1
8	total_water_area_fraction[*]	1
9	water_evaporation_flux_from_open_water	$\mathrm{kg\,m^{-2}\,s^{-1}}$
10	direct_throughfall_flux	$\mathrm{kg\,m^{-2}\,s^{-1}}$
11	surface_runoff_flux_delivered_to_rivers	$\mathrm{kg\,m^{-2}\,s^{-1}}$
12	net_groundwater_flux_to_rivers	$\mathrm{kg\,m^{-2}\,s^{-1}}$
13	open_water_area_fraction[*]	1
14	open_water_surface_height	m

[*] Standing and open water both refer to the water on the land surface in direct contact with the atmosphere, but the former corresponds to the ephemeral water on the land surface, while the latter corresponds to the water in rivers and lakes. Total water refers to the combination of standing and open water, taking into account any overlap between the two.

order in which the components are called does not impact on the outcome of the simulation. The `Model` is responsible for the exchange of information between components, including their potential temporal accumulation and aggregation and/or their potential spatial remapping (using an `Exchanger` object), and is responsible for the time ~~iteration~~ advancement of all components (using a `Clock` object).

The `Component` object provides infrastructure to support the science component; e.g. reading input (using `DataSet` objects), writing output (using `Record` and `RecordStream` objects), and state memory allocation (using `State` objects). The `Component` class itself is subclassed into the actual framework components represented by the `SurfaceLayerComponent`, `SubSurfaceComponent`, and `OpenWaterComponent` classes, which are used to enforce inward and outward transfers corresponding to the framework interfaces. Each accommodates the description of the physical processes of a given part of the terrestrial water cycle (i.e. the science component) following an initialise-run-finalise paradigm. `DataComponent` and `NullComponent` classes are also provided as a convenience to allow any of the three framework components to be either replaced with appropriate data or removed. In both cases the replacement generates outward data transfers, in the former case, from data, in the latter case, zeros. Attempted inward data transfers are quietly ignored.
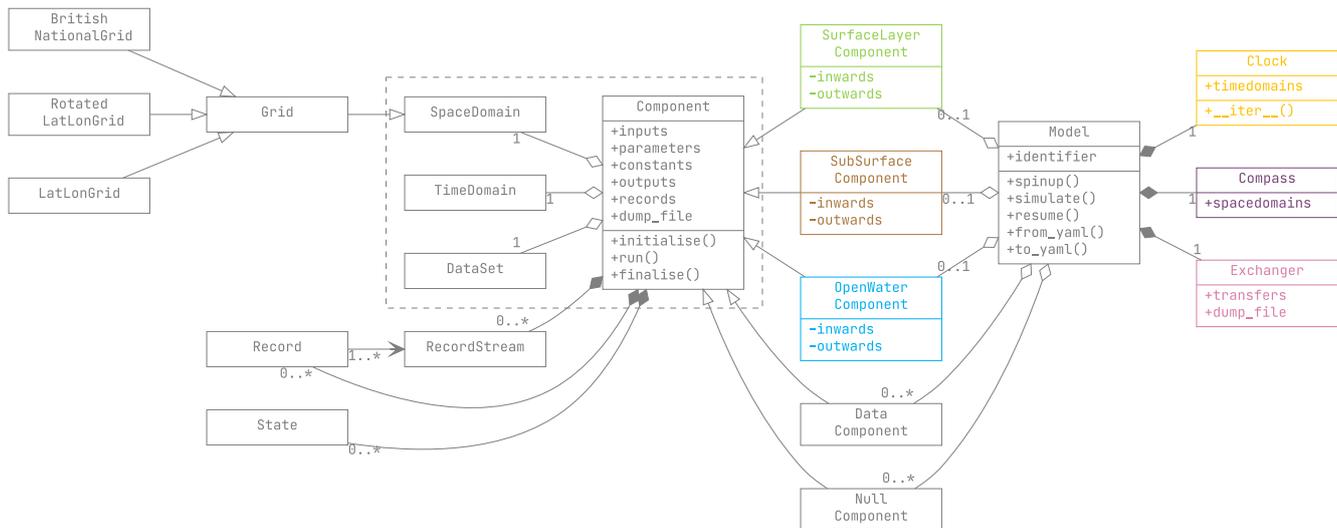
Figure 2. UML class diagram of the `unifhy` Python package.

2.3 Flexible discretisation

The framework modularity makes it possible to resolve the processes in each science component at their own temporal and spa-
tial resolutions. Each `Component` is discretised individually with its own instances of the `TimeDomain` and `SpaceDomain`
classes defining their temporal and spatial discretisations, respectively.

In the framework, the `TimeDomain` class limits instances to temporal discretisations that are regularly-spaced. While
each component could theoretically run on any temporal resolution independent of the resolution of the other components,
it is essential to make sure that restarting times exist across the simulation period in case of unexpected interruption of the
execution. In order to achieve this, the `Clock` object makes sure that the temporal resolutions are constrained such that,
across the three components, the component temporal resolutions are required to be integer multiples of each other, and the
component temporal extents to span the same simulation period. These temporal discretisations act as contracts signed between
the components and the framework to guarantee that the latter can orchestrate the simulation, but this does not need to preclude
components from employing sub-time steps or adaptive time stepping schemes internally.

In the framework, the `SpaceDomain` class is subclassed into a `Grid`, intended to encompass all structured gridded spatial
discretisations. The distinction between `SpaceDomain` and `Grid` is done in anticipation of additional subclasses to be created
in the future (see subsection 6.2). The `Grid` class itself currently features three subclasses corresponding to two discretisa-
tions on spherical coordinate systems (latitude-longitude and rotated-pole latitude-longitude) as well as one discretisation on
a Cartesian (projected) coordinate system (the British national grid), but additional subclasses can easily be developed. Inter-
nal spatial remapping between differing component discretisations relies on the remapping functionality provided by ESMF
(Collins et al., 2005). If components are to be resolved on different spatial discretisations, not only the components must con-
serve the quantities in the continuity equations, but the remapping operation must also be conservative. Discontinuities being

intrinsic to the land system, e.g. in land cover or soil properties, it appears unrealistic to directly apply traditional interpolation methods for the remapping since they assume continuity, whereas supermeshing techniques (Farrell et al., 2009), where a supermesh is the union of the components meshes, offer solutions to remain conservative in the remapping without the need for a continuity assumption. Since the current implementation of the framework does not yet feature an explicit supermeshing technique across the three components, the `Compass` object makes sure that components are discretised using space domains of the same class (i.e. in the same coordinate system), that they span the same region, and that their spatial resolutions are encapsulated in one another, which effectively guarantees that for each pair of coupled components, one is the supermesh for both of them.

2.4 Open science library

Alongside the framework infrastructure itself, an initial library of open source science components complying with the standard framework interface is available. This allows users to explore alternative combination of components as alternative solutions to simulate the terrestrial water cycle.

Additional components can be exploited by the framework so long as they comply, or can be made to comply, with the framework interface via a particular Python class template (see Script 7).

Land system and hydrological modellers are encouraged to become contributors to the framework by sharing their science components with the rest of the community. These contributions can be implemented purely in Python, but can also rely on Fortran, C, or C++ programs called by interface middleware. Contributors need not handle basic functionalities such as memory allocation nor input/output operations, as these are handled by the framework. Ideally, the use of the framework will simplify model development allowing framework contributors to focus on scientific development (see section 4).

2.5 Meaningful data

The interface specification is effectively a data specification. To guarantee the unambiguous specification of that interface, as well as to bring to the framework and to users alike a full awareness of the physical meaning and spatio-temporal context of input and output data, the NetCDF Climate and Forecast (CF) Metadata Conventions (Eaton et al., 2020) are exploited in the framework. These conventions provide a robust guide for describing, processing, and sharing geophysical data files. They are used in a variety of applications, including for global model inter-comparison efforts such as CMIPs (e.g. Eyring et al., 2016). In particular, the CF standard names list provides the main ontology followed for the naming of the fields in the framework interfaces, although given it does not include some concepts relevant specifically for hydrology, some digression from this ontology exists in the framework until these concepts are submitted for inclusion in the CF standard names list.

The `DataSet` class responsible for providing each `Component` with input data relies on reading CF-NetCDF files. This enables the framework to check the compatibility between the data and the configured component, both physically and spatio-temporally. In addition, all record files and dump files are generated as CF-NetCDF files. Such CF-NetCDF files are processed with the package cf-python (Hassell et al., 2017; Hassell and Bartholomew, 2020).

3   Usage of the framework

3.1   Configuration

In this section, the framework configuration workflow is presented. The user can configure the framework either using the Application Programming Interface (API) directly, or using an intermediate YAML (Yet Another Markup Language) configuration file.

3.1.1   Application Programming Interface

The first step in this workflow is to define the temporal and spatial discretisations. The user has to instantiate `TimeDomain` and `SpaceDomain` objects. The framework comes with a variety of constructor methods for these two objects, including using existing data structures, e.g. `from_field`, or using the limits and spacing of the discretisation, e.g. `from_start_end_step` for `TimeDomain` and `from_extent_and_resolution` for `SpaceDomain`. Examples using the latter are presented in Script 1.

```python
from unifhy.time import TimeDomain
from datetime import datetime, timedelta
from unifhy.space import LatLonGrid

td = TimeDomain.from_start_end_step(
    start=datetime(2007, 1, 1, 0, 0, 0),
    end=datetime(2017, 1, 1, 0, 0, 0),
    step=timedelta(hours=1)
)

sd = LatLonGrid.from_extent_and_resolution(
    latitude_extent=(49, 55),
    latitude_resolution=0.5,
    longitude_extent=(-11, 3),
    longitude_resolution=0.5
)
```

Script 1. Example of temporal discretisation (to generate hourly timestepping), and spatial discretisation (to generate a regular 0.5° latitude-longitude grid) using the framework's API.

The second step consists in selecting the NetCDF files containing the input data. To do so, the user has to instantiate a `DataSet` object (Script 2). These files must comply with the CF-conventions (subsection 2.5).

```
1  from unifhy.data import DataSet
2
3  ds = DataSet(
4      files=['file.nc'],
5      select='flow_accumulation'
6  )
```

Script 2. Example of data specification using the framework's API: selecting a variable in a CF-NetCDF file.

The third step, which completes the configuration of a `Component`, is to provide these three objects to the selected component alongside values with units for the component parameters and constants. Additionally, the user can select the variables to
185 record for this component, whether component outward transfers and/or component outputs and/or component states with customisable temporal ~~resolution (multiple~~ resolutions (multiples of its `TimeDomain` resolution) and summary statistics (mean, minimum, maximum, instantaneous). In Script 3, the open water science component RFM, based on the RFM model (Bell et al., 2007; Dadson et al., 2011), is used and configured (note that the science components do not come with the framework and need to be installed separately). Instantiating a Component will be successful only if all the inputs, parameters, and con-
190 stants required by the science component are provided and compatible in names, units, time and space dimensions with the component and its time and space domains.

```
1   from unifhycontrib.rfm import OpenWaterComponent
2
3   ow = OpenWaterComponent(
4       timedomain=td,
5       spacedomain=sd,
6       dataset=ds,
7       saving_directory='.',
8       parameters={'c_land': [0.20, 'm s-1'], 'cb_land': [0.10, 'm s-1'],
9                   'c_river': [0.62, 'm s-1'], 'cb_river': [0.15, 'm s-1'],
10                  'ret_l': [0.20, '1'], 'ret_r': [0.10, '1'],
11                  'routing_length': [50000, 'm']},
12      constants={'a_thres': [1, '1']},
13      outputs={'outgoing_water_volume_transport_'
14               'along_river_channel': {timedelta(days=1): ['mean']}
15  )
```

Script 3. Example of component configuration using the framework's API: an open water component based on the RFM model.

The fourth and last step in the configuration workflow is to gather three components, one of each of the three types `SurfaceLayerComponent`, `SubSurfaceComponent`, and `OpenWaterComponent` to form a model. In Script 4, the variables 'sl', 'ss', and 'ow' are instances of each, respectively, configured similarly to the example in Script 3.

```python
from unifhy.model import Model

md = Model(
    identifier='example_run',
    config_directory='.',
    saving_directory='.',
    surfacelayer=sl,
    subsurface=ss,
    openwater=ow
)
```

Script 4. Example of model configuration using the framework's API.

195   Note, the three components forming the model need to comply with the temporal and spatial discretisation constraints formulated in subsection 2.3 for the instantiation of a `Model` to be successful.

3.1.2   Configuration file

An alternative to the API is the use of a configuration file written using the human-readable serialisation language YAML. This provides both a more accessible configuration approach for users less comfortable with programming and a way to easily share
200   configurations with other users. The complete configuration workflow presented above using the API can be formulated in a single YAML file. For reasons of brevity, only an equivalent for the third step above, i.e. configuring one component (Script 3), is presented in Configuration 1. Entire configuration files can be found in the Supplement.

Configuration files can then be loaded using the API to instantiate the `Model` directly (Script 5). Note, after the successful instantiation of a `Model` using the API (i.e. Script 4), such a YAML file is automatically created in the configuration directory.

```python
from unifhy.model import Model

md = Model.from_yaml('example_run.yml')
```

Script 5. Example using the framework's API to instantiate a Model from a YAML configuration file.

```
1   openwater:
2     module: unifhycontrib.rfm
3     class: OpenWaterComponent
4     saving_directory: .
5     timedomain:
6       start: 2007-01-01 00:00:00
7       end: 2017-01-01 00:00:00
8       step: timedelta(hours=1)
9     spacedomain:
10      class: LatLonGrid
11      latitude_extent: [49, 55]
12      latitude_resolution: 0.5
13      longitude_extent: [-11, 3]
14      longitude_resolution: 0.5
15    dataset:
16      flow_accumulation:
17        files: [file.nc]
18        select: flow_accumulation
19    parameters:
20      c_land: [0.20, 'm s-1']
21      cb_land: [0.10, 'm s-1']
22      c_river: [0.62, 'm s-1']
23      cb_river: [0.15, 'm s-1']
24      ret_l: [0.20, '1']
25      ret_r: [0.10, '1']
26      routing_length: [50000, 'm']
27    constants:
28      a_thres: [1, '1']
29    records:
30      outgoing_water_volume_transport_along_river_channel:
31        timedelta(days=1): [mean]
```

Configuration 1. Excerpt from YAML configuration file equivalent to Script 3.

3.2 Simulation

A configured `Model` can then be used to start model spin-up cycle(s) and/or to start a simulation run over the entire simulation period specified in the time domains of the components (Script 6). The spin-up period can either be within or outside of the simulation period, so long as the datasets given to the components contain data for it.

```
1   from datetime import datetime, timedelta
2
3   md.spin_up(start=datetime(2007, 1, 1, 0, 0, 0),
4             end=datetime(2008, 1, 1, 0, 0, 0),
5             cycles=3)
6
7   md.simulate(dumping_frequency=timedelta(days=100))
```

Script 6. Example using the framework's API to start simulations with a Model.

Both spin-up and simulation runs can produce dump files, that is files containing intermediate snapshots in the simulation period with all the information required to resume the simulation in case of an unexpected interruption. The user can specify a dumping frequency to choose how often such snapshots should be saved. Once the `Model` is re-instantiated using its configuration file created through Script 4, the simulation can be resumed using any snapshot in these dump files. Moreover, these files can be used to provide initial conditions for the component states in replacement or in addition to the spin-up cycles.

Note, detailed documentation is available online and accessible at unifhy-org.github.io/unifhy.

4 Contribution to the framework

If the science components already available in the open science library (subsection 2.4) are not sufficient or suitable for the needs of users, they have the opportunity to create their own. New science components for use in the framework can be developed as Python subclasses of the framework's internal `SurfaceLayerComponent`, `SubSurfaceComponent`, and `OpenWaterComponent` classes.

The approach to developing a science component is designed to require minimal development effort, and can be divided into five steps. The first step is to declare a Python class whose base class is one of the `SurfaceLayerComponent`, `SubSurfaceComponent`, or `OpenWaterComponent` classes (e.g. lines 1-3 in Script 7). The second step is to provide a description for the component using the docstring of the class (e.g. line 4 in Script 7). The third step is to declare the component interface, i.e. to indicate which transfers in the standard interface are used and produced (e.g. lines 7-8 in Script 7). The fourth step is to define the component characteristics, including its inputs, parameters, constants, states, and outputs in their corresponding class attributes (e.g. lines 9-23 in Script 7). The fifth and last step is to implement the three class methods `initialise`, `run`, and `finalise` (e.g. lines 26-34 in Script 7, where the `pass` statements should be replaced by the

actual implementation of these methods). This initialise-run-finalise (IRF) paradigm is based on the interfacing standards BMI (Peckham et al., 2013; Hutton et al., 2020) and OpenMI (Harpham et al., 2019).

Instances of newly created `Component` classes can then be created and, thanks to their base class, they inherit the functionality that make them readily usable in the framework, as described in section 3.

For existing models, the contributor may need to perform some refactoring of their source code, namely to comply with the framework interfaces and to comply with the initialise-run-finalise paradigm. The creation of a Python class is a requirement for use in the framework, however, the `initialise`, `run`, and `finalise` methods can call software which can be interfaced with Python, such as existing Fortran, C, or C++ programs.

Note that on a scientific level, there is no a priori restriction on the degree of complexity models must meet to be refactored into science components, only their compatibility with the framework standardised interface is expected. Nonetheless, (Blyth et al., 2021) provides a good overview of the class of models primarily targeted.

A blank template is available on GitHub at unifhy-org/unifhycontrib-template to provide a starting point for contributors to package their new or existing models into framework compatible Python libraries.

5 Case studies using the framework

5.1 Selected science components

A selection of existing models have already been refactored into science components compatible with the framework. These include the Artemis (Dadson et al., 2021), RFM (Lewis and Hallouin, 2021), and SMART (Hallouin et al., 2021) models.

The Artemis model provides a simple runoff production model designed to be comparable with the runoff-production models typically embedded within climate models, which combines Penman-Monteith evaporation (Monteith, 1965) with Rutter-Gash canopy interception (Gash, 1979), TOPMODEL runoff production (Clark and Gedney, 2008), and a degree-day-based snow accumulation and melting model (Moore et al., 1999; Hock, 2003; Beven, 2012). The River Flow Model (RFM) is a runoff routing model based on a discrete approximation of the one-directional kinematic wave with lateral inflow (Bell et al., 2007; Dadson et al., 2011). The Soil Moisture Accounting and Routing for Transport (SMART) model is a bucket-style rainfall-runoff model based on the soil layers concept (Mockler et al., 2016).

Note, the Artemis and RFM model parameters are not optimised, while the SMART model parameters are optimised for each catchment separately using a standalone version of the model (Hallouin et al., 2019) and selecting the best performing parameter set from a Latin Hypercube Sampling (McKay et al., 2000) of 10^6 parameter sets, using a subset for the period 1998-2007 of the driving and observational data used by Smith et al. (2019), and the modified Kling-Gupta Efficiency (Kling et al., 2012) as objective function.

5.2 Selected configurations

The capabilities of the framework are demonstrated through three different configurations summarised in Table 2.

```python
import unifhy

class SurfaceLayerComponent(unifhy.component.SurfaceLayerComponent):
    """Component description"""

    # Component definition
    _inwards = {'inward_name'}
    _outwards = {'outward_name'}
    _inputs_info = {
        'input_name': {'units' : '',  'kind': ''}
    }
    _parameters_info = {
        'parameter_name': {'units' : '', 'valid_range': [0., 1.]}
    }
    _constants_info = {
        'constant_name': {'units' : '',  'default_value': 1.}
    }
    _states_info = {
        'state_name': {'units' : ''}
    }
    _outputs_info = {
        'output_name': {'units' : ''}
    }

    # Component implementation
    def initialise(self, input_name, parameter_name, constant_name, state_name, **kwargs):
        pass

    def run(self, inward_name, input_name, parameter_name,
            constant_name, state_name, **kwargs):
        pass

    def finalise(self, parameter_name, constant_name, state_name, **kwargs):
        pass
```

Script 7. Template for a science component contribution: example on a fictional surface layer component.

Table 2. Framework configurations.

Framework Component	Science Component	TimeDomain	SpaceDomain	DataSet[1]
Configuration 1: running a simple land system model				
SurfaceLayerComponent	Artemis	Hourly	WGS84 0.5 degree	ERA5
SubSurfaceComponent	Artemis	Hourly	WGS84 0.5 degree	ERA5
OpenWaterComponent	RFM	15 minutes	WGS84 ~0.008 degree	HydroSHEDS
Configuration 2: routing previously simulated runoff				
SurfaceLayerComponent	NullComponent	–	–	–
SubSurfaceComponent	DataComponent	Daily	OSGB 1 km	CHESS-land
OpenWaterComponent	RFM	15 minutes	OSGB 1 km	CHESS-land
Configuration 3: adding explicit surface evaporation processes in a rainfall-runoff model				
SurfaceLayerComponent	Artemis	Hourly	WGS84 0.5 degree	ERA5
SubSurfaceComponent	SMART	Hourly	Catchment (one grid cell)	–
OpenWaterComponent	SMART	Hourly	Catchment (one grid cell)	–

[1] See Appendix A for more details on data sources.

The first configuration puts the Artemis and the RFM models together to form a simple land system model. It demonstrates
260 the flexibility in the temporal and the spatial resolutions of the various components. Indeed, the surface layer and the subsurface
components are taken from the Artemis model and configured to run at an hourly timestep on a 0.5 degree resolution latitude-
longitude grid, while the open water component from RFM is used and configured to run at 15-minute intervals on a 0.5/60
(~0.008) degree resolution on a latitude-longitude grid.

The second configuration demonstrates the possibility to replace science components with datasets. To do so, the surface and
265 subsurface runoff outputs from the JULES model (Best et al., 2011; Clark et al., 2011) available in the CHESS-land dataset
(Martínez-de la Torre et al., 2018) are put together as a `DataComponent` and used in place of the subsurface component,
which is then coupled with the open water component of the RFM model, both on a 1 kilometre resolution on the British
National grid. The surface layer component is removed by setting it as a `NullComponent`.

The third and last configuration puts together the Artemis and SMART models. It demonstrates the possibility to substitute
270 parts of an existing model (i.e. SMART) with parts from another model (i.e. Artemis) and explore the impacts on the model
performance. The SMART model is a rainfall-runoff model for application to hydrologically meaningful spatial elements (e.g.
catchments, sub-basins), for which the existing gridded space domains are irrelevant. However, the model can be run on a single
spatial element assumed to represent the whole catchment until more complex geometries are supported in the framework (see
subsection 6.2).
275 Note, the details of the three configurations are available as YAML configuration files in the Supplement.
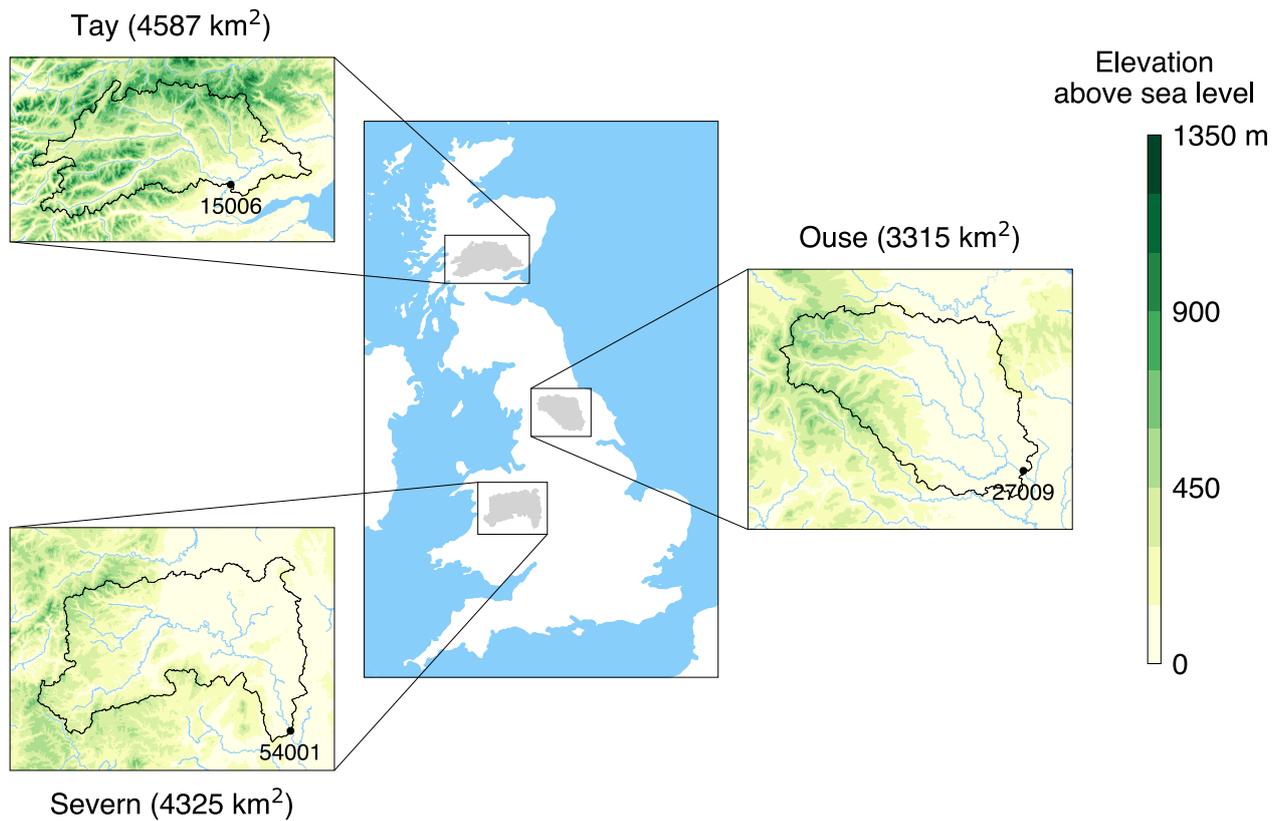
Figure 3. Location of the three study catchments in Great Britain. In the zoomed-in panels, the dots correspond to the outlets of the catchments and their adjoining five-digit labels correspond to the number of the National River Flow Archive (NRFA) hydrometric stations at these outlets. The elevation is based on digital spatial data licensed from the UK Centre for Ecology & Hydrology, ©UKCEH (Morris and Flavin, 1990, 1994).

5.3 Selected study catchments

The three configurations are applied to three British catchments, selected to explore the capabilities of the framework: the upper Severn catchment predominantly located in Wales, the Ouse catchment located in North East England, and the Tay catchment located in East Scotland (see Figure 3). These three catchments cover a range of climatological, topographical and geological settings. Their base flow indices (BFI) are 0.53, 0.39, and 0.64, respectively (Boorman et al., 1995). The three configurations applied to these three study catchments form nine case studies. The simulation period considered is 2008-2017.

5.4 Results

Figure 4 showcases the river discharge simulated with the three framework configurations described above, focussing on the river discharge at the catchment outlet in the line plots (a, c, e), and the spatial distribution of river discharge at the end of the simulation in the gridded plots (b, d). For reasons of brevity, only the Tay catchment is shown in the main text, figures for the other two study catchments are available in Appendix B. These figures confirm qualitatively the plausibility of the framework simulations. Indeed, the overlaid hydrographs suggest that the overall observed discharge pattern is captured by the simulations, while the spatial distributions of river discharge sketch a realistic picture of the catchment river network.

In addition, a quantitative evaluation of the performance of the framework simulations is done with respect to the river discharge at the catchment outlet where observed and simulated time series are compared using the non-parametric Kling-Gupta efficiency (R_{NP}). This is a composite metric made of three equally-weighted components r_S, α_{NP}, and β, assessing the agreement in the dynamics (i.e. correlation), the variability, and the volume (i.e. bias) of the discharge time series, respectively (Pool et al., 2018). Table 3 features these metric components computed for the three configurations and the three study catchments using the Python package `hydroeval` (Hallouin, 2021).

The comparative performance of the three configurations for each catchment in turn informs the most suitable combination of components for a given temporal and geographical context. For instance, the third configuration appears to be the most suitable in the Tay catchment, if one is solely interested in simulating the river discharge accurately (R_{NP} R_{NP} of 0.766), while the second configuration would be preferred for the Ouse and Severn catchments (R_{NP} R_{NP} of 0.674 and 0.706, respectively). However, these conclusions are metric-dependent and the analysis of the components of the composite metric can reveal the strengths and weaknesses of a given configuration, e.g. while the third configuration performs highest on the composite metric in the Tay catchment, its ranking on capturing the flow variability is the lowest of the three configurations (α_{NP} α_{NP} of 0.940).

Some caveats in this comparison are that the third configuration used a calibrated model unlike the first and second configurations, and the second configuration used data from a model constrained to conserve mass and energy, unlike the other configurations that only conserve mass. This likely skews the comparison.

This brief analysis of the results is used to demonstrate the potential of the framework to elicit the most suitable combination of components to simulate the hydrological behaviour of a given region; it is not to draw definitive conclusions as to which combinations should be used for the catchments selected here. Moreover, this analysis focuses on one hydrological variable, the river discharge, but other hydrological variables such as e.g. soil moisture or evaporation could also be considered.

6 Future developments

6.1 Implicit spatial heterogeneity

The spatial heterogeneity of real-world hydrological processes can be accounted for in models by either adjusting the resolution of their spatial discretisation explicitly (i.e. through finer mesh elements) or implicitly (i.e. through sub-mesh units). The former is currently possible using the framework but can be computationally costly, although flexible discretisation allows
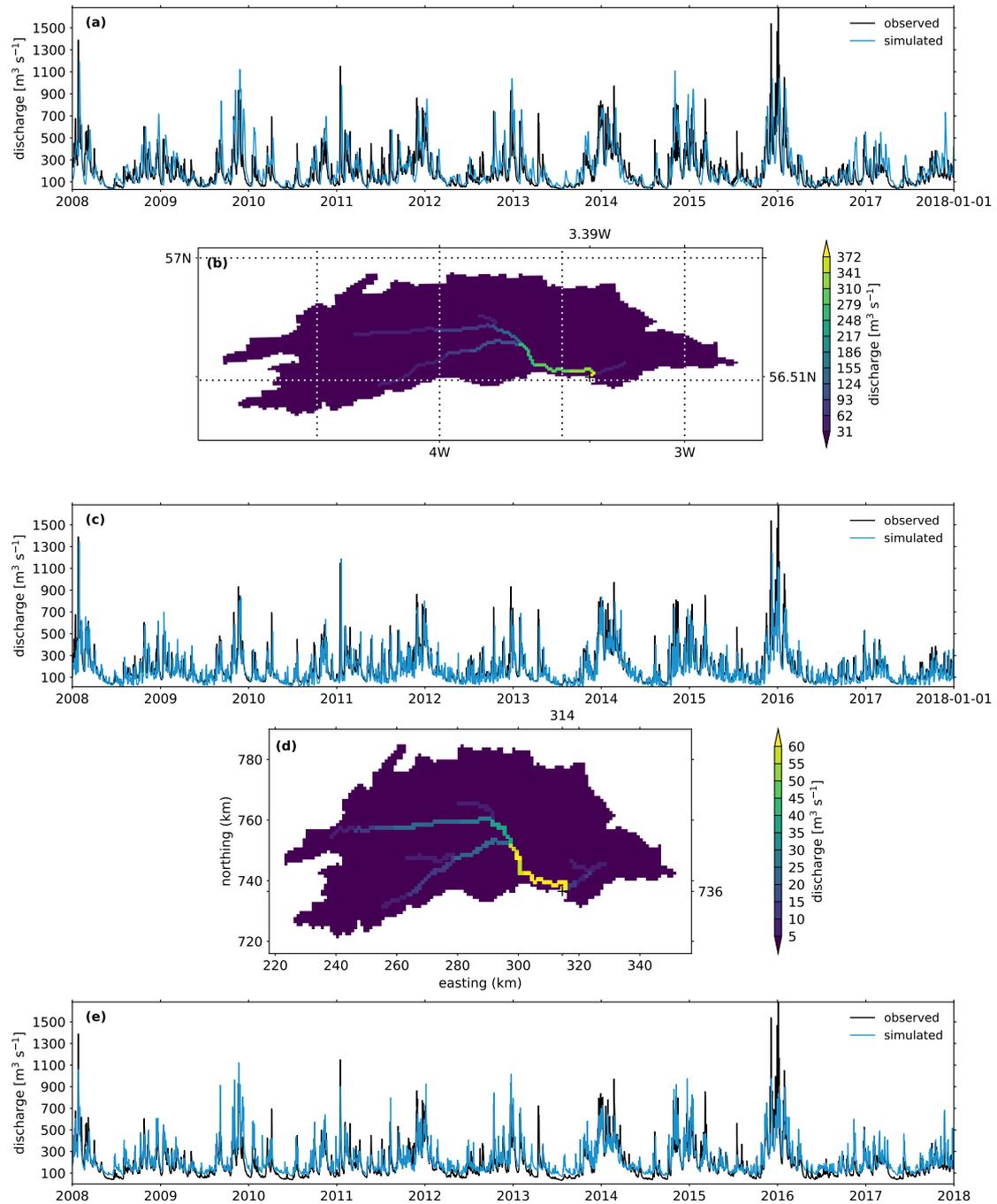
Figure 4. Simulation of the river discharge with the three configurations for the Tay catchment: **(a)** observed and simulated hydrographs with configuration 1 at the catchment outlet [3.39 °W, 56.51 °N], **(b)** gridded simulated discharge with configuration 1 for the last simulation step [2018-01-01], **(c)** observed and simulated hydrographs with configuration 2 at the catchment outlet [314, 736], **(d)** gridded simulated discharge with configuration 2 for the last simulation step [2018-01-01], **(e)** observed and simulated hydrographs with configuration 3 at the catchment outlet.

Table 3. Quantitative comparison of the three configurations for the three study catchments.

Catchment	Configuration	Performance metrics			
		R_{NP}	r_S	α_{NP}	β
Tay	1	0.667	0.692	0.981	1.126
	2	0.743	0.773	0.979	0.881
	3	0.766	0.821	0.940	1.139
Ouse	1	0.456	0.614	0.870	1.361
	2	0.674	0.705	0.945	0.875
	3	0.493	0.790	0.882	1.447
Severn	1	0.495	0.721	0.909	1.411
	2	0.706	0.719	0.946	0.933
	3	0.218	0.840	0.926	1.762

most of the cost to be focussed on the part(s) of the water cycle where finer resolutions are justified. Implicit resolutions are
315 not currently supported in the framework but are often used by land surface models, e.g. tiling or mosaic schemes to consider
spatial heterogeneity within the grid cells of the atmospheric models to which they are coupled. These schemes consider varied
biophysical behaviour depending on e.g. land cover types. Some hydrological models also use such schemes in the form of
hydrological response units (HRUs), where the unit (i.e. the tile) is typically based on a combination of soil types and/or ele-
vation bands and/or land cover types. These sub-mesh units need not be geographically located, but they can be hydrologically
320 connected nonetheless (e.g. flow matrix in TOPMODEL (Beven and Freer, 2001) in use e.g. in HydroBlocks (Chaney et al.,
2016), intra-hillslope configuration in CLM (Swenson et al., 2019), unit-to-unit routing in ORCHIDEE (Nguyen-Quang et al.,
2018)). Such schemes will be valuable for later versions of the framework, although it is anticipated that such implementation
will not be trivial. In addition, the explicit supermesh required in the remapping operation (see subsection 2.3) will need to be
extended to consider this implicit discretisation (i.e. sub-mesh) as well.

325 **6.2 Unstructured spatial meshes**

Structured grids may not be sufficient for some components. For example, existing land surface layer models often inherit
their spatial discretisation from an associated atmospheric model. In atmospheric models, the Earth's poles cause problems
when using regular latitude-longitude discretisations because the grid cells get smaller as the coordinates converge towards
the poles, therefore unstructured meshes are often preferred instead, e.g. reduced grids (e.g. ECMWF's IFS model (Hortal and
330 Simmons, 1991)), icosahedral grids (e.g. DWD's ICON model (Zängl et al., 2015), IPSL's DYNAMICO core (Dubos et al.,
2015)), or cubed spheres (e.g. UK Met Office's LFRic model (Adams et al., 2019), NOAA's FV3 model (Putman and Lin,
2007)). Moreover, triangular grids are also used in some hydrological and hydraulic models (e.g. PIHM (Li and Duffy, 2012),

CHILD model (Tucker et al., 2001)). Finally, rainfall-runoff models are typically applied on drainage basins, where space domains based on highly complex polygons may also prove useful to support such models as components for the framework.

335   Supporting such spatial discretisations would extend the range of models that can be refactored into components for the framework, however, current remapping functionalities may fall short to deal with these, since e.g. ESMF currently does not support unstructured grids with cells with more than four edges. In addition, unlike structured grids, unstructured grids require additional horizontal connectivity information. To remedy this, the use of alternative libraries such as TempestRemap could be explored (Ullrich and Taylor, 2015; Ullrich et al., 2016), while the UGRID conventions could be relied upon to complement the CF conventions for the description of unstructured meshes.

6.3 Parallel execution

The framework can leverage high performance computing through internal parallelisation and through the generation of many model instances to form an ensemble of water cycle simulations.

For internal parallelisation, the modular framework is readily structured to offer opportunities for both task decomposition (i.e. execute components concurrently) and domain decomposition (i.e. compute spatial subsets of the modelled region concurrently). While we anticipate most applications using an implementation of the Message Passing Interface (MPI), there is no a priori reason why other parallelism techniques such as OpenMP or OpenACC could not be used. However, if different approaches are used in different coupled components, load balancing would likely be an issue. If task decomposition is being used, the relationship between components will need to consider the spatio-temporal scales being modelled in each component, e.g. coupling of "fast" physics components may require adjustments rather than increments, ruling out concurrent in favour of sequential coupling (Balaji et al., 2016). If domain decomposition is used, the distribution of the spatial super-mesh on the processing elements will need to be communicated to the framework to enable the transfer of information across component, albeit the domain decomposition itself is anticipated to be the responsibility of the component contributors. To achieve such parallelisation, a variety of solutions can already be found in existing modelling frameworks, such as ESMF (Collins et al., 2005), OASIS-MCT (Valcke, 2013; Craig et al., 2017), or CPL7 (Craig et al., 2012).

Usage in large ensemble experiments represent an "embarrassingly parallel problem" with many available implementation mechanisms. The flexibility offered by the object oriented framework design makes it easier to perturb selected aspects of a given framework configuration to produce many alternative models.

6.4 External model coupling

360   Models of the land system are typically used with atmospheric and ocean models, e.g. in Earth system models. This means that the framework will not only need to be usable standalone but also in a coupled configuration. This will involve considerations regarding memory allocation, time synchronisation, and domain decomposition. And this will require the formulation standard interfaces between the framework components and the external models (e.g. Polcher et al., 1998; Best et al., 2004). In addition, such a modular framework for the land system can contribute to the improved coarse-grained concurrency of Earth system models (Balaji et al., 2016; Lawrence et al., 2018).

7 Conclusions

~~This framework~~ The framework presented in this manuscript, UniFHy, represents the first implementation of a new modular blueprint to model the terrestrial water cycle. It is open source and comes with extended online documentation. By design, this Python package is intended to be easy to use, with a low entry bar for people with little programming experience. Indeed, installing a Python package is straightforward and only a few steps in a Python script are needed to set up and run a complete model in a Jupyter notebook, which is likely to prove useful for teaching and training activities alike. It is also intended to be easily customisable, through choosing from a library of compatible science components those most suitable for a given ~~region and for a given objective~~ modelling context. Finally, it is intended to be easily extensible by creating new components, which should streamline the development and sharing of new science for the terrestrial water cycle.

In comparison to other hydrological and land surface modelling frameworks, this framework consciously reduces the degrees of freedom offered to the model developers in view to maximise the potential for reusability of their contributions with the other interested modelling communities. Indeed, unlike highly granular frameworks such as SUMMA or Raven, UniFHy prescribes the level of granularity to three modelling components, much like in Earth System modelling frameworks such as ESMF or OASIS-MCT. In addition, unlike other component-based modelling frameworks such as PyMT or LandLab, UniFHy prescribes the information to be exchanged between modelling components through its standardised interfaces. In addition, it controls the time advancement and the state memory allocation for the user which will be a crucial advantage when it is coupled in Earth System models. Nonetheless, UniFHy should directly be able to benefit from existing modelling environments such as LandLab, FUSE, or SUPERFLEX to develop modelling components.

Later versions of the framework will implement the additional developments discussed in section 6 and explore avenues for complementing this framework with other modelling environments. In addition, the extension of the blueprint to include other ~~geochemical~~ biogeochemical cycles (e.g. carbon, nitrogen, phosphorus) as well as anthropogenic influences is planned. In the meantime, we hope that the science library will grow with new contributions from the land, hydrology, and groundwater modelling communities, and stimulate collaborations between them.

Code availability. The framework is open source and available on Zenodo (Hallouin and Ellis, 2021). The science components are also open source and available on Zenodo, i.e. Artemis (Dadson et al., 2021), RFM (Lewis and Hallouin, 2021), and SMART (Hallouin et al., 2021). The online documentation is accessible at https://unifhy-org.github.io/unifhy.

Data availability. The input data used in the case studies is publicly available using the references provided in Appendix A. The observed river flow data is publicly available from NRFA (http://nrfa.ceh.ac.uk/, last access: 10 October 2021). The framework output data is available upon request from the corresponding author.

395 **Appendix A: Data sources**

Table A1. Sources for data used in configuration 1.

Variable name	Dataset name	Data DOI	Related publications
precipitation flux	ERA5	10.24381/cds.20d54e34	Cucchi et al. (2020)
specific humidity			
surface downwelling shortwave flux in air			
surface downwelling longwave flux in air			
air temperature			
wind speed			
surface albedo[1]	–	–	–
vegetation height	GLAS	–	Los et al. (2012)
leaf area index	MOD15A2H	10.5067/MODIS/ MOD15A2H.006	–
topmodel saturation capacity	HWSD	–	Nachtergaele et al. (2012)
saturated hydraulic conductivity			
topographic index	–	–	Marthews et al. (2015)
flow direction	HydroSHEDS	–	Lehner et al. (2008);
flow accumulation			Lehner and Grill (2013)

[1] Produced using suite u-ag343 accessible at https://code.metoffice.gov.uk/trac/roses-u.

Table A2. Sources for data used in configuration 2.

Variable name	Dataset name	Data DOI	Related publications
surface ~~runoff flux~~ runoff flux delivered to rivers	CHESS-land	10.5285/c76096d6-45d4-4a69-a310-4c67f8dcf096	Martínez-de la Torre et al. (2018)
~~subsurface_runoff_flux~~ net groundwater flux to rivers			
flow ~~direction~~	–	–	Davies and Bell (2009); Martínez-de la Torre et al. (2019)
flow ~~accumulation~~			

Table A3. Sources for data used in configuration 3.

Variable name	Dataset name	Data DOI	Related publications
precipitation flux	ERA5	10.24381/cds.20d54e34	Cucchi et al. (2020)
specific humidity			
surface downwelling shortwave flux in air			
surface downwelling longwave flux in air			
air temperature			
wind speed			
surface albedo[1]	–	–	–
vegetation height	GLAS	–	Los et al. (2012)
leaf area index	MOD15A2H	10.5067/MODIS/MOD15A2H.006	–

[1] Produced using suite u-ag343 accessible at https://code.metoffice.gov.uk/trac/roses-u.

Appendix B: Additional results

Author contributions. All co-authors designed the blueprint for the framework. TH and RJE developed the framework implementation in Python. TH performed the simulations. TH and RJE processed the simulation outputs. TH prepared the manuscript with contributions from all co-authors.
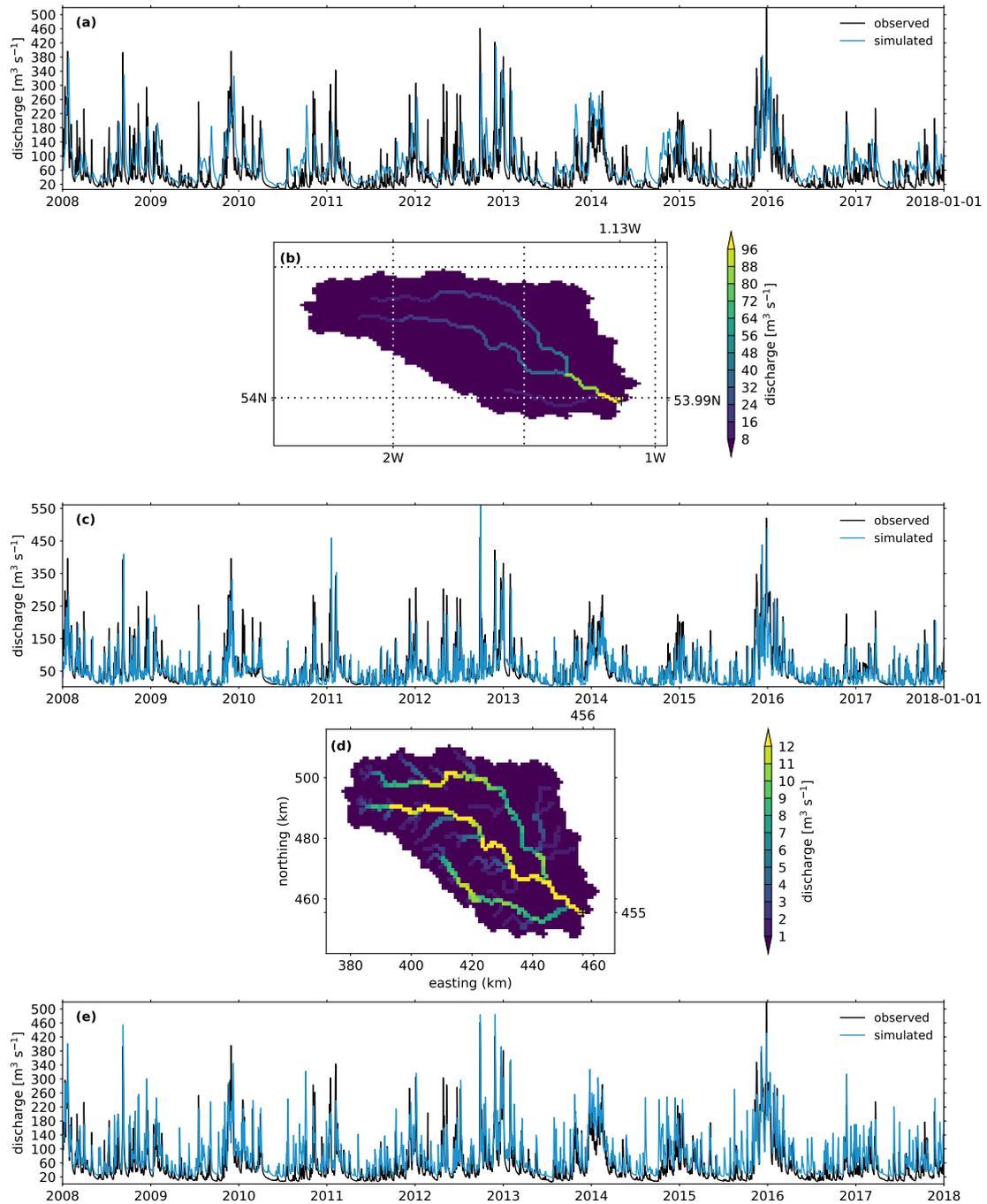
Figure B1. Simulation of the river discharge with the three configurations for the Ouse catchment: **(a)** observed and simulated hydrographs with configuration 1 at the catchment outlet [1.13 °W, 53.99 °N], **(b)** gridded simulated discharge with configuration 1 for the last simulation step [2018-01-01], **(c)** observed and simulated hydrographs with configuration 2 at the catchment outlet [456, 455], **(d)** gridded simulated discharge with configuration 2 for the last simulation step [2018-01-01], **(e)** observed and simulated hydrographs with configuration 3 at the catchment outlet.
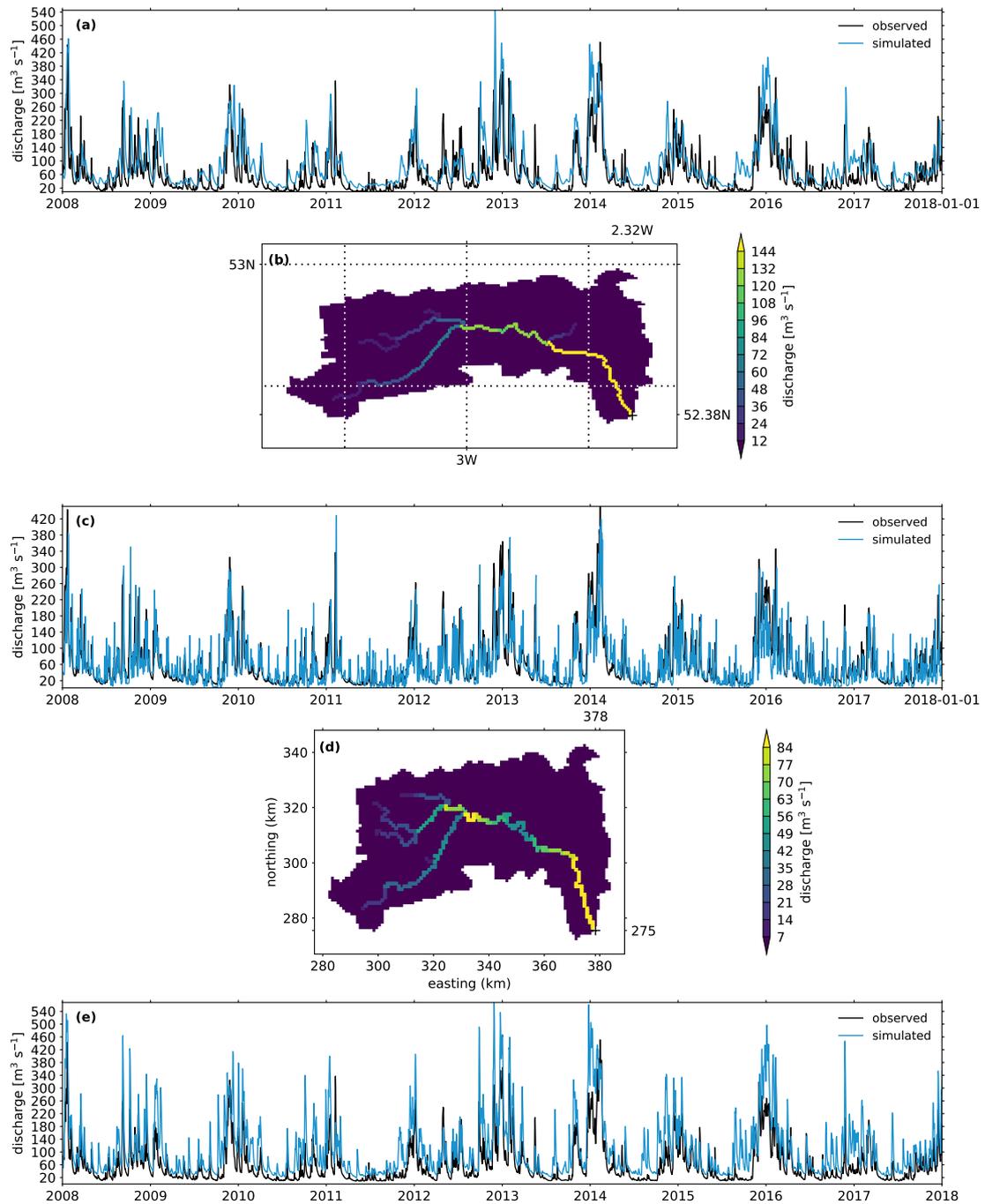
Figure B2. Simulation of the river discharge with the three configurations for the Severn catchment: **(a)** observed and simulated hydrographs with configuration 1 at the catchment outlet [2.32 °W, 52.38 °N], **(b)** gridded simulated discharge with configuration 1 for the last simulation step [2018-01-01], **(c)** observed and simulated hydrographs with configuration 2 at the catchment outlet [378, 275], **(d)** gridded simulated discharge with configuration 2 for the last simulation step [2018-01-01], **(e)** observed and simulated hydrographs with configuration 3 at the catchment outlet.

400   *Competing interests.*   The authors declare that they have no conflict of interests.

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405   providing the rainfall and potential evapotranspiration data used to calibrate the SMART model, Helen Davies for providing the HydroSHEDS dataset, and Huw Lewis for providing a Python version of RFM used to create an open water component for use in the framework.

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