Hydro-JULES: Next generation land surface and hydrological prediction

1. Motivation

Understanding the risks and opportunities presented by the changing water cycle is one of the most pressing challenges facing scientists, water managers and policymakers in the 21st century [1]. The Paris Agreement challenges scientists to improve our understanding of the water cycle's role in the Earth system, to quantify the risks and impacts of anthropogenic warming and environmental change on hydrological extremes, and to provide more precise estimates of the availability of water resources worldwide. The Sendai Framework for Disaster Risk Reduction reinforces the importance of understanding hydro-meteorological hazards to support risk-based management and to provide timely and accurate predictions. Arising from the 2030 agenda, the Sustainable Development Goals emphasise the need to remove the constraints that water insecurity places on economic growth [2, 3], and highlight the transformative benefits arising in both developed and developing economies from well-managed water resources and reduced vulnerability to extremes [4]. In the United Kingdom, the 2016 National Flood Resilience Review [5] has stressed the importance of accurate assessments of current and future flood risk, and stimulated innovation to provide better predictions of floods across all time-scales. Moreover, the resilience of key economic and infrastructure assets to current and future water resources availability and extremes demands robust, defensible, physically-consistent projections to support long-lived investment decisions [6].

The UK is a world leader in weather, climate and hydrological science and in order to accelerate progress in integrated modelling in this field, NERC Council agreed in October 2016 to commission the development of a state-of the art terrestrial hydrological model to couple to the JULES land-surface model and related hydrological models. The new programme, Hydro-JULES, is supported under NERC National Capability and delivered by CEH in partnership with NCAS and BGS. In March 2018, a period of consultation with members of the UK academic and research community indicated widespread support for the development of community hydrological model developed alongside and in conjunction with JULES, and a shared desire to bring together the land-surface modelling community with the hydrological community for mutual benefit (see Appendix A). The long-term vision for this investment in hydrological science under National Capability funding is that it will enable a far-reaching, world-leading research agenda that could not otherwise be pursued by individual research groups and will provide leadership for the research and academic communities in hydrological and land-surface science, both in the UK and overseas.

The development of an integrated UK and global modelling system that goes from global climate and local rainfall through the terrestrial hydrological system to flood inundation assessments and consequent impacts will enable the UK to push the frontiers of hydrological science, supporting and enabling collaborative work across the research and academic community to (i) address important science questions in the fields of land atmosphere feedbacks, carbon and nutrient cycles, data science and integration with novel instrumentation and Earth observation technologies; (ii) quantify the risks of hydroclimatic extremes (e.g., floods and drought) in a changing environment to support long-range planning and policy decisions; and (iii) improve hydrological forecasting using new sensors and modelling technology.

2. Project summary

The major project outcome will be a world-leading integrated terrestrial hydrological model that goes from global weather and local rainfall through the terrestrial hydrological system to flood inundation assessments and their consequent impacts. The Hydro-JULES model and its associated datasets will enable UK science to tackle outstanding research questions in hydrological science and will provide a national resource to support research both specific to the Hydro-JULES project and beyond. Hydro-JULES will provide the UK hydrological and land-surface communities with the model and research infrastructure to tackle the most pressing internationally-important research questions in this field, which include:

- How do hydrological systems respond to present-day climate variability and how can the impacts of future climate change best be quantified in ungauged locations, in data-sparse regions and under non-stationary conditions?

- To what extent can new observational and modelling techniques improve our understanding of how extreme precipitation, especially high-intensity convective precipitation, drives flooding?
- How will changes in land-use and land management affect surface permeability, soil water storage, runoff, river flows and flood inundation?
- What are the combined probabilities of fluvial, pluvial, coastal and groundwater flooding in response to changes in climate, and can a coupled approach to flood risk estimation quantify those risks more effectively?
- How will biogeochemical and nutrient cycles respond to current and future variability in the hydrological cycle, especially under conditions of changing climate and land-cover?
- To what extent can assimilation of observed hydrological states and fluxes (e.g., soil moisture and stream flow) improve hydrological and meteorological predictions, and on what time-scales?
- Can uncertainty in large-scale hydrological predictions be attributed to specific hydrological processes in order to target future process-based research?
- What is the sensitivity of Earth system components (e.g., vegetation, carbon cycle, aerosols, land ice, sea ice, ocean circulation and biogeochemistry) to changes in the hydrological cycle; and can enhanced representation of terrestrial hydrology in Earth system models help constrain responses to such changes?

3. Project objectives

The Natural Environment Research Council (NERC), represented by its Research Centres, academic partners and collaborators is the UK's leading funder of hydrology and is ideally placed to make the necessary step change in hydrological research. This project will be undertaken in close collaboration with the wider NERC academic and research community in order to realise the development and deployment of a world-leading terrestrial hydrological model and to ensure that the model is comprehensively applied to outstanding hydrological and Earth system science questions and to support robust projections of changes in the hydrological cycle and extremes in the future.

The following recommendations were approved by NERC Council, December 2016.

O1. Integration of the 3-dimensional terrestrial water cycle in such a way as to ensure consistency across space and timescales, in the horizontal and vertical, and ensuring conservation of water across the various components.

O2. Integration with the atmosphere to ensure consistency in evapo-transpiration across the land-atmosphere interface, and full representation of the space/time heterogeneity of precipitation, which is fundamentally important for surface water flooding and the functioning of terrestrial water cycle.

O3. Ability to be integrated with models of the coastal ocean to represent river outflows (including nutrients), estuaries and the effects of tides and storm surges.

O4. Integration of the water cycle with other key terrestrial cycles to ensure consistency in the treatment of water, heat, carbon and nitrogen cycles, which are critical for modelling and understanding the Earth system.

O5. Flexibility to constrain the terrestrial system model with observations through stand-alone testing and through the process of data assimilation.

O6. Flexibility within terrestrial system model to allow testing and inter-comparison of different approaches to specific components.

O7. Flexibility of the terrestrial system model to permit its coupling to atmospheric and other model components through an appropriate standardised interface, and to permit its coupling to the Met Office Unified Model.

O8. Formal processes for quantification of uncertainty, including the propagation from driving meteorological variables through the hydrological system.

4. Project structure and collaboration

The Hydro-JULES project is organized into six work packages. The first sets out the common framework within which the model will be coordinated, and provides for direct engagement with the research, academic and stakeholder communities who will contribute to and benefit from the model.

Work packages 2–4 develop new underpinning science in hydro-meteorology, surface and soil hydrology, and groundwater science, which will feed enhanced component models into the Hydro-JULES system. Work package 5 develops four new application streams, one with a UK focus on natural hazards, one with a global focus to support ODA-aligned water resources assessments and global hydrological outlooks; one to harness new data assimilation technology to improve hydrological forecasts, and one task providing targeted support to the UK's contribution to internationally-coordinated hydrological and Earth system modelling programmes. Work package 6 brings together the UK and overseas hydrological communities so that Hydro-JULES can benefit from continued interactions and provide support to the research and academic communities.

The Hydro-JULES programme will work together with other NERC National Capability programmes concerned with hydrological and other Earth system processes, through the understanding of environmental controls on nutrient cycles linking terrestrial biogeochemistry with the oceans. Hydro-JULES will also collaborate with the Met Office through the JWCRP, including JULES, and through it the Met Office Unified Model and UKESM programmes. Hydro-JULES will also provide underpinning science to the UKEP programme. Further afield, we will interact closely with key European Commission programmes including the Horizon 2020 PRIMAVERA consortium for high resolution modelling and with WMO initiatives to improve hydrological outlooks.

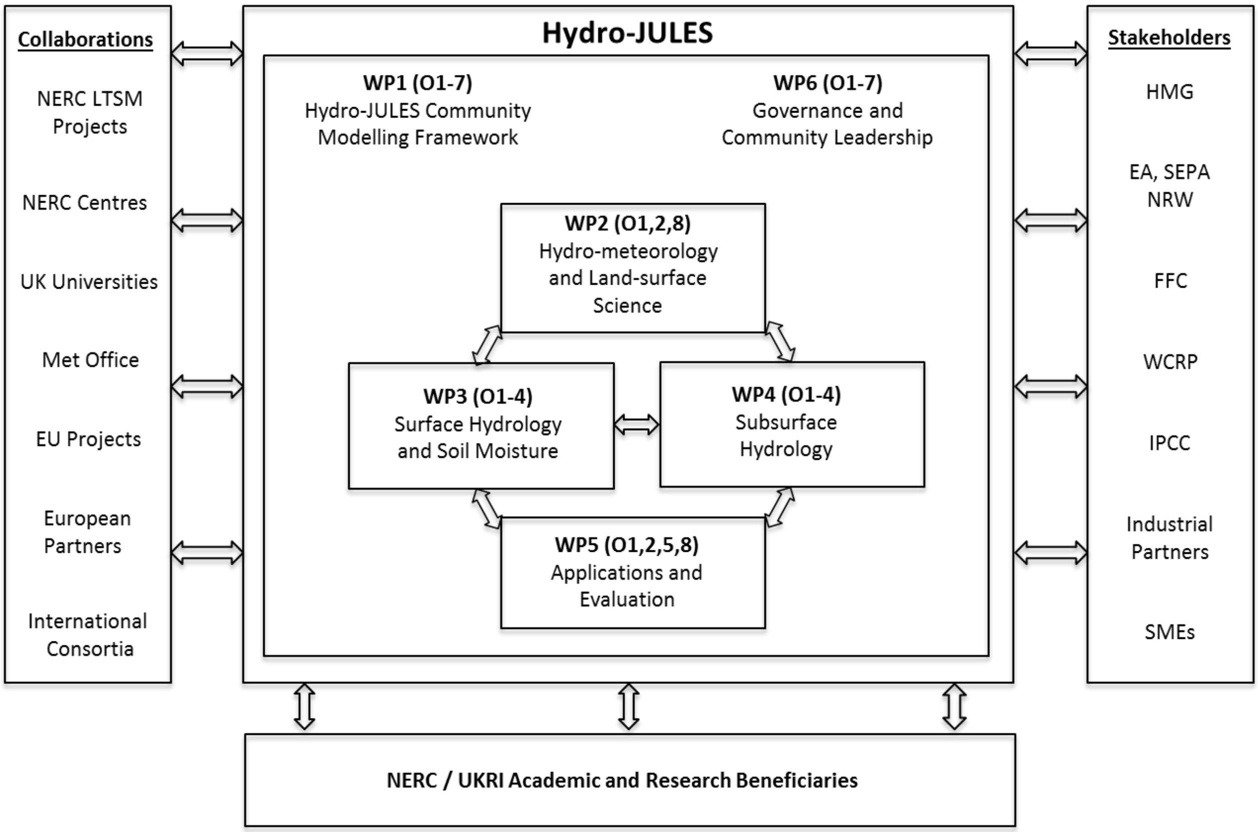

Figure 1: Project structure and interactions between Hydro-JULES work packages and academic and research partners, stakeholders and end-users.

5. Work packages and deliverables

Hydro-JULES will construct a new open-source modelling system for the terrestrial water cycle. New process representations will be developed to ensure representation and prediction of water fluxes between the land surface and atmosphere at spatial and temporal scales that support wider applications such as Earth System Modelling and meteorological forecasting (through improvement of JULES) and flood forecasting, agricultural management, etc. (through improved water cycle representation).

The Hydro-JULES project contains six major work packages (see Figure 1).

5.1 WP1: Hydro-JULES Community Modelling Framework [4 FTE: CEH 2 / NCAS 1.5 / BGS 0.5]

Task 1.1 Design and implement Hydro-JULES modelling framework and interfaces

We will design and develop a software platform to enable use of Hydro-JULES by researchers and model developers. This platform will provide version control of code, data and model configurations. The software framework will be functionally independent of the science framework, although the science aims will influence software needs and will include the ability to use and interchange open-source science modules developed in Work Packages 2–5 within a framework which provides flexible interfaces between model components [7]. Interfaces will also be developed between the hydrological model and other Earth system model components including the Met Office Unified Model (via JULES), models of the shelf seas and coastal oceans, and models of biogeochemistry and terrestrial nutrient transport [8]. Through community consultation, interfaces will be developed to cater for model developments foreseen in the next 10–20 years. We will ensure that interfaces that we develop will: (i) not impact the numerics of any model component; (ii) catalyse the development of more comprehensive models of the terrestrial water cycle; and (iii) future-proof Hydro-JULES against forthcoming alterations to the UM atmospheric dynamical core. In order to ensure the early delivery of a model that is fit for purpose, the resourcing of this work package will be prioritised, and its deliverables will be scheduled early in the work programme to allow the opportunity for iterative development and review.

Task 1.2 Consult research community and stakeholders on requirements and implementation

Interactions with researchers, stakeholders and users will be accomplished through regular workshops and consultations to ensure that the modelling system designed to take account of foreseeable future design requirements. The community process for gathering requirements and specifying use cases will be broad and inclusive, beginning with a workshop in Autumn 2018 and continuing through the establishment of working groups to consult on model integration and on specific processes which will persist through the lifetime of the programme. Papers on the modelling framework will be published in peer-reviewed journals and we will conduct an end-user review of the modelling system mid-way through the project to inform further model development and to highlight innovative application opportunities.

Task 1.3 Build archive of driving data, model configurations, and supporting datasets

In order to promote collaborative use of Hydro-JULES an open archive of quality-controlled driving data and model configurations, with supporting configurational datasets will be provided. To enable collaborative experiments to be reproduced across and between research groups to support reports and publications, an open access repository will be created to define and store model options and configurations. This will ensure reproducibility, support open-access publications, and will enable the UK to participate fully in internationally-coordinated hydrological and Earth system model experiments.

Task 1.4 Provide user training support and managed access via JASMIN

Formal training courses will be made available to the research and academic community, with a regular schedule to allow researchers straightforward access to training materials and support. Software support will be made available to those who wish to install and use the model, in addition to support for model developers in the wider community. Application support, and support for those in the research and academic communities who wish to use Hydro-JULES to support funding applications, will also be provided on a collaborative basis. Online training materials will be developed and made available free of charge. A user interface will be developed allowing easy access to Hydro-JULES in the cloud via JASMIN, whilst permitting open access to the code repository for advanced users and model developers.

<u>Deliverables (O1-7)</u>: ***D1.1*****:** Community consultation reports gathering user requirements and giving use cases for the Hydro-JULES system. ***D1.2:*** Design phase report for interface framework in Hydro-JULES code base. ***D1.3*****:** Development of prototype modelling system with version control and links to JULES. ***D1.4:*** Paper describing interface framework and coupling structure. ***D1.5:*** Open access repository of shared driving data. ***D1.6:*** Open access database of quality-controlled supporting datasets and facility to store model configurations (JASMIN). ***D1.7:*** Test stage review report. ***D1.8:***

Verification stage report including consultation with stakeholders. ***D1.9:*** Papers evaluating model performance against global and national datasets; benchmarking studies.

5.2 WP2: Hydro-meteorology and land-surface science [2 FTE: 1.5 / 0.5 / 0]

Task 2.1 Improve quantification of hydro-meteorological extremes

Well-constrained measures of hydro-meteorological variability are essential for accurate hydrological modelling. In the absence of fine-resolution precipitation data it is impossible to evaluate hydrological model performance and to attribute uncertainties to key physical processes. This work package, in collaboration with NCAS, will investigate and improve our scientific understanding of key physical processes responsible for the production of heavy precipitation, its persistence, and the emergence of spatial and temporal correlation structures that influence flooding. Heavy precipitation generated by convective systems leads to flooding when rain persists in the same location. Understanding the combination of cloud physical processes responsible for producing heavy rain in conjunction with the dynamics that cause the regeneration of cloud cells as well as the key up- and downdraught scales involved is essential to understand sub-daily variability. This will be achieved using new and existing data from projects such as COnvective Precipitation Experiment (COPE) [9]. In addition, we will develop new algorithms to estimate hydrometeor properties using hitherto underutilised NCAS and Chilbolton dual-polarisation radar data, and we will assess the utility of these estimates for flood modelling.

Task 2.2 Develop current and future scenarios for flood and drought risk modelling

This task will deliver an enhanced sub-daily 1 km historical gridded rainfall product (CEH-GEAR). This dataset, which is based on analysis of data from Met Office and other UK rain gauges, will be extended to include sub-daily temporal resolution, and will be made freely available to the research and academic community. This task will also include the production of datasets on future climate for use with Hydro-JULES and to support other applications in the hydrological community including the use of UKCP18 outputs and high resolution CONVEX rainfall outputs which quantify hydro-meteorological extremes.

Task 2.3 Quantify uncertainty in hydrological predictions

Considerable uncertainty is introduced to hydrological predictions through spatial heterogeneity of precipitation measurements and projections. Predictions of hydrological extremes can vary by several orders of magnitude as a result. This task will investigate the role of the spatial pattern of precipitation forcing on hydrological and flood related uncertainties. It will also consider the precipitation (rain and snow) interaction with the land across space and time and quantify the impact of rainfall intensity distribution in time and space on hydrological outcomes. Partitioning of uncertainty between driving data and hydrological model components will also form a key part of this task [10], in order to target future research at model components where uncertainties are greatest, and to inform and prioritise future process-based research [11].

Task 2.4 Improve understanding of canopy processes and evaporation from multiple sources

There is a pressing need in hydrological and land-surface models to reconcile the calculation of evaporation rates from soil, canopy and vegetation at local, national and global scales. The work will consider the physics of evaporation in land-surface hydrological models, particularly in order to resolve interactions between vegetation and the atmosphere. This work package will provide modelling capability necessary to understand the links between changing land cover and the hydrological response of catchments to rainfall. These links are often mediated through evaporation of intercepted water from the canopy store but are not usually well represented in hydrological models. This task will result in enhanced understanding of canopy and evaporation processes, which will reduce global biases in land-surface evaporation and provide a firm basis to quantify the impacts of changes in the water balance resulting from changes in land-cover, including natural vegetation and crops.

Deliverables (O1-2, O8): ***D2.1*****:** Papers analysing performance benefits of X-band dual polarisation radar for flood forecasting at selected UK locations. ***D2.2:*** Development of CEH-GEAR gridded rainfall dataset at 1 km and CHESS 1 km UK-scale land-surface forcing datasets ***D2.3:*** Development of UKCP18 and high-resolution convection-permitting model projections for UK hydrological applications; papers analysing projections. ***D2.4:*** Papers quantifying uncertainty in hydrological model components including interactions between meteorological uncertainty and hydrological modelling uncertainty. ***D2.5:*** Papers describing and evaluating improvements to canopy interception evaporation*.* ***D2.6*****:** Papers analysing model experiments on hydrological effects of land-cover changes in UK and overseas.

5.3 WP3: Surface Hydrology and Soil Moisture [2 FTE: 2 / 0 / 0]

Task 3.1 Improve model representation of infiltration, soil hydraulics and runoff generation

The soil hydraulics and runoff schemes in Hydro-JULES will be developed to include lateral transport to take account of new developments in hydrological science [12]. Specifically, this task will tackle the challenge arising from use of the Darcy-Richards equation in large-scale hydrological modelling of the unsaturated zone, noting in particular that the scaling of results from experimental studies at scales ~1–10 m cannot be expected to account for non-Darcian fluxes (attributable, for example, to variably saturated conditions or flow through macropores) in locations and at scales where these are relevant [13]. Enhancements will also be included to represent the particular behaviour of frozen, organic, and highly weathered tropical soils. Model developments delivered under this task will be guided by the interface framework established in WP1 and will provide physically-based mass, energy and momentum flux closure [14], with no *a priori* constraint on the structure of the model's discretisation of space and time. Beyond better physical realism, this task will deliver improved predictions of runoff to support streamflow forecasts and identify areas prone to surface water flooding.

Task 3.2 Improve river routing and inundation mechanisms

Whilst routing schemes in global hydrological models are well developed, there is a range of code enhancements that can be deployed to improve simulation of inundated across a range of scales [15]. This task will consider the range of inundation processes represented in hydrological and land-surface models and will seek to include not only kinematic routing functions which are presently implemented but also diffusion wave solutions for large-scale applications and shallow water equation solvers for finer resolution limited-area applications [16]. In parallel with the inclusion of new routing and inundation physics, this work package will also take advantage of high-resolution topographic datasets and make preparation for use with emerging EO products that will become available during the lifetime of the programme. The new routing schemes will be designed in order to be coupled to models of freshwater lakes and wetlands, and to models of estuarine environments, shelf seas and coastal oceans [8].

Task 3.3 Enhance model representation of nutrient transport along river pathways

The ability to couple macronutrient transport processes (C, N, P) into simulations of river flow and heat transport in Hydro-JULES will improve representation of biogeochemical processes in Earth system models and models used for environmental prediction. These additions will enable impact-based assessments of changes in climate, vegetation and land-use on river water quality and biogeochemistry but will also, through JULES and UKESM, enhance our ability to test basic hypotheses on the role of terrestrial hydrology in governing biogeochemical interactions in the Earth system [17-19]. This task offers clear synergies with other NERC National Capability programmes which will develop the basis for nutrient transport modelling at scales relevant to Hydro-JULES.

Task 3.4 Include anthropogenic influences on the water cycle

The impact of the changing water cycle on managed water systems is a key challenge for the 21st century [20, 21]. Moreover, it is recognised that in many locations around the world the effect on the water balance of anthropogenic interventions in the water system is of equivalent magnitude to key fluxes in the natural system [22]. For both these reasons, it is vital that global models of the terrestrial water cycle include representation of anthropogenic interventions in the water cycle. This task will develop a framework to represent anthropogenic water demand, crop water use, irrigation, and the impact of impoundments and will investigate their sensitivity to global environmental change. The framework will enable Hydro-JULES to simulate anthropogenic interventions in the water cycle and will support the collaborative uptake of Hydro-JULES to inform UK infrastructure adaptation policy and build capacity in ODA-supported programmes.

Deliverables (O1-4): ***D3.1***: Papers describing improved soil hydraulic scheme(s), tests and benchmarking against existing models. ***D3.2:*** Prototype model of vulnerability to pluvial flooding using improved soil hydraulics and infiltration model. ***D3.3:*** Papers describing additional routing and inundation physics incorporated into Hydro-JULES in collaboration with academic and research community. ***D3.4:*** Framework to include nutrient transport and interface with existing models. ***D3.5:*** Scheme to take account of managed water (domestic, irrigation, industrial water demand; inter-basin transfers; impoundments) and to interface with existing models.

5.4 WP4: Subsurface Hydrology [2 FTE: 0.5 / 0 / 1.5]

Task 4.1 National scale groundwater process model

Groundwater plays a key role in UK water resources both directly from abstraction from boreholes and springs, and indirectly from supporting river baseflow. It forms a crucial source of agricultural, industrial and public water supply in many regions of the UK, particularly in the south-east of England. During drought, groundwater provides resilience to the water supply system; yet after prolonged rainfall, leading to sustained above-average recharge, groundwater can add to flood risk in some locations [23]. Led by BGS, this work package will develop an enhanced representation of groundwater in Hydro-JULES, ensuring that groundwater systems are simulated, and issues such as recharge processes, hyporheic zone interactions, groundwater flooding and groundwater resources including drought response, can be addressed under both current and future conditions using the best available surface and groundwater science. This model will draw on expertise within BGS and will make use of extensive data on groundwater systems as well as aquifer properties in the UK in order to achieve levels of accuracy appropriate to problems at the UK scale.

Task 4.2 Novel supporting datasets for groundwater science

Supporting datasets will be generated both from sub-surface monitoring records and relevant databases for estimating model parameters. Where available, we will take advantage of new and existing Earth Observation (EO) sources for validation of groundwater storage [24]. For situations where it is necessary to represent groundwater processes globally (for example in global ESM applications), we will develop a simplified representation of groundwater suitable for use in data-sparse regions [25]. This model component will be based on a distributed numerical solution to the groundwater flow equation and provide a time varying, spatial representation of groundwater head.

Deliverables (O1-4): ***D4.1***: Papers documenting enhanced national groundwater model in Hydro-JULES, including coupling to Hydro-JULES surface hydrology modules. ***D4.2:*** Papers documenting groundwater model incorporated into Hydro-JULES and JULES for use in global ESM applications. ***D4.3:*** Database of quality-controlled datasets supporting national and global configurations of the groundwater flow models (including specific yield and saturated hydraulic conductivity). ***D4.4:*** Studies of groundwater availability for water resources applications using IPCC climate change projections together with coupled Hydro-JULES system. ***D4.5:*** Papers assessing UK risks from groundwater flooding under current and future scenarios.

5.5 WP5: Applications and Evaluation [1.5 FTE: 1.5 / 0 / 0]

Task 5.1 Enable science for hydrological applications

Hydro-JULES will be applied and tested in several high-profile case studies in the UK for use in applications of particular stakeholder interest. In the first instance, attention will be paid to the necessary science developments required to enhance hydrological outlooks for the UK. Key links already in place with Defra / EA, the Flood Forecasting Centre and the Met Office's UK Environmental Prediction Programme will be maintained and extended. The stakeholder requirements for these applications will be sought at an early stage in the project. Applications of the coupled modelling system in overseas locations will be supported, where possible, in collaboration with additional funding streams, so that the UK research and academic community can be enabled to offer the greatest possible contribution to overseas development.

Task 5.2 Exploit data assimilation techniques for observations from multiple sources

Building on substantial earlier work on data assimilation in hydrological modelling [26], and through NASA's Land Information System [27] and other data assimilation initiatives [28, 29], this task will exploit the potential for wider use of data assimilation techniques for state-updating and parameter estimation. We will develop a protocol and demonstrator product to assimilate COSMOS-UK, satellite soil moisture data and river flow data. This work will result in a first-generation near-real-time UK soil moisture data product through blending of model output data, observed data (COSMOS-UK) and satellite data. This novel dataset will provide information on soil moisture drought for agricultural and ecological applications and will offer data on antecedent soil saturation for flood forecasters prior to extreme rainfall. Moreover, the new dataset will enable a range of scientific studies into soil moisture dry-down processes and land-atmosphere feedbacks and coupling, to improve model process descriptions and enhance skill in hydrological simulation. Further applications of more advanced data assimilation techniques, including the use of ensemble Kalman filters and 4-D variational methods for hydrological state updating and adjoint approaches to parameter estimation, will be explored in collaboration with project partners.

Task 5.3 Participate in international benchmarking and inter-comparison projects

Benchmarking and evaluation protocols will be developed to support Earth system modelling applications, in collaboration with NCAS, the UKESM project and with modelling groups in the UK and overseas. The maintenance of clearly-defined model configurations will enable participation in world-leading model inter-comparison programmes including ISIMIP and WCRP GEWEX-coordinated experiments, in addition to the delivery of UK science components in preparation for participation in forthcoming CMIP7 and AR7 experiment cycles. This work package will also develop a procedure for the formal quantification of model uncertainty in large-scale hydrological predictions in order to understand the relative magnitude of uncertainties across model sub-components and to direct further research.

Deliverables (O1-2, O5, O8): ***D5.1***: Stakeholder consultation report on underpinning science requirement for hydrological modelling. ***D5.2:*** National hydrological modelling data portal providing access to1 km Hydro-JULES outputs at UK scale. ***D5.3:*** Data assimilation protocol for soil moisture and river flows with Hydro-JULES including links to NASA LIS ***D5.4:*** Prototype 1 km national soil moisture product combining Hydro-JULES soil moisture with COSMOS-UK and EO products. ***D5.5:*** Report on applications of Hydro-JULES, including partnerships with UK, overseas, and WMO programmes ***D5.6:*** Papers and reports documenting ESM science studies that have benefited from improved representation of hydrological cycle in Hydro-JULES. ***D5.7:*** Published protocol to quantify uncertainty in large-scale hydrological model predictions and report recommending further understanding in the hydrological process chain.

5.6 WP6: Organization, engagement and community leadership [0.5 FTE: 0.5 / 0 / 0]

This work package supports the necessary tasks to ensure effective leadership and organisation of the project and to maintain engagement with the academic and research communities and with stakeholders and the general public.

Task 6.1 Convene project steering committee and establish protocols

The Programme Director will be Simon Dadson, appointed via CEH and reporting to Director, CEH and Executive Director, NERC. He will be supported by a Project Manager (20% FTE), and a Model Integration Scientist (30% FTE) who will ensure integration between model science components and maintain dialogue between the NERC research centres, the academic community, and other stakeholders. A project steering committee will be established which will comprise the Programme Director, Project Manager, Work Package leaders and at least one member from each of the partner institutes, and will meet monthly with responsibility for reviewing progress, monitoring performance, forward planning and resolving any problems or delays. For consultative purposes, the project will provide regular updates to the CEH Science Board, and an external science advisory panel will be appointed. Policies will be instituted to set out good practice for interaction between stakeholders, including a fair-use policy, communications strategy, open access policy, policies for the administration of working groups, formal structures to organise interactions between stakeholders and to set out links with related programmes including JULES, JWCRP, and other UKRI-funded programmes.

Task 6.2 Create knowledge exchange opportunities with academic and research community

Knowledge exchange with the academic and research communities will be promoted through the establishment of working groups to tackle particular issues associated with key elements of the workplan. These include surface water (including inundation), groundwater, managed water, evaporation, and interfaces, although others may be added to serve particular emerging needs. The working groups will permit engagement with Hydro-JULES core developments and will also catalyse the uptake of Hydro-JULES outputs by the research and academic communities.

Specific initiatives that will enable closer interaction and engagement will include:

- Annual science community meeting
- Provision for collaboration with doctoral students and early-career researchers
- Funding for early career and advanced visiting fellowships to draw in particular expertise from the research and academic communities
- Open access publication strategy

Task 6.3 Engage with stakeholders to raise awareness and create engagement opportunities

A series of stakeholder-facing workshops will be organised to raise awareness amongst the end-user community to gather requirements and create opportunities to use outputs from Hydro-JULES and related projects in further work. Specifically, we will reach out to public-sector stakeholders in the Met Office, ECMWF, EA, NRW, SEPA, Flood Forecasting Centre, Scottish Flood Forecasting Service, Public Health England, and to SME stakeholders in James Hutton Institute, Sayers and Partners, HR Wallingford and JBA. CEH will raise awareness of Hydro-JULES via continued participation in the Environment Agency's Theme Advisory Group for Flood and Coastal Risk Management. A series of workshops will be organised in order to establish and maintain these links, with a further flexible schedule of activities to act on ideas that emerge in partnership with stakeholder groups. It is recognised that priority for delivery within Hydro-JULES is for key underpinning science to advance national capability. The operationalisation of this science is a research endeavour in its own right and will require additional research projects to enable its implementation.

Task 6.4 Establish platforms for public relations and outreach

Under this task, a suite of public relations and outreach activities will raise awareness of Hydro-JULES and other related research amongst the general public, including participation in public-facing events such as Flood Expo, the Royal Society Summer Exhibition, and other science festivals in the UK. A website will be established to collate information about the project from multiple channels and to ensure that all communities are able to access the right information about the programme and its outputs. We will seek to raise awareness of the programme via traditional print and broadcast media, and we will create an online presence for Hydro-JULES making full use of digital and social media and taking advantage of citizen science opportunities that may arise.

<u>Deliverables (O1-7)</u>: ***D6.1***: Shared repository of project documents. ***D6.2:*** Establishment of project board and International Advisory Panel. ***D6.3:*** Programme of academic and research community workshops through which working groups can convene; ***D6.4*** Programme of annual open meetings; ***D6.5*** Dissemination of research findings through participation in national and international academic conferences. ***D6.6*** Stakeholder engagement with key participants (Defra/EA, SEPA, NRW, FFC, etc). ***D6.7*** Strategy documents for early career researcher support including collaborative and CASE studentships and support for visiting students and researchers. ***D6.8*** Publication strategy and fair use policy. ***D6.9*** Fellowship programme to enable collaboration with academic and research community. ***D6.10*** Programme of user training workshops. ***D6.11*** Website and social media presence. ***D.6.12*** Programme of participation in events to engage the general public.

6. Project management and resource commitments

The Programme Leader (PL) will direct advances in the hydrological model development across the Centres. The PL will also have responsibility to work with the wider community, including HEIs, the Met Office, to coordinate the strategic development of the next generation of hydrology in JULES. CEH will provide a team of ca. 8 FTEs with skills in hydrological, land surface, vegetation, soil moisture, and physically-based numerical modelling, as well as data assimilation, software development/programming and technical code managers. BGS will contribute ca. 2 FTEs to deliver system conceptualisation and parameterisation and code development in groundwater modelling. NCAS will contribute ca. 2 FTEs in model and software development to focus on the technical expertise for coupling code design and implementation and in the use of high-resolution meteorological data. The fixed budget for the programme is given in Table 1, below. The scheduling of work packages will take place according to the Gantt chart given in Figure 2, below.

Table 1. Budget allocation and distribution across programme partners.

RO	Cost per annum	Total cost
CEH	£881k	£4.405M
BGS	£177k	£885k
NCAS	£142k	£710k
Total	£1.2M	£6.0M

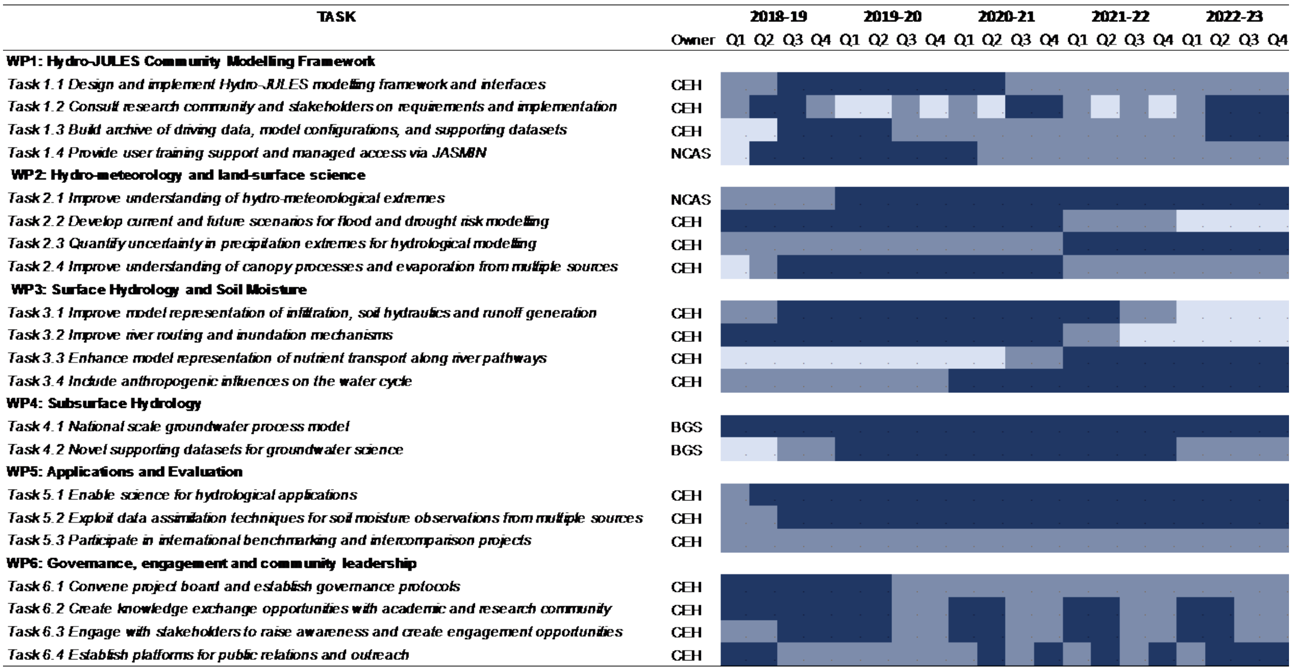

Figure 2: Project work package and task schedule (blue shading indicates relative levels of activity).

7. Wider relevance

Further long-term outcomes of this National Capability Programme will be enhanced model performance for flood and drought prediction and therefore improved accuracy of estimation and forecasting of hydrological extremes and water resource management. The physical models could be linked with impact datasets to provide direct hazard-impact forecasts of hydro-meteorological extremes (floods and droughts) to benefit vulnerable communities. As well as increased human resilience associated programmes will provide improved understanding of the response and recovery rates of ecosystems to such extreme events.

Hydro-JULES will draw on and contribute to the development of the underpinning CEH National Capability programmes that determine ecosystem and soil carbon response to land use and climate change (SPEED and Soil Organic Carbon-Dynamics) as well as LOCATE and UKESM. Existing national observatories will provide data. Furthermore, the ambitions of Hydro-JULES are such that extensive collaboration will be required with the wider research community (HEIs, MO, EA, Defra etc.). Following community workshops and engagement through current and recent NERC programmes, e.g. Macronutrient Cycles, Flooding from Intense Rainfall, Storm Risk Mitigation, Drought and Water Scarcity and the Changing Water Cycle, we envisage strategic partnerships and new highlight topics in hydrology and computational modelling.

Hydro-JULES will provide the basis of new studies in physically-based land hydrology and integrated modelling of the UK at high resolution, leading to future competitive research programmes under strategic partnership or highlight topic funding lines. At the global scale the capability developed in Hydro-JULES will be of direct benefit to global initiatives to provide early warning and longer-term outlook-style hydrological services, such as those currently provided by CEH/Met Office and WMO Global Hydrological Status and Outlook System. In addition, this NC programme will underpin UK research in GCRF and ISCF by providing advances in predictive systems for soil moisture evaluation and water resources. Examples of pressing ODA-related issues for which capacity can be built include hydrological drivers of flood and drought in food producing regions, links between surface water hydrology and the transmission of water-borne and water-related diseases (e.g., cholera, schistosomiasis and malaria), and the provision of clean, safe drinking water for communities in water insecure environments. It will also drive innovation in sensor development, models for land management, and offer modelling technology to support precision farming and water resource management in the UK and overseas. The Hydro-JULES coupled model will in the longer term provide essential underpinning hydrological science and advanced terrestrial models in support of the UK Environment Prediction (UKEP) programme, supported by NERC National Capability from CEH, NOC and PML, which has the long-term aim of building a high resolution, coupled atmosphere, land surface and coastal ocean model.

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APPENDIX A – Consultation Outcomes

Consultations were conducted during March 2018. Consultees were drawn from the academic and research communities in hydrology and land surface science. Notes from the consultation meeting are included below. Additional consultations have taken place with representatives from the Met Office and wider atmospheric science communities via the Joint Weather and Climate Research Programme.

Initial dissemination of planned Hydro-JULES activities has taken place via the EA's FCERM R&D Theme Advisory Group pending a focussed meeting of the stakeholder group, which has been assembled in consultation with Prof. Doug Wilson (EA), comprising representatives of Defra, EA, SEPA, and NRW. An open meeting to launch the programme is planned for September 2018.

Hydro-JULES pre-project meeting 23 March 2018, CEH Wallingford

Meeting Note

Attendees in person:

CEH: Simon Dadson, Alan Jenkins, Eleanor Blyth, Jan Polcher (CEH/LMD/CNRS), Vicky Bell, Douglas Clark, Steve Cole, Gwyn Rees, Chris Taylor.

BGS: Chris Jackson

NCAS: Pier Luigi Vidale

Met Office: Martin Best, Nicola Gedney, Huw Lewis

Sarah Chadburn (U. Exeter), Hannah Cloke (U. Reading), Jim Hall (Oxford U.), Louise Heathwaite (Lancaster U.), Justin Sheffield (U. Southampton), Anne Verhoef (U. Reading)

By circulation:

Nick Reynard (CEH), Andrew Hughes (BGS), Alan MacDonald (BGS), Rowan Sutton (NCAS)

Paul Bates (Bristol U.), Keith Beven (Lancaster U.), Wouter Buytaert (Imperial College), Jim Freer (Bristol U.), Enda O'Connell (Newcastle U.), Thorsten Wagener (Bristol U.), Adrian Butler (Imperial College), Peter Cox (U. Exeter).

Objectives

1. Present the recommendations of NERC Council for discussion amongst members of the research and academic communities;

2. Discuss ways in which research and academic stakeholders may wish to engage with the programme; and

3. Put forward suggestions for additional research programmes that might be enabled by research undertaken under Hydro-JULES.

Agenda

0900 Welcome and Outline of Hydro-JULES [SD]
0920 Introductions
0945 Key advances required in hydrological and land-surface science [SD]
1100 Coffee
1130 Discussion of objectives agreed by NERC Council [AJ]
1300 Lunch
1400 Implementation framework (governance; interfaces; relation to JULES) [EB & JP]
1500 Partnerships, engagement, and sustainability [SD]
1600 Tea and finish

Meeting notes

The meeting opened at 0900 with welcoming remarks from Mark Bailey and Simon Dadson, and introductions from participants.

0945-1100 Discussion led by Simon on "Key advances required in hydrological and land-surface science"

Priorities The need to develop an outline timeline and priority list was discussed and emphasised by participants, both for the 5 years of Hydro-JULES and beyond. It was considered that a diagram linking the NERC Council objectives would add clarity and enable the relations between activities to be explained more easily.

What Hydro-JULES can usefully offer is a framework for advancing hydrological science at the national scale and an integrated model for assessing hydrological impacts of future environmental change. The importance of retaining sight of a wider aim (beyond developing tools) to bring about an intellectual advancement in UK hydrological science was stressed, as was the need to retain flexible model structures and interfaces in order to serve this aim.

A large part of the Hydro-JULES work programme involves improving the representation of processes in JULES, and improving the way that those processes are linked together. Two major points were raised: first, the need to understand quickly which processes were to be targeted initially; second, to maintain the spirit of the vision for Hydro-JULES that by recognising the integration between processes it will be possible to make more and better progress together. This is particularly the case in tackling research problems where the land-surface and hydrological communities have complementary skills.

Processes Five science areas for targeted improvement were identified: **groundwater, surface water (incl. inundation), managed water, soil hydraulics, evaporation**. It was noted that whilst the first three had to date received relatively little attention from those working within the JULES community there was deep expertise in the UK and international scientific communities and it should be the role of Hydro-JULES to enable the community to come together in these areas. The last two areas are represented in JULES but there is significant scope for future improvement.

Framework for advancing hydrological science The advantages of producing a consistent framework through Hydro-JULES were discussed. Key principles were suggested that (i) the model needs to be flexible for different uses and transparent – e.g. to state assumptions, clarify relationship between components; (ii) the advantage of a consistent framework is that a broad range of interactions can be represented (e.g., inundation – recharge – evaporation; drought – vegetation – evaporation); (iii) the physically-based coupling of energy and water in JULES (which is amongst its biggest scientific advantages) should not be overlooked.

The importance of identifying and articulating clearly the "customer" for Hydro-JULES was stressed, because this would help set priorities. NERC and UKRI are the immediate customers, on behalf of the academic community. Three specific stakeholder communities were identified: (1) Earth System Modelling (2) Global water resources – lots of advances have already been achieved elsewhere and will benefit from collaboration (3) UK-scale customers. For this last category there are already several tools that have developed over a long period of time in response to user requirements. The need to maintain and develop links with the broader hydrological community (particularly in statistical hydrology) was emphasised. Whilst Hydro-JULES will offer improvements in process representation, additional research projects will be required to connect those improvements to activities that might improve operational hydrology.

Outcome: Identify structures to allow engagement with community – e.g. working groups in each process area and to cover interactions.

1130-1300 Discussion led by AJ around the objectives agreed by NERC council

The NERC Council objectives will be taken forward via the Hydro-JULES implementation plan, which will be drafted at the outset of the project, giving the opportunity to set out an approach and priorities. Three main ideas through which the objectives might be viewed are: integration, flexibility and formal processes. Widespread support was expressed for the presentation of the objectives with the aid of a diagram, in which #1 (representation of a fuller and more integrated water cycle; process understanding and representation) is the most important; #2-4 are relevant interfaces; and #5-8 express desirable properties of the resulting system.

Links to other programmes Some objectives will require strong links to other programmes such as Macronutrient Cycles, UKEP, UKESM, and LOCATE in order to ensure successful delivery. It was also noted that detailed storm surge modelling is already done well elsewhere which provides further opportunities for collaboration, especially in order that the two-way land-ocean connection might be considered. A process to deal with items that might be outside the scope of Hydro-JULES was discussed so that key tasks might be prioritised or delivered in partnership.

Scale An initial focus on two important scales: 1 km resolution for the UK, and 25 km resolution for global model would help the scope of the programme to remain achievable. Nonetheless it was considered worthwhile to consider the appropriate scales at which each of the five processes articulated in Section 1 should be represented, owing to the well-known dependence of physical representation on scale. This selection of scales also influences any distinction between vertical and horizontal processes during the model development phase.

Uncertainty A clear sense emerged that a framework for quantifying uncertainty in model parametrisations and predictions should be put in place at the outset and not postponed until later. Recent developments in the quantification of uncertainty should be used within Hydro-JULES, including approaches that are already well developed in hydrology. It was noted that there might also be opportunities to use other techniques, e.g., those inspired by stochastic physics.

Data assimilation Opportunities for DA were discussed, noting that DA is already well used in operational hydrology, and hydrological and meteorological forecasting. DA capability for JULES is currently being added via NASA's Land Information System, but not for streamflow. It was noted that opportunities in the field of DA are large and diverse and that priorities should be established in the implementation plan (e.g., relating to initial states, parameter values, uncertainties). The topic was, in general, considered suitable for a wider funded programme to bring together significant UK and international expertise in the area, once a suitable model was in place.

Outcome: Prioritisation of work streams in the implementation plan should reflect the discussion of the Hydro-JULES objectives set by NERC Council.

1400-1500 Discussion around EB's presentation on governance, interface etc.

Interfaces and coupling The advantages of a coupler were agreed, especially in relation to the flexibility and interoperability of components. There are time and CPU costs, but it offers some future-proofing. Discussion of how processes dominated by vertical and horizontal fluxes could be combined emphasised the need to consider technical issues around the design of interfaces. It was viewed that such a discussion would be worthwhile because it would set out how we see those interfaces operating for the next 10-20 years.

- The interfaces need to cater for developments foreseen in this period.
- The interfaces should not have any impact on the numerics of any model component.
- Developing interfaces between land surface and hydrological models will catalyse the development of more comprehensive models of the continental water cycle.
- One specific advantage of a coupler is that it will isolate JULES from any forthcoming overhaul of the UM atmospheric dynamical core.

- It was agreed that we should not restrict ourselves to use of the OASIS coupler, which is just one of many approaches.

Outcome: A working group should consider the interfaces/coupler. Centre on a joint (land-hydrology) paper which takes insights from existing approaches but articulates a vision of how best to structure a land-surface hydrological model to foster novel interdisciplinary science.

1500-close: Discussion around Partnerships, engagement, and sustainability

The need to provide a mechanism to engage the wider community – including those who do not choose to participate in Working Groups – was emphasised (e.g. ask for comments on documents and plans). A wider meeting will be planned for the autumn to allow us to set out our plans for the programme and allow wide engagement. It was hoped that part of that meeting might be given to the discussion of possible processes for wide stakeholder engagement and identification of future funding opportunities.

Information on the programme's goals should be made available soon, with responses to common questions so that the programme's aims can be defended and clarified if necessary (e.g. relationships to other projects and models, including JULES itself).

User support and community engagement Community engagement is viewed as a priority and a budget for supporting users should be considered, either through masterclasses, summer schools or direct user support. Provision of a cloud-based platform for use of Hydro-JULES (e.g. JASMIN/MAJIC) would greatly facilitate community engagement. A Fair Use Policy should be developed at the outset.

International links The importance of emphasising international links was highlighted, including (but not limited to):

- WRF-Hydro (https://ral.ucar.edu/projects/wrf_hydro/overview) and similar initiatives in the USA, National Water Model.
- We are keen to reach out to the hydrological community (in France, the US and Australia, in particular) and to see them produce code that is ready to interface to other (incl. atmospheric) models. It was noted that the joint JULES-Orchidee meeting was well-received and something similar might work for hydrology/Hydro-JULES.
- Explore links to Canada/John Pomeroy/Global Water Futures, including recent review papers.
- Links exist through JULES with Australian Bureau of Meteorology and other research endeavours; also via NIWA in New Zealand.
- Also links to GEWEX (we already have people in common).
- Poster on Hydro-JULES for upcoming Canadian and GEWEX meetings?

Funding The implementation plan should identify opportunities for further funding and give indicative timelines. The extensive role of hydrology in climate change, the carbon cycle, natural hazards, ecosystems and resource economics places it centrally within the UKRI landscape. Several funding streams of interest were suggested:

UK

- DTP renewals may provide the opportunity for collaborative studentships.
- Research Programmes in each of the 5 (process) areas?
- Highlight Topics, which are problem-focussed and need to start from a "big question" connected to Hydro-JULES.
    - Links between the water cycle and the carbon cycle (cross-cutting)
    - Water in the Anthropocene (cross-cutting).

- Future UKRI funding may seek to encourage cross-council programmes, which could encourage interdisciplinary strands of Hydro-JULES research: e.g. engineering and social science, economics. EPSRC for DA work, also including stochastic physics.

Overseas

- DfID/Newton Fund opportunities. Future GCRF opportunities.
- International Opportunity Fund to support networking – e.g. on anthropogenic factors.
- Satellite Catapult funds / UKSA?
- Joint NSF-NERC proposal(s) to link hydrological communities.
- ExtremeEarth has no consideration of hydrology; could offer novel computing and hardware technologies
- UKRI–BEIS international opportunity, ~£100M

Process integration A mechanism is needed that can allow both process/specialist studies and interdisciplinary/integrated studies. There is a need for fundamental model-based innovation to advance the representation of processes, but also an imperative not to advance them in isolation but to join components and seek to understand the interactions between processes. Ideally, such a framework, supported under National Capability funding, will allow Discovery Science across a broad hydrological base, not only amongst the Hydro-JULES delivery partners but the wider research and academic communities.

Outcome: plan for a wider engagement meeting early on (Autumn 2018), with mechanisms to allow input from the widest possible group of stakeholders.

Meeting notes: D. Clark, J. Polcher, E. Blyth, S. Dadson