Changing Water Cycle Programme
Science Plan 2009-2014

1. Introduction

The Changing Water Cycle Programme directly relates to delivery of the NERC Strategy (in particular Climate System (CS), Sustainable Use of Natural Resources (SUNR) and Natural Hazards (NH) Science Themes) and UK Governments Strategic Goals with respect to the adaptation to, and mitigation of, climate change.

This Research Programme will run initially for four years with funding approved by NERC Council of £10.1 million (£5million from the Climate System Theme; £2.3M from Natural Hazards Theme, £2.8M from SUNR Theme). It is anticipated that this Research Programme will make a significant contribution to the *Living With Environmental Change* programme. The programme will have global dimensions and take advantage of international collaboration opportunities; the programme will also have a more specific regional focus on the UK/European region and an overseas developing region, South Asia. The programme will be fully interdisciplinary, aiming to bring science understanding across four themes in a fully integrated way.

This programme will address the urgent needs to understand the changes taking place now, to improve projections of changes that will take place over the next 10-60 years; and, through LWEC, work with partners to develop methods and approaches to use this knowledge to support the management of the water system.

2. Research Programme Goals

The following goals for the programme have been defined:

1. To develop an integrated, quantitative understanding of the changes taking place in the global water cycle, involving all components of the earth system – the atmosphere, ocean, land surface and geosphere, cryosphere and biosphere.

2. To improve predictions for the next few decades of regional precipitation, evapotranspiration, soil moisture, hydrological storage and fluxes, focusing on the requirement to quantify and narrow the uncertainty in predictions.

3. To understand how local to regional scale hydrological and biogeochemical processes are responding and will respond to changing climate and land use, together with their consequent impacts on the sustainable use of soil and water.

4. To understand the consequences of the changing water cycle for water-related natural hazards, including floods and droughts, and to improve prediction and mitigation of these hazards.

The Changing Water Cycle Programme goals were recommended by the NERC Theme Leaders based on the challenges in the three NERC Strategic Themes: CS, SUNR and NH. These goals are very broad in scope and thus the focus of the programme will be directed via key themes, as defined by a science writing group which was appointed in March 2009. The four programme themes are detailed in Section 4 and cover elements of science from the three NERC Strategy Themes (CS, SUNR, NH) which have come together in this programme.

The programme will be directed to support inter-disciplinary, cutting-edge science, coordinating and integrating across the relevant communities.

The programme will not necessarily provide direct predictions, but concentrate on funding the fundamental science that will underpin predictive capability and quantify and improve uncertainty in predictions. The programme will build on observational evidence and process understanding to support predictive models and consider key uncertainties and thresholds relevant to improving model predictive capability. Projects will focus on timescales to improve predictive capability 10-60 years into the future. Thus, the focus is not looking at initialising decadal prediction models, nor into the period of equilibrium response that climate stabilisation achieves past ca.+60 years. These decadal timescales also align with the timeframes policy-makers are interested in.

The geographical scope of the programme is detailed in Section 3.3.

3. Strategic Context

3.1 Introduction

There is increasingly strong evidence that the global hydrological cycle is changing and intensifying, and it is expected to change further in the future. The IPCC Technical Report on Climate Change and Water (IPCC, 2008) concluded that:

- "Increased precipitation intensity and variability is projected to increase the risks of flooding and drought in many areas."
- "Climate change challenges the traditional assumption that past hydrological experience provides a good guide to future conditions."
- "Changes in water quantity and quality due to climate change are expected to affect food availability, stability, access and utilization."

This climatic variability and change is superimposed at the local scale onto a large number of other changes that affect the quantity and quality of water within hydrological systems, including land cover change, changes in the abstraction and return of surface and groundwater, and changes in water management practices. Past patterns and future trends therefore reflect a combination of multiple signals from multiple drivers. Adapting to such a changing water cycle presents enormous challenges. In order to develop long-term adaptation and mitigation measures to minimise loss, not only of direct hazards, such as floods and droughts, but also indirect hazards, such as wildfires, subsidence and the triggering of landslides, it is essential to project potential changes in the drivers of the hydrological system, and the distribution and nature of future impacts, at the regional scale.

However, projections of changes in the water cycle, at global and local scales, remain uncertain. This uncertainty manifests itself in different ways at different space and time scales, but essentially arises from our incomplete understanding of the climate system and limitations in our ability to model that system. Much of the uncertainty is associated with our understanding and representation of the water cycle as part of the climate system.

This programme contributes to improved understanding and representation of the changing water cycle, to understanding of the consequences of a changing water cycle, and to the development of procedures to use this understanding within water management. **A key feature of the programme is the integration of the consideration of the impacts of a changing water cycle alongside the 'science' of the changing water cycle.** This will not only enable the development of impact assessment procedures that utilise the best available science, but will also ensure that the science is directed towards aspects of the changing water cycle directly relevant to the impact and management communities.

3.2 Scientific Background: uncertainty in the changing water cycle

Predictions of water-related variables show very high uncertainty. For example, the Intergovernmental Panel on Climate Change fourth assessment report (IPCC AR4) states that throughout much of the tropics there is no consensus amongst existing climate models about whether greenhouse gas induced warming will lead to more or less rain – i.e. there is no consensus on the sign of the change, let alone the magnitude. In general, even when the sign is clear, the nature of changes in rainfall characteristics (i.e. frequency, intensity) is not, and these characteristics are critical for many impacts, such as those affecting hydrology and ecosystems.

The exchanges of water between the ocean, land and atmosphere are fundamental elements of the climate system. Changes in the hydrological cycle will not be spatially uniform and will lead to shifting of evaporation and precipitation patterns; changes over the ocean will be determined by the atmospheric and oceanic states. Over land precipitation and evaporation are moderated by atmospheric circulation, the availability of water in the soils, the physiological response of vegetation to high temperature, increasing CO_2 levels, water scarcity and human interventions. Current predictions for the 21st century suggest an overall increase in precipitation but with considerable regional variability, linked to changing circulation patterns. Generally higher latitudes are predicted to get wetter and the, already dry, subtropics drier. However, model uncertainty is high. Uncertainty for climate projections of changing precipitation on the regional scale is a limiting factor in producing credible hydrological predictions at regional and catchment scales, and it is unclear what impact these model uncertainties have on simulations. Most large scale, dynamical components of the global water cycle are represented in the current generation of climate and earth system models, although models continue to have real problems with major monsoons and synoptic-scale rain-bearing systems in both the tropics and extra-tropics. Rainfall characteristics (intensity, frequency) are still very challenging. Furthermore, many water-related processes are incompletely represented (for example exchanges of water between atmosphere, ocean, vegetation, soil and groundwater). Human activities are substantially modifying the water cycle regionally – with changing land cover, land use (particularly irrigation), dams and water extraction reducing river flows to the ocean. It is unclear how these interventions impact on the climate regionally and globally.

Changes in surface and groundwater regimes are not only driven by climatic variability and change, but also by water delivery into catchment systems (e.g. via glacially-fed rivers) and river basin characteristics, in particular land cover, its management and the use and management of surface and groundwater resources. Hydrological changes may be attributable to natural climate variability and /or to anthropogenic impacts (notably land use and water management). It is important to quantify the changes, including any threshold responses, and to seek to identify the separate or linked causes of changes. Detection and accompanying explanation of any changes has potential to enhance confidence in prediction of how the water cycles may change into the future.

Water security is a fundamental issue for the world's population. Changes in the water cycle may have major consequences for plant processes, soil properties and function, groundwater recharge and runoff generation, water flow paths across and through the landscape, river flows and river and groundwater quality, biogeochemical cycles and groundwater-surface water interactions. While the impacts of the changing water cycle upon each of the above processes are important in their own right, improved prediction of feedbacks between these processes are crucial to an integrated understanding of the consequences and adaptation to or mitigation against them. The IPCC (2008) technical paper on climate change and water noted that increased precipitation intensity and variability is projected to increase the propensity for flooding and drought in many areas.

It will be important to constrain uncertainties in flood and drought risk based on improved precipitation forecasting and on understanding feedbacks between climate and land use change and land surface processes (including mediation via vegetation and variation in glacial meltwater delivery) which may amplify local and regional impacts.

3.3 Geographical Focus

The programme will operate at two scales. Improved understanding and representation of some aspects of the changing water cycle requires a *global perspective*, particularly in terms of (but not restricted to) global ocean-atmosphere-climate interactions with water and energy cycles. The *regional scale* focuses, within the global context, on Northern Europe and an overseas developing area (aligned with the Ecosystem Services for Poverty Alleviation Programme, ESPA). The UK will be a particular European focus area, especially in terms of feedbacks to properly inform a potential future NERC action on climate change adaptation, as well as detection and attribution to capitalise on National Capability and existing data. The Changing Water Cycle science plan writing group have recommended that the overseas regional focus should be South Asia. Collaborative projects between Indian and UK partners will address regional issues that fit within the programme's global context, for example, reflecting the global research activity on monsoons (within CLIVAR and GEWEX), the need to understand the potential teleconnections of the Indian Monsoon and weather patterns in Northern Europe and the influence of Himalayan glacial meltwater variation on South Asian water supply.

South Asia, in particular the catchments of the Indus and Ganges rivers and the Indian Ocean (to 20^{o}S), has been selected as the most feasible region, where UK science can make the greatest contribution, due to the following:

- Improved understanding of the Indian monsoon, and improvements in its modelling is seen as a science priority - there are potential connections between the South Asian monsoon and weather patterns in northern Europe.
- Existing links between the UK and Indian science communities in terms of both collaboration and expertise
- Very high level of water usage (particularly in Ganges basin) and potential water scarcity in the future.
- Important (and poorly understood) interactions between climate, Himalayan glaciers, groundwater and water resources.

4. Research Themes

The outcome-driven programme Goals (Section 2) will be addressed via four linked science themes. These four themes outline the questions and issues that need to be tackled in order to deliver the outcomes specified by the programme's Goals. Table 1 (p.12) summarises how the themes' research foci relate to the programme goals.

1 **Land-Ocean-Atmosphere Interactions:** Understanding how feedbacks within the water cycle directly affect hydrological stores and fluxes.

2 **Precipitation:** Improve our understanding, observations and modelling to underpin the prediction of ongoing and future changes in precipitation and evaporation, their variability and impacts, from global to regional and local scales.

3 **Detection and Attribution:** To quantify and understand causes of changes in water cycle components over periods of record; and to use this understanding to work towards delivering robust prediction of changes in water cycle components.

4 **Consequences of the changing water cycle:** The implication of change in climate and land use for the assessment of water related hazards to and effects on human and natural systems.

The science themes are broad, and there are strong linkages between them. Detailed descriptions below highlight key *potential* topics within each theme. It is recognised that it may not be possible to address all of these topics through CWC funding alone. It is envisaged that some gaps will be filled through collaborations and links with other funded initiatives through the CWC working groups.

The delivery of the Science Themes will be implemented as specified in a separate *Implementation Plan*, which should be read in conjunction with this document. The *Implementation Plan* provides further details on standards and guidelines, data management requirements and science collaborations. The science will be delivered through funded interdisciplinary, cross-theme projects, funded cross-theme Working Groups (one per programme Goal) and through science coordination and programme management activities such as targeted knowledge exchange and outreach activities.

4. 1 Theme 1: Land / Ocean / Atmosphere / Interactions and Feedbacks

Aim of Theme
Understanding how feedbacks within the water cycle affect hydrological stores and fluxes.

Feedbacks and interactions between the surface and the atmosphere are of crucial importance to the global hydrological cycle. There is good evidence that interactions between the land and ocean surface states and precipitation are important at a wide range of scales – from kilometres to global. This theme should consider how the integrated effect of these processes influence regional precipitation and large scale atmospheric circulation patterns. These interactions occur via various processes including surface-atmosphere exchanges, boundary layer dynamics and atmospheric circulation patterns (for example blocking system and storm tracks) leading, for example, to the intensification of droughts over land and salinity anomalies in the ocean. To improve regional representation of future climates it is important to understand these interactions and feedbacks and to quantify the uncertainties in their representation within climate models.

Research Focus
Feedbacks operate on many different space and time scales. It is necessary to develop an integrated framework within which the magnitude and relative importance of each feedback can be assessed and understood. Within the context of this framework, research in the programme should consider in more detail some key feedbacks, at either the global or regional scale as appropriate.

- **The impact of the land surface on the persistence of large-scale rainfall anomalies.**
  Land surface feedbacks on rainfall occur locally through the enhancement of rain-bearing systems, and, regionally and globally, through the modulation of atmospheric circulation patterns. The soil moisture and vegetation states are key and hence these effects are likely to be most pronounced in the transition between wet and dry regions. We need to quantify regions and scales where these feedbacks are important, understand better conditions which lead to the persistence of regional precipitation anomalies (in particular, the persistence of droughts) and ensure these feedbacks are correctly represented within regional and global models.

- **The impacts of changing ocean surface state and atmospheric water vapour and precipitation patterns.**
  Ocean surface state, temperature and salinity, and near surface atmospheric temperature/humidity and wind speed impact strongly on ocean evaporation and ultimately on atmospheric circulations and the export of water vapour from the ocean to land. We need to quantify better recent and future changes in ocean evaporation and the contribution of maritime humidity to terrestrial precipitation.

- **Feedbacks between the atmosphere and natural and anthropogenic changes and interventions.**
  Human activity is radically modifying the terrestrial water cycle through land cover changes and water interventions, such as ground water extraction, impoundments and irrigation. In addition increasing greenhouse gases will cause changes to all components of the water cycle and human activities. These processes interact with each other and with the overlying climate. We need to quantify these interactions and

include, where relevant, in water resource assessments. This study is particularly relevant to South Asian regional studies – a region where glacial melt, a high proportion of irrigated land and over–exploitation of water resources (such as groundwater) interact.

Integrated studies encompassing these feedbacks should combine the use of existing observations (including Earth Observation data) with process parameterisations and regional and global climate models.

Outcome
A better understanding of the role of feedbacks and ocean-atmosphere-land interactions relevant to the hydrological cycle will improve our representation of rainfall, soil moisture and runoff within the next generation of Climate and Earth System models. Improved (and appropriate) process models as well as better use of regional and global data sets should contribute to more accurate understanding and predictions of all components of the future water cycle at scales from global to local. This will lead to increased confidence in impacts of climate change on the water sector and on wider hydrological characteristics of the Earth System (e.g. ocean salinity). An assessment of water resources, including these feedbacks, is a critical requisite for the UK and south Asia to successfully adapt and plan for climate change within the next decades. Therefore direct beneficial impacts are expected for government departments, notably DEFRA and DECC and related agencies such as the Environment Agency. The programme should work closely with the Met Office to ensure the pull through of this knowledge into future climate predictions.

4. 2 Theme 2: Precipitation

Aims of theme
Improve our understanding, observations, modelling and prediction of ongoing and future changes in precipitation and evaporation, their variability and impacts, from global to regional and local scales.

This is an extremely large research area, but improvements here are central to improved projections of changes in the water cycle. There are key gaps in our understanding of the current state of the global water cycle – particularly over the oceans – and on the reasons for differences between models in their projected changes in precipitation (at all space and time scales). For example, how much of the uncertainty is due to differences in the representation of large-scale atmospheric features, and how much is due to the representation of small-scale precipitation formation processes? There is considerable potential for combining multiple sources of observations, with parameterisations and models operating at different spatial and temporal scales, to address these issues. There are strong links to existing NERC programmes (e.g. CASCADE) and International programs (YOTC, AMY and GEWEX/CEOP and CLIVAR).

Research Focus
Research within the programme will be focused on one or more of the following key themes:

- **Sources of precipitation in the global water cycle**. This will involve, for example, the development and evaluation (using high quality reference data) of more reliable observation-based evaporation and precipitation datasets over both ocean and land, an assessment – using observations and models – of the relative influence of ocean and land evaporation on precipitation over both ocean and land, and an evaluation of both the transport of water and moisture recycling.

- **Improved understanding of precipitation formation physical processes**– Process studies aimed at evaluating and improving the small-scale physical parameterisations in weather and climate models. The NERC Storm Risk Mitigation programme will lead on improving representation of precipitation processes in mid-latitude cyclones associated with hazardous (high intensity) precipitation. Research under the changing water cycle theme could include, for example, formation of tropical convective precipitation over land and ocean (warm rain (congestus) and deep convection), clouds, microphysical processes and precipitation formation, aerosol-cloud-precipitation interactions, and the formation of orographic precipitation.

- **Role of large-scale circulation changes in determining regional evaporation and precipitation changes**. This topic focuses on the large-scale controls on evaporation and precipitation. Potential research issues include (i) understanding/quantifying the two-way interactions between the water cycle and large-scale circulation patterns in the extratropics (e.g. NAO, storm tracks and blocking and tropical-extratropical interactions (ENSO, MJO), and (ii) understanding/quantifying tropical precipitation variability (e.g. understanding the role of multi-scale precipitation interactions with dominant modes of tropical variability).

- **Changes in extreme precipitation events.** The focus here should be on understanding the factors driving potential changes in relevant extreme precipitation events, and the factors determining uncertainty in potential changes, concentrating on the large-scale features which generate either prolonged anomalous dry periods or persistent anomalous wet periods (short-term extreme events are the focus of the NERC FREE programme). This research should link explicitly with Theme 4 to determine "relevant" indicators of extreme precipitation.

These research foci could be addressed through projects employing potential approaches such as modelling frameworks, improved use of Earth Observations and novel metrics and diagnostics of the changing water cycle and precipitation.

Outcomes

- Improved understanding of changing precipitation and evaporation over the oceans and land from observational datasets and coupled ocean-atmosphere models.
- Assessment of model's ability to capture modes of their variability important for hydrological/biogeochemical predictions/ocean salinity at ocean basin, to regional, to local scales.
- Improved regional precipitation predictions over land and oceans on seasonal to decadal timescales to assist policy decisions in all aspects of regional water resource and water quality management.
- Improved parameterisations of precipitation processes in weather and climate models, which will lead to improved projections of regional precipitation patterns over land and ocean. The programme should work closely with the Met Office to ensure the pull-through of this knowledge into future climate predictions.

4. 3 Theme 3: Detection and attribution of water cycle changes

Aim of theme
This theme aims to quantify and understand the drivers, their relative importance and interactions, of changes in water cycle components over periods of record, and use this understanding to work towards delivering the basis for robust prediction of future changes in water cycle components.

The relative importance of different drivers of hydrological change in the UK and South Asia needs to be quantified; these include both human-induced climate 'change' and naturally-driven climatic variability, and land and water use and management. For the UK, the aim is to understand the degree of influence of past variability in precipitation (see also Theme 2), together with identification of the roles of land cover and management changes on surface and groundwater hydrology in order to inform the sustainable use of soil and water. For Southern Asia, it is important to understand also how monsoon changes have influenced the hydrology of glacier-fed river basins of the sub-continent. Whilst the focus is on the UK and South Asia, it will be necessary to use information from larger geographic areas to quantify and understand "local" changes. This theme covers all components of the water cycle at and below the land surface. It includes frozen water as terrestrial snow and ice, but not ice sheets and sea ice. Central to this theme is development of a solid understanding of the complex and interlinked drivers of the land-based water cycle, including oceanic evaporation, atmospheric transport, land surface modification of hydrology through changes in land cover and the management of water and other resources.

Research Focus
Research under this theme falls into three broad areas:

- *Develoment of techniques*. What (novel) approaches/ technology provide 'best' detection of change? How can we best identify 'fingerprints' (i.e. expected signals from key drivers) of change from different causes? What are the appropriate time-scales for 'best' fingerprinting? How do we best address these detection and attribution issues in areas where data are sparse? How do levels of data availability influence confidence levels for predictions?
- *Quantification and understanding of change*. How have components of the water cycle changed in space and time over the last century and/ or instrumented period? What are the relative influences of the drivers over time? What are the scales of spatial and temporal variation of changes and the key drivers and the processes driving observed change? What are the key uncertainties in observed change? Is there evidence of key thresholds in UK or Indian subcontinent river systems?
- *Application of results to other hydrological systems* to gain maximum benefit from on-going research. How can all results be generalised and thus applied to other (local and regional) hydrological systems? How can these outputs be translated into maximisation of the sustainable use of soil and water?

Outcomes
The theme should provide explanations of what has caused changes in the water cycle over periods of record, attributing observed changes to specific causes as far as possible. This will be accompanied by knowledge of the degree to which the linking of specific cause to specific effect is achievable, and knowledge of interactions between different drivers of water cycle change, including effects of processes operating at different spatial and temporal scales. The influence of the level of data availability on the ability to detect and attribute change should be

elucidated as also, as far as possible, the ability to transpose findings to areas of sparse observations. The degree to which knowledge gained from locations with an observed record can be generalised for wider applicability is an important basis in paving the way for dependable projections of future changes and the sustainable use of soil and water.

4. 4 Theme 4: Consequences of the Changing Water Cycle

Aim of Theme

This theme seeks science effort to determine the implications of change in climate and land use for the assessment of water-related hazards to human and natural systems. Activities undertaken in themes 1, 2 and 3 should be informed by and integrated with the aims of this theme. This integration will be enabled via cross-goal Working Groups (for further detail, see the programme Implementation Plan), bringing together all the programme themes.

Research Focus

This theme explores the potential consequences of the changing water cycle. The theme, like the others, is very broad, and research will therefore concentrate on:

- **New and innovative ways of using existing and emerging climate science to estimate potential consequences of climate and other changes on catchment systems, the sustainable use of natural resources, and natural hazards**.
  It will be important to understand how the hazards associated with the changing water cycle will vary over time and space and how this partitions between climate change and land management drivers. Furthermore, we are interested in how we can use climate knowledge to infer consequences of the changing water cycle without waiting for improvements in climate models following from Themes 1, 2 and 3. We seek innovative ways of using existing information to make credible predictions on consequences and that link to other themes across the programme. For example, how can the information contained within the IPCC AR4 and AR5 climate model simulations, and the UKCP09 projections, be used in innovative ways to construct scenarios for change in hydrologically relevant climatic characteristics, and how do such methods improve on existing procedures? Research in this area may examine consequences across any aspect of the water cycle (within the study regions), and indeed different impact areas will likely require different types of innovative approaches.

- **Consequences that are currently highly uncertain.**
  Possible areas of research include:
  What are the consequences of the changing water cycle for soils, nutrient cycles, river and groundwater processes? Such potential effects are not well understood. Work is needed across a range of soil types from organic peatlands through organo-mineral soils and mineral soils. Similarly changes in irrigation practice (e.g. across South Asia) may have major consequences for flow pathways, soil and river biogeochemistry and groundwater. A key aspect of such research is to identify key climate information and variables which determine responses.
  What changes in the global and regional water cycle will lead to critical thresholds in the terrestrial water cycle at regional to local scales? The sustainability of ecosystems and associated services are constrained by weather patterns at regional or local levels

and thresholds beyond which they become non-viable need to be accurately estimated for effective adaptation.

How will the changing water cycle impact ecosystem services? The scale of likely impacts on water provision and water security, reliability of hydroelectricity generation schemes, fire risk, sustainability of agriculture and sustainability of aquatic ecosystems, such as wetlands at regional or local levels in both the developed and developing world is of critical importance to the well-being of communities.

How can we reduce uncertainty in prediction of impacts of land cover (e.g. urban developments, vegetation cover) interactions with the water cycle under changing climate? Changing vegetation cover, due to changing climate and agricultural practice, can result in changes in recharge, runoff and groundwater and surface water quality increasing strain on infrastructure either supplying water or transferring it to or from populated areas. Planning systems throughout the world require reliable predictions of return period (of both floods and droughts) with known degrees of confidence that can be used to adapt to these impacts of our changing water cycle. Hazard and susceptibility models need linkage to process understanding to quantify uncertainty to allow practitioners to plan effectively and respond to emergencies in a timely and appropriate way.

Research may be based around case study catchments (either modelling or field-based studies), but such studies must be able to demonstrate how the results are genuinely transferable, can be used in a more generic way or can be up-scaled. The theme does *not* cover studies applying established techniques to estimate impacts on hydrological regimes, water quality or freshwater ecosystems.

Research in this theme must demonstrate strong engagement with appropriate stakeholders to ensure maximum relevance of the research.

Outcome

The underpinning science provided by this theme will allow more rapid and appropriate development of science-based mitigation strategies to respond to and minimise the hazards to human and natural systems caused by changes to the water cycle. We expect these to occur through the development of adaptation options at the local to river basin scale. The development and growth of collaborations between the climate science and meteorological modeling communities and hydrological science afforded by this theme will be a major step forward and assist knowledge exchange at the science-policy interface. Key beneficiaries are expected to be government bodies with statutory duties in land and water management and regulation and the water industry, who need to be able to plan for future change in water supply and quality.

Table 1: This table identifies how each of the four programme themes can deliver against each of the programme goals, within the context of the 5-year programme.				
Programme Goal	**Theme 1**	**Theme 2**	**Theme 3**	**Theme 4**
To develop an integrated, quantitative understanding of the changes taking place in the global water cycle, involving all components of the earth system – the atmosphere, ocean, land surface and geosphere, cryosphere and biosphere	Understand feedbacks associated with increasing CO_2, changing soil moisture patterns and ocean properties (impacting on atmospheric water vapour)	Evaluation of current P/E datasets. Understanding P-forming physical processes (to improve model parameterisation) Role of large-scale circulation in δP/ E	Identification and understanding of changes in all components of the water cycle over last century	Developing knowledge of how the consequences of changes in the water cycle impact on other earth system components
To improve predictions for the next few decades of regional precipitation (P), evapotranspiration, soil moisture, hydrological storage and fluxes, focusing on the requirement to quantify and narrow the uncertainty in predictions.	Improved representation of appropriate feedbacks in models	Quantification of role of P in uncertainty	Provision of evaluation methods of model (climate, hydrological) hind-casts. Provision of guidance on future reliable extrapolations.	Predict changes in soil and groundwater flow quantity and paths, soil moisture and groundwater storage patterns, agricultural impacts and coupled feedbacks
To understand how local to regional scale hydrological and biogeochemical processes are responding and will respond to changing climate and land use**,** together with their consequent impacts on the sustainable use of soil and water.	Improved understanding of feedbacks will underpin better assessment of response and interaction of biogeochemical cycles to future changes, leading to improved assessments of impacts and possible adaptation strategies.	Assessment of influence of P via coupling atmospheric to land/biogeochemical models; varying complexity/scale	Water cycle responses to changing climate, land cover, land/water management and sustainable use of soil and water resource.	Soil structure and chemistry impacts, flow paths in soil/groundwater, changes weathering, erosion, nutrient cycles, water quality. How these might amplify local and regional climate change impacts.
To understand the consequences of the changing water cycle for water-related natural hazards, including floods and droughts, and to improve prediction and mitigation of these hazards	Improved understanding of conditions which lead to the persistence of regional precipitation anomalies (in particular, the persistence of droughts)	Understanding flood/drought cycles	Provision of more accurate uncertainty estimations (and spatial and temporal variation) to inform process/model predictions	Flood and drought impacts, water quality hazards, ground stability, wildfire susceptibility, soil erosion, critical thresholds in water-related environmental processes with major consequences, rapid responses, early warning systems

4.4 Inter-disciplinary needs

In accordance with the cross-cutting and interdisciplinary nature of the programme, the Science Themes have some common activities, interdependencies and inter-relationships. There are a number of cross-cutting issues such as evaluation and uncertainty, scaling, thresholds and consequences. A consultation was carried out amongst the Changing Water Cycle Writing Group to formulate a consistent view and understand what each community and discipline has to offer. The programme, by design, includes contributions from a number of different disciplines including large-scale (climate, ocean-atmosphere) modelling; hydrology; biogeochemistry and hydrogeology (including groundwater process and modelling). There are a number of issues that are common to all disciplines which can be addressed via the CWC programme. This section identifies those issues where the CWC Programme can add value by directing its funding and ensuring synthesis between these common areas in different programme projects.

Scaling of models remains an issue, both in terms of scaling up (groundwater/hydrology) and down (climate/atmospheric). This is mainly in a spatial context, e.g. catchment scale, but also a temporal one. This also has a bearing on the integration of models (hydrological-atmospheric-groundwater-climate) if they are to represent the appropriate processes, feedbacks and thresholds accurately.

In addition, uncertainty in the system needs to be quantified both in terms of understanding the intrinsic chaotic nature of natural systems and clarifying and defining uncertainty in our own understanding and representation of the processes. We need to know what key outputs are needed from existing (hydrological, climate, groundwater…) models to best parameterise and develop new models, what the main parameters driving uncertainty are and methods of transposition to data-sparse areas. Specific examples may be precipitation uncertainty (needed in particular for groundwater model input) or better scenarios of land management/land use change (in response to socio-economic, climate, population change). Work needs to address the end-to-end integration of models, propagation and any constraints.

All these models need to be informed and backed-up by accurate, precise, high-resolution data. This can potentially be acquired through remote sensing observation, improvements in palaeo-data and access to such data/models. However there is also uncertainty in this data, especially land cover and land management and 'natural' river flow time series.

In order to join up the results relevant to these cross-theme issues, the Changing Water Cycle Programme will undertake ongoing synthesis activities throughout the life of the programme. This will bring together key results and preliminary research findings from the funded projects as they occur to develop a framework for tackling uncertainty, scaling and thresholds. The synthesis phase and framework will be developed by a series of cross-theme Working Groups, one per Goal, that will be coordinated by the Science Management Team.

One aim of the programme is to provide information and evidence to support the sustainable management of water systems. It is therefore essential that water management stakeholders are engaged in (i) overall programme synthesis (see Implementation Plan) and (ii) individual research projects.

The programme Implementation Plan contains further detail on processes to direct the programme activities in a fully inter-disciplinary way.

5. Relationship to other initiatives

This CWC Programme will make a significant contribution to the *Living With Environmental Change (LWEC)* programme and promoting interdisciplinary working between different research and end-user communities will be fundamental to its success. This will provide the framework for collaboration with other UK programmes. For clarity and to define implementation processes, it is important to make the distinction between programmes with which the CWC aims to collaborate directly and those which are doing similar and/or relevant science with which the CWC programme can engage or align with.

There is clearly a strong link between this programme and the water theme within the Ecosystem Services for Poverty Alleviation programme (ESPA), particularly in the area of climate impacts, and there is a need that activities within these two programmes are aligned and collaboration is facilitated. The distinction between the programmes can be characterised as the Changing Water Cycle having a focus on the prediction of future changes and the impacts that these changes will have, whereas ESPA is focussed on impacts and adaptation measures in the particular context of poverty alleviation.

Other potential international alignments could come from the Global Energy and Water Cycle Experiment (GEWEX), the Global Water Systems Project (part of the Earth Systems Partnership) and UNESCO-IHP amongst others. GEWEX (and the International Geosphere-Biosphere Programme, IGBP) in particular has strong interests in land-ocean-atmosphere feedbacks and links to related atmospheric processes: Coordinated Energy and Water Cycle Observations Project (CEOP) and Cloud Systems Study (GCSS). A list of potential international opportunities for alignment and engagement can be found in Annex A (p.17).

Within Europe the EU funded WATCH and HighNoon projects will provide very relevant data, models and analyses on which the programme can build and the development of the HyMEx[8] (HYdrological cycle in the Mediterranean EXperiment) provides a complementary approach to the CWC programme, focusing on quantification and processes in the Mediterranean.

In the UK, the CWC Programme has strong synergies with Met Office and NERC cutting-edge modelling programmes and consortia such as HiGEM, JRP, QESM. There are potential links to be made to existing and future NERC initiatives such as FREE, Oceans 2025, the Arctic and Storms programmes and the ESM Strategy. The research may link to the Virtual Observatory initiative and could provide a pilot for data and model exchange and interaction. Awareness of the research agendas of the FREE and Storms programmes is essential in order not to duplicate work, but notable gaps in those programmes include high quality science on understanding, predicting and mitigating pluvial flooding and very extreme events. It will be important to pursue close working relations with the UK Technology Strategy Board (with regard to innovation and technology) and the water industries and environmental regulators in the UK and overseas (with specific regard to the water framework directive), as well as Defra and DFID). There are clear links to be made with the Defra Ecosystem Approach initiatives. Pilot and exemplar catchments in the UK should include both data-rich and data-poor examples. Successful delivery of the science will be dependant on close collaborations between the climate science/modelling community and the hydrological community. Most of the themes have cross-cutting links to past, existing and/or future programmes with a remit very much related to that of the CWC programme.

6. Key UK opportunities

The UK community is well placed with access to the Met Office-based family of Climate and Earth System models – including the HiGEM, PRECIS and QESM models. The JULES land surface model has been developed considerably in recent years – in both its ease of use and functionality and will be an important resource. Access (and collaboration in) all these models will be considerably aided through the recent Joint Research Programme (JRP) agreement between NERC and the Met Office. The UK community has a good track record in integrating advanced observations and models, and the land theme within the NCEO is good example of this.

The UK has a number of strengths that the Changing Water Cycle Programme can build on or develop. The Research Programme work is supported by UK National Capability: skills in atmospheric, climate and hydrological modelling, its integrated climate-hydrology community, expertise, data (especially precipitation and temperature data for NW Europe). The BGS contributes models (groundwater in particular) and software and the National Geoscience Data Centre, and CEH contributes to detailed hydrological and water resource modelling and observation including JULES land surface development, river flow archives and the newly revised land cover map. There is Earth system modelling expertise involving Met Office (Hadley Centre) and UK Universities via the JRP and CEH and NOCS has significant expertise in development and analysis of observation and model based evaporation and precipitation datasets. The newly established NCEO also provides potential for coordinated research in Earth Observations.

It is expected that projects funded via the programme will use Sections 5 and 6 of the Science Plan to guide them towards potential collaboration and alignment opportunities. These should, where possible, be written into the grant application and the Impact Plan. The programme coordination and management team[9] will be able to advise and facilitate such collaboration and alignment (see the Programme Implementation Plan for further detail).

[9] See Implementation Plan, Section 4

7. Annex A

UNESCO-International Hydrological Programme's (IHP) Associated Programmes:

- Groundwater Resources Assessment under the pressures of Humanity and Climate Change (**GRAPHIC**)
- Ecohydrology
- Water and Development Information for Arid Lands – A Global Network (**G-WADI**)
- International Flood Initiative (**IFI**)
- Internationally Shared Aquifers Resources Management Programme (**ISARM**)
- International Sediments Initiative (**ISI**)
- Joint International Isotopes in Hydrology Programme (**JIIHP**)
- From Potential Conflict to Co-operation potential (**PCCP**)
- Water Education and Training (**WET**)
- World-wide Hydrogeological Mapping and Assessment Programme (**WHYMAP**)

World Meteorological Organisation (WMO): Suites of WMO initiatives of the Technical Commissions, Secretariat and the Regional Associations.

International Association of Hydrological Sciences (IAHS) specifically Commissions working groups which include:

- Predictions in ungauged basins (PUB)
  Precipitation
- Task Force on the use of GRACE data

US CUAHSI (Consortium of Universities for the advancement of Hydrologic Science Initiative):

UNESCO HELP (Hydrology for the Environment, Life and Policy) programme

Year of Tropical Convection (YOTC); World Meteorological Organisation: commenced on 1 August 2008, is a joint World Climate Research Programme (WCRP) – World Weather Research Programme (WWRP)/THORPEX initiative. YOTC is a year of coordinated observing, modelling, and forecasting with a focus on organized tropical convection, its prediction, and predictability.