Natural Hazards Theme - Theme Action Plan 3

Natural hazards[1] are of increasing concern for humanity as the rate of natural disasters is increasing dramatically as a consequence of population growth and increased vulnerability caused by global trends in urbanisation, land-use, and stressing of ecosystems. The UK has a tradition of excellence and international leadership in the forecasting and mitigation of natural hazards science. The NERC Natural Hazards (NH) theme[2] and underlying strategy[3] (which sits within the overall NERC strategy for 2007–2012 *Next Generation Science for Planet Earth*) provide the basis for 10 theme challenges (Table 1).

The challenges are built around **3 Thematic Research Drivers**, set out in the Natural Hazards strategy[3]: 1) Natural hazards and their consequences need to be ***forecast*** effectively; 2) ***communication and application*** of scientific knowledge and understanding of natural hazards needs to be much improved; and 3) much more emphasis and financial resource need to be invested in ***mitigation*** strategies.

	Theme Challenge	High- level priorities	Key Science Goals (applications)	Key Science priorities (processes)	Actions
Theme Grand Challenge: Reducing societal exposure to natural hazards by better forecasting, integrated risk assessment & scientific advice.					
Uncertainty, risk and scientific advice					
1	**Integrated risk assessment & scientific advice *****	To reduce human and economic losses through enhanced analysis of probability, uncertainty & risk and improved scientific communication. *(Main partners include: ESRC, EA & EPSRC & others from LWEC)*	To improve decision making through provision of clearer natural hazard science advice and better engagement with users.	1) New approaches and methodologies for integrated risk assessment; 2) New cross-sectoral science tools.	*Analysis, propagation and communication of probability, uncertainty and risk* (£2.5M); *Increasing resilience* (£4.6M).
2	**Uncertainty in forecasting & risk assessment *****		To increase uptake of natural hazard science by decision makers & expand its utilization, and enhance communication between scientists.	1) New tools and protocols for improved usage of natural hazard based probability, uncertainty and risk in natural hazard assessments.	Analysis, propagation and communication of probability, uncertainty & risk (£2.5M); Quantifying uncertainty (£0.75M). *Increasing resilience* (£4.6m)
Hydro-meteorological Hazards					
3	**Storms *****	To increase understanding and prediction of coupled hydro-meteorological processes and how these will alter with climate change. *(Main partners include: EA, DEFRA,& MetOffice plus others from LWEC)*	To enhance predictions of storm impacts at a regional (catchment or coastal cell) level.	1) Convective scale storm processes; 2) Coupling of storm models with other hydro-meteorological models.	Storms (£4.9M**)**, *Next generation weather and climate prediction systems* (£0.4M)
4	**Flooding ****		To improve flood forecasting through enhanced weather prediction and catchment characterization.	1) Catchment hydrological interactions and vulnerability; 2) Groundwater flooding; 3) Pluvial flooding.	Changing Water Cycle (£2.3M); ***Flooding from intense rainfall***
5	**Droughts, heatwaves, & wildfires ****		To assist decision-making through better prediction of heatwaves, droughts, wildfires and their impacts.	1) Development of blocking highs; 2) Catchment response to drought; 3) Wildfire triggers & impacts.	Changing Water Cycle (£2.3M); ***UK Droughts***
6	**Coastal flooding & coastal erosion *****		To enhance coastal zone management with improved predictions of climate change and human impacts on coasts	1) Integrated coastal systems impacts modelling; 2) Coastal sediment dynamics	*Coastal sediment systems* (£3.0M)
Geohazards					
7	**Landslides & subsidence ****	To increase understanding of the spatial and temporal distribution of inherently unpredictable geohazard events to mitigate risks and support societal resilience. *(Main partners include: DFID & the Wellcome Trust plus others from LWEC)*	To enhance decision-making through development of improved ground stability assessments.	1) Hydrometeorological controls on ground stability; 2) Landslide triggering; 3) Dynamics of multi-phase sliding.	*Increasing resilience* (£4.6M); *Arctic Programme* (£2.4M); ***UK Droughts***
8	**Volcanoes *****		To improve probabilistic risk assessment of volcanoes, locally and globally.	1) Assessment of multiple volcanic risks; 2) Impacts of emissions; 3) Eruption triggering.	*Increasing resilience* (£4.6M)
9	**Earthquakes *****		To improve probabilistic risk assessments in earthquake prone regions.	1) Assessment of multiple earthquake-related risks; 2) Tectonic thresholds characterization	*Increasing resilience* (£4.6M)
10	**Tsunamis *****		To improve probabilistic risk assessments of tsunamis.	1) Tsunami trigger characterization; 2) Tsunamigenic potential	*Arctic Programme* (£2.4M)

Table 1. Natural Hazard Theme Challenges, goals, science priorities and actions
PROGRESS: ***** To be started; ****** In Progress; ******* On course.
ACTIONS: Agreed Actions show financial contribution from the NH theme; ***bold italicized Actions*** are detailed in this TAP.

Society's continued need for natural hazard focused science has been well illustrated by events over the last year. According to the Centre for Research on the Epidemiology of Disasters (CRED), earthquakes, floods, landslides, and extreme weather conditions made 2010 the deadliest year in the past two decades. Some 373 natural disasters killed almost 300 000 people in 2010, affecting nearly 207 million others, and costing nearly £70 billion in economic losses[4]. New science is essential to provide society with knowledge to mitigate the impacts of such hazards better, with commensurate potential for minimization of human and economic loss. Science supported by the NH theme will quantify critical processes at appropriate temporal and spatial scales and build these into models that shape decisions about risk management. The science required to meet these challenges will incorporate monitoring, experimental studies, and the development of uncertainty-encompassed physical models. The breadth and complexity of the theme will ensure multidisciplinary engagement across almost the entire NERC community, as well as close working with non NERC partners - required to effectively deliver reduced societal risk from natural hazards.

Five-year view of the theme 2008-2013

Summary of actions approved in TAPS 1 and 2 and their impact on the five year landscape

The NH theme has contributed to the development of eight actions to date. Together they span the Theme Challenges, and also have achieved a balance between terrestrial and marine science. Collectively, their outputs should have a significant impact on risk reduction. The science will provide data and models to underpin risk modelling, as well as support new approaches to the analysis and communication of uncertainty. The investments set-out by the actions will bring-together multiple scientific and analytical strands within interdisciplinary programmes. Each has substantial for buy-in from other partners, particularly from the Living With Environmental Change (LWEC) partnership, or has the potential for this. The actions are described below by sub-Theme; the other themes contributing to these, and their sum value is shown (Table 1 only shows NH contribution).

Uncertainty, risk and scientific advice: The NH Strategy emphasized that communication of scientific knowledge and understanding of natural hazards needs to be much improved to inform risk management. The inconsistent handling of uncertainty, widely recognised as a barrier to effective communication and take-up of science, was thus focused-upon by an action on *Analysis, propagation and communication of probability, uncertainty and risk (NH)* (preceded by a scoping study – SAPPUR). This will lead to the generation of a research programme (£2.0M) which will develop new methods to account for model limitations, combine evidence from different sources, account for unquantifiable uncertainties and improve the handling of uncertainty in risk models. A research network (£0.4M) will tackle the fragmentation of NH community in relation to its usage of uncertainty and risk. It is expected that the programme and network will be commissioned in 2011. Some aspects of the quantification and communication of uncertainty were also addressed within the *Quantifying uncertainty in predictions of regional and local climate change and climate impacts (CS, NH)* action. This led to the EQUIP Project, which evolved from a sandpit; this is creating methods to combine observations and models to quantify the uncertainty in predictions of regional and local climate change and climate impacts (particularly focusing upon hydro-meteorological ensembles), as well as developing strategies and benchmarks to evaluate alternative methods for generating predictions. It is expected that outputs from both of the above projects will support a wide range of NH activities.

Hydro-meteorological Hazards: Acknowledging storms as a major UK hazard, the *Storm risk mitigation through improved prediction and impact modelling (NH)* (£4.9M) action was developed in the first TAP. The resulting research programme is optimising modelling of mid-latitude cyclonic storms, over a range of temporal and spatial scales, and improving prediction of their impacts. This is enhancing our ability to predict how enhanced greenhouse gas- induced pre-conditioning of the atmosphere will affect the generation and evolution of mid-latitude storms. It is also assessing vulnerability to cyclonic storms at catchment and regional coastal-management scales. *The Changing water cycle (CS, SUNR, NH)* action is delivering a research programme which addresses decadal changes in the hydrological cycle that are expected to play a central role in governing a vast range of climatic impacts. It spans interests within all of NERC's science themes including, under the NH theme, the changing frequency of floods and droughts. The first projects in the (£10.1M) research programme were announced in autumn 2010. It is expected that the final outputs of the programme will have a substantial bearing on the modelling of hydro-meteorological hazards beyond 2013. Many intermediate products should be available before then; some may be expected to be utilized within the flooding and drought-focused actions described in this TAP. The *Coastal sediment systems (NH)* programme (£3.0M) will deliver a systems framework for prediction of estuarine – open-coast exchange as well as intermediate complexity geomorphic landform models. It will undertake sensitivity testing under a range of climatic, sea-level and management scenarios and inform coastal flood and coastal erosion risk analysis. The remaining hydro-meteorological action focuses on developing capacity to underpin research into meteorological extremes in future years. A (£4.4M) programme *Contributing to the UK's development of next generation weather and climate prediction systems (CS, TECH, NH),* should ensure that the UK will continue to lead research into predictions of extreme weather. This will provide the basis for short-range prediction-, and mitigation-of, a wide range of hydro-meteorological hazards.

Geohazards: The main investment into geohazards has been that on the *Increasing resilience through multi-hazard assessment of earthquake-prone and volcanic regions (NH)* (£4.6M) programme. This addresses the need to develop risk-based approaches to natural hazards research through improved communication and advice, based upon mitigation-oriented science. The NH Strategy identified that the NH science is of no ultimate value unless it is effectively integrated into human actions and decision-making procedures. It emphasized the major challenge in making sure that the scientific knowledge is applied effectively, requiring collaboration with other disciplines in the social and political sciences. In this respect, this action is closely aligned with the wider international disaster risk reduction agenda, with its emphasis on integrated risk assessment and improved scientific advice, towards-which it will contribute. The other dominantly geohazard science action developed by the theme has been the NH element of the *Arctic Research Programme (ESS, CS, NH, BIO)* action. The instigation of this was dictated by emerging challenges – science needs that became increasingly apparent and urgent since the Natural Hazards Strategy was developed. The NH element of the (£15M) programme addresses poorly understood hazards, including those associated with submarine slope stability and tsunamis. These are now seen as emerging and potentially substantial threats (both local and global) in light of the rate of environmental change in the Arctic region.

These actions constitute an integrated set which is well-spread across the Challenges in the NH theme and will help to maintain the research capacity of the community to deliver science across the theme in future. All actions contribute towards multiple challenges; it is expected that each will produce generic benefits to the theme.

Summary of proposed actions that require a decision from SISB in 2011

Two new actions are proposed within this TAP. To be identified as theme priorities, both fit the NH strategy, are timely, and have the potential to deliver high quality science. Each is expected to make a significant impact in relation to increasing societal resilience to social and economic loss. Their prioritization reflects: the maturity of the existing science in their fields; the potential of the NERC scientific community to develop predictive systems within the relevant areas; the need for improved scientific advice; and, with a longer-term thematic view, the need to build foundations for future NH research.

The new focus is on two of the biggest hydrometeorological hazards affecting the UK, namely floods and droughts. New science is needed to minimize future risks associated with these that are expected to grow with climate change and increasing resource pressures. These hazards are prioritized for research investment now, not only because an increased understanding of UK weather extremes is of major interest to LWEC partners – who have fast-evolving concerns about knowledge gaps, but because the scope of existing projects or programmes (outside, as well as within NERC) of relevance has recently become much clearer. (For instance, the science within projects arising from the NERC *Storm risk mitigation through improved prediction and impact modeling,* as well as the initial phase of the *Changing Water Cycle* programmes is now relatively apparent. There was previously a possibility of substantial thematic overlap; however, it is now clear that the proposed actions focus on different meteorological drivers, and timescales.)

At the recommendation of SISB, both actions have a systems-based approach, with substantial interaction with organizations outside NERC (mostly LWEC partners, such as the Met Office and Environment Agency). Each action will provide exciting, yet policy-relevant research. Each also cuts across traditional thematic boundaries, which should provide opportunities for them to develop several novel science areas.

These have been designed as fully 'self-contained' actions which will deliver research programmes that generate excellent science and form the basis of new tools for decision-makers. Both involve many partners, and have the interest of several more. However, because of the current financial climate, neither has a firm commitment to contribution from other key Research Councils - notably EPSRC and ESRC – which could substantially add further to the value of NERC investments through the joint development and uptake of flooding and drought science. These organisations will be undertaking reviews of their science portfolios, including their contributions towards research into hydrometeorological hazards and emergencies, later this year (ESRC this spring, EPSRC this summer). If, following review, they decide to further invest in these areas, there should be a major opportunity to design and build joint cross-Research Council programmes, or other collaborative initiatives (as advocated by LWEC), into which the actions set-out here will fit. For this reason it is proposed that commissioning of these actions should be delayed at least until all cross-council partnership opportunities have been fully explored (2012?).

1. Flooding from Intense rainfall (NH)

Flooding is the most costly natural hazard affecting the UK and is brought to public consciousness every time there is a significant event. In all, around 5.4 million properties in the UK, or one in six properties, are at risk of river or coastal flooding. Many more are at risk of flash flooding caused by torrential downpours. Rapidly evolving pressures driven by future climates as well as increasingly stringent financial regimes pose major challenges in developing cost-effective flood risk management schemes. It is likely that future approaches will need to consider novel, radically-different approaches from those adopted in the past, including wider utilisation of flood risk management based on the adaptation of natural systems – about which many processes are presently insufficiently well understood.

Climate change is expected to increase the risk of flooding, as was illustrated by the 2004 Foresight report on future flooding - which identified risks over the next 30–100 years. In recognition of this, a number of research programmes that address future UK flood risk have been developed over the last decade by several Government Departments, agencies and Research Councils. These include the joint Defra/ EA Flood and Coastal Erosion Risk Management R&D Programme, the EPSRC Flood Risk Management Research Consortium (FRMRC), and the NERC Flood Risk from Extreme Events (FREE) Programme. However, the combined effort of these initiatives is now in marked decline, despite the need to: a) continue research into cost-effective flood risk management solutions; b) meet the recommendations of the Pitt review (2008)[5] which highlighted areas where more knowledge is required in order to reduce flood risk reduction; and c) satisfy Scottish, English, Welsh[6,7] and European[8] legislation.

Because of this, and recognising the constraints on future funding, senior representatives of the flooding research (including user) community considered in 2010 the future research delivery options that may be pursued by the LWEC partnership. They suggested the development of a coherent UK flooding research plan to ensure that money is spent wisely, to maintain research impact, and to account for changing research priorities. As a consequence, LWEC is now producing the UK's first *Flooding Research Strategy*, and making recommendations about its implementation, including the development of governance frameworks for multi-partner delivery and investment. This has involved a major review of research across all aspects of flooding, and has worked towards prioritisation within 4 main themes - *Engineering; Social and Economic; Environmental and Hydrology and Climate Change* - via online consultations, and Scottish as well as UK workshops. Although the *Flooding Research Strategy* is still in draft it is already possible to identify key natural science priorities within it. All are based upon significant knowledge gaps that are likely to have a detrimental effect on flood risk reduction, unless rectified soon. They, unsurprisingly, mirror many of those identified in the Pitt Review. Those associated with inland flooding highlight: pluvial floods; the need for increased planning of land-use to minimize discharge; and a better appreciation of flooding arising from summer (convective) storm events. It is proposed that the *Flooding from Intense rainfall* action (primarily addressing Theme Challenge 4 -Flooding) will focus upon these issues. Whilst the *Flooding Research Strategy* also highlights issues associated with coastal flooding, it is expected that many of these will be tackled by the *Coastal Sediments* programme, which should have a substantial role in coastal flooding risk reduction within the next decade.

As argued above, the contributions of other research councils to the action could add substantially to the impact of the programme (which would be disproportionately large relative to the collective resource applied). In the case of EPSRC this may involve developing collaborative research into fields such as flood-defence infrastructure and urban drainage; in the case of ESRC this may involve researching options for the development of flood incident management strategies.

2. UK Droughts (NH, CS)

Droughts have the potential to cause enormous socio-economic damage through their impact on water supply, health, food security, and infrastructure. The 1976 summer UK drought, for instance caused widespread water rationing, an estimated £500 million in failed crops, about £60 million in structural damage to property and thousands of associated fires (11,000 over five months in Surrey alone)[9,10]. Whilst the 2003 summer drought had a significant impact in the UK[11], its impact on mainland Europe was much greater[12], and highlighted the extent of the susceptibility of much of industry, populations and infrastructure of such events[13,14].

Droughts pose a significant hazard to the UK and are likely to increase in frequency, as well as severity, as a result of climate change[10]. No comprehensive assessment has been made of the cost to the nation of a major drought today, however, a 1976-like event - on agriculture and structural damage alone (and not accounting for other costs – e.g. those associated with energy, business, environment and health) - would cost between £2 and £3 billion. It is not difficult to project that future drought events could cost the country a very great deal more.

Recognising the extent of our societal exposure to drought, it is perhaps surprising that the science associated with the prediction of droughts and their impacts, as well as adaptation measures to cope with these, is (compared with other hazards such as flooding) relatively immature. Despite UK investment into drought research in recent years, much of it funded by Government departments or agencies[15], and industry[16], our ability to forecast droughts and predict their impacts on groundwater , surface water or ecological systems (and their recovery) remains poor. Furthermore our knowledge about the associations between the stressing of these systems and the occurrence of secondary hazards - such as wildfires, or ground stability – is very basic.

To some extent this is because droughts have not been conspicuous in public consciousness (a succession of many non-drought high-profile natural hazard events has hit the headlines since 2005 - causing UK drought risk to recede from the public memory). It is also, in part, because the water industry and regulators have so-far been successful in combating drought using a scenario approach (with parallels in flood planning). Indeed, the UK is thought to have some of the best-organised drought planning in the world.

However, it is also because the science has been challenging to work-upon. Firstly, this is because of the rarity of droughts, and especially long droughts, in the historic record. But it is also because droughts have multiple drivers, both meteorological (e.g. anticyclonic blocking) and societal (e.g. supply & demand balance, water storage, transfer and utility trends). Furthermore, contributors and impacts of drought have traditionally been considered in isolation, largely because the data, science and analytical tools have existed in different sectors, and have had multiple owners. Most research programmes, associated datasets and models have thus been developed separately, have been inaccessible to most academic researchers, or have evolved along parallel strands.

There is now an urgent need to coordinate research effort (including building on past outputs) to ensure that the UK has a better scientific basis for decision-making with regard to droughts. This is essential - particularly to reliably identify the occurrence, intensity and impacts of future droughts, which may well exceed the envelopes of past droughts[17]. The *UK Droughts* action will bring together the resources of many key organizations, including the EA, DEFRA, UKWIR, CEH, BGS and MetOffice to develop the science which will underpin decision-making in relation to droughts. As noted above, the action would benefit from additional contributions from other research councils, such as EPSRC and ESRC (to address issues such as infrastructure, water-transfer and social response to water scarcity), and BBSRC to address agricultural aspects more comprehensively than will be in the programme set-out in the action.

The *UK Drought* action will address NH Theme Challenge 5 (Droughts, blocking-highs and wildfires), particularly key science priority 2 (catchment response to drought). The action will also address NH Theme Challenge 7 (Landslides and subsidence) particularly in relation to hydrometeorological controls on ground stability (key science priority 1) associated with drought.

A view of those areas of science within the Natural hazards Theme that will be developed by 2013.

Given that details of the research to be delivered by actions in previous TAPs will not be known until commissioning is complete, it is not clear what remaining scientific gaps will need to be filled by future TAP actions. Providing a concise picture of the scope and timing of future actions remains difficult as the theme should retain some contingency to take up opportunities, such as those afforded by the international disaster reduction community - particularly following a major disaster.

However, several areas are emerging as possible candidates for TAP actions in future years: a) Whilst the relationship between terrestrial landslides, earthquake and volcanic processes will be considered within the *Increasing resilience through multi-hazard assessment of earthquake-prone and volcanic regions* action, much more research is required on the occurrence of landslides, particularly under changed climates; b) similarly, whilst heatwaves are associated with droughts, they require a different scientific focus - particularly in urban settings (a future action could build on UK droughts – if the action is funded); c) an action on *volcanic emissions* will be considered following evaluation of the emergency, and immediate RM research that was conducted as a result of the Eyjafjallajokull eruption; and d) the security of soils, food and agriculture, in relation to flooding and droughts, particularly in the developing world requires significant research. It is likely that an action on soil security (led by SUNR?), would engage DfID, and other international partners and consider mitigation options.

It is anticipated that, following advice from SISB and decision by Council, a further challenge on Space Weather may be added to those of the NH Theme. If this is the case, it is expected that an action on *Space Weather* would be a high priority because of rapidly increasing societal exposure to such events as a result of fast-increasing reliance on technologies that may be affected by solar events.

Existing major investments

The main financial investments made by the theme through actions in TAPs 1-2 are shown in Table 1. These are related to the cross-cutting challenges 1&2 (Integrated risk assessment and scientific advice, and Uncertainty in forecasting risk assessment), They occur within all RCC programmes, notably within NCAS and the BAS Complexity programme, in the EPSRC/ESRC/NERC/Defra Collaborative Centre of Excellence in Understanding and Managing Natural and Environmental Risks (the 'Risk Centre') and, until recently, the RCUK Modelling Uncertainty in Complex Models (MUCM) project – all of which have developed science that will contribute to the *'Analysis, propagation and communication of probability, uncertainty and risk'* Programme. The main investments contributing to the hydro-meteorological challenges in Challenge 3 will support the *'Storm risk mitigation through improved prediction and impact modelling'* programme; these have included, up until recently, the FREE Programme, the UK-COPS Consortium Grant, as well as several RCC Programmes. Until late 2010 the largest investment under Challenge 4 (Floods) has been the FREE Programme, which ended as elements of the *'Changing Water Cycle Programme' (CWC)* (2008 TAP) commenced. Flooding forms a significant component of the *'CWC'* and *'Ecosystem Systems and Poverty Alleviation'* (ESPA) directed programmes, as well as RCC programmes, most notably those of CEH (including WA01 Water Extremes) programmes. The existing investments relevant to Challenge 5 (Droughts, heatwaves and wildfires) are the same as those in Challenge 4; most research in these has been focused on droughts. Current investment in Challenge 6 (Coastal Erosion & Flooding) is mainly in elements of Directed Programmes, such as CWC and ESPA, as well as through

RCC programmes. Much of the ongoing work, for instance addressing sediment mobility at POL, and sea-floor mapping in BGS, will provide a platform upon which the '*Coastal Sediment systems Programme'* will be built. Currently there are no directed programmes in the geohazard challenges, including Challenge 7 (Landslides), Challenge 8 (Volcanoes), Challenge 9 (Earthquakes) and Challenge 10 (Tsunamis). Similarly, apart from with work being undertaken with the RCCs, the most significant investments are those on the Earth's crust Growth (Afar Consortium and COMET) and Sumatran earthquakes (Challenge 9) – which will contribute to the programme on *'Increasing resilience through multi-hazard assessment of earthquake-prone and volcanic regions'* through the development and testing of new approaches in monitoring and modelling. The lack of recent investment into geohazard research in recent years will be partially remedied by this action.

Wider strategy issues

All of the actions will provide knowledge and information through close stakeholder engagement, enabling rapid use and exchange of data and models. The development of an interdisciplinary programme of work will enhance the career progression of NERC staff and new researchers. **Training**, particularly in areas of interdisciplinary science, will be encouraged, especially in the programme on '*Increasing resilience through multi-hazard assessment of earthquake prone and volcanic regions'*. It is anticipated that all actions will utilise **research facilities** and equipment across a range of NERC current investments within research and collaborative centres. The science developed within the NH theme will have a high **international** profile, particularly as the programme on '*Increasing resilience through multi-hazard assessment of earthquake prone and volcanic regions'* and the '*Arctic Research Programme'* will be based on science that will be largely developed, and with major significance, overseas. Such activities will be enmeshed within broader international initiatives, such as the UN International Strategy for Disaster Reduction (UN-ISDR) agenda, and the Interdisciplinary Research for Disaster Reduction (IRDR) programme. The actions are likely to inform priorities for use of international science resource facilities, such as the International Ocean Drilling Program (IODP). **Knowledge Exchange** is extremely important to the NH Theme, the success of which may only be determined by the increase in our understanding and capacity to model societal risks imposed by natural hazards, and ultimately, by how much these are reduced; this will be jointly owned with players outside NERC. Successful KE should be reflected in stakeholder acceptance of forecasts and advice as well as the uptake of measures to decrease societal exposure of natural hazards by the scientific, policy and financial (e.g. insurance) sectors. The actions proposed will have substantial and measurable **economic impact** that cannot solely be monitored through standard publication metrics alone. Knowledge Transfer Partnerships (KTPs), in conjunction with the Technology Strategy Board, being established with elements of the insurance industry, notably Willis and the Lighthill Research Network. Such partnerships, and internships, are expected to expand in scope in future years. It is likely that through the development of such partnerships, as well as with other co-funders, several challenges associated with **data and information** management may need to be resolved (e.g. resourcing common facilities, data storage, ownership of models or IPR).

Size of community

NERC currently invests over £25M in NH research, of which over 80% occurs in Directed Programmes and Consortium Grants, suggesting a sizeable NH community. The main areas of NH thematic growth are those associated with development of approaches in probability, uncertainty and risk and integrated modelling. Workshops & community events held in relation to the proposed actions on *Flooding from intense rainfall* and *Drought action* have been well attended by NERC scientists with international reputations, as well as young researchers, suggesting that the proposed levels of investment will be readily accommodated within the community.

Relevant co-funding contributing to actions.

It is expected that the action on *Flooding from intense rainfall* will be supported by several LWEC partners, most notably the EA, DEFRA and the MetOffice. The nature of the support will depend on the scientific priority to be addressed. It is also expected that these partners will contribute to the *Drought* action.

1 Natural earth processes – occurring in the solid earth, oceans or atmosphere – with the potential for inflicting damage or having economic and social consequences, immediately or over a longer term, and locally, regionally or globally (UNDP, 2004; Lerner-Lam, 2007)
2 Biodiversity (BIO), Climate System (CS), Earth System Science (ESS), Environmental Pollution and Human Health (EPHH), Natural Hazards (NH), Sustainable use of Natural Resources (SUNR) and Technologies (TECH)
3 Natural Hazards Strategy: http ://ww w.nerc.ac.uk/about/strategy/documents.asp
4 The Lancet, Volume 377, Issue 9764, Page 439, 5 February 2011
5 Learning Lessons from the 2007 Floods, an independent review by Sir Michael Pitt, Cabinet Office, June 2008.
6 The Climate Change Act (2008) requires a UK-wide climate change risk assessment every five years accompanied by a national adaptation programme that is also reviewed every five years. The Act has given the Government new powers to require public bodies and statutory organisations such as water companies to report on how they are adapting to climate change.
7 Future Water (2008) The Government's overall strategy for water looks mainly at water supply and provision. It reaffirms Making space for water as the basis for managing river and coastal flooding. However, it also sets out a vision for better management of surface water to address the dual pressures of climate change and housing development.
8 European Union Directives, including the Water Framework Directive (2000/60/EC) and Floods Directive (2007/60/EC), require consolidated river basin management planning, assessment and mapping of hazards and risks, and preparation and use of flood risk management plans. The frameworks set out in the directives closely match those already applied in the UK.
9 Number of droughts likely to increase under climate change: Met Office website http ://ww w.metoffice.gov.uk/corporate/pressoffice/2010/pr20100526.html
10 Ian Currie 'The 1976 drought'
11 Marsh: The UK drought of 2003 - an overview: http ://ww w.nerc-wallingford.ac.uk/ih/nrfa/yb/yb2003/drought2003/
12 Robine et al. (2008). Comptes Rendus Biologies 331 (2): 171–178
13 Fink et al. (2004). Weather, Vol.59, 8, 209-216
14 European Environment Agency (2003). Environmental issue report No. 35. EEA Copenhagen, 54 pages
15 For instance: Hannaford et al. (2009 The Spatial Coherence of European Droughts). Bristol, Environment Agency.
16 For instance: Water Industry Research (2007) 'Drought and Demand: Potential for Improving the Management of Future Droughts'.
17 In relation to our questions about droughts …'We should aim to get the right answers for the right reasons because the right reasons can be essential for getting the right answers at all if conditions shift beyond our range of prior experience - as the result of extreme events, climate change, or shifts in land use, for example' - Kirchner essay: The birth of the National Center for Hydrologic Synthesis (NCHS).

UK Droughts (NH, CS)

Council approved £6.5m for this action

In the view of the wider UK public, droughts[1] are not presently seen as a large risk as they have not had a nation-wide impact in recent years[2]. However, they remain a substantial threat to water supply, biodiversity, environment[3], food security, energy security, the economy and wider society, and may become more frequent or intense with climate change[4].

Decision-makers[5] find it challenging to make informed adaptation and management choices[6] in relation to droughts as it is difficult to predict their occurrence, duration, intensity and extent of impact. Currently the many drivers of drought, both meteorological (e.g. anticyclonic blocking) and societal (e.g. supply[7] & demand balance[8], water storage, transfer and utility trends), are considered in isolation[9]. Consequently we have a very poor understanding about how they jointly influence the behaviour of complex groundwater[10], surface water or ecological systems – as well as the hazards and resources associated with the stressing of these - such as wildfires, ground instability, water-, food- and ecosystem-services[11]. It is clear that our knowledge of many interacting processes that govern the behaviour of these systems and their impacts in periods of water scarcity is extremely poor.

Given the risk of costly and damaging droughts to water security and society[12], it is crucial that we improve our capacity to predict their occurrence, intensity and extent of impact. Whilst extended range (seasonal) rainfall forecasts have the potential to inform drought management, the necessary levels of forecast skill are quite high in particularly risk-averse decision-making environments (e.g. water supply). However, there are several ***scientific goals*** that are both achievable and have the potential to inform decision making in key user sectors - to:

a) Characterise the historical occurrence, intensity, geographical pattern and impacts of drought in the UK through identification of the contribution of multiple drivers of drought, including antecedent conditions (e.g. cumulative dry winters[13]) and water utility patterns.

b) Identify, model and predict the climate drivers of key drought types at lead times from months to years. A particular focus should be on the potential for exceedance of the historical envelope, for example through the interaction of climate change with natural climate variability[14].

c) Identify the nature, extent of impact, interaction and functioning of key ecological and hydrological systems during periods of water scarcity – addressing in particular non-linear responses, system thresholds[15] and potential for recovery.

d) Develop integrated tools to assess the risks associated with drought, by coupling new and existing models that describe the drivers, feedbacks and impacts, to support decision-making before, during and after drought events, and determine optimal adaptation and management strategies.

Programme Objective: To identify and predict the interrelationships between multiple drivers and impacts of UK droughts - over daily to multi-annual timescales and on spatial scales from metres to 500 km - to inform adaptation and management decisions before, during and after drought events.

Delivery Mechanism: The integrating nature of the scientific goals (above) and the need to bring key stakeholders together, demands a systems-based approach. The adoption of such an approach in the past has been hampered by scientific and cultural challenges associated with bringing-together environmental systems that are complex, heterogeneous on all scales, poorly characterized by direct measurement, and have originated (and are 'owned-by') different sectors (e.g. atmospheric and ground-based). However, the changing future political landscape, including the increased focus on adaptation, pursuit of efficiency through integration, maximisation of past research investments, increased partnership (e.g. LWEC) and greater access to data and models, now make a systems- based approach both a viable and desirable option.

The research programme will last for 5 years and comprise four workpackages (WPs). Each WP will be undertaken by a separate consortium. All will commence at the start of the Research Programme. WP 4 will support a part-time research programme coordinator, focussed both on research and user communities, and an advisory group, comprising representatives of end-users, such as SEPA, EA, UKWIR, Defra and the insurance industry, as well as leading scientists, to ensure a high level of connectivity between workpackages. The remainder of the research in WP4 will begin at the start of year 2.

WP1 addressing scientific goal a) will build an integrated understanding of past droughts, distinguishing and quantifying the roles of multiple drivers and their impacts through analysis of historical data. It is necessary to use past records to build a sufficiently large archive of events to enable analysis and characterization of patterns of events. It will address three main periods i) 2000-present; ii) 1970-2000; and iii) 1920-1970[16]. The WP will entail accessing relevant meteorological, hydrological, groundwater, water abstraction, water consumption, reservoir storage, water licencing (agricultural and industrial – including power generation) and land-use and other stakeholder-response data which is currently distributed across several key organisations (notably the EA, DEFRA, UKWIR, CEH, BGS and MetOffice). Much of the 2000-present data should be readily extractable and allow rapid analysis. Harvesting of older datasets will take more time; analysis of these may be undertaken later in the programme.

WP2 addressing scientific goal b) will improve the assessment of the climate drivers of drought on timescales relevant to drought management. Building on the understanding and characterisation of past droughts in WP1, and working closely with decision-makers, it will also address the question of when, and at what lead times (in the range months to decades), useful predictive or scenario information can be provided. A particular focus will be the provision of early warning that the envelope of historical changes may be exceeded[17]. Scientific questions that will need to be addressed include understanding the processes and drivers of blocking and the North Atlantic Oscillation, in both summer and winter. This process-level understanding will be used to evaluate and improve climate models and their initialisation[18]. New science opportunities arise because of the availability of high resolution climate and weather forecasting models with improved simulation of blocking, higher resolution and longer atmospheric reanalyses (ERA-Interim, ACRE), coordinated model comparison activities (TIGGE, CMIP5) and observational campaigns (including DIAMET).

WP3 addressing scientific goal c) will undertake fundamental observational, experimental and exploratory research on the key ecological and hydrological processes that are impacted-upon and govern hazard generation and water resource limitation in the critical zone[19]. It will address the effects and feedbacks (including carbon fluxes and water quality indicators), of changes in precipitation, humidity, soil moisture and water reservoirs on selected ecosystems, combustible systems, swell-shrink clays (including the effects of cover sequences), surface water and groundwater[20]. The WP will focus on processes that control non-linear interactions and potential trigger points (e.g. to instigate wildfires through the availability and aridity of fuel and ignition sources), as well as differentiate ecosystem health impacts caused by heat, as opposed to dehydration[21]. It will develop a better understanding of impacts and response during the onset, within, and immediately following, a drought. It is anticipated that the WP will utilise trial sites within selected catchments, mesocosm experiments and exploratory modelling. The WP will facilitate intercomparison of existing models (e.g. hydrological, such as G2G and JULES[22]), which will inform the development of WP4.

WP4 addressing scientific goal d) will develop a prototype framework of models that integrates process understanding across meteorological, ecological, hydrological and geological regimes to enable coherent scenarios of drought impacts to be generated for the first time. This will incorporate the science and critical relationships established in WPs1-3, but also utilise and adapt existing models, such as those addressing agricultural, water quality and wider socio-economic impacts. Experience in related areas such as climate modelling shows that interactive coupling of environmental systems that were previously treated as having fixed 'boundary conditions' is a highly challenging scientific task in itself, as new feedbacks are brought into play. Therefore WP4 will begin early in the programme, building on a subset of existing models, but will evolve its component models in response to progress in WP 1-3. To assess their value as decision support tools, the integrated models will be tested for their ability to simulate the system interactions identified in WP1 for certain key historical droughts. The coupling will be facilitated by the recent development of standardised environmental modelling protocols (OpenMI). WP4 will be supported by the NERC KE Programme in water security, which will enable connections with a community of practice in this area and will facilitate KE activities (described in the Economic Impact section below).

Partnerships: Given the shared interest of several LWEC partners in generating and delivering science that will substantially enhance decision-making associated with droughts, the development of a coherent collaboration is critical to the impact of the programme. DEFRA, EA, MetOffice, as well as UKWIR will be partners in the programme, providing access to complementary ongoing research, facilities and in-kind support. Partnerships with BBSRC and ESRC, and with the Defra/UKWIR Regis programme, will be sought to develop interactions with the agricultural and socio-economic impact science and modelling within WP4. The programme will also support many other stakeholders, including SEPA, OFWAT, WAG, SNH, NE and UKCIP. In addition, it is expected that many existing modelling initiatives such as JULES, *FutureFlow*[23] (EA), The Water Security pilot study (CEH, BGS) will provide foundation elements. WP3 has the potential to build-upon existing catchment-centred research facilities such as the Defra Demonstration Test Catchments (e.g. Pont Bren and Hodder), the Virtual Observatory, facilities developed within the *Biodiversity & Ecosystem Service Sustainability* (BESS) programme, the Pilot Environmental Platforms of Natural England and those of NERC research centres. The outputs of WP4 are expected to contribute to the ongoing development of integrated environmental hazard information services. International opportunities for collaboration exist through a Belmont Forum action on Water Security under development[24], spearheaded by *US National Science Foundation* with initial interest from *Agence Nationale de la Recherche*, and *Deutsche Forschungsgemeinschaft*. An international workshop (WP4) will be run to explore opportunities afforded by international collaborative research partnerships.

Current investments and National Capability Needs: Existing NERC investments that should be built-upon include the *Changing Water Cycle* Programme (particularly the land-use and drought elements), the *Rural Economy and Land Use* (RELU) Programme (with ESRC) and the *Probability, Uncertainty and Risk Research Network.* The programme is complementary to the *Changing Water Cycle* Programme in that it focuses on the shorter timescales (seasonal to inter-annual) that are most relevant to drought management and takes a broader view across environmental impacts of drought. Significant collaboration with CEH (particularly in usage of the Landcover map, JULES and Grid2Grid and BGS is envisioned. There will be significant HPC requirement for WPs2+4.

Action investments: The total proposed budget from NERC (Excluding KE) will be £6.5m at the 100% funding scenario. Budgets of the individual WPs are WP1 £1.2M, WP2 £1.0M, WP 3 £3.0M, and WP4 £1.3M.

Economic impact: The outputs of this research will be widely used in drought adaptation and management by the Met Office, SEPA, EA, Defra, other LWEC partners, water companies, local authorities, third-sector organisations, land-use managers, the insurance industry, the National Trust, RSPB, HPA, the construction industry, energy companies, oil and gas companies, instrumentation and monitoring companies and the agriculture, transport and retail sectors. In addition, secondments / placements of people between research teams and between research and user organisations (e.g. policy placements, internships) will be used to build the community and exchange knowledge. Partnership research grants will be used to encourage the engagement between researchers and users, with a minimum contribution of 25% of total grant value (in-kind or cash) from the users. Towards the end of the programme, there will also be regional events, often in partnership with other existing events, to disseminate outcomes, models and knowledge to local authorities, land owners, regulators and others to encourage uptake of the knowledge. This investment will inform the public debate on adaptation in relation to drought adaptation and management.

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1 Droughts are multifaceted both in their characteristics and range of impacts; nonetheless, a distinction may be drawn between meteorological droughts (defined essentially on the basis of rainfall deficiency), hydrological droughts (where accumulated shortfalls of runoff or aquifer recharge are of primary importance) and agricultural droughts (where the availability of soil water during the growing season is the critical factor). For the purposes of this action, a drought is defined as: "an extended period of below average rainfall that leads to a reduction in the availability of water" (EA).

2 Despite regional events - cf. http ://ww w.bbc.co.uk/news/uk-england-11018474

3 Particularly ecosystems, in terms of river flows and wetlands.

4 Murphy, J.M., et al., 2009: UK Climate Projections Science Report: Climate change projections. Met Office Hadley Centre, Exeter, UK, 192pp

5 Including here scientists, policy-makers, regulators, water companies, industrial and agricultural water suppliers and users, as well as individuals (e.g. farmers).

6 For instance, to respond to statutory Water Resources Management Plans or Drought Plans.

7 Water supply is complicated as availability is not the only control; the pressure to get water to consumers is another - fluxes within the reticulation network are very important within particular supply areas (e.g. the London ring main and the Yorkshire ring mains).

8 The consequences of increasing and competing demand will exacerbate the effects of meteorological/hydrological and agricultural drought. Demand issues are complex; for instance, standpipes were planned to be used in the 1975/76 drought because of problems with reticulation pressures not the amount of water available per se.

9 Drought and demand: http ://ww w.lec.lancs.ac.uk/cswm/Drought_Demand.php

10 Groundwater plays a critical role in UK water resources; it is the largest source of water in SE England - so any significant reduction in groundwater flow will have very significant impacts on surface water abstraction and water supply. The impacts of heterogeneity of major and minor aquifers on groundwater storage under low flow (drought) conditions are highly uncertain. Furthermore, there are significant knowledge gaps in understanding groundwater recharge in differing aquifers (in the Chalk it seems that recharge continues during a drought (or other periods of no apparent recharge, due to storage in the unsaturated zone).

11 The main reason for this is because of the rarity of droughts, and especially long droughts, in the historic record.

12 European droughts over the last 30 years have cost c.£200 Billion (EC, 2007); future costs are of concerns to the incipient UK Water Research and Innovation Framework (UKWRIF)

13 This should identify the impact of different sequences of seasonal changes (e.g. dry winter–wet summer–dry winter or wet winter–dry summer–dry winter) on drought.

14 Water companies and regulating authorities, in accordance with statutory water company plans, including Water resources management plans and Drought Plans, have historically triggered drought actions on the basis of worst recorded droughts - an approach that may be inappropriate in the future.

15 http ://ww w.nerc.ac.uk/research/programmes/lwec/documents/lwec-pr-marrs-report.pdf

16 Whilst data have been collated for post-1800 droughts (Marsh et al 2007, Weather 62(4) 87-93) data of reasonable quality are only likely to exist for post-1920 droughts.

17 This should also include identification of data and information needs to support the long-term robustness of drought forecasting and typing to support adaptation and mitigation.

18 At a recent UK workshop on blocking (Reading Dec 2010) some key questions were identified, including understanding the different weather impacts of different blocks, the role of diabatic feedbacks in blocking, the differences between summer and winter blocking, and the climate system drivers of blocked seasons.

19 The Critical Zone encompasses water with soil, rock, air, and biotic resources in terrestrial environments and ranges from the top of the vegetation down to the bottom of the aquifer: Lin 2009:HESSD: C1162–C1166.

20 It should consider the role of non-aquifers and minor aquifers supporting low flows, and regional differences (North-West, South East) across large catchments.
21 The heat balance of drought-affected systems will be influenced by the degree of hydration (e.g. dry clays will radiate much more heat than those that are wet).
22 http ://ww w.jchmr.org/jules/
23 This is generating spatially coherent rainfall and PE datasets for the whole of the UK from the UKCP09 outputs. These are being used to drive rainfall runoff and groundwater models to produce projections of changes in river flows and groundwater levels to the end of the century.
24 This aims to bring together regional observations and modelling to develop a global picture and improve regional and seasonal-decadal predictions of extreme hydrometeorological events (floods and droughts) and their impacts to support management. It will build on the ongoing NSF Water Sustainability and Climate and the ANR Global Environmental Change and Societies programmes.

Flooding from Intense rainfall (NH)
Council have approved £5.2m for this action

Intense rainfall events commonly last for a few hours, or even a few minutes, but present flood forecasters and flood risk managers with major problems. These groups have great difficulty predicting when, where, and how much precipitation will occur, as well as managing the large volumes of overland flow – mainly because of exceedance of the capacity of the surface for infiltration, enlargement of areas of saturated ground, or overwhelming of drainage capacity of channel networks, coupled with rapid and unusual hydrological and geomorphic responses to rainfall and runoff. Our knowledge of processes associated with such extremes is poor and we cannot predict associated flood risks with confidence, particularly as these are commonly exacerbated by changes in flood routing, dynamic adjustments to river channels, the widespread mobilisation of sediment and organic debris, as well as the occurrence of blockages – as seen during the flash floods at Lynmouth (1952), Boscastle (2004); Helmsley (2005), Cumbria (2009); and Cornwall (2010).

Sir Michael Pitt (2008)[1], in his appraisal of flood risk management and emergency response, highlighted that more knowledge is required to reduce flood risk associated with surface water flooding, particularly the use of land-management to minimize discharge and a better appreciation of flooding arising from summer (convective) storm events. Similarly, catchment susceptibility, the prediction of convective storms and pluvial flooding have been identified as research gaps by LWEC's *First UK Flooding Research Strategy*[2] (in-draft). The prioritisation of these topics by the Government, providers and users of research, as well as widespread recognition that the occurrence of high intensity rainfall is likely to increase as a result of climate change[3,4,5,6]. Arising from these considerations is an urgent need to develop new science with respect to intense rainfall events that appropriately informs i) risk mitigation and adaptation options; ii) improved planning & operational maintenance of catchments, channels and flood defence infrastructure; and flood incident management (real time forecasting, flood fighting and evacuation strategies). Thus a NERC-led, LWEC, UK-focused research programme will address the following ***scientific goals*** - *to*:

a) Improve the length and accuracy of forecasts of the occurrence and intensity of rainfall associated with convective storms.
b) Identify the susceptibility to high-intensity rainfall of different catchment types, based on characterisation of the properties that govern the dynamic, non-linear, hydrological and hydro-morphological processes which initiate, extend and intensify associated flood risks.
c) Enhance flood risk-management through the development of both flood risk estimation and real-time forecasts of floods associated with high-intensity rainfall, integrating multiple meteorological and hydro-morphological processes occurring before, during and after intense precipitation events.

Programme Objective: To reduce the risks of damage and loss of life caused by surface water and flash floods through improved identification, characterisation and prediction of interacting meteorological, hydrological and hydro-morphological processes that contribute to flooding associated with high-intensity rainfall events.

Delivery mechanism: The programme should last for 5 years and comprise three workpackages (WPs), each run by a separate consortium. WP 1+2 will run during the first four years; WP3 will run during years four & five. WP 3 will support a part-time research programme coordinator, focussed both on research and user communities, and a programme advisory group, comprising representatives of end-users, such as SEPA, EA or Defra and leading scientists), to ensure a high level of connectivity between workpackages.

WP1 addresses scientific goal a) and convective precipitation. Whilst mid-latitude cyclonic storms (common in the winter) are the focus of the NERC *Storm risk mitigation through improved prediction and impact modelling* programme, there is no similar investment to enhance our capability to predict the temporal and spatial patterns and intensities of heavy rainfall associated with convective storms (most common in the summer). Yet, floods driven by these storms pose the greatest inland flood risk to life and trigger rapid morphological instability, with commensurately high sediment and debris loadings. The occurrence, as well as their spatial and temporal intensity, of convective precipitation is difficult to forecast. The research will focus on:

a) *Extracting maximum information from new and existing observation sources;*
b) *Improving techniques for small scale data assimilation within multi-scale environments; and*
c) *Developing methods to quantify and reduce error growth within models.*

The main aim is to improve the capability of the Unified Model to represent observed features in the first few hours of the forecast. Priorities are to assimilate pre-convective boundary layer structures and existing convective storm structures in such a way that immediate subsequent developments match reality[7,8]

WP2 addressing scientific goal b) - catchment sensitivity to high-intensity precipitation - will characterise the thresholds and non-linear trends in extreme hydrological and hydro-morphological behaviour associated with intense rainfall falling on different types of catchment. Building on recent research[9,10,11,12,13] this will consider characteristics such as degree of urbanisation, land-use, and potential debris sources that influence consequential flood risks. The research will focus on:

a) *Historically assessing selected catchments with suitable archived data (taking due account of uncertainty) where flooding associated with significant morphological responses to high intensity rainfall has occurred, or where this type of flood risk is high (including compilation and assessment of extreme event data for those catchments);*
b) *Parameterizing the increased complexity of the hydrological cycle under extreme conditions;*
c) *Physically observing hydro-morphological dynamics within field experiments and undertaking forensic analyses of intense precipitation events that occur during the study (on an opportunistic basis by rapid response teams).*
d) *Generalising findings at selected catchments to ungauged catchments in general.*

Research will identify and quantify catchment parameters that affect *susceptibili*ty to floods caused by convective storms including basin area, shape, topography, soils (including soil moisture, taking into account pre-conditioning) and land-use (urban as well as rural), including sediment and debris sources. It will address, through measurement and modelling[14], the significance of short-term responses in rainfall-runoff relations, flow-routing, groundwater behaviour and propensity for excessive erosion, landsliding and rapid channel change/avulsion under a range of intense precipitation regimes[15,16,17,18]. The influence of existing infrastructure (including reservoirs and flood-defences) and blockage potential will be accounted for, across multiple scales and throughout the selected catchments[19,20]. Small catchments, that are particularly susceptible to high intensity rainfall events, are commonly unguaged; however, sedimentary analysis[21] should allow elucidation of the frequency and magnitude of past floods in relation to climate and land-use changes within them[22].

WP3 addressing scientific goal c) and the reduction of risks imposed by high-intensity rain events**,** will improve the effectiveness of flood risk management by increasing the spatio-temporal accuracy of predictions and lead-time on flood warnings to identify catchments and communities most at risk. It builds-upon the outcomes of WPs 1+2, and will draw on the critical involvement of key LWEC partners. The research will focus on:

a) *Modelling the rainfall inputs to pluvial and flash flooding,*
b) *Incorporating morphological, sediment and debris dynamics in flood prediction, including pluvial and flash floods.*
c) *Developing and enhancing risk management solutions.*

The first of these - *a)* involves more accurate forecasts of short duration, high-intensity rainfall generated by convective storms, and incorporating rainfall-runoff models that account for the effects of long-duration, pre-cursor events which saturate soils, as well as other conditions that facilitate rapid runoff, such as snow cover. This will provide the opportunity to test the outputs of WP1 and investigate improvements to real-time flood warning that result from improved weather projections. The second focus – *b)* will explore the development of real-time hydro-morphological analyses and flood forecasts that account for non-linear, dynamic behaviour of fluvial systems (based on combining outputs from WPs 1+2). It will be particularly useful in catchments where sediments and debris are known to influence the standard of flood defence (e.g. the Kindle, in NW England), but also may have notable applications in pre-event planning. The development of risk management solutions – *c),* will focus on: i) coupling analyses of flood hazard and vulnerability to predict consequences, ii) improved modelling support and advice for flood risk managers with respect to joint hydrological, geomorphological and debris impacts, iii) development of event risk reduction strategies through, for example, identifying and clearing critical potential blockage locations, closing bridges at times of high risk, reducing debris loadings by moving potential debris (such as parked cars or fallen trees) from flood paths, modifying evacuation plans, or providing specific advice on areas at risk (which may differ in relation to geomorphological and debris-related flood risks); and iv) assessing and optimising management with respect to potentially competing, objectives for flood risk management, conservation and biodiversity, particularly with respect to operational strategies for removing sediment, vegetation and debris from channels and floodplains. WP3 will be supported by the NERC KE Programme, which will enable connections with a community of practice in this area and will facilitate KE activities (see below).

Partnerships: The shared interest of several LWEC partners in generating and delivering this science demands coherent collaboration. The Met Office will contribute staff to support WP1 in developing capabilities that enhance the next generation UK convective scale prediction system - based on the UKV configuration of the Unified Model[23]. It will also make available supercomputer resources to support WP1+3 and for other modelling to provide enhanced guidance to the Flood Forecasting Centre[24]. The EA and Defra will ensure that policy, flood risk management, and operational decision-making is based on the new science through development, uptake and application of those tools and techniques that achieve 'proof of concept'. In fact, the EA is currently planning a project that will develop new tools based on expected research outcomes from the programme. It is expected that the EA and other key partners will provide researchers with open access to existing catchment tools and datasets and facilitate, where possible, new data capture. They will focus on exploring and delivering catchment management and adaption options based on modelling outputs from WP4, in particular to address issues related to flood defence infrastructure and the social and economic barriers to flood risk adaptation. Links with SEPA, EPSRC and ESRC would greatly add to the take-up scientific impact of the programme and are actively being investigated. International collaboration opportunities exists via a new Belmont Forum, led by the US NSF, with initial interest from *Agence Nationale de la Recherche* (France) and *Deutsche Forschungsgemeinschaft*[25].

Current investments and National Capability Needs: Existing NERC investments that should be built-upon include the NERC FREE programme (particularly the land-use elements), and the *Storm risk mitigation through improved prediction and impact modelling* Programme, the *Rural Economy and Land Use* (RELU) Programme (with ESRC), The *Changing Water Cycle* and *Lowland Catchment Research* (LOCAR) Programmes. WP2 will build on the EPSRC FRMRC programme and existing national flood risk modelling tools (such as the FEH and Grid-to-Grid). Opportunities should be sought to benefit from existing test catchments (e.g. the Pont Bren, Hodder) including the Defra/EA test catchments, the SCAMP project, GLOCOPH, and the Welsh upland research platform in the Dyfi catchment (NERC Virtual Observatory). Significant collaboration with CEH (particularly in usage of the Landcover map, JULES and Grid2Grid) and BGS is also envisioned. There will be significant HPC requirement for WP1, but less for WP2 and WP3).

Action investments: It is anticipated that the total proposed budget from NERC will be £5.2m at the 100% funding scenario (WP1 £1.0M, WP2 £3.0M, WP3 £1.1M). At less than 100% funding the framework in WP1 will be dominated by existing models..

Economic impact: The outputs of this research will be used by the Met Office, SEPA, EA, Defra, other LWEC partners, as well as other end-users, including water authorities, local authorities, land-use managers, the insurance industry, river engineers, environmental consultants, the HPA the National Trust, RSPB, the construction industry, instrumentation and monitoring companies and the agriculture, transport and retail sectors. It will have a major influence on flood risk management and operational delivery of channel maintenance by competent authorities including the EA. The modelling will enable meteorological and catchment processes to be presented in more accessible and transparent formats that will be helpful in informing public debates on adaptation and balancing river management goals for flood defence and biodiversity. Partnership research grants will be used to encourage the engagement between researchers and users, with a minimum contribution of 25% of total grant value (in-kind or cash) from the users. Towards the end of the programme, there will also be regional events, often in partnership with other existing events, to disseminate outcomes, models and knowledge to users to encourage uptake of the knowledge.

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1 Learning Lessons from the 2007 Floods, an independent review by Sir Michael Pitt, Cabinet Office, June 2008.

2 http ://ww w.lwec.org.uk/strategic-activities/uk-first-flood-research-strategy

3Fowler & Kilsby, 2003. A regional frequency analysis of United Kingdom extreme rainfall from 1961 to 2000. International Journal of Climatology, 23, 1313-1334.

4 Fowler & Kilsby 2003. Implications of changes in seasonal and annual extreme rainfall. Geophysical Research Letters, 30(13), 1720

5 Pall et al. 2011 Anthropogenic gas contribution to flood risk in England and Wales in Autumn 2000. Nature, 470, 382-385.

6 Min et al. 2011. Human contribution to more-intense precipitation extremes, Nature, 470, 378–381

7 This will be carried out in collaboration with Met Office research staff with the aim of improving the capability of the Unified Model to represent observed features in the first few hours of the forecast.

8 This WP will be able to take advantage of datasets generated during the COPE experiment to study the development of convective storms, if- COPE is funded.

9 Evans et al. 2008. An update of the Foresight Future Flooding 2004 qualitative risk analysis. Cabinet Office, London.

10 Jackson et al. 2009. The impact of upland land management on flooding: insights from a multi-scale experimental and modelling programme. Journal of Flood Risk Management, 1, 71-80.

11 Lane & Thorne. 2007. River Processes. In: Thorne et al. (eds). Future Flooding and Coastal Erosion Risks. London: Thomas Telford, 82-99.

12 Marshall et al. 2009. The impact of upland land management on flooding: results from an improved pasture hillslope. Hydrological Processes, 23, 464-475.

13 Sear et al. 2010. Guidebook of Applied Fluvial Geomorphology. Thomas Telford, London.

14 Some of these will be stationary/stable, some of which will change slowly, and some of which will respond rapidly (within the duration of a single, extreme rainfall event).

15 Harvey. 2007. Differential recovery from the effects of a 100-year storm: Significance of long-term hillslope-channel coupling; Howgill Fells, northwest England. Geomorphology, 84 192-208.

16 Lane et al. 2007. Interactions between sediment delivery, channel change, climate change and flood risk in a temperate upland environment. Earth Surface Processes and Landforms, 32, 429-446.

17 Reid et al. 2008. The timing and magnitude of coarse sediment transport events within an upland, temperate gravel-bed river. Geomorphology, 83, 152-82.

18 Raven et al. 2009. The spatial and temporal patterns of aggradation in a temperate, upland, gravel-bed river. Earth Surface Processes and Landforms, 34, 1181-1197

19 Wallerstein. 2008. Accounting for sediment in rivers – A tool box of sediment transport and transfer analysis methods and models to support hydro-morphologically-sustainable flood risk management in the UK. Flood Risk Management Research Consortium, Research Report UR9.

20 Environment Agency 2010. Key Recommendations for sediment management – A Synthesis of River Sediments & Habitats (Phase 2) Science Report.

21 For example, Macklin & Rumsby, 2007. Changing climate and extreme floods in the British uplands. Trans. Inst. Br. Geogr. 32, 168–186.

22 In practise, most catchments remain ungauged, and there is a need to develop optimal procedures for predicting the hydrological response in sparsely or ungauged catchments by transferring data from gauged catchments.

23 Staff may be based in Reading or Exeter. The teams carrying out these activities will have access to the Met Office supercomputing facility and observations archives on the same terms as internal Met Office research projects.

24 To the extent possible within operational constraints, the Flood Forecasting Centre will make available resources to monitor and evaluate the performance of such trial concepts in comparison with existing guidance products with the aim of bringing them into operational use at the earliest opportunity. This will require work on how the improved forecasts can be incorporated into guidance and advice that ultimately improve response decisions. The coupling of readily-available information on catchment susceptibility (e.g. potential for blockages from leaf fall) with precipitation forecasts is critical here.

25 This aims to bring together regional observations and modelling to develop a global picture and improve regional and seasonal-decadal predictions of extreme hydrometeorological events (floods and droughts) and their impacts to support management. It will build on the ongoing NSF Water Sustainability and Climate and the ANR Global Environmental Change and Societies programmes. An international workshop (? summer 2011) will explore opportunities afforded by international collaborative research partnerships.