PAPER 18.1

Environmental Risks to Infrastructure Innovation Programme

NERC SCIENCE OF THE ENVIRONMENT

NERC ENVIRONMENTAL RISKS TO INFRASTRUCTURE INNOVATION PROGRAMME. PROGRAMME SUMMARY AND PROJECTS OVERVIEW

1. Background

The Environmental Risks to Infrastructure Innovation Programme (ERIIP) is a collaboration between the Natural Environment Research Council (NERC) and infrastructure owners, operators, policy-makers and regulators to enable the UK infrastructure sector to use environmental science to identify, quantify and manage environmental risks, such as those from extreme weather and climate change.

Through ERIIP, NERC are investing £5 million over 5 years to fund projects that take the outcomes of existing research and translate these into industry-relevant information, tools to help identify environmental risk, assess their impacts on infrastructure and develop solutions.

Infrastructure owners and operators, engineering consultants, contractors, insurers and investors, policy and civil society representatives, and regulators can join the Programme and become members of the Environmental Risks to Infrastructure Innovation Community (ERIIC). Current members of the Programme are:

- Arup
- Atkins
- EDF Energy
- Environment Agency
- High Speed 2
- HR Wallingford
- London Underground
- National Grid
- Network Rail
- Scottish and Southern Energy (SSE)
- Scottish Water
- Temple Group
- Translink NI
- Transport Scotland
- UKWIR
- WSP

This report brings together key figures on projects funded since 2014.

2. Breakdown of projects funded to date

The Programme is open to a range of projects, from short term (3-6 month) feasibility studies, to longer-term, translational projects. The proposed projects must use existing science research (knowledge, data, models or skills) and translate this into outputs that meet the needs of the end user(s) (as opposed to generating new research outcomes).

The following types of innovation projects have been considered for funding:

- Syntheses and mapping of existing research in a particular area to aid and transfer knowledge to the industry;
- Bringing together data from disparate sources (e.g. related to different environmental hazards, or environmental data with data on the engineering or economic impacts sourced from academia or project partners);
- Translation of existing data, knowledge, expertise into tools, solutions and approaches to meet a specific industry need;
- Decision-support tools incorporating NERC data or knowledge;
- Scenarios of environmental risks and their impacts on infrastructure;
- Model synthesis, merging and manipulation to answer a specific challenge, need or issue.

Since 2014**, sixty collaborative projects** have been funded through the Programme. Case studies on the complete projects can be found on the CIRIA website.

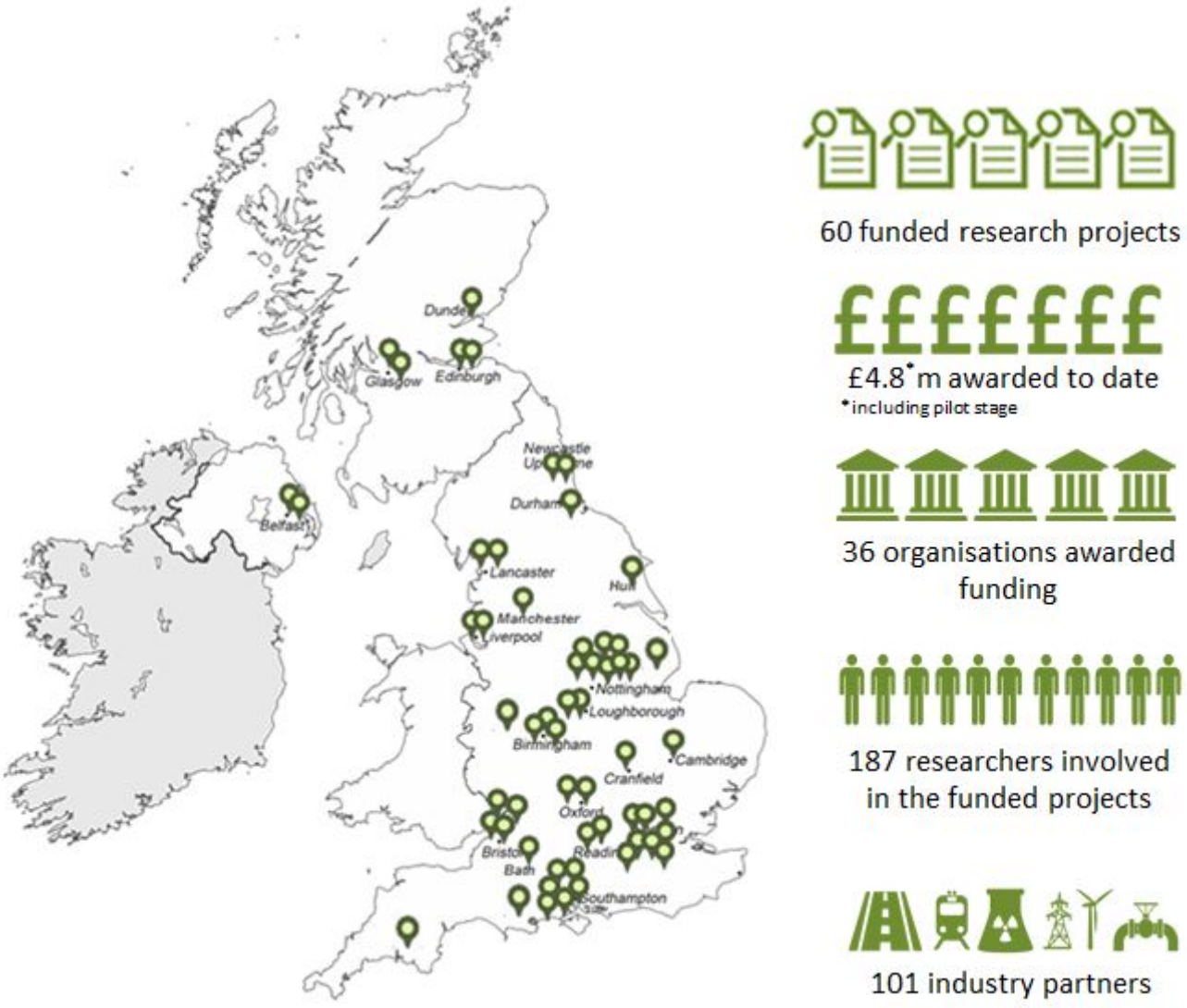

Figure 1: Geographic distribution of awarded Research Organisations across UK and key figures of awarded projects

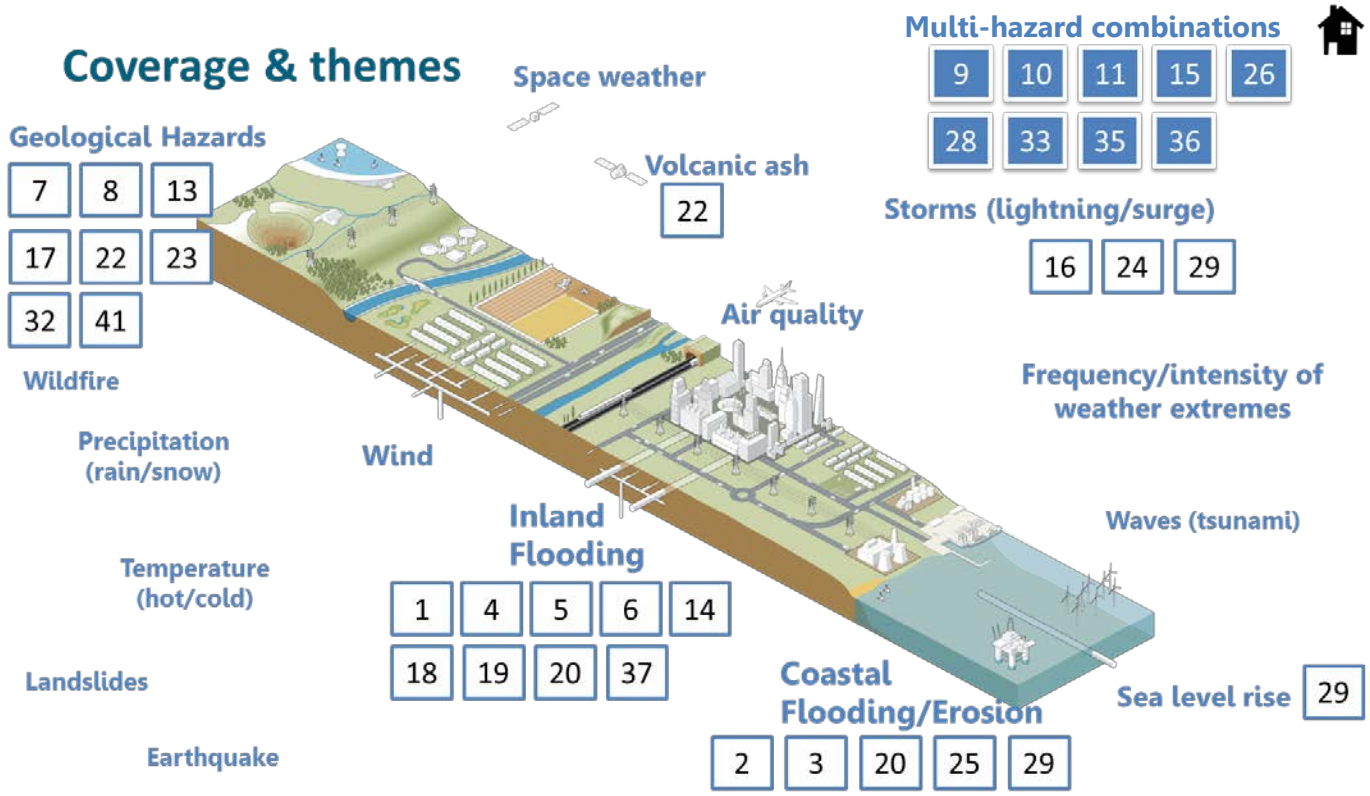

Figure 2: Distribution of completed projects across coverage & theme

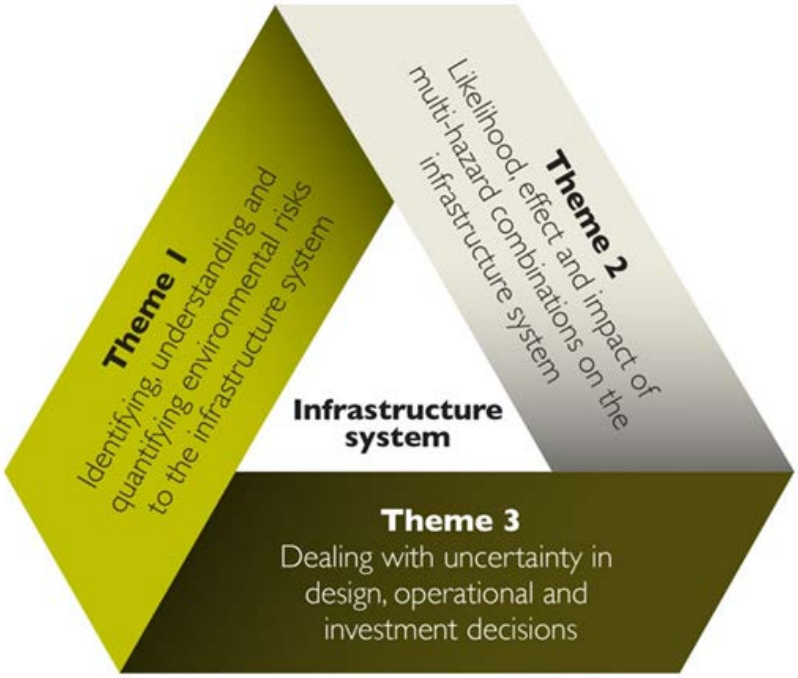

Figure 3: Three key themes the Environmental Risks to Infrastructure Innovation Programme focuses on

Project Number	Title	THEME 1	THEME 2	THEME 3
2014				
1	Groundwater and Flood Risk...	X		X
2	Sandscaping for Mitigating...	X		
3	Examining Risks of Coastal...	X		
4	Improved techno-economic...	X		
5	Co-creating railway flood...	X		
6	Assessing the risk of groundwater...	X		X
7	Vulnerability of proximal...	X		
8	Modelling the geological factors...	X		
9	Dynamic heat risk management...	X		X
10	Towards managing risk...		X	X
11	Climate science support...	X		X
12	Wind Turbine Foundation...	X		X
13	The Proactive Infrastructure...	X		X
14	Risk Based Performance Forecast...		X	X
15	A tool to improve prediction...	X		X
16	Quantifying the risks...	X		X
17	Communicating And Visualizing...	X		X
18	Quantification of risks to bridges...	X		X
19	Evaluating the resilience...	X		X
20	FoRUM - Flood risk...	X		X
21	Understanding the effects...	X		
22	Volcanic Ash Hazard...	X		
2015				
23	What threat do turbidity currents...	X	X	
24	Storm Risk Assessment...	X		X
25	Coastal landfill and shoreline...	X	X	
26	Multi-Hazard Resilience...		X	X
27	The Proactive Infrastructure...		X	X
28	Weather-induced single point...		X	X
29	Toolkit to improve resilience...	X		X
30	Delivering resilient power...	X		X

Project Number	Title	THEME 1	THEME 2	THEME 3
31	Real-time assessments...	X		X
32	Software for quantifying...	X		X
33 / 34	InSAR for geotechnical...	X		X
35	Environmental influences...		X	X
36	Assessing the risk...		X	X
37	Piloting a real-time...	X		X
2016				
38	The Proactive Infrastructure...	X		X
39	Predictive jellyfish bloom...	X		X
40	E-Rise: Earliest detection...	X		X
41	New field-scale calibration...	X		
42	Decision support...	X		X
43	Reducing the ice hazard...	X		X
44	Protecting airspace...	X		X
45	Synthesising Unprecedented...	X		X
2017				
46	Early warning decision...	X		X
47	Single Event Effects...	X		X
48	FREEDOM: Forecasting Risk...	X		X
49	Seismic imaging...	X		X
50	Debris Effects on BRIdge...	X		X
51	Combination Hazard...		X	
52	Space weather disruptions...	X		X
53	Weather-wise...	X		X
54	Quantitative Assessment...	X		
55	Playing Games to Understand...		X	
56	RV-DSS: An industry-friendly...		X	X
Innovative monitoring				
57	Innovative condition...		X	
58	WireWall: a new approach...	X		
59	Jellyfish and Seaweed...	X		
60	Reducing storm-induced...	X	X	X

Figure 4: Overview of all projects (i.e. completed and on-going) classified under key theme(s)

Part 3 provides details of titles, research organisation and partners.

Part 4 provides a fuller description of each of these projects.

3. List of funded projects

	Applicant/Grant Holder	Research Organisation	Title	Project partner(s) *(ERIIC members in bold)*
2014 Call (Pilot Call) – projects now complete				
1	Dr Dina D'Ayala	University College London	Groundwater and Flood Risk in the London Rail Infrastructure Network: Building Resilience into Existing Masonry Infrastructure Assets	**Arup (Ove Arup and Partners Ltd) (UK), London Underground**
2	Professor Andrew Plater	University of Liverpool	Sandscaping for Mitigating Coastal Flood and Erosion Risk to Energy Infrastructure on Gravel Shorelines: a case study approach	The Crown Estate, NOC, Royal HaskoningDHV, **National Grid, Environment Agency**, Natural England, BGS
3	Dr Taku Fujiyama	University College London	Examining Risks of Coastal Flooding to Port Systems	Department for Transport, Dover Harbour Board
4	Dr Ana Mijic	Imperial College London	Improved techno-economic evaluation of Blue Green Solutions for managing flood risk to infrastructure	UK AECOM, **Environment Agency**
5	Dr Nevil Quinn	University of the West of England	Co-creating railway flood resilience: applying the science of blue-green-grey infrastructure	South Gloucestershire Council, **Network Rail Ltd,** Somerset County Council
6	Dr Christopher Jackson	NERC British Geological Survey	Assessing the risk of groundwater-induced sewer flooding to inform water and sewerage company investment planning	Thames Water Utilities Limited
7	Dr Simon Jude	Cranfield University	Vulnerability of proximal infrastructure to sand washout from burst water pipes and leaking sewers	Anglian Water Services Limited, BT, Lincolnshire County Council
8	Dr Rachel Dearden	NERC British Geological Survey	Modelling the geological factors in pipe failure for better infrastructure management	Yorkshire Water Services Ltd
9	Dr Lee Chapman	University of Birmingham	Dynamic heat risk management to reduce the costs of propagating hot weather delays on the railway network.	**Network Rail Ltd**
10	Dr Christian Wagner	University of Nottingham	Towards managing risk from climate change through comprehensive, inclusive and resilient UK infrastructure planning	Thames Estuary Partnership, Government of Western Australia, Horizon Digital Economy Research
11	Professor Douglas Crawford-Brown	University of Cambridge	Climate science support for robust decision making in wind energy investments and policies	Cambridge CleanTech Ltd, EVANCE ltd
12	Dr David Gunn	NERC British Geological Survey	Wind Turbine Foundation Ultrasonic Spectral Characterisation (WINSPEC)	E.ON New Build and Technology Ltd
13	Dr Jonathan Chambers	NERC British Geological Survey	The Proactive Infrastructure Monitoring and Evaluation (PRIME) System: Technology Demonstrator for Remote Monitoring of Transportation Earthworks	Canal & River Trust, **Network Rail Ltd,** Scottish Canals
14	Dr Huapeng Chen	University of Greenwich	Risk Based Performance Forecast of Flood Defences Affected by Changing Environments	**HR Wallingford Ltd**

15	Mr Jason Sadler	University of Southampton	A tool to improve prediction of real time environmental risk to UK rail infrastructure	Rail Safety and Standards Board (RSSB)
16	Dr George Blackburn	Lancaster University	Quantifying the risks of tree failure to guide proactive management and increase the resilience of electricity distribution networks.	Scottish Power Energy Networks
17	Professor John Wainwright	Durham University	Communicating And Visualizing Erosion-associated Risks To Infrastructure (CAVERTI)	Wear Rivers Trust
18	Professor Thorsten Wagener	University of Bristol	Quantification of risks to bridges from erosion and blockage: An elicitation of expert views	JBA Trust
19	Dr Dapeng Yu	Loughborough University	Evaluating the resilience of critical infrastructure for emergency response to extreme flood events in Leicester City	**Environment Agency,** Leicester Resilience Forum, Leicester City Council
20	Professor Jim Hall	University of Oxford	FoRUM - Flood risk: Building Infrastructure Resilience through better Understanding and Management choices	**Environment Agency**, AIR Worldwide, CH2M HILL UNITED KINGDOM, **HR Wallingford Ltd**, **Network Rail Ltd**, Thames Water Utilities Limited, JBA Trust
21	Dr Iain Jonathan Rae	University College London	Understanding the effects of space weather on water sector infrastructure	**Atkins Global**
22	Dr Jeremy Phillips	University of Bristol	Volcanic Ash Hazard to UK Nuclear Generating Facilities	**EDF Energy Nuclear Generation Ltd**
2015 Call – projects underway				
23	Dr Peter Talling	National Oceanography Centre	What threat do turbidity currents and submarine landslides pose to strategic submarine telecommunications cable infrastructure?	**Atkins Global**, Chevron Energy Technology Company, Flintshire Geoscience Limited, Global Marine Systems Limited, **HR Wallingford Ltd**, Long Haul and Submarine Systems, Ocean University of China, **Scottish Water**, Shell International Exploration & Produce, Victoria University of Wellington
24	Professor Richard Dawson	Newcastle University	Storm Risk Assessment of Interdependent Infrastructure Networks	**Arup (Ove Arup and Partners Ltd) (UK), Atkins UK**, Northern Powergrid**, Scottish Water**
25	Professor Robert Nicholls	University of Southampton	Coastal landfill and shoreline management: implications for coastal adaptation infrastructure	East Solent Coastal Partnership, **Environment Agency**, New Forest District Council, Southern Coastal Group
26	Professor Jim Hall	University of Oxford	Multi-Hazard Resilience Estimation and Planning for Interdependent National Infrastructure Networks	**Arup (Ove Arup and Partners Ltd) (UK)**, Department for Transport, **HR Wallingford Ltd**, **High Speed Two HS2 Ltd,** JBA Trust, **Scottish Water**
27	Dr Jonathan Chambers	NERC British Geological Survey	The Proactive Infrastructure Monitoring and Evaluation (PRIME) System: Automating Decision-Support and Enabling Intelligent Earthworks Management	**Arup (Ove Arup and Partners Ltd) (UK), Atkins Global**, Canal and River Trust, Geosense Ltd, **High Speed Two HS2 Ltd, ITM, National Grid Plc, Network Rail Ltd,** Rail Safety and Standards Board (RSSB), Scottish Canals, **Transport Scotland**

28	Dr David Jaroszweski	University of Birmingham	Weather-induced single point of failure assessment methodology for railways	**Network Rail Ltd**
29	Dr Taku Fujiyama	University College London	Toolkit to improve resilience of critical ports and dependent national supply chain systems against extreme sea level rise (storm surge) events	**Network Rail Ltd**, Department for Transport, **Atkins Global, Arup (Ove Arup and Partners Ltd) (UK),** ABP (Associated British Ports)
30	Dr George Blackburn	Lancaster University	Delivering resilient power, road and rail networks by translating a tree failure risk model for multi-sector applications.	**Atkins Global**, BlueSky International Limited, Scottish Power, Energy Networks, **Scottish Water, Transport Scotland**, UK Power Networks
31	Dr Sean Wilkinson	Newcastle University	Real-time assessments of wind related damage to electricity infrastructure Societal Theme Sustainability	Energy Networks Association, Western Power Distribution**, National Grid Plc**
32	Dr Simon Mudd	University of Edinburgh	Software for quantifying shallow landslide hazards to transportation infrastructure under changing climate and forest management	Coffey Geotechnics, Forest Research, Forestry Commission Scotland, **Network Rail Ltd, Transport Scotland**
33	Dr David Hughes	Queen's University of Belfast	InSAR for geotechnical infrastructure: enabling stakeholders to remotely assess environmental risk and resilience. (joint with NE/N012852/1, Dr Francesca Cigna, BGS)	Department of Enterprise, Trade, Investment NI, **Translink**, Transport NI
34	Dr Francesca Cigna	NERC British Geological Survey	InSAR for geotechnical infrastructure: enabling stakeholders to remotely assess environmental risk and resilience. (joint with NE/N013018/1, Dr David Hughes, Queen's University of Belfast)	Department of Enterprise, Trade, Investment NI, **Translink**, Transport NI
35	Dr Andrew Tye	NERC British Geological Survey	Environmental influences in pipe corrosion (EPiC)	**Scottish Water**, Welsh Water (Dwr Cymru), Yorkshire Water
36	Dr Sue Dawson	University of Dundee	Assessing the risk to the coastal and rural road network in Scotland due to the effects of storms and extreme rainfall events	**Transport Scotland**
37	Dr Dapeng Yu	Loughborough University	Piloting a real-time surface water flood risk mapping service within ResilienceDirect to support local emergency decision-making	**Atkins Global**, Cabinet Office, Department for Communities and Local Gov, **Environment Agency**, Leicester City Council, Leicester Resilience Forum, Met Office, **Transport Scotland**
2016 Call - projects underway				
38	Jonathan Chambers	NERC British Geological Survey	The Proactive Infrastructure Monitoring and Evaluation System (PRIME): Enabling Intelligent Earthworks Management	**Arup (Ove Arup and Partners Ltd) (UK),** Canal and Rivers Trust, **Environment Agency**, Geosense Ltd, Highways England, **High Speed Two HS2 Ltd**, ITM, Kier Construction Ltd, **Atkins Ltd, National Grid Plc, Network Rail Ltd**, Rail Safety and Standards Board (RSSB), Scottish Canals, **Transport Scotland**
39	Erica Hendy	University of Bristol	Predictive jellyfish bloom dispersal maps for UK coastal electricity generating facilities	**EDF Energy Plc**, Scottish Salmon Producers Organisation, **Scottish and Southern Energy SSE plc**

40	Ivan Haigh	University of Southampton	E-Rise: Earliest detection of sea-level rise accelerations to inform lead time to upgrade/replace coastal flood defense infrastructure.	**Environmental Agency, EDF Energy Plc, HR Wallingford Ltd**
41	Mike Clare	National Oceanography Centre	New field-scale calibration for turbidity current impact modelling	Shell International, **HR Wallingford Ltd**, Cheveron Energy Technology Company, Victoria University of Wellington, Imperial College London
42	Richard David Williams	University of Glasgow	Decision support framework to incorporate river bank stability in pipeline crossing risk assessment	**Scottish Water**
43	Lee Chapman	University of Birmingham	Reducing the ice hazard on smart motorways	Highways England, Exactrak, **Transport Scotland**
44	Helen Dacre	University of Reading	Protecting airspace infrastructure: A tool for calculating along-flight volcanic ash dosage	Civil Aviation Authority, British Airways Plc
45	Kevin Horsburgh	National Oceanography Centre	Synthesising Unprecedented Coastal Conditions: Extreme Storm Surges (SUCCESS)	**Environment Agency, EDF Energy Plc**
2017 Call - projects underway				
46	Daniele Zonta	University of Strathclyde	Early warning decision support system for the management of underwater scour risk for road and railway bridges	**Transport Scotland, Network Rail Ltd,** SEPA, **Arup (Ove Arup and Partners Ltd) (UK)**
47	Keith Andrew Ryden	University of Surrey	Single Event Effects in Ground Level Infrastructure	**EDF Energy Plc, Atkins**
48	Donald Telfer Monteith	NERC Centre for Ecology and Hydrology	FREEDOM: Forecasting Risk to upland water treatment assets from the Environmental Exacerbation of Dissolved Organic Matter levels.	**Scottish Water**
49	Shane Donohue	Queen's University of Belfast	Seismic imaging for improving flood defence management	**Environment Agency,** Canal & River Trust, Northern Ireland Water/Aecom, RSK Challenge
50	Gustavo Adolfo de Almeida	University of Southampton	Debris Effects on Bridge resilience and Flooding	**Network Rail Ltd**, **Environment Agency**
51	Thomas James Coulthard	University of Hull	Combination Hazard of Extreme rainfall, storm Surge & high Tide on estuarine infrastructure (CHEST)	**Environment Agency, Network Rail Ltd,** Welsh Water, **EDF Energy Plc**
52	Biagio Forte	University of Bath	Space weather disruptions to satellite navigation and telecommunications: ionospheric scintillation	**EDF Energy Plc, Atkins**
53	Pablo Ballesteros Perez	University of Reading	Weather-wise: working with the weather to improve construction productivity	Costain
54	Jian Guo Zhou	Manchester Metropolitan University	Quantitative Assessment Tool for Wind Effect on Wave Overtopping Seawalls	Royal HaskoningDHV, **HR Wallingford, Environment Agency, EDF Energy Plc**, Torbay Council

55	Simon Frederick Tett	University of Edinburgh	Playing Games to Understand Multiple Hazards and Risk from Climate Change on Interdependent Infrastructure.	**Transport Scotland, Scottish Water,** SGN, SEPA, Inverclyde Council, National Centre for Resilience, Climate Ready Clyde, Adaptation Scotland/SNIFFER
56	Donya Hajializadeh	Anglia Ruskin University	RV-DSS: An industry-friendly resilience-based interdependency assessment tool - case study North Argyll	**Transport Scotland, Scottish Water**, **Scottish and Southern Energy SSE Plc**, **Atkins**, **Arup (Ove Arup and Partners Ltd) (UK)**
2017 – Innovative monitoring call				
57	Haida Liang	Nottingham Trent University	Innovative condition monitoring of electricity transmission assets	**National Grid,** Opus International Consultants (UK) **,** Mosdorfer CCL Systems
58	Jennifer Brown	National Oceanography Centre	Wire-Wall: a new approach to coastal wave hazard monitoring	Sefton Council, Balfour Beatty Plc, **Environment Agency**, Channel Coastal Observatory, Marlan Maritime Technologies
59	Sevrine Sailley	Plymouth Marine Laboratory	Monitoring jellyfish and seaweed ingress into nuclear plants	**EDF Energy**
60	Stephen Krause	University of Birmingham	Innovative monitoring for contamination of water supply systems	Affinity Water, **UK Water Industry Research (UKWIR)**, Thames Water, Portsmouth Water, **Environment Agency**

4. Details of funded projects

Where projects have been completed, a case study has been published and is available on the CIRIA website.

	Title	Description
2014 Call (Pilot Call) – projects now complete		
1	Groundwater and Flood Risk in the London Rail Infrastructure Network: Building Resilience into Existing Masonry Infrastructure Assets	The aim of this project was to generate an assessment procedure that helped rail infrastructure asset owners and consultants ascertain the vulnerabilities of their assets and understand their behaviour, particularly in regards to groundwater levels. The network that was studied was the London Underground, and the case study was the Circle Line between Victoria and High Street Kensington stations. Increased precipitation poses a significant risk on rail transport infrastructure as it increases the extent and likelihood of disruption associated with ground conditions and groundwater levels. Understanding these hazards and determining the response of the asset is fundamental to build resilience into infrastructure networks. The assessment utilised a finite element model built specifically for the project that assessed the response (stress and deformation fields) of the tunnel lining and track bed under varying groundwater levels and reduced condition of the drainage system in the tunnel. The response of the system was presented in 2D images that helped TfL understand the scale of the

		vulnerability of the asset, informed their decision making process and improved their management strategies, thus minimising disruption to service. The model can be readily transferred and used to assess heritage assets, the whole London Underground network or other assets where groundwater hazard is a major concern.
2	Sandscaping for Mitigating Coastal Flood and Erosion Risk to Energy Infrastructure on Gravel Shorelines: a case study approach	This project aimed to assess the viability of 'sandscaping' as a means of coastal defence and resilience in the UK by using new modelling tools and producing evidence to assess its potential in the Dungeness/Romney Marsh region. The occurrence of severe coastal storms, coupled with sea-level rise, is leading to the increased likelihood of coastal flooding events and coastal erosion with consequent impact on vital coastal infrastructure. This project explored an innovative approach to coastal defence. Landscaping involves the use of sand and gravel in large-scale coastal schemes. However, unlike traditional beach recharge, the large volumes of material added to the coast can be distributed over time through the action of tides and waves without detriment to the scheme in the short term. Sandscaping is proving to be successful in creating new environments that add to the natural protective function of the beach to reduce coastal erosion and providing important habitats. Flood risk, particle tracking and coastal evolution models were used to enable a range of potential solutions to be modelled and explored for different climate conditions.
3	Examining Risks of Coastal Flooding to Port Systems	The aim of this project was to identify the cascading effects on other parts of the transport and distribution infrastructure resulting from the inability to operate a port as a result of tidal surges. Ports are vital elements of the UK's infrastructure both commercially and in maintaining vital supplies where there are limited stockpiles or which have limited storage lives, for example fuel and food. This project has helped raise awareness and quantify the risks associated with tidal surges by achieving the following: • A new model to predict the height and duration of tidal surges (in a specific ports estuary); • An assessment of the consequent impact on port activity and inland distribution logistics for a range of scenarios; • Understanding of the current risk communication mechanism between stakeholders including the port, rail and energy sectors; • Consulting key stakeholders (Immingham Port and Department for Transport) on how the developed model could be applied by stakeholders to inform decisions. The stakeholders have been equipped with a new tool to predict potential tidal surge, which would contribute to improved resilience of their operations.
4	Improved techno-economic evaluation of Blue Green Solutions for managing flood risk to infrastructure	This project considered the strategic role that Blue-Green Solutions that is integrated Sustainable Urban Drainage Systems (SuDs) play in management of environmental risk, with a particular focus on flood risk to infrastructure. This was done via a cost-benefit analysis of SuDS retrofit schemes at a strategic (macro) level. The SuDS mapping 'Adaptation Support Tool' (AST), developed by Deltares as part of the Climate KIC, Blue Green Dream project, was used to engage stakeholders in co-creating a set of intervention options. The wider SuDS co-benefits were assessed using the value transfer approach provided by CIRIA's 'Benefits of SuDS Tool' (BeST), which encompasses the standard approach to flood risk appraisal by Multi-Coloured Manual (MCM) Handbook. The approach was applied to a test case study area: Decoy Brook, in Barnet, North London. The project showed that as part of planned strategic infrastructure provision, spend on mitigating environmental impacts on infrastructure via SuDS interventions can support multiple benefits. The work defined a replicable approach that can be transferred to generic guidelines for doing wider cost-benefit analysis of SuDS at a strategic level. The case study indicates that the pathway towards wider scale SuDS retrofit is to split the investment among multiple stakeholders (including critical infrastructure owners) by highlighting the additional services provided for the same amount of investment.

5	Co-creating railway flood resilience: applying the science of blue-green-grey infrastructure	This project focuses on identifying opportunities to increase transport network resilience through natural flood management. The project had two main objectives: (1) to explore the potential for blue-green-grey infrastructure in improving railway network resilience; and (2) to support significantly closer partnership working, involving knowledge exchange and collaboration between different stakeholders. The term 'grey infrastructure' refers to traditional drainage methods, whereas 'blue and green infrastructure' refers to making better use of vegetation, wetlands, floodplains and landscape to attenuate water, infiltrate and manage flooding (also known as natural flood management). Two case studies explored the challenges of understanding flood risks, determining impacts and their costs as well as looking at innovative, local and natural approaches to improve flood resilience and deliver other ecosystem services that could ultimately be valued. This was achieved within the context of partnership working, cooperation and co-creation of possible solutions.
6	Assessing the risk of groundwater-induced sewer flooding to inform water and sewerage company investment planning	The project investigated the risk of groundwater-induced sewer flooding within the Chalk catchment of the River Lambourn, Berkshire. Infiltration from extreme high groundwater levels experienced during recent winters resulted in the Thames Water Utilities Ltd's (TWUL) sewerage network being overloaded in this catchment. Similar issues occurred elsewhere. The output was an integrated groundwater-sewer network model that was used to identify relationships between infiltration into sewers and groundwater levels at specific points on TWUL's sewer network, and to estimate historic and future groundwater flood risk and how this varies across the catchment. This will help inform TWUL's response to groundwater flood risk, their decision-making process and their asset management planning.
7	Vulnerability of proximal infrastructure to sand washout from burst water pipes and leaking sewers	This aim of this project was to establish the impact on adjacent infrastructure from burst water mains in sandy soils. Resulting pressurised water can create abrasive slurries and cavities, which can contribute to further infrastructure failures. Some 35 case studies were identified where this had occurred, in particular in soils with very high sand contents. Due to the co-located and interdependent nature of modern infrastructure systems (as illustrated by Figure 1), failures can cascade from one infrastructure to others both spatially and temporally. This project identified and examined the cross-infrastructure and societal impacts from burst water mains and sewers. A series of new maps of soil–sand content for England and Wales were produced enabling the identification of areas potentially vulnerable to sand washout from leaking water mains and sewers. The maps indicated that large areas of East Anglia, the North West and London had high levels of vulnerability.
8	Modelling the geological factors in pipe failure for better infrastructure management	The aim of this project was to develop a spatial model that would provide information on the environmental, topographical and geo-hazard factors contributing to pipe failures within the Yorkshire Water region. Previous methods of assessing how soil conditions contribute to pipe failure have generally not considered additional interacting factors, particularly how surrounding parent material and landscape influence the flow of water through the soil. Initially, models were developed to predict the expected number of bursts per unit area in the clean water pipe network. Cast iron still accounts for 80 per cent of the clean water network, while plastic pipes are now the most commonly used. Further environmental (e.g. road type (A, B or C)), topographical (e.g. elevation, slope) and geo-hazard (e.g. soil corrosivity, ground movements) information were added to this null model. Outputs from the model included significant factors causing pipe failure in the Yorkshire Water region, and maps of model residuals highlighting under or over-predictions of the density of pipe failures. Both of these outputs can be used to inform the development of resilience in the pipe network (i.e. reducing leakages). Information regarding the significant model covariates can be examined in conjunction with maps of environmental or geo-hazard properties (e.g. shrink swell) so that improved engineering solutions may be adopted. Maps of model residuals can be used to identify

		other factors (not included within the model), which may contribute towards higher than expected pipe failures (e.g. water source).
9	Dynamic heat risk management to reduce the costs of propagating hot weather delays on the railway network.	This project had two aims – firstly to identify the impact of heat on the railway infrastructure and directly address an evidence gap identified by Network Rail (NR), and secondly to investigate the potential of an alternative method for heat-risk management that would improve the efficiency of the railway network on hot days. High temperatures can cause many problems for the railway infrastructure such as line-sag, rail buckles, equipment overheating, a reduced opportunity for maintenance and heat stress for customers and staff. Without adaption, these problems are set to increase in a future warmer climate. The project developed an innovative method to analyse proprietary NR datasets, and produced a database of heat-related incidents in south-east England from 2006 to 2013. The analysis showed the temporal and spatial distribution of heat-related failures for specific asset types, including the financial costs and number of delay minutes for each incident. The project also produced a case study that showed the effect that the hottest July day on record (1 July 2015) had on the railway network.
10	Towards managing risk from climate change through comprehensive, inclusive and resilient UK infrastructure planning	This project looked at how large scale and major infrastructural developments can be managed through partnership-led governance ensuring better informed and more viable, long-term decision making. It considered the need to find new methodologies to inform and reconcile planning approaches and effectively manage and balance multiple stakeholder interests. To address this need, the application of a novel, values-based and data-driven decision framework for infrastructure planning and stakeholder engagement (the 'values-based decision framework'), originally developed for environmental planning in Western Australia, has been explored in the context of infrastructural development in the Thames Estuary. Four stakeholder engagement workshops were held in London to define a complete set of values relevant to the Thames Estuary infrastructure and to provide organisations with instructions on how to adapt their processes. The findings of the workshops also informed the development of a software prototype supporting comprehensive, secure and sustainable infrastructure development planning through the integration of stakeholder and citizen opinions and insight with (frequently uncertain) quantitative data (e.g. on water levels). Given the short duration of the project (six months), it was not designed to deliver a real-world system, but an exploratory proof-of-concept. Nevertheless, the work demonstrated that, if further refined, the methodology could make a useful and unique contribution to infrastructure and environmental planning in the Thames Estuary.
11	Climate science support for robust decision making in wind energy investments and policies	The objective of this research was to improve the ability of wind energy organisations to use advanced climate science information for decision-making. These would identify, assess and select locations of wind turbine deployment where investments are robust under a range of uncertain climate scenarios. Renewable energy, including wind power is a key element in climate change mitigation. Investments in wind turbine arrays are driven by many factors including the wind speed and variability of a location, and the environmental and social acceptability of the proposed installation. Public and private sector investment in wind power is a collective action issue involving a range of stakeholders, including wind turbine companies, the National Grid, the Department of Energy and Climate Change, energy infrastructure engineers, local communities and energy investors. The project looked at the needs of the different decision makers and considered how the outputs of climate models needed to be interpreted by investors and developers, and any associated uncertainties. It then provided outputs that could be readily understood by non-specialists.
12	Wind Turbine Foundation Ultrasonic Spectral Characterisation (WINSPEC)	The WINSPEC project aimed to demonstrate the feasibility of the ultrasound method on engineered structures in a marine environment. Developed in partnership with E.ON Technologies (Ratcliffe) Ltd (now Uniper Technology Ltd), it addressed E.ON's need of assessing the structure and conditions of wind farm foundations safely and from within the wind turbine. The project evaluated the characteristics of ultrasonic echoes for assessing the condition of wind turbine foundation structure. It involved numerical modelling of the ultrasonic reflectivity of a foundation in good condition, laboratory tests and experimentation on layered concrete – steel

		samples similar to materials used offshore. WINSPEC provided the catalyst for the development of a potential routine commercial inspection service for monopile wind turbine foundation condition for which E.ON have filed a patent to protect foreground IP arising from related trials commission by E.ON. Foundation condition information will have a major impact on offshore wind farm management because it will enable improved estimates of wind turbine life cycle and better prioritisation of retrofitted repairs.
13	The Proactive Infrastructure Monitoring and Evaluation (PRIME) System: Technology Demonstrator for Remote Monitoring of Transportation Earthworks	The principal objective of this project was to demonstrate the newly-developed Proactive Infrastructure Monitoring and Evaluation (PRIME) remote condition monitoring technology on existing rail and canal pilot study sites. The PRIME system has been developed in response to the increasing rate and severity of failures in flood defence, transport, and utilities earthworks. This is due to aging assets (many canal and rail earthworks are over 100 years old) combined with more extreme weather events. Asset failures are expensive, costing hundreds of millions of pounds a year in the UK alone, not to mention risks to human health and disruption of transport systems, utilities and the wider economy. Current monitoring technologies are generally inadequate for monitoring the internal condition of these infrastructure earthworks. The project demonstrated the reliability of the PRIME hardware platform for remote condition monitoring. Also, cost-effective information with real operational value has been provided to asset owners. Crucially, this project has produced an excellent basis for the final development of the software components of PRIME, comprising a fully automated workflow and web-based dashboard, which is the focus of the new PRIME project that began in January 2017.
14	Risk Based Performance Forecast of Flood Defences Affected by Changing Environments	The aim of this project was to explore a new approach to forecasting the performance of flood and coastal defence embankments. The project applied recent work at the University of Greenwich to develop a novel method of modelling asset deterioration with time. Earth embankments form a significant element of the UK's flood defences. At present, annual damage to UK properties due to flooding totals around £1.3bn and this is projected to rise significantly (Defra, 2012). An understanding of the predicted performance of such structures is crucial, particularly in light of climate change and extreme events. Condition grading currently relies on expert judgement and the use deterministic deterioration curves, which has acknowledged limitations in terms of assessing deterioration and reliability over time. Combining these approaches provided reliable evaluations of the probability of flood defence assets suffering from deterioration, which can be used to support decision making in relation to maintenance, planning and investment decisions. The technique provides decision support for the Environment Agency's teams responsible for earth flood embankment assets.
15	A tool to improve prediction of real time environmental risk to UK rail infrastructure	This project aimed to illustrate how the combination of precipitation, climatic and soil data can be used to assess asset risk failure. Soil type, soil moisture deficit and rainfall intensity are three environmental variables that can combine over time and space to represent risks to the rain infrastructure, particularly in relation to derailment. . Data on these parameters is available to researchers at sufficiently high spatial and temporal resolution for the UK, providing the potential to test this research. This project set out to integrate high resolution precipitation data, long-term climatic averages and soil clay content data, with location data for tracks, assets (hard and soft structures including embankments, cuttings, retaining walls, culverts, bridges, crossings, viaducts and tunnels) and incidents. The prototype has been presented to a number of industry and academic stakeholders, identifying areas for potential development, possibly in partnership with industry. Research outputs included a presentation at RSSB collaboration ingenuity events, UK rail research conferences and paper submissions to the Institution of Engineering and Technology (IET).

16	Quantifying the risks of tree failure to guide proactive management and increase the resilience of electricity distribution networks.	The aim of the project was to develop scientifically based, robust and objective method to predict tree failure in severe weather conditions. The initial objectives were to: • Develop a model (TREFALL) that permits a wide area assessment of trees susceptible to uprooting or stem breakage in severe weather; • Undertake detailed data collection to those trees outlined in the first phase, and use this to provide more realistic estimates of the loading and resistance components of the wind throw model; • Prepare a case study with Scottish Power energy networks ('Scottish Power') that demonstrates the research outputs. Tree failure can cause significant damage to electricity supply networks. It is possible to reduce the impacts on electricity networks by felling trees that are close to power lines and at more risk of failure in severe weather conditions. This project allows a replicable and objective risk assessment of trees that are close to a power supply network, resulting in a risk value assigned to each individual tree. This model has been applied to the Scottish Power network across north Wales and north-west England. The outputs of this model are being incorporated into the Scottish Power workflow via the advice of project subcontractor ADAS.
17	Communicating And Visualizing Erosion-associated Risks To Infrastructure (CAVERTI)	The aim of the CAVERTI project was to develop decision-support tools for visualising and communicating risks of soil erosion due to a range of farming practices and conditions and associated risks to infrastructure. Soil erosion is a major environmental problem, affecting agriculture, the natural environment and urban areas through sediment-related damage to roads, buildings and infrastructure. Negative impacts include lower water quality, loss of the nutrient-rich upper soil layers, sedimentation of waterways and eutrophication of water bodies (excessive richness of nutrients causing a dense growth of aquatic plants). This is a major issue for the Wear Rivers Trust (WRT), the project partner, as well as for farmers, landowners, land agents and policy makers. The team engaged a variety of key stakeholders in a series of workshops in order to gather relevant data and be able to draw on land end users' experience. The team built on: • The outcomes of the workshops; • Experience from previous projects; • Field measurements of key sites to develop an online tool that can be used to minimise risk of soil erosion and address sediment transportation.
18	Quantification of risks to bridges from erosion and blockage: An elicitation of expert views	This project used the knowledge of a group of experts to derive information on the vulnerability of structures to scour. The aim was to develop fragility functions for application within a risk modelling framework and used to inform and support decision making. The group of experts provided advice on scour vulnerability factors, expressed in terms of the estimated probability of bridge failure associated with flood events of varying severity (also expressed in probabilistic terms), and quantitative assessments of uncertainty about those failures. The findings confirm that assessment and inspection protocols are vital for risk mitigation, while identifying that there are critical knowledge gaps in the understanding of scour processes. Importantly, the views given suggest there is wider uncertainty in relation to the problem of scour in the future than might be inferred from statistical analyses of past failure events. The information also identified where further work would benefit towards incorporating fragility functions into risk/reliability models. The ultimate aim would be to give more focus to possible improvements in industry protocols that help to reduce the risk of failure or collapse.
19	Evaluating the resilience of	The aim of this project was to evaluate the robustness of flood emergency planning and response in terms of its dependency on critical infrastructure nodes and networks in Leicester City. The city is

	critical infrastructure for emergency response to extreme flood events in Leicester City	ranked 16 out of the 4215 in terms of surface water flooding risks of the settlements assessed across England as part of the National Priority Ranking (Defra, 2009). To achieve this aim three objectives were set: • Identify the potential 'pinch points' within infrastructure networks and critical nodes in Leicester City during an extreme flood event; • Evaluate the impacts of infrastructure failure on emergency response; • By taking account of interdependencies, propose how the whole emergency planning and response systems could be made more resilient and robust. This project demonstrated a simple yet novel approach to evaluating the resilience of emergency response during extreme flood events using existing datasets and tools. The project has gone beyond what emergency response stakeholders are already aware of, i.e. flood hotspots, and highlighted the indirect, cascading impacts of flood events on emergency services' response time at the city-scale. The project combined existing flood modelling data from the Environment Agency and Leicester City with other sources of data to assess the City's accessibility during pluvial and fluvial flood scenarios of various magnitudes, used in a geographical information system (GIS) to generate user-friendly information and mapping. The project provides evidence to guide strategic planning for decision makers before and during emergency response to extreme flood events.
20	FoRUM - Flood risk: Building Infrastructure Resilience through better Understanding and Management choices	The objective of the FoRUM project has been to promote a shared understanding of the methods used for assessing flood risk and determining future infrastructure investment need between public, private and academic sectors. By providing a platform for developing a common understanding of alternatives approaches and the uncertainties associated with each, FoRUM has laid the foundation for the coevolution of future advances that respond to the increasingly nuanced and complex stakeholder questions concerning how to invest limited resources to maximise flood resilience. In particular, the FoRUM project has contributed to: • Strengthening industry and academic partnerships: providing timely input to scoping future developments of the Long Term Investment Scenarios (LTIS) and laying the foundation for a greater contribution of the academic community to these developments; • Influencing policy and practice: assisting policy makers (national and local) in developing a better understanding of the credibility of flood risk analysis, including articles and the first event based validation of the national risk assessment; • International outreach and impact: continuing to raise awareness of the leading nature of UK approaches, including a presentation on the credibility of national scale risk models to highly influential EU Working Group F; • Legacy: initiating the collation of dissipate information on the development National Flood Risk Assessment (NaFRA), including both development reports and past attempts at validation.
21	Understanding the effects of space weather on water sector infrastructure	The potential impact of space weather on critical national networks is of paramount importance and, therefore, currently under investigation; more specifically, the University College London and their industry partner Atkins Global are developing an industry standard screening framework to assess potential vulnerabilities to the water sector. Through the analysis of existing datasets, the project team are developing initial probability distributions of relevant space weather drivers, necessary to determine the probability of satellites or ground systems encountering damaging radiations or adverse effects due to extreme space weather (with a particular focus on solar wind). The project outputs will help the project partner identify the space weather effects the water sector is most vulnerable to as well as relevant thresholds of hazard. Overall, the project will improve the industry's understanding of the intelligence needed to identify vulnerabilities to space weather, the variability and probability distribution of space weather and

		how water sector thresholds relate to space weather variability.
22	Volcanic Ash Hazard to UK Nuclear Generating Facilities	This project investigated the likelihood and potential impacts of volcanic ash on nuclear generating sites in the UK. Volcanic ash was transported to the UK from moderate-sized Icelandic volcanic eruptions in 2010 and 2011, resulting in deposits of trace amounts of ash and changes in air quality. It is now important to rigorously assess potential impacts on nuclear power facilities in the UK from volcanoes in neighbouring regions. This project has produced a comprehensive probabilistic assessment of volcanic ash hazard to UK nuclear generating facilities (as representative of critical infrastructure), and created a database of predicted volcanic ash airborne concentration and thickness for the UK under credible future eruption scenarios. The project conducted an expert elicitation exercise in collaboration with EDF Energy to identify potential ash impacts on nuclear generating power station.
2015 Call – projects underway		
23	What threat do turbidity currents and submarine landslides pose to strategic submarine telecommunications cable infrastructure?	The aim was to gain and disseminate knowledge on the industry challenge of why exactly, how often, and where are seafloor cables broken by natural causes, primarily subsea landslides and sediment flows (turbidity currents). The global economy relies on uninterrupted use of a seafloor network of telecommunication cables that carry ~99 per cent of all inter-continental digital data traffic. Submarine cables have considerable importance because this data traffic includes the internet, defence information, financial markets and other services that underpin daily lives. With trillions of pounds traded daily via subsea networks, multiple cable breaks in important regional hubs can have major implications. Repairs can cost up to £100m. Global Marine Systems Ltd provided access to an industry database, enabling the first global statistical analysis of the frequency and causes of cable breaks. Geographic 'pinch-points' at risk from specific hazards were identified, which helped the partners, including the global umbrella body for the subsea cable community, to design more effective routes. A briefing document was provided to the Cabinet Office setting out the basis for why submarine cable breaks should be included in the UK National Risk Register. The project has enabled offshore industries and government to perform more informed risk assessments globally.
24	Storm Risk Assessment of Interdependent Infrastructure Networks	Electricity infrastructure provides a vital service to consumers. In the UK, there are thousands of miles of overhead lines and other assets, which are vulnerable to environmental risks. Of these, wind has caused more disruptions in the UK, and the future risks associated with windstorm disruption are uncertain as climate models are unable to represent these processes. Storm Risk Assessment of Interdependent Infrastructure Networks (STRAIN) benefitted from new high resolution simulations of future wind climate using the UK Met Office's 1.5 km climate model that can represent convective storm processes that are the cause of many storms across the UK. Integration of this high resolution climate modelling data with information on the structural properties of electricity network assets, and an infrastructure network model, has enabled significant improvements in the analysis of current and future wind risks. A case study in Humberside has demonstrated that while the risk of wind-related failures is high, climate change will not have a statistically significant effect on the site (although other sites may vary). This information can be used to support more investment in measures that will improve the reliability of electricity supply to UK consumers.
25	Coastal landfill and shoreline management: implications for coastal adaptation infrastructure	Management and protection of coastal landfills represent extremely timely issues as approximately two thousands landfills in England and Wales are located in coastal flood plains and/or erosion zones. Rising sea levels may lead to flooding of landfills and flushing of contaminants from the waste; this, in combination with coastal erosion, can potentially cause contaminant release into the marine environment. The University of Southampton and their industry partners Environment Agency, Standing Conference on Problems Associated with the Coastline, Eastern Solent Coastal Partnership and New

		Forest District Council are estimating the long-term impact of coastal processes affected by sea level rise on three selected landfills, investigating different management options to prevent pollution (e.g. waste material removal, site protection, etc.). The project partners will be provided with three case studies which will improve their understanding of the impact of these landfills on shoreline management plan strategic alternatives (i.e. hold the line, managed realignment, and no active intervention) under different climate change scenarios.
26	Multi-Hazard Resilience Estimation and Planning for Interdependent National Infrastructure Networks	The aim of this programme of innovation was to develop prototype tools for application by infrastructure system designers, owners and operators. The aim is to help identify system vulnerabilities to weather extremes and multi-hazard events, which have caused many infrastructure system failures in recent years. The tools would also identify interdependencies between different infrastructure networks (such as power or transport) and help develop cross-sector infrastructure thinking and improve understanding of multi-hazard events. The outputs from the project included: • A report that partners can use as a go-to set of instructions and guidance for assessing natural hazard risks for infrastructure resilience; • Initial mock-up versions of a web-based infrastructure networks spatial risk analysis to satisfy specific requirements of the partners as a basis of exploring further development and application.
27	The Proactive Infrastructure Monitoring and Evaluation (PRIME) System: Automating Decision-Support and Enabling Intelligent Earthworks Management	Nowadays, a significant number of earth structures (e.g. cutting, embankments and dams) within the transportation and utilities sectors are old and poorly engineered compared to modern standards. To tackle increasingly high levels of failure and maintenance costs, exacerbated by increased rainfall events, the British Geological Survey and their industry partners Arup, Atkins Global, Canal and River Trust, Geosense, HS2, ITM, National Grid, Network Rail, Rail Safety and Standards Board, Scottish Canals and Transport Scotland are developing a low-cost early warning system for remote monitoring of vulnerable earthwork structures. This tool will assist asset managers, consultants and monitoring service providers as a decision-support tool by assessing internal conditions of assets to guide remediation and maintenance strategies as well as providing early warning of potential failure events.
28	Weather-induced single point of failure assessment methodology for railways	Weather-related disruptions of rail services often result in severe delays and related financial losses. In this regard, it is extremely important to identify critical sections of the rail network given weather-related incidents at different locations can have vastly different impacts on overall network disruption (due to topology and timetable). Building on previous collaborative research projects and based on past recorded events, the University of Birmingham and their industry partner Network Rail are developing a transformative data-driven approach to map the network criticality to weather-induced natural hazards and to identify the “typical” disruption characteristics of such events. The main output of the project will be in the form of criticality maps indicating locations from which delays tend to propagate widely; this will help the project partner to improve extreme event management and inform climate change adaptation prioritisations.
29	Toolkit to improve resilience of critical ports and dependent national supply chain systems against extreme sea level rise (storm surge) events	Ports and their infrastructure located close to the sea are exposed to the risk of significant damage and disruption due to extreme weather events, most likely exacerbated in the future by sea-level rise and climate change impacts. In this context, the Port of Immingham, the largest importer of biomass and coal for electricity production, in December 2013 experienced a one-week operation disruption due to a storm surge. The storm-tide warning system the Port is currently reliant on is not always effective; additionally, barriers between port, rail and energy sectors make it difficult to foresee how the impact of flooding during extreme surge events would propagate through their own sectors. The University College London and their industry partners Department for Transport, ABP Humber, Network Rail, Arup and Atkins are developing a tool to predict surge water levels and inundation at Immingham along with a data system to measure its knock-off effects.

		The forecasted time series of water levels at the port entrance will be translated into detailed flood risk maps within the port. These tools will enable the port operators and stakeholders to simulate height and time of potential flooding across port infrastructure for 1) actual tidal surges forecast within a 24 hour window, and 2) hypothetical tidal surge events based on various long-term climate change and surge scenarios.
30	Delivering resilient power, road and rail networks by translating a tree failure risk model for multi-sector applications.	Tree failure can cause significant damage to electricity supply networks, potentially resulting in compensation claims and fines for the electricity operators. In order to reduce the impact of felling trees on electricity networks located close to power lines and at higher risk of failure in severe weather conditions, the Lancaster University with their industry partner Scottish Power are developing a model that will permit a wide area assessment of trees susceptible to uprooting or stem breakage in severe weather. Collection of data on trees identified in the first phase will be carried out, in order to provide more realistic estimates of the loading and resistance components of the wind throw model. The project outputs will help decision-making on vegetation management by reducing the likelihood of failed infrastructure, cutting costs for both customers and infrastructure providers.
31	Real-time assessments of wind related damage to electricity infrastructure Societal Theme Sustainability	Despite significant improvements in weather forecasts in recent years, the potential impact of weather events and, specifically, windstorms on the electricity infrastructure needs further investigation. The Newcastle University and their industry partners Energy Networks Association, Western Power Distribution and National Grid are developing and assessing a decision-support tool for producing real-time assessments of the consequences and significance of wind-related storm damage to electricity infrastructure. The tool will provide quantitative information for electricity infrastructure operators, emergency responders, government and the media on the extent of disruption resulting from windstorms. In addition to real-time predictions, it will also provide an accurate framework for developing more effective adaptation strategies for current and future climate scenarios. The tool will quantify the consequences of windstorms by linking electricity assets and fragility information to forecast intensities of wind and produce estimates of damage; these data will then feed into consequence models to determine potential effects on exposed populations.
32	Software for quantifying shallow landslide hazards to transportation infrastructure under changing climate and forest management	A significant challenge to infrastructure owners, governments and landowners is how to manage the risk of land-slides along long linear corridors requiring use of large topographic datasets. Hazards are not just derived from near the networks, but from upslope, and predicting the landslide runout risks from source areas onto road networks is beyond the capabilities of desktop geographic information systems (GIS) software. The project used existing runoff and slope stability models, including models that accounted for root cohesion of different trees species, to generate slope stability maps and link them to transport networks. In addition, an extension to the project that funded related work in Nepal, a developing country, was used to generate a new topographic map of high resolution and create inundation and stability maps, currently being used by both Nepalese government agencies and NGOs. A University of Edinburgh model ingests soil, vegetation and topographic data, to calculate slope stability. It also used a routing method to distribute the relative risks onto linear networks (examples used were A roads in England and Scotland). This resulted in maps of road segments that could be classified into low, medium or high hazard.
33	InSAR for geotechnical infrastructure: enabling stakeholders to remotely assess environmental risk and resilience. (joint	The aims of the project were to apply innovative satellite interferometric synthetic aperture radar (InSAR) techniques to monitor ground movement around critical infrastructure in Northern Ireland, to validate and ground truth InSAR techniques with unmanned aerial vehicle (UAV) data, embed this technology within the project partners, and generate a step-change in how the project partners gathered geotechnical data on ground deformation across their transport networks. None of the project partners were using remote sensed InSAR data to monitor their infrastructure, including transport networks and areas of mine subsidence, despite this technique being used in other industries such as mining and oil exploration. The challenge of the project was to find a practical and cost-effective methodology to enable stakeholders to engage with, and take

	with NE/N012852/1, Dr Francesca Cigna, BGS)	advantage of InSAR techniques and data. The project team successfully processed InSAR data and produced ground motion maps over the target areas. UAV data was also successfully gathered over stakeholder sites and integrated with InSAR data. The project showed that InSAR has immense potential to be used to improve geotechnical risk assessment procedures but there are still barriers to its use, in particular uncertainty over costs of the raw data and processing, and spatial control and resolution of the InSAR data point.
34	InSAR for geotechnical infrastructure: enabling stakeholders to remotely assess environmental risk and resilience. (joint with NE/N013018/1, Dr David Hughes, Queen's University of Belfast)	Joint with project above.
35	Environmental influences in pipe corrosion (EPiC)	Failures in the clean water supply network result in significant financial losses to the water industry, while at the same time causing inconvenience to the general public (e.g. road closures, water supply problems to domestic and business premises). The British Geological Survey and their industry partners Yorkshire Water, Scottish Water, Dŵr Cymru (Welsh Water) will address the extent to which a range of geo-hazards (e.g. shrink swell clay, collapsible deposits, soil corrosiveness) and environmental factors (e.g. terrain analysis, drainage, population density, roads) influence the spatial distribution of pipe failures across the Yorkshire Water region. Through the utilisation of spatial models, the aim will be to assess whether knowledge required could be used in (i) identifying areas where soil / geological / environmental factors are causing a greater than expected number of pipe failures, and (ii) whether improved spatial knowledge of problem areas based on model outputs could be used to develop improved engineering solutions. Project outputs will be in the form of (i) 'heat maps' for each significant co-variable that provide an indication of the intensity of effect and (ii) a combined 'heat map' generated by combining all the co-variables for each cell. This project will help partners to adopt more effective engineering solutions by identifying areas with higher than expected failure rates and by demonstrating where there are greatest potential pressures on the pipe network, based on existing knowledge of the effects of environmental and geo-hazard factors across YW.
36	Assessing the risk to the coastal and rural road network in Scotland due to the effects of storms and extreme rainfall events	Road networks in Scotland represent vital links to remote communities, often featuring a lower road density than other parts of the UK. Consequently, severance of the access of these communities to services and markets because of natural hazards (e.g. coastal flooding caused by sea level rise), can have significant economic and social consequences. The University of Dundee (UoD) and Transport Research Laboratory (TRL) along with their industry partner Transport Scotland have developed a methodology for assessing the risk to coastal and rural road infrastructure from coastal hazards. The methodology is based on an innovative, more robust calculation system, which includes flood risk factors in asset inspections and develops a national hazard coastal map incorporating coastal morphology. This methodology was applied to a case study site on Transport Scotland's network vulnerable to coastal flooding; an estimate of the increase in costs due to more frequent flooding was carried out. The methodology developed provided information on the magnitude of risk as well as how this may be affected by climate change and economic costs. Overall, the project provided the partner with an insight into the factors affecting the risk to their coastal infrastructure from storms and with a methodology for assessing such risk. In turn, this can provide the evidence required to prioritise resources, plan budgets and form a business case for action, reducing disruption for users of the network and maintenance costs for owners.
37	Piloting a real-time surface water flood risk mapping service	While nationwide flood risk maps are available, during a previous ERIIP pilot project (Yu *et al*, 2014), it became clear that emergency responders across the UK urgently require a real time, surface water flood risk mapping service to support decision making during emergencies. This pilot project aimed to:

	within ResilienceDirect to support local emergency decision-making	• Identify, understand and quantify surface water flood risks to the infrastructure system pertinent to emergency response in real time in Leicester City; • Establish real time forecasting of surface water flooding for selected surface flooding hotspots identified by the emergency responders within Leicester City; • Pilot test real time surface water flood risk mapping within ResilienceDirect. We have achieved the above aims and beyond. A live system has been developed that provides real time street-level forecast of surface water flood risks for Leicester City (calibrated) and 14 other cities (uncalibrated) in the UK, to street-level resolution. The system has been evaluated by various stakeholders. Commercialisation opportunities are being discussed with several parties. Links with the Cabinet Office ResilienceDirect platform are being tested. Further development of ResilienceDirect, agreed by the Cabinet Office will see the real time system provide live surface water flood forecast and accessibility mapping for major cities in the UK.
2016 Call - projects underway		
38	The Proactive Infrastructure Monitoring and Evaluation System (PRIME): Enabling Intelligent Earthworks Management	Flood defence, transportation and utilities earthworks are becoming increasingly vulnerable due to their age and more extreme weather conditions. Geotechnical asset failures can result in significant disruption and associated economic and social impacts. The conventional approaches to assessing geotechnical assets - mainly surface observations - have limitations. The NERC British Geological Survey with its industry partners (Arup, Canal and River Trust, Environment Agency, Geosense Ltd, Highways England, HS2, ITM, Kier Construction, Atkins, National Grid, Network Rail, Rail Safety and Standard Board, Scottish Canal and Transport Scotland) are developing the Proactive Infrastructure Monitoring and Evaluation System (PRIME). This will combine geophysical ground imaging technology and wireless telemetry to create decision-support tool for the early identification of deteriorating conditions, providing the user with a near-real-time remote condition monitoring system.
39	Predictive jellyfish bloom dispersal maps for UK coastal electricity generating facilities	The sudden 'en masse' appearance of jellyfish can negatively affect the performance of cooling water systems of coastal power stations, resulting in reduction of electricity production and consequent severe financial losses. The University of Bristol, in collaboration with its industry partners EDF Energy, Scottish Salmon Producers Organisations and Scottish and Southern Energy, is developing a tool that will predict the probabilities and scales of a bloom at EDF's Torness Nuclear using (a) a generic probability grid and (b) a prediction based on an observed bloom in the North Sea. Such tools will allow rapid risk evaluation and inform operational response by the industry partners.
40	E-Rise: Earliest detection of sea-level rise accelerations to inform lead time to upgrade/replace coastal flood defense infrastructure.	Detecting accelerations in the rate of sea-level rise is not straightforward, due to the considerable inter-annual variability evident in sea level at regional/local scales. However, these forecasts are important for long-term planning for coastal infrastructure. The University of Southampton and its industry partners Environment Agency, EDF Energy and HR Wallingford are exploring the feasibility of combining in situ and satellite-based data with statistical models to develop a toolbox which will help identify timings (with uncertainties) of sea-level rise rates and, accordingly, to estimate lead times. Such tool will help the industry partners to better plan for the future and implement more effective adaptive pathways.
41	New field-scale calibration for turbidity current impact modelling	Subsea infrastructure networks provide critical global communication links and energy supplies. However, they are vulnerable to fast-moving seafloor flows of sediment, known as "turbidity currents" which can lead to disruptions in supply. Damage to oil and gas pipelines can also result in severe environmental implications and economic losses. The National Oceanographic Centre, in collaboration with its industry partners - Shell International, HR Wallingford, Chevron Energy Technology Company, Victoria University of Wellington and Imperial College London - are investigating this topic. The project will consider emergent direct monitoring technologies and current modelling approaches. A summary report detailing the

		modelled impacts of real-world turbidity currents on a range of seafloor infrastructure, and providing guidance for design, mitigation measures and future data acquisition strategies is also planned.
42	Decision support framework to incorporate river bank stability in pipeline crossing risk assessment	Over the past 10-15 years, the risk of river erosion at drinking water and wastewater pipeline crossings has been evaluated through ad-hoc inspections. The University of Glasgow, along with its industry partner Scottish Water, is developing a decision-support framework to incorporate river bank stability in pipeline crossing risk assessment. The project will evaluate the uncertainty in the existing low-cost app-based inspection database by (a) re-surveying a sample of crossings using the existing app (b) augmenting this information with Google Earth imagery, high-res aerial images and legacy LIDAR records to assess the uncertainties in the existing database. The outputs from the project will inform future approaches to future risk assessments.
43	Reducing the ice hazard on smart motorways	As part of a nationwide trial of smart motorways, 'all lane' and 'hard shoulder running' are being used to increase network capacity on critical sections. However, this will increase the ice hazard during winter, due to significant surface temperature differences between inside lanes and outside lanes or previously un-trafficked hard shoulders. The University of Birmingham, in collaboration with its industry partners Highways England, Exactrak and Transport Scotland, is developing a decision-support system that will provide real-time temperature measurements via low-cost sensors. The project will provide tacit knowledge of temperature differences on multi-laned roads to inform the overall winter maintenance strategy. A prototype decision support system will also provide real-time measurements on the selected road section leading to efficiency savings for the project partner.
44	Protecting airspace infrastructure: A tool for calculating along-flight volcanic ash dosage	Aircraft engine manufacturers' susceptibility guidelines for volcanic ash describe engine tolerance limits in terms of a dosage (i.e accumulated concentration over time). Current Civil Aviation Authority (CAA) regulations refer to peak concentrations. New tools are required to support any decision to change volcanic ash regulations from current peak ash concentration limits to along-flight ash dosage limits. The University of Reading is working with its industry partners CAA and British Airways to develop a decision-support tool by combining volcanic ash data and optimal flight-routing software, both generated during past NERC funded projects. Such a tool will help decision-makers assess the sensitivity of along-flight ash dosage estimations to the spatial and temporal resolution of the volcanic ash information. This will in turn enable new regulations to be developed, based on the latest understanding of volcanic ash hazard to aircraft engines. These new regulations will ultimately result in a more resilient UK airspace infrastructure.
45	Synthesising Unprecedented Coastal Conditions: Extreme Storm Surges (SUCCESS)	The National Oceanography Centre is collaborating with its industry partners Environment Agency and EDF Energy to improve their understanding of the impacts of extreme coastal surge and wave events for key coastal locations determined with the partners. For these locations, a number of "black swan" storm surges events will be synthesised that have not been observed but that are physically plausible. This will involve data from major past North Sea surges and wider European storm systems to drive a Met Office model. The project partners will be provided with 2-D data fields for storm surges and waves along relevant affected regions as well as new calculations of extreme value statistics for those regions. Additionally, site-by-site analyses of tide/surge/wave combinations will be carried out, feeding into the downstream modelling of the two partners. # Overall, the project outputs will support project partners in planning and mitigation, the siting and protection of coastal infrastructure, and long-term investment decisions.
2017 Call - projects underway		
46	Early warning decision support system for the management of underwater scour	Flood induced scour is a major cause of bridge damage and failure in the UK. This can result in loss of lives, traffic disruption and economic losses. The University of Strathclyde and its industry partners Transport Scotland, Network Rail, SEPA and Arup are developing a probabilistic decision-support system based on past scour inspection data and rainfall forecast, together with sensor technology to monitor and predict possible failure risks. This will support the project partners in

	risk for road and railway bridges	planning future maintenance, repair and rehabilitation strategies.
47	Single Event Effects in Ground Level Infrastructure	The potentially negative effects on ground-level electronic systems produced by extreme space weather events are recognized, but not fully understood and difficult to quantify. The University of Surrey and its industry partners EDF Energy and Atkins are developing a system to evaluate the vulnerability and probability of failure of these electronic and micro-electronic systems. The project will exploit the latest research and models on solar events. This will help inform partners' procurement and retrofitting approaches to achieve resilience criteria and failure tolerance.
48	FREEDOM: Forecasting Risk to upland water treatment assets from Environmental Exacerbation of Dissolved Organic Matter levels.	The UK water industry is facing the problem of increasing Dissolved Organic Matter (DOM) levels in water supply catchments, which result in greater treatment costs and affect the performance of treatment infrastructure. The Centre for Ecology and Hydrology, in collaboration with Scottish Water, is developing an innovative tool which will help predict where and when excessive DOM levels are likely to occur, in relation to climate change effects. Accordingly, the user will be able to better predict DOM-related risks and prioritise investment in water treatment assets to treat these elevated levels, and/or to initiate sustainable catchment planning to reduce the rate of increase.
49	Seismic imaging for improving flood defence management	Water-retaining earthworks are vulnerable to increasing extreme weather events and climate change. Condition assessment usually relies on visual observations as opposed to invasive inspection. The Queen's University of Belfast and its industry partners Environment Agency, Canal and River Trust, Northern Ireland Water/Aecom and RSK are exploring the feasibility of using seismic surface waves (SW) as a non-invasive and relatively low-cost technique that can be used to assess internal condition as a means of providing early warning of the need to consider remedial measures.
50	Debris Effects on Bridge resilience and Flooding	It is estimated that 30% of bridge failures in the UK and US are as a consequence of the accumulation of debris at the bridge piers, which results in increased forces on bridge piers and affect flow patterns resulting in river bed scour. The University of Southampton and its industry partners Network Rail and Environment Agency will exploit recent laboratory research tests relating to debris accumulation patterns to develop a decision-tool based to help asset owners identify the risk of such phenomenon.
51	Combination Hazard of Extreme rainfall, storm Surge & high Tide on estuarine infrastructure (CHEST)	Sea-level rise and predicted changes to UK storm patterns affecting both coastal surge and river flows increase the threat to the UK estuarine infrastructure system caused by such events. The University of Hull and its industry partners Environment Agency, Network Rail, Welsh Water and EDF Energy will be using recently developed fast numerical models to stimulate combinations of these hazards in two estuaries – the Humber and Dyfi. The model results will produce worst-case and other scenarios, identifying particular reaches in the form of digital maps. This will help infrastructure owners assess risks.
52	Space weather disruptions to satellite navigation and telecommunications: ionospheric scintillation	The modern world is increasingly reliant on systems that make use of Global Navigation Satellite Systems (GNSS), e.g. transport, surveying, emergency services, etc. Space-weather phenomena affecting the ionosphere can dramatically impact GNSS, causing extremely costly disruptions of navigation and telecommunication systems. The University of Bath and its industry partners EDF Energy and Atkins are developing global maps of risk in order to help forecast the occurrence of such phenomena in terms of the combination between likelihood and severity for specific systems and their interdependencies.
53	Weather-wise: working with the weather to improve construction productivity	At a macro level, the UK is committed to tens of billions of pounds of investment in civil infrastructure over the next five years. At a micro level, extreme weather conditions or even combinations of non-extreme combinations can seriously affect construction productivity in relation to delivery of this investment. The University of Reading and Costain's Weather wise project is exploring the feasibility of using long-term multi-variable historical weather data in scheduling construction programmes both in terms of timing and, for larger schemes, in terms of location.

54	Quantitative Assessment Tool for Wind Effect on Wave Overtopping Seawalls	The effects of wind on wave overtopping of sea defences are an issue of increasing concern. There are currently no reliable and proven methods to quantify such risks. The Manchester Metropolitan University working with its industry partners Royal HaskoningDHV, HR Wallingford, Environment Agency, EDF Energy and Torbay Council plan to extend an existing two-fluid model to quantify wind effects, validate this with physical modelling tests and subsequently develop an assessment tool and database. This will better inform allowances made for overtopping than the safety margins adopted nowadays.
55	Playing Games to Understand Multiple Hazards and Risk from Climate Change on Interdependent Infrastructure.	Improving the understanding of climate change impact on infrastructures and their key interdependences is vital for the industry to identify suitable adaptation solutions, as is a shared understanding of issues across owners and operators. For this project, the University of Edinburgh is working with a number of such organisations: Transport Scotland; Scottish Water; SGN; SEPA; Inverclyde Council; National Centre for Resilience; Climate Ready Clyde and Adaptation Scotland/SNIFFER. Building on the use of games in the development community, the team will develop a scenario-based table top game based on simulated weather and climate. This will allow the infrastructure owners and Inverclyde to plan adaptation strategies particularly around multiple hazards and cascading infrastructure failure.
56	RV-DSS: An industry-friendly resilience-based interdependency assessment tool - case study North Argyll	In the last decade, the Scottish infrastructure network has been facing the challenge of increasingly frequent and severe environmental hazards. In order to gain a deeper understanding of the vulnerability and resilience of the infrastructure network, the Anglia Ruskin University along with its industry partners Transport Scotland, Scottish Water, SSE, Atkins and ARUP have adopted a recently developed decision-support system to identify critical interdependencies between Water, Transport and Energy networks, applying it to a real case study in Scotland. Small/medium-sized cities with high vulnerability of urban population have not previously been studied for interdependency-induced failures. This project will focus on North Argyll in Scotland and it will consider the implication of community isolation in resilience of interdependent infrastructure systems. This tool provides means of optimising design and investment strategies for the partners in order to achieve greater resilience as a cohort.
2017 – Innovative monitoring call		
57	Innovative condition monitoring of electricity transmission assets	Environmental factors (e.g. air pollution, salinity in coastal areas, etc.) can accelerate corrosion of critical metal infrastructure assets. The current monitoring approach consists of capturing data via high-resolution colour imagery taken from helicopters and manually processing them to classify extent and nature of corrosion. Nottingham Trent University is collaborating with its industry partners Mosdorfer CCL Systems, National Grid and Opus International Consultants to translate the technology and methods developed for science-based archaeology in the form of remote-imaging at standoff distances to condition monitoring of infrastructure in the energy sector. The ability to track conditions over time will promote an understanding of how such assets perform and deteriorate throughout their lifecycle. This innovative method will deliver significant maintenance, planning and cost benefits necessary for critical infrastructure assets and society as a whole, with potential for broader application in other sectors.
58	Wire-Wall: a new approach to coastal wave hazard monitoring	Coastal defences are vital measures to prevent flooding and protect people, vehicles and houses from the harm caused by large waves; however, building strong coastal defences can be extremely costly and require a large amount of data. The accuracy of models currently utilised to estimate the “overtopping hazard” is assessed through field experiments, which are expensive and difficult to carry out. The National Oceanographic Centre is collaborating with its industry partners Balfour Beatty, Channel Coastal Observatory, Environment Agency, Marlan Maritime Technologies and Sefton Council to obtain monitoring data at Crosby, in the North West of England. This information will be used to optimise the design of WireWall, a new system that will measure the coastal overtopping hazard. Such system will employ a 3-dimensional grid of wires that sense

		contact with saltwater. This contact signal will be used to measure the volume and speed of overtopping at vulnerable locations on the 900-meter-long seawall at Crosby. The new data collected will be used to test the models used when designing this new seawall through the comparison of estimated and observed overtopping hazards. In the future, WireWall could be incorporated into new seawalls themselves to enable long-term monitoring.
59	Monitoring jellyfish and seaweed ingress into nuclear plants	Jellyfish and seaweed debris ingress into nuclear plant water intakes causes the plants to shut down, resulting in direct cost a million pound per day of closure. Building on existing modelling methodologies and new remote sensing technologies, the Plymouth Marine Laboratory is collaborating with its industry partner EDF Energy to develop a methodology for predicting jellyfish blooms and tracking seaweed debris using remote-sensing products before they reach the power plant. The habitat modelling and remote sensing techniques will allow the project partner to have a more pro-active approach to these events and reduce the cost of ingress events.
60	Innovative monitoring for contamination of water supply systems	Water treatment and supply assets are susceptible to peaks in groundwater turbidity caused by (a) fast groundwater recharge through fractures during storm events or (b) in response to subsurface disturbance related to groundwater engineering or foundation works in the vicinity of groundwater abstraction infrastructure. These turbidity spikes are infrequent and therefore not easily predictable, resulting in a loss of supply as a result of water contamination, damage to assets and infrastructure and consequent economic losses. The University of Birmingham and its industry partner NERC British Geological Survey are developing an innovative borehole monitoring approach based on fibre-optic cables for temperature-sensing borehole installations. Such monitoring system, along with additional numerical groundwater modelling, will help better understand the mechanisms of turbidity events and, therefore, predict risk zones where fracture flow might contribute to critical turbidity events. This new monitoring approach will enable water companies to adequately assess the risk to their water supply systems and infrastructure and to implement adaptation measures that ensure the safe functioning of production and supply infrastructure.