Institution: Newcastle University

Unit of Assessment: 12

Title of case study: Enabling Climate Resilient Infrastructure Systems

Period when the underpinning research was undertaken: 2009-2020

Details of staff conducting the underpinning research from the submitting unit:

Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Prof. Stuart Barr	Chair Geospatial Systems Engineering	2004-2020
Prof. Richard Dawson	Chair Earth Systems Engineering	2004-present
Dr. Sarah Dunn	Lecturer in Structural Engineering	2014-present
Prof. Hayley Fowler	Chair Climate Change Impacts	2001-present
Prof. Stephanie Glendinning	Chair Civil Engineering	1998-present
Prof. Chris Kilsby	Chair Hydrology and Climate Change	1997-present
Dr. Sean Wilkinson	Reader in Structural Engineering	1999-present

Period when the claimed impact occurred: 2014-2020

Is this case study continued from a case study submitted in 2014? N

1. Summary of the impact

As a result of our internationally leading research, infrastructure is today better prepared for climate change. Our improved projections of future climate, and models describing infrastructure performance in a changing climate, are now embedded in industry design guidance and practice, and in statutory adaptation reporting. Our geospatial infrastructure database model has underpinned development of the UK's first National Infrastructure Strategy, a £895bn pipeline of infrastructure expenditure until 2050. We also informed the development of new government guidance that ensures climate resilience is considered in all government infrastructure expenditure (£27bn in 2020/21). Initially proven in the UK, our research now informs global climate policy and international businesses, including engineering consultancies and insurance brokers (US$9bn revenue in 2019).

2. Underpinning research

Our research has addressed four barriers that had hindered climate resilient infrastructure. Our interdisciplinary research programme has: (i) provided high resolution climate information tailored to engineering design, (ii) characterised how infrastructure asset performance is impacted by a changing climate, (iii) modelled how interdependence between infrastructure sectors creates new failure pathways for climate risks, and (iv) provided decision-support tools that enable resilience to be mainstreamed into infrastructure investment decisions.

2.1 Climate information for infrastructure design

We developed two new robust methods to provide information on (flood, drought, heat, wind) climate hazards at the high spatio-temporal resolution required by infrastructure engineers. (a) We undertook the first analysis of outputs from the Met Office's new 'convection permitting' climate models (that is able to reproduce small scale atmospheric processes). We provided more reliable projections of how the frequency, intensity, timing, and spatial extent of short duration, extreme rainfall will change in the future [P1]. This is now used in surface water management design guidance. (b) To fully exploit this new climate model data for risk assessment, we developed and used a unique dynamic copula framework for stochastic rainfall modelling which preserves spatial-temporal dependence and reproduces interannual persistence [P2]. This allows the long-term impacts of change in climate variables over large catchments and nations to be assessed, a significant advance beyond the previous state of the art which did not account for spatial-temporal dependence. Our range of new statistical methods have been used by utilities and insurers to analyse flood and drought risks across large catchments, and assess multiple climate risks to 571 European cities.

2.2 Characterisation of engineering performance in a changing climate

Our research has improved the performance and reliability of energy, road and rail infrastructure assets by producing fragility functions to describe the likelihood of failure during an extreme event, and establish the long-term relationship between climate change, the engineering performance of infrastructure, and societal impacts. For example, we developed a new method to analyse 12,000

weather related failures in the electricity network to produce fragility functions for distribution assets [P3] subsequently used by utilities. Multi-year experiments on our unique, full-scale transport infrastructure embankment [P4] identified critical factors that control the magnitude and distribution of pore water pressure in embankments in response to weather events, providing increased sophistication in the understanding of climate-engineering processes in infrastructure.

2.3 Geospatial 'systems-of-systems' modelling of infrastructure

Modern infrastructure systems are interdependent, relying on each other to function. Through our pivotal role as geospatial modelling leads in the Infrastructure Transitions Research Consortium, Newcastle developed NISMOD-DB (National Infrastructure Systems Model Database), the world's first data platform for national scale analysis and modelling of infrastructure. The platform is built on a technology stack of PostgreSQL, PostGIS and Neo4j systems. It integrates national scale information on the location, asset performance, geo-temporal patterns of infrastructure demand, supply and capacity, flows and connectivity, and dependencies between networks. This has enabled the first national infrastructure assessment to consider cascading failure between different infrastructure networks (e.g. water supply, electricity transmission, major roads, railways, telecoms) which has highlighted geographic hotspots of infrastructure criticality across the nation [P5].

2.4 Valuing resilience in investment decisions

Newcastle led the iBUILD programme that brought together engineers and economists to develop new business models for infrastructure. We developed a number of new methods to assess systemic risks, value the benefits of climate resilient infrastructure, and support decision-making. This included new collaborative approaches to decision-making (e.g. https://tinyurl.com/collabdecision), as well as new decision-support methods based on graph theory. This enables engineers and policy makers to identify the most cost-effective locations across an infrastructure network to invest in adaptation measures to minimise risk. The method integrates information on network flows, capacity and performance, connectivity, and exposure to climate hazard. Application in Newcastle showed six carefully sited interventions reduced transport infrastructure impacts from flooding by a half [P6].

3. References to the research

[P1] Kendon, E.J., Roberts, N.M., Fowler, H.J., Roberts, M.J., Chan, S.C., Senior, C.A., 2014. Heavier summer downpours with climate change revealed by weather forecast resolution model. *Nature Climate Change*, 4, pp.570–576. doi:10.1038/nclimate2258.

[P2] Serinaldi, F., Kilsby, C., 2012. A modular class of multisite monthly rainfall generators for water resource management and impact studies. *Journal of Hydrology*, 464-465, pp.528-540. doi:10.1016/j.jhydrol.2012.07.043.

[P3] Dunn, S., Wilkinson, S., Alderson, D., Fowler, H., Galasso, C., 2017. Fragility Curves for Assessing the Resilience of Electricity Networks Constructed from an Extensive Fault Database. *Natural Hazards Review*, 19: 04017019. doi:10.1061/(ASCE)NH.1527-6996.0000267.

[P4] Glendinning, S., Hughes, P., Helm, P., Chambers, J., Mendes, J., Gunn, D., Wilkinson, P., Uhlemann, S., 2014. Construction, management and maintenance of embankments used for road and rail infrastructure: implications of weather induced pore water pressures. *Acta Geotechnica*, 9(5), pp.799-816. doi:10.1007/s11440-014-0324-1.

[P5] Thacker, S., Barr, S., Pant, R., Hall, J. W., Alderson, D., 2017. Geographic hotspots of critical national infrastructure. *Risk Analysis*, 37(12), pp.2490-2505. doi:10.1111/risa.12840.

[P6] Pregnolato, M., Ford, A., Robson, C., Glenis, V., Barr, S., Dawson, R., 2016. Assessing urban strategies for reducing the impacts of extreme weather on infrastructure networks. *Royal Society Open Science*, 3(5), 160023. doi:10.1098/rsos.160023.

The research has been funded through the following projects:

[RG1] NERC CONVEX: CONVective Extremes (Fowler; 02/11-07/15; £464,635 (NE/I006680/1)

[RG2] EU FP7 INTENSE: INTElligent use of climate models for adaptatioN to non-Stationary climate Extremes (Fowler; 02/2014-01/2019; €1,986,800.80, grant no. 617329)

[RG3] EPSRC RESNET: RESilient electricity NETworks for Great Britain (Wilkinson, Dawson, Kilsby; 09/11 - 03/16; £977,839, grant no. (EP/I035781/1)

[RG4] Willis Research Network Fellowship (Kilsby; 2010-present; £541,170.85)

[RG5] EU FP7 ECLISE: Enabling CLimate Information Services for Europe (Fowler, Wilkinson; 02/2011-05/2014; €3,408,670.50, grant no. 265240)

[RG6] EPSRC eROAD: Emergency Resource Location-Allocation and Deployment (Dunn; 05/17-08/19, £97,071, grant no. EP/P02369X/1)

[RG7] EPSRC iSMART (Glendinning; 07/12-06/17, £1,671,674, grant no. EP/K027050/1)

[RG8] EPSRC ITRC: Infrastructure Transitions Research Consortium (Barr, Kilsby; 02/11–01/16; £4,793,012, grant no. EP/I01344X/1)

[RG9] EPSRC & ESRC iBUILD: Infrastructure BUsiness models, valuation and Innovation for Local Delivery (Dawson, Glendinning, Wilkinson; 08/13–03/18; £3,567,86, grant no. EP/K012398/1)

4. Details of the impact

Globally, by 2100 climate change impacts on infrastructure are estimated to be US$4.2tn under a 2^{o}C scenario (i.e. if the Paris Agreement is met), and as much as US$13.8tn if not (https://tinyurl.com/globinfra). The Global Commission on Adaptation calculate that investment in climate resilient infrastructure provides a benefit to cost ratio of about 4:1. Newcastle University's research has been at the forefront of providing data, methods, and guidance that have enabled engineers and decision-makers to implement climate resilient infrastructure in practice.

4.1 Design guidance for future flooding

Flooding is the greatest climate risk to infrastructure, particularly flash floods. We worked with engineering consultants to translate our high-resolution climate information (Section 2.1) into design guidance for UK Water Industry Research (UKWIR): Rainfall Intensity for Sewer Design, Report 15/CL/10/16. Our work showed the previous assumption of a +20% allowance for future climate was insufficient and needed to account for regional variability e.g. guidance on additional design peak rainfall intensity from climate change is now +35% in East Scotland, and +55% in West Scotland. This work has provided '*a basis for the long-term planning and asset management of drainage and wastewater services across all Great Britain*' to manage the long-term risk of sewer flooding and pollution from sewer systems, comprising an annual spend of around £1bn [E1].

Our models of future extreme rainfall and flood frequency have also been used by Willis Towers Watson, the world's third largest insurance broker (2019 revenue US$9bn). This includes stress testing insurance portfolios against climate risks in reporting to the Bank of England, and has allowed Willis to "*increase our climate service offerings to several of our UK insurance clients which are representing [the] majority of the UK insurance market*" [E2].

4.2 Design of robust water resources management

After flooding, the Climate Change Committee (CCC) identified drought as the next most significant risk to the UK. Our stochastic rainfall model (Section 2.1, P2) has been used by Southern Water, water supplier to over 2.5 million people, to design their 2019 Water Resource Management Plan for infrastructure provision worth £1.8bn. Our approach is now standard across the UK water industry forming the basis of the new drought resilience framework for the Environment Agency, and has '*entirely changed the planning paradigm, and significantly enhanced the resilience of the water resource infrastructure of the most water stressed regions of the UK*' [E3].

4.3 Climate change adaptation strategies

Windstorms caused 20% of all electricity customer disruptions between 1995 and 2011. Our fragility models of electricity assets (Section 2.2), and high-resolution climate information (Section 2.1), were used to undertake a national scale risk assessment of the UK electricity transmission network to future climate, and to assess the vulnerability of 520,000 miles of overhead lines on the distribution network. This was used by energy regulator Ofgem, the National Grid, and all the Distribution Network Operators on the British mainland in their statutory 2016 Adaptation Reporting Power (ARP) submissions e.g. E4 and E5: "*helping the industry to understand the potential impacts of climate change on wind patterns*" (SP Energy Networks Adaptation Report) and "*this work was subsequently used by all the other distribution network operators on the British mainland to inform their 2nd round Climate change Adaptation Report submissions*" (Western Power letter, E4a) to assess current and future impacts of climate change.

Combining the fragility functions and climate projections, the National Grid was able to identify high risk 'hotspots' for windstorm and flooding on their network, providing a basis to prioritise adaptation.

This included advice on where to site £3m in demountable flood defences to achieve the greatest reduction in risk, whilst maintaining confidence in the resilience of power supply, thereby generating savings of £11m in wasted investment through asset depreciation [E4b].

Our research has also been applied to Highways England's and Network Rail's infrastructure networks which comprise around 50,000 and 200,000 geotechnical assets respectively (Section 2.2). Network Rail are investing £1.3bn in maintenance and renewal between 2019-2024. We have worked with Mott MacDonald for over 20 years, most recently to apply our detailed slope stability analyses under a range of future climate scenarios. This has enabled Motts to better *"justify expenditure to regulatory bodies such as the Office of Rail and Road (ORR)"*, saving the taxpayer significant amounts of money as *"emergency repairs may cost 10 times planned works, which in turn may cost 10 times that of maintenance activities"* [E6].

Prof. Dawson was appointed to the Adaptation Committee of the Climate Change Committee (CCC) in 2019. He has provided oral evidence direct to ministers on climate change adaptation [E7]. Moreover, the CCC's advice on preparing for climate change is reflected in legislation and the government's National Adaptation Plan which impacts upon every inhabitant of the UK.

4.4 National infrastructure assessment

Prof. Dawson led the Infrastructure section of the UK's 2nd Climate Change Risk Assessment (CCRA) evidence report [E7]. This was used by government to directly inform the UK government's National Adaptation Plan. Prof. Fowler is a contributing author to the 3rd evidence report to be published in 2022, and a member of Network Rail's Weather Action Task Force.

NISMOD-DB hosts several hundred national infrastructure network datasets, and manages information flows for infrastructure simulation, and enables visualisation of data and simulation results. This was used to provide the first national mapping of locations across England and Wales at risk of cascading failure from infrastructure interdependencies [P5]. This was crucial evidence on cross-sectoral infrastructure risks in the 2nd CCRA evidence report (Ch4, p27). Furthermore, it enabled and underpinned the National Infrastructure Commission's first National Infrastructure Assessment [E8], which included consideration of how climate change will impact upon the nation's infrastructure. This proposed a pipeline of £895bn of infrastructure investment up to 2050 that the government have mostly committed to build in the National Infrastructure Strategy.

4.5 Valuing resilience in infrastructure investment decisions

We led the iBUILD research programme, in partnership with the Universities of Leeds and Birmingham. At the request of Infrastructure UK (now the Infrastructure and Projects Authority), a department in HM Treasury, iBUILD supported the development of supplementary guidance to the Green Book for infrastructure spend [E9]. The guidance drew from contributions across the iBUILD team, including Newcastle's methods (Section 2.4) to value the benefits of resilient infrastructure. The Green Book is issued by HM Treasury and is used to appraise all government funded policies, programmes and projects. In recent years government infrastructure expenditure in the UK has been ~£20bn per year, but this is forecast to increase in the new National Infrastructure Strategy. The changes in the methods available to users of the Green Book enable government to derive additional value from infrastructure investments.

4.6 Influencing climate resilient infrastructure in policy and practice around the world

Our research has had significant impact internationally. As Coordinating Lead and Contributing Authors for the Intergovernmental Panel on Climate Change (IPCC) 6th Assessment Reports, Profs. Dawson and Fowler are providing advice to 187 governments on climate change adaptation.

As co-authors of the *Global Research and Action Agenda on Cities and Climate Change Science*, our recommendations on adaptation of infrastructure and cities were approved by all 187 member states of the UN Framework Convention on Climate Change in 2018 [E10a]. ICLEI (an international body representing 1750 local governments in 84 countries) state this "*will strengthen evidence-based, science-driven action in cities*" [E10a]. Further, our risk assessment model results have been used by the European Environment Agency to identify adaptation priorities for cities and infrastructure across Europe. [E10b]

Many of the organisations we have worked with [inc. E1, E2, E4, E6] operate internationally and have extended the reach of our research. For example, our research on characterising engineering performance has benefited consultants "*As a global company we are able to use this work to give us*

a competitive edge in our international consultancy work" [E5]. Furthermore, our work to quantify flood risk, and define 'event windows' for insurers has played "*a vital role in winning and retaining clients and maintaining a competitive edge…. driving revenue*" for Willis Towers Watson who operate in over 100 countries with a revenue of US$9bn (2019) [E2].

5. Sources to corroborate the impact

[E1] **Letter from Technical Director of JBA** setting out how Newcastle University's research informed design guidance now used by the UK's water companies and environmental agencies.

[E2] **Letter from Managing Director, Willis Research Network**, setting out importance of Newcastle University research for understanding and managing flood risk in Europe, and undertaking stress tests for the Prudential Regulation Authority.

[E3] **Letter from Water Resources Planner, Southern Water** confirming Newcastle advised on and provided ensembles of stochastic rainfall data to design their £1.8bn Water Resource Management Plan as well as: (i) Water Resource South East (WRSE) planning carried out by Atkins, (ii) the Water UK National Water Resource Long Term Planning framework, and the Water Resource Management Plans for (iii) Thames Water and (iv) Anglian Water.

[E4] **(a) Letter from Engineering Policy manager at Western Power** confirming Newcastle's role in helping to improve the resilience to windstorm outages for their 7.8million customers. **(b) Letter from Environmental Engineer at National Grid** stating how Newcastle's research contributed to their climate change adaptation and resilience planning, including saving £11m.

[E5] **Adaptation Reporting Power** – second round reports from OfGem, National Grid, UK Power Networks, Northern Powergrid, Western Power (quoted above), Electricity Northwest, SP Energy Networks (quoted above), Scottish and Southern Energy, Electrical Networks Association refer to Newcastle University's contribution to their adaptation planning: https://tinyurl.com/arp2energy

[E6] **Letter from Technical Principal at Mott MacDonald** confirming how Newcastle research, integrating climate change and geotechnical expertise, has improved the management of 250,000 infrastructure assets owned by Network Rail and Highways England.

[E7] **Confirmation that Professor Dawson chaired the Infrastructure evidence Report for the 2nd Climate Change Risk Assessment**: Dawson et al., 2016. UK Climate Change Risk Assessment Evidence Report: Chapter 4, Infrastructure. Report prepared for the Adaptation Sub-Committee of the Committee on Climate Change, London. www.theccc.org.uk/wp-content/uploads/2016/07/UK-CCRA-2017-Chapter-4-Infrastructure.pdf. This work informed **PostNOTE 621 Infrastructure and climate change**: https://post.parliament.uk/research-briefings/post-pn-0621/ ; and led to Professor Dawson being asked to give oral evidence to the **EFRA Select Committee** on flooding, 20th October 2020 https://committees.parliament.uk/oralevidence/1083/html/

[E8] **National Infrastructure Commission (2018)** https://nic.org.uk/studies-reports/national-infrastructure-assessment/ sets out a plan for £895bn over the next 30 years. The report cites the important role of NISMOD, the Infrastructure Transition Research Consortium, and Newcastle University. This has since been mostly accepted by the Government in the UK's first National Infrastructure Strategy www.gov.uk/government/publications/national-infrastructure-strategy

[E9] **HM Treasury (2015) Valuing infrastructure spend: Supplementary guidance to the Green Book**,https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/417822/PU1798_Valuing_Infrastructure_Spend_-_lastest_draft.pdf The report cites the contribution of the iBUILD programme and research team in the development of the guidance.

[E10] **Global Research and Action Agenda on Cities and Climate Change Science** which was approved by the UNFCCC's 187 member states at the 48th Session of the Intergovernmental Panel on Climate Change in Seoul, Korea in October 2018, www.ipcc.ch/site/assets/uploads/2019/07/Research-Agenda-Aug-10_Final_Long-version.pdf

[E10a] Support from **ICLEI - Local Governments for Sustainability** https://tinyurl.com/citiesaction

[E10b] **Urban adaptation in Europe (2020)**: European Environment Agency assessment supported by Newcastle University risk analysis and data https://tinyurl.com/eeaurban