Institution: University of Southampton		
Unit of Assessment: 07 Earth Systems and Environmental Sciences		
Title of case study: 07-02 Rising Tide: Informing management, planning and policy on acceleration of sea level rise, increased coastal flooding and changes in tide around the UK coast and globally		
Period when the underpinning research was undertaken: September 2010 – July 2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Periods employed by submitting HEI:**
Ivan Haigh	Associate Professor	April 2012 – present
Robert Nicholls	Professor	January 2004 – September 2019
Mark Pickering	Senior Research Support Officer	October 2016 – July 2017, February 2018 – August 2019
Matthew Wadey	Research Fellow	January 2013 – September 2016
Hagen Radtke	Research Fellow	April 2017 – March 2018
Addina Inayatillah	Research Assistant	March 2018 – September 2020
Period when the claimed impact occurred: October 2012 – December 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

Research at the University of Southampton (UoS) has advanced understanding of sea level change. Building on this underpinning research, our impact-generating activities have:

(**A1**) Provided analysis and tools to inform the Environment Agency's Thames Estuary 2100 Plan to protect London from flooding, and justified the use of a projection with greater sea-level rise.

(**A2**) Supported the Environment Agency, local authorities and other organisations across southern England in the preparation for, response to and recovery from major flood incidents;

(**A3**) Designed new realistic worst-case coastal flooding scenarios for the UK National Risk Register of Civil Emergencies;

(**A4**) Advised Storm Surge Barrier operators around the world, via the I-Storm network, on issues relating to operation, maintenance and future upgrades in response to sea-level rise; and

(**A5**) Provided key input to national and international briefings, reports and government inquires for policy makers in regard to growing flood risk and raised public awareness of sea-level changes.

2. Underpinning research

Understanding changes in sea level is critically important as it affects the livelihoods of hundreds of millions of people living in coastal areas and is a key indicator of climate change. Our programme of research, supported by grants from NERC and EPSRC (listed in Section 3), has significantly advanced understanding of sea level change in three key areas that underpin this Impact Case Study (substantiated by research outputs [**3.1-3.6**] listed in Section 3):

1) Sea level rise: Over the last decade, there has been considerable debate as to whether the rate of sea-level rise is currently accelerating globally and, if so, by how much. Research led by Haigh between 2012-18, and involving Radtke, provided new insights into sea level accelerations globally. We developed and applied a novel approach in which different acceleration detection methods were contrasted using sea-level records artificially extended to the year 2100 [**3.1**]. We used this innovative framework to show that the most important approach to the earliest possible detection of a statistically significant sea level acceleration lies in improved understanding (and subsequent removal) of interannual variability in sea level records.

2) Coastal flooding: Coastal floods, driven by extreme sea levels, are amongst the costliest natural hazards, and will increase in occurrence/severity with sea-level rise. A team led by Haigh between 2012-20, including Nicholls, Wadey, Inayatillah and >10 BSc and MSc students, compiled an innovative new database called 'SurgeWatch' to systematically document and improve understanding of coastal flooding mechanisms and consequences. Integrating a variety of data sources, we spent the last 10 years collating information on ~1000 distinct flooding events that have impacted the UK over the last 2000 years [**3.2**]; producing the most comprehensive national database on coastal flooding in the world. We analysed the dataset and gained valuable new insights into spatial footprints and temporal clustering of storm surge events [**3.3**]. A key finding was the identification of specific categories of spatial footprints of surge events around the coast.

3) Changes in tides: It has been observed for almost a century that tidal amplitudes have changed considerably at many locations, but these variations were previously thought to only occur locally, and the causal mechanisms were poorly understood. From 2010-20, Pickering and Haigh pioneered research into tidal changes. Pickering, supervised by Nicholls and collaborating with Deltares (an independent, institute for applied research in the field of water in the Netherlands) and IBM, undertook, using numerical models, the first assessment of the future changes in tide on regional and global scales [**3.4**]. Substantial tidal changes were identified at ~10% of the world's 136 largest coastal cities where socio-economic impacts are most acute. PhD Student Robert Mawdsley, supervised by Haigh, carried out the first global assessment of past changes in tidal levels [**3.5**]. These studies established unequivocally that widespread, sometimes regionally-coherent, positive and negative changes in tidal levels have occurred in the past two centuries and will take place in the future with sea-level rise. Recently, Haigh and Pickering [**3.6**] led a major international effort to comprehensively map changes in tides, develop an understanding of the range of mechanisms causing these changes, and assess their potential impacts.

3. References to the research

3.1 Haigh, I.D., et al., 2014. Timescales for detecting a significant acceleration in sea-level rise. *Nature Communications*, **5**, 3635, https://doi.org/10.1038/ncomms4635.

3.2 Haigh, I.D., Ozsoy, O., **Wadey, M.P.,** et al, 2017. An improved database of coastal flooding in the UK from 1915 to 2016. *Scientific Data*, **4**: 170100, https://doi.org/10.1038/sdata.2017.100.

3.3 Haigh, I.D., Wadey, M.P., et al., 2016. Spatial and temporal analysis of extreme sea level and storm surge events around the UK coastline. *Scientific Data*, **3**: 160107, https://doi.org/10.1038/sdata.2016.107.

3.4 Pickering, M.D, et al., 2017. The impact of future sea-level rise on the global tides. *Continental Shelf Research*, 142: 50-68, https://doi.org/10.1016/j.csr.2017.02.004.

3.5 Mawdsley, R.J., **Haigh, I.D.,** Wells, N.C. 2015. Global changes in tidal high water, low water and range. *Earth's Futures*, 3(2): 66-81, https://doi.org/10.1002/2014EF000282.

3.6 Haigh, I.D., **Pickering, M.D.,** et al., 2019. The Tides They Are a-Changin': A comprehensive review of non-astronomical changes in tides. *Reviews of Geophysics*, 57, https://doi.org/10.1029/2018RG000636.

Research grants; NE/I009906/1, PI Haigh, 2012-16, £625k; NE/P009069/1, PI Haigh, 2017-18, £127k; NE/S010262/1, PI Haigh, 2019-22, £790k; EP/K013513/, Co-I Haigh, 2013-16, £222k

4. Details of the impact

The impact that our activities have generated are categorised here into five main areas. These are ordered by spatial scale, from our impact-generating activities at city [**A1**], to regional [**A2**], then national [**A3**] and finally national/international [**A4**, **A5**] level.

(A1) 10-year review of the Thames Estuary 2100 Plan: Between 2016-20, Haigh worked with the Environment Agency (EA), to provide significant strategic input to the Thames Estuary 2100 Plan (TE2100) [**5.1-5.5**]. TE2100 sets out how the EA will continue to protect one of the world's most important coastal cities, London, from flooding. The EA estimate that 1.3 million people and £275 billion worth of property/infrastructure are currently at risk from tidal flooding in London [**5.1**]. Furthermore, within the Thames tidal flood zone there are also 400 schools, 16 hospitals, 4 world heritage sites, and critical energy, transport and water infrastructure. Within the TE2100 adaptive Plan, 10 indicators of change are being monitored by the EA to assess whether they need to make key interventions (such as building a new Thames Barrier) at an earlier, or later, date. The Plan therefore requires regular formal review (with detailed reviews in 2015 and 2020).

Between 2016-20, Haigh led three studies for the EA that have directly informed the 10-year review. In 2016, Haigh was invited to a series of meetings with the EA TE2100 team. As a direct outcome of these talks, the EA identified that they needed to do more, looking ahead to the 10-year review, to: (1) better identify changes in sea level that significantly depart from the assumed projections; and (2) understand the lead times to enact the flood management interventions.

Between 2017-18, the EA partnered with UoS on the NERC funded E-Rise project, led by Haigh and involving Radtke, which specifically explored these two issues [**5.2**]. A key outcome of this project was the development of an innovative toolbox that has allowed the EA to carry out sensitivity testing with different rates of sea-level rise to examine how quickly different sea-level accelerations can be detected, and to compare these with the lead times necessary for upgrading defence infrastructure [**5.1,5.2**]. Following the success of this project, Haigh was then commissioned by the EA in 2019-20 to lead a study (involving Inayatillah), which provided the evidence base for assessment of changes in the first 2 indicators (mean sea level and extreme sea level) in the 10-year review [**5.3**]. In this study, we built on our underpinning research [**3.1, 3.4-3.6**] and developed a significant enhanced framework for monitoring changes in mean and extreme sea-level, that utilised newly digitised long (>100 year) sea level records from historical sources. Sarah Smith, EA London Area manager states [**5.1**]: "*The results of this study, and the E-Rise web-based toolbox, were fundamental in supporting the decision over which sea level rise projection we should use for the 10-Year Review of the Plan, which is key to defining the timings of all major intervention works to be carried out in the future*". Guided by our study and underpinning research [**3.4-3.6**], the EA have moved to using a higher sea-level rise projection to define timings of key intervention works. Furthermore, they have incorporated changes in tides into the TE2100 Plan, and this will be a major focus looking ahead to the 15-year review [**5.3**]. In 2020, Haigh was commissioned again [**5.4, 5.5**], this time to lead a study to assess closures of the Thames Barrier, that provided the evidence base for changes in the 5th indicator (Thames Barrier operation) in the 10-year review. Here we carried out the most detailed investigation to date of how the number of barrier closures has varied in the past. We then wrote a sophisticated flexible set of software tools that estimates the number of future closures for: (1) any given sea level rise and/or change in fluvial flow change to 2100; (2) any defined closure matrix (the water level and river discharge thresholds that determine when the Barrier is closed); and (3) any given magnitude of forecast error [**5.5**]. Sarah Smith says [**5.1**]: "*This tool has been incredibly useful in helping us to plan changes to the closure matrix, which is fundamental to optimising the operational lifetime of the Barrier and associated fixed flood defences. It has also greatly improved the ease with which we can assess the impacts upon future closure numbers of changes in the projections of sea level rise and fluvial flow, and the impacts of improving the magnitude of error in forecasts used to determine whether the Thames Barrier needs to be closed to prevent coastal flooding*".

(A2) Major Flood Incident Planning UK South Coast: Since 2012, Haigh has played a central role in supporting the EA and local authorities across southern England in the preparation for, response to and recovery from, major flood incidents, which is vital for saving lives and protecting infrastructure [**5.6-5.9**]. The largest increases in flood risk in the UK are predicted to occur along the south coast. Flood exposure is particularly high in Portsmouth, which after London and Hull contains the highest number of properties exposed to coastal flooding of any UK city. These impact-generating activities have stemmed from Haigh's sustained involvement with SCOPAC, an influential network of organisations that share an interest in the management of the southern English coast. Haigh has presented results relating to our underpinning research [**3.1-3.3**], on many occasions at SCOPAC meetings and has also been commissioned to undertaken various projects for SCOPAC; the full list is summarised in [**5.6**] and two examples are outlined below.

In 2019-20, Haigh was commissioned to characterise coastal flood events across the four incident categories (elevated, significant, serious, catastrophic) for the South and South West Region to inform the EA's Flood Major Incident Plan (MIP) [**5.7**]. MIPs are strategic plans designed to communicate the strategy for response to a major event. Using our underpinning research [**3.2, 3.3**], we evaluated the characteristics of past flood events, matched them against the four MIP levels and theorised what a catastrophic coastal flood incident might look like [**5.7**]. Neil Watson, EA Coastal Engineer states [**5.8**]: "*This [work] represents a highly credible storm scenario rationale which will consolidate storm response escalation thresholds and have a major impact on how the EA plans and resources extreme coastal events in future. The local element of the Major Incident Plan has been updated to reflect the storm footprints and severity categories that Ivan Haigh has derived from historical and plausible future events*".

In 2019-20, Haigh was again commissioned to lead a study, involving Inayatillah and Wadey (now a coastal engineer with a local authority), to assess how unusual the substantial flooding that occurred along the south coast in the winters of 2013/14 and 2014/15 was, in the longer-term context [**5.9**]. The aim was to provide practical information sources for engineers and a broad range of stakeholders. Neil Watson, EA says [**5.8**]: "*This work has greatly assisted our interpretation of what we have experienced and what changes are ahead with respect to coastal storms. It has been agreed that the analytical approaches developed by Haigh and Inayatillah in this study would be formally incorporated into SCOPACs coastal monitoring programme of the region, to routinely support seasonal flood defence maintenance decisions and future planning*".

(A3) Flooding scenarios for the National Risk Register: In 2016, Haigh helped develop the coastal flooding scenarios for the UK's National Risk Register [**5.10,5.11**]. The Risk Register provides an updated government assessment of the likelihood and potential impact of a range of civil emergency risks that may directly affect the UK. Annual average economic damages from coastal flooding in the UK are estimated to be £540 million today, and are expected to more than double to £1.2-1.9 billion by the 2080's due to sea-level rise. Coastal flooding is therefore one of the top four priority risks for the UK Government and hence, is included in the Risk Register.

In 2016, the Department for Environment, Food and Rural Affairs commissioned HR Wallingford, the Health and Safety Laboratory and UoS (Haigh) to develop new coastal flooding scenarios for the National Risk Register [**5.10**]. Ben Gouldby, Chief Technical Director Flood Risk, HR Wallingford says [**5.11**]: "*Preparing such scenarios required an understanding of the risk, based on up-to-date impact assessments that apply the latest understanding in scientific methods. We were therefore pleased to commission Haigh to work with us on the project and his SurgeWatch database [**3.2**] and state-of-the-art research on the spatial footprints of coastal flood events [**3.3**], were central to the project".* As a team, we developed a state-of-the-art statistical modelling approach (validated against the SurgeWatch database [**3.2**]) that generated a wide range of possible coastal flood scenarios with realistic spatial footprints. Ben Gouldby states [**5.10**]: *"The previous edition of the Risk Register only included a severe east coast flood event. However, based directly on the results of Haigh's spatial footprint research, we developed five realistic worst-case scenarios that might impact different stretches of the English and Welsh coast, that exactly match the broad categories of observed events identified previously in his research [**3.3**]. Our work has assisted the development of improved emergency flood management plans and these have already been exercised in subsequent significant flooding events. We estimate a modest value for the reduction of flood damage, as a result of these improved plans, to be of the order of £20m per event".* Many stakeholders have praised this enhancement; for example, Neil Watson, EA states [**5.8**]: *"These new scenarios incorporate local/regional differences in flooding that has allowed us to quantify the potential damaging consequences of realistic worst-case flooding scenarios along the specific stretches of coastline we are responsible for and much better prepare response plans"*.

(A4) Storm Surge Barrier Network: Since 2018, Haigh has been advising Storm Surge Barriers around the world, on sea level issues relating to our underpinning research [**3.1-3.6**], and was commissioned to undertake a study to guide future operation of surge barriers in the Netherlands [**5.12**]. More than 20 large storm surge barriers (and many smaller ones) are in operation worldwide today, protecting ~30 million people and trillions of pounds of infrastructure.

Following the success of the aforementioned impact-actives with the EA [**5.1, 5.2**], Haigh was invited in 2018 to present the results of our underpinning research [**3.1-3.3**] at the I-STORM (an international Network of storm surge barriers) annual conference. As a result, Haigh was subsequently invited to the Netherlands in 2019 by Rijkswaterstaat (Ministry of Infrastructure and Water Management) to discuss how storm surge barrier operation may alter in the future with sea-level rise. Based on these interactions, and the aforementioned work Haigh undertook for the Thames Barrier [**5.4, 5.5**], the UoS was formally invited to be part of the I-STORM network in early 2020; only the third university worldwide in this network. In his testimonial, Marc Walraven Senior Advisor Storm Surge Barriers Rijkswaterstaat says [**5.12**]: *"In the short time Southampton has been a member, Haigh has already played a key role in advising our international storm surge barrier network on sea level issues, and we are confident he will play an increasingly important role looking ahead to the future"*. In 2020, Haigh was commissioned by Rijkswaterstaat, to undertake a one-year study to assess past and future changes in closures of their six barriers. Marc Walraven states [**5.12**]: *"This study is currently underway but already has played a key role in guiding operation, maintenance and potential upgrades of our barriers. Ivan's work has greatly assisted us in considering different options for undertaking important maintenance works".*

(A5) Policymaker and public engagement: Between 2015-20, Haigh and Pickering undertook wide-ranging engagement with policymakers on national/international scales, by contributing to reports, briefings and government inquires relating to sea level rise, coastal flooding and changes in tide. These activities are listed in [**5.13**] and select examples are outlined here. In 2017 and 2020, Haigh was asked to lead the United Kingdom Marine Climate Change Impacts Partnership (MCCIP) report on coastal flooding, which was significantly informed by our underpinning research [**3.2, 3.3**]. The primary aim of the MCCIP is to provide a framework to transfer high quality evidence on marine climate change impacts, and guidance on adaptation, to policy advisors and decision-makers. In 2019, Haigh was invited to co-author the 3rd UK Climate Change Risk Assessment (CCRA) Evidence Report, and throughout 2020 has assisted in the analysis and development of the narrative for the Infrastructure chapter, informed by our underpinning research [**3.1-3.6**]. The CCRA report is high profile and widely used by policy makers and in developing the Government's next National Adaptation Programme. Our pioneering work on change tides [**3.4-3.6**] has been instrumental in, as Matthew Palmer, Met Office states in his testimonial [**5.14**]: *"making it clear that changes in tides are important and of significant magnitude along certain stretches of coastline and should be accounted for in future national and international vulnerability and impact assessments".* As a result, Pickering was invited to co-author the latest UK Climate Programme (UKCP) Marine Report, published in 2018, and projections of changes in tides were included in it for the first time [**5.14**]. UKCP provides the sea level projections used by most coastal decision makers to inform coastal management, planning (e.g., defence upgrades) and policy in the UK. In 2019, Pickering was invited to be a contributing author of the International Panel on Climate Change's (IPCC) Sixth Assessment Report, due to be published to policymakers in 2021. This will be the first IPCC assessment report to include information on past and future changes in tides.

Since 2014, we have also undertaken sustained public engagement which has helped ensure that sea-level rise, coastal flooding and changes in tide remain at the forefront of the public debate on climate change [**5.15**]. Worldwide TV, radio and newspaper media coverage [listed in **5.15**] followed the online publication of our underpinning research articles [**3.1-3.6**]. Haigh's research on sea-level rise in the Thames, and subsequent impact-generating activities in the TE2100 Plan, was featured in a major four-part documentary called Sinking Cities, shown on PBS in the US in 2018, Channel 4 in the UK and worldwide (via Amazon Prime) in 2019. Since 2015, we also delivered >20 face-to-face public engagement events about our underpinning research to a total audience of >1,000 people. Additionally, the extensive SurgeWatch coastal flood database we have compiled [**3.2**] has been made freely available via a website we developed, with interactive graphical presentations, educational videos and news articles. Since its launch in 2015, the website has been viewed ~150,000 times by people in 190 countries. The dataset has been downloaded by numerous organisations, including local authorities, insurance companies and engineering consultancies. The full list of media coverage, the engagement events we delivered, and further detail on our website viewing statistics and downloads are provided in [**5.15**].

5. Sources to corroborate the impact

5.1 E-RISE project summary report;
5.2 Sea-level report (Confidential) led by Haigh and commissioned by EA;
5.3 Barrier closure report (Confidential) led by Haigh and commissioned by EA;
5.4 Barrier closure tool report (Confidential) led by Haigh and commissioned by EA;
5.5 Testimonial from Sarah Smith, Area Manager, EA;
5.6 Summary of SCOPAC activities;
5.7 MIP report led by Haigh and commissioned by SCOPAC;
5.8 Storm analysis report led by Haigh and commissioned by SCOPAC;
5.9 Testimonial from Neil Watson, Environment Agency;
5.10 Report co-authored by Haigh and commissioned by DEFRA;
5.11 Testimonial from Ben Goulby, Chief Technical Director Flood Risk at HR Wallingford;
5.12 Testimonial from Marc Walkden, Chair of I-STORM International Network;
5.13 Summary of policy engagement during the REF2021 period;
5.14 Testimonial from Matthew Palmer, Met Office;
5.15 Summary of public engagement during the REF2021 period.