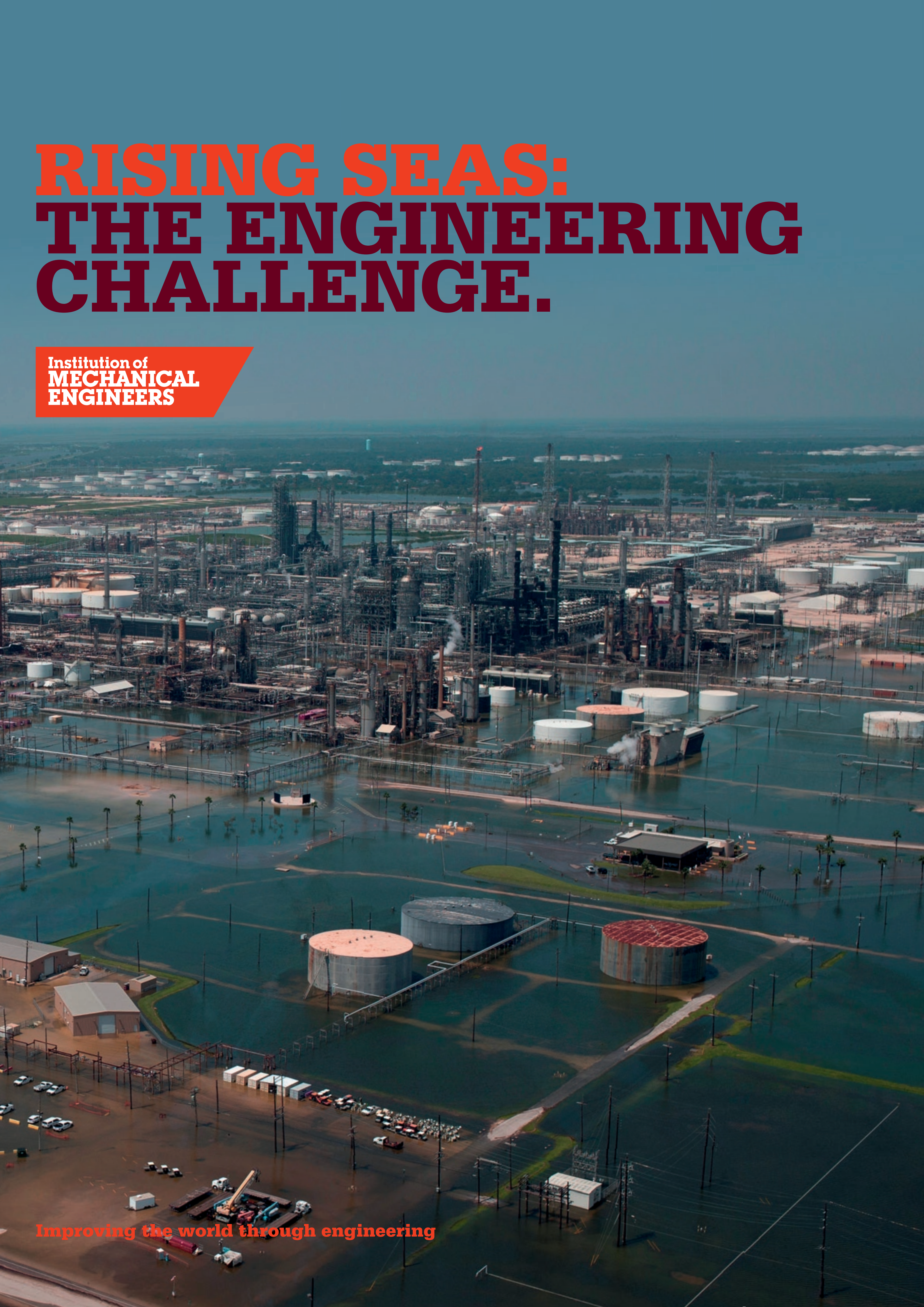
RISING SEAS: THE ENGINEERING CHALLENGE.

Institution of
MECHANICAL
ENGINEERS



Improving the world through engineering

> In essence, the engineering challenge of designing for rising seas and the associated risk of coastal flooding is rooted in instability.

Dr Tim Fox CEng FIMechE
Chair, Process Industries Division Board

Cover image: Flood waters caused by Tropical Storm Harvey at the Motiva Enterprises Oil Refinery in Port Arthur, Texas.

This report has been produced in the context of the Institution's strategic themes of Education, Energy, Environment, Healthcare, Manufacturing and Transport and its vision of 'Improving the world through engineering'.

Published November 2019.
Design: teamkaroshi.com

CONTENTS

EXECUTIVE SUMMARY

SEA LEVELS ARE RISING

Sea levels around the world have been relatively stable from a human perspective for about 5,000 years, over which time engineering has emerged and evolved as a distinct foundation of modern civilised society, along with its principles, guiding assumptions and design methodologies. This perception of the shoreline as being in a fixed, ‘stable’ environmental state, in which we have become deeply rooted culturally, psychologically and technically, is in distinct contrast to the large-scale variations of sea level that have taken place over geological time. At the last high-water point, some 120,000 years ago, sea level reached more than 6m higher than its present value and on the long timeframe it has varied over a 120m vertical range depending on the degree to which land-based ice has covered the globe.

Today, the world is warming and as a consequence mountain glaciers and polar land-based ice sheets are melting, discharging large volumes of meltwater into the planet’s oceans. This along with the thermal expansion of the sea water itself is causing seas to rise relative to coastlines across the globe. Indeed, there are many parts of the world where the impacts of sea level rise are already being felt on a daily basis, as communities experience loss of livelihoods from saltwater contaminated agricultural land and fresh water fishing grounds, changed ecologies reducing traditional hunting and abandoned flood prone infrastructure leading to lost employment opportunities. It is also resulting in frequent flooding of homes, permanent loss of utilities and blighted insurance zones. In these locations the shoreline is no longer perceived as fixed or stable.

Beyond the very real hardship being experienced by impacted communities today, the major challenge of present-day sea level rise lies in the uncertainty associated with the rate at which it will increase into the future and the height to which it will ultimately rise. This in turn depends on the difficulties that the scientific community face in attempting to predict changes to large-scale ice sheets covering Greenland and Antarctica. These two regions contain 99% of the ice covering the planet and are exhibiting increased and accelerating rates of melting, the long-term trends of which are hard to predict. In the case of Antarctica, this uncertainty in melt rate is compounded by the highly unstable and unpredictable nature of several large-scale coastal glaciers in the West of the continent. The collapse of these could lead to a multi-metre rise in global sea level on a short, potentially centennial timescale.

WE ARE NOT PREPARED

The most significant risk arising from the lack of scientific consensus on projections of sea level rise, particularly regarding the potential contribution of melting land-based ice in Greenland and Antarctica, is that of future coastal flooding. Given the long timescales over which buildings and engineered infrastructure are planned, built, operated, upgraded, extended and eventually decommissioned (which can be in the range of 25 to 250+ years, depending on function and use), a long-term view is essential today if we are to adequately prepare for future coastal flooding from rising seas. Whilst scientific studies continue to provide more accurate predictions, engineers need to design new buildings and infrastructure, and retrofit those already in place, using the best data currently available and considering “worst-case” and “best-case” scenarios for informed decision making. In some cases the design outcome may utilise barriers and walls to protect buildings and infrastructure, in others it may elevate designs on stilts, enable them to float temporarily or plan for occasional ingress of flood waters, and in the extreme some sites may be ruled out for occupation and those that already exist, but are highly vulnerable to flood events, abandoned.

The coastal flooding of individual homes, the building services and local infrastructure that support them (such as power, gas, water, sewage, telecoms, roads), and the communities in which they are located is a major disruption to people’s lives, with significant consequences for personal health, well-being and finances. Equally, coastal flooding of industrial infrastructure, such as oil refineries; gas processing plants; chemical and petrochemical plants; pharmaceuticals manufacturing and food processing factories; bulk material handling facilities; water and wastewater plants; power stations; and renewable energy processing sites (such as biofuels and biogas plants) can lead to multifaceted consequences that include technical, socio-economic, health and environmental impacts. These engineered infrastructures are, for technical, logistical and economic reasons, often located on tidal estuaries or at the coastal shoreline and essential to energy security, medical and food supply chains and a nation’s key manufacturing industries, building and construction sectors and agriculture. However, despite their central importance to economic well-being, in many cases the risk of future sea level rise induced coastal flooding to these assets could be being substantially underestimated.

AN ENGINEERING RESPONSE

Rapidly rising sea levels across the globe potentially present society with a significant shift in one of the most fundamental of baselines, the height of high tide. This warrants a new perspective for numerous professions, but first and foremost for engineers, who have an unquestionable professional responsibility to take this knowledge into account when designing new buildings and engineered infrastructure and retrofits to those that already exist. This report discusses the findings of a “scoping exercise” undertaken by the Institution of Mechanical Engineers to help the engineering community explore our professional response to a sustained multi-metre sea level rise this century, of possibly up to 3 metres or more. The work was done as a collaborative project with the Rising Seas Institute (RSI), based in Florida USA, and included input from individual members of a broad range of professional engineering institutions, as well as local and national government bodies, leading academics, and thought leaders on the topic, both in the UK and overseas.

There is much more work that needs to be done to understand the implications of multi-metre sea level rise, on both the built environment and industrial infrastructure, and to develop and implement measures to ensure they are fit-for-purpose, future-proof and adaptable in an era of rapidly rising sea levels. Today, there is little evidence of owners and operators of buildings or industrial assets, either in the public or private sector, having awareness of the challenges of future coastal flooding caused by sea level rise or making the necessary investments to implement adaptations or build resilience. Planning for, and adapting to, these risks is vital, particularly in the light of the potentially significant contribution melting land-based ice in Greenland and Antarctica may make to sea levels later this century.

To support such planning, engineering design specifications, standards, guides, technical approaches, methodologies and tools need to be reviewed and revised as appropriate and deliver coastal flooding adaptations for new builds and retrofits that address the uncertainties in sea level rise predictions. This, together with the necessary supporting changes to the skills requirements and training and education of engineers. Ultimately, techno-economic considerations will demand the development of sophisticated approaches based on adaptative pathways, probabilistic methodologies and engineering approaches to ’future proofing’ design. Given that buildings and infrastructure being designed today will potentially still be functioning in 30, 50 and 100 years or more, engineers need to be designing for the first metre of sea level rise now, recognising that it could happen as early as mid-century. Beyond the first metre, the profession needs to consider how it will handle the additional metres as and when they arrive during the potential operating life of the design.

In response to this challenge, in the short-term the engineering profession needs to urgently develop simple design guidance and methodologies that consider the possibility of a dynamic and potentially sudden rise in relative sea levels globally, with a paticular focus on ”worst-case” rises and options to accomodate such scenarios. As a starting point, this report presents a simple, pragmatic methodology that enables engineers to balance risk sensitivity (impact/probability) with anticipated design life in the determination of a ”worst-case” sea level rise for use in design calculations, as well as suggested adaptive engineering solutions to a range of potential impacts and initial pointers to existing advice and guidance.

RECOMMENDATIONS

The consequences of coastal flooding of the built environment, building services and industrial infrastructure are multifaceted and include technical, socio-economic, health and environmental impacts. Homes, places of work and communities are at the centre of a cohesive, healthy, functioning civilised society and engineered industrial assets are vital in the modern world. The latter contribute to economic well-being, energy security, medical and food supply chains as well as a nation's key manufacturing industries, building and construction sectors and agriculture. Adapting these components of modern life to the impacts of sea level rise induced coastal flooding is essential for a successful outcome to the influence of climate change in the 21st Century and beyond.

In this regard, the Institution of Mechanical Engineers recommends that Governments around the world:

1. Recognise in coastal flooding policy, strategy and investment decisions the emerging evidence base that indicates the possibility of sea level rises this century significantly greater than previously anticipated and prepare for a minimum of a 1 metre rise in sea level this century but plan for 3 metres of rise. In this regard, consideration should be given to what measures will be required to address a 3 metre rise and actions taken to ensure an adaptive-ready built environment and infrastructure.
2. Ensure that policy and strategy include consideration of industrial infrastructure, including but not limited to oil refineries; gas processing plants, chemical processing plants, pharmaceuticals and biopharmaceuticals manufacturing and food processing factories, water and wastewater treatment and processing plants, bulk materials handling facilities, power stations and renewable energy processing sites (biofuels, biogas etc), much of which are located alongside tidal estuaries or on the coastal shoreline.
3. Set up industry task forces to work with the Professional Engineering Institutions to better define adaptive approaches to future fluvial, pluvial and sea level related coastal flooding events, for sea level rises up to 3 metres this century, and the requirements for assessment of the impacts on the building services and industrial infrastructure. In this regard, we strongly suggest that UK Government convenes such a task force to include the UK's environment agencies, the Health and Safety Executive (HSE), Defra, BEIS, MHCLG and industry expert representatives, to take ownership of the industrial resilience planning for future sea level induced coastal flooding.

INTRODUCTION

The world's climate emergency is commonly perceived as presenting a single challenge to society, that of responding to climate change, and much confusion exists as to the response that is required and on what timescale. In fact, there are three quite different challenges demanding three parallel and simultaneous responses:

- Minimising the degree to which climate will change, by reducing greenhouse gas (GHG) emissions, generally referred to as climate change 'mitigation';
- Adapting society to the climate change that will occur because of past GHG emissions, and those that will occur while action on mitigation is undertaken, as well as building capacity for resilience to the impacts of more frequent and extreme weather events (for example, heat stress, drought, damage from high storm winds, flooding from heavy precipitation, cold stress, blizzard disruption);
- Adapting society to the rise in sea level that will occur as a result of past and future GHG emissions and building capacity for resilience to the impacts of more frequent and extreme weather events superimposed on higher seas (for example, coastal flooding from higher, more energetic waves, storm surges, heavy rainfall).

Some academics, researchers, thinkers and commentators propose a fourth response: geoengineering and climate repair, in which engineered interventions are made in the climate system and cryosphere to reduce or reverse climate change and reduce the rate of sea level rise, possibly eventually stopping it.

The Institution of Mechanical Engineers (IMechE) has, during the past two decades, primarily focused its climate emergency-related activity on raising awareness of the first two challenges, and supporting the engineering profession in contributing to the required societal responses of reducing GHG emissions and adapting to anticipated changes in climate, as well as helping build capacity for reliance against the associated impacts. The driver for this additional, third, parallel focus on sea level rise is a professional concern that the emerging evidence base from subject matter experts, which indicates the possibility of sea level rise this century significantly greater and more rapid than that anticipated in the most recent projections of the IPCC, is not being adequately considered by the engineering profession, or in national policies and strategies for adaptation to future coastal flooding.

Engineered structures, constructs, devices and systems typically have a 'design life' of 25–30 years (in the case of civil structures such as earthworks and bridges, the design life is much longer at 60 years and 120 years respectively), but with upgrades, life extensions and refurbishments they can often be in service for 50–100 years, or more. However, rapidly rising sea levels potentially present engineers with a significant shift in two of the most fundamental of design life baselines: a) ocean and tidal water levels, both in normal state and in short duration extreme water heights; and b) the coastal shoreline. This warrants a new perspective for engineers.

Far beyond any single building or piece of engineered infrastructure, all coastlines, estuaries and rivers of the world will be radically altered as base sea level rises, to levels not witnessed in tens of thousands of years. Effects will touch every coastline and tidal estuary in the UK and globally, and with large amounts of the world's industrial infrastructure, such as oil refineries and gas processing plants, chemical and petrochemical plants, pharmaceutical manufacturing and food processing factories, water and wastewater treatment plants, bulk materials handling facilities, power stations and renewable energy processing plants (biofuels, biogas etc) located alongside tidal estuaries, at the coast or very close to current sea level, the impact on industrial production across a wide range of sectors will be significant. These infrastructures underpin modern economies and are vital to a nation's future economic well-being. Add to this the effect on the built environment, centres of population and maritime routes of trade, as many sea- and river-based towns and cities experience frequent coastal flooding and possibly become indefensible on technical or economic grounds, and it is clear that the disruption to global supply chains and economic activity will be substantial. Those ports and coastal-located cities and industrial infrastructures that wish to maintain their useful, functioning economic status, must begin to plan today for adaptation to a new era of altered tide ranges and flooding regimes.

This report, researched and prepared jointly by IMechE's Process Industries Division Board and Construction & Building Services Division Board, with input from across the Institution's Boards and Regional Committees, members of sister Institutions and external subject matter experts, presents the findings of a 'scoping exercise' undertaken to help the mechanical, and broader, engineering community develop our professional response to sustained multimetre sea level rise, possibly this century.

SEA LEVEL YESTERDAY, TODAY AND TOMORROW

SEA LEVEL IS NOT AN ABSOLUTE

It is well understood among geologists and oceanographers, that sea level has changed many times in the past[1,2]; indeed there is plenty of evidence for this in the physical world around us. For example, in the South West of England there are numerous raised wave-cut platforms (marine terraces) and beaches, as a result of past higher sea levels, and rias (drowned valleys) from lower sea levels. Examples of the former include Prawle Point in Devon and of the latter at Falmouth Harbour in Cornwall (the third deepest natural harbour in the world), and similar evidence presents itself at coastal locations across the globe.

In recent geological times, sea level has risen and fallen over a range of approximately 120m, largely as a result of the freezing and thawing of ice sheets in response to changes in surface temperatures on a natural cycle of about 100,000 years[1,2]. For example, during past periods of warming (125,000 and 400,000 years ago), a large portion of Greenland was free of ice and sea levels were 6m higher than today [3]; conversely at the maximum extent of the last Ice Age (between 26,500 years and 19–20,000 years ago) the level was about 120m lower[1,2]. In the more recent past, and within the timescale of human occupation of the British Isles, as the ice sheets from the last Glacial Maximum melted, a large area of land that connected Northern Europe with the east of what is now England and Scotland, known as Doggerland, was completely submerged (8,500 to 8,200 years ago). This is now the location of the sea bed of the North Sea, with a high point at Dogger Bank.

A COMPLICATING FACTOR – GEOGRAPHY AND LAND MOVEMENTS

Sea level rises globally through two main processes as surface temperature increases: by thermal expansion of ocean waters absorbing heat from the warming atmosphere, and by additional volumes of water being added to the oceans from melting land-based glaciers and ice sheets[4]. The latter is the dominant post-glacial mechanism (it is important to note that melting sea ice does not increase seawater volumes). The resulting increase in global mean sea level will, at any given location, translate into a local sea level rise that is quite different as a result of various factors, including ocean circulation, gravitational effects of large bodies such as the ice sheets in Antarctica, the geography of local coastal features such as bays and inlets, and localised land mass movement in the vertical plain[5,6]. Such land mass movement can be a result of number of physical processes, including isostatic rebound effects[7] from the last Ice Age, in which land that was previously covered by thick ice of considerable weight is rising, and is counter-balanced by adjacent falling land that wasn't covered by ice. Land can also be sinking in the vertical plane, as a result of subsidence due to excessive human abstraction of groundwater and/or the weight of manmade structures upon the surface. Examples of isostatic rebound include the British Isles, where Scotland and the North of England are going up and the south coast of England is going down, and of extreme subsidence include Jakarta in Indonesia[8] and previously Tokyo in Japan[9].

SEA LEVEL IS RISING

Global mean sea level (GMSL) has risen approximately 0.2m over the 20th and early 21st centuries[4,5], primarily as a result of melting glaciers and the thermal expansion of seawater in warming oceans, and it rose at an average rate of 3.2mm per year between 1993 and now[10]. It is currently rising at 5mm per year[11].

Since 1900, 0.2m (20cm) of rise may appear to be a relatively small figure, but for many coastal communities around the world it has already impacted significantly upon their homes, infrastructure, livelihoods, economy and way of life. For example, in the US states of Louisiana, Rhode Island and Florida, dramatic changes have taken place to landscapes, and as levels of saltwater have increased, large areas of coastal marshland have seen ecosystems and wildlife substantially impacted[12]. This has in turn affected livelihoods based on fishing and hunting, exposing communities to economic loss and hardship. In these areas, frequent flooding of homes and infrastructure, such as roads, drainage ditches and canals, water and wastewater systems, and power and gas conduits, often leads to long interruptions to basic services, with disruption to lives and businesses while repairs are instigated. In some cases, such flooding has become so frequent that local authorities and utility providers have ceased to carry out repairs and maintenance, effectively abandoning whole communities on economic grounds, and householders and businesses are no longer able to secure insurance for their properties.

In the UK, the 0.2m rise in GMSL translates into an average relative sea level rise of about 0.16m (16cm)[13], the impacts of which are felt most noticeably in the eastern, North Sea-facing coastal counties of the nation, including Norfolk and Yorkshire. These counties have coastlines composed of relatively soft rocks, and in combination with higher high tides and the exacerbating effects of storm waves, they are eroding faster than in any other part of Europe [14]. For example, in some parts of the East Riding of Yorkshire, erosion rates of 4m a year are experienced on average, and individual cliff loss incidents can result in up to a 20m inland shift of the shoreline. Elsewhere in the UK, as with Louisiana, Rhode Island and Florida, coastal habitats have been impacted by sea level rise, and it is estimated that, since the late 1800s, 85% of saltmarsh habitat has been lost in England[14].

HOW HIGH WILL IT RISE IN THE FUTURE AND HOW FAST?

Atmospheric and ocean temperatures globally are increasing, seawater is expanding, and land-based ice is melting, adding substantial volumes of water to the sea. So the key question from an engineering perspective, is how high will it go in the coming years and how fast will it rise?

In attempting to answer this question there are many uncertainties, including for example:

- how warm the planet will become and on what timescale as a result of GHG emissions to the atmosphere, which in turns depends on our collective ability to reduce our GHG emissions, the response of natural stores of GHGs to global warming through positive feedback loops (such as permafrost melts, ocean bed methane stores etc) and society's willingness to remove GHGs from the atmosphere or geoengineer the climate through solar radiation management; and
- the detailed physical response of the remaining land-based ice sheets and glaciers to that level and rate of warming.

Within the context of some of these anticipated uncertainties, the UN IPCC does attempt an answer. In its most recent assessment[15], it considers four potential scenarios based on greenhouse gas concentration trajectories (Representative Concentration Pathways – RCPs), with the highest GHG levels (RCP 8.5) projecting a maximum GMSL rise of 1.10m by the end of this century. However, it is important to note that this figure does not include the full sea level rise potential of Antarctica, due to scientific uncertainty related to the possible collapse of marine-based segments of the continent's ice sheet. This is important, as the ice covering Antarctica combined with that of Greenland represents 99% of ice on Earth, and observations show that ice losses from these areas are increasing and currently account for one third of the total rise in GMSL[4,16]. Ice losses have tripled from Antarctica alone over the past two and a half decades[4].

The key challenge with predicting the potential contribution from Antarctica, is that floating ice shelves adjacent to the coastline act as barriers to the flow of land-based ice into the sea, and there is considerable uncertainty associated with their thinning due to melting from above and below. This could result in pathways opening for accelerated flow of inland ice to the sea, which would then in turn melt and add further to sea level rise. This is a particular concern for the ice shelves of the West Antarctic Ice Sheet, the largest such accelerations having been observed in the areas that include the Pine and Thwaites Glaciers[4]. The latter, which has about the same land area as the UK, has sufficient ice volume alone to result in 1m of sea level rise, and when combined with that from other vulnerable parts of the sheet, a total increase of 3.3m would take place[16]. It has been suggested jointly by the British Antarctic Survey and Centre for Polar Observation and Modelling[4] that the instability of the West Antarctic Ice Sheet could contribute dramatically to sea level rise rates on centennial timescales, possibly by a factor of as much as ten. Although Antarctica may seem remote, due to the complex way in which sea level rise resulting from loss of ice in the region distributes across the planet, it actually has a greater effect on land masses in the Northern Hemisphere, than that which arises from the more local ice loss on Greenland.

In its evidence submission to the UK Government's Environment, Food and Rural Affairs Committee (EFRA) 2019 Inquiry into 'Coastal flooding and adaptation to climate change'[17], the UK Met Office provides mean sea level change projection figures for London at 2100[5], derived from the UK Climate Projections 2018 (UKCP18)[6], for low and high emissions scenarios of 0.29–0.7m and 0.53-1.15m respectively. For Edinburgh these figures are lower, at 0.08–0.49m and 0.3–0.9m, due to land uplift in the north of the UK resulting from post-glacial isostatic rebound[7]. The numbers for London are similarly quoted as 'extremely likely' by England's Environment Agency in its written evidence[14] to the same EFRA Inquiry, and its Thames Estuary 2100 Plan (TE2100 Plan) [18] assumes a 1m rise for sea level rise planning. However, the Met Office makes the point that the UKCP18 projections do not rule out substantial additional sea level rise associated primarily with dynamic ice discharge from the West Antarctic Ice Sheet[5]. Indeed, it states that based on the scientific evidence, the 'H++ scenario' estimate for a low-probability, high-impact range of UK sea level rise to 2100 provided by the previous UKCP09 projections (ie a UK range of 0.93–1.9m not accounting for vertical land movements)[19] is a reasonably plausible high-end scenario.

The uncertainty associated with the instability of the West Antarctica Ice Sheet, along with that regarding the rate at which the land-based ice in Greenland will melt, has led to a range of organisations making estimates of future sea level rise that exceed IPCC projections. These have included, for example, the US National Oceanic and Atmospheric Administration (NOAA) which, in its January 2017 report[20], stated that "the projections and results presented in several peer-reviewed publications provide evidence to support a physically plausible GMSL rise in the range of 2.0 metres (m) to 2.7m, and recent results regarding Antarctic ice-sheet instability indicate that such outcomes may be more likely than previously thought… we recommend a revised 'extreme' upper-bound scenario for GMSL rise of 2.5m by the year 2100...". Likewise, in Tamil Nadu, India, work is being undertaken to understand the potential impact on the state, and the city of Chennai in particular, of a 3m sea level rise by 2050[21] and the Dutch are considering a rise of up to 3m by the end of the century[22].

The instability of the ice in Antarctica, and associated unpredictability in loss rates, also lead to considerable uncertainty in projections of sea level rise over longer timeframes than 2100. Recent exploratory work undertaken by the Met Office to develop sea level projections for the UK to 2300[23], found rises for London and Cardiff of approximately 1.4–4.3m for the high emissions rate scenario, and values for Edinburgh and Belfast of 0.7–3.6m. However, it was noted that these figures could be substantially higher as a result of accelerated ice mass input from West Antarctica.

Some subject matter experts advocate[24] that it is reasonable to assume that ice mass input and associated sea level rise will continue the exponential rates of increase now being measured. If that is the case, then the rate of sea level rise in the next century will likely be substantial. For example, while rates as high as 0.5m per decade may seem impossible to conceive, within the timeframe of human experience, about 14,000 years ago sea level rose about 20m in four centuries[25]; which averages 0.5m per decade.

One important point to make here is that, contrary to a common misconception, efforts to reduce the amount of GHG emissions associated with human activity, including implementation of energy efficiency measures and the deployment of energy infrastructure based on renewable resources, will not prevent sea levels rising for several centuries[4]. However, depending on the response of natural feedback loops in the world's climate system impacted by current and near-term atmospheric GHG levels[26], emissions reductions will affect the degree to which sea level will rise in the long term and the rate at which it reaches that height[4].

THE ENGINEERING CHALLENGE

The primary areas of concern for the engineering profession with regard to rising seas, is the resulting impact on human populations and the coastal environment, the increased risk of coastal flooding to existing buildings and infrastructure, and how to design new buildings and infrastructure to account for future sea levels. In order to address these concerns, it is necessary to understand the physical mechanisms that will contribute to the risk of coastal flooding in any given location.

THE BASELINE – MEAN SEA LEVEL

As discussed earlier, an increase in GMSL will, at any given location, translate into a local sea level rise that is quite different as a result of various factors, including ocean circulation, gravitational effects of large bodies such as the ice sheets in Antarctica, the geography of local coastal features such as bays and inlets, and localised land mass movement in the vertical plain. The translation of a projected GMSL to a future relative sea level for a given location, accounting for all these effects, is technically straightforward, and by including calculations for local tide ranges, a projected mean sea level can be determined. However, it is important from an engineering design perspective to emphasise that the current uncertainties associated with the melting of the ice in Greenland and Antarctica, make such projections highly uncertain.

THE IMPACT AMPLIFIERS AND THE TRIPLE WHAMMY

For engineering design, projected values of future mean sea level for a given location are of limited use, as superimposed onto this new (increased) height are potentially several other physical mechanisms, which will have significant impact on the risk of coastal flooding. In this regard, the key parameters needed to define the limiting boundary of the design calculations, are the height of the water level associated with the most extreme high tide that will occur during the design life (that is a perigean spring tide, also known as a king tide), along with the maximum height to which this level might be increased by an extreme weather event, and the probability of the two coinciding. In the worst-case design scenario, a triple whammy of an extreme high tide at a coastal location on the mouth of a river, would coincide with a severe storm surge, making landfall at the coast during a prolonged period of heavy rainfall.

Having determined the limiting boundaries of the design, the traditional engineering approach would then be to make a series of judgements based on historical assessment of the probability of the extreme event occurring, and set appropriate working design limits that balance risk with the cost of abatement/mitigation measures to protect against the event. It is, however, important to point out that design approaches and calculations based on an historical assessment of the probability of a coastal flooding event occurring, are rooted in an assumption of a stable status quo in sea level and climate. Yet both are becoming increasingly unstable with the uncertainty associated with ice melt rates in Greenland and Antarctica, and the frequency and severity of extreme weather events increasing in many parts of the world[11]. For example, observed relative mean sea level rise in a number of locations has led to extreme sea levels increasing during the last 150 years[27] and the UKCP18[6] projections anticipate higher winds and waves in UK waters in the decades ahead.

In essence, the engineering challenge of designing for rising seas and the associated risk of coastal flooding is rooted in instability.

OUR INFRASTRUCTURE AND OUR HOMES AND SETTLEMENTS

From an engineering perspective, the key areas to address with regard to future coastal flooding as a result of sea level rise, are the potential impacts on the built environment, such as homes, business and commercial premises, retail and entertainment centres, and engineered infrastructure. The latter includes not only roads, railways, electrical power grids, telecommunications networks and gas and water pipelines, as considered in the UK's National Flood Resilience Review 2016[28], but also the industrial infrastructure that is essential to medical and food supply chains, broader energy security and a nation's key manufacturing, building, construction and agriculture sectors – infrastructure that underpins a country's socio-economic well-being. Flood-induced failure or disruption of food, health and energy services not only results in economic loss but can also lead to human suffering through hunger and illness and in extreme cases, such as hypothermia and contamination-related disease, mortality.

INDUSTRIAL INFRASTRUCTURE – THE LIFEBLOOD OF THE ECONOMY

Within the context of this report, industrial infrastructure is defined as engineered assets that are designed, built and used in the processing industries. These include, but are not limited to, the oil and gas, chemicals, petrochemicals, pharmaceuticals, food and drink, water, minerals, metals, power generation and broader energy (including biofuels, biogas production) sectors. Examples of such infrastructure are oil refineries; gas processing and liquefied natural gas (LNG) regasification plants; chemical and petrochemical processing plants; cryogenic plants for air separation and liquefaction; pharmaceuticals and biopharmaceuticals manufacturing factories; food processing plants; water and wastewater processing plants; steel mills; cement factories; bulk materials handling facilities; power stations; and biogas upgrading plants. These sectors and their infrastructure are the economic lifeblood of any industrialised economy, providing most of the energy and materials vital to other sectors such as manufacturing, agriculture, building, construction and transport, as well as for the health, sustenance and socio-economic well-being of a nation's population, and disruption to their production can be of local, national and international significance.

For technical and economic reasons, such as import of the feedstock or energy supplies needed for the industrial process being carried out, export of the plant's production to market, or access to water for the provision of process cooling, industrial infrastructure is typically located alongside tidal estuaries or on the coast. This dependency makes them vulnerable to coastal flooding and, in a future of higher mean sea levels, this vulnerability is likely to increase.

Flooding of industrial infrastructure can result in a wide range of short-term and long-term technical impacts, including but not limited to those presented, for example, in **Table 1**. These can lead to significant local and national economic loss, as well as international supply chain disruption and potentially catastrophic accidents, such as pressure or heat-related explosions, liquid spillages and releases of gas, which could result in toxic contamination of the ground, air, surface water or groundwater. In the case of water, at many industrial plants there are process feedstocks or processed products stored in large volumes at ground level or underground, as well as historic effluent containment sites and contaminated land, and ingress of flood waters to storage and containments could lead to pollution incidents with long-term contamination outcomes.

Table 1: A range of potential impacts of coastal flooding on industrial infrastructure

Potential Impacts of Coastal Flooding
Overload of surface wastewater systems.
Restricted access to processing plants and factories.
Water/saltwater ingress into motors, pumps and other operationally critical electrical equipment.
Disruption to underground services such as electrical power, gas, internet and telephone systems, leading to loss of power supply, energy services and plant control systems.
Disruption to transport services critical to feedstock supply and processed product distribution.
Moisture damage to process feedstocks and dry products.
Increased moisture levels leading to accelerated corrosion of plant, storage facilities and pipelines.
Loss of primary containment due to corrosion of vessels and/or pipelines.
Hydraulic uplift of submerged plant, pipelines, storage vessels and foundations.
Failure of primary storage tanks due to hydraulic uplift.
Loss of secondary containment due to bunds filled with water.
Effluent treatment overload and/or failure.
Loss of secondary containment due to overload of effluent systems.
Leaching out of historic ground contamination.
Environmental and ecological damage through chemical or product spillage.
Temporary, long-term or permanent shutdown of plants and factories.

Beyond the immediate economic and environmental outcomes from these technical impacts, the consequences of coastal flooding of industrial infrastructure are complex and multifaceted and include a broad range of possible socio-economic and health-related affects. For example, damage to a processing plant or part of the infrastructure supporting it, might lead to temporary disruption of production or, in the worst case, a permanent shutdown of the facility, with significant and possibly severe socio-economic implications locally through temporary or permanent loss of jobs, livelihoods and employment opportunities. The latter outcome can be potentially devastating for local communities, particularly if the impacted business is the main employer in the area. If the plant is a pharmaceuticals manufacturing factory, or water or wastewater processing facility, then there are also potential health implications though loss of medicine supply, shortages of potable water or treatment of effluent.

However, despite the central importance of industrial infrastructure to developed and developing economies alike, there has been extremely limited progress to date on implementing measures for adaptation to sea level rise. Indeed, there is little evidence globally of owners and operators of such infrastructure, in either the public or private sector, having awareness of future coastal flooding risks from sea level rises and the potential impacts on their businesses, or making the necessary investments to adapt and build resilience.

Furthermore, these owners and operators may not necessarily completely understand or appreciate the full strategic importance of their plants and factories and, if they do consider flood risk, may act in isolation and solely from their own business's perspective. Adaptation measures for coastal flooding clearly therefore need to account for the emergence of these possible silos and ensure a co-ordinated and joined-up approach, that embraces all potential stakeholders at local, regional and national levels. For example, though it is unquestionably important to prepare domestic dwellings for sea level rise impacts such as coastal flooding, if infrastructure operators cannot supply electrical power or gas to these homes from their power stations and gas plants, or adequate food and medicines supply from their food processing factories, pharmaceutical manufacturing plants and port facilities, it is of limited value. Strategic consideration will clearly need to be given to the availability of raw materials and finished products, in the event of coastal flooding associated with future sea level rise scenarios.

HOMES, WORKPLACES AND COMMUNITIES – THE SERVICES THEY NEED

Coastal communities around the world, ranging from small hamlets and villages to towns, cities and large urban conurbations, are at risk of coastal flooding from future sea level rise. In the past, small communities, such as farmsteads close to the shoreline, have had to move inland due to increased frequency of flooding, and indeed within the history of the human occupation of the British Isles, a large-scale migration by Mesolithic peoples to higher ground, from the rising seas encroaching on Doggerland, took place 8,500 to 8,200 years ago. In its modern form of 'managed retreat', this fundamental human response will most likely continue to apply to rural communities, particularly those that are economically disadvantaged and/or in remote areas, as their lives and livelihoods are impacted by a combination of frequent flooding and the degradation of agricultural land from salination of the groundwater table by higher tides. As noted earlier, this is already a reality in the low-lying communities of Louisiana, Florida, Rhode Island and other coastal states of the USA[12]. However, unlike Doggerland in the Mesolithic Period, many of today's threatened communities are on a very large scale[29], some at Megacity scale, and moving to higher ground is a more difficult option.

The built environment is, from an engineering perspective, composed of two elements: the buildings and structures themselves; and the engineered services that support their functioning, such as electrical power, water and gas utilities, and the provision of drainage, sewage, district heating, internet and telecoms. It is the latter element, building services, that specifically concerns IMechE, and **Table 2** presents some of the impacts that coastal flooding will potentially have on these.

As sea levels rise and coastal flooding risk increases, these impacts will be increasingly experienced by towns, cities and urban conurbations worldwide and, in the extreme case of a high tide combined with a storm, long-term damage will occur. For example, following Hurricane Katrina in Louisiana and Sandy in New York, many building service systems did not return to normal, and it proved necessary to replace and renew systems extensively. The impact of corrosive seawater on low-level services and even buried services can be catastrophic. In the New York subways, for example, copper-based signal and communication systems that were flooded have since had to be replaced – this time with fibre networks – at high cost.

Table 2: A range of potential impacts of coastal flooding on building services

Potential Impacts of Coastal Flooding
Overload of surface wastewater systems.
Basement and ground floor levels underwater.
Underground car park levels flooded and inaccessible.
Service ducts flooded and inaccessible.
Access routes to buildings flooded, including roads, cycle routes and pedestrian paths.
Water/saltwater ingress into ground-level electrical power systems and equipment.
Disruption to underground services such as electrical power, water, gas, sewage, district heating, internet and telephone systems leading to loss of utilities.
Increased moisture levels leading to accelerated corrosion of pipes and service ducts.
Hydraulic uplift of submerged pipes, utility ducts, tanks and equipment foundations.

Generally, buried services may be designed to cope in wet ground, but not in saltwater, and corrosion is a serious risk when seawater reaches them through surface flooding or ingress to the local water table. Beyond such extreme events, once the high tide level reaches buildings, they and their services will flood twice daily, at each high tide. This situation is not tenable.

For engineers, a significant body of guidance has already been published on ways to manage flood risk, both fluvial and coastal, much of it aimed at 'sustainable' communities. While this guidance can and should be usefully applied to new community developments, it has limited value for existing communities, and in many cases does not adequately cover future projections for sea level heights and extremes in weather. A broader range of engineering solutions needs to be developed to protect existing buildings, communities and their building services systems from sea level-induced coastal flooding. These systems will need to meet the capacities required while simultaneously delivering zero-carbon services through retrofits and refurbishments. Solutions must be developed for each type of service, and research into areas already affected should be used to direct new, innovative techniques, for example the use of fibre-optic cables instead of copper at the New York subway. The proposed 'flood safe house', which is constructed on structural supports that can raise the house[30], is another such innovation.

It is also noted that sustainable communities and buildings must consider the prospect of becoming independent, self-sufficient, functioning 'islands', with for example highly localised energy systems for supply and distribution, if the surrounding landscape is flooded and access routes fail or become disrupted. This approach was seen to be successful in New York City during Superstorm Sandy. Some building owners already consider such issues, an excellent example being the UK's NHS, which needs to ensure that hospitals can continue to function during periods when local connectivity is disrupted[31], including during flooding.

Liverpool Docks Redevelopment

Liverpool is similar to many long-established UK coastal cities, such as London, Portsmouth and Southampton, located at or close to sea level with extensive former dockside areas. These now redundant infrastructures, specifically the old Liverpool and Birkenhead Docks, are being redeveloped as a site for high-quality waterfront city properties. The scale of investment being committed is substantial, in excess of £6bn at the Liverpool Waters site and £5bn at Wirral Waters, over a 40-year development period. It therefore makes good economic sense to ensure that worst-case projections of sea level rise are taken into account at the design stage.

Solutions at Liverpool include a large-scale tidal barrier, the Mersey Barrage[32], which would protect the river Mersey from its outlet into the Irish Sea all the way to Manchester. This barrier would effectively protect all existing buildings as they currently stand, and hence minimise the necessary remedial works. At the same time the barrier could be used to generate electrical power using tidal changes, a form of net zero-carbon renewable energy.

If the barrage does not proceed, then the waterfront developments must anticipate and prepare for significant sea level rise. Engineering solutions for building services might include them being installed above ground level, rather than underground, using innovative approaches such as third-floor access via bridge links, so that they are protected in the event of flooding. Lower levels of buildings could be used as open entrance features, atrium areas and public spaces, making space for water during flooding events, with occupied areas starting from level 1 or 2 upwards.

WHAT CAN WE DO, WHAT ARE OUR ADAPTATION OPTIONS?

The research undertaken for this report, has found that there is considerable work to be done to adapt the built environment and industrial infrastructure to meet the potential challenges of future sea level rise-induced coastal flooding. The starting point for this work is to understand the available options, and these broadly divide into five key areas as described below.

DO WE CONSTRUCT BARRIERS AND WALLS?

Constructing impermeable barriers and solid walls around buildings and infrastructure, or increasing the height of those that already exist, to keep flood waters out, is a well-established engineering approach to the risk of flooding[33], whether coastal or inland. In the case of barriers, for relatively low-risk threats these might be temporary and only deployed during periods when weather and/or tidal conditions portend a flood incident; examples of these include those used by England's Environment Agency[34]. Although potentially an effective solution, the main challenges associated with this option are that during construction it can result in significant GHG emissions (particularly if based on the use of materials such as concrete and steel); often involves large capital and operational costs potentially of the order of US$ billions; can be unsightly and impactful on the local environment and ecology; can act to contain rainfall runoff water, adding to localised flood threats; and raises the question of how high to go in the context of the uncertainty regarding future sea level rises. This last challenge is of concern, because overdesign of barriers and walls has economic cost implications and might lead to accusations of unnecessary and unjustifiable overspend. A further overarching difficulty exists in the length of the barriers and/or walls that might need to be constructed at substantial cost to protect entire communities at city and industrial infrastructure scale.

An alternative to impermeable 'hard' barriers is the use of natural environments to reduce coastal flooding risks, and these might, for example, include sandscaping (see side box) or mangroves[35]. The latter is a recognised and often-used method in the tropics, for example in India and Southeast Asia, for providing significant protection against coastal flooding and saving lives, by dissipating the energy of the storm surge and reducing inland ingress of potential flood waters associated with storm surges.

DO WE PUT BUILDINGS AND INFRASTRUCTURE ON STILTS?

Similarly, raising structures off the ground to avoid flood waters, as either a retrofit or new-build option, is for individual buildings a typical engineered response to a risk of flooding[36], as evident today in the coastal areas of Louisiana, Rhode Island and Florida[12]. However, extending this approach to industrial infrastructure such as an oil refinery or chemical processing plant, though not technically impossible, is difficult to conceive from an economic perspective for retrofit of established facilities and new-builds alike. In the case of the latter, an elevated site away from the coast is a more likely option to be favoured, with the delivery of process feedstock, export of product and, if necessary, provision of cooling water to be facilitated via pipelines, conveyers and transport vehicles. If a new-build location potentially vulnerable to future coastal flooding is selected for the convenience of access to the water, or in the case of retrofits, then as with the approach of constructing barriers and walls, there are challenges in deciding how high to raise the structure to accommodate the uncertainty in future sea level rises. There is also an additional engineering problem to solve in the delivery of the services that provide utilities such as electrical power, gas, water, telecoms and drainage of sewage and rainwater runoff. In some adaptations to date this has proved difficult and too expensive to do, in terms of either protecting underground services and providing resilient connection to point of use, or providing alternative novel solutions, and the work has simply been abandoned or not started[12]. When extending the need of service provision to industrial infrastructure, which adds process feedstock, effluent and product to the utilities and drainage requirement, the challenge becomes far greater.

DO WE CREATE FLOATING BUILDINGS AND INFRASTRUCTURE?

A less common, but technically possible, adaptation method, is that of allowing structures to float on flood waters and provide the service via flexible connections. Although to date largely limited to individual buildings, there are current examples of designs and new-builds of more expansive residential developments that utilise this approach and maintain the position of the structure by tethers or columns[37]. In the case of industrial infrastructure, a modular approach to new-build or retrofit design might enable components of plant, such as storage tanks, bunds or vessels and compact processing units, to float and lift with a flood event. In such a design the tethered structure’s services would be provided via flexible connections protected by emergency isolation valves and decoupling devices. Current applications of this approach include small nuclear plant[38].

DO WE DESIGN TO ALLOW WATER IN?

An alternative approach to designing structures to keep water out, is that of adapting to the increased risk of flood events, by engineering space to allow water in, albeit in a managed and controlled way. Such space might be established outside the structure in the geographical landscape through the creation of temporary inlets or lakes[39], or inside structures by allocating dual-purpose ground-level areas that effectively become large-scale culverts or weirs during flood events. Engineering these areas requires careful consideration of effective space management, to ensure the free ingress and flow of flood water without hindrance from stored or dumped items; the provision of adequate advance warning systems to alert the owners, operators and managers of structures with sufficient time to take necessary action; and careful consideration of moisture barriers, doors and seals to prevent damage to the 'dry' areas, as well as methods that enable effective and timely restoration of the temporary 'wet' area to normal dry operation. Such restoration measures might include tiled floors and walls, raised electrical power outlets/sockets, and strategically placed covered drains to underground soakaways or tanks that can be used to receive flood waters after external waters have receded.

DO WE MOVE TO HIGHER GROUND?

Beyond engineering solutions to keep water out or allow it in on a managed and controlled basis, an approach to frequent sea level rise-induced coastal flooding that is gaining increased recognition and acceptance, is that of 'managed retreat'[40]. In this approach, individual building occupants or entire communities relocate away from coastal regions to new sites, or extensions to existing 'host' communities, on higher ground; in the UK, Fairbourne in Wales has been identified as a potential candidate for managed retreat[41]. Although an obvious solution from a purely logical perspective and technically straightforward in engineering terms, this approach is highly complex from a socio-economic-political perspective and, as has been evident in the case of Isle de Jean Charles in Louisiana and Staten Island in New York, involves significant emotional and psychological dimensions that are routed in the human 'sense of place' and 'place attachment'[12]. Although such considerations are not as directly related to the relocation of industrial infrastructure, they do have an indirect bearing on decisions to move through the impact on individuals and communities of loss of livelihoods and employment opportunities. If the plant or factory to be moved is the sole local employer, the impact could be economically and socially devastating. However, from an engineering perspective, the relocation of industrial infrastructure in mid-life economically, is unlikely to be a practical solution or make economic sense.

Taking a radical approach to rising seas – India

India is taking the issue of sea level rise seriously, and undertaking significant work to understand potential impacts, as well as develop an adaptation approach in which all options are considered possible: managed retreat, soft adaptation and hard adaptation [21,35]. With a large proportion of its 1.2 billion people and industrial infrastructure located in large-scale, low-lying coastal cities and planes, such as Kolkata, Mumbai, Chennai and the Tamil Nadu Eastern Coastal Plains, adaptation and building capacity for resilience against sea level-induced coastal flooding are integrated fundamentally with the nation's economic development agenda. Such is the importance of being prepared for rising seas to India's future socio-economic well-being, that worst-case scenarios with up to 3m of increase by 2050 are being considered[21] with west 'monsoon' coast and east 'tropical cyclone' coast perspectives reflecting highly localised climate change impacts on weather and extreme sea heights.

In parallel, 'rise agnostic' adaptation methodologies, tools and measures are being developed by multidisciplinary teams[42], bringing together physical scientists, social scientists, behavioural scientists, political scientists, psychologists, economists, lawyers, engineers, professional communicators and public engagement experts. Other, more developed nations, such as the UK and USA, have much to learn from India's approaches to sea level rise adaptation and an emerging framing of the challenge as different forms of flooding exacerbated by increased tidal heights.

‘BUILD BACK BETTER’ OR ‘IMPROVE, PROTECT AND PREPARE’?

‘Build back better’ is a commonly quoted and widely accepted adaptation method for creating more resilient communities after the impacts of extreme weather, including flooding related to heavy rainfall, powerful waves or storm surge events. However, although this approach is certainly applicable at the individual building and community infrastructure level, it is not necessarily an acceptable policy for coastal flooding of industrial infrastructure, particularly in cases where ground contamination or surface water or groundwater contamination has occurred. Instead, an adaptation policy of ‘improve, protect and prepare’, which seeks to minimise potential impacts for the remaining lifetime of the infrastructure, may well be a better approach on economic and, depending on the national significance of a specific asset’s production, strategic grounds. However, it should be recognised that such an overarching approach for industrial infrastructure, rather than being a panacea, would need detailed technical and socio-economic assessment of proposals to be carried out on a case-by-case basis.

‘Protect’ – Bacton to Walcott Sandscaping Scheme

Protecting industrial infrastructure can often involve the construction of a barrier or wall where it makes socio-economic sense to do so, such as in the case of the gas terminal at Bacton on the north Norfolk coast[43]. The Bacton gas terminal is a complex of six gas terminals which supply one third of the UK’s gas, receiving gas from offshore fields in the Southern and Central North Sea, as well as the Netherlands via the Bacton-Balgzand pipeline (the BBL), and imports and exports gas from/to Continental Europe via an interconnector with Zeebrugge in Belgium. The location of this important industrial infrastructure close to the shoreline makes it vulnerable to coastal flooding, and to provide protection into the future an ambitious barrier has recently (summer 2019) been constructed in the form of a large-scale sandscaping scheme[44]. The latter involved the placing and engineering of 1 million m3 of sand in front of the terminal, along with an additional 0.5–0.8 million m3 in front of the adjacent villages of Bacton and Walcott, at an estimated cost of £17–22m. A joint project between England’s Environment Agency, North Norfolk District Council and the terminal operators, by protecting industrial as well as community assets against flood risk along 5.7km of coast, the scheme provides a good example of a positive socio-economic adaptation based on an engineering intervention.

DESIGNING IN AN UNCERTAIN WORLD

The starting point for an engineer beginning the design of a new-build or retrofit, is to consider the requirements of the applicable design codes, guides, regulations and standards and, in the first instance, this might typically be the relevant Eurocodes such as the Structural Eurocodes and other standards available through BSI. In the case of adaptation, this would be BSI EN ISO 14090, Adaptation to climate change – Principles, requirements and guidelines[45]. Developed by ISO technical committee ISO/TC 207/SC7, this recently published ISO aims to be a general overarching standard that provides a framework for organisations to use when considering climate change impacts and effective adaptation options. It lays out a flexible way for organisations of all sizes, regardless of sector, to identify potential impacts, prioritise actions and make an adaptation plan that is standardised, consistent, verifiable and replicable across projects and sites. ISO 14090 demonstrates international best practice and helps build an organisation's capacity for resilience against climate change. It is the first of a range of ISO standards in this area. Subsequent standards currently in development to provide detailed methodologies in specific areas, will include ISO 14091, Adaptation to climate change – Vulnerability, impacts and risk assessment[46], and ISO TS 14092, GHG Management and related activities: requirement and guidance of adaptation planning for organizations including local governments and communities[47]. Although a good starting point, ISO 14090, 14091 and 14092 are not design codes or guides, or indeed regulatory requirements, and direction for engineers on the next technical step beyond understanding potential impacts and making prioritised adaptation plans, particularly regarding sea level rise, is not available. In general, the engineering profession and the appropriate regulatory bodies have not recognised fully the implications of rising seas for engineering design codes, guides, methodologies and tools, and in this regard a new approach is needed for the implementation of engineered adaptation measures in the design of new-builds and retrofits. CEN and CENELEC, the official European Standards bodies, have been working with the European Commission to modify certain infrastructure standards to cater for adapting to the future climate under the EC Mandate M/515[48]. Within the UK, and following a joint workshop with IEMA, BSI is now planning a standard on Adaptation Pathways, a concept which is referred to in ISO 14090, and which would fill a gap in detailed guidance where ISO 14090 points the direction. Of course, organisations can – and do – draft their own adaptation and resilience requirements; the energy sector uses ETR 138[49] to guide the flood-proofing of substations, for example. This kind of action should be encouraged.

To support such an approach, IMechE is advocating for simple guidance to be rapidly produced for use, when engineers are designing both new-builds and retrofits of industrial infrastructure and the built environment. These must deliver, in the short term, sensible and workable coastal flooding adaptation measures that address the current uncertainty in sea level rise predictions, while an extensive review and revision takes place of all relevant engineering design codes, standards and guides, technical approaches, methodologies and tools. In the longer term, a detailed and more sophisticated probabilistic modelling and adaptive-ready based approach needs to be developed and delivered.

A NEW SHORELINE, A NEW BASELINE FOR DESIGN

Rapidly rising sea levels potentially present engineers with a significant shift in one of the most fundamental of design parameters: the position of the shoreline. The challenge is how to design new buildings and industrial infrastructure, and retrofits of existing assets, to account for the uncertainty of this position during their operational lifetime (which can range from 25 to 100+ years) within the constraints of affordability and economic viability. This uncertainty affects not only calculations of static and dynamic structural loading from the impact of coastal flood water or elevated groundwater tables, but a wide range of design details such as protection from scour, moisture ingress and moisture-driven corrosion.

The starting point for meeting this challenge, is for the engineering profession to develop simple design guidance that considers the possibility of a dynamic and potentially sudden rise in relative sea levels. This work should evaluate proposed design approaches and methodologies through the lens of a worst-case scenario rise and explore options to accommodate such a scenario. The question is, based on the evidence currently available, what should that worst case be?

A first step towards answering that question in the immediate short term, might be to initially adopt a simple pragmatic methodology, which balances risk sensitivity (impact/probability) with anticipated design life, such as that proposed by John Englander in the Englander 9-Box Matrix[50], **Table 3**. The latter provides worst-case sea level rises accounting for uncertainties in the potential contribution of melting land-based ice in Greenland and Antarctica, relative to a 2020 baseline, for three operational design lifetimes of 30 years, 50 years and 100 years, and risk sensitivities of 'low', 'medium' and 'high'. The function of the building or infrastructure being designed determines the degree of risk sensitivity, for example a nuclear power station would be 'high' and a local sports facility would be 'low'.

In applying this Englander 9-Box Matrix approach, it is important to note that the matrix presents recommended design figures for an increase in GMSL, and these will need to be adjusted for local variables such as vertical land mass movement, ocean currents, bay impoundment effects etc, to determine the increase in relative sea level and subsequently the new 'normal' high tide mark. The latter can then be used in association with figures for the additional contribution resulting from extreme high tide, storm surge and heavy rainfall events, to determine the local worse-case limit design height. **Table 4** illustrates an example of how the outcome of this simple calculation might look in practice.

Table 3: Englander 9-Box Matrix[50], reproduced with permission of the Rising Seas Institute[51]

	Location: Global Average		
Risk/Sensitivity	**30 Years***	**50 Years***	**100 Years***
Low	30cm (1ft)	60cm (2ft)	2m (7ft)
Medium	60cm (2ft)	1.3m (4ft)	4m (13ft)
High	1m (3ft)	2m (7ft)	6m (20ft)

*Reference Year = 2020

Table 4: Example calculation of the local worse-case limit design height for local sea level rise-induced coastal flooding

Hypothetical case – for concept only	**30 Years (2050) (mm)**	
Projected Local Mean Relative Sea Level Rise – **Medium Risk Sensitivity**		500*
Storm Surge (including additional wave height)	1,200	
Potential Runoff (Pluvial Flooding)/River (Fluvial) Flooding	380	
Extreme High Tide	300	
Short-Term Flooding Total		1,880
Total – Limit Design Height for sea level rise-induced coastal flooding		2,380

*Relative sea level, in this example adjusted down by 100mm from GMSL

One point to note regarding the sea level rise values presented in Table 3, is that for all three levels of risk sensitivity, GMSL increases by at least 1m in the next 50 to 100 years, and for the medium and high cases exceeds 3m on the same timescale. This suggests that, in the simplest terms, the engineering profession should be designing now for the first metre of sea level rise, recognising from the values in Table 3 that this could possibly happen as early as mid-century, and simultaneously considering how designs will be adapted for the additional metres, as and when they arrive during the operating life of the building or infrastructure. The Singapore government recently went one step further and announced that it is simply going to design on the assumption that sea level will rise 4m this century[52].

In the short term, beyond making an initial simple 'first step' calculation of worst-case flood height available to practising engineers, novel solutions to the specific technical engineering challenges presented by increased coastal flooding, will need to be developed, as well as for the techno-economic issues associated with the uncertainty of future sea level rise. The former might include, for example, an overarching policy of contingency planning and building redundancy into systems, as well as more specifically some of the potential solutions suggested in **Table 5**. While the latter techno-economic dimension may demand the development of more sophisticated probabilistic, adaptive pathways and adaptive-ready approaches to 'future-proofing' design. Both areas will require high levels of innovative thinking.

Table 5: Adaptive engineering solutions to challenges of sea level-induced coastal flooding

Challenge	Adaptive Engineering Solution
Overload of surface wastewater systems.	Segregation of rainwater and process effluent streams to avoid overload.
Restricted access to processing plants and factories.	Raise transport infrastructure and provide alternative multisurface modes such as hovercraft, along with suitable temporary docking facilities.
Water/saltwater ingress into motors, pumps and other operationally critical electrical equipment.	Existing equipment can be protected by local bunds/walls and pumps drainage; new-build projects should ensure critical equipment is sufficiently elevated.
Disruption to underground services such as electrical power, gas, internet and telephone systems leading to loss of power supply, building services and plant control systems.	Elevate services and/or provide sealed water-tight, corrosion-proof ducting for underground services.
Disruption to transport services critical to feedstock supply and processed product distribution.	Raise transport infrastructure and provide alternative multisurface modes such as hovercraft or airships, along with suitable temporary docking facilities.
Moisture damage to process feedstocks and dry products.	Elevate feedstock and product stores, protect with local bunds/walls, and/or provide sealed water-tight, corrosion-proof containment for stores underground.
Increased moisture levels leading to accelerated corrosion of pipes, service ducts, plant, storage facilities and pipelines.	Increased inspection frequencies of critical assets. Post-flood events washdown and clean-up to avoid mud/silt build-up.
Loss of primary containment due to corrosion of vessels and/or pipelines.	Increased inspection frequencies improved protective coating systems.
Hydraulic uplift of submerged plant, pipelines, storage vessels and equipment foundations.	Localised groundwater pumping and provision of bunding or sealed coffer dams.
Failure of primary storage tanks due to hydraulic uplift.	Localised groundwater pumping and provision of bunding or sealed coffer dams.
Loss of secondary containment due to bunds filled with water.	Increased bund capacity, protection against flood inflow and bund drainage pumps.
Effluent treatment overload and/or failure.	Protection of effluent streams from inundation from rainfall and floodwater. Increased effluent storage with mobile effluent treatment facilities or increased capacity permanent facilities.
Loss of secondary containment due to overload of effluent systems.	Provide back-up effluent systems.
Leaching out of historic ground contamination.	Capture leachates from the ground and develop effluent treatment/re-use of contamination material.
Environmental and ecological damage through chemical or product spillage.	Provide emergency feedstock and product handling protocol for flood events.
Temporary, long-term or permanent shutdown of plants and factories.	Develop spare industrial capacity and put in place cross-supply agreements with facilities exposed to less flood risk.
Water ingress to high-value processing units.	Modular design to enable floating units with flexible service connections.
High-inundation risk anticipated during operational lifetime but wall or barrier too expensive.	Modular design to permit raising or floating of critical plant components and possible relocation.
Limited budget in the short term for adaptation measures such as wall or barrier construction, raising services etc.	Design incorporates 'extension' points for adding additional protection at a later date.
Access routes to buildings flooded, including roads, cycle routes and pedestrian paths.	Raise transport infrastructure and provide temporary floating pontoons and/or alternative multisurface modes such as hovercraft, along with suitable temporary docking facilities

PROBABILISTIC DESIGN, ADAPTATION PATHWAYS AND ADAPTIVE CAPACITY

Although an engineering response in the short term to the rapidly emerging evidence base for larger than previously anticipated sea level rises this century urgently demands a simple pragmatic approach, such as that outlined above, techno-economic considerations in the longer term will likely require the development of substantially more sophisticated methodologies to assess cost benefits, risks, uncertainties and timeframes of proposed solutions. In this regard, design approaches will need to be developed that are based on probabilistic modelling, possibly similar in character to those used for design in other highly uncertain environments, such as earthquake engineering, as well as sea level rise sensitivity analysis for base designs. Further, to meet economic criteria, an adaptive pathways and adaptive-ready approach may need to be taken that embraces no-regrets and low-regrets interventions, to improve the resilience of the built environment and industrial infrastructure in the short term, but enable future adaptive solutions through the designing in of 'extension' enablers for adding additional protection at later dates. For example, in the simple case of a wall or barrier, this might involve designing the height of the structure to meet a minimum anticipated sea level rise (say 1m), but engineering the foundations and reinforcing grid to readily accept additional height when economically justified against observed increased risk.

From a risk perspective, it is the insurance industry that might ultimately become one of the principal drivers for changing how buildings and industrial infrastructure are designed to meet the challenge of coastal-induced sea level rise. Any project that is debt-financed, must be able to obtain insurance for most of the perils it will be exposed to throughout the life of the project (or at least the life of the debt). In this regard, insurance for property damage and business interruption is normally a relatively short-term product, typically obtained for the construction phase of a project and normally up to two years in the operational phase. If insurers become aware that a risk moves from being a low possibility to being highly likely, then it will become uninsurable for that peril, or insurance for it will be prohibitively expensive. As awareness of sea level rise-induced coastal flooding risk increases, risk exposure will increase among project funders and insurers, and it will become a much larger focus of attention in due diligence processes, and therefore also in engineering design. (It should be noted that although projects built [and owned] on company balance sheets might be treated differently from an insurance perspective, anything which can materially impact the finances of a company should be on its risk radar. Industrial infrastructure sites which could be impacted by sea level rise [directly or indirectly] could fall into that category.)

There is a general lack of awareness within the engineering profession, and broader industry at large, of what credible worst-case scenarios actually look like for projects and businesses, and the likelihood of their occurring. Many organisations simply think that a climate change or sea level rise-related event will not impact their building, infrastructure or project, and in part this is reinforced by current design practice, which uses historically based probability data. For example, a 1-in-500-year event sounds incredibly remote to most organisations, but in an environment that is rapidly changing in terms of the incidence of extreme weather events and sea level rise uncertainty, if a building or industrial infrastructure site has exposure for a design life of 40 years, the likelihood of an event occurring becomes much higher. Many might argue that a particular 1-in-500-year event might in the coming decades be a 1-in-200-year event because of sea level rise and the increased frequency of extreme weather events, and that the exposure over time is completely different.

EDUCATION AND TRAINING

Creative, innovative, adaptable, resilient, good communicators and socially adept; these are the characteristics that will be important in the engineers we need to help ensure a successful societal response to the challenges of future sea level rise. But how can the current technical education and training system, which was largely designed to meet the requirements of a climate-stable and sea level-static world, transform itself to deliver 'fit-for-purpose' engineers in this new highly dynamic and unstable environment?

As a starting point, it will be important to ensure that a basic working knowledge of rising seas, climate change impacts, future coastal flooding risks, adaptation measures and resilient sustainable design is provided throughout all the engineering disciplines, including mechanical, civil, chemical and electrical. The Engineering Council and the profession's Institutions have a major role to play in this regard and need to be encouraged to push hard for these subjects to be deeply embedded in course programmes and highlighted to students as important topics. Currently there are just a few specialist courses available that do this, such as the flagship degree-level programme on Flood and Coastal Engineering[53] offered at Brunel University, in association with England's Environment Agency, and though these help to tackle the shortage of specialised engineering skills, they cannot address the needs of the profession more broadly. In many cases the Professional Engineering Institutions set and accredit the curriculum for engineering programmes, so they are well placed to drive this change.

Beyond university and college curricula, for the engineering education and training system to deliver engineers with the requisite characteristics in the timescale needed to meet the challenge, the engineering profession must rapidly move away from its obsession with attracting future engineers and technicians from the narrow pool of 'STEM devotees'[54]. Instead, engineering will need to inspire and attract an expanding and more diverse range of people with non-traditional academic profiles. This means making education and skills training more accessible, relevant, responsive and transformative to new cohorts, and a radical recrafting of the profession's narrative about itself. Upskilling and continuous professional development also have an important part to play in redefining the role of the profession and extending diversity across businesses, academia and other organisations in both the public and private sectors. In this regard, careful thought is needed on methods of access, such as part-time and e-learning options[55], and the exact skills required to be developed in practising engineers and technicians, in order for the training to be successful in helping the profession deliver the necessary change. In turn this requires a deeper understanding of the future role of engineering in society, the urgent testing and building of an evidence base for successful, impactful, transformative interventions in schools, colleges, industry and wider society, and a rollout to scale through strategic collaborations that create an education, skills and accreditation system 'fit for purpose' in meeting the challenges of rising seas.

WHAT NEEDS TO CHANGE?

The primary priority for governments around the world, is to recognise in coastal flooding policy, strategy and investment, the emerging evidence base that indicates the possibility of sea level rises this century significantly greater than anticipated in the most recent IPCC projections. Addressing this newly emerging evidence will help drive adaptation to the risks of coastal flooding and resilience capacity building in communities and industries worldwide. Planning for, and adapting to, flooding and coastal change across a range of climate futures is essential, and England's Environment Agency has already shown considerable leadership, by recognising the need to design for a 2˚C temperature rise but plan for 4˚C of rise. Similarly, with regard to sea level, IMechE advocates that governments should prepare for a minimum of a 1m rise in sea level this century, but plan for 3m of rise, particularly in the light of increasing awareness of the potentially significant contribution later this century of melting land based ice such as that in Greenland and Antarctica. Singapore may be the first to show global leadership in this regard, in that the nation is considering planning for 4m of rise in the case of coastal defence infrastructure renovations and 5m for new builds.

The second priority for governments, is to ensure that coastal flooding policy and strategy consider industrial infrastructure, including but not limited to oil refineries, gas processing plants, chemical processing plants, pharmaceuticals and biopharmaceuticals manufacturing and food processing factories, water and wastewater treatment and processing plants, bulk materials handling facilities, power stations and renewable energy processing sites (biofuels, biogas etc), many of which are located alongside tidal estuaries or on the coastal shoreline. These engineered infrastructures are vital to a country's economic well-being and are essential to energy security, medical and food supply chains, and a nation's key manufacturing industries, building and construction sectors and agriculture.

Other priorities for governments include:

- Taking responsibility to provide support to the engineering community, to ensure existing and new industrial infrastructure achieves resilience to coastal flooding;
- Working closely with the Professional Engineering Institutions to better define a probabilistic and adaptive-ready approach to sea level rise-induced coastal flooding risk;
- Taking an adaptive pathways approach to the emerging sea level rise projections and investment opportunities for the building of adaptive and resilience capacity, in which planning, implementing and modifying strategies for managing resources take place iteratively in the face of uncertainty and change;
- Accepting that in the case of industrial infrastructure, coastal flooding risks may need to be increasingly managed at a national rather than local level, to ensure the realisation of nationwide considerations in relation to industrial production and energy security.

Successful delivery of these priorities will require considerable buy-in and open transparent collaborative working among many actors. The track record of governments and private industry alike for such a level of co-operation and data sharing, both internally across departments and externally, in support of the common good, is historically poor. That is not to say that it cannot be done, but for success, governments and their agencies will need to establish and draw on a substantial skills base in brokering, nurturing, encouraging, facilitating and delivering truly open transparent collaborative working within effective partnerships with multiple players. The significant changes required may ultimately need a degree of regulatory intervention and compliance monitoring, alongside collaborative coalition.

RECOMMENDATIONS

The consequences of coastal flooding of the built environment, building services and industrial infrastructure are multifaceted and include technical, socio-economic, health and environmental impacts. Homes, places of work and communities are at the centre of a cohesive, healthy, functioning civilised society, and engineered industrial assets are vital in the modern world to economic well-being, energy security, medical and food supply chains, as well as a nation's key manufacturing industries, building and construction sectors, and agriculture. Adapting these components of modern life to the impacts of sea level rise-induced coastal flooding, is essential for a successful outcome to the influence of climate change in the 21st century and beyond.

In this regard, IMechE recommends that governments around the world:

1. Recognise in coastal flooding policy, strategy and investment decisions the emerging evidence base that indicates the possibility of sea level rises this century significantly greater than previously anticipated and prepare for a minimum of a 1 metre rise in sea level this century but plan for 3 metres of rise. In this regard, consideration should be given to what measures will be required to address a 3 metre rise and actions taken to ensure an adaptive-ready built environment and infrastructure.
2. Ensure that policy and strategy include consideration of industrial infrastructure, including but not limited to oil refineries; gas processing plants, chemical processing plants, pharmaceuticals and biopharmaceuticals manufacturing and food processing factories, water and wastewater treatment and processing plants, bulk materials handling facilities, power stations and renewable energy processing sites (biofuels, biogas etc), much of which are located alongside tidal estuaries or on the coastal shoreline.
3. Set up industry task forces to work with the Professional Engineering Institutions to better define adaptive approaches to future fluvial, pluvial and sea level related coastal flooding events, for sea level rises up to 3 metres this century, and the requirements for assessment of the impacts on the building services and industrial infrastructure. In this regard, we strongly suggest that UK Government convenes such a task force to include the UK's environment agencies, the Health and Safety Executive (HSE), Defra, BEIS, MHCLG and industry expert representatives, to take ownership of the industrial resilience planning for future sea level induced coastal flooding.

CONTRIBUTORS

IMechE Process Industries Division

- Dr Tim Fox CEng FIMechE (Report Author)
- Richard Tiplady CEng MIMechE ACGI
- Dr Thanos Moros CEng FIMechE
- Karen Stevenson AMIMechE
- Dr Simon Rees CEng FIMechE FRSA MRINA
- Darren Hollins CEng FIMechE
- Ian Hancock Eng Tech MIET IEng MIMechE
- Graham Leason CEng FIMechE
- John Phillips CEng FIMechE

IMechE Construction and Building Services Division

- Frank Mills CEng FCIBSE MIMechE MASHRAE
- Stephen Mills CEng MIMechE

IMechE Thermofluids Group

- Dr Carola Koenig PGCert CEng MIMechE MASME FHEA

IMechE Power Industries Division

- Grant Spence CEng FIMechE

IMechE Members

- Richard Craig CEng MIMechE
- Rob Johnson CEng FIMechE

External Subject Matter Experts

- John Dora CEng FICE FIEMA FRMetS FPWI
- John Englander FIMarEST

Image credits
Covers: Reuters/Adrees Latif; p02: GomezDavid;
p14: Alamy/Ed Darack p24: Yuri_Arcurs.

REFERENCES

[1] Archer, David. The Long Thaw. (Princeton University Press, Princeton, 2009).

[2] Englander, John. High Tide on Main Street. 2nd Edition, Revision 2.1 (The Science Bookshelf, Boca Raton, 2014).

[3] Dutton, A. et al. Sea-level rise due to polar ice-sheet mass loss during past warm periods. Science 349, 6244 (2015): https://science.sciencemag.org/content/349/6244/aaa4019

[4] Written evidence submitted by the British Antarctic Survey and Centre for Polar Observation and Modelling (FCC0024). EFRA Inquiry into 'Coastal Flooding and adaptation to climate change (2019): https://www.parliament.uk/business/committees/committees-a-z/commons-select/environment-food-and-rural-affairs-committee/inquiries/parliament-2017/coastal-flooding-and-adaptation-to-climate-change-17-19/publications/

[5] Written Evidence submitted by the Met Office (FCC0017). EFRA Inquiry into 'Coastal Flooding and adaptation to climate change (2019): https://www.parliament.uk/business/committees/committees-a-z/commons-select/environment-food-and-rural-affairs-committee/inquiries/parliament-2017/coastal-flooding-and-adaptation-to-climate-change-17-19/publications/

[6] UKCP18, UK Climate Projections. MetOffice: https://www.metoffice.gov.uk/research/approach/collaboration/ukcp/index

[7] https://www.nasa.gov/feature/goddard/glacial-rebound-the-not-so-solid-earth

[8] BBC, Jakarta, the fastest-sinking city in the world. (2018): https://www.bbc.co.uk/news/world-asia-44636934

[9] Deltares, Sinking Cities, An integrated approach towards solutions. (Deltares, Delft/Utrecht, 2013 – updated 2015).

[10] Chambers, D.P. et al. 2017. Evaluation of the Global Mean Sea Level Budget between 1993 and 2014. Surveys in Geophysics 38, 309 (2017).

[11] WMO, The Global Climate in 2015–2019. (World Meteorological Organisation, Geneva, 2019).

[12] Rush, Elizabeth. Rising: dispatches from the new American shore. (Milkweed Editions, Minneapolis, 2019).

[13] Kendon, M., et al. State of the UK climate 2017. Int J Climatol. 38 (2018).

[14] Written Evidence submitted by the Environment Agency (FCC0007). EFRA Inquiry into 'Coastal Flooding and adaptation to climate change (2019): https://www.parliament.uk/business/committees/committees-a-z/commons-select/environment-food-and-rural-affairs-committee/inquiries/parliament-2017/coastal-flooding-and-adaptation-to-climate-change-17-19/publications/

[15] IPCC, 2019: Summary for Policymakers. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. (UN-IPCC, New York, 2019).

[16] Written Evidence submitted by International Thwaites Glacier Collaboration (FCC0006). EFRA Inquiry into 'Coastal Flooding and adaptation to climate change (2019): https://www.parliament.uk/business/committees/committees-a-z/commons-select/environment-food-and-rural-affairs-committee/inquiries/parliament-2017/coastal-flooding-and-adaptation-to-climate-change-17-19/publications/

[17] https://www.parliament.uk/business/committees/committees-a-z/commons-select/environment-food-and-rural-affairs-committee/inquiries/parliament-2017/coastal-flooding-and-adaptation-to-climate-change-17-19/

[18] Environment Agency, Thames Estuary 2100, Managing flood risk through London and the Thames Estuary – TE2100 Plan. (Environment Agency, London, 2012). Available at: https://www.gov.uk/government/publications/thames-estuary-2100-te2100/thames-estuary-2100-te2100

[19] http://www.mccip.org.uk/media/1410/summary.pdf

[20] NOAA, Global and Regional Sea Level Rise Scenarios for the United States. Technical Report NOS CO-OPS 083. (National Oceanic and Atmospheric Administration. Silver Springs, 2017).

[21] IGCS, Future Sea Level Rise: Assessment of Loss and Damage in Chennai in 2050. Final Report. (IIT Madras, Chennai, 2017).

[22] Dr. Robert W. Corell, communication on meetings with Queen Beatrix and Dutch Ministers, 2008.

[23] https://www.gov.uk/government/publications/exploratory-sea-level-projections-for-the-uk-to-2300

[24] https://www.johnenglander.net/

[25] https://www.johnenglander.net/sea-level-rise-blog/why-sea-level-will-rise-for-centuries-ultimately-100-feet/

[26] Steffan, W., et al. Trajectories of the Earth System in the Anthropocene. PNAS 115, 33 (2018).

[27] Written evidence submitted by University of Southampton (FCC0020). EFRA Inquiry into 'Coastal Flooding and adaptation to climate change (2019): https://www.parliament.uk/business/committees/committees-a-z/commons-select/environment-food-and-rural-affairs-committee/inquiries/parliament-2017/coastal-flooding-and-adaptation-to-climate-change-17-19/publications/

[28] HM Government, National Flood Resilience Review. (HM Government, London, 2016).

[29] https://www.weforum.org/agenda/2019/01/the-world-s-coastal-cities-are-going-under-here-is-how-some-are-fighting-back/

[30] https://inhabitat.com/amphibian-houses-rising-water/

[31] Department of Health, Planning for a resilient healthcare estate, Health Building Note 00-07. (UK Department of Health, London, 2014).

[32] https://news.liverpool.ac.uk/2019/10/02/new-mersey-barrage-design-generates-more-benefits-than-clean-energy-production/

[33] https://www.ice.org.uk/what-is-civil-engineering/what-do-civil-engineers-do/thames-barrier

[34] https://www.gov.uk/government/publications/sanway-and-byfleet-temporary-defences/sanway-and-byfleet-temporary-defences

[35] Byravan, S., et al. Sea Level Rise: impact on major infrastructure, ecosystems and land along the Tamil Nadu coast. (Centre for Development Finance, IFMR and Humanities and Social Sciences, IIT Madras, Chennia, 2010).

[36] https://articles.extension.org/pages/13861/elevating-your-home-to-protect-against-flooding

[37] https://www.wallpaper.com/architecture/latest-floating-architecture-projects

[38] https://www.npr.org/sections/thetwo-way/2018/04/30/607088530/russia-launches-floating-nuclear-power-plant-its-headed-to-the-arctic

[39] https://phys.org/news/2018-12-cities-room.html

[40] https://grist.org/article/retreating-from-rising-seas-isnt-a-win-or-defeat-its-a-reality/

[41] https://www.theguardian.com/environment/2019/may/18/this-is-a-wake-up-call-the-villagers-who-could-be-britains-first-climate-refugees

[42] https://www.edexlive.com/news/2019/apr/15/iit-madras-new-centre-of-excellence-will-help-predict-coastal-climate-with-increased-accuracy-5796.html

[43] https://www.shell.co.uk/content/dam/royaldutchshell/documents/lubricants/bacton-021799-asset-fact-sheets-marketing.pdf

[44] https://www.north-norfolk.gov.uk/tasks/coastal-management/bacton-to-walcott-coastal-management/

[45] https://www.iso.org/standard/68507.html

[46] https://www.iso.org/standard/68508.html

[47] https://www.iso.org/standard/68509.html

[48] https://ec.europa.eu/growth/tools-databases/mandates/index.cfm?fuseaction=search.detail&id=523#

[49] http://www.ena-eng.org/ENA-Docs/D0C3XTRACT/ENA_ET_138_-_Annex_Extract_180902050351.pdf

[50] www.risingseasinstitute.org/englander9box

[51] www.risingseasinstitute.org

[52] Singapore Government, Factsheet: Singapore Climate Action Efforts (Ministry of the Environment and Water Resources, 2019). Available at: https://www.mewr.gov.sg/search?q=sea%20level

[53] https://www.brunel.ac.uk/business/Centre-for-Flood-Risk-and-Resilience/e-learning-courses

[54] IMechE, Five Tribes: Personalising Engineering Education. (Institution of Mechanical Engineers, London, 2014).

[55] https://www.brunel.ac.uk/business/Centre-for-Flood-Risk-and-Resilience/e-learning-courses

Institution of
Mechanical Engineers

1 Birdcage Walk
Westminster
London SW1H 9JJ

T +44 (0)20 7304 6862
F +44 (0)20 7222 8553

environment@imeche.org
imeche.org