A Climate Change Report Card for Infrastructure

Working Technical Paper

Transport: Inland Waterways, Ports and Marine Infrastructure

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1.0 **Highlights and key messages**

1.1 Ports and marine infrastructure: overview

Ports, harbours and related marine infrastructure play a vital economic role. 95% of the UK's imports and exports are transported by sea; more than 40 million passenger journeys are typically made annually, and there is extensive recreational use particularly in estuaries and inshore waters. Many different products are handled and services provided, and there are considerable differences in both the scale of operation and governance arrangements.

Modern marine infrastructure is designed to operate in a dynamic physical environment and to withstand storm surge events and high winds. Extreme weather can nonetheless cause disruption to certain operations, and older infrastructure is potentially more vulnerable to the effects of climate change. The main climate variables of relevance to ports, harbours and marinas are sea level rise, storm surges, wind and wave climate, fog, and changes in erosion and sediment transport. Sea level rise is reasonably well understood, and current indications are that sea level rise will overshadow changes in wind and waves, storm surges and fog. However, confidence in the projections for these other critical parameters is low.

Flooding and physical damage, together with disruption to operations such as pilotage, berthing, cargo handling and storage, fishing, and recreational activities are the main potential impacts of climate change. The effects of the projected long-term changes in the mean would be exacerbated by any increase in the frequency of extreme events. The implications of the 'unlikely but plausible' high++ sea level rise scenario are of particular concern.

Port activities are also susceptible to any climate-induced disruption to access/onward transport or power supply resulting from flooding or erosion and to extreme heat affecting key road and rail infrastructure.

Modern physical assets and equipment in UK ports will typically have a 20-100 year design life and their design will typically have incorporated sea level rise (at least under a two degree warming scenario). However, some ports, harbours and marinas rely on much older infrastructure, designed to withstand pre-climate change conditions. Quays may therefore need to be raised; VTS, radar and other sensitive equipment re-located; or cargo-handling or storage facilities modified as sea levels rise or if storminess increases. Breakwaters and harbour walls may be overtopped more frequently, or may be damaged by storm events. Piling or other forms of protection may be more susceptible to washing out and to erosion. Operations and activities such as loading and stacking along with conservancy functions including dredging may also need to be modified.

Incorporating climate adaptation measures into new or replacement infrastructure tends to be preferred because retrofitting existing infrastructure can be both technically complex and expensive. Decisions about when to invest will depend on local circumstances, but effective adaptation will require a sound combination of technological development and long-term planning based on a robust dataset to ensure timely and climate-proof investment. Ensuring preparedness through awareness raising, capacity building and data management therefore represent key short-term challenges.

Climate change will also affect the natural environment. Coastal and intertidal habitats may become more vulnerable - potentially adding to the uncertainties faced by those developing new marine infrastructure – and problems with invasive alien species may also be exacerbated. Changes in the distribution of some species due to increases in air and water temperatures could affect both commercial and recreational fishing and wildlife-related recreational activities. When the uncertainties regarding recreational use carrying capacity are also taken into account, it is possible in the medium to long term that climate change could affect the nature, distribution and/or intensity of recreational use more fundamentally than it affects commercial ports.

Whilst the major ports' adaptation reports demonstrate a high level of agreement about the nature and likely significance of potential climate change impacts, research is urgently needed to improve understanding of how the many – typically smaller - ports, harbours and marinas relying on older infrastructure will be affected by climate change. Further, a combination of high adaptation costs and low levels of confidence in projected changes for certain critical marine parameters hampers adaptation planning even in the major ports. Research into storm surges, winds and wave, fog and sediment processes therefore remains a high priority.

In addition to modelling and other work to improve confidence in the evidence and projections, research is required to facilitate understanding of climate change consequences for coastal and estuarine habitats and species. This is important to facilitate planning of infrastructure development including the infrastructure supporting activities such as fisheries and wildlife-based recreation. It should also enable the identification of management measures necessary to minimise any infrastructure-related problems associated with invasive non-indigenous species.

1.2 Inland waterways: overview

Inland navigation characteristics also vary in terms of scale of operation and governance arrangements. The majority of the UK network is characterised by seasonal recreational use, where inland navigation can be a key contributor to the local economy. However, whereas some waterways are heavily used, others are less so. There are also marked differences in the level of experience of boaters: some waterways may have a high proportion of relatively inexperienced users at certain times of the year.

Inland navigation infrastructure is not designed to withstand the same range of extremes as marine infrastructure. It also tends to be older and potentially more vulnerable to the effects of floods and droughts which can affect not only structural integrity but also vegetation growth. In addition, the use of some parts of the canal network depends on an adequate supply of surface water. Behavioural issues are especially relevant to the use of inland navigation infrastructure – for example where users are inexperienced in navigating in strong stream or low flow conditions.

The main climate variables of relevance to inland navigation are air and water temperature, and seasonal changes or extremes of precipitation. High flows can cause overtopping and flooding of land-based assets, culverts, etc. They can also exacerbate bank erosion or scour and associated deposition; increase the risk of a failure or breach; and result in safety issues for users. Low flows conversely can lead to groundings or even waterway closures, and can threaten structural integrity or lead to subsidence. Water shortages might affect the operational viability of parts of the canal network; and bankside and in-channel vegetation management requirements are susceptible to changes in both temperature and flow.

Depending on the nature of the assets at risk, adaptation on inland waterways may involve raising, strengthening, replacing or otherwise modifying quays, moorings, embankments or bank protection. Headroom, weir or sluice capacity, bank erosion, sediment management and water supply issues might also need to be addressed. The condition and residual life of assets will be critical in determining whether modification or replacement is required and when. Regular monitoring and condition assessments supported by long-term and well-managed data will be invaluable, not only in deciding when to upgrade infrastructure but also in ensuring effective communication with users, issuing warnings, etc. Some of these requirements may become more urgent if warmer temperatures lead to increased numbers of recreational users.

As with marine and coastal areas, climate change will also affect the ecology of inland waters. Related adaptation measures could therefore include changes in vegetation management to deal with algal blooms, excessive weed, or invasive species; structural integrity issues if characteristic riparian species are lost; or additional towpath maintenance. Opportunities to use soft engineering solutions for bank protection or to develop buffer strips might also be explored.

Although there is a reasonable level of agreement about the nature of potential climate change impacts on inland-navigation infrastructure, there is a notable lack of robust evidence. Both high and low flow conditions have the potential to require significant adaptation particularly of older infrastructure, but little research has been carried out and local levels of awareness are often low. This is compounded by uncertainties about changes in seasonal rainfall and evapotranspiration - and hence the consequences for flow. Even for parameters where there is more confidence, levels of preparedness seem poor - for example, warmer air and water temperatures increasing numbers of recreational users and affecting vegetation growth; or potential future summer water shortages. Given the small scale at which many inland navigation authorities operate, their limited resources and the scale of adaptation likely to be necessary in the medium to long term, the development of a national 'toolbox' of possible adaptation measures would be useful.

Overall, it seems likely that inland navigation authorities may both face additional challenges and find climate change adaptation comparatively more difficult than many commercial ports. Awareness raising, capacity building, data management and user education are therefore urgent short term priorities.

2.0 Introduction and context

2.1 UK port and harbour characteristics

As an island nation, the port and harbour sector is vital to the UK economy. In 2012, UK ports handled around 500 million tonnes of freight traffic almost a third of which was inward traffic (DfT, 2013): maritime routes typically account for around 95% of the UK's imports and exports (Thornes et al, 2012). Hundreds of ports around the UK have statutory harbour authority powers but in 2012 only 110 were active commercial ports and fewer than half of these handled 98% of overall traffic (DfT, 2013).

Cargoes handled in the UK's ports and harbours include unitised goods; liquid bulk e.g. crude oil; and dry bulk e.g. coal, ores and agricultural products. Many ports specialise - for example in handling containers or trade vehicles; others provide a base for the offshore industry, including oil and gas or offshore wind and other renewables. Some ports are major ferry terminals; others are fishing harbours; and others combine commercial and recreational traffic. In 2011 there were more than 46 million international, domestic and island, ferry and cruise passenger journeys to, from and within the UK (DfT, 2012).

Governance arrangements also vary. Whilst there are some notable exceptions, many large ports are privately owned. Other ports are operated by local authorities or run as trust ports (DfT, 2012). The former often focus on recreational and fishing activities. Irrespective of their size, the majority of ports are statutory harbour authorities with conservancy functions to ensure safety of navigation. Many but not all coastal and estuarine marinas are located within harbour authority areas: however marina ownership and governance arrangements depend on local circumstances.

The port and harbour sector is therefore characterised by variety. The activities of each port or harbour determine the nature of its infrastructure and will affect its capacity to adapt to climate change.

2.2 UK inland navigation characteristics

Over the decades, the UK inland waterway network has changed from an essentially commercial operation to the point where - with a few exceptions including tidal rivers such as the Rivers Thames and Trent, the Manchester Ship Canal and parts of the canal network - it is now used primarily for leisure and recreational purposes. In recent years, planning policy has promoted the use of inland waterways for freight as a carbon-efficient alternative to road transport (Freight Transport Association, 2011).

The inland navigation network is strongly regional with most navigable waterways in the Midlands, Yorkshire, the North West and East Anglia and some in Scotland. By comparison, there are relatively few inland waterways in the South and South East or in much of Wales.

The four main players managing UK inland navigable waterways are:

- the Canal and River Trust (CRT, formerly British Waterways), responsible for more than 3,000km of canals and rivers[1]
- the Environment Agency, the second largest navigation authority with responsibility for managing around 1,000km of England's rivers including the non-tidal Thames, the Medway Navigation and the Fens and Anglian systems. The Environment Agency's navigational responsibilities are expected to transfer to CRT in 2015[2]
- the Broads Authority, with responsibility for a further 200km[3] of navigable waterways in Norfolk and Suffolk, and
- Scottish Canals (formerly British Waterways) in Scotland.

All other navigations are managed by a variety of much smaller organisations[4] including trusts and voluntary groups. The scale of operation varies from ship canals down to the narrow canal network, and many inland marinas are privately owned and operated. Some inland navigations are heavily used and over-subscribed by boating users, whereas others are under-utilised. Several restoration projects are ongoing and many more are in the pipeline (IWAC, 2009).

Recreational navigation use tends to be strongly seasonal and often local, with many waterways having a high percentage of regular users. Some areas, though, have relatively higher proportions of boats available for hire and as a result a greater proportion of relatively inexperienced boaters. For inland waterways, the governance

[1] http://canalrivertrust.org.uk/canals-and-rivers **Accessed 18th March 2014**

[2] https://www.gov.uk/government/policies/protecting-and-improving-people-s-enjoyment-of-the-countryside/supporting-pages/funding-the-canal-and-river-trust **Accessed 18th March 2014**

[3] http://www.broads-authority.gov.uk/managing/rivers-and-broads.html **Accessed 18th March 2014**

[4] **See** http://www.aina.org.uk/docs/96918GBWaterways_4.pdf **Accessed 18th March 2014**

arrangements and the experience of users can both be key factors affecting climate change adaptation capacity.

3.0 Navigation infrastructure

3.1 Port and harbour infrastructure

UK harbour authorities provide and maintain quays, wharves and other infrastructure; carry out dredging, channel marking and wreck removal; and regulate activities in the harbour including the movement of vessels. They also operate vessel traffic management services (VTS) and where relevant provide pilots to assist transiting vessels.

As well as quays, wharves, jetties and other berthing facilities, ports and harbours may have locks and docks; cranes and cargo handing equipment; and VTS, radio and radar equipment within their physical assets and infrastructure. The nature of the assets varies according to the type of port and the scale of its operations. Infrastructure to landward can include port offices, cargo handling and storage facilities and waste reception facilities. Some ports and harbours may depend on and be responsible for the maintenance of breakwaters, flood defence structures, other assets on tidal rivers including river walls and banks, and possibly associated footpaths. Approach channels, berths and turning areas may be dredged to ensure continued safe access for vessels. Unless agitation techniques are used, arrangements will need to be in place to dispose of the dredged sediment.

Marinas in coastal and estuarine areas will have some kind of mooring infrastructure (typically pontoons) as well as lifting gear, offices/buildings and waste reception facilities. Many also have breakwaters or similar protective structures requiring maintenance, and some have locks or sills. Many marinas also undertake dredging in their approaches and around berths.

3.2 Existing vulnerabilities in port and harbour infrastructure

Port activity takes place in a dynamic physical (tidal) environment: infrastructure must therefore cope with substantial variations and withstand significant natural forces irrespective of climate change. Modern marine infrastructure is designed to withstand storm surge events and to accommodate anticipated changes in sea level. Nonetheless, several of the major ports' climate adaptation reports to Government[5] identified port assets potentially facing an unacceptable risk of flooding, and the storms of winter

[5] Under the Climate Change Act 2008, certain companies with functions of a public nature including ten major ports were directed to prepare climate adaptation reports describing how they are assessing and acting on the risks and opportunities associated with a changing climate (Defra, 2009).

2013-2014 highlighted the potential problems which can be faced by older harbour infrastructure when exposed to extreme events[6].

Other areas of existing vulnerability for seaports, harbours and marinas or recreational facilities relate to the physical processes affecting sediment transport and hence dredging requirements. Changes in the strength and direction of storms or reduced freshwater flows can both lead to changes in erosion and deposition. The Port of London Authority, for example, carries out regular post-storm hydrographic surveys to monitor the natural migration of sandbanks and hence navigation channels in the outer Thames Estuary. The Port of Boston on the Lincolnshire coast was one of a number of ports affected by reduced river discharges during late 2011 and early 2012: sediment that would normally be transported by flow from the River Witham was deposited in the Haven where it accumulated - threatening to cause a hazard to navigation until it was rapidly transported seaward to The Wash by the flood flows later in the year.

Extreme weather, wind and wave conditions can cause operational problems, for example preventing vessels entering sheltered harbour waters (Port of Dover, 2011); making it difficult for pilots to board vessels safely; or potentially compromising safe berthing procedures for certain types of vessel (MHPA, 2011).

Unusually amongst the UK's major ports, the Port of London Authority (PLA) has jurisdiction over a significant length of tidal river navigation. The PLA's climate change adaptation report (PLA, 2011) highlighted several issues more typically experienced by inland navigation authorities, for example:

- changes in water level are drying out of the river banks, requiring drought-resilient species to be planted
- the upper reaches of the tidal river experience variations in water levels due to precipitation changes and abstraction upstream in the non-tidal Thames: navigational safety was therefore a consideration in a residual flow agreement between Thames Water and the Environment Agency (Thames Water, 2010).

3.3 Inland navigation infrastructure

Depending on the nature of the water body, infrastructure in river and canal navigations can include sluices, culverts, weirs and tunnels. Berthing facilities vary from mooring posts or buoys through piled quays or finger jetties to pontoons in on- or off-line marinas. In some areas, river or canal embankments are also flood defences maintained by a third party organisation such as the Environment Agency in England. In others, the navigation authority might be responsible for erosion control. Canal navigation authorities typically operate and maintain locks and associated infrastructure (including water supply and/or storage where relevant) and manage towpaths. CRT maintains 15 km of docks as well as many thousands of associated locks, bridges, embankments and

[6] http://www.bbc.co.uk/news/uk-england-26044323 Accessed 4th April 2014

aqueducts[7]. In privately operated marinas, the owner is responsible for infrastructure maintenance.

3.4 Existing vulnerabilities in inland navigation infrastructure

Physical infrastructure may be vulnerable - for example to flooding or erosion – but inland waterways are also arguably more susceptible than ports to safety and related behavioural risks. Both low and high flow conditions can pose communication challenges for the navigation authority as well as safety risks, particularly for inexperienced users. Safety issues include those associated with manoeuvring a vessel in strong stream conditions or where increased water levels reduce operating headroom (IWAC, 2009). On the River Thames, for example, the Environment Agency displays warning boards at locks to warn users of conditions that may make navigating difficult and dangerous[8]. Red boards, advising users of all boats not to navigate because of strong flows, have been displayed with increasing frequency in recent years, in turn affecting both recreational use and hire boat markets.

Extreme low flows or drought conditions can cause riverbank desiccation and problems of vegetation die-back and erosion affecting physical assets. Low flow conditions can also reduce the natural transport of sediment through the system with the resulting accumulations potentially threatening safety of navigation and requiring dredging. Unusually low and high flows can both have more serious implications for structural integrity. Low water levels can threaten the integrity of navigation infrastructure through removal of hydraulic support from the waterside face (Brooke and White, 2010) whereas high flows can cause damage through seepage or erosion or exceed the capacity of culverts, weirs and sluices. Such problems are illustrated respectively by the breach of the Grand Western Canal at Halberton, Devon, in November 2012 after water spilled over the top of the embankment during torrential downpours and flooding[9]; and the six-week closure of more than 95 km of the Leeds-Liverpool canal due to drought conditions in the summer of 2010[10].

The canal network is heavily dependant on surface water run-off - especially during the summer - and parts of the system are already susceptible to low flow conditions. The operation of some stretches relies on a stored water supply or the diversion of water from a nearby watercourse, and some older reservoirs already have a lower capacity than when originally constructed because of changes in reservoir safety requirements (IWAC, 2009). A few canals (e.g. Gloucester and Sharpness; Llangollen) also carry water

[7] **https://www.gov.uk/government/policies/protecting-and-improving-people-s-enjoyment-of-the-countryside/supporting-pages/funding-the-canal-and-river-trust Accessed 18th March 2014**

[8] **http://riverconditions.environment-agency.gov.uk/** Accessed 30th April 2014

[9] http://www.devon.gov.uk/index/environmentplanning/natural_environment/country_parks/grand_western_canal/canal-breach.htm Accessed 30th April 2014

[10] www.bbc.co.uk/news/uk-england-10835222 Accessed 4th April 2014

for industry and drinking water purposes. Whilst these are typically river-fed, any reduction in supply could have significant wider consequences.

Finally, the vulnerability of an organisation is related to its adaptive capacity. Aside from the four main inland navigation authorities, many inland waterway operators are small organisations with limited budgets. These factors, combined in some cases with relatively low levels of awareness, can increase vulnerability to the effects of climate change.

4.0 Potential impacts of climate change

The key climate parameters for UK port and marine infrastructure are sea level rise, wave climate, storm surges, wind and fog. Those likely to be of most relevance to inland navigation are seasonal precipitation and flow; air and water temperature; and extreme floods or drought. The consequences of changes in any combination of these parameters for erosion and sediment transport are equally important for navigation infrastructure in both the coastal and inland environments.

4.1 Temperature

Increases in both air (Defra, 2012a) and water (Defra, 2012b) temperature of around 1°C over the past 70-100 years have been recorded. Recent air temperature increases may be slightly lower than previously estimated (IPCC, 2014a; Lewis and Crok, 2014), but a certain amount of warming is nonetheless inevitable and some adaptation will therefore be required. Indeed, referring to the recent observed pause in global surface temperature rise, the Met Office (2014b) concludes that this neither materially alters the risks nor invalidates the fundamental physics underlying conclusions with respect to global warming.

UK air temperatures are projected to increase by up to 4.2°C from the baseline period of 1961−1990 for the 2080s under the medium emissions scenario (central estimate). In most regions of the UK both winter and summer mean temperature increases are projected to be in the range 3°C - 4°C (UKCP09). In Scotland an increase of 2°C - 3°C is projected. Warming is expected to be greater over land than at sea (IPCC, 2014a), but water temperatures are also expected to increase – by around 2.5°C by the 2080s. As with air temperatures, water temperature may not increase consistently. Average UK sea temperatures were lower in 2008-2012 than in 2003-2007 (MCCIP, 2013); but seven of the ten warmest years on record have nonetheless occurred in the last decade, with the strongest observed warming in the southern North Sea (Wadey et al, 2013).

By the end of the 21^{st} century it is almost certain that there will be more unusually hot and fewer unusually cold days almost everywhere and that heatwaves will be longer and more frequent (IPCC, 2014a). However, unusually cold winters may also still occur from time to time.

4.2 Rainfall

There has been no particular trend in annual average rainfall in the UK since records began. Average annual total rainfall in the 2080s is not projected to change significantly from the baseline period of 1961−1990 under medium emissions scenario. However, projected seasonal changes are likely to be particularly relevant to the inland navigation sector. Winter rainfall has increased in Scotland and northern England over the last 50 years (Watts and Anderson, 2013). Projections suggest further and more widespread increases combined with significant summer reductions in many areas (UKCP09).

The medium emissions scenario, 50% probability UKCP09 projections suggest the following changes in precipitation in the UK by the 2080s:

- an increase in winter precipitation of between 10% and 20% across much of England and Wales, with an increase of up to 30% across central southern Britain
- a reduction in summer rainfall of between 10% and 20% in Scotland and the North of England; 20% to 30% in East Anglia, the Midlands and Southern Central England (i.e. covering much of the canal network); and possibly up to 40% in the South and South West of England (UKCP09).

In addition, more of the rainfall is expected to fall in intense episodes, particularly in winter.

The winter of 2013-2014 was characteristic of what might be expected more in the future (Met Office, 2014a). A series of persistent, powerful storms and heavy rainfall resulted in England and Wales receiving 435mm of rain, the wettest winter since records began in 1766. In February 2014, parts of the South East and Central Southern England received almost two and a half times the monthly average rainfall. However, it is too early to conclude that these events were linked to or caused by climate change (Met Office, 2014a).

Projections for more extreme precipitation events are not confined to the winter months. Days of very heavy rain are likely to become more frequent throughout the year (Met Office, 2014b). Over much of the UK except the south of England, the wettest day in summer could be up to 10% wetter. Any increase in the frequency of extreme rainfall events in the summer months could have potentially significant implications for inland navigation activities (IWAC, 2009).

Significant changes in seasonal rainfall combined with higher temperatures will impact on river flows and water levels in the canal network. River flows are a function of evapotranspiration as well as precipitation, and there are uncertainties about the projections for both parameters particularly evapotranspiration rates (Kay et al., 2013). By the 2050s, changes in summer river flows could range from a 20 per cent increase through to an 80 per cent decrease[11]. However, to date there is little evidence to date of changes in very low flows and there is no clear pattern of drought (Watts and Anderson, 2013). The Met Office (2014b) similarly concludes that there is no evidence of a link between recent dry summers and climate change.

4.3 Sea level rise

Sea levels have risen by approximately 0.14m since the beginning of the 20th century, as much as doubling the risk of flooding at many coastal locations (MCCIP, 2013). Mean estimates of future sea level rise have remained relatively steady over the past decade, with the medium emissions climate change scenarios suggesting a rise of around half a metre by the end of the 21st century (Wadey et al, 2013). Research indicates that eustatic sea level rise is now outpacing isostatic rebound in Scotland, but there are nonetheless some remaining differences in regional projections (Rennie and Hanson, 2011; Masselink et al, 2013) - notably slightly higher increases in the south and east relative to the north and north-west. Central 2080 estimates under the medium emissions scenario for London and Cardiff, for example, are for an increase of 0.36m with projections for Edinburgh and Belfast being 0.24m and 0.25m respectively (MCCIP, 2013).

Potentially more important insofar as port infrastructure is concerned, however, is the UKCP09 high++ scenario, an 'unlikely but plausible' scenario under which sea levels could rise between 0.9m and 1.9m by 2100 as a result of the collapse of the Antarctic sea ice sheet. Partly for this reason, longer term rates of sea level rise are very uncertain (IPCC, 2014b; Nicholls et al., 2011).

4.4 Wave climate, wind, storms and sediment transport

In addition to sea level rise, wave climate, storminess and high winds are all of significance to port operations and are to some extent inter-related. Changes in these variables can also affect erosion and sediment transport. These are all parameters where there is lower confidence in the projections.

UKCP09 shows little evidence of a change in the frequency or intensity of UK storms. There is strong natural variability in wave climate and the role of anthropogenic forcing is uncertain (Woolf and Wolf, 2013). There is currently no consensus on the future storm and wave climate *inter alia* because of the diverse projections of future storm track behaviour. No significant evidence exists for future changes in storm related extreme sea levels for the UK due to low confidence in the simulation of extreme winds in climate models (Horsburgh and Lowe, 2013). Notwithstanding that changes in wind climate affect both large-scale wave climate and longshore current regimes (IPCC,

[11] http://www.environment-agency.gov.uk/research/137595.aspx **Accessed 18th March 2014**

2014b), at present the indications are that both storm surge levels and seasonal mean significant wave heights will increase only modestly (by less than 0.1m in terms of mean significant wave height) (Masselink and Russell, 2013). There is also low confidence in trends calculated from measurements of mean and extreme winds (IPCC, 2014b).

Despite these various uncertainties, it is widely accepted that if a storm surge is superimposed on a high tide, flooding or rapid erosion can result - and even a modest increase in storm surge levels combined with raised sea levels compared to the present situation could therefore increase flood risk. Various papers confirm the link between sea level rise and the increasing probability of extreme events in coastal regions, with direct consequences for both coastal flooding and erosion (Wadey et al (2013) although it is expected that mean sea level rise will overshadow the changing frequency and magnitude of storm surges and wave climate over the next 100 years (Horsburgh et al., 2011). The Met Office (2014b) concludes, meanwhile, that improving understanding of changes in storminess is an urgent research need.

Sea level rise will impact sediment re-distribution (IPCC, 2014b). 17% of the UK coastline is already suffering from erosion, and erosion rates on these coasts are expected to increase due to sea level rise. The Foresight project (Government Office for Science, 2004) confirmed that the areas under the greatest threat from erosion are along major estuaries (e.g. Severn, Thames and Humber) and along the east coast. However, predicting changes in erosion is problematic in the absence of a clear understanding of coastal processes under a scenario of sea level rise. Increased erosion means that more sediment is being made available for transport and the same processes that lead to erosion can also affect patterns of sediment movement.

4.5 Fog

Boorman et al. (2010) review the UKCP09 regional climate model projections to determine possible future changes in fog frequency, concluding that reductions in numbers of fog days are likely in most UK regions throughout all seasons with the exception of southern Britain. Northern Britain and North Wales might expect reductions of 50% or more in the number of winter fog days but the equivalent in southern Britain and the Midlands is a projected increase of between 0% and 30%. In autumn reductions over most of the UK of 10% - 30% are projected with the exception of the Scottish Islands which might experience an increase. There is, however, a great degree of uncertainty attached to fog predictions.

4.6 Arctic sea ice

The last seven years (2007-2013) have witnessed the seven lowest Arctic sea ice extents ever recorded (MCCIP, 2013). Arctic sea ice cover is more than 90% certain to continue shrinking and thinning (IPCC, 2014b) and models predict that the Arctic Ocean will be almost ice free in summer sometime between by 2030 and 2080 (Giles et al., 2013).

However, there is also some suggestion that melting in the Arctic could result in an increase in cold winters in the UK and Northern Europe, partly counteracting the direct warming effects of climate change (MCCIP, 2013).

5.0 Potential impacts of climate change for port and navigation infrastructure

The changes in climate variables highlighted above will have various consequences for the effectiveness of port and inland waterway infrastructure and associated navigation operations, both as a result of shifts in the mean and during extreme events. In some cases there are also regional differences in how changes in certain climate variables will affect activity.

5.1 Potential implications for ports and harbours

5.1.1 Sea level rise combined with changes in storms, wind, wave climate and sediment transport

Maritime navigation and port operations are directly affected by a number of metocean variables including sea level, wind, waves and ice, but more complex geographical response variables such as ocean circulation and estuarine morphology are also relevant (PIANC, 2008a).

Insofar as marine infrastructure in the UK's major ports is concerned, isostatic and eustatic changes have long been factored into design. Relative sea level rise projections have not changed materially (i.e. in design terms) since many modern facilities were constructed. The same applies to many marinas and leisure navigation facilities. Of more potential concern to these ports and marinas would be the UKCP09 high++ scenario: a rise in sea level of this magnitude within the design life of existing infrastructure would cause far greater problems than the currently projected mean sea level increases. Current sea level rise projections seem likely only to be an issue in ports and harbours relying on older infrastructure designed according to the then prevailing conditions. Such – often smaller - facilities probably already experience operational problems in severe weather.

The relative timing of the high tide and the storm surge is crucial for some ports and harbours, particularly in the south west (Wadey et al, 2013) where the tidal range is up to 12m. Wright (2013) similarly discusses the relative susceptibility to storm surges of ports in the southern North Sea and the Bristol Channel where the funnel-shaped coastal configuration can exaggerate the height of the surge and where, in combination with strong winds, there could be a significant increase in flood risk. This inter-relationship was highlighted during the storms of winter 2013-2014 when, for example:

- the ABP ports of Hull, Goole, Immingham, Grimsby, Lowestoft and Ipswich were all affected by the tidal surge of 5th December 2013. The Port of Immingham was temporarily closed; road traffic was disrupted in Hull and roads around the port in Lowestoft were closed due to flooding[12]
- a number of smaller ports including Boston and Wells-Next-the-Sea also experienced disruption and damage. In Boston, although the port itself escaped relatively unscathed *inter alia* as a result of taking rapid and effective action in response to the warnings received, local road infrastructure was severely disrupted and this had a consequent short term impact on port activity
- ports and harbours along the Bristol Channel experienced significantly increased water levels during the 3rd January 2014 event with some of the greatest damage being experienced when a storm surge coincided with high spring tides[13]. Problems included overtopping at The Quay, near the lock at Gloucester Docks, the closure of the Portway road link to Bristol Port and flood warnings *inter alia* for Royal Portbury Dock[14].

Various authors note that there will be operational issues if winter weather becomes rougher around UK (Pinnegar et al., 2012). Port of Dover (2011) in their adaptation report confirm how - depending on sea state, wind speed and wind direction - severe weather can already affect safety of navigation leading to timetabling delays (e.g. for ferry services) and, in certain conditions, to port closures. ABP's ports including those on the Humber similarly identified key risks relating to engineering and VTS functions associated with projected changes in sea level, flooding frequency, air temperature and storminess (ABP, 2011). Any increase in the frequency of high winds could lead to more frequent disruption to the boarding or landing of pilots or to escort tug connections at sea (MHPA, 2011).

Wind projections are also highly uncertain but very relevant. Wright (2013) notes the potential for more frequent stronger winds to affect bulk gantry and container crane operations and stacking, ship handling issues, pilot transfers and bunkering. PIANC (2008a) discuss other wind-related issues including any reduction in calm weather windows affecting berthing and departure times, impacting particularly on high-risk terminals (e.g. oil and gas). Such effects may lead to a requirement to enlarge anchorage areas for waiting vessels.

Although projections are also highly uncertain, wave climate changes affecting operations such as roll-on roll-off services could potentially lead to disruption to ferry services – for example off North West Scotland where disruption of 5% of sailings at present could increase to 12% by 2020 as a result of a combination of sea level rise,

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[12] http://www.abports.co.uk/newsarticle/76/ Accessed 4th April 2014
[13] http://www.gloucestercitizen.co.uk/Gloucestershire-roads-left-water-River-Severn/story-20397453-detail/story.html#ixzz2xrlA3Zb7 Accessed 4th April 2014
[14] http://www.bristolpost.co.uk/Severn-storm-surge-Latest-updates-Bristol-area/story-20395641-detail/story.html Accessed 4th April 2014

storm surges and increased storminess (Pinnegar et al., 2012). A practical example of this type of disruption was provided by the winter 2013-2014 storms when it was widely reported that fishermen in the south west of England were unable to work for several weeks because of extreme sea conditions[15]. Nonetheless it remains the case that there is little evidence of any significant changes in wind and wave climate (UKCP09) and the Met Office (2014b) conclude that it is too early to say whether such events are linked to climate change.

In the case of the Mersey (MDHC, 2011), extreme high water could cause the uncontrolled opening of lock gates, in turn affecting navigational safety and the loading/movement of products. Inundation of tidal structures as a result of sea level rise is also an issue for some inland navigation authorities (CRT, 2012).

Whilst the robust nature of port infrastructure may reduce its vulnerability to erosion *per se*, increased erosion and sediment transport changes within the wider system may increase dredging requirements in navigation channels, berth boxes, etc. In their 2011 adaptation reports, several major ports highlight changes to sedimentation patterns as potentially affecting navigational access to the port in turn requiring changes in dredging regimes. Ports will also have to deal with any concerns about the effect of dredging on estuarine and coastal geomorphology and ecology as these are also affected by changing climate (Masselink and Russell (2013), Reeve and Karunarathna (2009), Brooke (2013)).

5.1.2 Rainfall

In addition to the risk of flooding from the sea causing damage to or inundation of port infrastructure, and in line with the UK 2012 Climate Change Risk Assessment (Ramsbottom et al., 2012), several ports' adaptation reports (2011) also identified an increased risk of surface water – or pluvial - flooding due to changes in rainfall patterns. Pluvial flooding could result from either long term seasonal changes or an increased frequency of extreme events. Some of these reports also highlight increased winter rainfall as potentially resulting in damage to cargoes (e.g. animal feed) being handled or stored (MDHC, 2011).

5.1.3 Fog

The east coast ports of Port of London Authority (PLA, 2011) and Harwich Haven Authority (HHA, 2011) note that any increase in the incidence of fog could cause problems - in the PLA's case potentially resulting in closure of parts of the port because of the increased risk of collision on the busy tidal Thames through London. On the west coast, however, ports such as Milford Haven may benefit from a reduction in the number of fog days (MHPA, 2011).

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[15] http://www.bbc.co.uk/news/uk-england-26448635 Accessed 4th April 2014

5.1.4 Air and water temperature

Whilst gradual increases in average ambient temperatures are unlikely to significantly affect most port operations (other than possibly increased number of pest species causing damage to stored products such as grain; MDHC, 2011), extremes of heat could have several operational implications. Plant and equipment designed to operate in temperate regions may malfunction in very high temperatures (Wright, 2013). Tarmac surfaces may melt or rails may buckle (as was recorded in the 2003 heatwave) causing transport difficulties within the port estate or affecting onward transport (Met Office 2014b). In common with many other businesses (Baglee, et al., 2012) ports may also need to invest (e.g. in air-conditioned vehicles or offices) to protect the welfare of staff and ensure acceptable working conditions.

Insofar as exceptionally cold weather is concerned, Wright (2013) acknowledges the potential for benefits if the frequency of snow and ice reduces. He also notes the problems cold weather causes for travel and transport beyond the port (both personnel and cargos) and the potential for snowfall disruption on site (e.g. to straddle carrier operations). Milford Haven (MHPA, 2011) raise equivalent issues including employees being unable to travel to work; and the effects of very low temperatures (including diesel freezing) on port operational viability. Notwithstanding the general warming, there is therefore still a need to plan for exceptionally cold winters (Met Office, 2014b).

Water temperature increases could have particular implications for fishing ports and harbours. The northward movement of certain marine fish species as sea temperatures increase could adversely affect both sea angling and commercial fishing activities, with potentially significant local economic implications. Northern Ireland could be particularly badly affected by climate-induced changes (Simpson, 2013). Marine recreational fishing, which currently makes an important contribution to the local economy, is vulnerable not only to species migration but also the any increase in strong winds and gales. Indeed, tourism throughout Ireland is dependent on air and sea travel: any increase in the frequency of bad weather could therefore affect tourism more generally.

As warm water species appear in greater numbers in UK waters and as their exploitation becomes commercially viable, both commercial and recreational fishermen are responding to new opportunities (MCCIP, 2013). It is possible that species migration, availability, populations, etc. could lead to an increase in fishing effort in some areas, with associated requirements for supporting infrastructure. European fisheries policy will, however, also be important in determining the extent to which investment in infrastructure is justified.

Water temperature increases will further affect the viability of infrastructure-dependent recreational activities such as wildlife watching tours and other forms of recreational boating and water sports.

Finally, air and water temperature increases will contribute to the well-documented reductions in the extent of Arctic sea ice. The first two commercial vessels used the Northern Sea Route between Asia and Europe in 2009. 34 ships did so in 2011. By 2030 the Northern Sea Route and the North West Passage could together account for 2% of global shipping traffic with as much as 5% by 2050 (MCCIP, 2013).

5.2 Potential implications for inland navigation

5.2.1 Precipitation

Changes in precipitation, including seasonal variations and increases in the frequency of extreme events (i.e. floods and droughts) are likely to have consequences for inland navigation - both directly and, depending on evapotranspiration rates, for flow levels in rivers and canals.

In addition to potential damage to land-based assets and flooding of culverts caused by more frequent surface water flooding, CRT (2012) highlight that increased precipitation and associated higher and/or faster flows can:

- exacerbate bank erosion and scour around structures (e.g. bridge abutments);
- lead to overtopping occurring more often and with greater depth; and
- increase the risk/frequency of flood-induced breaches (e.g. failure of earth embankments).

Changes in the frequency and duration of severe weather events could also affect inland navigation infrastructure through changes in sediment run-off, sediment transport, or deposition (IWAC, 2009). Additional sedimentation in navigable water bodies can increase the risk of groundings; it can also reduce flood conveyance capacity in waterways or storage capacity in reservoirs. In both cases there might be an associated requirement for increased dredging.

Too much water can raise safety concerns including strong streams and reduced clearance (headroom) under low structures. In the longer term, infrastructure may need to be modified to ensure continued viability of navigation (IWAC, 2009).

Too little precipitation can also cause significant problems. One of the biggest risks to inland navigation transport is the availability of water to maintain adequate depth for safe navigation, particularly in the canal network. There is a growing gap between supply and demand as pressure increases on water storage infrastructure, including reservoirs that supply the canal system (Thornes et al, 2012).

Low water levels in rivers and especially in canals can threaten the integrity of navigation infrastructure: removal of hydraulic support from the waterside face can lead to an increased risk of failure. Operational concerns include an increased frequency of groundings and the risk of navigation closures on safety grounds.

5.2.2 Air and water temperature

The additional evapotranspiration associated with higher air temperatures – at least in some months (Kay et al., 2013) - could lead to local drying out and fissuring of clay embankments and other earth structures with consequences including settlement, erosion and undercutting (Brooke and White, 2010). Desiccation can also result in subsidence damage to buildings and other structures (CRT, 2012).

Changes in temperature can affect characteristic vegetation types. Warmer summers may extend growing seasons with consequences for vegetation management both in-stream (where warmer waters are likely to increase aquatic weed growth potentially leading to thick mats affecting safety of navigation and therefore require clearance) and bank side (riparian and towpath). Structural integrity could be affected where vegetation serves an engineering purpose: if the characteristic root mat is lost, a structure may become more vulnerable (Brooke and White, 2010). Non-indigenous invasive species may become established, potentially affecting the viability of navigation on the watercourse or the integrity of the river or canal banks.

Warmer water temperatures can also lead to an increased prevalence of algal blooms with potential consequences for the recreational use of the water body.

In winter, parts of the inland navigation system freeze over, preventing vessel movement and increasing the risk of damage to both vessels and infrastructure. Warmer winters may reduce this risk (Thornes et al., 2012).

6.0 Key thresholds and sensitivities

Various authors recognise that climate change will mainly compound the existing risks, faced on a daily basis by transport operators (e.g. Thornes et al., 2012). However, some ports do identify existing thresholds above which operations are constrained or halted. ABP (2011), for example, note that certain of their ports will close if sustained wind speeds exceed 55 knots from a SSW or WSW direction; that cranes cannot be operated in gale force 9 or greater; that pilotage is suspended in wind speeds exceeding 40 knots; and that the efficiency of refrigerant units is compromised if air temperatures exceed 30°C. Equivalent thresholds will exist for many other ports. Although confidence in the projections for most of these variables is currently low, any significant increase in the frequency of events exceeding these thresholds would have detrimental impacts on port operations.

This low confidence also means that, at present, it is assumed sea level rise will be the 'controlling factor' in terms of the significance of any impacts. From this starting point, it is reasonable to assume that ports and harbours with modern infrastructure should not be significantly affected by sea level rise and increased storminess within the next 20-50 years (i.e. the residual infrastructure lifetime). The high++ sea level rise scenario, however, would compromise operational efficiency at some ports. Quays are at a fixed elevation and regular inundation would increase the risk of damage to both built infrastructure and cargoes (Thornes et al., 2012); indeed, even based on current projections, ports and harbours relying on older infrastructure and/or in relatively exposed coastal locations could experience operational difficulties during extreme events.

The inland navigation sector will be sensitive to changes in seasonal precipitation and to increases in air and water temperature in the medium to long term. However, there do not seem to be any specific common 'thresholds' beyond which the network overall would be expected to experience problems. In the short term, extreme events are nonetheless likely to cause damage and disruption, taking into account the age and condition of infrastructure in parts of the existing network.

7.0 Assessment and management of climate change risks

7.1 Assessing and managing risks in ports and harbours

Seaports operate in a dynamic physical environment and infrastructure is designed to cope with extreme conditions. Port of Sheerness, Mersey Docks and Harbour Company, The Felixstowe Dock and Railway Company and PD Teesport are amongst the harbour authorities who stress in their 2011 adaptation reports that port operators already need to be prepared for extremes of rainfall, storm surges, heatwaves and high winds.

Ensuring navigational safety is of paramount importance to harbour authorities. Where climate change could have safety implications, early action will be needed to reduce vulnerability and increase resilience. Wright (2013) for example highlights that a combination of sea level rise and storm surges increases the risk of water ingress into sensitive VTS equipment systems with consequent power loss - potentially leading to a temporary closure of the port for safety reasons. Harwich Haven Authority (HHA, 2011) was one of a number of ports to identify the need to move sensitive equipment out of flood risk areas as a high priority adaptation action.

Insofar as other types of infrastructure are concerned, many of the UK's major ports have expanded in recent decades and, as such, have relatively modern infrastructure. The design of infrastructure less than (say) 20 years old will already have taken into account factors such as sea level rise; the same applies to modern marina infrastructure. Much new port infrastructure will have a 50-100 year design life; physical assets such as cranes and other cargo handling equipment are likely to have a design life of 20-50 years.

Investment decisions will have been informed by data available at the time. However, when the contingency provisions in the design (including the factor of safety) are also taken into account, it is clear that infrastructure in some ports and marinas will not be especially sensitive to minor changes in current sea level rise projections. Changes beyond 2050-2080 will then most likely be accommodated when the next programme of capital works is undertaken (e.g. PD Teesport, 2011).

There are other examples, however, of ports, harbours and marinas where day-to-day operations rely on much older infrastructure, designed to withstand 'normal' (i.e. pre-climate change) conditions. In the longer term, quay elevation will need to be raised and cargo-handling equipment in some ports may need to be modified as sea levels rise (Thornes et al., 2012). Where assets are poorly maintained or are reaching the end of their useful life, they may be especially vulnerable to extreme events and less able to accommodate long-term change. Breakwaters and harbour walls in particular may be overtopped more frequently, or may be damaged by storm events. Piling or other forms of protection may be more susceptible to washing out and to erosion.

Incorporating climate adaptation measures into new or replacement infrastructure tends to be preferred because retrofitting existing infrastructure can be both technically complex and expensive. There are few costed adaptation examples from the port and harbour sector, but Burgess and Townend (2004) provide an example of where raising coastal defence structures required re-engineering of the structure to mitigate scour around the toe, increasing costs by two to four times in order to provide a similar level of performance.

In addition to adapting physical infrastructure, some port activities and operations including harbour authorities' conservancy functions may need to be modified. Any increase in storminess and in particular wind strength could lead to safety issues for berthing or pilotage operations. Exceptional storms could also affect sediment transport and hence dredging requirements. Any increase in the incidence of fog could cause operational problems.

It will be vital for ports to understand which assets and operations are vulnerable in order to be able to strike an acceptable balance between the potentially high costs of retrofitting port infrastructure, and the cost implications of climate-induced damage and disruption (and possible temporary port closures). Climate change projections are maturing but are still subject to change. Activities such as raising a breakwater or installing new quayside equipment can be very expensive. Adapting to climate change will inevitably require investment at some time in the future. Decisions about *when* to invest, however, will depend on local circumstances. Where there has been extensive recent investment in modern infrastructure (including many of the major ports), there may be no perceived urgency to respond to climate change. For other - typically smaller – ports relying on older infrastructure, investment in adaptation may be required relatively earlier or planned renewal projects may need to be brought forward.

Acquiring consent for marine works can be a lengthy process. Construction in the marine environment can take many months and sometimes years depending on the scale of the activity. Adequate data are essential to inform both the design and the decision on *when* the investment is required. A port or harbour may need to decide, for example, whether to invest in retrofitting its existing infrastructure in ten years time, or to incorporate additional capacity to cope with climate change when the asset requires renewal anyway in twenty or thirty years time.

With the exception of sea level rise, there is low confidence in the current projections for many of the climate variables of direct relevance to port operations. Understanding the direction and rate of change in these critical climate variables is therefore likely to rely on locally acquired data. The need to make timely decisions about climate change-related investment should provide an important incentive for ports to collate or secure access to existing data collected by others; to undertake targeted new data collection where necessary; and to manage these data over the medium to long term. Effective adaptation will require a sound combination of technological development and long-term planning (Thornes et al., 2012). A robust, long term dataset will be vital in:

- informing decisions on when to upgrade or replace existing infrastructure
- highlighting trends in variables such as wind and wave climate which may require a change in working practices for procedures such as pilotage, berthing, or stacking
- providing an invaluable baseline for future expansion or development projects.

The above discussion highlights two further important considerations: awareness and capacity. Smaller ports and harbour authorities may be less aware of climate change issues; they may also have less capacity to be able to respond, for example in terms of data collection and management and/or investment opportunities. As the operations of some of these organisations will also rely on older infrastructure, the overall risks of climate change to their activities are likely to be relatively greater than the picture painted by the UK major ports' 2011 adaptation reports.

7.2 Assessing and managing risks for inland navigation

Whilst rivers are also dynamic natural systems, the extent of natural variation for which inland navigation infrastructure is designed is proportionately less than for seaports (i.e. whilst high river flows have to be accommodated, there is no equivalent to tidal range). Canals are even less dynamic. This historic 'consistency' in terms of design requirements means that inland navigation infrastructure is potentially more susceptible to the effects of climate change than its coastal and estuarine navigation equivalent. As such, many inland navigation authorities are likely to have to replace, upgrade or retrofit infrastructure to accommodate the effects of changes in precipitation, temperatures, etc.

Depending on the nature of the assets at risk, adaptation might involve raising, strengthening, replacing or otherwise modifying quays or berths, embankments and other flood defence infrastructure, or exploring alternative (e.g. non-structural) flood risk management solutions. Weir or sluice capacity or headroom issues may also need to be addressed; bank erosion and the effects of desiccation may require attention; and an understanding of any changes in sediment management or dredging needs will be required. Low flow conditions associated with reduced (summer) rainfall may affect the structural integrity of infrastructure and/or mean that new water supply or water storage options have to be assessed.

As with ports, harbours and marinas, decisions on risks and hence investment requirements will have to be based on an understanding of the design and residual life of existing assets and infrastructure; the nature of activities undertaken and the characteristics of users; and the relevant climate change variables. However, as relatively more of the network relies on older infrastructure designed for pre-climate change conditions, inland navigation may be more vulnerable to extreme events and less able to accommodate the effects of climate change. Embankments may be overtopped more frequently or damaged by high flows. Piling or other forms of bank protection may be more susceptible to washing out and to erosion.

Where infrastructure is in good condition, but is simply unable to cope with the consequences (for example) of changes in seasonal precipitation causing more frequent higher or lower river levels, climate change may be costly to accommodate. The identification and collation of existing information, the collection of new data and the management of long term datasets will therefore be essential to inform timely investment decisions. Adequate data will help the navigation authority to decide whether to invest in upgrading existing infrastructure or wait until that infrastructure is due to be replaced; and when to invest – for example in a new piece of machinery to manage vegetation (i.e. the point at which this becomes an economically more efficient option than continuing to employ extra manual labour for the same purpose). A long-term data set can be crucial in informing such 'just-in-time' decisions. Indeed a key finding of the IWAC report (2009) was the need for effective, long term, data collation and management.

Where measures – for example retrofitting flood resilience measures on high risk assets or automating key structures - are expensive, investment in information gathering can allow the organisation to prioritise so as to incur costs in a predictable and managed way. CRT (2012) highlight how a combination of modelling (e.g. of breach risk), improving asset inspection procedures and associated training, and agreed operational practices and design standards all contribute - enabling the organisation to make well-informed and timely decisions on infrastructure investment.

Installing or updating telemetry and SCADA (supervision control and data acquisition) systems, generating a targeted long-term dataset, and undertaking regular risk assessments are likely to be important actions for all navigation authorities (IWAC, 2009).

Regular monitoring and condition assessments are also vital – for example where fissuring, settlement, erosion or undercutting could affect inland navigation infrastructure. These activities will support site-specific decisions on whether and when maintenance, raising, strengthening or retro-fitting actions are required to ensure the continuing integrity (condition, capacity and resilience) of physical assets. Monitoring will also be important in:

- informing decisions on appropriate vegetation and wildlife management measures, including adaptive management solutions;
- enabling inland navigation authorities to establish the viability of navigation in times of exceptionally high or low flow, ensuring effective communication of warnings and managing user expectations in the event of a navigation closure.

Any works to replace or construct new physical assets must be 'future-proofed' so that their design takes into account relevant climate change projections. Working in partnership with the relevant flood risk management agency (for example, Environment Agency in England) will enable the navigation authority to understand any role of navigation infrastructure in flood risk management - for example flood flow conveyance.

For inland navigation authorities, however, a number of other factors will also be critical in ensuring climate change risks are handled appropriately and cost-effectively. Most inland waterways are used for recreational boating. Some users are experienced in navigating in a range of conditions, but others are not so. Communicating with users, particularly across a wide network is more difficult than in a port situation, and compared to the marine environment a relatively higher proportion of recreational boaters are unfamiliar with handling a vessel during an extreme event.

Overall therefore, and when the low investment levels in much of the inland waterway network are also taken into account, it seems likely that inland navigation authorities may both face additional challenges and find climate change adaptation comparatively more difficult than many of the commercial ports.

8.0 Broader drivers and interactions

8.1 Drivers of change potentially affecting UK ports and harbours

Climate change adaptation in the UK ports and harbour sector needs to take place in the context of various other drivers of change.

8.1.1 World trade and shipping routes

Notwithstanding the economic crisis it is clear that trade patterns are changing globally. Recent years have seen significant changes in trade with emerging key players such as China, India and Brazil. The move towards unitisation (including containerisation) continues to increase and the trend towards larger ship sizes also seems likely to continue[16]. Several UK ports – including Felixstowe, London, Bristol, Liverpool and Southampton - have developed or are developing to accommodate the largest container ships. Approach channels have been deepened and new quayside infrastructure installed. As container vessel size increases, more attention is likely to be paid to the use of feeder vessels to transport containers to ports unable to accommodate the larger vessels. This is preferable to transport by road with its associated consequences for both emissions and congestion (PIANC, 2011).

8.1.2 Energy and fisheries policies

At a UK level, in addition to unitisation, two of the most important drivers of change in port and harbour activities in the last 10-20 years have been energy policy and fisheries policy. Specifically, until very recently there has been a strengthening move towards offshore wind and other marine renewables. This has enabled certain ports to develop to service these sectors. The fishing fleet, meanwhile, has reduced considerably over recent decades with inevitable consequences for ports and harbours supporting fishing activity. The 2014 re-negotiation of the EU Common Fisheries Policy seems unlikely to significantly improve the situation in the short term, but the longer-term projections associated with changing water temperatures (IPCC, 2014a; b) could have local implications for port and harbour infrastructure demand.

8.1.3 Environmental legislation

Since the early 1980s, UK port and harbour development has needed to demonstrate compliance with an increasing range of environmental protection legislation - much but not all of it derived from the EU. Regulations such as those implementing the EU Habitats and Birds Directives, Water Framework Directive and revised Waste Framework Directive all have implications for navigation-related infrastructure developments in that they focus attention on avoiding, mitigating and compensating for any adverse impacts of an activity or new development on protected environmental features. These features will also be affected by climate change.

8.2 Drivers of change potentially affecting inland waterways

With the advent of cheap foreign holidays in the 1960s and 1970s, recreational use of both harbours and inland waterways began to reduce. In recent years, however, this

[16] **DNV, 2012. Shipping 2020. Norway** **file:///C:/Documents%20and%20Settings/Jan/My%20Documents/Downloads/Shipping%202020%20-%20final%20report_tcm141-530559.pdf Accessed 4th April 2014**

trend may have started to reverse with the increasing popularity of 'stay-cations' and as the UK's attractiveness as a destination for overseas visitors has increased. In 2009 tourism was worth nearly 9% of UK GDP (Simpson, 2013), with water-based activities such as sailing, diving, sea angling, kayaking and wildlife experiences (e.g. boat trips to watch whales, seals or seabirds) being amongst those experiencing the greatest recent increases. Such activities are strongly weather-dependent.

Climate change – in particular warmer summers in the UK – may consolidate this trend as more people stay in the UK for their holidays. Indeed, given the projected increases in summer temperatures and in the frequency of heat-waves and droughts in southern Europe, northern European countries like the UK may become more attractive for holidays (Defra, 2012). Such changes would lead to a related increase in absolute numbers engaging in recreational water sports, not only in the freshwater environment but also in coastal and marine areas. Simpson (2013) suggests that parts of coastal England are particularly likely to benefit from both increased tourism and the opening up of new destinations as a result of rising summer temperatures and milder 'shoulder' seasons.

9.0 Interdependencies

<u>9.1 Port and harbour interdependencies</u>

9.1.1 World trade

Much UK port traffic is international in nature. Climate-related factors that could affect future patterns of world trade, with potential consequences for UK seaports include:

- the reduction in Arctic sea ice and the associated opening of the North West Passage and North East Passage (Pinnegar et al., 2012) which will reduce the distance from Europe to the Far East by some 3000 km, providing quicker, shorter journeys with potentially significant savings in both cost and carbon;
- climate-induced changes in economic productivity: if cropping patterns and other types of economic activity around the globe alter at a regional level as a result of climate change (IPCC, 2014a), these changes could have implications for the affected nations' imports and exports and hence for seaborne trade.

9.1.2 Road and rail transport

Disruption to port activities can disrupt supply chains (Becker et al., 2012) Parts of the transport network on which many UK port activities depend are especially vulnerable to climate change risks. 12,000 km of road and 2,000 km of rail are already at risk of flooding, rising to up to 18,000km and 2,000 km respectively at risk by 2050 (Thornes et al., 2012). Flooding or erosion of key transport infrastructure – as evidenced by the disruption caused during the winter storms of 2013-2014 – can have significant implications for transport to and from ports, in turn impacting on port operations.

In addition to flooding and erosion of key transport links, other climate-related risks to transport infrastructure include heat damage to roads, buckling of rails due to excessive heat, bridge failures caused by scour, impacts on structures caused by floating debris or washing out of fill, and landslides (Thornes J et al, 2012).

9.1.3 Energy industry

Various authors highlight the vulnerability of parts of the energy sector to extreme weather events, with knock-on consequences for other energy-dependent sectors including ports. For example the capacity of power stations exposed to significant likelihood of flooding is expected to increase from 10 GW currently to up to 22 GW by the 2050s (McColl et al., 2012).

In addition to causing disruption to terminal operations, navigational safety could be compromised if VTS systems are affected by power outages, in turn likely forcing the temporary closure of the port. Whilst some major ports may have back-up generators (e.g. ABP, 2011) or similar provisions to help ensure safety of navigation is not affected, other port operations including cargo loading and unloading typically depend entirely on external energy providers. Prolonged or frequent power outages can therefore have very serious economic consequences.

9.1.4 Natural Environment

Climate change could make the prediction - and hence mitigation - of the environmental impacts of new port and navigation-related developments more challenging, not necessarily because the nature or magnitude of impacts will alter, but because climate change will affect natural habitats. Some species are particularly vulnerable to changes in water temperature. Intertidal mudflat and saltmarsh habitats are already being lost due to a combination of rising sea levels and a fixed line of flood defence particularly along urbanised coastlines (IPCC, 2014b), a phenomenon known as 'coastal squeeze'. Jones et al (2013) suggest that the percentage of UK saltmarsh at risk could increase from 30% to 43% by the 2080s. Potential direct or indirect impacts on saltmarshes already represent a key concern for many port or marina developments.

Climate change will increase the vulnerability of many of the habitats typically affected by port and marina developments, but there remain some significant uncertainties - for example in separating out the effects of climate change from other damage (Mieszkowska et al., 2013). Those planning new infrastructure projects will therefore need to accommodate these additional uncertainties.

Climate change is also expected to exacerbate existing problems with invasive non-indigenous species (Mieszkowska et al., 2013). Shipping has long been associated with the introduction of marine alien species, both through hull fouling and ballast waters.

The UK has yet to ratify the 2004 International Convention for the Control and Management of Ships' Ballast Water and Sediments, but measures on marine invasive species are also being explored to meet the requirements of the EU Marine Strategy Framework Directive and a new EU invasive species regulation will enter into force on 1st January 2015, although the extent to which this will apply to marine species is not yet clear[17]. Depending on the nature and effectiveness of technological solutions for ballast water exchange and/or treatment measures, there could be medium-longer term implications for ports and port infrastructure. Although it has historically been considered impractical and unnecessary for ports to undertake shore-side ballast water treatment[18], in future reception facilities for materials filtered out of ballast waters might need to be provided.

Finally, Mieszkowska et al (2013) identify that artificial man-made habitats (such as those in ports and marinas as well as coastal defence structures) can support high densities of invasive non-native species due *inter alia* to reduced competition from established native species. This type of effect can, in turn, enhance the 'stepping stone' effect whereby non-indigenous species spread via areas of suitable habitat in an otherwise inhospitable environment (for example via hard engineering structures in an area of naturally soft sediments).

9.2 Inland navigation interdependencies

Parts of the canal network depend for their operational effectiveness on an adequate supply of water from rivers or reservoirs. If this is not available, navigation is constrained. Measures such as enforced lock sharing may be required (Brooke and White, 2010) and, in extreme conditions, temporary closures of parts of the network may be necessary. In the longer-term, incentives to encourage boaters to use less water-stressed parts of the network might be used: however, such actions would clearly have significant consequences for the local economy in affected areas.

Other interdependencies identified, for example by Canal and River Trust (2012) in their adaptation report, include:

- the role of relevant regulators in taking action to reduce runoff rates and control flood risks from new development and (to promote) projects to increase flood storage
- the need for landowners to take measures to reduce soil erosion in land draining to canals and canal feeders, or to improve nutrient controls in reservoir catchments
- the responsibility of third parties in ensuring that their locks, weirs, and other tidal structures are operated so as to protect CRT assets upstream.

[17] http://www.endsreport.com/43379/eu-agrees-open-ended-invasive-species-regulation Accessed 17th April 2014
[18] http://www.ukmarinesac.org.uk/activities/ports/ph6_3_4.htm Accessed 30th April 2014

9.2.1 Modal shift

Finally, of relevance to both ports and harbours and inland navigation, the evolving low carbon agenda could in future change the balance of different modes of transport (Thornes et al., 2013). This could, in principle, favour a shift towards waterborne transport (PIANC, 2011). However, the commercial and sociological issues involved in such shifts are complex and future societal preferences are difficult to anticipate.

10.0 Adaptation requirements

10.1 Adaptation requirements for ports and harbours

10.1.1 Commercial ports

Several of the major ports' adaptation reports (2011) identified the possible need for flood risk management measures in the short to medium term. These measures are required not only to deal with flooding associated with storm surges but also with that resulting from increased precipitation and flooding of the port estate and access roads *inter alia* due to inadequacies in the drainage network. Other, mostly longer-term adaptation measures could potentially include:

- modifications of assets e.g. cranes which are susceptible to damage due to high winds and storm conditions
- changes to working practices which are subject disruption due to high winds or storm conditions e.g. pilotage, escort tugs, berthing
- reviewing cargo stacking or storage options to minimise damage due to changes in wind, precipitation or temperature
- raising quays and/or cargo handling equipment to accommodate sea level rise
- modifying dredging and disposal practices in response to changes in both sediment transport patterns and in relative sea levels
- tackling increased risks associated with high temperatures (e.g. melting of road surfaces or buckling of rails within the port estate; installing air conditioning in offices)
- resolving issues with water supply or water shortages.

Infrastructure modifications could also be required in response to changes in trade patterns, international supply chains or markets/demand for certain types of goods.

Flood risk management was high on the agenda of most of the major ports. Whilst there may be a short-term imperative to move sensitive assets out of flood risk areas, longer term options require careful thought. Where the costs of adapting physical infrastructure to an increased flood risk prove to be unacceptably high, or where conventional solutions such as raising and strengthening defences are technically unsustainable, ports and harbours may need to explore alternative options. Wadey et al

(2013), for example, anticipate a move towards pumped flood management systems complementing seawalls and flood embankments. Other options to accommodate a level of flooding (rather than preventing it) by improving infrastructure resilience or introducing flood-proofing measures might similarly be considered (IPCC, 2014b).

Another area in which the adaptation of infrastructure may be required is dredging and disposal. Where accumulated sediment is causing an increasing risk to navigational safety, additional dredging might be necessary. As dredging and disposal can be expensive and can have adverse environmental impacts, local factors will need to be used to assess whether there is a viable alternative to dredging (e.g. fluid mud navigation, current-deflecting walls (PIANC, 2008b)). If no feasible alternatives exist, the environmental assessment and identification of optimal dredging timing, method, etc. will need to consider that water quality and ecology are also likely to be affected by climate change (see Section 9.1).

The port or harbour authority can handle many of these actions and – if adequately resourced - can make the appropriate modifications to port contingency plans, master plans, etc. In other respects, however, continued port operational viability will depend on the actions of others, for example managing any implications for road and rail networks outside the port estate or for power supplies.

10.1.2 Marine recreational use

Insofar as marinas and other facilities supporting recreational use are concerned, many of the potential issues and impacts (and likely adaptation measures) will be similar to those required in ports and harbours. However, it is likely that water-based recreational activities and hence the infrastructure upon which they depend will be more affected by the vulnerability of certain types of habitat and species to climate-induced changes.

Recreational boating tends to take place in more sensitive, smaller and/or shallower water environments than commercial port activities. Coastal habitats in particular have experienced significant losses over recent decades, not only due to development but also to coastal squeeze (Mieszkowska et al., 2013). Whilst many recreational users already undertake their activities in an environmentally responsible manner, climate change could restrict recreational use if certain sensitive environments are judged to have reached their carrying capacity. The potential socio-economic opportunities associated with an increase in recreational water use as a result of warmer summer temperatures could therefore be tempered by constraints on the use of sensitive areas. Furthermore, changes in the distribution of species such as whales, seals, seabirds and some fish species (e.g. due to changes in water temperature) could have significant implications for the viability of wildlife-watching trips (Simpson, 2013) and for both commercial and recreational angling. In the medium to long term it is therefore possible that climate change could affect the nature, distribution and/or intensity of recreational use more fundamentally than it affects commercial ports. If such changes are significant, there could be associated implications for infrastructure requirements in harbours supporting these activities, with adaptation potentially involving the obsolescence of facilities in some locations and demand for new or improved facilities in others.

10.1.3 New infrastructure development

It will be vital for ports and harbours to understand the range of issues raised by climate change and to incorporate adaptation into new infrastructure that may still be in use at the end of the century (Becker et al., 2012). Those planning new developments will need to understand not only the consequences of climate change for infrastructure design but also for the natural environment in which the development will take place (Brooke, 2013). The vulnerability of certain species and habitats to climate change could affect the extension or expansion of existing infrastructure. As noted above, many ports, harbours and marinas are located in environmentally protected areas. Ensuring that environmental impacts are avoided or adequately mitigated or compensated can already be challenging when designing and developing new infrastructure. Climate change will affect both coastal and marine habitats and the ecosystem goods and services they provide. Identifying and mitigating the potential impacts of new infrastructure development could therefore become more complicated.

10.2 Adaptation requirements for inland navigation

The Canal and River Trust in their climate adaptation report (CRT, 2012) identify several high priority adaptation actions to deal *inter alia* with:

- damage to assets associated with river flooding
- inundation of tidal structures as a result of sea level rise
- flooding of culverts
- increasing run off of sediment particularly from agricultural land leading to an increased requirement for dredging.

Medium term actions (i.e. lower priority issues or those which are only expected to become significant over time) include measures to address:

- shortage of water to supply canals due to reduced summer rainfall
- ground subsidence causing damage to buildings and other infrastructure
- overtopping of canal banks because of inadequate weir or sluice capacity.

The IWAC report (2009) highlighted similar measures amongst a range of infrastructure-related actions to deal with the effects *inter alia* of high and low flow conditions and increased air and water temperatures. In addition to adapting existing physical assets, however, other operational and safety issues and management procedures may need to be addressed through a combination of warning systems, behavioural changes and, in some cases the provision of new infrastructure.

10.2.1 Adaptation implications of increased precipitation

In addition to addressing the potential damage to infrastructure and the physical capacity issues discussed above, high flow levels and more frequent strong stream conditions require user education and the issuing of warnings (CRT, 2012). On some waterways, it may also become necessary to provide additional moorings or safe havens and take other measures to ensure the safety of less experienced boaters (IWAC, 2009).

Adaptation may also be needed to reduce river bank erosion caused by increased flow. Rather than conventional and often expensive engineering such as steel sheet piling, 'soft engineering' solutions (e.g. willow spiling, plant rolls and coir revetments) may be used to stabilise the bank and minimise erosion. If the problem is caused or exacerbated by boat wash, additional measures including vessel speed restrictions can help to reduce erosion (Brooke and White, 2010).

10.2.2 Adaptation implications of reduced (summer) precipitation

By 2050, average summer river flows in England and Wales could reduce by as much as 50 to 80 per cent (Environment Agency, 2010). Two key areas of concern arising from these projected reductions are increases in the frequency of low flow conditions particularly in natural rivers, and the possibility of water shortages affecting the supply for canals.

As already indicated low flow conditions can increase the risk of groundings or affect the integrity of infrastructure through desiccation or the removal of hydraulic support from the waterside face. In such cases, monitoring to detect potential problems followed by appropriate maintenance will be vital.

As competition for water increases, summer water resource availability is likely to become more of an issue in the UK (CRT, 2012). Water allocation and water accounting measures are already being implemented in relation to domestic and agricultural/industrial uses in Mediterranean countries such as Spain and Portugal (European Commission, 2012). In the UK, the Lower Thames Operating Agreement (Thames Water, 2010) provides an example of where navigation was a factor in water allocation decision-making. More attention might be focussed on such agreements in future. The need to secure a long-term supply of water for dependent navigable waterways will require affected navigation authorities to prepare water resources, conservation and use strategies (ie. understanding and setting out their requirements). Particularly where there are uncertainties, this should also act as an incentive to become involved in others' strategic water planning initiatives, for example the preparation and review of river basin management plans under the EU Water Framework Directive (IWAC, 2009).

Low flow conditions can also have significant consequences for ecology because of the associated reduction in dissolved oxygen, upon which aquatic life depends. It will therefore be important to ensure navigation-related activities do not exacerbate the situation. Releasing stored water or holding water to maintain levels; operating locks and sluices to improve aeration; or placing constraints on dredging or boating activity can all help in this respect.

10.2.3 Sediment management

In order to reduce additional dredging requirements, sediment run-off can be managed (in cooperation with the landowner as necessary) through the creation of buffer strips, reed beds or similar. Buffer strips help to intercept run-off, reducing the amount of sediment and nutrient pollution entering the watercourse (Environment Agency, undated).

Removal of accumulated sediment from water storage reservoirs is a laborious and expensive process. Where monitoring indicates a potential problem, preventative measures such as buffer strips and silt traps should be investigated as adaptive management options. If sediment is allowed to accumulate to such an extent that the capacity of the reservoir is compromised, it may be necessary to seek an alternative water resource, further compounding any problems resulting from reductions in summer rainfall.

10.2.4 Behavioural challenges

Many of the adaptation measures relevant to inland waterways involve awareness raising and behavioural changes. Educating users about the implications of their actions, and how modifying their behaviour can both help to save money and protect the environment, can be an effective way of achieving shared objectives (Brooke and White, 2010). Self-imposed speed restrictions could save fuel (and money) as well as reducing breaking wash and hence bank erosion. A voluntary Code of Practice might be drawn up to educate users about water conservation measures when using locks. Raising awareness of safety issues and appropriate responses is similarly likely to become more important as the frequency of extreme events increases, and it will be critical to ensure for example, that users know: what to do in times of strong stream conditions or when encountering low flow conditions; the location of safe havens; and what measures to take in the event of entanglement in thick vegetation.

11.0 Opportunities

As well as challenges, climate change may also bring benefits. Some of the major ports adaptation reports (2011) identified potential beneficial effects and opportunities associated with climate change, for example:

- any reduction in the number of frost, snow or ice days could aid safe and efficient port operation
- rising sea levels could reduce dredging requirements in some ports, harbours and marinas
- climate change may present an opportunity to invest in on-site wind or solar renewable energy projects
- in harbours where commercial and recreational uses are (or could be) combined, increasing air temperatures could lead to increased opportunities in turn benefiting marina operators and other businesses.

Opportunities may also arise in the form of win-win solutions designed to meet both port and nature conservation objectives, for example the beneficial use of dredged material for habitat protection and enhancement projects (Brooke, 2013). Indeed, many initiatives for the protection or restoration of natural ecosystems are seen as no- or low-regret options – initiatives that will deliver benefits irrespective of climate change (IPCC, 2014b).

Warmer and drier summers are likely to have wider benefits for the UK tourism industry. Additional water-based activities will, however, need to be carefully managed to ensure that neither environmental nor recreational carrying capacity is exceeded. Marina and inland waterway managers will need to be vigilant: monitoring such changes; assessing their implications; and participating in relevant strategic planning and management initiatives to maximise opportunities in a sustainable manner. Local factors will determine the most appropriate management options for water, towpath and land-based recreational activities.

On inland waterways, the implementation of win-win measures can potentially combine some of the adaptation requirements of the navigation sector with those of other sectors. Integrated sediment management initiatives, for example, can help to deliver flood defence, agricultural and nature conservation benefits as well as meeting navigation needs. Buffer strips can create valuable habitat and contribute to achieving good ecological status under the Water Framework Directive.

With the projected reductions in summer rainfall, it may also be appropriate in some inland waterway systems to explore whether winter precipitation can be stored to provide a water resource during the summer months. If such a need is identified, possible win-win initiatives which also contribute to sustainable drainage, flood defence, agricultural, or nature conservation objectives should be investigated.

Other opportunities may arise in the form of ‘no regrets’ measures. Steps to conserve water by undertaking maintenance - preventing leakage and losses and improving the management of locks, sluices and weirs - will be of benefit regardless of the rate of change of climate parameters. Preparing a Code of Practice to help ensure that all users are aware of potential risks and know how to react to warnings will similarly be valuable irrespective of climate change (IWAC, 2009).

12.0 Confidence in the science

12.1 Confidence in the science relating to ports, harbours and marine infrastructure

The major ports' adaptation reports all stress that a high level of preparedness for extreme events is already vital for existing day-to-day operations. For major/modern ports it therefore seems reasonable to conclude that there is a high level of consensus in what is already happening and that this is based on a satisfactory amount of evidence.

Existing preparedness is similarly important for smaller port operators. However, due to the limited capacity of many such operators, their evidence base is probably somewhat less rigorous. Older infrastructure may also be more vulnerable. Therefore for these operators, levels of both consensus and confidence in the evidence are lower.

In terms of what could happen in the period 2050 - 2090, most of the major ports' adaptation reports confirm that, whilst there is an acceptably high level of both consensus and evidence regarding projections of sea level rise, there is a lack of evidence with regard to potentially significant changes in variables such as fog, wind, waves and storminess. Overall, therefore, for modern ports, harbours and marinas, confidence in what could happen is at best medium.

As discussed throughout this paper, adaptive capacity restrictions and/or older infrastructure in many smaller ports and harbours potentially compound these uncertainties. Overall confidence in what could happen for these operators in the period 2050 – 2090 is therefore low.

When specific aspects of port, harbour and marina infrastructure and activities are considered, the following conclusions can be drawn with regard to confidence:

- vulnerability of sensitive equipment and identified assets in major/modern ports and marinas to sea level rise and/or increased pluvial flood risk: high agreement supported by robust evidence
- vulnerability of assets and infrastructure in smaller ports and harbours (especially facilities relying on older infrastructure) to sea level rise and/or increased pluvial flood risk: medium agreement but limited evidence
- physical damage to infrastructure in smaller ports and harbours (especially facilities relying on older infrastructure) due to increased frequency of extreme events, storminess, waves: medium agreement but limited evidence
- disruption to port and harbour operations such as pilotage, berthing, cargo handling and storage, also ferry services, fishing and recreational activities due

to increased frequency of extreme events (storm surge, rainfall, wind and waves, fog): medium agreement but limited evidence
- disruption to port and harbour operations as a result of power outages, flooding or erosion of key transport routes, etc.: high agreement, medium evidence
- changes in sediment transport affecting dredging requirements: low agreement, limited evidence
- changes in air and water temperature affecting location of recreational and/or fishing activities: low agreement, medium evidence
- vulnerability of coastal and estuarine ecosystems affecting future port and recreational development: low agreement, medium evidence.

12.2 Confidence in the science relating to inland waterways

As with smaller ports, for many inland navigation authorities there is less existing, consolidated evidence, both about what is happening and what could happen. With the possible exception of some of the larger inland navigation operators, the level of both consensus and confidence in existing evidence is therefore at best medium.

The effects of climate change on the inland navigation network seem likely to be relatively more site-specific than the changes affecting ports and harbours. Further, there are considerable uncertainties regarding future rainfall and evapotranspiration projections including seasonal variations. As local changes may not reflect global patterns (Watts and Anderson, 2013) there may therefore be less opportunity for these operators to draw on nationally derived data. Given that these organisations also tend to employ fewer staff and may have comparatively less adaptive capacity, the overall level of confidence in the future impacts of climate change for inland navigation-related infrastructure is considered to be low.

Insofar as specific aspects of inland navigation infrastructure and activities are considered, the following conclusions can be drawn with regard to confidence:
- vulnerability of physical assets and infrastructure to more frequent or longer duration high or low flow conditions associated with extreme events and/or changes in seasonal precipitation: medium agreement but limited evidence
- water resource shortages in summer affecting supply to parts of canal network: high agreement but limited evidence
- changes in in-stream and bankside vegetation due to air and water temperature increases and to changes in seasonal precipitation/flow: high agreement, medium evidence
- risks to users associated with more frequent or longer duration high or low flow conditions: medium agreement but limited evidence
- changes in run-off and occurrence of high or low flow conditions affecting dredging and sediment management: low agreement, limited evidence
- overall increase in recreational water use as a result of warmer air and water temperatures: medium agreement, limited evidence.

13.0 Research gaps and priorities

13.1 Research gaps and priorities for ports, harbours and marinas

Many of the larger ports seem to be reasonably well prepared for climate change at least in the short to medium term. However, relatively little work appears to have been carried out to investigate the possible implications of climate change for ports, harbours and recreational facilities where day-to-day operations rely on older infrastructure. Many of these are smaller organisations. Some are less well informed, have a lower adaptive capacity and/or are constrained by a lack of resources. Research to develop a comprehensive understanding of climate change implications and adaptation requirements for such organisations is therefore a high priority. In addition, as these will face many of the same risks as their larger/more modern counterparts, the uncertainties in the projections for the climate variables discussed below are equally relevant to smaller ports and harbours.

The ability of ports, harbours and marinas – even those with modern infrastructure - to plan for effective climate change adaptation is hampered to some extent by the current lack of confidence in projections for key variables such as wind and wave climate, storminess and fog, including changes in the frequency of extreme events. Many of these gaps in knowledge are highlighted elsewhere (IPCC, 2014b; Pinnegar et al., 2012; Buckley et al, 2012) as are similar concerns about the processes driving erosion, accretion and sediment transport (MCCIP, 2014). At the present time, it appears that changes in these critical characteristics will be relatively insignificant and that sea level rise will be the driving force of change. The major ports' adaptation reports, however, stress the sensitivity of many port activities to such variables. A combination of model development (to overcome limitations and deliver greater certainty in projections) and improved long term monitoring and data management, will therefore be beneficial – both in determining when to invest in infrastructure, and informing decisions on ongoing activities/operations and contingency planning.

Another important consideration in adaptation planning for all ports, harbours and marinas is the likelihood of the high++ sea level rise scenario. Ongoing research both into this possibility and changes in other parameters which might arise from a four degree warming scenario will provide useful information for all organisations involved in developing and managing marine infrastructure.

Finally, an improved understanding of the effects of climate change on coastal and estuarine habitats and species will aid those providing infrastructure to support fishing or wildlife-based recreational activities as well as those preparing environmental impact assessments for future port development or expansion. Such evidence, along with research into carrying capacity, will be important both in avoiding and minimising adverse impacts and in recognising and exploiting opportunities to deliver win-win solutions which improve the resilience of both navigation and nature (Brooke, 2013). Research will also be useful to help ensure that marine infrastructure does not inadvertently exacerbate problems with invasive non-indigenous species.

13.2 Research gaps and priorities for inland navigation

Insofar as inland navigation is concerned, the IWAC report (2009) identified some of the key issues facing the inland navigation sector at a generic level. It is not clear, however, the extent to which the recommendations of the IWAC report (e.g. to install or improve monitoring systems; build capacity; undertake risk-based assessments; and set thresholds for action) have since been implemented. Further, whilst it is anticipated that the larger organisations - CRT, Environment Agency, Broads Authority and Scottish Canals - will be relatively better prepared than many of the smaller inland navigation authorities and operators, resourcing is an issue throughout the sector.

Improving local level monitoring, data collation and long-term information management have already been identified as high priority actions (IWAC, 2009). Such evidence gathering initiatives will provide the sector with more certainty as to what is required. Nonetheless, the practical difficulties and costs associated with the physical adaptation of inland navigation infrastructure should not be underestimated. Given the small scale at which many inland navigation authorities operate, their limited resources and the scale of adaptation likely to be necessary in the medium to long term, the development of a national 'toolbox' of adaptation measures would be useful. Such a toolbox should include both conventional and novel solutions; options for modifying as well as replacing existing assets; innovative water conservation measures; mechanisms for identifying and realising win-win opportunities; and recommendations *inter alia* for developing water resource strategies and for future-proofing new developments. CRT (2012) for example highlights as a high priority action the setting of design standards for all relevant assets to deliver adaptation requirements in future works. Attention is also required to the development of effective and reliable means of communicating operational changes, restrictions and warnings to users (IWAC, 2009).

Leading on from the above, more specific areas where research is required to support the adaptation of inland navigation infrastructure include (IWAC, 2009):

- options for improving the resilience of assets and infrastructure including the use of (drought-tolerant) vegetation in engineering;
- water allocation; innovation in water conservation; water resources and storage opportunities;
- measures to reduce sediment contained in run-off from reaching water bodies and alternatives or improvements to avoid or minimise the adverse effects of dredging;
- understanding of the carrying capacity of natural systems, and of water-ecology interrelationships;

- understanding of vectors for transfer of alien species; and methods for the management or eradication of invasive species; and
- ‘win-win’ options for habitat creation or restoration schemes.

At a strategic level, a better appreciation of existing and projected levels of use of along with a supply-demand analysis of the infrastructure would facilitate adaptation planning; and a holistic vulnerability assessment of UK inland navigation infrastructure could also contribute to improved preparedness.

Finally, adaptation planning will also benefit from improved understanding of changes (including local changes) in seasonal precipitation (Met Office 2014b); inter-relationships with evapotranspiration and river flow (Watts and Anderson, 2013); and associated implications for the integrity/adequacy of built infrastructure and for vegetation management. In the short term, however, some of the main challenges appear to relate to the likely increase in the frequency of extreme events (both rainfall and drought). Research into local level characteristics, frequency and consequences of such events will therefore assist inland navigation authorities in improving levels of preparedness.

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