European Commission

JRC SCIENCE FOR POLICY REPORT

Impacts of climate change on transport

A focus on airports, seaports and inland waterways

Christodoulou A., Demirel H.

2018

Joint Research Centre

EUR 28896 EN

Contact information
Name: Aris Christodoulou
Address: European Commission, Joint Research Centre, Expo Building - C/ Inca Garcilaso 3, 41092, Seville, Spain
Email: aris.christodoulou@ec.europa.eu
Tel.: +34954488276

JRC Science Hub
https://ec.europa.eu/jrc

JRC108865

EUR 28896 EN

PDF	ISBN 978-92-79-97039-9	ISSN 1831-9424	doi:10.2760/378464

Luxembourg: Publications Office of the European Union, 2018

How to cite this report: Christodoulou A., Demirel H., *Impacts of climate change on transport - A focus on airports, seaports and inland waterways*, EUR 28896 EN, Publications Office of the European Union, Luxembourg, 2018, ISBN 978-92-79-97039-9, doi:10.2760/378464, JRC108865.

Impacts of climate change on transport

The report assesses the impacts of climate change on transport for Europe using projections of climate data, coastal inundation, river flooding and river discharge data. Impacts considered include those of sea level rise, storm surges, extreme weather events and floods on airports and seaports, as well as floods and droughts on inland waterways. Main outputs include the identification of transport infrastructure at risk in future time periods and the estimation of economic impacts.

This is a re-edition of: Christodoulou A., Demirel H., Impacts of climate change on transport - A focus on airports, seaports and inland waterways, EUR 28896 EN, Publications Office of the European Union, Luxembourg, 2017, ISBN 978-92-79-76902-3, doi:10.2760/447178, JRC108865.

Contents

Executive Summary

Transport systems can be affected by climate change as they are exposed to weather conditions while their protection or adaptation requires substantial planning and investment. Changes of the current climate conditions that can affect transport include sea level rise, increase of the intensity and frequency of storms and winds, increase of temperature, changes in the intensity and frequency of extreme precipitation events, floods and droughts. Potentially vulnerable to these changes are both transport infrastructure and operation, while the impacts can be either permanent, e.g. loss of infrastructure, or temporary, e.g. disruption of services. Finally, climate change may also have positive effects by reducing transport disruptions at certain locations, e.g. through the reduction of ice formation.

Climatic changes to potentially affect transport systems include both gradual ones, such as sea level rise, and intensification of extreme events. The latter are more disruptive for transport systems but also the ones the effects of which are more difficult to assess. The main reason is the level of detail required to capture the impacts on transport in combination with the ambiguity of long-term projections.

The work took place in the context of the PESETA III project (Projection of Economic impacts of climate change in Sectors of the European Union based on bottom-up Analysis)[1] and the focus has been on the analysis of the impacts of climate change on seaports, airports and inland waterways. The three sectors were selected to complement the transport sector analysis that was conducted during the previous edition of the PESETA project and was focusing on road, and rail transport.

In order to prepare for the impacts of climate change, this study seeks answers to the following questions: How will climate change affect transport operations?', 'How significant are the anticipated changes?', 'Where will the most severe impacts take place in Europe?', 'How to measure vulnerability of different modes to climate change?'.

Among several climate stressors, sea level rise, storm surges, floods, wind gusts and droughts are selected considering the relatively high impacts they have. Furthermore, there are not many studies examining the vulnerability of airports, seaports and inland waterways to these stressors. Taking benefit from the multi-sectoral coverage of the PESETA III project, data from the JRC (Joint Research Centre) groups working on the physical impacts of climate change have been combined with transport data and impact functions. More specifically, the following data have been provided by the relevant individual project teams of PESETA III.

- Coastal inundation information – including data on mean sea level, tides and the combined effect of waves and storm surges – from the team working on the coastal impacts of climate change.
- Flood hazard maps with inundation depth for rivers from the team working on the impacts of climate change on river floods.
- Wind gust data from the team working on the climate change datasets.
- Discharge data for rivers from the team working on the impacts of climate change on water resources.

The coastal and river inundation maps have been produced based on ensembles of models as discussed in detail in the relevant reports. The discharge data used for the analysis of the impacts on inland waterways refer to five model runs. The wind gust data have been used mainly in an exploratory manner as there are reservations about the reliability of wind projections; only data from one model run have been used, mainly as an example.

[1] https://ec.europa.eu/jrc/en/peseta

The time periods of the analysis of the impacts considered and in general the perception of time is determined taking into account the temporal dimension of the data used. Coastal inundation maps have been produced for different return periods and years, while for the case of river inundation maps climate projections are used to estimate the severity and frequency of events. On the other hand, river discharge data – on which the estimation of low water days is based – refer to daily values from 1981 to 2099. In any case, the results are presented with reference to time periods representing the short-term, mid-term and long-term future within the century. The short term future for the sea level rise analysis corresponds to year 2030 and the long term to year 2080. In the context of the analysis of discharge and wind gust data for which daily values have been obtained, short-term future (including also present) corresponds to the 2011-2040 period, long term future to the 2071-2099 (2100 for wind gusts) period and mid-term future to the 2041-2070 period.

Furthermore, the characteristics of the available datasets determine the methods used to analyse impacts. For the case of coastal and river flood impacts, inundation maps referring to specific points in time have been obtained directly from the relevant physical impacts teams and overlaid with transport infrastructure maps. Practically, the timing of reaching the inundation levels reported in the maps or the corresponding levels of global warming does not really affect the results as the reported impacts are based on the assumption that the technical characteristics of the infrastructure and the importance of the site (seaport or airport) will remain unchanged over time. The same assumption has been made for the case of inland waterways as transport demand and navigation-related thresholds are assumed to remain constant over time. The effect of reaching the applied inundation levels earlier or later would only shift the timing of the occurrence of the reported impacts accordingly.

A limitation of the analysis of the impacts on airports and seaports has to do with the information required to quantify the impacts. By making the analysis at European level it is difficult to obtain detailed information regarding the characteristics of each seaport or airport considered in order to properly asses its vulnerability or resilience. Furthermore, it is also difficult to collect information on the transport or economic activity in order to evaluate the impact of disruptions. On the other hand, the analysis for inland waterways is focusing on four points as to utilise discharge data for the estimation of the impacts of droughts, it is necessary to take into account location specific characteristics.

According to the results of the analysis, the number of airports that face the risk of inundation is projected to increase by almost 60% between 2030 and 2080. In 2080, 196 airports will be under the risk of inundation. Inland airports can be affected by river floods and the most severe impacts are projected to take place in regions near the North Sea coastline. Regarding wind, higher wind gust speeds are projected in the middle and end of the century, for the North Sea, Baltic Sea and Adriatic Sea.

Seaports are exposed to storm surges and sea level rise by default and are vulnerable to flooding. Climate change is expected to have more severe impacts in northern Europe, where Europe's top 20 cargo seaports are located. In total, 852 ports face the risk of inundation in 2080 and the number of seaports to be exposed to inundation levels higher than 1m is projected to increase by 80% from 2030 to 2080.

Inland waterways are vulnerable to climate change because river navigation depends on water levels. Droughts have the most disruptive impacts for inland waterways because low water levels impose limitations to navigation services. The consideration of location specific characteristics is very important for the analysis of the impacts of droughts on inland waterways using river discharge data. Hence, the focus of the analysis has been on four specific locations of Rhine and Danube where substantial part of the total freight activity in the EU takes place. For the majority of locations and model runs considered, a reduction of low water days is projected which means fewer disruptions to the operation of the inland waterway transport system.

1 Introduction

Extreme weather events affect transport infrastructure and management. Even if infrastructures are designed to cope with various stresses along their life, the increase of frequency and severity of extreme weather events will, nevertheless, increase their deterioration pace. Additionally, transport services have to be managed in order to reduce possible disruptions and accidents that may become more frequent due to adverse weather conditions. In the transport sector, the impacts of climate change will vary by mode and region. According to the climate change model outputs, impacts will be widespread and costly. The impacts will require significant changes in planning, design, construction, operation and maintenance of transport systems.

Transport infrastructure and operations are more sensitive to extreme events - such as storm surges, floods and wind gusts – than to incremental changes of temperature or precipitation. Furthermore, transport operations are generally more sensitive to climate change than infrastructure. Airports face various climate change related risks including sea level rise and storm surges while high winds are a key hazard especially for landing and taking off. Seaports' operations might be disrupted by sea level rise, storm surges, floods and extreme winds. Extreme weather events affecting inland waterways (IWW) include floods during which water levels exceed the maximum permitted ones and droughts due to which water levels become critically low imposing limitations to navigation services.

Following up on PESETA II where preliminary results were achieved with respect to the impacts of climate change on the transport sector focusing on roads and railways, this report analyses the impacts on airports, seaports and inland waterways.

The climate change impacts considered are the following:

- Sea level rise and extreme weather events affecting airports and seaports
- Wind gusts affecting airports and seaports
- Floods affecting airports, seaports and inland waterways
- Droughts affecting inland waterways

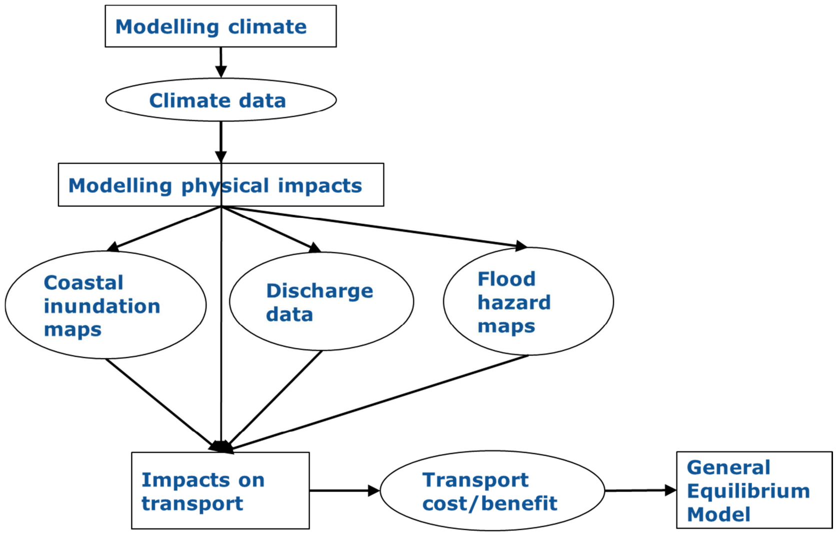
In order to assess the impacts of climate change on transport networks, four major factors are considered: exposure to climate stressors, vulnerability, resilience and adaptation.

For the analysis of the impacts of climate change on transport the following data, provided by the relevant individual project teams of JRC PESETA III, are used:

- Coastal inundation information – including data on Mean Sea Level, tides and the combined effect of waves and storm surges – from the team working on the coastal impacts of climate change.
- Flood hazard maps with inundation depth for rivers from the team working on the impacts of climate change on river floods.
- Wind gust data from the results of the climate projections for airports and seaports.
- Discharge data for rivers from the team working on the impacts of climate change on water resources.

The analytical approach followed is summarised in Figure 1.

Figure 1. Data exchange with the other impact study groups



This report aims to explore future trends regarding changing exposure of airports, seaports and inland waterways to weather-induced risks under climate change, as well as to assess infrastructure deterioration, service disruptions, damage costs and adaptation costs in future time intervals.

2 Vulnerability of the transport sector to climate change

Depending on the global warming scenarios and the geographic location of regions, transport modes and system components could be affected by one or several simultaneous changes of the climate conditions including hotter summers, extreme precipitation events, increased storminess and sea level rise. According to the PESETA II report, (Nemry and Demirel, 2012) more frequent extreme rainfalls and floods (river and pluvial floods) as projected for different regions in Europe could increase the maintenance costs for road transport infrastructure by €50-€192 million per year for the period 2040-2100. Furthermore, 4.1% of the coastal road infrastructure in Europe faces the risk of permanent or episodic inundation from sea level rise and storm surges. The value of infrastructure (considering deterioration and damage costs) at risk was estimated to be approximately €18.5 billion.

2.1 Impacts on transport

The impacts of climate change on airports, seaports and inland waterways could be summarized as follows[2]

a) Increased summer temperatures:
   - Affect aircraft performance and may cause airplanes to face cargo restrictions, cruise altitude changes, flight delays, and cancellations.
   - Damage infrastructure/equipment/cargo.
   - Reduce asset lifetime.
   - Increase energy consumption for cooling cargo.
   - Reduce water levels imposing restrictions for inland navigation and increasing fuel consumption.
   - Increase accidents (e.g. grounding for IWW).
   - Reduce costs relevant to snow or ice removal.

   According to the projected trends all regions will be affected by higher summer temperatures. The frequency, intensity and duration of heat waves all over Europe are projected to increase.

b) Increased precipitation:
   - Cause flooding of airports, seaports and IWW.
   - Cause land infrastructure inundation and damages to cargo/equipment.
   - Impose navigation restrictions for IWW.

   In summer, Nordic countries are expected to experience increased precipitation, while in Southern regions precipitation will likely decrease. For regions in the middle, trends are inconsistent across models.

c) Decreased precipitation:
   - Cause water shortages and reduce ability to meet demand.

d) More frequent extreme winds:
   - Damage infrastructure of seaports and airports.

   Expected increase of extreme wind speeds in the northern and central Europe, especially in the British Isles and North Sea coast during winter periods. However, trends are inconsistent, observation data for many

[2] *Based on* Van den Brink et al (2005), Frei et al (2006), Von Storch et al (2006), Fowler et al (2007), Beniston et al (2007), Rockel et al (2007), Makkonen et al (2007), Von Storch et al (2008), Nikulin et al (2011), Velegrakis (2013), Melillo et al (2014), Eurocontrol (2013), Bruisma et al (2012), Becker et al (2011), Sierra et al (2017), Yang et al (2017)

regions are missing and there is a weakness of models to reproduce available observed data.

e) Sea level rise and sea storm surges:
   - Increase tides in ports' facilities, put low level aviation infrastructure at risk of regular and permanent inundation.
   - Modify wave propagation patterns and change wave penetration into ports.
   - Cause loss of ground access to airports.
   - Damage port infrastructure/cargo.
   - Cause sedimentation/dredging issues in ports/navigation channels.
   - Increase port construction/maintenance costs.

   Shoreline retreat will be observed everywhere. However, the magnitude depends on local morphology and human-induced subsidence. An increase of storm surges has been forecasted along the North Sea coast, especially for the German and Danish coasts.

f) Change in frequency of winter storms:
   - Affects all modes.

   Decrease in mean snow precipitation but more frequent extreme snow precipitation events have been projected for the Nordic countries (Makkonen et al., 2007)

g) Thawing permafrost:
   - Causes airport embankment failures, increases maintenance needs.
   - Damages infrastructure; coastal erosion affects road and rail links to ports.

   Thawing has already been observed.

h) Reduced ice cover:
   - Contributes to opening new northern shipping routes and reduces ice loading on infrastructures such as piers.
   - Extends shipping seasons.
   - Reduces fuel costs.

i) Earlier River Ice Breakup:
   - Increases ice-jam flooding risk.

The impacts of climate change on airports, seaports and IWW can be broken down to sub-categories, namely impacts on infrastructures, services, operations and maintenance. A list of the impacts of climate change on airports, seaports and IWW can be found in the Appendix.

Two important points from reviewing the relevant literature are the following:

a) transport as a sector is more sensitive to extreme events, such as storm surges, floods, wind gusts than to incremental changes of temperature or precipitation,
b) transport operations are more sensitive to climate change than transport infrastructure

The climate stressors that have been selected in order to calculate the impacts of climate change on airports, seaports and IWW in the present study are: sea level rise plus storm surges, floods, droughts and wind gusts. Other stressors, such as increased temperature and extreme heat have relatively limited impacts in comparison to the selected ones.

2.2 Weather-induced costs

Transportation infrastructures are designed to be resilient and cope with various stresses including extreme weather events but transport services have to be managed to reduce possible disruptions and increase safety conditions during periods of adverse weather conditions.

There are fewer studies examining the vulnerability of air and water transport modes than of road or rail. However, climate change can affect more severely air and sea transport modes than land transport (EUROCONTROL, 2008; Becker et al, 2013).

According to a U.S. study, (ACRP, 2012) very few airports are currently considering ways to address the effects of climate change, although 70% of airport delays are the result of severe weather events and such events are on the increase. Furthermore, according to a study by EUROCONTROL focusing on Europe: "although an increasing number of organisations now consider that climate change will have a negative impact on their organisation, a smaller number have already begun planning or implementing resilience measures" (EUROCONTROL, 2013).

In 2011, the United States saw 12 weather/climate disasters costing at least $1 billion each. (Koetse and Rietveld 2009). For some major airports, a closure can cost more than $1 million an hour (Pejovic et al. 2009), while the closure of airports due to the volcanic ash cloud from Iceland in 2010 was estimated to have costed 0.5 billion euro per day (Nokkala et al, 2012).

Storms can have devastating impacts and extreme winds can severely damage port and airport facilities. According to the SwissRe (Schwierz et al., 2010) loss model, an insured storm loss of nearly 7 billion Euros can be expected once every 10 years and of 30 billion Euros once every 100 years. On the other hand, some areas could also benefit from climate change (e.g. due to opening of arctic routes and the reduction of ice formation) and new opportunities could arise from developing and improving seaports.

The quantitative analysis of current and future vulnerability of air- and sea-borne transport is a challenge for the European Union. Particular attention should be paid to the contributions and follow-up activities of research projects financed within European research framework programs. Four interesting projects focusing on the impacts of climate change on transport that have now been completed are: WEATHER[3], EWENT[4], ECCONET[5] and MOWE-IT[6]. These projects have been of utmost importance in gathering available information and providing initial estimates of potential impacts on the transport sector. According to the estimation and major findings of these projects, sea level rise, floods and extreme precipitation are expected to have the most severe impacts on the transport sector. Several climate factors that are considered to be first order explanatory factors (e.g. average precipitation versus extreme precipitation, snow of freezing days) and their trends in different climate scenarios have been used in order to produce an outlook of future impacts for transport.

According to the FP7 project WEATHER, the estimated total annual costs of climate change on transport for the period 1998-2010 were €2.5 billion including €1 billion annual indirect costs due to disruptions. For the cost estimation, mainly impacts of winter conditions (42%) and floods (45%) were considered. The impacts on air transport were estimated to be equal to 16% of the total costs, while the impacts on maritime and IWW were estimated to be below 1% of the total costs as illustrated in Table 1.

[3] https://www.weather-project.eu/weather/index.php
[4] https://www.weather-project.eu/weather/inhalte/research-network/ewent.php
[5] https://www.ecconet.eu/
[6] http://www.mowe-it.eu/

Table 1. Current weather induced costs for transport in million Euros (source: WEATHER project)

	Road	**Rail**	**Air**	**Maritime**	**IWW**	**Intermodal**	**Total (mil. €)**	**%**
Storm	174	3	155	20	-	1	354	15.7
Winter	759	52	147	-	-	0	959	42.5
Flood	822	-	60	-	5	0	886	39.3
Avalanche	-	6	-	-	-	-	6	0.2
Heat and drought	50	-	-	-	-	-	50	2.2
Total (mil. €)	1805	61	362	20	5	2	2254	
%	80.1	2.7	16.0	0.9	0.2	0.1		

The EWENT project assessed the impacts of extreme weather events on the EU transport system. Furthermore, it evaluated adaptation and mitigation measures that aim to reduce the costs of weather impacts. The methodological approach was based on a generic risk management framework, followed by impact assessment and completed by mitigation and risk control measures. The current costs due to extreme weather events, including all phenomena is presented in Table 2.

Table 2. Current costs due to extreme weather, including all phenomena in million or billion Euros (ca.2010) (source: EWENT project)

Transport Mode	**Accidents**	**Time costs**	**Infrastructure**		**Freight & Logistics**
			Physical Infra	**Maintenance**	
Road	>10 bill.	0.5-1.0 bill.	ca 1 bill.	ca 0.2 bill.	1-6 bill.
Rail	>0.1 bill.	>10mill.	-	>01.bill	5-24 mill.
IWW	ca. 2 mill.	-	-	-	0.1-0.3 mill.
Short sea	>10 mill.	-	-	-	0.2-1 mill.
Aviation	-	>0.6 bill.	-	-	0.5-2.3 mill.
Light traffic	>2 bill.	-	-	-	-
TOTAL (€)	>12 bill.	>1bill.	ca 1.bill	>0.3 bill.	1-6 bill.

The ECCONET project focused on the effects of climate change on the IWW network. The project had two major objectives: a) analysis of various effects of climate change on IWW transport and related sectors, and b) analysis of adaptation strategies and recommendation of a strategic framework for the development of IWW. According to the results moderate impacts should be expected in the near future.

The goal of the MOWE-IT project was to identify existing best practices and develop methodologies in order to assist transport operators, authorities and transport system users to mitigate the impacts of natural disasters and extreme weather phenomena on the transport system performance. Aviation, road, rail, IWW and maritime transport are covered.

Infrastructure deterioration and damage costs were calculated during the PESETA II project. The project considered exposure of road and rail infrastructures to weather-induced risk under climate change in two future time intervals (2040-2070 and 2070-2100). For road transport infrastructure, weather stresses were found to be responsible for 30% to 50% of the road maintenance costs in Europe (€8 to €13 billion per year). Around 10% of these costs (approximately €0.9 billion per year) were associated with extreme weather events of which heavy rainfalls and floods were found to play the most important role.

2.3 Key elements for the vulnerability analysis of the transport sector

To analyse the vulnerability of airports, seaports and IWW to climate change, parameters related to infrastructure life-span, design and relevant thresholds should be considered. As a result of the vulnerability of different transport modes, intermodal transportation will be also affected by climate change. Relevant effects might include secondary impacts on other modes or disruptions of the supply chain for freight transport. Furthermore, the combination of the impacts on different modes might have cumulative effects disrupting significantly the transport system of certain areas. In these cases, by not considering the effects on intermodal transport, the impacts of climate change might be underestimated. However, the consideration of the impacts on intermodal transportation for all Europe requires a large number of relevant data and is beyond the scopes of this study

2.3.1 Life expectancy of transport infrastructure

Transport infrastructures are designed to resist stresses that include extreme weather conditions and regular maintenance takes place. Typical life-spans of transport infrastructures are presented in the following bullet points but there might be variations among different countries according to their construction codes:

- Airports: 70 years
- Seaport: 100 years
- Road pavement: 10-25 years

2.3.2 Thresholds

The impact functions for airports, seaports and IWW to be considered include sea level rise and storm surges, floods and strong winds. Extreme winds affect both airports and seaports. However, there are certain difficulties in using wind data including lack of information regarding extreme wind speeds, relatively low resolution of reporting stations and inconsistencies in measurement characteristics (IPPC, 2012). Impact functions that affect the transport modes covered in this study and relevant thresholds are presented in Table 3.

Table 3. Impact functions and their thresholds per transport mode.

Transport mode	Impact Function	Threshold
Airport	SLR + storm surge	Inundation level
	flooding	Inundation level
	wind gust	>10 m/s, >15 m/s, >20 m/s, >25 m/s
Seaport	SLR + storm surge	Inundation level
	flooding	Inundation level
	wind gust	>35 m/s
IWW	flooding	Inundation level
	drought	Number of days with discharges corresponding to low water levels

Sea level rise thresholds for seaports, above which port facilities or operations are affected, vary by port design and depend on the height of the port and protective measures such as sea walls that shield port facilities. Coastal building codes may apply to port terminals and other buildings. According to ASCE (American Society of Civil Engineers), buildings in flood zones are required to have 0.30 meters of freeboard while certain essential facilities are required to have 0.60 meters of freeboard (ASCE, 2006). Freeboard height standard is set according to a flood event of a 100-year return period (FEMA, 2011a). The lowest floor, including freeboard, needs to use flood-damage resistant materials (FEMA, 2011b). Coastal buildings must be designed to withstand wave loads that are 1 meter high and parts of such buildings (Coastal Zone A) should be able to withstand waves of 0.45-0.90 meters (ASCE, 2005; FEMA, 2011a).

With respect to wind speeds, impacts of winds on airports can occur at wind speeds of 13m/s to 18m/s (OFCM, 2002). According to the 2005 ASCE Design Standards, buildings and other structures must be able to withstand the basic 3-second wind gust and aviation control towers, air traffic control centres, emergency aircraft hangers must be designed to withstand greater pressures from winds (ASCE, 2005). Wind damages to structures increase non-linearly as wind speeds increase. For example, Powell and Reinhold (2007) found that light, moderate, and severe wind damage thresholds correspond to loss levels of around 2%, 12%, and 60% of insured value. Furthermore, winds equal to or greater than 55 m/s caused about 30 times higher losses than winds between 25 and 41 m/s.

2.4 Data used

Climate model outputs and spatial databases are combined in order to assess the impacts of climate change. The climate change projections can be retrieved from the WCRP EURO-CORDEX[7] initiative. Each climate scenario is based on the combination of a Global Circulation Model (GCM) and a Regional Climate Model (RCM) which downscales geographically the GCM global climate projections. RCMs have 0.11 degree spatial resolution. More information can be found in Dosio and Paruolo (2011) and Dosio et al (2012).

[7] http://www.cordex.org/, http://euro-cordex.net

2.4.1 Sea level rise plus storm surges

In order to determine locations of exposure and predict the vulnerability of transport infrastructure due to sea level rise plus storm surges, an inundation model is used that has been developed at European scale by the PESETA III team working on coastal impacts. The model (Vousdoukas et al, 2016) estimates total water level integrating mean sea level, tides and the combined effect of waves and storm surges, and superimposes this information on the selected digital elevation model. Furthermore, the model incorporates the coastal protecting structures, enhancing the reliability of the projections. For the spatial analysis of inundation risk for airports and seaports, the projected water level according to RCP8.5 for the years 2030 (representing short-term future) and 2080 (representing long-term future) is utilized. The water level is a combination of sea level rise projections, maximum tidal amplitude and the 100-year return level of the episodic hydrodynamic components, i.e. storm surges and waves.

2.4.2 River floods

In order to find transport infrastructure under risk of flooding, the inundation maps produced by the PESETA III group working on river floods (Alfieri and Feyen, 2016) are implemented. These maps are based on an expansion of the cascading model approach (Barredo et al., 2007). The rainfall-runoff model is calibrated using discharge observations at 481 gauging sites. 21-year meteorological datasets and generalised extreme value fitting are utilized to derive flood peaks for 100-year return periods for each pixel. The data are downscaled to 100m resolution and maps are derived for the entire European river network. Finally, output maps of more than 37 000 hydraulic simulations are merged into a pan-European flood hazard map. Details regarding the model can be found in Alfieri et al (2013) and Alfieri et al (2015b). The flood maps were calculated for a set of scenarios based on an observed climate and for specific flood return periods. Climatic projections were used to derive the projected frequency and intensity (i.e., the return period) of flood events in the future. Hence, the impacts of climate change in future periods are represented by the increase of frequencies of flooding events.

2.4.3 Wind gusts

A wind gust is defined as a rapid, sudden, brief increase in the speed of wind. Gusts are reported when the peak wind speed reaches at least 8 m/s and the variation in wind speed between peaks and lulls is at least 5 m/s (NOAA, 2017). As has already been mentioned there are reliability issues regarding wind projections and the analysis of the impacts of winds has been made in a rather exploratory manner considering only the results of the following run (RCP8.5):

Table 4. Reference details regarding the climate model on which wind gust data are based

Institute	**RCM**	**Driving GCM**
CLMcom	CCLM4.8-17	CNRM-CERFACS-CNRM-CM5

The variable applied in this study is daily maximum near-surface wind speed of gust (m/s) and the data refer to daily values from 1981 to 2100. The data are used to find the number of days with wind gusts speeds exceeding certain limits. The number of days reported refer to annual average number of days over the three periods of analysis and the historic period:

- Short term future: 2011-2040
- Mid-term future: 2041-2070
- Long-term future: 2071-2100
- Historic period: 1981-2010

2.4.4 Droughts

The impacts of droughts on inland waterways are modelled with the help of discharge data obtained from the group working on the water sector of PESETA III. The data are based on the results of five model runs (Table 5):

Table 5. Reference details regarding the climate models on which discharge data are based

Institute	RCM	Driving GCM	Run
CLMcom	CCLM4.8-17	CNRM-CERFACS-CNRM-CM5	1
		ICHEC-EC-EARTH	2
IPSL-INERIS	WRF331F	IPSL-IPSL-CM5A-MR	3
SMHI	RCA4	MOHC-HadGEM2-ES	4
		MPI-M-MPI-ESM-LR	5

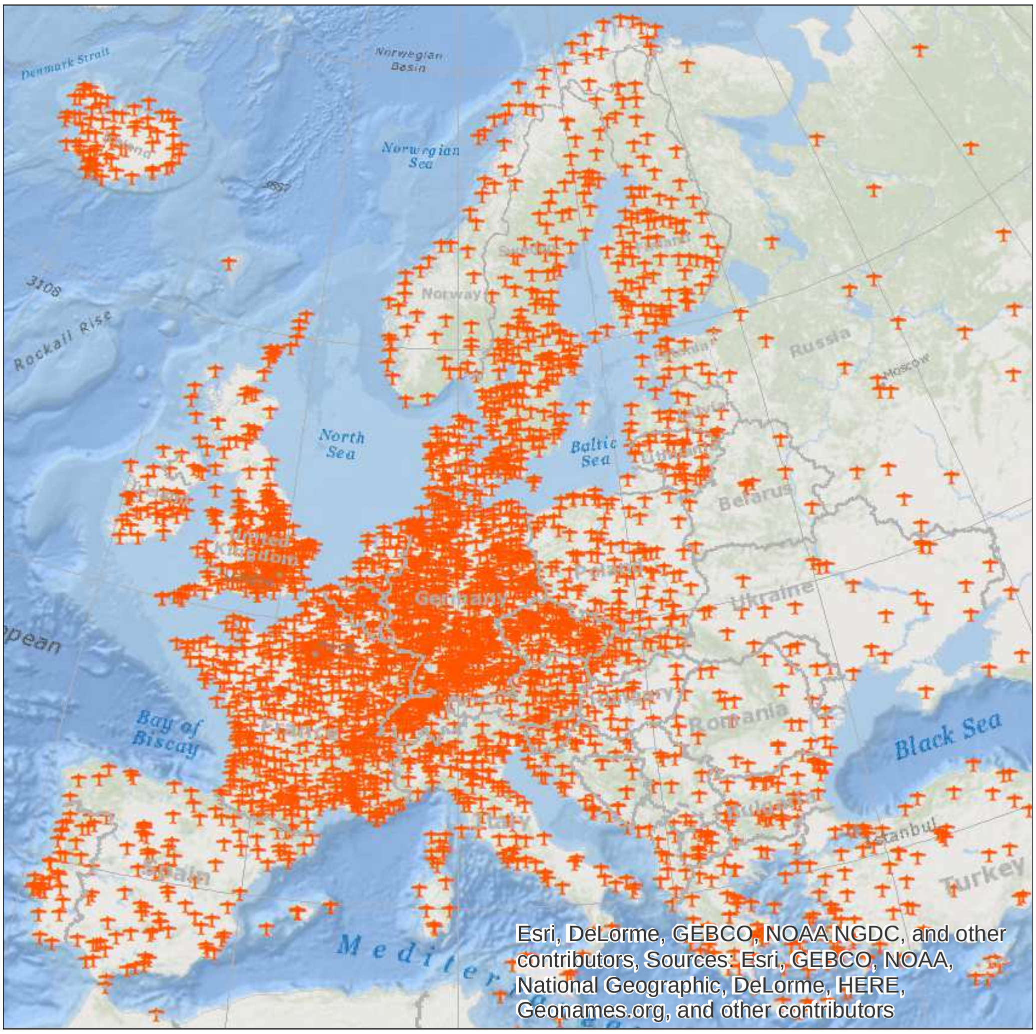
They refer to average daily values of discharges (in m^3/s) and cover the period from 1981 to 2099 (only for run 4 the last year of projection is 2098). They are the output of the LISFLOOD model, a GIS-based hydrological model (Van Der Knijff et al, 2008). The data are used to calculate the number of days for which discharges fall within certain thresholds. The results are aggregated to four time periods and the values reported refer to annual average number of days over the three periods of analysis and the historic period:

- Short term future: 2011-2040
- Mid-term future: 2041-2070
- Long-term future: 2071-2099
- Historic period: 1981-2010

2.4.5 Transport infrastructure databases

For the location of the airports, the geospatial airport infrastructure database of Eurostat, GISCO is used. A map of all airports (2847) is presented in Figure 2; 2788 of them are characterised as 'main' in the Eurostat airports database. The dataset includes EU and neighbouring countries significant for air transport analysis.

Figure 2. Location of airports in the GISCO/Eurostat database



For the location of the seaports, the geospatial seaport infrastructure database of Eurostat, GISCO is used. It contains a point feature class with the location of 2877 European ports, where 1731 of them are classified as important and 372 belong to the Trans-European Transport Network (TEN-T). Point coordinates are derived from several input sources, including ports lists from EMSA, Lloyds, Norie's Seaports of the World, the GISCO Ports 2010 dataset and the UN/LOCODE 2007 list. The ports within the database cover a wide range of different characteristics – from small private marinas up to large industrial harbours differing in types and volumes of cargo traffic, fishing, and other activities (industry, passenger transport, cruise tourism, yachting).

3 Results for airports, seaports and inland waterways

3.1 Results for airports

Airports play a central role in the EU for both passenger and freight transportation. The International Airports Council estimated the total economic impact of airport and aviation related activities for 2015 at €338 billion across the EU. According to EUROCONTROL, the air traffic in Europe will nearly double by 2030 in comparison to 2010 and Europe will have difficulties to meet this huge demand due to shortage of runway and ground infrastructure at major airports. Infrastructure investments have already been planned to enlarge and improve airports' infrastructure.

Airports are vulnerable to extreme weather events the frequency and severity of which is projected to increase due to climate change. In this section the impacts of climate change on airports are considered by identifying infrastructure projected to be exposed to extreme weather events of various severity levels.

3.1.1 Impacts of sea level rise and storm surges on airports

Several airports in the EU are located at coastal zones and face the risk of inundation due to sea level rise and sea storm surges. The Intergovernmental Panel on Climate Change (IPCC) projected that global mean sea levels would rise by 18–59 cm above 1990 levels by the 2090s (where the lower bound corresponds to the lower estimate for the lowest emissions scenario, and the higher bound corresponds to the upper estimate for the highest scenario). Sea level rise in northern Europe could be higher than the global average by an additional 15–20 cm due to changing climate patterns (air and water currents) reaching up to 38–79 cm in Denmark. Local sea level rise will actually vary with ocean circulation patterns, gravitational effects, land subsidence or uplift along some coastlines, and other factors.

The number of airports in Europe projected to be affected by sea level rise and extreme events are listed in Table 6. According to the analysis, there is a continuous increase of sea levels and, as result, an increase of the number of airports that face the risk of inundation until the end of the century. At the North Sea coast, where the impacts of sea level rise are more severe, a large number of airports face the risk of inundation. According to the projections, the number of airports to be inundated by water levels between 1 and 3 meters will almost double (from 23 to 42) from year 2030 to year 2080. The number of airports that face the risk of inundation in 2080 is 196.

Table 6. Number of airports under inundation risk for years 2030, 2080

Country Code	**2030**				**2080**			
	ind ≤1	1< *ind* ≤3	*ind* >3	**Σ**	*ind* ≤1	1< *ind* ≤3	*ind* >3	**Σ**
BE	-	-	-	**-**	1	-	-	**1**
CY	1	-	-	**1**	1	-	-	**1**
DE	14	1	2	**17**	15	3	2	**20**
DK	8	-	-	**8**	8	1	-	**9**
EE	4	-	-	**4**	3	1	-	**4**
EL	8	1	-	**9**	16	4	-	**20**
ES	2	1	-	**3**	4	2	-	**6**
FI	2	-	-	**2**	2	-	-	**2**
FR	6	1	-	**7**	9	3	-	**12**
HR	1	1	-	**2**	3	1	-	**4**
IE	6	-	1	**7**	6	3	1	**10**
IT	2	1	-	**3**	8	2	-	**10**
LT	-	-	-	**-**	-	-	-	**-**
NL	-	-	-	**-**	14	-	-	**14**
NO	20	3	2	**25**	25	3	2	**30**
PL	1	-	-	**1**	-	1	-	**1**
PT	2	-	-	**2**	3	1	-	**4**
SE	2	-	-	**2**	7	1	-	**8**
SI	-	-	-	**-**	1	-	-	**1**
UK	17	14	-	**31**	20	16	3	**39**
Total	**96**	**23**	**5**	**124**	**146**	**42**	**8**	**196**

Airports are resilient to sea level rise plus storm surges below 1m (ASCE, 2005; FEMA, 2011a) and could perform as expected with the help soft adaptation measures. However, inundation levels between 1m and 3m can adversely impact the operations of airports.

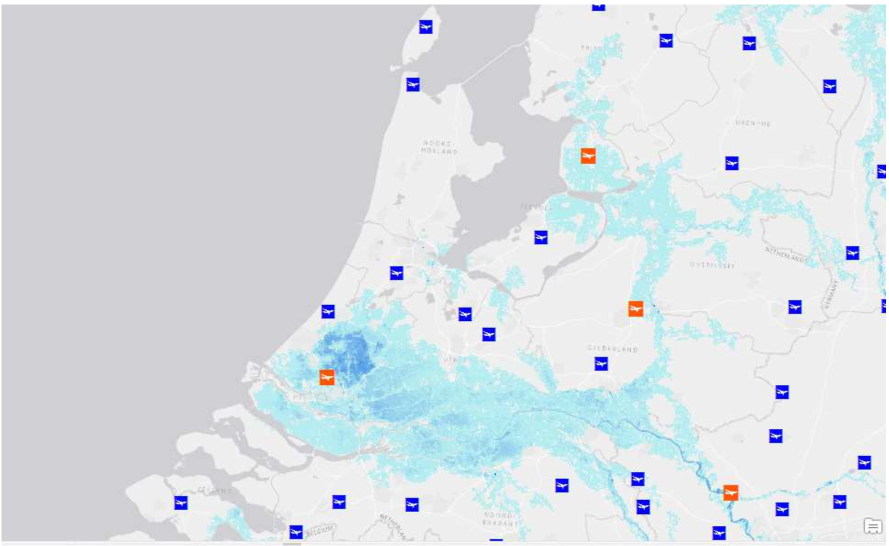
An indication of the cost of inundation can be found in relevant studies. According to Schade et al (2006) and Schade et al (2013) the total cost of permanent inundation could be nearly 5 billion Euro and will vary according to the design and operational capacity of the airport. Furthermore, according to Pejovic et al (2009), for some major airports, a closure can cost more than $1 million per hour. Adaptation of the transport sector to climate change should be considered as part of a broader multi-sectoral approach and a measure against sea level rise is the elevation of dikes. According to the literature, the cost of construction of dikes or levees to protect against 1 meter rise is between 756,000 and 4,004,460 euro/kilometre (Hippe, 2015).

Under the assumption that building dikes (levees) of one kilometre length is the adaptation measure of choice and considering the aforementioned costs, the adaptation cost for airports projected to be exposed to inundation levels up to 1 meter by 2030 is between 72 and 385 million Euros and by 2080 between 110 and 584 billion Euros. The adaptation cost for airports projected to be exposed to inundation levels more than 1 meter will be higher, while in some cases there will be permanent loss of infrastructure.

3.1.2 Impacts of river floods on airports

Inland airports can be affected by river floods and major impacts are projected for airports located close to the coastline of the North Sea. According to the flood maps, 17 airports are projected to be exposed to inundation levels higher than 3m during a 10year event and 26 during a 50year event. The airports (main airports according to the GISCO database) that face the risk of inundation in the area of the Netherlands are marked in red in Figure 3. Model estimations refer mainly to flash floods and major expected impacts include delay in operations and increased maintenance needs.

Figure 3. Sample of inundated airports in 100 years due to floods



The number of airports to be inundated under events of different severity are presented in Table 7.

Delays and cancellations have cumulative effect. For example, the closure of airports due to the volcanic ash cloud from Iceland in 2010 lead to 0.5 billion euro loss per day (Nokkala et al, 2012). Costs of delays considering value of time are estimated based on Ludvigsen et al. (2012) and Nokkala et al. (2012). According to the latter, the value of time to be used for cost estimation regarding airborne freight transport in EU27 is 33.3 Euro/ton/hour. The categorization – international, community and regional connecting points – of the European Parliament is used to estimate tons of freight for each airport. It is assumed that the impacts on airports projected to be inundated by up to 1m will be limited. The results are presented in Table 8 while international and community connecting points are retrieved from the GISCO database.

The costs in Table 8 refer to the impacts of different severity events the frequency of which is projected to increase significantly in the future due to climate change. The mean annual exceedance frequency of the 100year return period peak flow in Europe is projected to increase by 176% in Europe (Alfieri et al, 2015a) by the end of the century. The relevant change of frequency earlier in the century is 97% and 126% in the short-term future and mid-term future, respectively (Alfieri et al, 2015a). The change of frequencies will be even higher in some countries. For example in the Netherlands, the mean annual exceedance frequency of the 100year return period peak flow is projected to increase by 468% by the end of the century.

Table 7. The number of impacted airports due to floods

	Inundation levels (m)	10 years	20 years	50 years	100 years
Airport	< 1m	98	112	120	118
	1m - 3m	31	34	41	47
	>3m	17	22	26	27
	Total	**146**	**168**	**187**	**192**

Table 8. Estimated costs for values of time (million Euros)

	Inundation levels (m)	10 years		20 years		50 years		100 years	
		Int.	Com.	Int	Com	Int	Com	Int	Com
Airport	1m - 3m	55	52	70	57	70	68	75	78
	>3m	30	28	50	37	55	43	65	45
	Total	**85**	**80**	**120**	**94**	**125**	**111**	**140**	**123**
	Total	**165**		**214**		**236**		**263**	

3.1.3 Impacts of wind gusts on airports

Different models do not use the same wind gust parameterization (Schwierz et al, 2010) and as has already been mentioned wind gust projections are in general of low reliability. This, in combination to the level of detail (e.g. spatial aggregation level, wind direction) required to measure the impacts of winds on transport indicate that it is very difficult to obtain relevant trustworthy estimates. For this reason, the analysis of the wind data has been mainly exploratory and the analysis is restricted to the results of one climate model run (Table 4).

According to Peterson et al. (2008), delays or cancellations of flights occurred at sustained winds of 17.88 m/s or higher (for an hour), or gusts of 25.93 m/s or higher (no time limit). Pejovic et al. (2009) did not establish a threshold for high winds (indicated by 1-hour mean wind speed above the mean), but found that incremental increases in wind speed above the mean could increase the likelihood of delay.

In Table 9 results for selected TEN-T airports are presented. They refer to annual average number of days over the specified periods with wind gust speeds within the specified thresholds. Areas to be mostly affected can be found in North France and Norway.

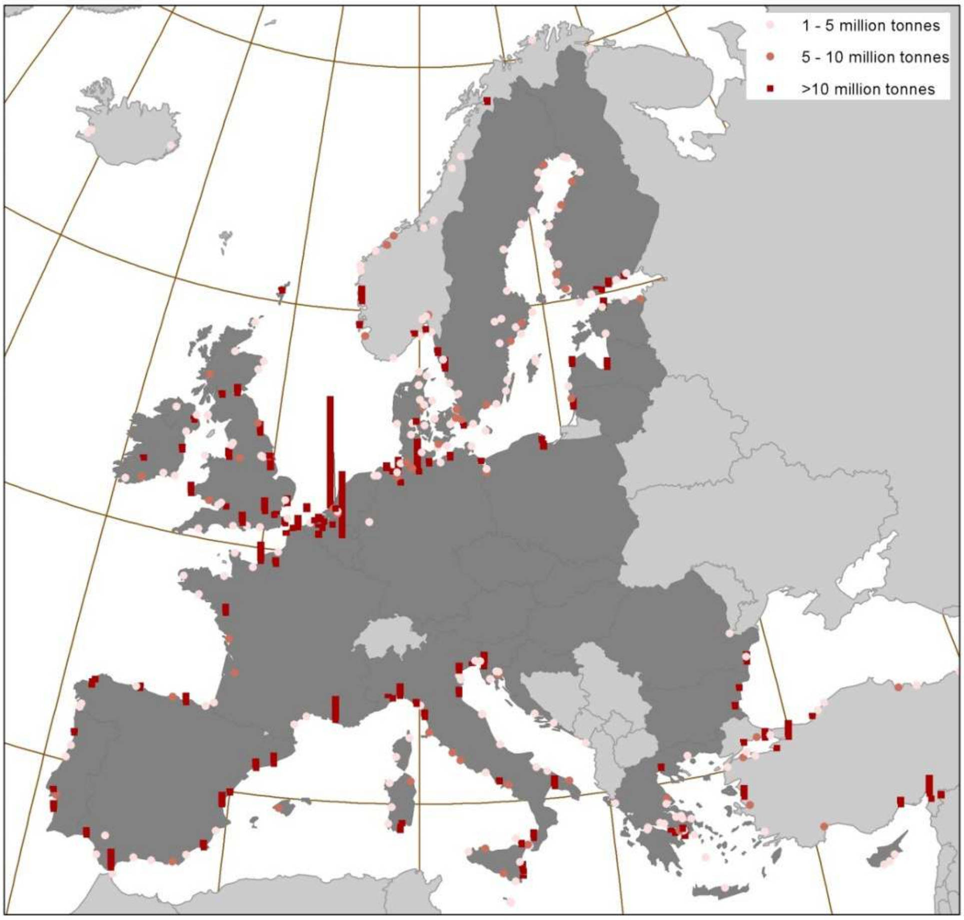
Table 9. Daily maximum near-surface wind speed of gust for selected TEN-T airports

TEN-T airports	Period	0_5 m/s	5_10 m/s	10_15 m/s	15-20 m/s	20-25 m/s	25-30 m/s	> 30 m/s
EDDW (BREMEN- DE)	1981-2010	50	192	160	49	5	1	0
	2011-2040	49	202	157	44	5	1	0
	2041-2070	49	197	159	46	5	1	0
	2071-2100	51	205	148	48	5	0	0
EGGD (BRISTOL-UK)	1981-2010	41	186	163	58	8	1	0
	2011-2040	40	188	164	56	8	1	0
	2041-2070	41	190	163	54	8	1	0
	2071-2100	45	192	154	57	7	1	0
EHRD (ROTTERDAM- NL)	1981-2010	48	228	141	38	2	0	0
	2011-2040	48	226	142	39	2	0	0
	2041-2070	42	231	146	36	1	0	0
	2071-2100	47	237	126	43	4	0	0
EIDL (DONEGAL- IE)	1981-2010	14	108	179	115	36	5	0
	2011-2040	15	112	171	119	33	7	1
	2041-2070	14	104	175	124	33	5	2
	2071-2100	11	106	176	123	35	6	1
EKBI (BILLUND-DK)	1981-2010	34	254	143	24	2	0	0
	2011-2040	39	247	147	22	2	0	0
	2041-2070	40	256	136	23	2	0	0
	2071-2100	36	254	133	32	2	0	0
ENZV (STAVANGER/ SOLA-NO)	1981-2010	19	134	180	94	25	4	1
	2011-2040	15	124	188	98	26	5	1
	2041-2070	15	125	184	105	23	4	1
	2071-2100	16	124	182	100	29	5	1
ESSV (VISBY-SE)	1981-2010	20	191	202	42	3	0	0
	2011-2040	14	126	129	33	2	0	0
	2041-2070	20	183	206	46	3	0	0
	2071-2100	21	196	192	44	3	0	0
LEMD (MADRID, BARAJAS-ES)	1981-2010	30	209	164	48	6	0	0
	2011-2040	32	207	161	49	7	1	0
	2041-2070	35	216	155	45	5	0	0
	2071-2100	34	213	159	44	5	1	0
LFRC (CHERBOURG MAUPERTUS-FR)	1981-2010	18	116	164	115	36	7	1
	2011-2040	15	118	174	109	34	6	1
	2041-2070	16	114	171	114	36	5	1
	2071-2100	17	120	173	109	31	7	1
LIMC (MILANO, MALPENSA- IT)	1981-2010	51	192	156	52	5	1	0
	2011-2040	53	198	149	51	5	1	0
	2041-2070	50	192	150	60	5	0	0
	2071-2100	61	191	141	59	5	0	0

3.2 Results for seaports

Seaports are particularly exposed to extreme weather events and are very important for the local and global economy, since nearly 80% of world freight is transported by ship. Seaports of Europe are gateways to other continents. 74% of extra-EU goods are shipped through ports. They are also important for intra-European trade: 37% of the intra-EU freight traffic and 385 million passengers pass by ports every year. A 50% growth of cargo handled in EU ports is predicted by 2030. Hence, Europe's ports need to adapt to handle the increased traffic. Figure 4 illustrates the EU cargo ports that handle more than 1 million tonnes of goods per year, while the bars refer to those ports that handle more than 10 million tonnes of goods per year.

Figure 4. Europe's cargo seaports



The present study aims to evaluate the impacts of extreme sea levels and river floods on seaports by identifying the ports projected to be exposed to different levels of inundation. The impacts of wind gusts are also considered but in an exploratory way.

3.2.1 Impacts of sea level rise and storm surges on seaports

Inundation due to sea level rise and storm surges could cause both temporary and permanent flooding, while such impacts are already observed in EU countries. In comparison to airports, seaports will be affected more by the projected sea level rise and sea storm surges as 64% of all seaports are expected to be inundated according to the (IPCC, 2012) projected global mean sea levels and combined effects of local waves and storm surges.

Major impacts of sea level rise and storm surges on ports include disruptions of operations and damages of port infrastructure, and vessels. Hinterland connections, such as road and railways to open sea ports, located on coastal areas will also be affected.

Results for 2030 and 2080 are illustrated in Table 10. According to the findings in Table 10 the number of ports that face the risk of inundation is expected to increase by more than 50% from 2030 to 2080. This trend is even stronger on the North Sea coast, where according to the GISCO database over 500 ports are located with traffic accounting for up to 15% of the worlds cargo transport (EUCC-D, 2013). In total, 852 important ports face the risk of inundation by the end of the century is 852.

Table 10. Number of seaports under inundation risk in 2030 and 2080.

Country Code	2030				2080			
	ind ≤1	1< *ind* ≤3	*ind* >3	Σ	*ind* ≤1	1< *ind* ≤3	*ind* >3	**Σ**
BE	-	-	1	**1**	1	-	1	**2**
BG	-	-	-	**0**	5	2		**7**
CY	9	-	-	**9**	11	-	-	**11**
DE	11	-	10	**21**	27	4	10	**41**
DK	12	19	5	**36**	44	40	6	**90**
EE	6	5	-	**11**	6	5	-	**11**
EL	151	14	-	**165**	155	14	-	**169**
ES	8	7	7	**22**	34	6	7	**47**
FI	8	16	-	**24**	11	19	-	**30**
FR	8	2	4	**14**	15	11	4	**30**
HR	8	4	-	**12**	26	50	1	**77**
IE	1	2	3	**6**	9	4	4	**17**
IT	40	10	1	**51**	33	19	-	**52**
LT	-	-	-	**0**	-	-	-	**0**
LV	-	-	-	**0**	-	1	-	**1**
MT	-	-	-	**0**	3		-	**3**
NL	-	-	-	**0**	1	-	1	**2**
NO	13	16	4	**33**	24	14	4	**42**
PL	5	3	-	**8**	9	6	-	**15**
PT	12	-	-	**12**	12	2	-	**14**
RO	-	1	-	**1**	-	1	-	**1**
SE	2	3	-	**5**	13	13	-	**26**
SI	-	-	-	**0**	-	-	-	**0**
UK	38	13	35	**86**	79	14	71	**164**
Total	**332**	**115**	**70**	**517**	**518**	**225**	**109**	**852**

Seaports are resilient to sea level rise plus storm surges under 1m and can operate without interruptions by adopting soft adaptation strategies. The number of seaports that face the risk to be inundated by more than 1m in 2030 is projected to be 185 and to increase to 334 in 2080. In 2030, the number of seaports projected to face inundation levels higher than 3m is 70, and will increase to 109 in 2080. With more information on frequency and duration of inundation events and with the help of Table 10 it would is possible to roughly estimate total damage costs.

Inundated ports face the risk of temporary closure. The total amount of damage when closing the port of Rotterdam for 24 hours could exceed 3 million Euro (Doll et al, 2011), while the sea shipping cost for other ports could reach the amount of 0.75 million Euros.

The cases of seaports projected to be exposed to inundation levels above 1m should be analysed in detail and adaptation strategies should be considered. The three main approaches to adaptation are the following: construction of storm defences, elevation of seaport to compensate for projected sea levels and relocation of seaport. Decisions have to be taken considering each case separately.

The last option, relocation, could be an option only where higher inundation levels occur (e.g. exceeding the 3 meters) and depending on the importance of the seaport as it is a very expensive solution. Port relocation requires the availability of an alternative location, with deep water and suitable transportation linkages – a rare commodity in most coastal areas (Becker et al, 2011). Furthermore, construction costs are high, around 4 billion Euros for international ports (Schade et al, 2006;Schade et al, 2013).

The cost of adaptation depends on the characteristics of the seaport and its location. Assuming that the adaptation measure of choice is the construction of dikes (levees) of one kilometre length and considering the construction costs reported in Hippe et al (2015), the adaptation cost for ports projected to be exposed to inundation levels up to 1 meter (Table 10) by 2030 is between 250 million and 1.32 billion Euros and by 2080 between 392 million and 2.07 billion Euros. It should be noted that hard coastal defences – including dikes, seawalls, breakwaters made of concrete, steel etc. – can cause environmental problems such as coastal erosion and habitat degradation (Airoldi et al. 2005).

An elevated port can be rendered inoperable if its intermodal connections remain unprotected. For seaports inundated at levels between 1 and 3 meters, beach nourishment might be needed. According to Nicholls et al, 2010, in absolute terms for the medium scenario, the cost of beach nourishment is expected to increase from €2.2 billion per year in the 2010s to €4.6 billion per year by the 2040s (dollar/euro parity is taken as equal). The cost of raising port ground levels by 1m is \$15 million per km^2 according to IPCC (1990). The estimation was based on Dutch procedures including design, execution, taxes, levies and fees and the assumption that the operation would take place as an one-off event (Nicholls et al, 2008). According to this and in order to provide an indicative adaptation cost, the cost (dollar/euro parity is taken as equal) of elevation of all seaports projected to be exposed to inundation levels between 1 and 3 meters will be 1.7 billion Euros per km^2 by 2030 and 3.4 billion Euros per km^2 by 2080.

3.2.2 Impacts of river floods on seaports

Some seaports may also be affected by floods and major impacts are projected to take place at the coast of the North Sea. According to the flood maps, 31 seaports will be inundated during a 10-year event at levels higher than 3m (Table 11). The results presented in Table 11 refer to total number of seaports projected to be inundated at different levels, during flood events of different severity.

Table 11. Impacts on seaports due to floods

	Inundation levels (m)	10 years	20 years	50 years	100 years
Seaport	< 1m	94	97	106	106
	1m - 3m	30	34	36	42
	>3m	31	33	39	42
	Total	**155**	**164**	**181**	**190**

For inundation levels exceeding 3 m, higher maintenance, operation and delay costs are foreseen. The cost estimates for values of time and delay are calculated according to Ludvigsen et al. (2012) and Nokkala et al. (2012). Only freight operators and shipper costs are considered; passenger delay costs are much lower as there are only few routes in Europe with large volumes of daily passengers. Time delay costs to European shippers are estimated between €0.19 and €0.96 million per year (Nokkala et al, 2012). Hence, delay costs for a 100year event are estimated between €36.1 million and €182.4 million.

The frequency of events causing river flows to peak is projected to increase significantly in the future due to climate change. The mean annual exceedance frequency of the 100year return period peak flow is projected to increase by 176% in Europe by the end of the century, by 97% in the short-term future period and by 126% in the mid-term future period (Alfieri et al, 2015a). As a result, without additional adaptation measures the seaports affected will be affected more frequently in the future

3.2.3 Impacts of wind gusts on seaports

Regarding the impacts of wind gusts on seaports, data referring to the historic period can be compared to the three future periods considered. The reliability issues regarding the wind gusts data have already been discussed in previous sections. Higher wind gust speeds are projected for the North Sea, Baltic Sea, southern Europe and Adriatic Sea.

The impact of high wind speeds is largely operational. The infrastructure itself, particularly the buildings, is resilient to very high winds/gusts. Hence, aim of adaptation measures should be to minimise the risk of accidents and avoid operational disruptions. The values in Table 12 refer to the annual average number of days over the indicated period with wind gust speeds within the indicated limits. When wind gust speeds exceed 30 m/s ports may be forced to close, while lower values may have an adverse effect on operations.

Table 12. Daily maximum near-surface wind speed of gust for selected TEN-T seaports

TEN-T seaports	Period	0_5 m/s	5_10 m/s	10_15 m/s	15-20 m/s	20-25 m/s	25-30 m/s	> 30 m/s
DEWYK (Wyk/Föhr- DE)	1981-2010	101	190	133	30	1	0	0
	2011-2040	103	191	134	28	1	0	0
	2041-2070	102	199	129	25	0	0	0
	2071-2100	102	191	129	34	1	0	0
DKEBJ (Esbjerg- DK)	1981-2010	44	227	147	36	3	0	0
	2011-2040	46	220	151	38	2	0	0
	2041-2070	45	228	150	32	1	0	0
	2071-2100	47	227	143	38	2	0	0
EEPRN (Pärnu- EE)	1981-2010	27	208	186	34	2	0	0
	2011-2040	29	202	188	36	2	0	0
	2041-2070	20	203	200	33	1	0	0
	2071-2100	27	212	181	35	2	0	0
FRLRH (La Rochelle-FR)	1981-2010	21	118	203	101	13	0	0
	2011-2040	20	123	204	96	12	1	0
	2041-2070	22	119	206	102	8	0	0
	2071-2100	22	124	210	90	9	1	0
GBNHV (Newhaven – UK)	1981-2010	19	131	163	106	32	6	0
	2011-2040	16	131	167	110	28	4	1
	2041-2070	17	128	169	112	28	4	0
	2071-2100	17	137	164	106	28	5	1
GRJNX (Naxos-GR)	1981-2010	9	130	180	93	36	8	1
	2011-2040	10	128	169	101	37	10	1
	2041-2070	10	126	177	91	42	11	1
	2071-2100	8	135	180	92	31	9	1
LVLPX (Liepaja-LV)	1981-2010	29	213	183	31	1	0	0
	2011-2040	31	213	179	32	1	0	0
	2041-2070	25	215	187	28	1	0	0
	2071-2100	30	220	171	34	2	0	0
PTAVE (Aveiro-PT)	1981-2010	21	188	186	57	5	0	0
	2011-2040	22	193	183	53	6	0	0
	2041-2070	27	196	182	46	5	0	0
	2071-2100	25	193	182	50	6	1	0
SEGOT (Göteborg- SE)	1981-2010	40	186	179	49	2	0	0
	2011-2040	39	187	180	48	3	0	0
	2041-2070	35	188	182	50	3	0	0
	2071-2100	37	186	183	48	3	0	0
SEMMA (Malmö-SE)	1981-2010	0	0	0	0	0	0	0
	2011-2040	71	255	110	18	2	0	0
	2041-2070	72	258	108	18	1	0	0
	2071-2100	79	248	108	20	2	0	0

3.3 Results for inland waterways

IWW play a significant role in freight transportation in Europe. According to the TRANSTOOLS[8] reference scenario, in 2005 approximately 293 million tons of freight was transported among the EU countries (excluding national trade) using IWW, an amount slightly smaller to the amount of freight transported by rail and to the one third of the amount of freight transported by road.

IWW is considered to be a very reliable mode, but can be more vulnerable to climate change than road or rail because of the reliance of river navigation on water levels. Extreme weather events affecting IWW include floods during which water levels exceed the maximum permitted ones and droughts due to which water levels become critically low imposing limitations to navigation services.

Besides the water levels, the formation of ice can also be disruptive to the operation of IWW especially in slow flowing rivers; for example shipping on the Danube was interrupted for several days during the winters of 2005 and 2006 due to ice formation (Scholten and Rothstein, 2016). The case of ice is not examined in this report because of its limited effects in terms of duration or frequency, which are expected to be further reduced due to the projected increase of temperatures in the (mid- and long-term) future.

Floods are considered to have less severe impacts on IWW transportation than droughts because of their relatively lower duration (Hendrickx and Breemersch, 2012; Scholten and Rothstein, 2016; Jonkeren et al., 2007). In addition, droughts can severely disrupt inland navigation services by reducing water levels either at completely non-navigable ones, or more frequently at levels at which operators are forced to reduce the vessels' load factors.

Droughts and as a result low water levels may disrupt IWW activity by imposing restrictions to the amounts of loads transported, increasing the number of vessels to compensate reduced load factors or increasing the travel time when vessels stop and wait for the water levels to rise again. Furthermore, a possible reaction of the market to disrupted navigation services might be shifting to more resilient to climate change (but more environmentally harmful in terms of carbon emissions per tonne of cargo) modes such as road. Jonkeren et al (2011) in a study focusing on the impacts of climate change on river Rhine found that the effect of low water levels on modal split is limited. In the same study it was estimated that the majority of the freight lost in IWW will be transported by road transport (around 70%) with negative impacts on the environment (higher emissions) and further loading of an already congested road network.

In the present study, the economic impacts of droughts will be quantified by focusing on the impacts of change of transport activity in terms cargo transported or better cargo transportation potential of a given fleet. The impacts of climate change on IWW will be estimated by combining physical impacts with activity data on the IWW network.

3.3.1 Assumptions

For the estimation of the impacts of climate change on inland waterways transport several assumptions and simplifications have been made. The most important are summarised in the following points:

a) The impact of floods on the inland waterway transport system are not analysed in detail. Floods are considerably less disruptive than droughts because of their relatively low duration and frequency.
b) Droughts are analysed focusing on four points on the rivers Danube and Rhine because location specific factors have to be considered. Taking into account that a substantial proportion of the total EU inland waterways

[8] More information on the TRANSTOOLS model: http://energy.jrc.ec.europa.eu/transtools/documentation.html

transport activity is taking place on these rivers and passing from Ruhrort and Kaub, the results are assumed to be indicative of the total impacts of climate change on inland waterways in the EU.

c) The estimation of the impacts of droughts is based on discharges. The relations between water levels and discharges for the four points have been determined using various data sources and they are assumed to remain unchanged over the projection period.
d) The assessment of the impact of droughts on transport activity is based on the relationship of the bearing capacity of vessels with water levels. Key variable is the level of discharges, or better, the distribution of the time periods according to discharge levels. Transport activity is given in average annual day tonnes and is assumed to correspond to normal water levels.
e) The transport activity considered is the total activity on the links intersecting the points examined. Activity and its distribution to different types of vessels are assumed to remain unchanged over the projection period.
f) Transport costs per day have been determined by combining cost data (cost per tonne) for specific trips with average travel time estimates for these trips. The difference between the low and high values used is meant to serve as an indication of the variation of prices that may occur for different reasons including direction of trip (upstream or downstream), seasonality etc. The potential impact of water levels on cost is not modelled explicitly and costs are assumed to remain constant over time.

3.3.2 Impacts of river floods on inland waterways

During severe flooding IWW services may be interrupted but even with more frequent floods and longer flooding periods, floods shall be less disruptive than droughts because their effects last only for a relatively short period.

For this purpose, a detailed assessment of floods' impacts on IWW is not taken place. However, in order to provide an indication of the magnitude of scale of potential impacts, the parts of the network with maximum projected water level difference exceeding the threshold of 5m during a 100-year and 10-year flood event are identified. The 5m threshold is only meant to indicate the change of high water levels.

To find the parts of the IWW network affected by floods, the inundation maps produced by the group working on floods (Alfieri and Feyen, 2016) are overlaid with the inland water navigation network (Figure 5). According to the model estimates, 10-year, 20-year, 50-year and 100-year return periods of maximum depths are identified. Both the TRANSTOOLS and the GISCO inland waterways networks are used since the TRANSTOOLS network is a generalised network that contains freight activity information and GISCO inland waterways represents the reality comprehensively with respect to spatial resolution.

Figure 5. Segments with depth difference higher than 5m between the 100-year and 10-year return period estimates indicating the difference of severity of the two events

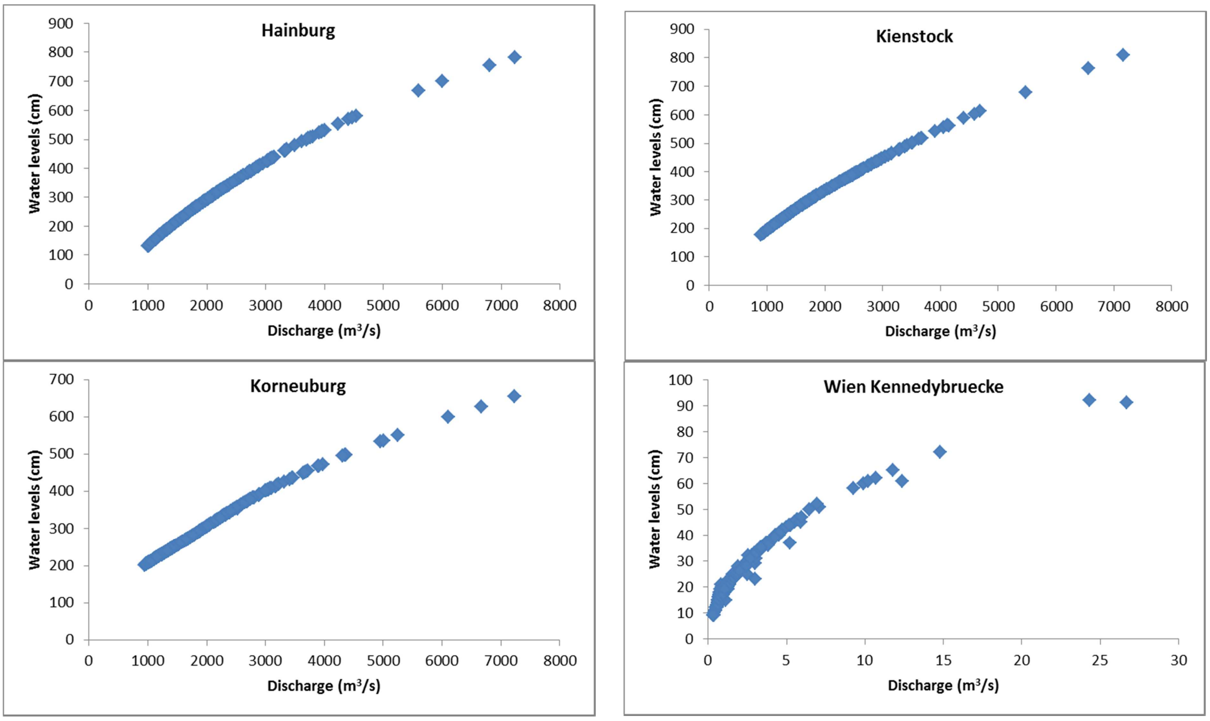
From the per grid comparison of the maximum depths for the 100-year return period and the 10-year return period, it is estimated that the difference of high water levels will exceed 5m for 344.45 km out of the 17419.30 km of the navigable network. The relevant segments of the network are marked in red in Figure 5. Moreover, the frequency of floods is projected to increase over time; more specifically, the mean annual exceedance frequency of the 100year return period peak flow is projected to increase by 176% in Europe by the end of the century while in certain countries such as the Netherlands the increase will be significantly higher (Alfieri et al, 2015a).

3.3.3 Impacts of droughts on inland waterways

Droughts and resulting low water levels can seriously affect IWW. Water levels are directly related to discharges and the riverbed morphology at a specific part of the river, which means that the relationship between water levels and discharges has to be location specific. The morphology of the riverbed changes over time and as a result water levels are difficult to compare over long time-periods. Hence, discharges are commonly used for relevant types of analysis instead of water levels (Nilson et al, 2012).

As an example of the close relationship between water levels and discharges, in Figure 6 the daily values of the two variables are drawn for four points on Danube for which both discharge and water level data are available. The data refer to 2010 and were obtained from BMLFUW (2012).

Figure 6. Relationship between discharges and water levels for four points on the Danube river (average daily values for 2010)

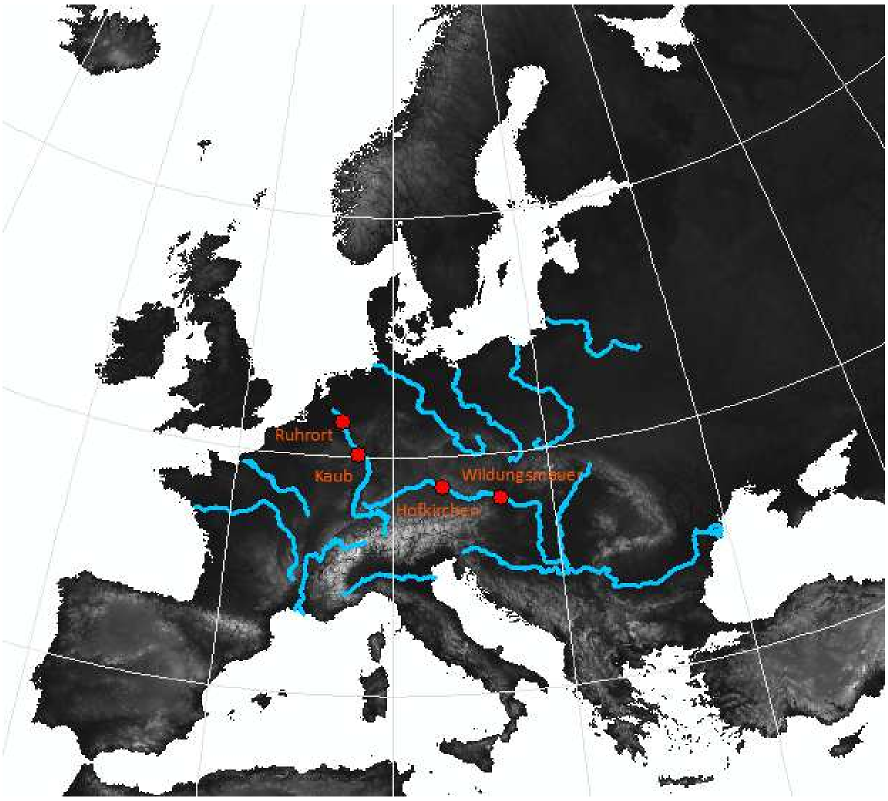


In this study, daily discharge values have been obtained from the group working on the water sector of PESETA III and combined with empirical data on water levels and discharges[9] in order to identify critical discharge levels which are then used to estimate the impacts on transport activity and relevant costs for different scenarios. The relation between water levels and discharges might change drastically over time and the U.S. Geological Survey estimated for the Mississippi and Misouri rivers changes of the waters levels corresponding to the same discharges more than two meters during the last two centuries[10] . Very detailed data are required to estimate these changes and the relationship between water levels and discharges in this project is assumed to remain constant during the projection period.

The analysis is conducted focusing on critical points on the Rhine and Danube rivers which account for a large part of the total activity on the IWW network. Only on Rhine takes place around 70% of the total IWW transport activity of the former EU15 member states (Jonkeren, 2007). Four points have been selected in total based on a combination of criteria including their importance as freight nodes, the effect of low water levels and the availability of data. The selected points are the following: Wildungsmauer (Danube), Hofkirchen (Danube), Ruhrort (Rhine) and Kaub (Rhine) and their position is shown in Figure 7. They were also analysed in the ECCONET project (Beuthe et al, 2014; Hendrickx and Breemersch, 2012) while Kaub is referred to as a key bottleneck of Rhine in several studies (Jonkeren et al, 2007; 2011; 2014; Beuthe et al, 2014). Jonkeren et al (2011) argue that they "have chosen Kaub as a reference point, because it is here that restrictions related to low water levels are most severe. For the barge trips that pass Kaub, the water level at Kaub is the critical point for the maximum possible load factor and thus also for the costs (or price) per tonne transported."

[9] E.g. ELWIS, 2016; Scholten and Rothstein, 2016; https://www.pegelonline.wsv.de/gast/start
[10] https://www.umesc.usgs.gov/aquatic/jwlosinski_5001295.html

Figure 7.Selection of critical points on the rivers Danube and Rhine



Low water levels affect IWW transportation by reducing the navigability of vessels. Practically, up to a certain level of water the maximum draught of the ship cannot be utilised and the ship has to be operated at limited capacity, i.e. the cargo that can be transported is reduced. As a result, more vessels have to be operated or ships have to wait until water levels will rise or the total amount to be transported has to be reduced in absolute values. Although the positive relationship between cargo amounts and water levels has been proven using detailed data for specific gauges, the number of ships seems to be weakly connected to water levels for both the Danube and the Rhine rivers (Scholten and Rothstein, 2016).

Furthermore, under certain demand it is expected that prices should have a negative relationship with water levels. Jonkeren (2007) found that price per tonne may increase significantly during periods of low water levels especially for vessels passing from Kaub. On the other hand, the results in Scholten and Rothstein (2016) are less clear. In general, market prices are affected by various factors, including seasonal demand, mode competition, direction of the trip (the prices for upstream trips are higher than those for downstream trips as fuel consumption is higher), the closure of a gauge for other reasons etc. The consideration of price differentiation according to water levels is beyond the scope of this study, especially taking into account the long term projections used and data restrictions.

The main steps taken in this study for the estimation of the economic impacts of low water levels are briefly the following:

- At first, discharge data are used to calculate the number of days with discharge values within location-specific thresholds.
- Then, the results are combined with data on IWW freight activity and indicators regarding the impact of water levels on the bearing capacity of different types of vessels to estimate the impact on the amounts of cargo transported.

- Finally, the resulting cost or benefit is estimated by combining freight activity with transport cost values and comparing with the reference period.

These steps will be described in more detail in the following sections.

Discharges

For the estimation of the impacts of low water levels discharge data of the 5 model runs reported in Table 5 have been used.

In order to be able to compare between the different scenarios and points a common indicator is calculated. The number of days with discharges below the 5th percentile of the 1981-2010 reference period is calculated for each of the four periods and the five model runs. The results are presented in Table 13.

Table 13. Average annual number of days with discharges below the 5th percentile of the historic period (1981-2010)

Locations on rivers	Run	1981-2010	2011-2040	2041-2070	2071-2099
Ruhrort	**1**	18	14	8	9
	2	18	14	20	41
	3	18	13	5	0
	4	18	12	23	27
	5	18	8	13	19
Kaub	**1**	18	11	4	6
	2	18	14	18	38
	3	18	12	4	0
	4	18	11	24	28
	5	18	6	9	14
Wildungsmauer	**1**	18	12	2	0
	2	18	5	5	8
	3	18	10	1	0
	4	18	11	13	13
	5	18	4	0	3
Hofkirchen	**1**	18	10	4	0
	2	18	8	12	21
	3	18	9	1	0
	4	18	8	13	15
	5	18	3	0	5

For both points (Wildungsmauer and Hofkirchen) on Danube and all the scenarios but one for Hofkirchen, the number of days with low discharges is projected to become smaller. For the locations selected on Rhine, for two runs in Kaub and three runs in Ruhrort, the number of days with low discharges is projected to increase, following an initial decline and two consecutive increases over the projection periods. The annual average number of days with discharges below the 5th percentile for the historic (1981-2010) period is in line (18 days) with the number of days with discharges below the 95th percentile of the flow-duration curve as calculated in the ECCONET project (Nilson et al,

2012) for the same gauges and the 1961-1990 time series. In the ECCONET project a general trend of over time decline of the number of days with discharges undershooting the 95th percentile of the flow-duration curve was observed during the observed period (1950-2005) for both Rhine and Danube.

Bearing capacity

The impacts of low water levels on transport activity and as a result on the corresponding costs depend on the draught of the vessel and the gauge of the channel or river. Before the complete seizure of transport activity, as water levels become lower, vessels operate at reduced capacity in order to reduce their draught.

The thresholds of water levels and discharges depend on the characteristics of the river or channel at a specific point and vary significantly. As a general indication, according to Middelkoop et al (2001) when the Rhine discharge is below 1000 to 1200 m^3/s ships on the route from Rotterdam to Basel via Germany have to reduce their loads, while for Vienna the total regulated low water level is 900 m^3/s (values from www.viadonau.org reported in NEWADA (2010)).

The technical characteristics, including draught and loading capacity, of the vessels operating on the inland waterway network are specified in UNECE (1996).

Table 14 presents the bearing capacity (as proportion) of different types of vessels at given water levels. It has been constructed based on relevant information provided in Scholten and Rothstein (2016) that has been adapted to correspond to the CEMT classification of inland waterways in order to be compatible with the freight activity data.

Table 14. Bearing capacity of different ship types at different water levels (taken from Scholten and Rothstein (2016) and adjusted)

Gauge (m)	CEMT 2	CEMT 3	CEMT 4	CEMT 5	CEMT 6
3.5	1	1	1	1	1
3	1	1	1	1	0.8
2.5	1	1	1	1	0.65
2	0.95	0.95	0.95	0.8	0.5
1.5	0.5	0.45	0.4	0.3	0.2

Table 14 is combined with the transport activity data to estimate the total capacity to be carried through a point at given water levels. However, as discharges are used instead of water levels, the discharges corresponding to the water levels in Table 14 for the specific points on Rhine and Danube have been estimated using data from various sources[11].

[11] Data sources considered include the following: ELWIS, 2016; Scholten and Rothstein, 2016; Bolle and Schwab, 1980; https://www.pegelonline.wsv.de/gast/start; http://undine.bafg.de/servlet/is/8606/

Using the discharge levels corresponding to the water levels of Table 14, the distribution of the number of days of each of the four time periods (the historic plus the three future periods) to the six following groups is calculated:

- Q0: number of days with discharges corresponding to gauge below 1.5m
- Q1: number of days with discharges corresponding to gauge between 1.5m and 2m
- Q2: number of days with discharges corresponding to gauge between 2m and 2.5m
- Q3: number of days with discharges corresponding to gauge between 2.5m and 3m
- Q4: number of days with discharges corresponding to gauge between 3m and 3.5m
- Q5: number of days with discharges corresponding to gauge higher than 3.5m

In Figures 8, 9, 10 and 11 the distribution for the four points for each of the five runs (Table 5) is presented. Besides the variation between the different runs, it is interesting to observe for certain runs an over-time trend towards decreasing the number of days with lower water levels and increasing the number of days with higher water levels. In these cases, the IWW network is projected to operate with fewer disruptions due to low water levels in the specific locations.

Figure 8. Distribution of the four time periods for the 5 model runs according to water levels for Ruhrort

Figure 9. Distribution of the four time periods for the 5 model runs according to water levels for Kaub

Figure 10. Distribution of the four time periods for the 5 model runs according to water levels for Wildungsmauer

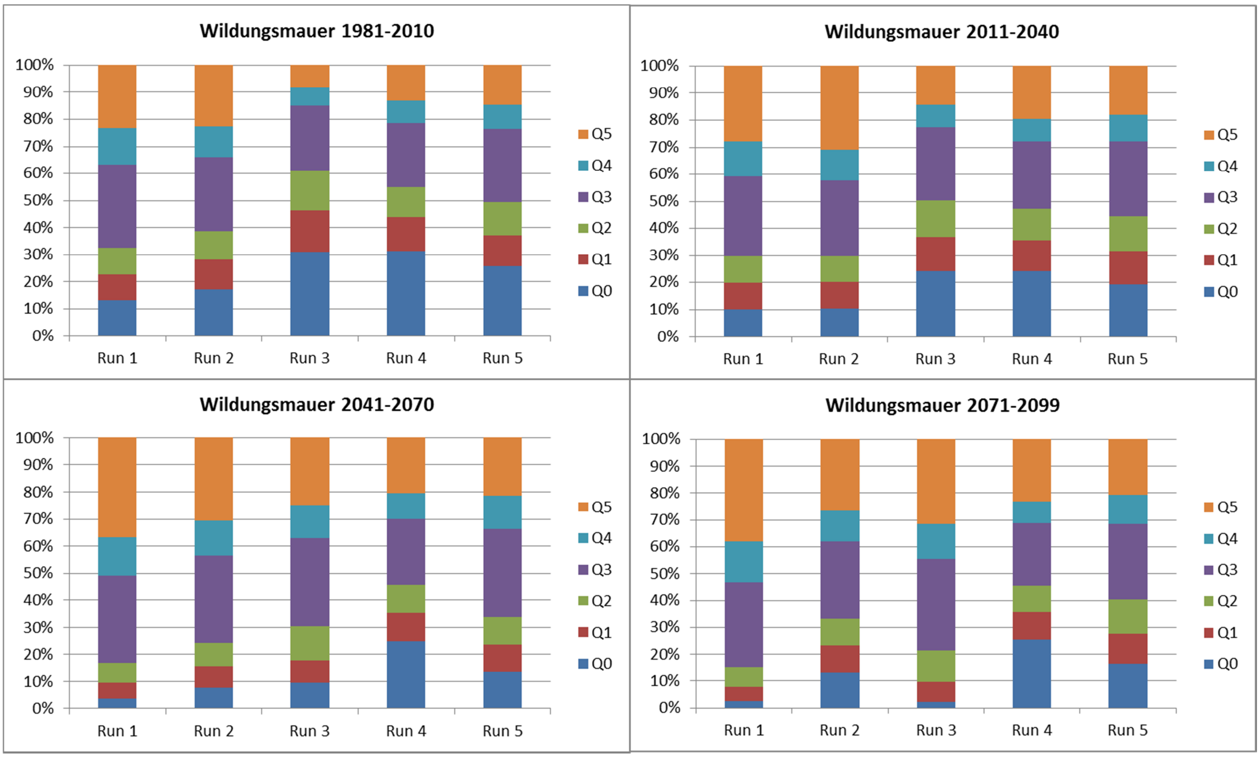
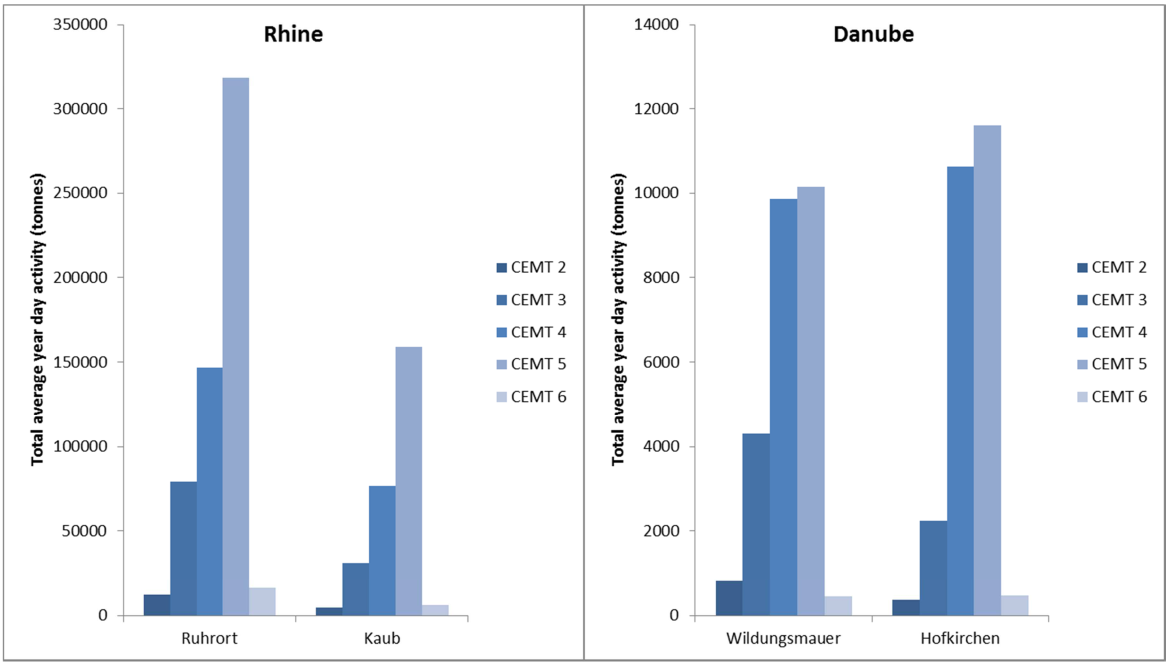


Figure 11. Distribution of the four time periods for the 5 model runs according to water levels for Hofkirchen

Freight activity

For the estimation of the economic impacts of low water levels, transport activity figures of the TNET model (Ibañez et al, 2016) for 2015 are used (Figure 12). Only freight transport is considered and the demand is based on the ASTRA-EC (ASSIST, 2014; TRT, 2003) projections. Transport activity is expressed in average year day tonnes carried by each type of vessel. Following the assignment of demand on the IWW network, transport flows for each link are estimated. The activity on the four points of interest (Ruhrort, Kaub, Wildungsmauer and Hofkirchen) is calculated by considering the flows (in terms of tonnes) on the links intersecting these points.

Figure 12. Transport activity by vessel type at the four points in Rhine and Danube



Economic valuation

Finally, the monetary costs or benefits are calculated by combining current activity data with bearing capacity restrictions and transportation cost. It is assumed that the TNET activity data refer to water levels that allow vessels to operate at full capacity.

To define the range of unit transport costs, data from various sources have been considered including Scholten and Rothstein (2016) and Bruinsma et al (2012). The range aims to capture price variation that may be attributed to various reasons including season, direction of trip (upstream-downstream), data etc.

Regarding the Rhine market, according to the ECCONET project (Bruinsma et al, 2012), transport cost varies from 3.5€/t to 7.5€/t for the Rotterdam-Duisburg trip and from 9€/t to 20€/t for the Rotterdam-Basel trip. According to Scholten and Rothstein (2016) the price range for trips from and to the ports of Amsterdam, Rotterdam and Antwerp is from 15€/t to 25€/t for Danube and from 5€/t to 12€/t for Rhine.

Transport cost values for specific trips on Danube and Rhine have been combined with the corresponding average travel time obtained from TNET (Ibañez et al, 2016) to calculate transport cost per tonne per day. Finally, the daily transport cost values applied to estimate the economic impacts are 4€/tonne/day (low) and 8€/tonne/day (high).

In Figure 13 the annual average costs or benefits for each projected future period (2011-2040, 2041-2070, 2071-2099) in comparison to the historic period (1981-2010) and for each run (Table 5) are presented. The values in Figure 13 refer to the average value of the cost range used. On the other hand, in Table 15 the range of the average annual cost or benefit considering the lower and upper transport cost values are presented.

For the majority of the cases (selected model runs and locations) a benefit is estimated as a result of the reduction of low water days. In the last period, a cost is estimated only for Ruhrort for three out of the five model runs and for Kaub for one model run. As an indication of the scale of magnitude, Jonkeren (2007) estimate the annual welfare loss due to low water levels for Kaub to €28 million while in 2003 the loss was estimated to be €91 million and in 1991 €79 million.

From the two points on Rhine, where freight activity by inland waterways is significantly higher than in Danube, the impacts are proportionally higher in Kaub, which is considered to be a key bottleneck on Rhine and seems to be benefiting from the projected discharges.

Figure 13. Average annual cost or benefit of low water levels (in comparison to the reference period)

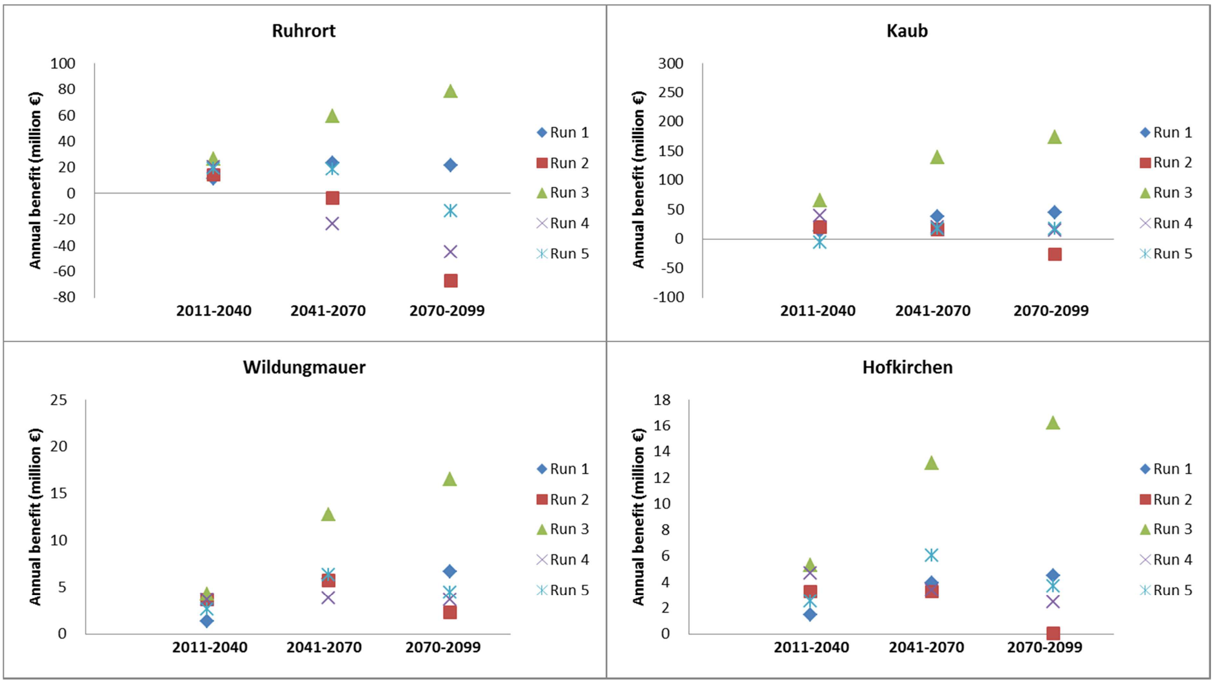


Table 15. Range of average annual cost or benefit (in million €) of low water levels in comparison with the reference period

Point	Run	2011-2040		2041-2070		2071-2099	
		Low	**High**	**Low**	**High**	**Low**	**High**
Ruhrort	**1**	7.24	14.49	15.49	30.99	14.59	29.17
	2	9.28	18.56	-2.55	-5.10	-44.70	-89.40
	3	17.80	35.60	39.40	78.80	52.07	104.13
	4	13.46	26.91	-15.52	-31.05	-29.86	-59.71
	5	12.65	25.31	12.33	24.66	-9.16	-18.32
Kaub	**1**	9.09	18.18	24.95	49.89	29.56	59.12
	2	13.03	26.06	11.15	22.30	-17.71	-35.42
	3	43.30	86.61	92.58	185.16	116.07	232.15
	4	26.55	53.09	13.02	26.04	9.57	19.13
	5	-4.27	-8.54	11.74	23.48	11.32	22.63
Wildungsmauer	**1**	0.89	1.78	3.94	7.89	4.45	8.91
	2	2.43	4.86	3.78	7.56	1.53	3.07
	3	2.81	5.63	8.47	16.95	10.99	21.97
	4	2.46	4.92	2.57	5.13	2.44	4.89
	5	1.77	3.54	4.21	8.41	2.93	5.86
Hofkirschen	**1**	0.98	1.97	2.61	5.22	3.00	6.00
	2	2.17	4.34	2.16	4.31	0.05	0.09
	3	3.52	7.05	8.74	17.48	10.82	21.65
	4	3.11	6.22	2.26	4.52	1.61	3.22
	5	1.67	3.33	4.02	8.05	2.43	4.87

3.4 Adaptation

The impact of climate change on airport, seaport and inland waterways operations depends on local conditions and the design of infrastructure. Hence, before proposing specific adaptation measures it is necessary to carry out vulnerability analysis and risk assessment. Adaptation measures to climate change impacts should be incorporated in technical regulations regarding design modification or rehabilitation of infrastructure. Parameters to be considered for the determination of adaptation measures refer to characteristics of climate change related events and include spatial extent, intensity, severity, frequency, predictability, duration and rate of occurrence (gradual to sudden) (Schneider et al., 2001). A selection of general adaptation measures for airports and seaports is presented in Table 16.

Table 16. Adaptation Strategies (adapted from NOAA, 2015)

Climate Change Stressor	Transport Mode	Action Example
Sea Level Rise Storm Surge	Airport	Protect infrastructure with dikes and levees (Steward et al, 2011)
		Elevate critical infrastructure (Schwarz, 2011)
		Repairs, replacement and redesign (Peterson et al, 2008) (Steward et al., 2008)
		Abandon or move coastal transportation system (Schwarz 2011)
		Incorporate climate change into future transportation planning (Peterson et al 2008)
	Seaport	Same as airports
		Construction of storm retention basins (Schwarz, 2011)
		Changes of infrastructure design, change in material specifications, protective strategies for critical components (Meyer, 2008)
Floods	Airport	Stringent design for flooding and for building in saturated soils (Meyer, 2008)
Wind gust	Airport	Incorporate potential of climate change into existing systems of planning for irregular operations (Steward et al, 2011)
		Incorporate relevant information into asset management and maintenance (Steward et al, 2011)
		Change design factors to incorporate more turbulent wind conditions (Meyer, 2000)
		Hardening facilities for higher wind loads (Steward et al, 2011; Klin et al., 2011)

For the estimation of the impacts of climate change on IWW it was decided to focus on a selection of points of the IWW network. Due to the nature of this mode's network, the location specific characteristics that define the gauge or discharge levels have to be taken into account in order to evaluate the impact of projected discharges. The results for the selected points show that for the two points on Danube the number of low water days is projected to decrease; a similar trend is projected for Kaub on Rhine according to the majority of the selected model runs and for Ruhrort according to two out of the five model runs that have been considered. The location specific nature of the relationship between discharges and water levels does not allow to generalise the total outcome and the variation of the projections of the model runs indicates that the risks of droughts should not be ignored.

The issue of adaptation of IWW is covered by reviewing relevant literature, the results of relevant projects such as ECCONET, EWENT, WEATHER and the reports produced by local, national or international organisations (AGN-UNECE, www.viadonau.org etc.).

ECCONET has identified main adaptation measures and together with stakeholders evaluated them in terms of feasibility (Ubbels et al, 2011; 2012). The following is a summary of adaptation measures:

- Development of lightweight structures, small vessels and vessels with flat hulls in order to increase the bearing capacity of vessels when water levels become lower.
- Install adjustable tunnels and blisters to enhance the navigability of the vessel under different (e.g. low water) conditions.
- Continuous instead daytime only operation especially of small vessels to increase the total operating hours.
- Use coupled convoys to increase volumes transported.
- Strategic alliances between IWW and other modes to improve the seamlessness of the supply chain during low water days.
- Take maintenance measures and improve river engineering to improve the navigability on the river under different water level conditions.
- Improve prediction methods of low water levels to improve the planning of shipments.

The cost effectiveness of adaptation measures is assessed in Breemersch et al (2012) and Holtman et al (2012). Breemersch et al (2012) conclude that the weight reduction of bigger ships is the most cost-effective solution. However, bigger ships have probably already reduced weight up to the marginal cost. Weight reduction for smaller ships is not so attractive due to the small margin of gain and relatively high cost. Installation of flat hulls can be promising but is costly while even the most interesting technical measures such as retractable aprons have relatively high cost which makes them unappealing under the projected changes of dry periods. Regarding operational measures Holtman et al (2012) conclude that the continuous operation of smaller ships increases transport costs but the operation of smaller ships in coupled convoys can be very effective. For more details on the assessment of the adaptation measures refer to the ECCONET project[12], Breemersch et al (2012) and Holtman et al (2012).

[12] https://www.ecconet.eu/deliverables/index.htm

4 Conclusions

The impacts of climate change on airports, seaports and IWW in Europe have been examined. For the cases of airports and seaports, it has been possible to identify infrastructure at risk and provide indicative costs while for IWW the impacts of climate change at critical points are assessed.

According to the results, various European airports located relatively close to the coast are projected to be exposed to higher sea water levels and face an increase of storm surge heights by the end of the century. Airports to be mainly affected by the end of the century are located in Norway, Germany, United Kingdom and Ireland, among others. Eight of those airports are projected to be exposed to inundation levels higher than 3m. Furthermore, inland airports could be affected by river floods and the most severe impacts are projected to take place in regions near the North Sea coastline.

Regarding seaports, more severe impacts are projected for northern Europe, where also the biggest cargo seaports of Europe are located. According to the results 852 ports in the EU face the risk of inundation by the end of the century, while the number of ports that face the risk to be exposed to water levels higher than 3 m will double from 2030 to 2080.

For inland waterways, the focus has been on specific locations of Rhine and Danube where the majority of freight activity in the EU takes place. For most of the cases considered a reduction of low water days is projected; according to this, the inland waterway transport system could operate with less drought-related disruptions.

The estimation of the impacts of climate change on transport requires relatively detailed data for both the identification of infrastructure at risk and the quantification of disruptions or damages. However, besides the general difficulty to provide climate projections at spatially disaggregate level, it is also very difficult to provide reliable projections for elements that can significantly affect transport such as wind. The need for detailed data makes the assessment of the impacts of climate change on transport for a large area such as Europe particularly challenging. In this respect, the limitations of this study were largely set by the data obtained.

The results of the analysis indicate at first the sectors at risk and the magnitude of damage to be attributed to different impacts. Furthermore, the most vulnerable areas and sites are identified indicating those spots that need to be closer examined.

Further analysis is required to quantify the impacts in detail and follow up projects should focus on mapping in detail Europe's critical infrastructure at risk from climate change, and estimating relevant costs. More detailed analysis would require information on the frequency and duration of the weather events considered. Furthermore, the qualitative characteristics of infrastructure of major seaports and airports need to be taken into account. Infrastructure at risk should be examined case by case in order to take into consideration particularities of the area, resilience of infrastructure and of course details regarding transport activity and economic importance. Studies focusing on specific cases and pilot projects could indicate important factors (e.g. of success) and highlight the main characteristics of a general methodology for analysing the impacts of climate change on certain transport sectors.

References

ACRP (Airport Cooperative Research Program), 2012. Airport Climate Adaptation and Resilience, Synthesis 33: Airport Climate Adaptation and Resilience reviews the range of risks to airports from projected climate change and the emerging approaches for handling them. TRB. DOI: 10.17226/22773

Airoldi, L., Abbiati, M., Beck, M., Hawkins, S., Jonsson, P.R., Martin, D., Moschella, P., Sundelöf, A., Thompson, R. and Aberg, P. 2005. An ecological perspective on the deployment and design of low-crested and other hard coastal defence structures. Coastal Engineering, 52, 10, 1073-1087

Alfieri, L., Salamon, P., Bianchi, A., Neal, J., Bates, P. and Feyen, L. 2013. Advances in pan-European flood hazard mapping, Hydrological Processes, 28, 4067-4077, DOI: 10.1002/hyp.9947

Alfieri, L., Burek, P., Feyen, L. and Forzieri G. 2015a. Global warming increases the frequency of river floods in Europe. Hydrology and Earth System Sciences, 19, 2247–2260

Alfieri, L., Feyen, L. Dottori, F. and Bianchi, A. 2015b. Ensemble flood risk assessment in Europe under high end climate scenarios. Global Environmental Change, 35, 199–212

Alfieri, L. and Feyen, L. 2016, Flood impact assessment for Europe in view of climate change. Interim report for DG CLIMA, Deliverable 7a, AA №340202/2015/721213/SER/CLIMA.C.3 – JRC 34181-2015 NFP "Climate Impacts and Adaptation in Europe, focusing on Extremes, Adaptation and the 2030s (PESETA3)

Ang-Olson, J. 2009, What Does Climate Change Mean for Airport Planning? Presentation to Transportation Research Board

ASCE (American Society of Civil Engineers), 2005. Minimum Design Loads for Buildings and Other Structures – ASCE

ASCE (American Society of Civil Engineers), 2006. Flood Resistant Design and Construction (24-05)

ASSIST, 2014. The ASTRA-EC model user guide. Project co-funded by European Commission 7th RTD Programme. Fraunhofer-ISI, Karlsruhe, Germany.

Baglin, C. 2012. Airport climate adaptation and resilience. National Research Council (U.S.), Transportation Research Board, Airport Cooperative Research Program, United States, & Federal Aviation Administration. Washington, D.C.: Transportation Research Board.

Barredo, J. I., de Roo, A. and Lavalle, C. 2007. Flood risk mapping at European scale, Water Sci. Technol., 56, 11–17, DOI:10.2166/wst.2007.531

Becker, A., Inoue, S., Fischer, M. and Schwegler, B. 2011. Climate change impacts on international seaports: knowledge, perceptions, and planning efforts among port administrators. Climatic Change, 110, 1-2, 5–29. DOI:10.1007/s10584-011-0043-7

Becker, A., Acciaro, M., Asariotis, R., Carera, E., Cretegny, L., Crist, P., Esteban, M., Mather, A., Messner, S., Naruse, S., Ng, A.K.Y., Rahmstorf, S., Savonis, M., Song, D., Stenek, V. and Velegrakis, A.F. 2013. A Note on Climate change adaptation for seaports: A challenge for global ports, a challenge for global society, Climatic Change 120, 4, 683-695. Available: htp://www.dx.doi.org/10.1007/s10584-013-0843-z

Beniston, M., Stephenson, D.B., Christensen, O.B., Ferro, C., Frei, C. Goyette, S., Halsnaes, K., Holt, T., Jylhä, K., Koffi, B., Palutikof, J., Schöll, R., Semmler, T., Melillo, J. M., Terese (T.C.) Richmond, and Gary W. Yohe (eds.) 2014. Climate Change Impacts in the United States: The Third National Climate Assessment, USGCRP, United States Global Change Research Program. 841 pp

Beuthe, M., Jourquin,B., Urbain,N., Lingemann,I., Ubbels,B. 2014, Climate change impacts on transport on the Rhine and Danube: A multimodal approach. Transportation Research Part D, 27,6–11

BMLFUW, 2012. Hydrographisches Jahrbuch von Österreich 2010, ed. Hydrographischer Dienst, Bundesministerium fuer Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft, Wien

Bolle, A. and Schwab, R., 1980, Jahrbuch der Hafenbautechnischen Gesellschaft, Siebenunddreissiger Band 1979/80, Springer, ISBN-13:978-3-642-81463-1

Breemersch, T., Heyndrickx, C., Bruinsma, F., Rietveld, P., 2012. Cost Effectiveness of IWT, Deliverable 4.2 of ECCONET project. Report prepared for the European Commission, Directorate-General for Energy and Transport.
Available: https://www.ecconet.eu/deliverables/index.htm (last accessed: 30/3/2017)

Bruinsma, F., Koster, P., Holtmann, B., van Heumen, E., Beuthe, M., Urbain, N., Jourquin, B., Ubbels, B., Quispel, M., 2012. Consequences of Climate Change for Inland Waterway Transport, Deliverable 3.3 of ECCONET project. Report prepared for the European Commission, Directorate-General for Energy and Transport. Available: https://www.ecconet.eu/deliverables/index.htm (last accessed: 30/3/2017)

Bucchignani, E. & J.M.m Gutierrez, 2015. Definition of different EWI's, to support the management of European CI. INTACT Deliverable D2.1, project co-funded by the European Commission under the 7th Framework Programme.

Curtis, S. (ed) 2007. Hurricane Katrina Damage Assessment: Louisiana, Alabama, and Mississippi. Reston, VA: American Society of Civil Engineers.

Doll, C., Klug, S., Köhler, J., Partzsch, I., Enei, R., Pelikan, V., Sedlacek, N., Maurer, H., Rudzikaite, L., Papanikolaou, A. and Mitsakis, V. 2011. Adaptation Strategies in the Transport Sector. Deliverable 4 of the research project WEATHER (Weather Extremes: Impacts on Transport Systems and Hazards for European Regions) funded under the 7th framework program of the European Commission. Project coordinator: Fraunhofer ISI, Karlsruhe, 30.9.2010.

Dosio, A., and Paruolo, P., 2011. Bias correction of the ENSEMBLES high-resolution climate change projections for use by impact models: Evaluation on the present climate. Journal of Geophysical Research D: Atmospheres, 116, 16, DOI: 10.1029/2011JD015934

Dosio, A., Paruolo, P., and Rojas, R. 2012. Bias correction of the ENSEMBLES high resolution climate change projections for use by impact models: Analysis of the climate change signal. Journal of Geophysical Research D: Atmospheres, 117, 17, DOI:10.1029/2012JD017968

ELWIS, 2016. Elektronischer Wasserstraßen – Informationsservice, Available: https://www.elwis.de/Aktuelles/index.html.

EUCC-D, 2013, Coastal & Marine, Coastal Climate Change, Ports and renewable energies: impacts, vulnerabilities and adaptation, Volume 22, No:1.

EUROCONTROL, 2008. Performance Review Report 2007: An Assessment of Air Traffic Management in Europe during the Calendar Year 2007, EUROCONTROL Performance Review Commission, Brussels

EUROCONTROL, 2013. Challenges of Growth 2013, Task 8: Climate Change Risk and Resilience, STATFOR, EUROCONTROL, Brussels

Eurostat, 2017. Maritime ports freight and passenger statistics, Available: http://ec.europa.eu/eurostat/statistics-explained/index.php/Maritime_ports_freight_and_passenger_statistics

FEMA (Federal Emergency Management Agency), 2011a. Coastal Construction Manual. Principles and Practices of Planning, Siting, Designing, Constructing, and Maintaining

Residential Buildings in Coastal Areas (Fourth Edition). Available: http://www.fema.gov/media-library/assets/documents/3293?id=1671

FEMA (Federal Emergency Management Agency) 2011b. Highlights of ASCE 24-05. Available: http://www.floods.org/PDF/ASCE24_Highlights_1008.pdf

FHWA (Federal Highway Administration), 2011. Impact of Design Features on Pavement Response and Performance in Rehabilitated Flexible and Rigid Pavements. Available: http://www.fhwa.dot.gov/publications/research/infrastructure/pavements/ltpp/10066/10066.pdf.

Fowler, H. J. , Ekstrom, M., Blenkinsop, S. and Smith, A. P. 2007. Estimating change in extreme European precipitation using a multimodel ensemble, Journal of Geophysical Research, 112, D18104. DOI:10.1029/2007JD008619

Frei, C., Scho, R., Fukutome, S., Schmidli, J. and Vidale,P. 2006. Future change of precipitation extremes in Europe: Intercomparison of scenarios from regional climate models, Journal of Geophysical Research, 111, D06105. DOI: 10.1029/2005JD005965

Hendrickx,C., Breemersch,T., 2012. The effect of climate change on inland waterway transport. Transport Research Areana-Europe 2012, Procedia – Social and Behavioral Sciences 48, 1837 – 1847.

Hippe, A., Becker, A., Fischer, M., Schwegler, B., 2015. Estimation of Cost Required to Elevate US Ports in Response to Climate Change: A Thought Exercise for Climate Critical Resources, CIFE Working Paper #WP138, December

Holtmann, B., van Heumen, E., Beuthe, M., Urbain, N., Jourquin, B., Ubbels, B., Quispel, M., Bruinsma, F., Koster, P., 2012. Evaluation Of Adaptation Measures: Nodus Model Results And Detailed Cost Analyses, Deliverable 3.4 of ECCONET project. Report prepared for the European Commission, Directorate-General for Energy and Transport. Available here: https://www.ecconet.eu/deliverables/index.htm (last accessed: 30/3/2017)

Ibañez-Rivas, N., Christodoulou, A., Valeri, E. (in press). TNET platform: an integrated transport modelling framework incorporating multimodal networks. JRC Science for Policy report. JRC100591

ICF (ICF International), 2008. Potential Impacts of Global Sea Level Rise on Transportation Infrastructure; prepared by ICF International for U.S. DOT Center for Climate Change and Environmental Forecasting.

IPCC (Intergovernmental Panel on Climate Change), 2012. Special report on managing the risks of extreme events and disasters to advance climate change adaptation (SREX), Cambridge University Press, Cambridge, U.K

Jonkeren, O., Rietveld, P. and van Ommeren, J., 2007. Climate Change and Inland Waterway Transport - Welfare Effects of Low Water Levels on the river Rhine, Journal of Transport Economics and Policy, 41, 3, 387–411

Jonkeren, O., Jourquin, B. and Rietveld, P., 2011. Modal-split effects of climate change: The effect of low water levels on the competitive position of inland waterway transport in the river Rhine area, Transportation Research Part A, 45, 1007–1019

Jonkeren, O., Rietveld, P. and van Ommeren, J., 2014. Climate change and economic consequences for inland waterway transport in Europe, Regional Environmental Change, 14, 953–965, DOI: 10.1007/s10113-013-0441-7

Klin, T.P., Putnam, J.E., Stewart, B. and Vigilante, M.I., 2011. Climate Change and Adaptation, in Adapting transportation to the impacts of climate change, transportation research circular, E-C152. Transportation Research Board of National Academies, Washington D.C. June.

Koetse, M.J and Rietveld, P. 2009. The impact of climate change and weather on transport: An overview of empirical findings. Transportation Research Part D, 14, 205-221.

Ludvigsen, J., Klæboe, R., Nokkala, M., Hietajärvi, A.-M., Leviäkangas, P., Oiva, K., Athanasatos, S., Michaelides, S. and Papadakis, M. 2012. Costs and consequences of extreme weather on European freight and logistics industries and supply chains. EWENT project working memo D4.4. Available: www.ewent.vtt.fi.

Makkonen, L., Ruokolainen, L., Räisänen, J. and Tikanmäki, M, 2007. Regional Climate Model Estimates for Changes in Nordic Extreme Events, Geophysica, 43, 1–2, 25–48

Meyer, M.D., 2008. Design Standards for U.S. Transportation Infrastructure: The Implications of Climate Change, prepared in support of Potential Impacts of Climate Change on US Transportation, Special Report 290, for the Transportation Research Board of the National Academies, Washington, D.C.

Middelkoop,H., Daamen,K., Gellens,D., Grabs,W., Kwadijk,J.C.J., Lang,H., Parmet,B.W.A.H., Schädler,B., Schulla,J., Wilke,K. 2001. Impact of climate change on hydrological regimes and water resources management in the Rhine basin. Climate Change, 49, 1-2, 105-128

Nadal, N., R. Zapata, I. Pagan, R. Lopez and J. Agudelo, 2010. Building Damage due to Riverine and Coastal Floods. Journal of Water Resources Planning and Management 136, 3, 327-336. ASCE. May/June 2010.

Nemry, F, Demirel, H., 2012, Impacts of Climate Change on Transport: A focus on road and rail transport infrastructures, JRC Scientific and Policy Reports, ISBN 978-92-79-27037-6 (pdf)

NEWADA 2010. Available here: http://www.rsoe.hu/projectfiles/newadaOther/output/wp4/staus_quo_reports_on_waterway_maintenance/Newada_4-1_SQR_waterway_maintenance_v10_vi (retrieved on December, 2016)

Nicholls, R.J., Hanson, S., Herweijer, C., Patmore, N., Hallegatte, S., Morlot, J.C., Chteau, J., Wood, R. 2008. Ranking Port Cities with High Exposure and Vulnerability to Climate Extremes: Exposure Estimates, OECD Environment working papers, pg.1-62, 0.1787/011766488208

Nicholls, R.J.,Brown, S., Hanson, S. and Hinkel, J., 2010. Economics of coastal zone adaptation to climate change, International Bank for Reconstruction and Development / World Bank 48pp. , Washington, US(World Bank Discussion Papers,10).

Nikulin, G., Kjellström, E., Hansson, U., Strandberg, G. and Ullerstig A. 2011. Evaluation and Future Projections of Temperature, Precipitation and Wind - Extremes over Europe in an Ensemble of Regional Climate Simulations. Rossby Centre, Swedish Meteorological and Hydrological Institute, Sweden. Tellus, 63A, 41–55.

Nilson, E., Lingemann, I., Klein, B., Krahe, P. 2012. Impact of Hydrological Change On Navigation Conditions, Deliverable 1.4 of ECCONET project. Report prepared for the European Commission, Directorate-General for Energy and Transport. Available here: https://www.ecconet.eu/deliverables/index.htm (last accessed: 30/3/2017)

Nokkala, M., Leviakangas, P., Oiva, K., 2012. The costs of extreme weather for the European transport systems EWENT project D4, ISBN 978-951-38-7853-5, Available: http://www.vtt.fi/inf/pdf/technology/2012/T36.pdf

NOAA, 2015. US Climate Resilience Toolkit. Available: https://toolkit.climate.gov/tool/transportation-climate-change-sensitivity-matrix

NOAA, 2017. Term definitions. Available here: https://graphical.weather.gov/

NOAA and San Francisco BCDC (San Francisco Bay Conservation and Development Commission) 2013. Oakland International Airport Vulnerability and Risk Profile. Adapting to Rising Tides. Available: http://www.adaptingtorisingtides.org/wp-content/uploads/2013/03/AirportProfileSheet_20130326.pdf.

NRC (National Research Council) 2008. Transportation Research Board Special Report 290: Potential Impacts of Climate Change on U.S. Transportation. Available: http://onlinepubs.trb.org/onlinepubs/sr/sr290.pdf.

OFCM (Office of the Federal Coordinator for Meteorological Services and Supporting Research) 2002. Weather Information for Surface Transportation: National Needs Assessment Report (No. FCM-R18-2002). U.S. Department of Commerce / National Oceanic and Atmospheric Administration.

Pejovic, T., Williams, V.A. Noland, R.B. and Toumi, R. 2009. Factors Affecting the Frequency and Severity of Airport Weather Delays and the Implications of Climate Change for Future Delays. Transportation Research Record: Journal of the Transportation Research Board, 2139, 97-106. DOI:10.3141/2139-12.

Peterson, T.C., McGuirk, M., Houston, T.G., Horvitz, A.H. and Wehner, M.F. 2008. Climate variability and change with implications for transportation. 90 pages. Transportation Research Board.
Available: http://onlinepubs.trb.org/onlinepubs/sr/sr290_variability.pdf.

Powell, M.D. and Reinhold, T.A. 2007. Tropical cyclone destructive potential by integrated kinetic energy. American Meteorological Society. Available: http://www.aoml.noaa.gov/hrd/Powell/BAMS_IKE_Paper_final.pdf

Rockel, B., Woth, K., 2007. Extremes of near-surface wind speed over Europe and their future changes as estimated from an ensemble of RCM simulations, Climatic Change, 81:267–280, DOI 10.1007/s10584-006-9227-y

Schade W, Doll C, Maibach M, Peter M, Crespo F, Carvalho D, Caiado G, Conti M, Lilico A, Afraz N. 2006. COMPETE Final Report: Analysis of the contribution of transport policies to the competitiveness of the EU economy and comparison with the United States. Funded by European Commission – DG TREN. Karlsruhe, Germany

Schade W., Senger, F., Rothengatter, W., Rühle, O., Brouwer, I 2013. TEN-T Large projects, Investments and costs, Report, Available:
http://www.europarl.europa.eu/RegData/etudes/etudes/join/2013/495838/IPOL-TRAN_ET(2013)495838_EN.pdf

Schneider, S., Sarukhan, J., Adejuwon, J., Azar, C., Baethgen, W., Hope, C., et al., 2001. Overview of impacts, adaptation, and vulnerability to climate change. In J. J. McCarthy, O. F. Canziani, N. A. Leary, D. J. Dokken, & K. S. White (Eds.), Climate change 2001: Impacts, adaptation, and vulnerability: Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change (pp. 75-103). Cambridge, UK: Cambridge University Press

Scholten, A. and Rothstein, B. 2016. Navigation on the Danube - Limitations by low water levels and their impacts, JRC Technical Reports, ISBN 978-92-79-64798-7, doi:10.2788/236234

Schwartz, H.G. 2011. Adapting to climate change: Another challenge for the transportation community, in Adapting transportation to the impacts of climate change, transportation research circular, E-C152. Transportation Research Board of National Academies, Washington D.C. June.

Schwierz, C., Köllner-Heck, P., Zenklusen, E., Mutter, D., Bresch, N, Vidale,P., Wild, M., Schaer, C. 2010. Modelling European winter wind storm losses in current and future climate. Climatic Change, 101, 485–514. DOI 10.1007/s10584-009-9712-1

Sierra, J.P., Genius, A., Lionello, P., Mestres, M., Mösso, C. Marzo, L. 2017. Modelling the impact of climate change on harbour operability: The Barcelona port case study. Ocean Engineering, 141, 64-78. Available: https://doi.org/10.1016/j.oceaneng.2017.06.002

Steward, B., Klin, I. and Vigilante, M. 2011. Climate change adaptation and preparedness planning for airports, in Adapting transportation to the impacts of climate change, transportation research circular, E-C152. Transportation Research Board of National Academies, Washington D.C. June.

TRB (Transportation Research Board), 2008. Highway Capacity Manual. National Research Council.
Available: http://sjnavarro.files.wordpress.com/2008/08/highway_capacital_manual.pdf.

TRT, 2003, Il modello ASTRA-Italia per la valutazione strategica di politiche di trasporto, Milano.

Ubbels, B., Quispel, M., Holtman, B., Bruinsma, F. 2011. Assessment Of Adaptation Strategies, Deliverable 2.2.2 of ECCONET project. Report prepared for the European Commission, Directorate-General for Energy and Transport. Available here: https://www.ecconet.eu/deliverables/index.htm (last accessed: 30/3/2017)

Ubbels, B., Quispel, M., Bruinsma, F., Holtman, B. 2012. Oveview of Adaptation Strategies, Deliverable 2.2.1 of ECCONET project. Report prepared for the European Commission, Directorate-General for Energy and Transport. Available here: https://www.ecconet.eu/deliverables/index.htm (last accessed: 30/3/2017)

UNECE (United Nations Economic Commission for Europe) 1996. European Agreement on Main Inland Waterways of International Importance' (AGN), ECE/TRANS/120/Rev.4. Economic Commission for Europe, Inland Transport Committee, United Nations, Geneva

U.S. CCSP (U.S. Climate Change Science Program) 2008. SAP 4.7: Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, Phase I. Published March 2008. Available:
http://www.climatescience.gov/Library/sap/sap4-7/final-report/.

Van Den Brink, H.W., Konnen, G.P., Opsteegh, J.D., Van Oldenborgh, G. J. and Burgers, G. 2005. Estimating return periods of extreme events from ECMWF Seasonal forecast ensembles, International Journal of Climatology, 25: 1345–1354

Van Der Knijff, J. M. , Younis, J. and De Roo, A. P. J. 2008. LISFLOOD: a GIS-based distributed model for river basin scale water balance and flood simulation. International Journal of Geographical Information Science, 189-212, DOI: 10.1080/13658810802549154

Velegrakis, A.F. 2013. Ports: Range of physical settings and environmental controls, Assessing climate risks for seaports: Scoping workshop Brussels 4-5 March 2013, https://ec.europa.eu/assets/jrc/events/20130304-sea-ports/20130304-sea-ports-velegrakis.pdf

Von Storch, H., Woth, K. 2006. Storm surges – the case of Hamburg, Germany, 2006 ESSP OSC panel session on "GEC, natural disasters, and their implications for human security in coastal urban areas

Von Storch, H., Woth, K., 2008. Storm surges: perspectives and options, Sustain Sci 3:33–43, DOI 10.1007/s11625-008-0044-2

Vousdoukas, M., Vousdoukas, E., Mentaschi, L., Dottori, F., Giardino, A., Bouziotas, D., Bianchi, A., Salamon, P., Feyen, L. 2016. Developments in large-scale coastal flood hazard mapping. Natural Hazards and Earth System Sciences, 16, 1841–1853

Woth, K. 2007. Future extreme events in European climate: an exploration of regional climate model projections. Climatic Change, 81, 71–95 DOI 10.1007/s10584-006-9226-z

Yang, Z., Ng, A.K.Y., Tae-Woo.Lee, P. d, Wang, T., Zhuohua. Qu, Sanchez Rodrigues V., Pettit, S., Harris, I., Zhang, D., Lau, Y. 2017. Risk and cost evaluation of port adaptation measures to climate change impacts. Transportation Research Part D: Transport and Environment. In press, available: https://doi.org/10.1016/j.trd.2017.03.004

List of abbreviations and definitions

ASCE	American Society of Civil Engineers
GCM	Global Circulation Model
IPCC	Intergovernmental Panel on Climate Change
IWW	Inland Waterways
JRC	Joint Research Centre
PESETA	Projection of Economic impacts of climate change in Sectors of the European Union based on bottom-up Analysis
RCM	Regional Climate Model
TEN-T	Trans-European Transport Network

List of figures

List of tables

Appendix

Table A1. Climate change stressors and airports. (adapted from NOAA, 2015)

Climate stressor	Physical infrastructure		Service, access, maintenance and operations
	Runways, taxiways, aprons	Airfield buildings and structures	Operations, maintenance and safety
Increased temperature and extreme heat	Concrete pavement buckling, Loss of non-concrete pavement integrity. (FHWA, 2011). (Baglin, 2012).	Needs for cooling and increased water and energy demand for cooling (Ang Olson, 2009; TRB, 2008; Baglin, 2012)	-More runway space in order to take off in order to meet safety margins, particularly at high altitudes or hot weather airports. (Ang-Olson, 2009; NRC, 2008; U.S. CCSP, 2008; Baglin, 2012) -Extreme high temperatures may limit the types of aircraft that can take off on certain days, reduce the ability of certain airports to take certain aircrafts, cause delays and cancellations due to the need to limit daytime flights, or put restrictions on payload to lower weight (Ang-Olson, 2009; Baglin, 2012; NRC, 2008).
Precipitation-driven inland flooding	Produce standing water on pavements, causing delays (OFCM, 2002).	Temporary flooding	Produce standing water on pavements, causing delays (OFCM, 2002).
Sea Level Rise + storm surge	Runways and taxiways, are vulnerable to flooding due to storm surge and sea level rise (Baglin, 2012).	Temporary or permanent disruption of the airport. The region's airfield capacity is insufficient to absorb air traffic, resulting in negative impacts on the region's economy.	Airports are designed for a working economic life of 70 years or less, therefore routine repairs, replacement, and re-design can take into account sea-level rise (Peterson et al., 2008). Airports are not expected to be replaced in the foreseeable future and there are practical difficulties with raising the elevation of airfield surfaces. The most likely response is to raise the elevation of surrounding berms or dikes. However, these could be overtopped in an extreme event.
	Storm surges may cause flight cancellations and delays (U.S. CCSP, 2008).	Storm surge and heavy precipitation can flood buildings, access roads, and disrupt fuel supply and storage (ICF, 2008).	Due to a severe storm, airport services can be completely disrupted by high wind speeds, precipitation, flooding, electrical outages, and debris impacts (NRC, 2008) delays and cancellations can have ripple effect (it can take airlines a long time to return their timetables to punctuality.)
Wind gust	No documented impact.	High winds can cause damage to terminal buildings at airports. High winds can cause construction materials to blow loose, placing debris and objects in the pathways of moving aircraft (Ang-Olson, 2009; OFCM, 2002)	Aviation commerce starts to be impacted at sustained winds of 10.28 m/s or greater or winds gusts over ~15.42 m/s. Delays or cancellations of flights occurred at sustained winds of 17.88 m/s or higher (for an hour), or gusts of 25.93 m/s or higher (no time limit) (Peterson et al., 2008). Pejovic et al. (2009) did not establish a threshold for high winds (indicated by 1-hour mean wind speed above the mean), but found that incremental increases in wind speed above the mean could increase likelihood of delay.

Table A2. Climate change stressors and seaports & waterways (adapted from NOAA, 2015)

Climate stressor	Physical infrastructure		Service, access, maintenance and operations
	Terminals and Other Buildings	Piers, Wharves and Berths	Operations, maintenance and safety
Increased temperature and extreme heat	Terminals often have open paved areas for storing cargo; higher temperatures and extreme heat can cause these paved surfaces to deteriorate more quickly (U.S. CCSP, 2008).	Most dock and wharf facilities are made of concrete and lumber, which are less sensitive to temperature fluctuations (U.S. CCSP, 2008).	High temperatures can improve port operating conditions in cold regions. Higher winter temperatures can increase safety and reduce interruptions if frozen precipitation shifts to rainfall, reducing ice accumulation on vessels, decks, riggings, and docks and reducing the occurrence of dangerous ice fog and the likelihood of ice jams in ports (NRC, 2008; IFC, 2011; Peterson et al., 2008).
Precipitation-driven inland flooding	Flooding can damage port structures and equipment in buildings	Flooding can damage piers, wharves, and berths.	-Increases in weather-related delays are likely with more precipitation. -Floods can completely submerge navigation locks and render them inoperable, leading to lock closure and disrupting river traffic (Peterson et al., 2008).
Sea Level Rise + storm surge	Higher sea levels can increase the risk of chronic flooding and eventually lead to permanent inundation of the facilities, especially for facilities that are not elevated or otherwise protected (USCCSP, 2008). Sea level rise can also exacerbate coastal erosion and flooding due to high tides (IFC, 2011).	Sea level with respect to dock level is an important consideration for clearance of dock cranes (e.g., the bottom of the crane will sit in water is the deck height is not high enough) and other structures; higher water levels may require facility retrofits (NRC, 2008).	Sea level rise coupled with storm events can increase the risk of coastal flooding, which can inundate rail and road access to the seaport, or inundate maritime facilities (NOAA and San Francisco BCDC, 2013)
	Storm surge and direct wave action can damage marine port buildings (Nadal et al., 2010). (Curtis, 2007). Fast moving water can undermine or damage building foundations (U.S. CCSP, 2008).	Strong waves can batter piers and scour pier supports, leaving berths inoperable; and storm surge can wash away asphalt paving (Nadal et al., 2010). There may be serious damage to both the piers/ wharves as well as the vessels.	Potential impacts due to a severe storm, seaport services can be completely disrupted.
Wind gust	Most buildings are built to withstand 3-second gust wind speeds of up to 38 m/s. Wind damage to structures increases non-linearly as wind speed increases.	High winds can damage or destroy piers, wharves, and berths (IFC, 2011). Wind has its most damaging effects on unreinforced structures (U.S. CCSP, 2008).	Small boat handling, tugboat movement, ferry docking, barge handling are all restricted during high winds (NRC, 2008; OFCM, 2002).

GETTING IN TOUCH WITH THE EU

In person

All over the European Union there are hundreds of Europe Direct information centres. You can find the address of the centre nearest you at: http://europea.eu/contact

On the phone or by email

Europe Direct is a service that answers your questions about the European Union. You can contact this service:

- by freephone: 00 800 6 7 8 9 10 11 (certain operators may charge for these calls),

- at the following standard number: +32 22999696, or

- by electronic mail via: http://europa.eu/contact

FINDING INFORMATION ABOUT THE EU

Online

Information about the European Union in all the official languages of the EU is available on the Europa website at: http://europa.eu

EU publications

You can download or order free and priced EU publications from EU Bookshop at: http://bookshop.europa.eu. Multiple copies of free publications may be obtained by contacting Europe Direct or your local information centre (see http://europa.eu/contact).

KJ-1A-28896-EN-N

JRC Mission

As the science and knowledge service of the European Commission, the Joint Research Centre's mission is to support EU policies with independent evidence throughout the whole policy cycle.

EU Science Hub
ec.europa.eu/jrc

@EU_ScienceHub

EU Science Hub - Joint Research Centre

Joint Research Centre

EU Science Hub

Publications Office

doi:10.2760/378464

ISBN 978-92-79-97039-9