WaterCap WP3, Activity 3.1

Impacts of climate change on water quantity and quality in the North Sea Region: review of the results and recommendations of six trans-national projects

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Executive Summary

WaterCap is a cluster project on water management in the North Sea region, connecting six recently-completed Interreg IVB funded projects. This report focuses on the main findings of these and other related projects, summarising the likely impacts of climate change on water quantity and quality in the North Sea region. We take a DPSIR (Driver-Pressure-State-Impact-Response) approach to reviewing and summarising the cluster projects.

Despite significant variability in the output of different climate models, the general expectation is for future climate to be characterised by warmer, wetter winters, slightly warmer summers, with more frequent extreme events, including intense rainfall events and droughts. Sea levels are expected to rise throughout the North Sea region by somewhere in the order of 20 to 80cm over the next century, although the upper limit could increase if Greenland ice sheet dynamics are affected by temperature increases.

These climatic drivers are expected to exacerbate existing pressures on water quantity and quality in the North Sea region, including flooding (coastal, riverine, lake and urban), drought, groundwater salinisation, eutrophication of surface water bodies and contamination of surface water and groundwater with heavy metals, pesticides and other industrial/urban pollutants. Other pressures not explicitly considered in the cluster projects include temperature effects on the structure and functioning of river, lake and marine ecosystems.

An increase in these pressures would, without any adaptive/mitigating response on society's behalf, have a number of negative impacts, such as damage to property and agricultural land, increased risk to human life from flooding, freshwater supply issues for human consumption and irrigation, and deterioration of important habitats with corresponding damage to protected species. Coastal lowlands appear to be most at risk, being particularly vulnerable both to flooding and groundwater salinisation.

Much work has been done on developing water management strategies, and there is much that the countries of the North Sea region can learn from one another. Groundwater, surface water and coastal waters may directly influence one another, and for proper adaptation and climate proof management a holistic approach is needed, integrating all aspects of the land-sea continuum. The paradigm of Integrated Water Resources Management, considering water as both a resource and a habit, is likely to have a significant role to play in decreasing vulnerability to climate change.

Contents

1. Introduction

The Interreg programmes aim at stimulating transnational cooperation in the North Sea region (NSR). NSR countries share many of the same problems and challenges, and by sharing knowledge and experience it is hoped that a more sustainable future may be secured for the whole region. The seven NSR Programme countries are Denmark, the Flemish region of Belgium, Germany, the Netherlands, Norway, Sweden and the UK.

WaterCap is a cluster project on water management in the NSR. The cluster connects six Interreg IVB funded projects: Aquarius, C2CI, CPA, CLIWAT, DiPol and SAWA (see Table 1 for a brief description of each project), with the aim of gaining added value through sharing and building on the outcomes of these projects.

The purpose of this report is to summarise key findings of the cluster relating to climate change effects on water quantity and quality in the NSR. We have chosen to adopt the commonly-used DPSIR framework (Driver-Pressure-State-Impact-Response), a causal framework for organising information about the state of the environment (EEA, 2003). As such, this brief introduction is followed by a description of observed and predicted climate change in the NSR ('Drivers', Section 2), expected water quantity and quality issues relating to these climatic drivers ('Pressures', Section 3), developments in assessing changes in the 'State' of the environment (e.g. flood risk maps; Section 4) and likely impacts of these pressures (Section 5). Many of the cluster projects are purely focused on planning, designing, implementing or testing adaptation/mitigation measures, so we conclude with a brief overview of some of the measures that have been studied in the NSR ('Responses', Section 6), although this will be looked at in more detail in WP5.

Project	Main aims	Pilot areas
Aquarius	Find and implement sustainable, integrated land-water management through engaging with land managers. Identify common technical, financial/institutional and participatory problems to achieving this aim, and work on solutions. Focus on water shortage for agriculture, riverine flooding and diffuse pollution issues.	Midden-Delfland (NL), Mariager Fjord (DK), Veenkoloniën (NL), Ilemal Jeetzel (D), Vestre Vansjø (NO), Tarland (UK), Smedjeåen (S)
C2CI	The 'water' strand of Cradle to cradle - Islands (C2CI) aims to develop and test new technologies and strategies for ensuring a sustainable drinking water supply in islands in the NSR.	Islands in the NSR
Climate Proof Areas (CPA)	Accelerate climate change adaptation process by joint development and testing of adaptation measures in pilot locations. Main focus on coastal and urban flooding, salinisation of groundwater and preservation of internationally important wetland/intertidal habitats.	Schouwen-Duiveland & Eastern Scheldt (NL); Wesermarsch (D); Arvika (S); Tichwell Marsh, Wicken Fen & Great Fen (UK)
CLIWAT	Improve understanding of the likely effects of climate change on the quantity and quality of groundwater and associated surface waters. Risk mapping, adaptive planning and solutions for groundwater-related issues including salinisation, flooding, contaminants from agriculture, landfill and other urban sources.	Oostende (B), Horsens, Als, Aarhus & Horlokke (DK); Northern & Southern Schleswig mainland (DK/D); Fohr & Borkum (D); Zeeland (B/NL); Tershelling & Fryslan mainland (NL)
DiPol	Monitoring/modelling to evaluate the likely impacts of an increase in frequency of intense rainfall events on the water quality of urban and coastal waters. Develop knowledge base and tools from which to design response plans. Focus on heavy metals, organic pollutants, pesticides.	Gothenburg (S), Copenhagen (DK), Oslo (NO), Hamburg (D)
SAWA	Development and testing of adaptive flood risk management plans (primarily fluvial and lake), identification and deployment of cost-effective local scale adaptive measures. Sharing of tools developed and flood awareness-raising through education. SAWA stands for Strategic Alliance for Integrated Water Management Actions.	Wands, Ilmenau & Ammersbek (D); Gaula & Tana (NO); Karlstad, Gota River, Lake Vänern (S); Hunze (NL)

Table 1 Brief description of the main aims of the 6 projects in the cluster and the location of pilot areas. Abbreviations: Belgium (B), Germany (D), Denmark (DK), Netherlands (NL), Norway (NO), Sweden (S).

2. Drivers: climate change in the North Sea region

Climate change projections for northern Europe indicate changes in both temperature and precipitation regimes in the future that, in some areas, will contribute to significant changes in water quantity and quality. Detailed predictions of climate change effects are however highly uncertain. This section makes use of the findings of CPA (WP1 Report, 2012), SAWA (Lawrence et al., 2012), Safecoast (Safecoast, 2008) and Climatewater (EEA, 2007; Bates et al., 2008) with respect to projected climate change in the NSR, with additional information from the fourth IPCC assessment report (IPCC AR4 SYR, 2007).

The first stage in producing regional predictions of future climate is to produce simulations derived from large-scale Global Climate Models (GCMs), which model atmospheric and, in some cases, linked oceanic processes. GCMs are typically run for the four 'SRES' greenhouse gas emissions scenarios, representing various alternatives as to how society and technology will develop over the coming century (IPCC SRES, 2000). Differences in CO_2 concentrations only become apparent from around 2050, so climate change impact analyses for periods prior to 2050 are generally only based on one emission scenario, typically A1B.

To be suitable for regional scale impact analyses, output from the chosen GCM is dynamically downscaled to a higher resolution grid using a Regional Climate Model (RCM). There are numerous possible GCM/RCM combinations, and these produce different climate projections at regional scales. It is therefore advisable to use climate data derived from several GCM/RCM combinations and to evaluate a range of results, rather than just taking one GCM/RCM combination. The spread in the projections indicates the level of agreement between projections, thus providing some measure of their uncertainty. Numerous climate change projections based on different global and regional climate models are available from, for example, the EU FP6 ENSEMBLES project (CR Special 23, 2010), and from earlier EU and regional projects.

Despite large variability between different climate models, several consistent patterns emerge which, if realised, could impact water quantity and quality in the NSR. These include increases in temperature with related changes in evapotranspiration and snow storage, changes in precipitation amount and intensity, and associated sea level rise. These are discussed further below. It is worth noting that there is often a difference between cutting-edge climate scenario predictions and the actual scenarios used to generate predictions about future water quantity and quality, which in turn are used to inform water management policies and practices. This is a complex, rapidly developing area with many uncertainties, and simplifications must inevitably be made. Handling and communicating such uncertainty is a key challenge for the scientific and policy communities.

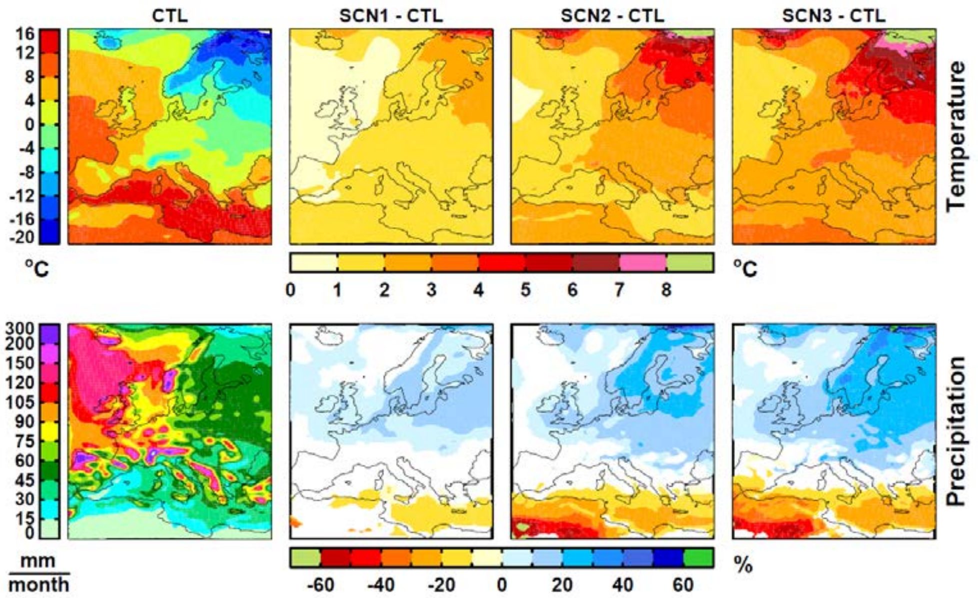
Temperature

For all countries in the NSR, temperature is expected to rise in the future. Whilst projected warming rates differ between countries, in most areas winter warming is expected to be greater than summer warming (Fig. 1). This temperature increase is in the order of 2-3ºC between a baseline period of 1960-1990 and 2060, and of 3-4ºC by the 2090s, but with the possibility of greater warming in the northern half of Norway and Sweden, particularly during summer.

Precipitation

Over the period 1901-2005, observations show an increase in precipitation over land north of 30° and an increase in intensity of precipitation (IPCC AR4 WG1, 2007; Chapter 3). Model outcomes regarding precipitation are less certain than temperature, and different climate modelling simulations often result in very different expected rainfall trends. Nevertheless, over the region as a whole these observed trends are expected to continue, with an increase in winter precipitation and larger increases in the northern part of the region. Summer precipitation is generally expected to decrease in much of the region, but with a transition zone between increase and decrease around the latitude of mid-Sweden, with a slight increase in summer precipitation in northern Sweden (Fig. 1). Precipitation extremes (heavy rainfall) are expected to increase throughout the region in both summer and winter; indeed, abundant rainfall during storms is more frequent nowadays than in the past.

Winter



Summer

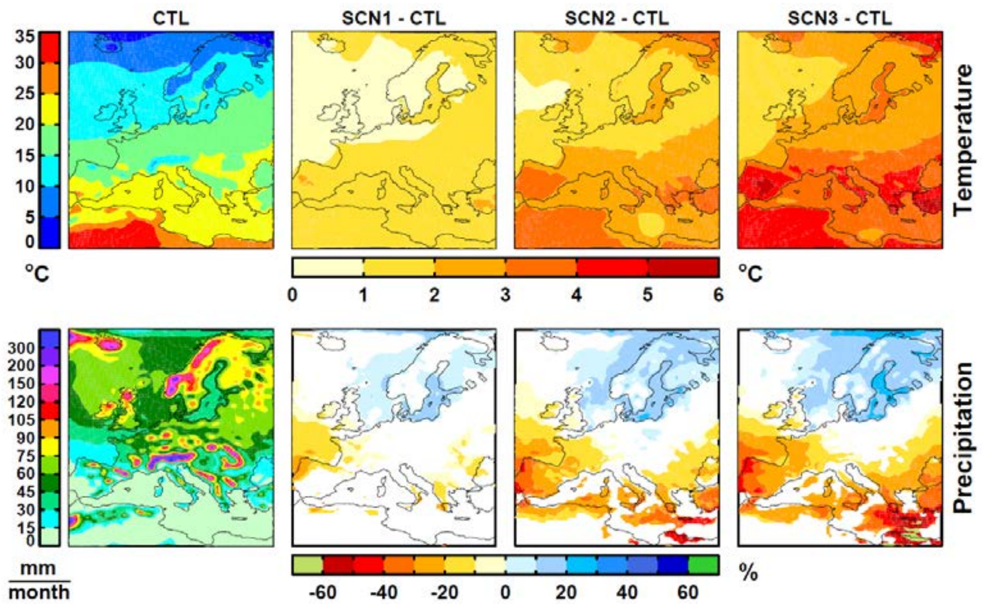


Figure 1 Change in temperature (top) and precipitation (bottom) for winter (Dec - Feb) and summer (Jun - Aug) from an ensemble of 6 regionally-downscaled GCM projections using the SRES A1b scenario. Shown are ensemble mean values for 1961-1990 (CTL) and the respective ensemble mean changes for 2011-2040 (SCN1), 2041-2070 (SCN2) and 2071-2100 (SCN3) compared to the baseline. From Kjellström et al., 2011

As well as changing amounts of precipitation, in northern latitudes the amount of precipitation falling as snow is likely to decrease. Such a decrease in snow cover has already been observed in most regions, particularly in spring, together with a thawing of permafrost and a decrease in glacier volume and areal extent (IPCC AR4 WG1, 2007; Chapter 4).

Sea level rise

There is strong evidence that, after a period of little change during the last 2000 years, global sea level rose during the 20th century. The rate of sea level rise is expected to increase over the coming century (Fig. 2 and Table 2), primarily due to thermal expansion of ocean water, with additional input from greater melting of land-based ice. The upper limit of the projected increase in global mean sea level cannot be taken as an upper bound for sea level rise, as there is limited knowledge of the likely impact of temperature changes on ice flow dynamics, which could have serious implications for ice sheet melting rates and thus sea level.

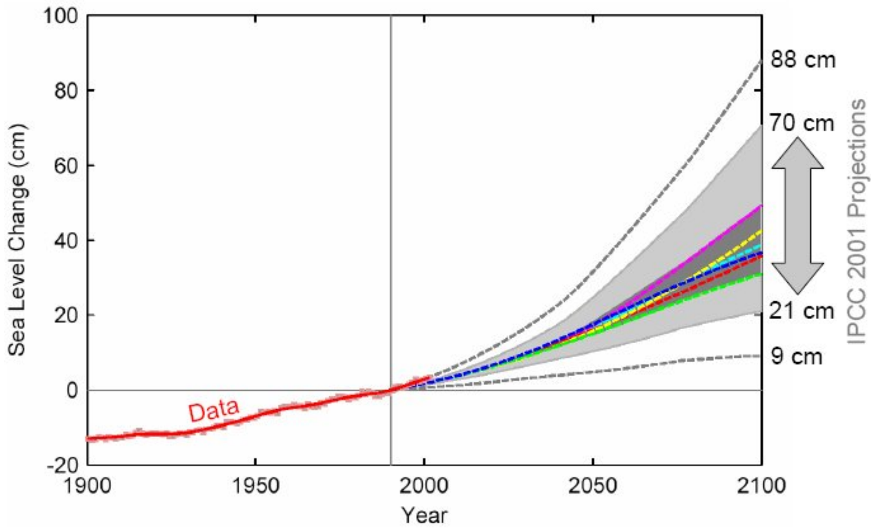


Figure 2 Global mean sea level rise as observed (Church and White 2006; red up to the year 2001), together with IPCC 2001 scenarios for 1990-2100. Source: www.realclimate.org

IPCC report	IPCC estimates of global sea level rise ranges (cm) in the period 1990-2100
1995 (SAR)	15 – 95
2001 (TAR)	9 – 88
2007 (AR4)	18 – 59

Table 2 Estimates of sea level rise (IPCC; Table modified from Safecoast, 2008)

Country	Region	Time period	Projected rise (cm)	Notes
Belgium	Flanders	1990-2100	20-200	
Germany	Lower Saxony	2000-2100	18-59	
The Netherlands		2000-2050	15-35	Excluding local subsidence
The Netherlands		2000-2100	35-85	Excluding local subsidence
UK	Southeast England	1980-2080	20-80	
UK	Eastern Scotland	1980-2080	0-60	
Sweden	Southern Baltic	2000-2100	0-80	
Sweden	Northern Norrland	2000-2100	0	
Norway		2000-2100	40-70	Greater in the south
Denmark		2000-2100	45-105	Excluding land subsidence; A2 scenario

Table 3 Projected change in relative sea level in selected countries and areas of the NSR. Source: CPA (WP1, 2012), SAWA (Lawrence et al., 2012), CLIWAT (handbook, 2012).

Figure 2 shows change in global mean sea level (observed and projected), but local sea level change ('relative' sea level change) depends on local tectonic movements, particularly whether the land mass is stationary, uplifting or subsiding. Much research has been focused on determining country specific and regional scenarios of sea level change within the North Sea countries. Due to the relatively recent ice age, uplift is common throughout the northern part of the NSR, as the crust continues to 'bounce back' to pre-glacial elevations. The net effect is little change in relative sea level in northern parts of Sweden, Norway and Scotland. Meanwhile, in the southern part of the region subsidence is more common, resulting in expected increases in relative sea level above the global mean increase (Table 3).

Although flooding related to increases in mean sea level over the 21st century and beyond will be an issue for low-lying areas, the most devastating impacts are likely to be associated with changes in extreme sea levels resulting from storms and storm-induced tidal surges. However, the detailed pattern and magnitude of change in extreme water levels remain uncertain.

Non-climatic drivers

Whilst this review is focused on climate change impacts on water quantity and quality, other drivers will be important and may exacerbate climate-related problems, or indeed outweigh them completely. Water resources, both quantity and quality, are influenced by factors such as land use, agricultural policy, the construction and management of reservoirs and waste water treatment. Water use is driven by changes in population, food consumption, economic policy, technology, lifestyle, society's views on the value of freshwater ecosystems and water management. Whilst the population in most NSR countries is expected to stabilise or decline (source: Eurostat), there is a high demand for space throughout much of the region, particularly in and around Hamburg, Bremen, London and central Holland, and an increase in urbanisation and therefore impermeable surfaces is expected. Secondary effects of climate change include projected increases in land capability for agriculture in certain regions, leading to potential agricultural intensification.

3. Pressure: expected water quantity and quality problems associated with climate change in the North Sea Region

In the North Sea Region, changes in precipitation amount and intensity, increases in evapotranspiration and rising sea levels are expected to generate 'pressures' on water quantity and quality, such as flooding, drought, eutrophication and salinisation. This section is not intended to provide an exhaustive list of the pressures faced by water bodies in the NSR, but to highlight the key anticipated pressures dealt with by the projects in the cluster (Table 4).

3.1 Water Quantity: Flooding

Sea level rise, more and more intense rainfall, increased storminess, land subsidence, drainage problems, spatial developments and higher river discharges are all likely to lead to increases in flood risk in the low-lying areas and flood plains of the NSR. Different kinds of flooding can be differentiated:

Sea flooding

Much of the NSR is low-lying and coastal, and as such is vulnerable to coastal flooding. Indeed, storm-surge related coastal floods in the NSR claimed over 2,500 lives during the 20th century and caused extensive damage (Safecoast, 2008). Future sea level rise throughout the NSR is certainly going to occur, and with it an increase in the risk of coastal flooding. Floods from the sea can be caused by overflow, overtopping and breaching of flood defences like dikes and barriers as well as flattening of dunes/dune erosion, often during a heavy storm and/or a spring tide. In estuaries and other transitional coastal waters, flooding may be caused by high rainfall and high sea level that blocks discharge through sea spill sluices (e.g. Hunze, Netherland), or leads to a back-up of water behind closed tidal barrages (e.g. Thames, UK).

A linked pressure which is likely to increase in the future is coastal erosion, either of beach-dune systems which help protect communities and agricultural land from flooding, or of cliffs, with coastal land sliding. Beach-dune systems are found throughout the NSR, and play a vital role in protecting communities and agricultural land from flooding. Retreating cliffs is a significant problem on the south and east coasts of England – the Holderness coast, for example, has retreated by around 2km over the last 1000 years, and at least 26 coastal villages have been abandoned (Safecoast, 2008).

Riverine and lake flooding

Future increases in precipitation amount and intensity may increase the magnitude and, in some cases, the seasonality of peak runoff and therefore riverine floods throughout the region. Many catchments in the NSR already experience river/stream flooding, including many of the Aquarius pilot catchments (Table 4 and Appendix), and in many regions (e.g. Belgium) the frequency of recorded floods has increased during the last century. Land use planning is obviously partly responsible for this increase, but variations in winter precipitation and increased frequency of heavy rainfalls will nevertheless amplify the risk.

Due to the significant role of catchment storage (e.g. lakes, snow, soil and groundwater) in altering the lag time between precipitation and runoff, there is not a simple one-to-one relationship between projected changes in precipitation and corresponding changes in runoff. Hydrological modelling based on regional climate scenarios is therefore required to assess the impact that climate change will have on land surface processes, such as stream flow generation leading to floods. Of the cluster projects, SAWA in particular focused on carrying out hydrological modelling to translate projected climate change scenarios into flood risk maps for the project's pilot basins. Work within the SAWA project also looked to predict climate change effects on seasonal discharge in the large Rhine and Meuse rivers. Results suggest higher winter flows and lower summer flows in both river systems, and in many of the pilot basins. The picture is not however uniform across the region. In areas where peak flows are currently dominated by spring and early summer snowmelt, the flood risk is projected to decrease due to a decrease in snowfall in these regions (Lawrence et al., 2012). This is the case, for example, in many larger catchments in the Nordic region. Simultaneously, an increase in the occurrence of extreme precipitation can increase the likelihood of floods in smaller catchments and in urban areas in the same region.

Where increased runoff discharges into lakes, an increase in lake levels might also be expected, leading to flooding of low-lying adjacent ground. Perhaps the best example of this in the pilot studies within the cluster projects is flooding in the cities of Karlstad and Lidköping, on Lake Vänern in Sweden (SAWA).

Urban flooding

A general increase in intense rainfall events, and in the magnitude of these events, is expected in the future. Storm water sewers and other urban hydrological structures have been constructed to cope with present-day climate, and even so their capacity is frequently exceeded, leading to urban flood events, particularly of basements, underground car parks and lowered streets. Rising groundwater levels may have the same end result. This is likely to become more of a problem in the future, leading to increased frequency of urban flooding and increased volumes of storm water overflowing untreated to recipient surface waters. SAWA and in particular CPA and CLIWAT include urban flooding as a pressure and, for certain pilot areas, carried out hydrological modelling under different scenarios of climate change to produce flood risk maps (e.g. Arvika, Sweden; Wesermarsch, Germany).

3.2 Water Quantity: Drought due to climate factors

Decreases in summer precipitation and higher summer temperatures are likely to result in increased water stress in many parts of the NSR, particularly in areas where there is already a delicate balance between water supply and demand for agriculture, drinking water, industry or energy generation. A decrease in water supply due to such climatic drivers could take the form of a drop in groundwater level due to decreased recharge, an increase in periods of low flows in rivers and a drying out of wetlands, all with potentially severe negative impacts on associated ecosystems. Secondary impacts of climate change may also lead to freshwater shortages, such as an increase in abstractions due to warmer temperatures and increasing need for irrigation. Water shortages are already being experienced in several of the Aquarius pilot study areas, and are also an area for concern within CLIWAT and CPA, in the latter particularly in relation to the loss of internationally important wetland habitats in the UK.

3.3 Water quantity/quality: Salinisation of groundwater

Salinisation of groundwater and associated reductions in the size of freshwater lenses on islands is a major problem in the low-lying coastal zones and islands of the NSR. At present, the main cause of saline intrusion into aquifers is generally considered to be excessive groundwater abstraction, but rising sea level will greatly exacerbate the problem. Modelling and mapping the likely extent of groundwater salinisation was a key focus of much of CLIWAT, whilst responding to the challenge motivated much of CPA and C2CI-Water.

3.4 Water quality issues

Contamination of rivers, lakes, wetlands, groundwater, estuaries and coastal zones is already a major problem throughout the NSR. Sources of contaminants range from sewage treatment works and industry discharges, runoff of manures, fertilizers, pesticides, bacterial pathogens and new emerging contaminants from agricultural land and fluxes of heavy metals and organic pollutants from urban areas and landfill sites. Most countries are going to be severely challenged to reach the Water Framework Directive targets of all waterbodies achieving ‘good’ ecological status by 2015.

The relationship between climate change and changes in water quality are not straightforward, and depend heavily on the specific dynamics of the pollutant in question. For pollutants transported by particles such as soil, increases in rainfall amount and intensity might be expected to lead to increased erosion of sediments and delivery of particle-adsorbed pollutants to waterbodies. We might therefore expect loads of contaminants such as phosphorus species, bacterial pathogens and heavy metals to increase, with a corresponding decrease in groundwater and surface water quality. Gaining a better understanding of this pressure was a major focus of the DiPol and CLIWAT projects. The effect of climate change on more water-soluble pollutants such as nitrate is less clear, and depends on the hydrology of the catchment in question. Where concentration/dilution effects dominate, decreases in summer rainfall may lead to higher nitrate concentrations, whilst higher rainfall in winter may lead to decreases in nitrate concentration (although loads would increase).

Perhaps lacking from the cluster projects is mention of the direct impacts of climate change on aquatic ecosystems. This topic has received considerable attention elsewhere however, including numerous EU-funded projects (e.g. WISER, EUROLIMPACS, REFRESH). In brief, some of the direct climate-related pressures on aquatic ecosystems, relevant to the NSR, include increasing water temperatures and decrease in lake ice cover. Increasing stream temperature will be particularly relevant in areas where cold water salmonid species are found. Increases in lake temperature and decreases in ice cover are expected to radically alter lake stratification, nutrient levels and oxygen content, with knock-on effects for biota and ecosystem functioning. Similar changes are expected in coastal waters. Many studies suggest that the risk of harmful algal blooms will increase in both fresh and coastal waters (e.g. Paerl and Paul, 2011).

Pressure	Likely drivers	Project	Pilot areas
Coastal flooding & coastal erosion	Sea level rise	CPA	Schouwen-Duiveland (NL), Wesermarsch (D), Eastern Scheldt (NL), Tichwell Marsh (UK)
		CLIWAT	Fryslan mainland (NL), Zeeland (B, NL)
Freshwater shortage (groundwater salinisation)	Sea level rise (saltwater intrusion into aquifers) Increased groundwater abstraction in coastal areas	CPA	Wesermarsch (D)
		C2CI	Many
		CLIWAT	Zeeland (B, NL), Tershelling (NL), Borkum (D), Fohr (D), Als (DK), Fryslan mainland (NL), Zeeland (B, NL), Oostende (B), Schleswig (DK, D)
Freshwater shortage (droughts)	Increased evapotranspiration Increased abstraction	CPA	Wicken Fen; Great Fen (UK)
		Aquarius	Veenkoloniën (NL), Ilemal Jeetzel (D), Smedjeåen (S)
		CLIWAT	Schleswig mainland (DK, D)
Riverine and lake flooding	Increased precipitation Building on floodplains	Aquarius	Midden-Delfland (NL), Smedjeåen (S), Tarland (UK)
		SAWA	Wands, Ilmenau (D); Gaula, Tana (No); Lake Vänern (S); Hunze (NL)
Urban flooding	Intense rainfall events Urbanisation	CPA	Wesermarsch (D), Arvika (S)
		CLIWAT	Horsens (DK), Schleswig (DK, D)
		SAWA	
Diffuse pollution – nutrients	Summer low flows Intense rainfall events Agricultural intensification	Aquarius	7 out of 8 pilot areas
		CLIWAT	Egebjerg (DK)
Urban pollution: heavy metals & other contaminants; landfill emissions	Intense rainfall events Increase in groundwater level Urbanisation	DiPol	All (Gothenburg, Copenhagen, Oslo, Hamburg)
		CLIWAT	Horsens (DK), Schleswig (DK, D), Horlokke (DK), Aarhus (DK)
Changes in lake and sea temperature and nutrient distribution; algal blooms	Increase in air temperature Decrease in ice cover (Marine: changing ocean currents)	e.g. WISER, REFRESH	
Increase in river water temperature	Increase in air temperature	e.g. WISER, REFRESH	

Table 4 Summary of the main water quantity and quality-related pressures in the NSR that are anticipated as a result of climate change, and the associated projects and pilot areas that deal with them. Source: see bibliography. For explanation of country abbreviations, see Table 1 caption.

4. State

Whilst the focus of the projects in the WaterCap cluster is generally towards responding or adapting to climate change pressures, this adaptation process can only be designed once a sensible assessment has been made of likely changes in the state of the environment, and the impact these changes may have on society and ecosystems. A change in 'state' may be any quantitative measure which can act as an indicator of the current condition of the environment of interest, such as flood risk maps, concentration of chemical contaminants, area of wetland habitat suitable for wading birds or volume of freshwater in a coastal groundwater aquifer. Our knowledge is still lacking in many areas, and several of the projects in the cluster aimed at improving our understanding of the system, developing tools to better map and model the current situation, and/or providing predictions of how the environment might change as a result of the climate change pressure.

Flood risk in the NSR was reviewed by Safecoast (2008), and some 38,000 km^2 are estimated to be at risk, in which some 14 million people live and work (Table 5). In terms of population at risk, the Netherlands is worst-off, whilst England and Denmark have long coastlines to manage and Belgium has the largest percentage of socio-economic developments within the 1km coastal strip (Table 5). To develop meaningful local flood risk management plans, local-scale flood risk maps are however needed, and the production of these maps was a big focus of many of the cluster projects, including CPA (particularly coastal and urban flood risk maps), SAWA (primarily catchment flood risk maps) and CLIWAT (urban and regional).

To gain a better understanding of the links between climatic drivers and changes in water quality, several projects carried out monitoring surveys. In DiPol, the focus of these surveys was on the link between rainfall intensity and the delivery of heavy metals, bacterial pathogens, pesticides and PAHs to urban and coastal waters and sediments, and they developed a web-based database of results. CLIWAT focused more on groundwater-related issues, and developed geophysical, monitoring and chemical methods to better describe sub-surface aquifers, again producing a large database of new results. A key conclusion of CLIWAT is that we still have insufficient knowledge of the water quality of most urban aquifers, and that more efficient monitoring is required.

DiPol, SAWA and CLIWAT carried out modelling studies to assess the likely impact of climate change on the water body of interest. CLIWAT produced a set of regional thematic maps of modelled changes in sea level, groundwater recharge, groundwater tables, catchment areas of waterworks, groundwater quality (saltwater intrusion, nutrients, pesticides), need for irrigation, etc., which are publicly-available on their website (http://cliwat.eu/; see also Hinsby et al., 2012). All modelling exercises of this sort are full of uncertainty, and work could still be done to improve these studies as more data is collected and model structure is improved. Some recommendations for improvements in groundwater modelling are made in the CLIWAT handbook (2012).

	Denmark	Germany	Netherlands	Belgium	United Kingdom	Rough totals
Total coastline length (km)	4,605	3,524	1,276	98	17,381	27,000
Developed 1km coastal strip (km^2)	9	11	12	48	-	-
Estimated area below mean sea level (km^2)	1,500	9000	19,000	2,500	6,500	38,000
Estimated population below mean sea level	<5,000	1,800,000	9,000,000	380,000	2,500,000	14,000,000

Table 5 Table showing the coastal setting in the low-lying parts of the North Sea Region considered in the Safecoast project. Table modified from Safecoast (2008).

5. Impact

The North Sea region is of high economic importance, with well developed countries and considerable gross domestic products that exceed the average of the 27 countries of the EU (expressed per capita). The population along the coasts is not however evenly distributed. Large stretches of rural areas are interspersed with urban areas with high population density. From north to south, major cities like Copenhagen, Hamburg, Bremen, Amsterdam, The Hague, Rotterdam, Antwerp and London predominate the coastal and estuarine zone.

The North Sea includes one of the most diverse coastal regions in the world with a great variety of habitats – fjords, cliffs, estuaries, deltas, banks, beaches, and marshes – some of which are designated as conservation areas at an international level, protected under the Birds and Habitats Directives, including land and marine-based Special Protection Areas (SPAs) and Special Areas of Conservation (SACs), which together form the Natura 2000 network. The Wadden Sea, for example, covers parts of the Netherlands, Germany and Denmark and is one of the largest wetlands in Europe, with 25,000 km^2 of mudflats, sandbanks, salt marshes and shallow seas. Over a third of this area is designated as a Natura 2000 site, and it is also a valuable nursery area for commercial fish such as herring and plaice and home to harbour seals (Safecoast, 2008). The NSR also contains many protected wetlands, which are significant at a global level. The Netherlands, for example, contains around 8,200 km^2 of Ramsar-listed wetlands, and Denmark some 20,800 km^2 (http://ramsar.wetlands.org).

It is within this socio-economic and environmental setting that the impacts of climate change on water quantity and quality need to be assessed. Table 6 is a non-exhaustive list of some of the key impacts identified during the review of the cluster projects.

Groundwater is a major source of drinking water in the North Sea region, so the state of groundwater in terms of its quality and quantity is of vital importance. An imbalance between groundwater supply and demand would have major negative consequences for agricultural production, drinking water supply, and for any associated ecosystems, such as wetlands and river systems, as many rivers are dependent on groundwater to sustain low flows during the summer months.

In terms of the impact of flooding, it is worth noting that the impact of a flood event can only be properly assessed when both the change in the extent and probability of the hazard and the change in the *consequence* of the hazard are known. This review mostly deals with the former, but changes in spatial and infrastructure developments and related socio-economic values will affect flood-related damage and casualties, and are therefore equally important.

These impacts can also be looked at within an ecosystem services framework, whereby climate change-induced pressures damage the services that an ecosystem is able to provide. This approach is not mentioned specifically within the cluster projects, but is increasingly used by policy makers as a tool to further justify the protection of environmentally-significant areas, going beyond the philosophy that these areas deserve protection due to their intrinsic value, to attempting to assign some monetary value to non-market services ecosystems provide society. Clearly the specific ecosystem service affected depends on the specific location, and it has not been possible to review every pilot study in this way. However, some indication of the kinds of ecosystem services that may be damaged by pressures such as coastal flooding, groundwater pollution, etc., are given in the Appendix tables (using the CICES classification; Haines-Young and Potschin 2011).

Pressure	**Possible impacts**
Coastal flooding	Damage to property and infrastructure Damage to agricultural land Decrease in land fertility/areas become unsuitable for agriculture Displacement of populations Risk to human life Loss of shallow intertidal habitat and associated negative ecological impact Loss of low-lying freshwater wetland and associated negative ecological impact Loss of areas of historical/cultural significance
Riverine and lake flooding	Damage to property and infrastructure Risk to human life Damage to agricultural land Areas become unsuitable for agriculture
Urban flooding	Damage to property and infrastructure Flux of contaminants to waterbodies
Freshwater shortage (drought)	Loss of wetland habitats and associated negative ecological impact Lack of freshwater for irrigation – lower agricultural yields Lack of freshwater for human consumption Damage to freshwater ecosystems Competition for water use (food, energy, aquatic/wetland ecosystems)
Freshwater shortage - groundwater salinisation	Shortage of freshwater for irrigation Decrease in land fertility Lack of freshwater for human consumption - possible negative impact on tourism Damage to associated freshwater ecosystems
Diffuse pollution - nutrients, bacterial pathogens	Eutrophication - damage to aquatic ecosystems Restrictions on bathing
Urban pollution: heavy metals & other contaminants	Damage to aquatic ecosystems Contamination of aquifers Restrictions on bathing
Urban pollution: landfill emissions	Aquifer pollution - damage to drinking waters Pollution of adjacent surface waters and damage to aquatic ecosystems
Changes in lake temperature and nutrient structure	Change in ecosystem structure and functioning Toxic algal blooms more common – bathing restrictions
Increase in river water T	Loss of coldwater salmonid species Change in ecosystem structure and functioning

Table 6 Major pressures and associated impacts in the North Sea region. Non-compliance with EU Directives can also be seen as impacts, but are not listed here, as can loss of designated status (e.g. Natura 2000 sites). For further information, see Appendix.

6. Responses

Responses to water quantity and quality issues may be aimed at reducing the driving force, the pressure, changing the state or reducing the impact of the pressure. WaterCap work package 5 has the specific objective of reviewing adaptation/response strategies and measures with regards water quantity and quality issues. Only a brief overview of this topic is therefore provided here. Table 8 provides a summary of some of the responses that are either recommended, developed, implemented or evaluated within the cluster projects. More information is available in the Appendix. Coastal flooding is a major issue throughout the North Sea region, and Table 7 provides more detail on the kinds of responses that have been applied in the region, and how these responses have varied between the countries examined as part of the Safecoast project.

Other more general responses not included in table 8, but equally important, include increasing communication and education regarding water quantity/quality issues. Part of SAWA's remit, for example, was to set up sustainable education centres, taught courses regarding flooding and computer games to engage the younger community. Awareness-raising events are also important, as are the production of handbooks to guide water managers and practitioners (e.g. the CLIWAT handbook). Decision management can be greatly strengthened and aided by making data freely available on the internet, in an accessible format. Steps have been taken towards this, but these resources could be further integrated and therefore strengthened. Finally, almost all the cluster projects included a strong element of stakeholder involvement in the development of adaptive approaches to integrated water management, recognising that it is only through engaging with water users, managers and the wider community that sustainable solutions can be identified and successfully implemented.

Many of the cluster projects make reference to integrated water management and spatial planning strategies for the management of water resources, and one of the key aims of Aquarius is to identify and highlight some of the other benefits that may result from adopting certain water management measures (such as improvements in biodiversity or opportunities for enhancing tourism and the recreational value of an area). Indeed, in their fourth assessment report the IPCC state an expectation that the paradigm of 'Integrated Water Resources Management' will be increasingly followed around the world. This would shift water, as a resource and a habitat, into the centre of policy making and has the potential to decrease the vulnerability of freshwaters and associated ecosystems to climate change (IPCC AR4 WG2 2007).

Category	Measure	Denmark	Germany	Netherlands	Flanders	England
Flood and erosion protection	Dike foreland management	2	3	1		1
	Coastal nourishments	3	3	4	3	1
	Primary defences	2	4	4	4	3
	Secondary dike lines	1	2	2		
	Managed realignment					3
Limiting potential consequences of floods and erosion	Restricting (new) developments in coastal zone	4	3	3	2	1
	Restricting (new) developments in flood-prone areas	1	1	1		3
	Construction of flood resistant buildings	2	1	1		2
	Storm surge warning	3	3	3	3	3
	Risk/crisis communication	1	2	2	2	3
	Evacuation planning	2	2	1	1	3
	Flood insurance	3	1		2	4

Table 7 National/regional emphasis on coastal risk management measures: (1) limited use, (2) some importance, (3) quite important, (4) crucial. Modified from Safecoast (2008).

Pressure	Possible impacts	Responses	Project
Coastal flooding	Damage to property & agricultural land, risk to human life, displacement, loss of historic sites	Develop integrated spatial planning and water management strategies to improve sea defences in a sustainable way, maximising other benefits	CPA
	Loss of shallow intertidal habitat	Protect intertidal areas, e.g. sand bank nourishment, oyster beds. Wetland restoration	CPA
	Loss of low-lying freshwater wetlands	Managed coastal realignment	CPA
River/lake flooding	Damage to property & agricultural land; areas become unsuitable for agriculture	Develop adaptive flood risk management plans and strategies for their implementation	SAWA
		Creation of wetlands for water storage	Aquarius
		Optimise storage capacity during floods using automated 3-weir flow regulation	SAWA
		Lake dredging	SAWA
		Develop emergency plans to deal with flood waves	SAWA
		Creation of decision support database of flood alleviation measures in the NSR; where possible, cost-benefit analysis of these measures	SAWA
Urban (pluvial) flooding	Damage to property, flux of contaminants to waterbodies	Assess adaptation/response needs. Design flood mitigation measures, e.g. separate sewage systems for rain water and sewage; increase of water storage in urban areas	CPA
		New urban infrastructure; better draining of surplus groundwater and excess rainwater	CLIWAT
		Sustainable Urban Drainage Systems (SUDS)	SAWA
Freshwater shortage (not salinisation)	Lack of freshwater for human consumption/agriculture	Water storage (small weirs), more efficient groundwater use (sprinkling, pivots)	Aquarius
		More efficient water storage: Artificial ponds; encourage active recharge of groundwater	Aquarius
	Loss of freshwater wetlands	Creation of wetland using low-cost non-engineering methods	CPA
Flooding/GW salinisation	Decrease in land fertility; areas become unsuitable for agriculture	Salt-resistant agriculture/aquaculture	CPA
Groundwater salinisation	Lack of freshwater for human consumption, agriculture and ecosystems	Better freshwater management systems on islands and low-lying coastal areas: use/storage of excess precipitation during wet periods of the year	CPA
		Desalination for drinking water, storage of winter rain water for summer use, sanitation and separation of household water, purification and reuse of waste water effluent.	C2CI
		Better knowledge of island subsurface/hydrological system. Optimise water supply well configuration	CLIWAT
		Increase storage capacity of polders/more pumps; monitor groundwater resource	CLIWAT
Diffuse pollution	Eutrophication - damage to aquatic ecosystems Restrictions on bathing	Identify technical, financial/institutional and participatory problems to achieving "farmers as water managers"	Aquarius
		P filters to reduce particulate P delivery to surface waterbodies	Aquarius
		Diffuse pollution mitigation measures, e.g. buffer strips, fencing streams, etc.	CLIWAT
Pollution from urban/industry	Damage to aquatic ecosystems Restrictions on bathing Aquifer pollution - damage to drinking waters	Ascertain contaminant sources, to target response. Monitoring or urban groundwater quality	DiPol
		Retention ponds	DiPol
		Simaclim regional relative risk ranking model - help prioritise actions & plan response	DiPol
		Water purification prior to discharge to surface water bodies	CLIWAT
		Landfill: evaluation and remediation if necessary (climate-proof)	CLIWAT

Table 8 Summary of the kinds of responses recommended, developed, implemented or evaluated in the cluster projects. For further information, see Appendix.

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Appendix

The following tables summarise the projects in the cluster within a Driver-Pressure-State-Impact-Response framework. For most of the projects, the drivers are not explicitly stated, as they all relate to climate change within the socio-economic context of the specific countries. For further details of the climate changes that are likely to give rise to the specific pressures mentioned, see sections 2 and 3.

The majority of the projects are made up of many sub-projects, some of which are geographically based (i.e. pilot areas or demonstration sites), some of which are more general. This summary information is therefore inevitably incomplete, but should provide a flavour of the main areas of knowledge which the projects aimed to contribute to, together with the main geographical location of the pilot basins.

Grey boxes highlight areas that the project focused on developing, with a description within that box of the work done or the main recommendations. For example, in CPA work was carried out to improve knowledge of the state of the environment by producing coastal and urban flood risk maps, but the majority of the project was related towards responses, either through recommending procedures to implement responses, actual implementation of responses, or evaluation of the results.

Sources of information used to compile appendix tables (for further details, see 'Bibliography'):

Comments from attendees at the WaterCap WP3 meeting in Tarland, Scotland, April 2012. This included representatives from CPA, C2CI, Aquarius and CLIWAT.

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Website (http://www.aquarius-nsr.eu)

C2CI: Website (http://www.c2cislands.org/) (no documentation available on website)

CPA: WP2 brochures for each of the 8 pilot areas
WP2 end report
WP4 end report
Website (http://www.climateproofareas.com/)

CLIWAT: CLIWAT handbook; website (http://cliwat.eu/)

DiPol: Final conference powerpoint presentations (http://www.tu-harburg.de/iue/dipol/final-conference-2011.html)
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SAWA final conference powerpoints and posters (http://conference.sawa-project.eu/information/papers/)

Where impact is also expressed as impact to ecosystem services, the service affected is described using the CICES classification (Haines-Young and Potschin, 2011)

Country abbreviations:
B: Belgium, D: Germany, DK: Denmark, NO: Norway, NL: Netherlands, S: Sweden, UK: United Kingdom

Other abbreviations: GW – groundwater; CC – climate change; WFD – Water Framework Directive, EIA – Environmental Impact Assessment

Aquarius

Pressure	State	Impact	Response		Multiple Benefits?	Pilot Area
			General	Technical		
Diffuse pollution	Surface water nutrient concentration; nutrient load delivered to lakes.	Damage to aquatic ecosystems; WFD non-compliance	Project aim: to find sustainable technical solutions, by identifying and overcoming the financial and participatory barriers. Approaches: • Farmer groups to tackle local problems • Local demonstration of solutions • National/international networks for discussion and knowledge sharing	Regain watering access to burn for farmers whilst minimizing negative impacts on WQ	Economic improvements for farmers	Mariager Fjord (DK)
				Testing P filters to reduce P delivery to stream (and ultimately lake) from sediment. In conjunction with other measures (reduce P fertilization, decreased tillage)		Vestre Vansjø (N)
Flooding	Flood risk	Damage to property and agricultural land		Creation of wetlands: site inventories, support for farmers during application process, participatory problem solving to establish demonstration sites	Biodiversity, water quality, flooding, droughts	Smedjeåen (S), Tarland (UK)
				Construction of 'nature friendly banks', maintained by farmers rather than Water Board	Biodiversity	Midden-Delfland (NL)
Water shortages	GW level, minimum flows in surface waters	Lack of water for agriculture. Damage to ecosystems		Water storage (small weirs; ponds), more efficient GW use (sprinkling), efficient irrigation techniques (pivots), artificial GW recharge	Buffering against floods, nutrient removal (ponds)	Veenkoloniën (NL), Ilemal Jeetzel (D)

C2CI - Water

Pressure	Change in State	Impact		Response	Pilot Area
		Description	**Ecosystem Service Impacted**		
Diminishing freshwater resources in island communities	Decrease in ground water levels, decrease in volume of freshwater lens, decrease in stream flows; increase in groundwater chloride concentration	Water shortage for agriculture, drinking, tourism. Decrease in quality of life.	Provision: drinking water. Cultural: Tourism, recreation, heritage.	Aim to develop and test methods for providing sustainable supplies of drinking water. E.g.: Desalination for drinking water Storage of winter rain for use in summer Sanitation and separation of household water Purification and reuse of waste water treatment plant effluent	

Climate Proof Areas (CPA):

Pressure	Change in State	Impact		Response	Pilot Area
		Description	Ecosystem Service Impacted		
Coastal flooding and coastal erosion	Production of coastal flood risk maps. Assessment of safety level.	Damage to property and agricultural land Increased risk to human life	Provisioning: food Cultural (heritage sites)	• More protection of property and agricultural land • Development of integrated spatial planning and water management strategies to improve sea defences in a sustainable way, maximising other benefits • New collaborations/networks between different bodies/agencies	Schouwen-Duiveland (NL), Wesermarsch (D)
		Loss of shallow intertidal habitat, biodiversity loss (loss of Natura 2000 status).	Cultural	• Experiments to test effectiveness of measures to protect intertidal areas and investigating possibility of wetland restoration. Found artificial sand nourishment to be a cheap and long-lasting solution • Creation of new alliances between organisations, leading to new solutions and new funding sources	Eastern Scheldt (NL)
		Loss of low-lying freshwater wetlands	Regulating: Flow, C sequestration. Cultural	• Managed coastal realignment; project to improve tourism/recreation facilities and thus increase visitor numbers and improve communication regarding coastal realignment • Implementation of wetland restoration	Tichwell Marsh (UK)
Salinisation of groundwater	Chlorine concentration	Shortage of freshwater for agriculture	Provisioning: water, food	• Research into better freshwater management systems on islands and low lying coastal areas. E.g. use/storage of excess precipitation during wet periods of the year • Research into more salt-resistant agriculture	Wesermarsch (D), Schouwen-Duiveland (NL)
Flooding: Increased frequency of overflow from stormwater systems	Production of urban flood risk maps	Damage to property; flux of contaminants to waterbodies		• Assess adaptation/response needs. Design flood mitigation measures, e.g. need for separate sewage systems for rain water and sewage, increase of water storage in urban areas • For the first time in a trans-national project, put key members from the value chain in the project: local problems on the national agenda to get external funding	Wesermarsch (D), Arvika (S)
Freshwater shortage, subsidence	Decrease in area of wetland	Loss of important habitat	Cultural	• Creation of additional wetland using low-cost non-engineering methods; initial assessment of results • Strong, long-term vision for steps needed to ensure future security of the area, strong usage of European Programmes	Wicken Fen; Great Fen (UK)

CLIWAT

Context	Pressures	Change in State	Impact	Response	Pilot Area
Development of tools/methods; general responses	Groundwater - related pressures (flooding, salinisation, pollution)	• Test and develop geophysical, monitoring and chemical methods to better describe the subsurface, particularly the shallow subsurface • Monitoring surveys; develop a database • Develop and apply models to evaluate the likely effects of climate change on groundwater quantity and quality. Identified model/data deficiencies • Production of regional thematic maps of changes in sea level, groundwater recharge, groundwater tables, catchment areas of waterworks, groundwater quality (saltwater intrusion, nutrients, pesticides), need for irrigation	Location-specific (see below) Ecosystem services impacted: Provisioning: food, water; Culture: tourism and recreation, heritage, spiritual	• Recommended technical measures (location and pressure specific; see below) • Production of handbook to assist production of management plans • Stakeholder involvement: development of adaptive approaches to water management using regional maps. Involve a broad range of stakeholders • Awareness-raising events • Finding a 'champion' can be key to successful implementation of measures	All
Result of monitoring/modelling: location-specific results	Urban GW flooding; pollution (sewage, roads, industry, landfills)	**Low-lying urban coastal areas**: • Increased risk of flooding in cellars, underground car parks and lowered roads • Increased water load on wastewater treatment plants • Decrease in water quality	Socio-economic; Damage to adjacent surface water ecosystems	Recommend: New urban infrastructure; better draining of surplus groundwater and excess rainwater. Monitoring of urban groundwater quality Water purification prior to discharge to surface waters	Horsens (DK), Schleswig (DK, DE)
	Salinisation of GW	**Islands**: • GW salinisation risk map • Thickness of freshwater lens	Damage to fragile dune ecosystems; Unsustainable domestic water supply; Decrease in land fertility (agriculture)	Require better knowledge of island subsurface and hydrological system. Use to optimise configuration of water supply well fields	Zeeland (B, NL), Tershelling (NL), Borkum (DE), Fohr (D), Als (DK)
	Salinisation of GW; Coastal flooding	**Polders**: • GW salinisation risk map • Coastal flood risk map	Reduced crop yield/areas become unsuitable for agriculture	Recommend: Increase storage capacity of polders/more pumps; maintain/increase freshwater lenses in dune and seepage areas; monitor groundwater resource	Fryslan mainland (NL), Zeeland (B, NL)
	Urban pollution: landfill sites	**Landfill sites**: • Risk of change in direction of contaminated groundwater plumes • Increase in contamination of surface waters	Contamination of drinking water; damage to surface water ecosystems	Recommend: Evaluation of hydraulic system prior to decision-making. If remediation required, design climate-proof facilities	Horlokke (DK), Aarhus (DK)
	Diffuse pollution	**Agricultural areas**: • High GW nutrient concentrations	Eutrophication of associated surface waters	Recommend diffuse pollution mitigation measures	Egebjerg (DK)

<u>DiPol</u>

Driver: increase in amount and intensity of rainfall

Pressure	**Change in State**	**Impact**		**Response**	**Area**
		Description	**Ecosystem Service**		
Delivery of pollutants to urban/coastal waters: **Sampling/stats** to examine link between pollutant delivery to urban/coastal waters and rainfall amount/intensity. Focus on heavy metals, PAHs, bacterial pathogens, pesticides, etc. Link established in 2 or 3 of the 4 pilot areas. Establishment of **web-based knowledge platform** to summarise results of monitoring. First attempt at estimating likely increase in pollutant delivery to the North Sea (**Scremotox**): uncertain, possible increase.	**Monitoring/modelling studies**. Expect: • Increase in sediment toxicity • Increase in surface water concentrations of heavy metals, PAHs and fertilizers • Pathogen levels exceed BD over larger area & for longer	Ecological deterioration (non-compliance with WFD). Restrictions on bathing (failure to meet BD)	Cultural	• Sampling and stats to ascertain contaminant sources, to target response • Modelling study to evaluate effectiveness of retention ponds (size matters) • Simaclim sensitivity tool, Simaclim regional relative risk ranking model - help prioritise actions & plan response	Pilot areas around Gothenburg, Copenhagen, Oslo, Hamburg North Sea

SAWA

Pressure	Change in State	Impact	Response	Pilot Area
Flooding - primarily fluvial and lake	• Development of flood risk maps for pilot basins • Development of regional flood risk maps	Damage to property, infrastructure and agricultural land. Risk to human life.	Basin specific: • Development of adaptive flood risk management plans in pilot areas. • Adaptive strategies for implementation of flood risk management plans	Wands, Ilmenau (D); Gaula, Tana (N); Lake Vänern (S); Hunze (NL)
			Develop/test adaptation measures, e.g.: • Optimising storage capacity during floods using automated 3-weir flow regulation • Sustainable Urban Drainage Systems (SUDS) • Effectiveness and EIA of lake dredging • Assess efficiency of emergency plan to deal with flood waves • Install 1700 ha storage basin, combined with nature reserve. • Anticipatory water management – flood forecasting system, focus on emergency response and temporary measures during peak discharge.	Ammersbek (D), Norway (NVE), Karlstad (S), Gota River (S), Noorderzijlvest waterboard (Drenthe & Groningen, NL)
			Synthesis of knowledge on measures: • Creation of decision support database of flood alleviation measures in the NSR; where possible, cost-benefit analysis of measures	
			Improve capacity of and communication with stakeholders/water managers: • Development of 3D visualisation tool for better communication of flood risk to stakeholders • Increase communication/education regarding flooding: taught courses, sustainable education centres, computer game	