DiPol
WP “Risk analysis”

SCREMOTOX

March 2012

1 Introduction

1.1 Background

Expected climatic changes (CC) will lead to more extreme discharges of rivers, extensive rainfalls in the watershed and increased seawater levels. Along with the obvious effect on flooding risks, these developments will have consequences for the water quality in terms of nutrients and contaminants that are flushed from streets and agricultural areas into rivers and transported to the coastal areas impacting bordering countries.

The Water Framework Directive (WFD) and the Marine Strategy Framework Directive (MSFD) demand activities from member states to prevent deterioration of coastal waters. In order to achieve a “good ecological/environmental status” of all surface waters, member states are obliged to suggest a “program of measures” in the river basins to be implemented ultimately by 2027. Currently planned programs usually do not address climate-induced changes of contaminant transport due to the complexity of processes and variability of regional conditions. However, unless CC impacts are integrated in the management concepts, member states will potentially fail in the attempt to reach the objectives of the European Framework Directives and to sustain a healthy aquatic environment.

Against this background, the project “Impact of Climate Change on the quality of urban and coastal waters”, designated by its acronym “DiPol” has the following overall objectives:

- to collect knowledge on the impact of CC on water quality, to communicate and raise awareness towards this knowledge,
- to improve the ability of decision makers to counteract these impacts on local and international level, and
- to facilitate public participation herein.

DiPol develops a series of activities to address these issues. The present report discusses the activities carried out under Working Group E “Scremotox and Coastal Transport”. These activities target the issue of climate change impacts on water quality on larger spatial scales, running from the North Sea sub-basins to the North Sea as a whole.

Most of the remaining activities in DiPol concentrate on 4 so-called Local Case Studies, being the Oslo Fjord (Norway), the Göta Alv River (Sweden), the Wilhelmsburg area in Hamburg (Germany) and the Harrestrup stream and the Kalveboderne Lagoon in Copenhagen (Denmark).

1.2 Objectives

The objectives of the work presented in this report are:

- To show the (relative) contribution of diffuse sources of pollution to coastal water quality on the scale of the North Sea, and
- To show the impact of climate change on this picture.

This North Sea wide assessment is based on data, information and model results developed for the North Sea. It is carried out next to the four local case studies mentioned above. It is noted that there is a scale difference between the local case studies and the North Sea wide assessment, both with respect to spatial and temporal scales. Where locally individual flood events or rain storms dominate the impact of climate change, the North Sea as a whole is

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controlled by longer time scales, which may make it respond to seasonal or even multi-annual trends.

2 Materials and methods

2.1 Overall methodology

Figure 2.1 shows the overall methodology adopted for the present assessment.

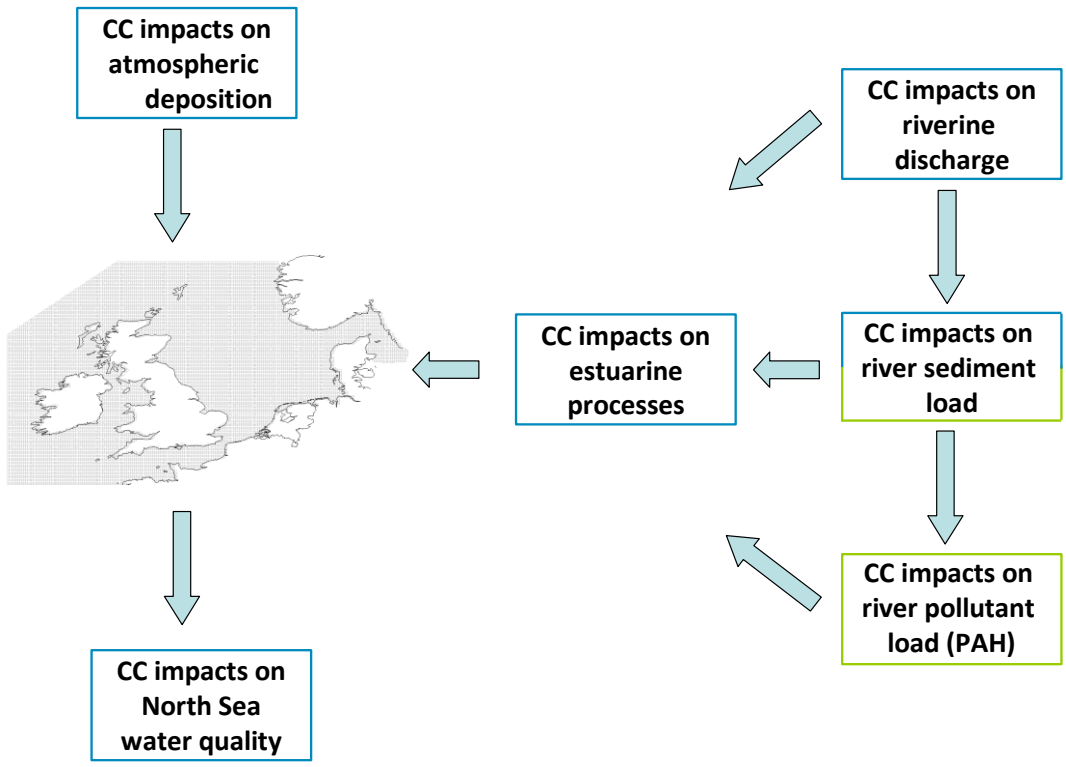


Figure 2.1 Overview of overall methodology

In the climate change perspective, the most relevant factors for the North Sea are considered to be the changes in the river discharges, in particular the expected increased frequency and/or intensity of floods, as well as the changes in the sea level. The expected increased frequency and/or intensity of floods may remobilise sediment deposits with a historical pollution burden. This may increase the flux of pollutants towards the estuary and the North Sea proper. The changing river discharge dynamics in combination with the changing sea level may affect the behaviour of estuarine systems; in particular it may change their efficiency to trap riverine particle-bound pollution fluxes. In view of the scope of DiPol, the abovementioned phenomena will be the focus of this report.

Other possible effects of climate change on the North Sea having an effect on diffuse pollution and on the assimilation capacity, such as changes in the sea surface temperature and changes in large scale circulation patterns will not be studied in detail. A recent review by EEA (2008) reports on sea surface temperature changes, while another review (ESF, 2007) points out that the North Sea has shown pronounced modifications in large-scale hydro-meteorological forcing, including a marked increase in oceanic inflow and sea-surface temperature in the 1970s and 1980s.

2.2 Climate change and river hydrology

Climate change will have significant global effects on runoff regimes. Studies investigating hydrological effects of climate change are often based on results from General Circulation Models (GCMs), which describe global weather patterns under solar and anthropogenic forcing (e.g. inputs of greenhouse gases). However, especially for precipitation, GCMs produce quite variable and even contradictory results. Changes in runoff can directly be calculated from runoff fields that are output of GCMs. Unfortunately, such data is not accessible for most models and in most GCMs river routing is not included. To obtain information on the changes in river regimes, additional routing of GCM runoff fields is needed. River discharges can be calculated with a hydrological model that includes a routing model, using meteorological variables directly from GCMs.

A study by Sperna Weiland et al. (2012) provides a thorough assessment of the global hydrological effects of climate change by directly applying daily climate data from an ensemble of twelve GCMs for two IPCC SRES scenarios (A1B and A2), for the period 2081-2100 as input to the global hydrological model PCR-GLOBWB. In this hydrological model, the river discharge is calculated using an explicit routing scheme based on the kinematic wave equation. The results obtained are compared to similar results for the 20CM3 control experiment (the period 1971-1990). Sperna Weiland reports that the combination of the hydrological model and GCM data gives deviations between simulated and observed discharges for many catchments. Additional inaccuracies must be anticipated when downscaling from the global scale to the North Sea scale. Furthermore, there was a large variability between the results obtained from different GCMs.

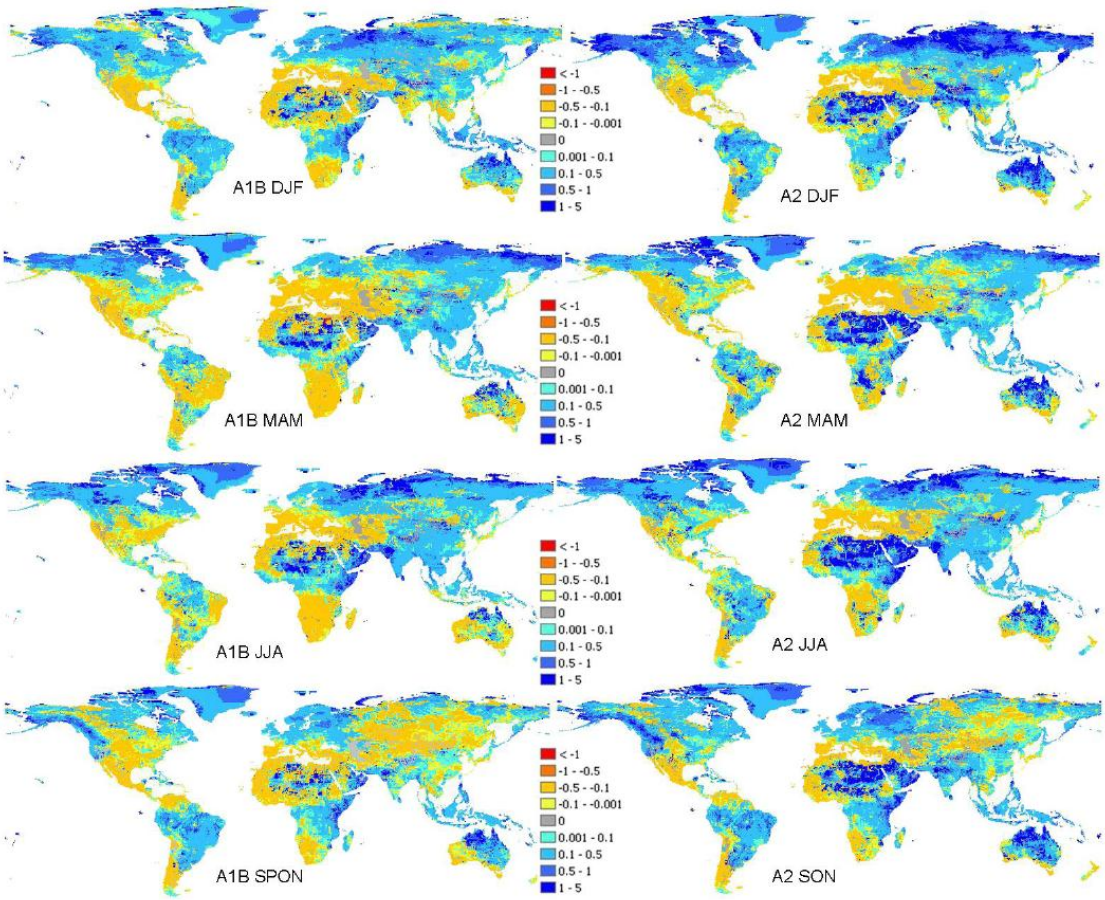
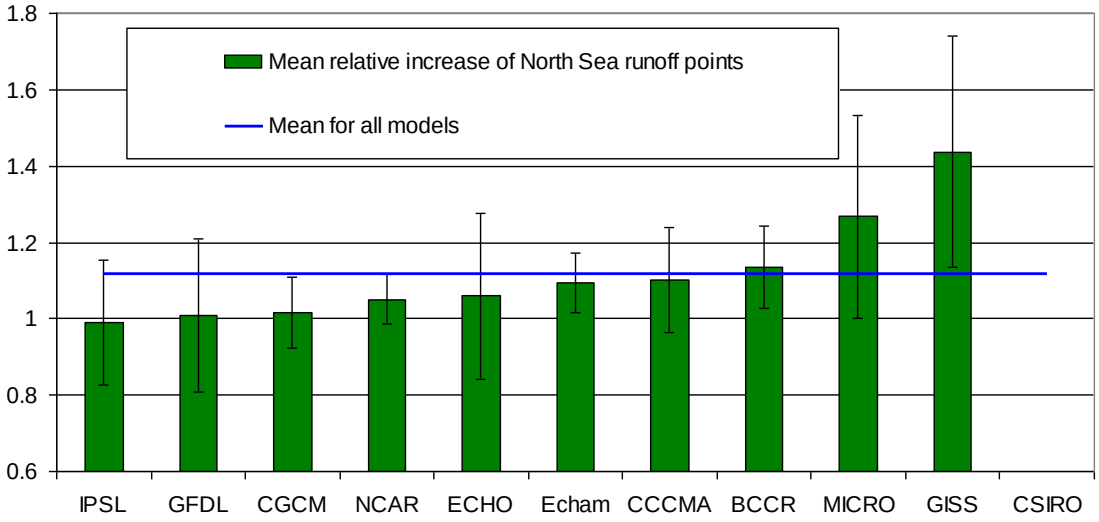


Figure 2.2 Seasonal discharge changes for the scenarios A1B (left) and A2 (right) relative to the discharges calculated for the 20CM3 control experiment. From top to bottom the seasons: DJF, MAM, JJA and SON.

As an illustration, Figure 2.2 shows the results from an ensemble forecast for all 12 GCMs, presented as mean runoff differences per season. The results illustrate that in the North Sea region, winter run-off is expected to increase, while summer runoff is expected to decrease. There are clear regional differences as well, with larger increases in the North and larger decreases in the South.

We used the changes in river run-off calculated by Sperna Weiland as a proxy for the expected changes in the present river inflows to the North Sea.



Results for 10 different GCMs, HADGEM based results have not been considered because they have been derived for a limited period. CSIRO results were omitted because they were very much different from all other models. The bars show the mean relative runoff change (scenario A2 relative to 20CM3) for all 99 inflow points from the PCR-GLOBWB model to the North Sea. The line shows the mean of the bars. Error bars show the standard deviation for the 99 inflow points.

Figure 2.3 Summary of initial results for North Sea region

Figure 2.3 shows initial results obtained for all GCMs, expressed as the mean relative runoff change (scenario A2 relative to 20CM3) for all 99 inflow points from the PCR-GLOBWB model to the North Sea. Initial results based on averages of all GCMs demonstrated that impacts on river run-off may be underestimated. Therefore, for the final results, presented in chapter 3 below, we selected the Echam model and the CCCMA model. Both models show results close to the average of all models. Echam shows a relative small variability between the 99 inflow points whereas CCCMA shows a relatively large variability.

2.3 Climate change and river suspended particulate matter (SPM) loads

2.3.1 General

Changes in riverine suspended particulate matter (SPM) loadings to the North Sea may occur in response to changes in discharge regimes envisaged within the context of climate change.

The source-dependent SPM load is relatively easy to measure but hard to predict accurately. The SPM loads of rivers vary several orders of magnitude within a year and can vary several orders of magnitude while the river discharge is the same. A variety of factors influences the “natural” SPM load of a river but the more significant factors are the river basin drainage area and the large-scale relief within the river basin (Syvitski et al., 2003). Although the flux of SPM carried by rivers is highly variable in space and time, it generally shows a dependency on the river discharge expressed by the “sediment rating curve” (Walling, 1974, 1977a, 1977b; Church and Gilbert, 1975).

2.3.2 Data availability

In the present study, we focus on the major rivers that drain into the North Sea. Although river discharge data are available for the 43 rivers included in our assessment (see Section 2.7),

the availability of concurrent SPM field data (related to the same monitoring location and time period) is limited. The selection of rivers analysed in the present work is primarily based on data availability. The primary dataset investigated refers to the River Rhine at the monitoring location Lobith for the time period 1989-2009 (data source www.waterbase.nl). Daily measurements of the water discharge and the suspended particulate matter sediment concentration are available for these 11 years.

For the river Elbe, river discharge and SPM data are available from http://www.arge-elbe.de/wge/Download/DDaten.php. The daily river discharge is measured at Neu Darchau (km 536.2), whereas the SPM concentration is measured at an upstream location Schnackenburg (km 474.5 km) on a monthly to bimonthly basis.

Other field data is available for the Göta Alv River (Sweden) and is tributaries. However, only turbidity is regularly measured whereas very few measurements of SPM are available. It is expected that the correlation between the SPM concentration and turbidity is strong however. The consistency of the data available is checked using the double mass curve approach (Asselman, 1997), in which the cumulative sediment transport (kg) is plotted against the cumulative discharge (m^3).

Within the North Sea region, the Norwegian river Glomma is ranked as the second largest river in terms of its fresh water volume. For this river, no SPM data are available.

2.3.3 Sediment rating curves

The statistical relationship between river discharge and SPM concentration or load, known as the “sediment rating curve”, is applied to discharge and sediment concentration data from rivers Rhine, Elbe and Meuse. The sediment rating curve commonly takes the power law form as follows:

$C_s=a*Q^b$ or $Q_s=a*Q^{b+1}$

Where C_s is the sediment concentration (kg/m^3 = g/l), Q is the river discharge (m^3/s), Q_s is the SPM load (kg/s), “a” is the rating coefficient and “b” is the rating exponent. Figure 2.4 provides an example of a sediment load rating curve. The power-law fit describes the long-term character of SPM load in river but does not reproduce the natural variability in the sediment concentrations. Scatter around the regression line is, among other things, caused by the variations in sediment supply due to, for instance, seasonal effects controlled by weather patterns, previous conditions in the river basin, channel recovery from extreme precipitation events and differences in sediment availability at the beginning and end of a flood. In fact, for many rivers, at any one discharge the sediment concentration can vary by several of orders of magnitude. This is not accounted for by the rating curve. Yet, sediment rating curves are suitable for determining long term average sediment transport rates with reasonable accuracy.

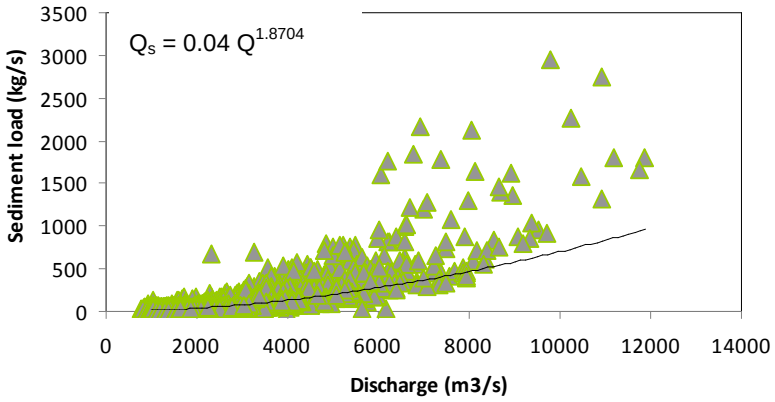


Figure 2.4 Example of a sediment rating curve (Rhine River, winter season, 1989-2009).

Steep rating curves, i.e. low “a” and high “b” values, should be characteristic of river sections with little sediment transport taking place at low discharge. An increase in discharge results in a large increment of SPM concentrations, indicating that either power of river to erode material during high discharge is high or that important sediment sources become available when water level rises. Flat rating curves are characteristic for river sections with intensively weathered materials or loose sedimentary deposits which can be transported at almost all discharges.

“a” and “b” are empirical coefficients and have no physical meaning. Asselman (2000) relates “a” to the erodibility of the soils and “b” to the erosive power of the river. High values of “a” occur in areas characterized by intensively weathered soils which can be easily eroded and transported whereas high values of “b” are indicative for rivers with a strong increase in erosive power when their discharge increases. Asselman (2000) argues that “b” values are also affected by the grain size distribution of the material available for transport, i.e. in rivers characterised by sand-sized sediments the power of the river to transport sediment will be more important than in rivers that mainly transport silt and clay. This gives rise to high “b” values.

Syvitski et al. (2000) claim that “a” is inversely proportional to the long term discharge and secondarily related to the air temperature and the basin’s topographic relief. The coefficient “b” correlates most strongly with the average air temperature and the basin relief and has a weaker correlation with the long-term river discharge.

Owing to natural and man-made factors, the rating exponent “b” typically varies between 0.5 and 1.5 and rarely exceeds 2.0 (Syvitski et al. 2000) while the rating coefficient “a” varies by several orders of magnitude. According to Achite et al. (2007), “b” generally stays in the range 0.3-2.5 with negative values of b in arid ephemeral rivers (Reid and Frostick 1997). It is important to note that although “a” varies by orders of magnitude, “b” is an exponent meaning that small changes in “b” are just as important to the resulting sediment load as large changes in “a”.

Regression coefficients “a” and “b” derived from the sediment rating curves for locations with the same sediment transport regime are found to be inversely correlated and plot on the same line (Asselman, 2000).

Sediment rating curves (sediment concentration versus discharge and sediment load versus discharge) were drawn for the Rhine dataset. The power-law sediment rating curve was determined for 5 subsets of the data set: 1) all data 2) summer (April to September), 3) winter (October to March), 4) rising discharge and 5) falling discharge, as described in Asselman (1997). The regression coefficients “a” and “b” derived for each data subset (Table 2.1) were found to negatively correlated and plotted on the same line (Figure 2.5). Given that the data refers to a single monitoring station and to the same time period, it describes to the same sediment transport regime. The “b” coefficient varies from 0.2 to 0.8 whereas “a” varies over almost 3 orders of magnitude.

Table 2.1 “a” and “b” coefficients derived for subsets of river discharge and sediment concentration data measured at Lobith, Rhine River.

	“a” value	**“b” value**
full dataset (1989-2009)	2.00E-04	0.6072
summer (April to September)	4.50E-03	0.1908
winter (October to March)	4.00E-05	0.8074
rising discharge	5.00E-05	0.7913
falling discharge	5.00E-04	0.4687
median	2.00E-04	0.6072

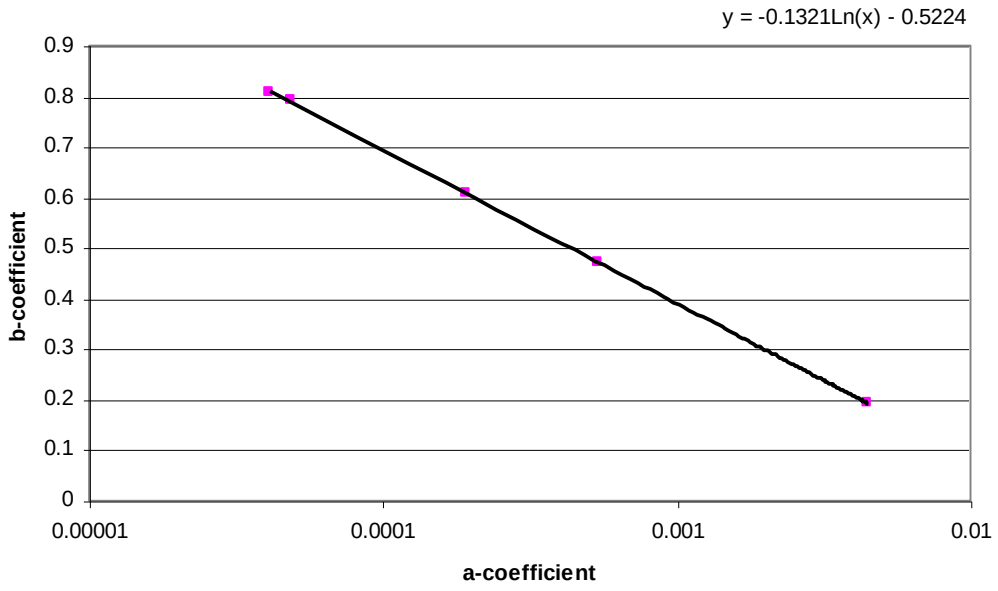


Figure 2.5 Relation between regression coefficients a and b; power functions fitted using non-linear least square regression.

The discharge and SPM data from the Elbe River could not be fitted with a power-law type sediment rating curve and have therefore been discarded. Possible reasons are: (1) the discharge and sediment data being taken from two different locations separated by a number of tributaries and are therefore not directly correlated, (2) the low frequency of SPM data, and (3) the presence of dams.

2.3.4 Upscaling the sediment rating curve approach

Sediment rating curves can be only regarded as representatives for a certain location under the present range of environmental and climatic conditions. Therefore, extrapolating the observations drawn from a single location to a regional scale is hampered by spatial and temporal variability in those factors that determine the shape of the sediment rating curve. In the absence of daily discharge and sediment data from most major rivers draining in the North Sea, upscaling requires, at the minimum, the understanding of the physical meaning of the calculated coefficients “a” and “b” and the evaluation of a number of assumptions.

Due to the lack of data for most rivers, we use the “b” coefficient derived from the Rhine dataset for the North Sea rivers. The value is fixed at 0.65. On the basis of observed or estimated mean values of their discharge and the SPM concentration, the value of “a” for individual rivers has been estimated:

$$SS = a \cdot Q^b \quad b = 0.65 \quad a = \frac{SS_{mean}}{\left(Q_{mean}\right)^b}$$

This implies that no distinction is currently made between rain-dominated or snowmelt-dominated rivers.

2.3.5 Global SPM load estimation approach

On the global scale, the estimation average sediment flux is often related to those parameters that influence the denudation rate, such as the temperature, the relief, the basin area or basin discharge and the basin location (longitude/latitude). Syvitski and coworkers (e.g. Syvitski et al., 2003) report the development of a model that predicts the long-term flux of sediment from river basins as a function of these basin-scale parameters grouped by climate zones (polar, temperate and tropics). Through multiple regression analysis on data from 340 rivers worldwide, the following general relation was derived as a function of discharge, relief and temperature:

$$Q_s = \alpha_6 \cdot Q^{\alpha_7} \cdot R^{\alpha_8} \cdot e^{kT}$$

where Q_s is the SPM flux (kg/s), α_6, α_7, α_8 and k are regression constants, R represents the basin relief and T represents the temperature determined for each climate zone. The reported values of the regression constants are $\alpha_6 = 0.0011$, $\alpha_7 = 0.53$, $\alpha_8 = 1.1$ and $k = 0.06$.

2.3.6 Effects of climate change

Though the approaches mentioned above have their conceptual and data availability related limitations, we assume they can be used to assess at least semi-quantitatively the changes that can be expected in the North Sea rivers SPM loads as a result of climate change. Implicitly, we assume that there are no other factors that cause simultaneous changes in the sediment yield and transport capacity of the river basins. Such factors could be changes in land use and longer term morphological changes (such as erosion and weathering affecting the basin relief).

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2.4 Climate change and river loads of hydrophobic chemicals

Many chemicals such as metals and polycyclic aromatic hydrocarbons (PAHs) are partly present in particulate forms, and thus their fate becomes connected to the fate of fine sediment particles in a river. Jolankai (1992) argues that diffuse pollution sources associated with surface runoff and/or erosion will lead to a chemical concentration in the river water ($g.m^{-3}$) which increases with river discharge ($m^3.s^{-1}$). This is the result of an increasing concentration of particles in the water with chemicals attached to the particles.

Fine sediment particles holding chemicals, can be deposited and temporarily stored in areas with a low sediment transport capacity. Chemicals may accumulate over longer periods (e.g. decades) in areas of sediment deposition, but may be released as a result of extreme floods (Westrich & Förstner, 2007).

The problem of re-mobilisation of historically polluted sediments is under discussion in different river basins. In an extensive study for The Port of Rotterdam, a research team compiled an inventory of historical polluted sediments in the Rhine River and its tributaries (Heise et al., 2004). In the Elbe Basin, a similar study has been completed (Heise et al., 2008). These studies witness that historically polluted sediments are considered a major threat for sediment management in large estuarine ports. The International Commission for the Protection of the Danube River (ICPDR) has set up an inventory of “Old Contaminated Sites” in potentially flooded areas (ICPDR, 2005). This inventory includes landfills, dump sites and storage facilities where harmful substances are deposited. In addition, an inventory was compiled of “Potential Accident Risk Spots”. This again illustrates the concern for historically polluted sediments.

Considering the above, and looking at the concentration of chemicals in the solid medium ($mg.kg^{-1}$) different possibilities exist and can be observed in large rivers (see Figure 2.6).

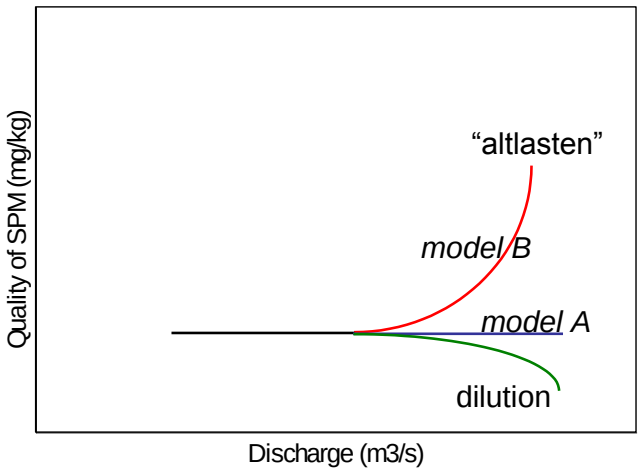


Figure 2.6 Theoretical models for the relation between the quality of suspended matter and the river discharge.

At moderate discharges occurring on average at least once a year, particles may be remobilised from the river bed that have recently settled during low flow periods. The quality of those particles reflects recent emission conditions. With increasing river discharge, representing events which do not occur frequently, older deposits may be mobilised which may be cleaner (green line in Figure 2.6), equally polluted (blue line in Figure 2.6) or more

polluted (red line in Figure 2.6) if they reflect a pollution history (historically polluted sediments, “altlasten” in German). This is illustrated in Figure 2.7 for the Rhine river (results copied from Heise et al., 2004).

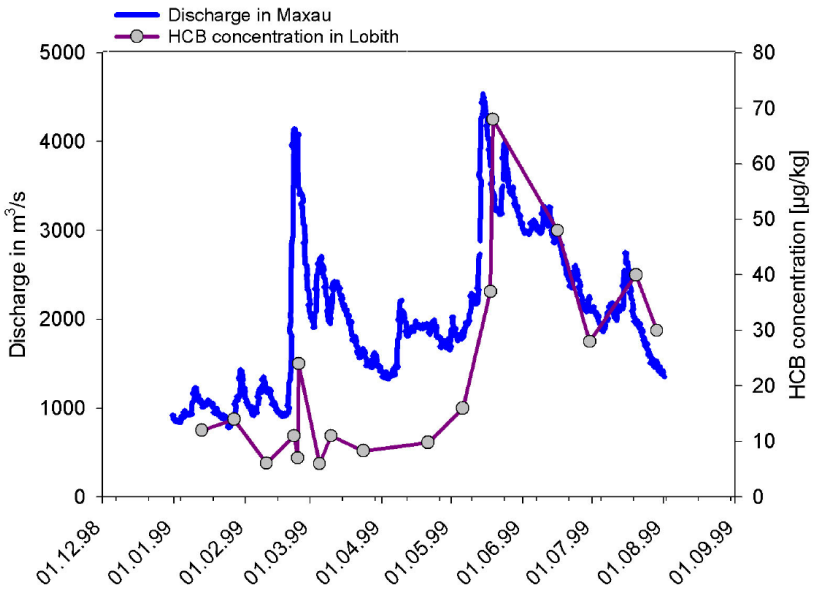


Figure 2.7 Relation between the concentration of hexachlorobenzene (HCB) in suspended matter and the river discharge in the Rhine River, observed in 1999.

In this report we will show the results from the analysis of existing data exploring the quality of SPM under high flow conditions. Already in 1995 (!), the government of The Netherlands recognised the importance of floods for metals and hydrophobic chemicals loads. Since then, arrangements are in place to specifically sample the concentration and the quantity and quality of SPM during floods at Lobith (Rhine River) and Eijsden (Maas River). The data collected since then are available for analysis.

Figure 2.8 Water quality sampling station at the station Lobith (River Rhine, German-Dutch border).

2.5 Climate change and estuarine retention

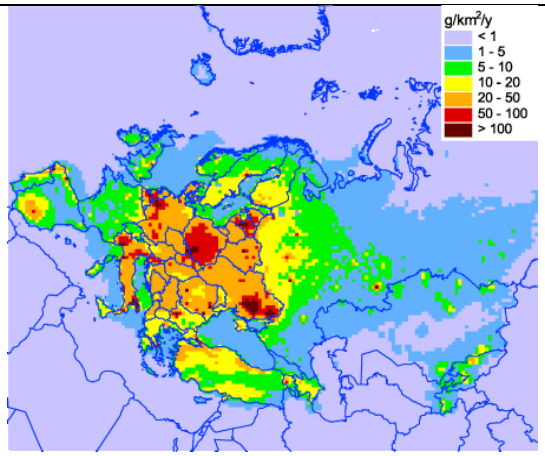
Estuaries have a distinct effect on the river fluxes of SPM and chemicals. Depending on the characteristics of an estuary and the substance properties, a substantial retention can occur.

Zwolsman (1994), estimated that the lowland North Sea estuaries retain ~80 % of the riverine particles input and the associated chemicals.

Various authors have reported on the physical and bio-chemical processes taking place in temperate estuaries. By means of a literature review, we will provide an overview, and assess qualitatively the effect that climate change may have on the retention properties of the North Sea estuaries.

2.6 Climate change and atmospheric deposition

Atmospheric deposition is determined by anthropogenic emissions to the atmosphere, climatic conditions and various physical and chemical processes taking place in the atmosphere. These can be quantitatively addressed by numerical modelling based on state of the art data. The European Monitoring and Evaluation Programme (EMEP) is a scientifically based and policy driven programme under the Convention on Long-range Transboundary Air Pollution for international co-operation to solve transboundary air pollution problems. This organisation provides quantitative deposition estimates derived from numerical modelling, see Figure 2.9. We are not aware of similar information for future time horizons under the influence of climate change.



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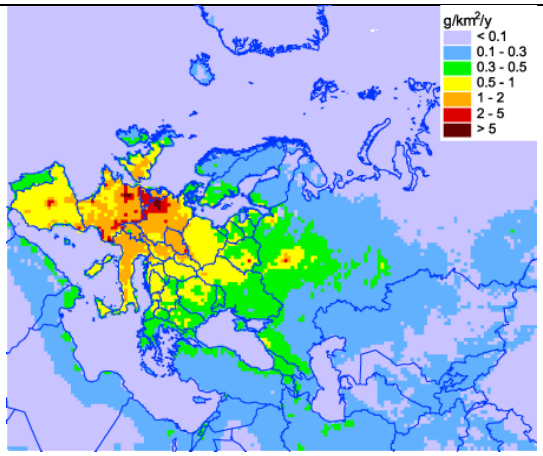

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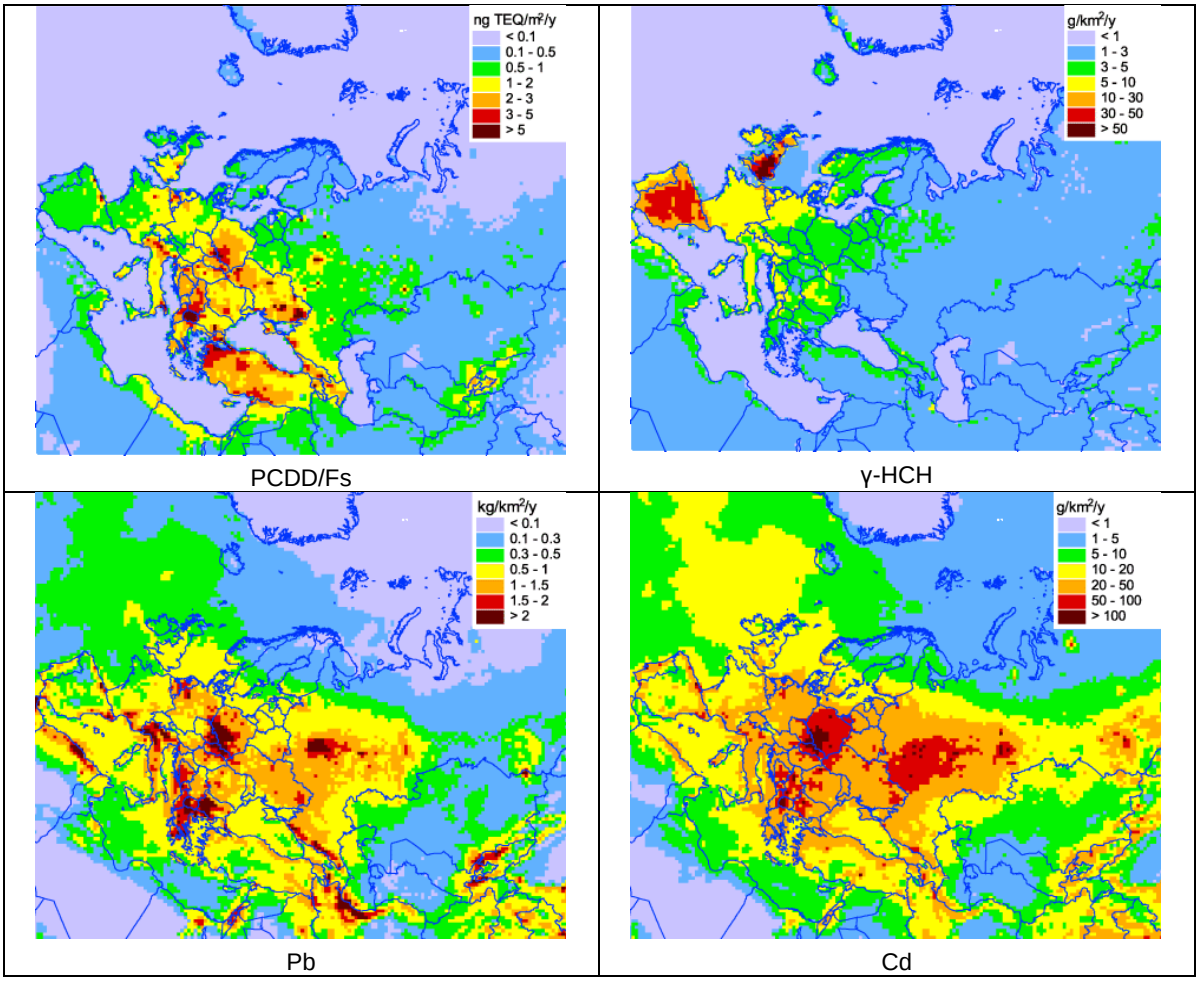

Figure 2.9 Simulated atmospheric deposition of various chemicals in 2008 (http://www.emep.int/)

2.7 Marine water quality modelling

The effect of rivers, atmospheric deposition and other pollution sources on the North Sea water quality has been estimated by means of the numerical water quality model Scremotox. This model was developed in the 1990s (Gerritsen et al., 2001). It was included in an international intercalibration exercise (Stolwijk et al., 1998), and proved to be fit-for-purpose to an acceptable level. An improved version of the Scremotox model was developed in 2005-2007 and has been validated on field data for the Southern North Sea (van Gils, 2007; 2008).

The Scremotox model simulates individual chemicals. It is applicable to a wide range of chemicals (metals and organic substances), while it takes into account the partitioning of the chemicals over the dissolved and particulate phases as well as the relevant physical and biochemical processes: settling, degradation and volatilisation. In view of the common lack of detailed data regarding the spatial and temporal variability of the concentrations of most chemicals, and in view of the common use of water quality target values expressed as an average concentration, the Scremotox model just calculates average conditions, and neglects the temporal variability.

Scremotox adopts the grid and the annually averaged residual currents from a hydrodynamic model. In the 1990s this was the “Promise” model (Gerritsen et al., 2001), while in 2006 Scremotox was linked to the Zuno model (Van Kessel et al., 2010).
An added feature of the Scremotox model is the “source apportionment” technique, where it breaks down the calculated water concentrations with respect to the relative contribution of different pollution sources. This greatly assists policy makers to understand the underlying causes of pollution problems and directs them to find the most promising interventions.

The original application of Scremotox was limited to the Southern North Sea. Figure 2.10 and Figure 2.11 show the input screens defining the pollution sources, while Figure 2.12 shows the input screen defining the simulated chemical’s characteristics. Figure 2.13 shows an example of the simulated total concentrations (benzo[*g,h,i*]perylene, 2004 emissions) while Figure 2.14 demonstrates the source apportionment functionality by showing the relative contribution of atmospheric deposition to the local concentration.

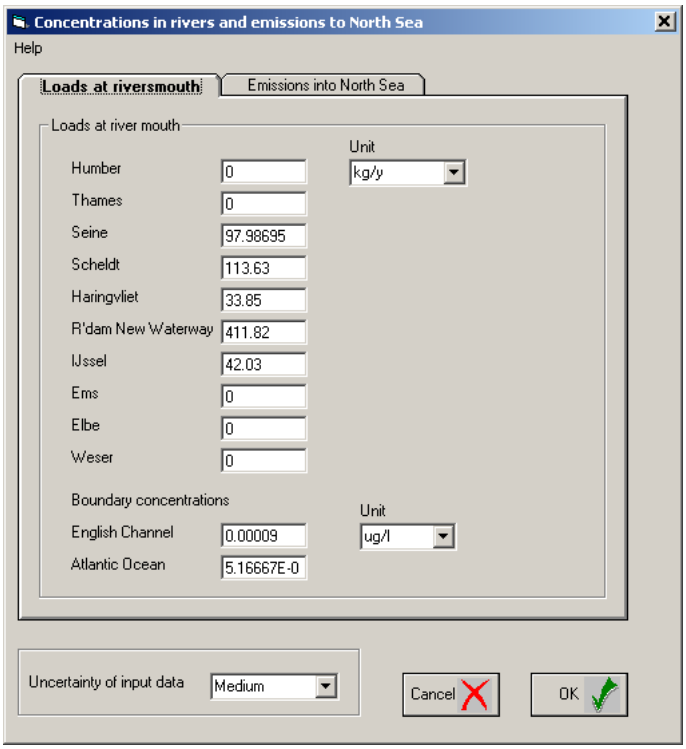

Figure 2.10 Scremotox (Southern North Sea) input screen defining river loads.

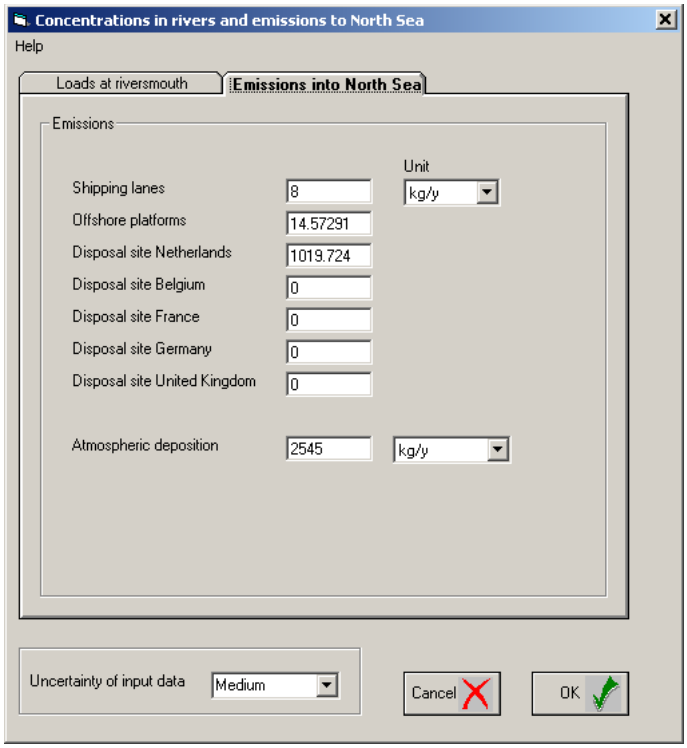

Figure 2.11 Scremotox (Southern North Sea) input screen defining other loads.

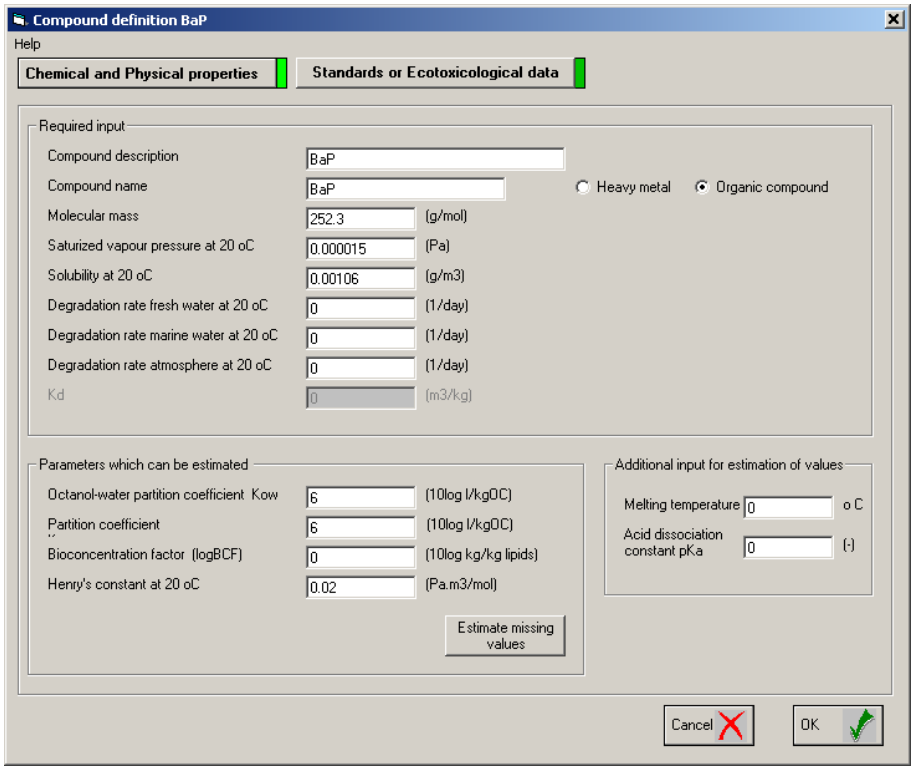

Figure 2.12 Scremotox (Southern North Sea) input screen defining substance characteristics.

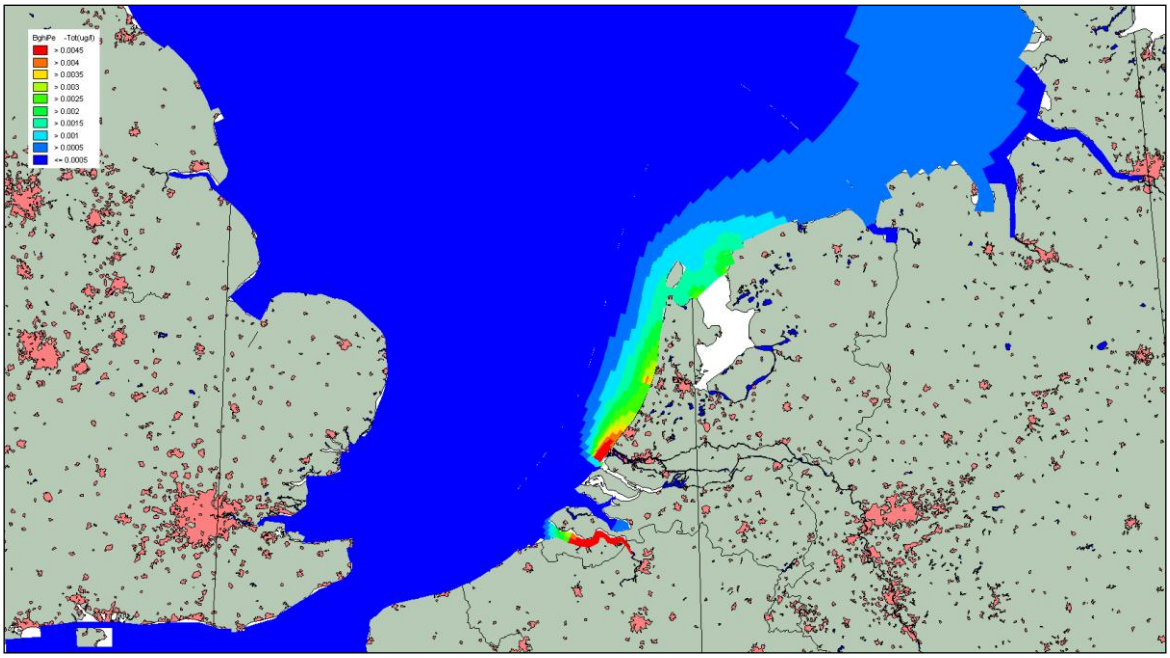

Figure 2.13 Scremotox predicted concentration of benzo[g,h,i]perylene in the Dutch coastal waters for 2004 emissions.

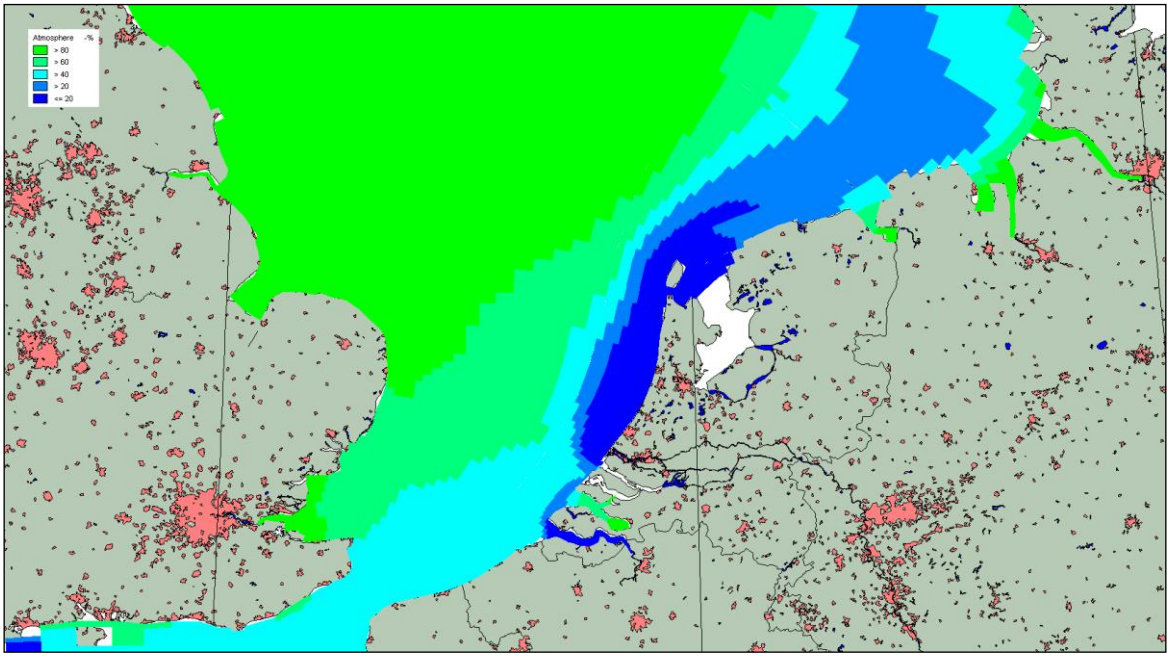

Figure 2.14 Scremotox predicted relative share of benzo[g,h,i]perylene stemming from atmospheric deposition (2004 emissions).

In view of the larger geographical extent of the present project, the Scremotox concept has been upscaled to the total North Sea. To this end, the grid and the residual currents of the so-called Continental Shelf Model have been adopted, see Figure 2.15. To preserve the simplicity and fast response of the model, the total North Sea application of Scremotox maintains the 2D (vertically mixed) approach of the existing Southern North Sea application. Despite the fact that the total North Sea area extends to substantially larger water depths

than the Southern North Sea, and therefore shows more (pronounced) stratification, the 2D approximation is considered sufficiently accurate for the present objectives.

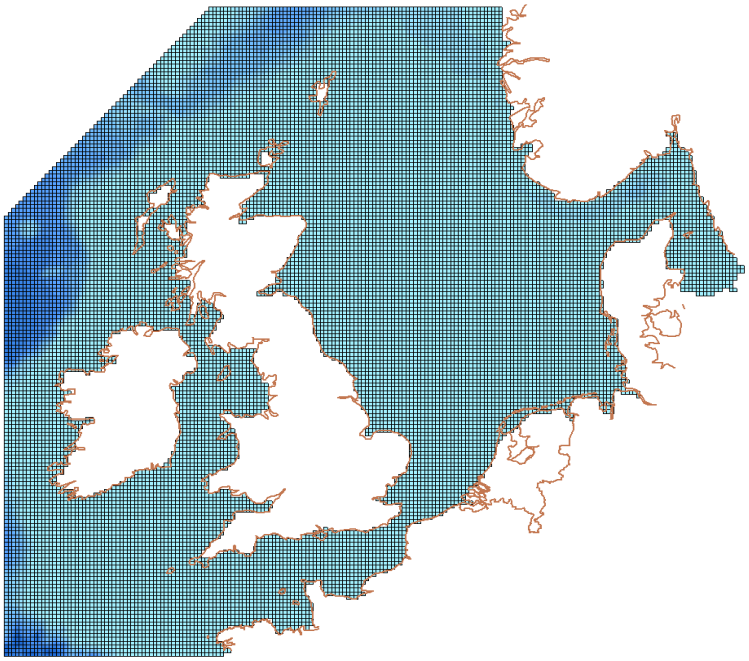

Figure 2.15 Domain and grid of the Continental Shelf Model

The rivers included in the Continental Shelf Model and the estimated current annually averaged discharges are compiled in Table 2.2. We note that these are not all North Sea rivers; some of them discharge into the Channel, the Atlantic and the Irish Sea.
Annually averaged river SPM concentrations have been derived from van Kessel et al. (2010). The emissions of selected chemicals have been estimated based on data collected by van Gils (2007; 2008, and references therein).

Table 2.2 Continental Shelf Model present average river discharges

River	m^3/s	River	m^3/s	River	m^3/s
01 Aulne	19	16 Baltic Sea	14490	31 Tweed	74
02 Vire and Orne	65	17 Gota (Goteborg)	531	32 Firth of Forth	88
03 Seine	461	18 Glomma + other	1117	33 Firth of Tay	214
04 Somme	26	19 Firth of Clyde	169	34 Spey	64
05 IJzer + other	20	20 Lyne (Carlisle)	30	35 Inverness Firth	152
06 Schelde	176	21 Lune (Lancaster)	31	36 Corrib	110
07 Haringvliet	969	22 Mersey (+ Dee)	84	37 Shannon	180
08 Nieuwe Waterweg	1597	23 Neath (Swansea)	37	38 Lee (Cork)	39
09 Noordzeekanaal	80	24 Severn	131	39 Blackwater	77
10 IJsselmeer	112	25 Tamar (Plymouth)	45	40 Dublin	34
11 Lauwersmeer	40	26 Exe	41	41 Foyle	49
12 Ems	120	27 Thames	68	42 Sligo Bay	90
13 Weser	536	28 Wash	48	43 Fergus	90
14 Elbe	864	29 Humber	246		
15 Skjern	14	30 Tyne	65		

3 Results

3.1 Climate change induced changes in the river Hydrology

The changes of the river discharges to the North Sea due to climate change have been estimated as discussed in Section 2.2. On the scale of the North Sea as a whole, the predicted change of the average discharge depends on the selected Global Climate Model (GCM) that drives the global hydrological model (as illustrated by Figure 2.3, for climate scenario A2). For the climate scenario A1b (selected as the standard scenario for DiPol), the two selected GCMs produce relatively small estimated changes of +1% and +6% respectively (Table 3.1). For the Baltic Sea the change is larger: of +18% and +23% respectively. For the North Sea as a whole, most GCMs and both selected models in particular show a distinct change of seasonal patterns: with increasing winter run-off and decreasing summer run-off (Figure 3.1, Figure 3.2).

Table 3.1 Projected changes of annually averaged river inflows due to climate change (scenario A1b, year 2050)

Change of annually averaged fresh water inflows	North Sea	Baltic
Global hydrology model driven by ECHAM5 GCM	+1%	+18%
Global hydrology model driven by CGCM3.1 GCM	+6%	+23%

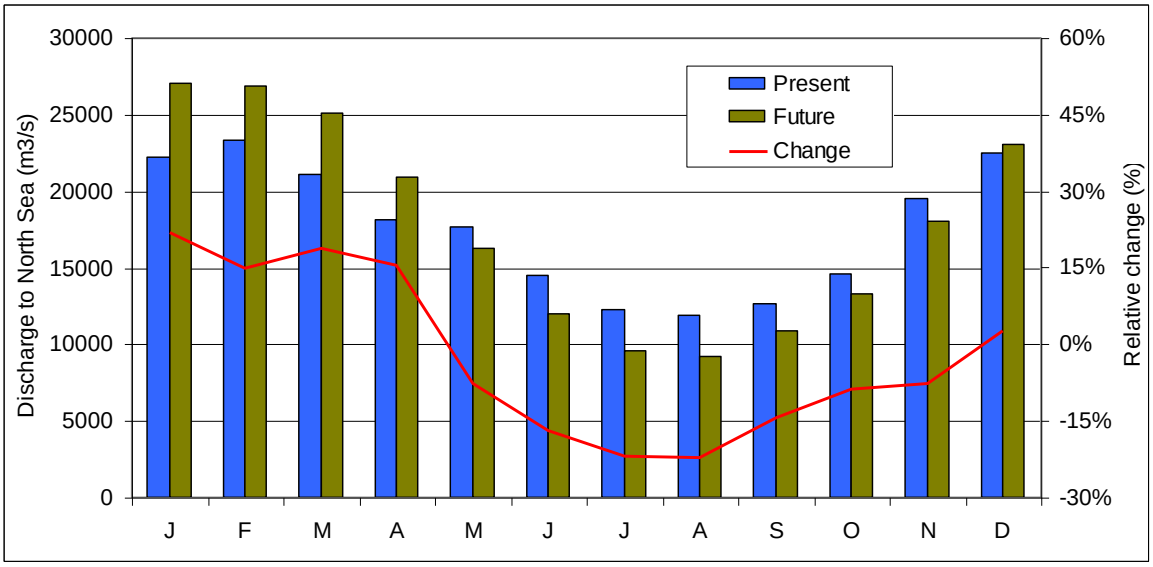

Figure 3.1 Estimated seasonal changes of the river discharges to the North Sea and the Baltic according to Scenario A1B (global hydrology model driven by the ECHAM5 model from the Max Planck Institute)

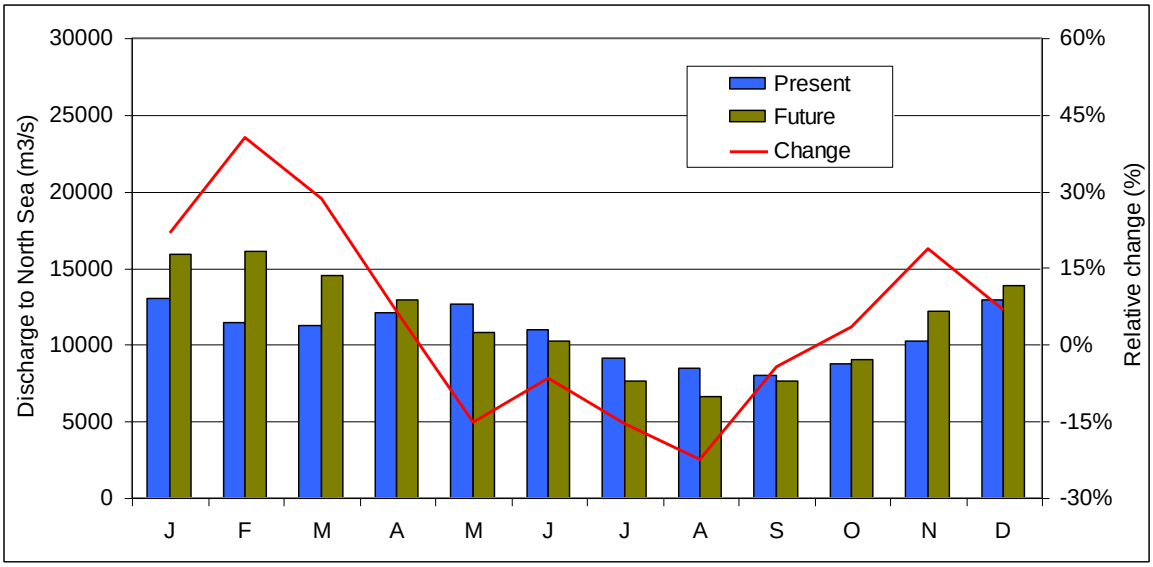

Figure 3.2 Estimated seasonal changes of the river discharges to the North Sea and the Baltic according to Scenario A1B (global hydrology model driven by CGCM3.1 GCM from the Canadian Centre for Climate Modelling and Analysis)

If we consider individual rivers, the different GCMs provide strongly variable estimates of the impact of climate change on the annually averaged river discharge. Figure 3.3 illustrates this variability: the CGCM3.1 based results anticipate a strong increase for the Weser and no increase for the Glomma, where the ECHAM5 based results indicate the opposite.

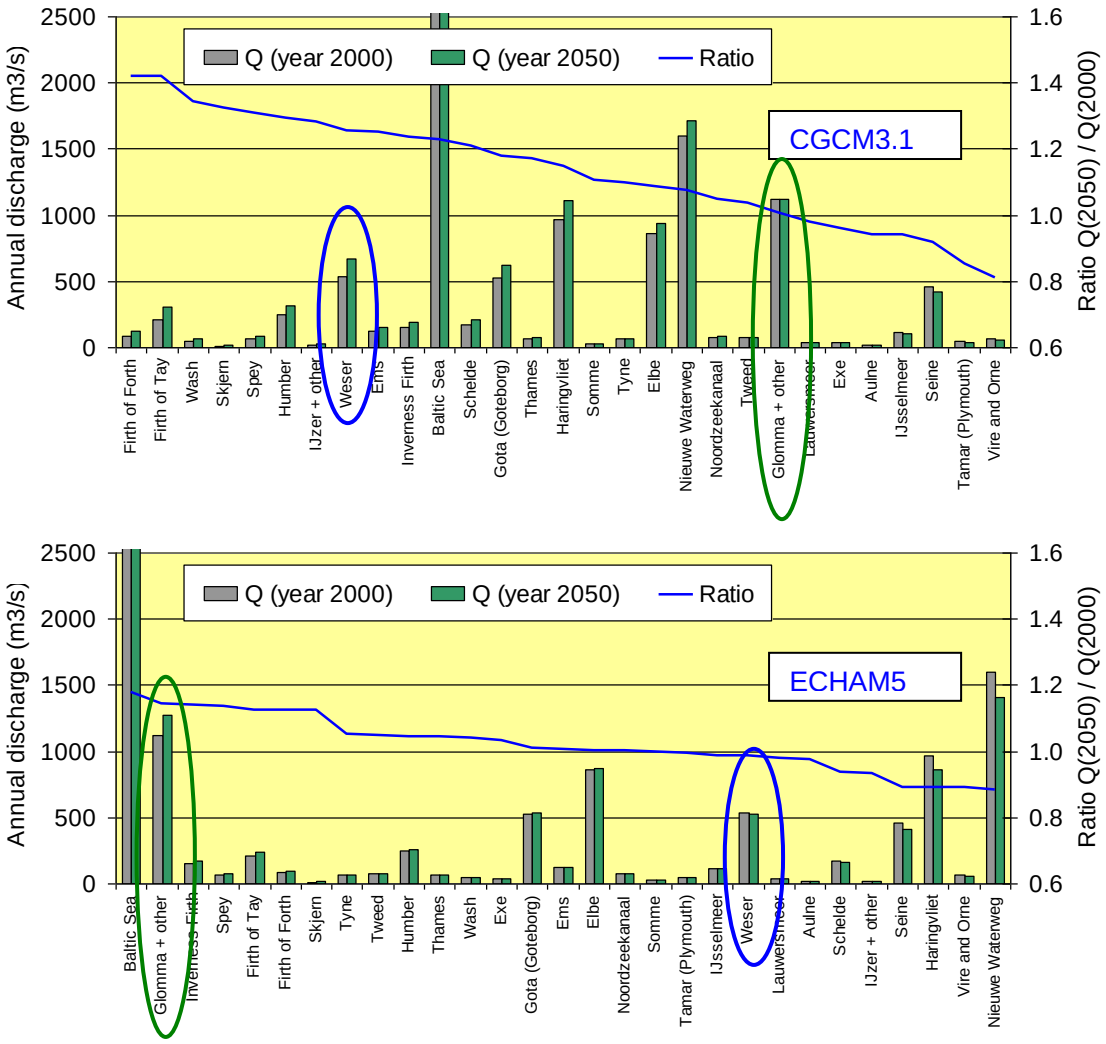

Figure 3.3 Illustration of variability of predicted change of annual discharge for individual rivers: CGCM3.1 based results (top) anticipate a strong increase for the Weser (blue ellipse) and no increase for the Glomma (green ellipse), where ECHAM5 based results (bottom) predict a strong increase for the Glomma (green ellipse) and a small decrease for the Weser (blue ellipse).

3.2 Climate change induced changes in the river SPM loads

The changes of the river SPM loads to the North Sea due to climate change have been estimated as discussed in Section 2.3. On the scale of the North Sea as a whole, the predicted change of the river SPM loads depends on the selected Global Climate Model (GCM) that drives the global hydrological model. Apart from that, we use two alternative approaches to estimate these changes: one based on sediment rating curves and one based on a global assessment by Syvitsky et al. (2003). For the latter approach we present estimates without accounting for temperature changes, and estimates accounting for a temperature increase of 1 ºC and 2 ºC respectively.For the climate scenario A1b (selected as the standard scenario for DiPol), the selected approaches and GCMs produce projected changes of the river SPM load towards the North Sea in the range of 1%-20% (Table 3.2). We note that the individual estimates are all highly uncertain, but they indicate that the

expected change of the river SPM loads is positive (increase), which may be larger than the expected increase of the annually averaged river discharges. For reference, Figure 3.4 and Figure 3.5 show the expected increase of the SPM loads per river as calculated by the sediment rating curve method.

Table 3.2 Projected changes of annually averaged river SPM loads due to climate change (scenario A1b, year 2050)

Change of annually averaged river SPM loads	**Sediment Rating Curve**	**Syvitski approach** (ΔT = 0ºC)	**Syvitski approach** (ΔT = 1ºC)	**Syvitski approach** (ΔT = 2ºC)
Based on ECHAM5 GCM	+6%	+1%	+6%	13%
Based on CGCM3.1 GCM	+17%	+6%	+13%	+20%

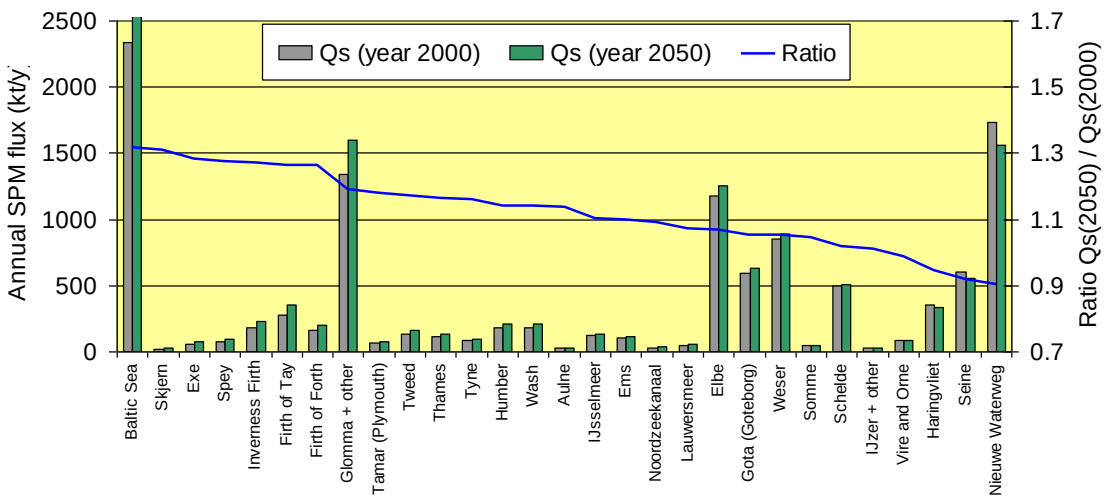

Figure 3.4 Estimated change of annual SPM load of North Sea rivers using sediment rating curves, according to Scenario A1B (global hydrology model driven by the ECHAM5 model from the Max Planck Institute)

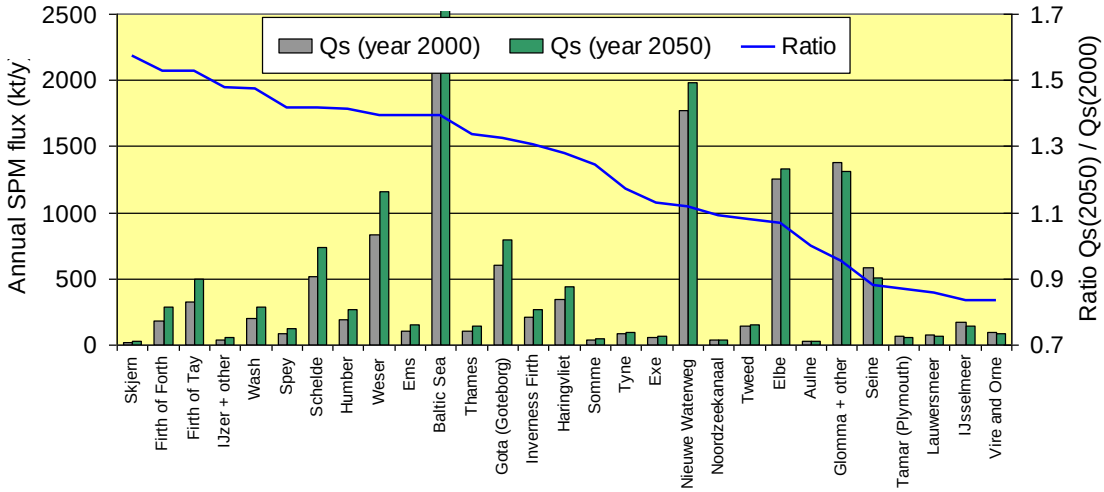

Figure 3.5 Estimated change of annual SPM load of North Sea rivers using sediment rating curves, according to Scenario A1B (global hydrology model driven by CGCM3.1 GCM from the Canadian Centre for Climate Modelling and Analysis)

On the basis of the available GCM results, we investigated if there is an expected trend towards more extreme years. Also in this case, the results depend on the GCM chosen. Table 3.3 demonstrates that one of the two GCMs results in a substantially higher standard deviation of the annual discharges and SPM loads. This implies that there is a larger variability and a higher chance of relatively high or relatively low annual discharges and SPM loads. The other GCM however, results in a lower standard deviation, and does not support this trend towards more extreme years.

Table 3.3 Simulated variability of river discharge and river SPM loads (control experiment 1970-1990 vs. scenario A1b, year 2050)

Standard deviation of annually averaged quantities	**Discharge (m3/s)**		**SPM load (kg/s)**	
	1970-1990	2050 (A1B)	1970-1990	2050 (A1B)
Global hydrology model driven by ECHAM5 GCM	777	1136	43	65
Global hydrology model driven by CGCM3.1 GCM	960	861	56	55

3.3 Climate change induced changes in the river contaminant loads

As discussed in Section 2.4, the impact of climate change on the river loads of chemicals depends on the SPM loads, but also on the quality of SPM at high discharges. The only data set that we are aware of that allows (to some extent) a systematic analysis of this relation is the existing data set for the Rhine River at Lobith and for the Meuse River at Eijsden. Figure 3.6 shows the concentrations of copper and benzo[*a*]pyrene in SPM as a function of the river discharge. The data have been obtained from Rijkswaterstaat and originate from the period 1996-2009. Because Figure 3.6 shows a lot of scatter, Figure 3.9 shows the same data but this time with all SPM quality data within certain discharge intervals averaged to one value. For the River Rhine, discharge intervals of 500 m^3/s have been selected, while for the River Meuse the intervals were 100 m^3/s. Figure 3.7 also shows the 1/10 year discharge and the 1/100 year discharge. We note that the available data cover a discharge range up to 1/100 years for the Rhine River and up to 1/10 years for the Meuse River.

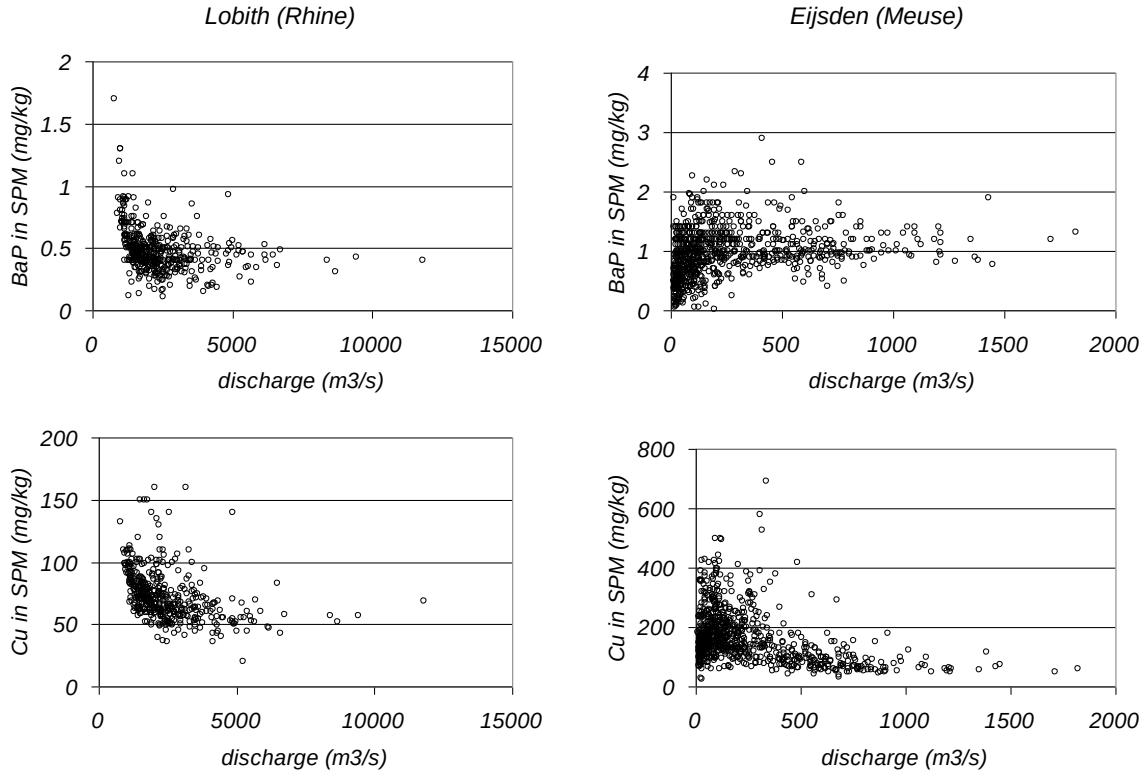

Figure 3.6 The quality of SPM at Lobith (Rhine River, left)) and Eijsden (Maas River, right): the concentrations of copper (bottom) and benzo[a]pyrene (top) as a function of the river discharge. Data have been obtained from Rijkswaterstaat and originate from the period 1996-2009.

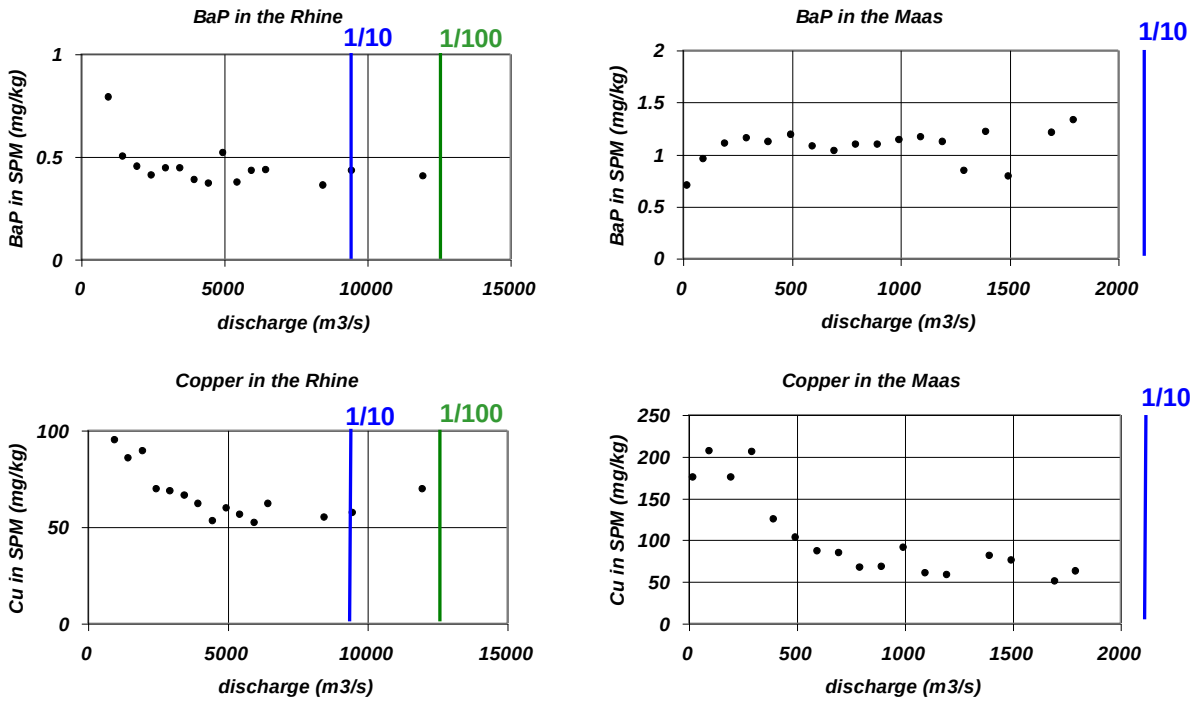

Figure 3.7 Average quality of SPM at Lobith (Rhine River, left)) and Eijsden (Maas River, right) per discharge class: the concentrations of copper (bottom) and benzo[a]pyrene (top).

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Looking at the high discharge range, Figure 3.6 and Figure 3.7 demonstrate that the quality of SPM does not seem to improve with increasing discharge: the “dilution model” (Figure 2.6) does not seem to apply. On the basis of the available data, it is hard to say whether “model A” or “model B” (Altlasten) is the more appropriate one. We note that data for many more substances than the two presented above are available. For most substances that are of a mostly anthropogenic nature, the results are very similar.

The expected increase of the river SPM loads due to climate change is expected to lead to a proportional increase in the contaminant loads. Potentially, the increase will be stronger, as a result of the mobilisation of historically polluted sediments.

3.4 Estuarine retention

Figure 3.8 presents a conceptual model of a temperate estuary (Fisher et al., 1988). According to Eyre (2000), a key feature of such an estuary is the reasonably constant freshwater supply, though the discharge generally increases in late winter and peaks in spring due to snow melt. Temperate estuaries are typically stratified for much of year due to the reasonably constant freshwater supply, primary physical forcing a two-layer circulation which promotes the retention of sediment and sediment associated chemicals. A turbidity maximum develops in the oligohaline region where salt and freshwater mix, due to the flocculation of river SPM. Temperate estuaries show a strong retention of sediment and associated chemicals on the way from river cities to coasts. The question arises what the changing seasonal patterns due to climate change will do with these temperate estuaries. Eyre (1998) suggests that temperate estuaries may be moving closer to “Mediterranean” estuaries.

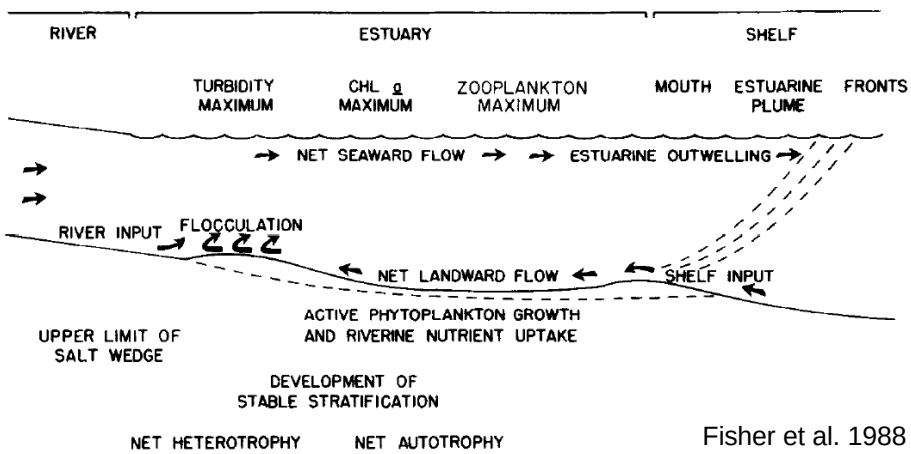
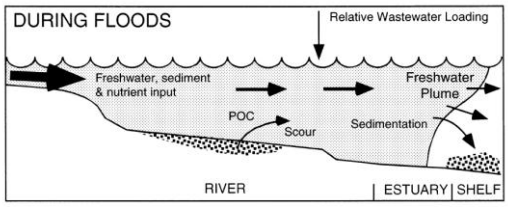
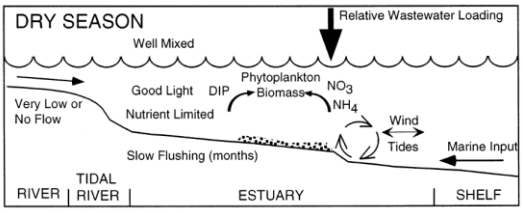


Figure 3.8 A conceptual model of Temperate Estuarine Processes (Fisher et al., 1988).

Table 3.4 provides an overview of the functioning of a Mediterranean estuary under flood and drought conditions respectively. The river particle loads and the loads of SPM and associated chemicals are transported almost exclusively under flood conditions. If we assume that the North Sea estuaries will move to a more Mediterranean state, the processes described in Table 3.4 will lead to a substantial reduction of the retention of SPM and associated chemicals in the estuaries as a result of climate change.

Figure 3.9 A Mediterranean estuary: the Llobregat River near Barcelona (Spain)

Table 3.4 Description of a "Mediterranean" estuary during floods and droughts respectively.

Floods ***Freshwater-dominated state***	***Droughts*** ***Marine water-dominated state*** ***Sealevel rise***
• high flushing rates • change in loads • seaward shift of turbidity cloud • scouring of benthic sediments/associated chemicals • remobilization of sediments • decrease of estuarine retention	• low flushing rates • change in loads • landward shift of turbidity cloud • loss of stratification • higher residence times • sedimentation
	

3.5 Scremotox

The original objective of this work was to show the (relative) contribution of diffuse sources of pollution to coastal water quality on the scale of the North Sea, and to show the impact of climate change in this context. The sections above have shown that solid quantitative projections on the scale of the North Sea as a whole for the situation under the influence of climate change are not available. For this reason, we were forced to abandon the second objective and carried out Scremotox simulations for the present situation only.

The Scremotox model for the whole North Sea has been used to show the approximate annually averaged concentrations of a typical particle-associated chemical, benzo[*a*]pyrene for the year 2005. The results (Figure 3.10) show that the highest concentrations are found where larger rivers flow out in shallow and/or semi-enclosed coastal areas (Elbe, Rhine-Meuse). In other areas, the river impact is only local, and not resolved by this coarse North Sea scale model. The Scremotox model has also been used to trace back the concentrations

in the North Sea to various pollution sources: (a) rivers, (b) atmosphere, (c) off-shore oil and gas production, and (d) shipping. The results show the dominance of the rivers near land and atmospheric deposition farther away from land. The other sources play a minor role (note the different colour scales used in Figure 3.10.

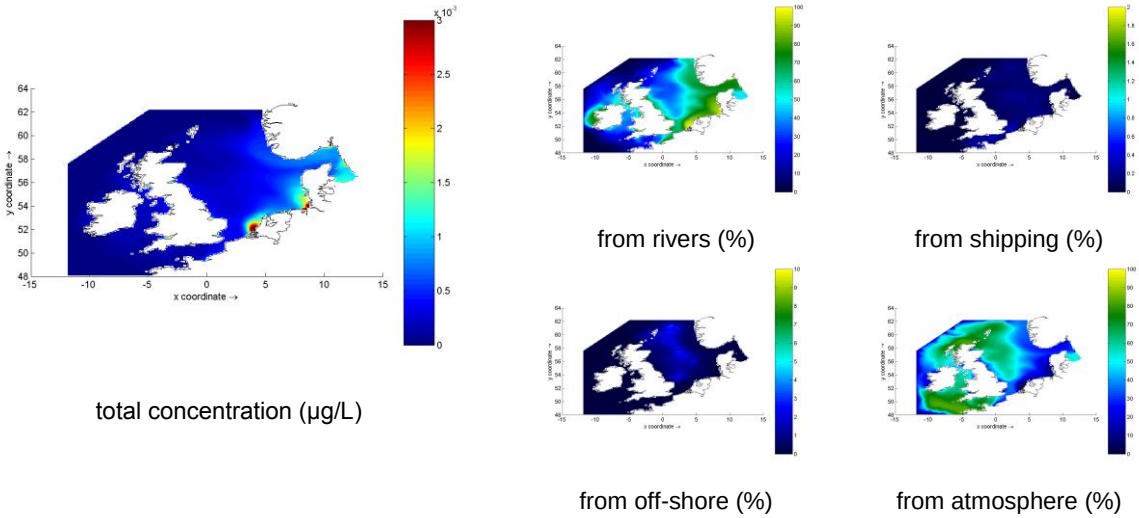


Figure 3.10 Simulated concentrations of Benzo[a]pyrene in the North Sea, based on the available emission data for 2005 (left) and the relative contribution of different emission types to the local concentrations (right).

Similar results are shown for cadmium in Figure 3.11 and tributyltin in Figure 3.12. These chemicals show a substantially different relative contribution of the different sources. For cadmium, the rivers are the dominant source, while for tributyltin shipping is the dominant source. We note that the results presented here are valid for the North Sea only. Towards the model boundaries and in other seas (e.g. the Irish Sea) the results are affected by boundary effects or missing data.

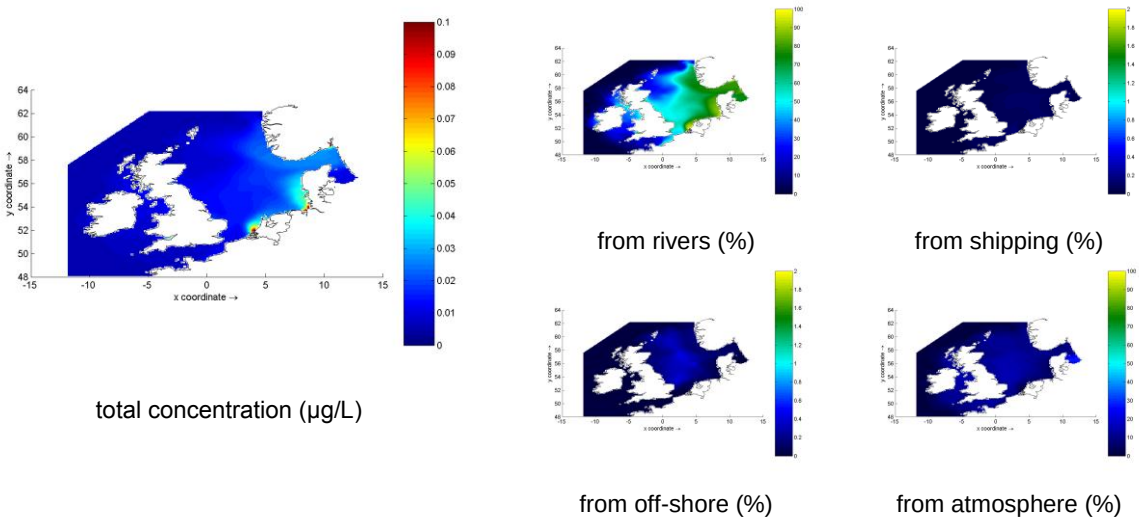
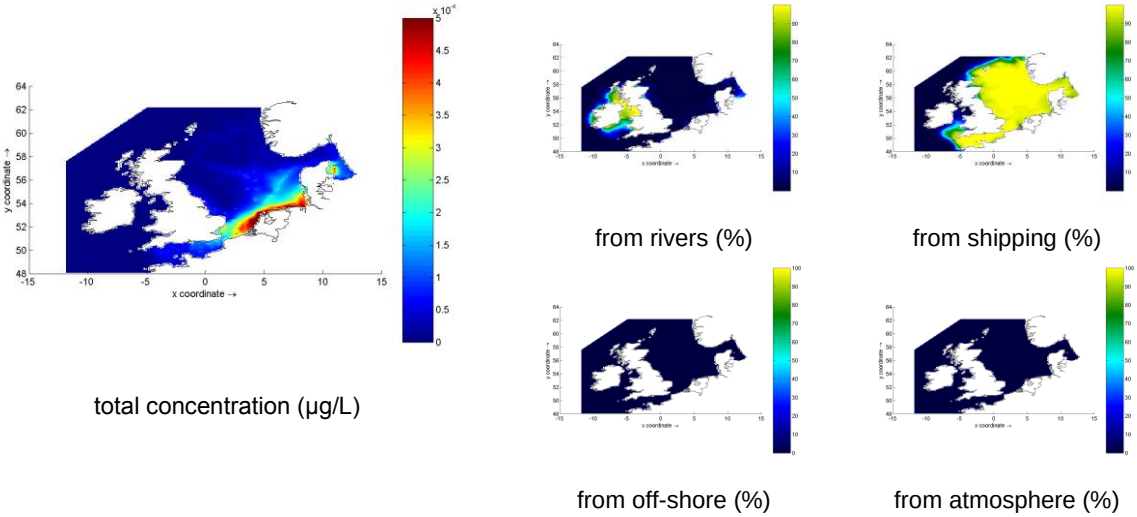


Figure 3.11 Simulated concentrations of cadmium in the North Sea, based on the available emission data for 2005 (left) and the relative contribution of different emission types to the local concentrations (right).



total concentration (µg/L)

Figure 3.12 Simulated concentrations of tributyltin in the North Sea, based on the available emission data for 2005 (left) and the relative contribution of different emission types to the local concentrations (right).

4 Synthesis

The assessment of the impact of climate change on diffuse pollution on the scale of the North Sea has been carried out by a methodology outlined in Section 2. The focus has mostly been on diffuse pollution from particle bound chemicals carried by the rivers draining into the North Sea. The assessment has been made in a quantitative way as much as possible, using for example the outcome from a Global Hydrological Model driven by different Global Climate Models, and a database of the measured quality of suspended solids dependent of the river flow. The results have been presented in Section 3, and are summarised in a qualitative way in Figure 4.1.

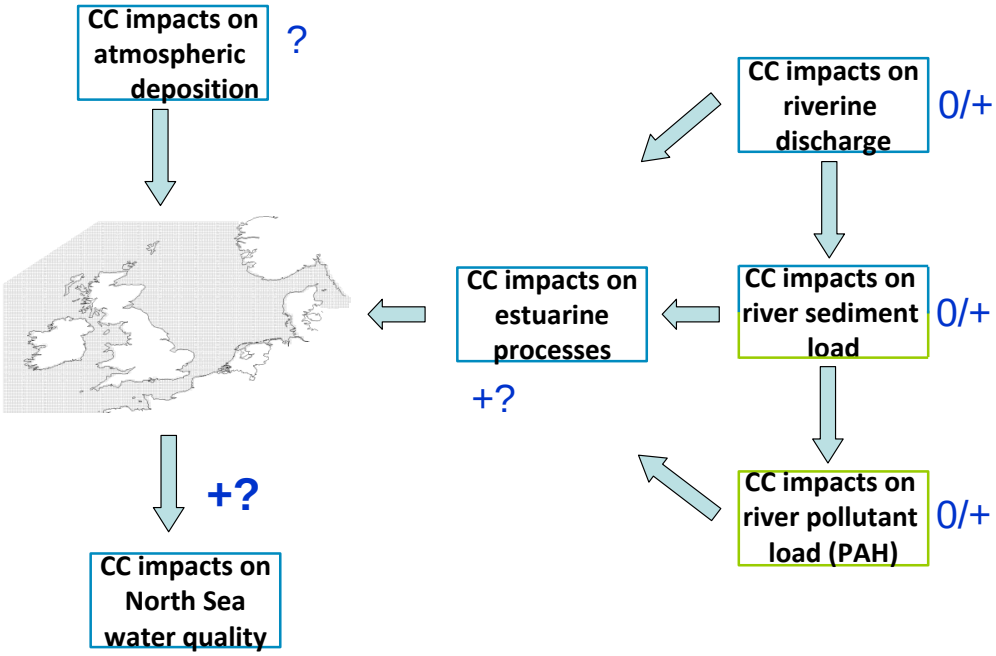


Figure 4.1 Qualitative overview of climate change impacts on the North Sea water quality affected by diffuse pollution

We conclude that there are reasons to be conscious of a possible climate change induced increase of (sorbed) chemicals run-off from rivers into the sea. However, there is no solid evidence of this process, in view of the uncertainty in the forecasted impacts of climate change on the river hydrology, on the river sedimentology and the changes in the estuaries along the North Sea's flat coasts. The possible increase of (sorbed) chemicals run-off from rivers into the sea will be associated to events, and on average it will not be a major change. More "event" water quality data are needed to improve insights (and have actually already been collected within DiPol during the 2011 Elbe flood). Monitoring long term changes of the sediment and biota quality in coastal lagoons could be a feasible way to implicitly measure the possible impact from events. We recommend such monitoring to be included in the management plans developed for the Water Framework Directive (WFD) and the Marine Strategy Framework Directive (MSFD).

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