Adapting to sea-level rise in the Netherlands

Journal:	*Wiley Interdisciplinary Reviews: Climate Change*
Manuscript ID:	draft
Wiley - Manuscript type:	Focus
Date Submitted by the Author:	
Complete List of Authors:	Kwadijk, Jaap; Deltares Haasnoot, Marjolijn; Deltares Mulder, Jan; Deltares; University of Twente, Water Engineering and Management Hoogvliet, Marco; Deltares Jeuken, Ad; Deltares Krogt, Rob; Deltares Oostrom, Niels; Deltares Schelfhout, Harry; Deltares Velzen, Emiel; Deltares Waveren, Harold; Rijkswaterstaat, Waterdienst Wit, Marcel; Deltares
Keywords:	Adaptation, Coastal squeeze, Tipping point, Flood defense, Fresh water supply

Article type: Focus Article

Adapting to sea level rise in the Netherlands

Jaap C.J. Kwadijk, jaap.kwadijk@deltares.nl Deltares
Marjolijn Haasnoot, marjolijn.haasnoot@deltares.nl Deltares
Jan P.M. Mulder, jan.mulder@deltares.nl Deltares and University of Twente
Marco M.C. Hoogvliet, marco.hoogvliet@deltares.nl Deltares
Ad B.M. Jeuken, ad.jeuken@deltares.nl Deltares
Rob A.A. van der Krogt, rob.vanderkrogt@deltares.nl Deltares
Niels G.C. van Oostrom, niels.vanoostrom@deltares.nl Deltares
Harry A. Schelfhout, harry.schelfhout@deltares.nl Deltares
Emiel H. van Velzen, emiel.vanvelzen@deltares.nl Deltares
Harold van Waveren, harold.van.waveren@rws.nl Ministry V&W / RWS Waterdienst
Marcel J.M. de Wit, marcel.dewit@deltares.nl Deltares

Keywords

sea level rise, adaptation, tipping point, flood defense, fresh water supply

Abstract

Studies on the impact of climate change and sea level rise usually take climate scenarios as their starting point. To support the Netherlands long term water management planning we carried out a study that started at the opposite end of the effect chain. We examined whether, and for how long, current water management strategies will continue to be effective under different climate changes. We do this by adopting the concept of “adaptation tipping points”, reached if the magnitude of change is such that the current management strategy can no longer meet its objectives. Beyond the tipping points an alternative, adaptive, strategy is needed. By applying this approach we answer the basic questions of decision makers *what* are the first issues that we will face as a result of climate change and *when* can we expect this.The results show, for instance, that climate change and the rise in sea level are more likely to cause a threat to the fresh water supply in the West of the Netherlands than to cause a threat from flooding. Our experience is that expressing uncertainty in terms of the period that the existing strategy is effective (when will a critical point be reached), appears more understandable for the policy maker/ water manager/ stakeholder, than plots showing a certain percentage of change in a certain projection year. We considered therefore the approach as practical to ease the dialogue between scientific and water management world.

Adaptation of the water management of the Netherlands to climate change and accelerated sea level rise became a policy issue with the publication of the Fourth National Policy Document on Water Management [1]. In 2001 the Commissie Waterbeheer 21e eeuw proposed three climate scenario's, a Lower, a Central and an Upper estimate [2,3], that could be used to design adaptation strategies. In a formal agreement [4] the water management community agreed to adopt, not surprisingly, the Central scenario to develop a series of adaptation measures. However, only four years later a new generation scenarios was provided [5], based on new insights from the IPCC 4th assessment [6]. These showed a much wider range of possible climate changes. The new scenarios resulted in two important issues for water managers, namely:1) the measures designed and formalized agreements between different administrations appeared to be insufficient already four years later, and 2) a central scenario was lacking as there were four provided. This experience put us on the track to shift to an alternative approach to support the Netherlands water management to prepare for adaptation to climate change and sea level rise.

Two basic approaches are used to support climate adaptation policy. The predictive top-down approach and the resilience bottom-up approach [7]. The top down approach is the most widely applied. The examples mentioned in the IPCC WGII chapter 17 [8] follow this approach. Climate scenario's play a key role in this approach as they form the starting point to prepare adaptation strategies.

Bottom-up approaches focus on risk management by examining the adaptive capacity and adaptation measures required to improve the resilience and robustness of a system exposed to climate change [9]. A successful example is the Thames 2100 study in which a bottom up approach has been used to identify flood defense measures along the Thames and prepare a flood defense plan in order to delay the replacement of the Thames storm surge barrier as long as possible [10]. However, not all studies are positive on the application of bottom-up approaches. Some conclude on the applicability of this approach that the time of the assessments is too long and the system that is described is too complex for a proper comparison of all the drivers. They conclude that *"vulnerability assessment often promises more certainty, and more useful results, than it can deliver"* [11, page 411].

In order to reduce the complexity of the bottom-up approaches and make them more applicable for decisions in water management adaptation, in our study we adopted the concept of "adaptation tipping point (ATP)". In the following sections we elaborate on the approach and illustrate ATP's from a historical perspective. Successively we will identify ATP's in the Netherlands water management system that may be reached in the near future due to climate change.

Adaptation tipping points

In climate change research literature the term tipping point is introduced to indicate the point where a system change initiated by an external forcing, no longer requires the external forcing to sustain the new pattern of change [12, 13, 14]. An example is the irreversible decay of the Greenland ice sheet [15]. In a slightly different sense, the concept also plays a role in GHG emission policy to set a standard for GHG reductions. The reductions should be such that the global temperature rise at the end of this century should not exceed 2 degrees Celsius. Although many reviews in the scientific literature [16,17,18] suggest that 2℃ cannot be regarded as harm-free or 'safe', beyond this limit, many believe that the behaviour of system earth will approach 'terra incognita" and might lead to dangerous impacts [19]. Plus 2 degrees Celsius as an adaptation tipping point, is also adopted as a long-term EU climate target of limiting the global mean temperature in 1996, and recently (March 2005) reconfirmed by the European Council (1996; 2005).

We have evaluated the water management sector in the Netherlands. Points where the magnitude of change due to sea level rise is such that the current strategy no longer will be able to meet the objectives, have been defined as “adaptation tipping points (ATP’s)”. The analysis has started from the perspective that the Rhine Meuse delta provides the natural boundary conditions for living and working in this region, summarized as the boundary conditions for socio-economic activities. We need to manage the system to maintain the proper conditions and achieve our objectives for living in the delta. In climate change communication, the use of tipping points often illustrates “points of no return” [20,14]. Note that exceeding our adaptation tipping points does not mean that water management is not possible anymore and that we might face catastrophic consequences. It simply means that we need alternative strategies to manage the system. From this viewpoint adaptation to climate change in itself has no value; we only do this to sustain our activities and preserve ecological values. Climate change only becomes interesting if it would lead to other decisions about our strategies. In other words, the driver for taking action is not climate change, but failing to meet the objectives. Reaching ATP’s might have natural, technical, socio-economical or political causes [21]. Therefore climate change should be considered as one of the issues(not necessarily *the* issue) to take into account in strategy development [e.g. 22, 23].

Approaches to identify the need for adaptation measures

In the classical ‘top down’ approach to climate adaptation (see figure 1; left panel), the underlying question is: *What if climate changes or sea level rises according to a particular scenario?* This is followed by analyzing the cause-effect chain from pressures to impact (the PSIR concept [24]). If the impact is such that policy objectives are not achieved, adaptation measures are defined to overcome this problem. Then the chain is analysed again, answering the question: *What if this particular scenario becomes reality and we implement measure x, are the objectives then achieved?*.

In the adaptation tipping point approach (see figure 1; right panel) the underlying question is: *How much climate change and sea level rise can the current strategy cope with*? and the analysis starts at the other end of the cause-effect chain. Policy objectives for different sectors and areas (determining the maximum allowable Impact) are taken as a starting point. Then, the current measures to achieve these objectives are described. This is followed by a sensitivity analysis to determine the optimal and critical boundary conditions (State). E.g. for navigation water depth is an important boundary condition. A water depth of > 4 m results in optimal conditions, while at lower water levels the suitability of the river gradually decreases to a critical minimum where no shipping is possible anymore. The State of the water system described in terms of relevant boundary conditions, can be related to Pressures in terms of climate and sea level. To do this, sometimes intermediate steps are needed. For example in case of river navigation, water depth needs to be related to river discharges.

Then, ATP’s in water management are the specific boundary conditions where technical, economic, spatial or societal acceptable limits are exceeded. The moment in time when an ATP will occur according to different scenario’s, defines the moment that alternative adaptation measures will be needed

Figure 1

Classical ‘top down’ approach and Tipping point approach to develop adaptation measures

Historical adaptation tipping points in the Rhine-Meuse delta

The long-term development of a low-lying deltaic area like the Netherlands (Fig. 2) , is determined by a delicate balance between demand and supply of sediments [see e.g. 25]. This delicate balance may provide a system tipping point in deltaic formation [e.g. 26]. Sediment-demand is depending on the change in hydraulic boundary conditions (like for instance a rise in sea level) and on the initial topography of the coastal area, that together determine the (potential) accommodation space for sedimentation. Sediment-supply is depending on the availability of sediment resources and on the transport capacity of the hydro- and aerodynamic forces within the system. The coastal evolution of the Netherlands during the Holocene illustrates the role of the sediment balance [see 27, 28, 29]. During periods with a negative sediment balance, the coast is retreating; when the balance is positive, the coast is extending. A lack of sediment-supply is responsible for the retreating trend of the coast during the last centuries.

Figure 2

The Rhine - Meuse delta

Through time, man has applied different strategies to cope with the ever changing physical conditions in the low lying grounds of the Netherlands. The history of human occupation of the country shows examples [e.g 30, 31,32].

From ca. 2500 BP artificial dwelling mounds have been built in the northern, 'swampy' part of the country, in response to a rising sea level causing more frequent flooding. In fact this might be considered as a first major adaptation tipping-point in occupation strategies: active interference with the physical conditions raising ground levels.

The era of water management started around 1200 – 1000 BP, when population increased and dwelling mounds became too small to accommodate the people. In parallel, agriculture more and more became an important activity. Techniques had been developed draining the extensive peat areas in order to create agricultural land. Around 800 BP another major adaptation tipping point was passed, when the development started of dike systems and active drainage by pumping. During the following centuries this system of water management has been optimized by successive technical (organizational and financial) innovations.

A more recent major adaptation tipping point was reached towards the end of the last century. The Eastern Scheldt storm surge barrier, final piece of the Delta Project protecting SW Netherlands against flooding, originally designed as a pure flood defense structure, developed into an integrated design. An increased ecological awareness and social - and political pressure resulted in the decision for an open barrier, not only serving safety against flooding but also ecological values and shell fisheries interests. The integrated approach that has been developed to achieve this, had to consider the entire estuarine system. During this proces the importance of the sediment balance for long-term morphodynamic boundary conditions, gradually became apparent [33, 34].

In 1990 this has resulted in a strategy change, when in the Netherlands a coastal policy was adopted based on the principle of Dynamic Preservation of the sediment balance [35]. Sand nourishments to an amount proportional to the yearly sediment deficit, must guarantee to achieve the objective [36]. Since 2000 the yearly nourishment volume is 12 Mm^3.

Available data, information and tools

To identify the effects of climate changes and sea level rise on the Netherlands water management system, simulation models are needed. To support the water management design in the Netherlands, a great number of models, tools and studies are available. The results of simulations of studies using these hydrological, hydraulic, morphodynamic, ecological and impact models are used to determine the sensitivity of different sectors and associated objectives, to sea level rise and climate change. The main available tools are very briefly described here. It is however beyond the scope of this paper to describe these systems in more detail.

To investigate morphological behaviour of the coast on the large scale associated with climate change, a large scale model of the Netherlands coastal system has been developed, based on a combination of different model concepts [37, 38, 39, 40, 41, 42, 43, 44]. Sediment balance studies of the system have been based on the national database for geological data and the geological mapping programme of Deltares / Geological Survey of the Netherlands [29]. In addition, for the active subsystems of the coast, bathymetric data have been used from the data base on bed level monitoring of Rijkswaterstaat, dating back to beginning of the 20th century [45].

For the rivers and estuary, the tools include a hydrological-hydraulic system to simulate river discharges in the Rhine and Meuse basins [46, 47] as well as a weather generator to allow for generating synthetic discharge series [48]. A hydraulic modelling system allows for simulating water levels as well as water quality in the South West estuaria and tidal areas [49, 50]. In the tidal area the assessment of the water levels and salt intrusion was carried out by executing a Monte Carlo experiment using this 1-D hydrodynamic model with different sea levels and upstream boundary conditions. A national groundwater and water distribution model is used to estimate effects on groundwater, agriculture and water level management of lakes and small ditches [51, 52,53]. An ecological model is used to assess effects on the availability and quality of habitats [54].

Climate change projections for the Netherlands based on the IPCC 2007 4th assessment [6] are published by [5]. High-end scenarios, beyond the range the IPCC provides are published by [55]. We used these projections to determine the trends (Table 1). Through a linear interpolation in time we used these scenarios to assess the earliest and latest date that a strategy is no longer effective. These changes were applied in the simulations by the various modelling systems

Table 1

Maximum climate change and sea level rise scenarios for 2100:

(1) KNMI-G scenario (moderate change) for 2100 [see 5];

(2) KNMI-W+ scenario (large temperature and circulation change over Europe) for 2100 [see 5];

(3) High-end Sea level rise scenarios for 2100 [see 55].

	smallest		largest	
	winter	summer	winter	summer
Temperature change	+1.8 (1)	+1.8 (1)	+4.6 (2)	+5.6 (2)
Rainfall change	+8% (1)	+ 6% (1)	+28% (2)	-38 % (2)
Evaporation change	0% (1,2)	+6% (1)	0% (1,2)	+30% (2)
Sea level rise	30 cm (1)	30 cm (1)	105 cm (3)	105 cm (3)

Identifying adaptation tipping points in current water management

As typical examples of the evaluation results of current water management in the Netherlands, we will focus on flood defense, on the protection of Rotterdam Harbour and on fresh water supply.

Flood defense

To ensure safety against flooding, safety levels for all flood defenses in the Netherlands, including the dunes, have been established by law [56]. Coastal dunes must be able to withstand a storm event with a certain probability of exceedance. This probability of exceedance should be 1 in 10,000 years for the Holland coast, and between 1 in 4,000 and 2000 years for the Delta coast and Wadden islands. For dikes along the tidal rivers in the western part of the country, the probability of exceedence should be between 1 in 2,000 and 1 in 4000 years (Fig. 3).

Figure 3

Flood safety standards in the Netherlands

Additionally, for the coast the Water Act prescribes the preservation of the coast line at its 1990 position. The latter requirement enables to maintain morphological boundary conditions for dune growth, and as such the sustainable preservation of safety levels. Preservation of the sand balance by sand nourishments, started in 1990 and has shown to be effective at the present rate of sea level rise [36, 57].

For the coast, an increase in sea level rise might be compensated by a proportional growth of the yearly nourishment volume. An increase in rise from the present 2 mm/year to between 3.5 and 10.5 mm/year until 2100, would require a sand volume of 25 to 74 Mm3/year (i.e between double and sixfold the present yearly amount). Technically and financially this is regarded to be feasible. Nourishments have been politically and socially accepted. Sand resources in the North Sea are abundant. Spatial reservations for future sand mining purposes must be able to safeguard ample availability. Optimization of both sand mining and nourishment, must be able to meet ecological requirements. Conclusion: even in the most extreme sea level rise scenario, the existing policy of protecting the sandy coast is not likely to encounter an ATP.

For dikes along the tidal river area in the western part of the country, technically and financially, no major adaptation tipping points are expected. Dike reinforcements and innovations must be able to cope with more severe hydraulic boundary conditions; expenses will grow, but remain feasible. Potential adaptation tipping points might arise on the social- and political level. Social acceptability of living behind giant dikes might decline. Increasing spatial claims of ever larger dikes, might invoke innovations in governance arrangements.

Protection of Rotterdam Harbour

The Maeslant Barrier (Fig. 4) is essential in the protection of the Rotterdam harbour and tidal river area against flooding. In this region the levees are designed to withstand water levels that have a probability of occurrence between 1/10000 and 1/4000 annually. To meet this safety level, the barrier closes if the water level at the outlet of the Waterway exceeds 3m or exceeds 2.90m upstream at Dordrecht. The return period of such an event is approximately 10 years. Rising sea level implies that the barrier will close more often. However, closing the Maeslant Barrier hinders navigation to and from the Rotterdam Harbour. According to the Rotterdam Port Authority a maximum closing frequency of once per year is acceptable. We considered this an ATP. The closing frequency of the Maeslant barrier depends on both the sea water level, the duration of storm events as well as the discharge of the rivers. Once closed, the discharge of the rivers and the period the gate is closed determine the water level rise behind the barrier, causing a back water effect and forcing parts of the river flow to follow a route more south into the SW estuary. Figure 4 shows that a 85 cm sea level rise would mean that the barrier would close approximately once every year. Another ATP, however is the maximum sea water level rise the barrier has been designed for. This is 50 cm.

Figure 4

The storm surge barrier (Maeslant kering) to protect the Rotterdam Harbour and exceedence frequencies ($year^{-1}$) of water levels in the Rotterdam Harbour assuming sea level rise between 0 and 150 cm [from 21].

Fresh water supply

The tidal river area is crucial for the freshwater provision (drinking water and agriculture) in the South West of the Netherlands (Fig. 5). A rising sea level and reducing river discharge in dry summers is leading to extra salinization of the ground - and surface water. An ATP for this sector would occur if the sea level rise in combination with lower river drainage, means that the normal salt concentrations required for key functions, can no longer be maintained. Distribution and water allocation is established in a series of water agreements between the national and regional administratons. To meet the requirements, the maximum allowable chloride concentration in the inland water system is 250 mg/l. Under current conditions inlet of fresh water needs to be stopped between once every 5 and 10 years [58]. However, frequency and duration of necessary closure of fresh water inlets, rapidly increases with rising sea levels and falling river discharges.

The present tolerable duration of a blocked water inlet due to elevated chloride concentrations varies between 12 and 48 hours at the main inlet points within the region. Model results show that within the range of the current climate scenario's, elevated chloride concentrations can be expected for much longer periods with a sea level rise of 35 centimeter. For a strategic inlet like Gouda, along the Hollandsche IJssel river, the number of days that the inlets must be closed in an average meteorological year will increase from 0 to 76 days. Discussions with the local water managers have indicated that this is such a dramatic change, that adaptive measures are considered insurmountable.

Figure 5

Chloride concentrations and drinking water intake points along the tidal rivers in SW Netherlands

Available time before adaptation measures need to be implemented

To estimate the maximum and minimum period available before decisions on adaptation measures in the Netherlands should be taken, we use the KNMI 2006 scenario's [5] as well as the High-end scenario's [55]: sea level rise until 2100 may vary between 30 and 105 cm (Table 1).

With respect to flood protection of the sandy coast and tidal river area, the current strategy can be continued within the evaluated range of sea level rise. This means that the current strategy is robust at least until the end of this century.

The Maeslant (storm surge) barrier can be used to protect the Rotterdam harbour up to a sea level rise of 50 cm. According to the upper limit of the considered range - a worst case of 105 cm SLR in 2100 relative to 1990 - this will be reached around 2050. Under the same worst case conditions, closing of the barrier would exceed a frequency of once a year, only a few years later. Apparently, around 2050 seal level rise for the first time might present an ATP for the protection of Rotterdan Harbour. This ATP would lead to a re-consideration of the way the Harbour needs to be protected.

Fresh water supply in the Western part of The Netherlands will be hindered to an unacceptable level when the sea level would rise with 35 cm relative to 1990. In the worst case, this ATP would occur around 2030.

According to the lower limit of the considered range of future sea level rise (35 cm in 2100), the Maeslant storm surge barrier would remain effective during the entire century; similarly, fresh water supply in the Netherlands would remain acceptable until 2100.

Discussion

The classical approach for the development of adaptation strategies is to use one or more climate scenarios as starting point for impact assessment and to define adaptation strategies based on the impacts. This top-down approach is useful to explore possible adaptation strategies. The results of such studies strongly depend on the chosen scenario(s) and the assumptions concerning scientific and socio-economic uncertainties related to these issues. Furthermore, as soon as there are new insights into climate change, the physical boundary conditions alter and may lead to other decisions on water management strategies. As an example in the water management in Netherlands, it has lead to the pitfall: that one scenario as best-estimate was taken. Consequently other scenario's and other possible futures which may had given useful information for the development of alternative adaptation strategies were ignored.

A bottom-up approach, i.e. vulnerability assessment of the management system, has received remarkably little attention so far. Nearly every study starts with (a) climate change scenario('s) and then tries to design strategies. In the vulnerability assessment using ATP's we showed in this paper, we answer the basic questions of decision makers: *what* are the first issues that we will face as a result of climate change and *when* can we expect this? The results of the study have formed a basis of long term planning in the national water masterplan 2009-2015 [59]. Findings of the research also have been input to the authoritive study on future adaptation options by the 2nd governmental Delta Committee [60, 61].

Our experience is that relating the climate change directly to the current water management strategy, and expressing uncertainty in terms of the period that the existing strategy is effective (when will a critical point be reached), appears more understandable for the policymaker/ water manager/ stakeholder, than plots showing a certain percentage change in a certain projection year. We therefore consider the approach as practical to ease the dialogue between scientific and water management world.

The ATP approach stimulates the policy makers to look at sensitivity of sectors and the durability of a strategy under different conditions. The critical limits may be exceeded at a particular climate and sea level, resulting from either climate variability or climate change. In this way it may become clear that due to climate variability also in the current situation, there may be a reason to adapt the strategy. It also enables easier assessments to balance the risk of climate change with other risks.

Application of the ATP approach is relatively easy under the condition that the management objectives are clear and quantified. Particularly for flood protection this is often the case and the examples were presented above. Application becomes more difficult if well defined standards are lacking. In these cases we propose two approaches to determine ATP's: (a) by interviewing the responsible authorities or stakeholders – e.g. this approach was followed for the assessment for the fresh water intake –; (b) by comparing the expected climate or sea level change with the variation observed in history. The latter approach assumes that the current strategy is designed to cope with the current variation. This implies that as long as change remains small relative to the observed variation, in the near future climate change may not be the main reason to adapt the water management strategy, but that other (socio-economic) drivers will be at least as important.

The method can be elaborated further to identify adaptation pathways. After an ATP has been reached, a new strategy is needed. This strategy will have an ATP by itself as well. Analysing different options and ATP's, may result in adaptation pathways. Adaptation pathways show different options and possible dead ends, once a strategy has been chosen [62].

Conclusion

A bottom up approach to assess the vulnerability of the Netherlands water management system to climate change and sea level rise in terms of ATP's, has been successful in answering the basic questions for decision makers: what are the most urgent effects and when will these occur?

In our experience the approach was understandable for decision makers and therefore we conclude that application of ATP's is useful to reduce the complexity of bottom-up approaches in development of adaptation strategies to climate change.

Surprisingly from the analysis, it appeared that not flooding from the sea, but reduction of the fresh water supply in the western part of the Netherlands, poses the first major threat from an increased sea level.

References

1 Ministerie van Verkeer en Waterstaat, 1998. Fourth national policy document on water management government decision. http://www.waterland.net/nw4/English/index.html

2 Können G., 2001. Climate scenarios for impact studies in the Netherlands, Royal Netherlands Meteorological Institute (KNMI), De Bilt, Netherlands. http://www.guntherkonnen.com/downloads/2001_ClimateScenarios.pdf

3 Commissie Waterbeheer 21e eeuw, 2000. Waterbeleid voor de 21e eeuw: geef water ruimte en aandacht die het verdient. Adviescommissie waterbeheer 21e eeuw. Ministerie van verkeer en waterstaat. Den Haag, Nederland (in dutch).

4 NBW, (2002). Het Nationaal Bestuursakkoord Water. http://www.helpdeskwater.nl/aspx/download.aspx?File=/publish/pages/473/nationaal_bestuursakkoord_water.pdf (in dutch)..

5 Van den Hurk B., A Klein Tank, G Lenderink, A van Ulden, G J van Oldenborgh, C Katsman, H van den Brink, F Keller, J Bessembinder, G Burgers, G Komen, W Hazeleger and S Drijfhout. (2006). KNMI Climate Change Scenarios 2006 for the Netherlands. KNMI Scientific Report WR 2006-01

6 IPCC (2007a). Summary for Policymakers. In: Climate change 2007: The Physical Science basis. Contribution of Working group I to the 4th assessment report of the Intergovernmental Panel on climate change (Solomon, S. D. Qin, M. Manning, Z. Cheng, M.Marquis, K.B. Averyt, M.Tignor and H.L Miller (eds) , Cambridge University press, Cambridge, UK and New York, USA.

7 Dessai and van der Sluis, 2008. Uncertainty and Climate Change Adaptation - a Scoping Study. Utrecht University, The Netherlands.

8 Adger, W.N., S. Agrawala, M.M.Q. Mirza, C. Conde, K. O'Brien, J. Pulhin, R. Pulwarty, B. Smit and K. Takahashi, 2007: Assessment of adaptation practices, options, constraints and capacity. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 717-743.

9 Carter, T. R., R. Jones, X. Lu, S. Bhadwal, C. Conde, L. O. Mearns, B. C. O'Neill, M. Rounsevell, and M. Zurek. 2007. New assessment methods and the characterisation of future conditions. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working

Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 133-171.

10 Environment Agency, 2009. The Thames Estuary 2100 Environmental Report Summary. http://www.environment-agency.gov.uk/static/documents/Research/TE2100_Environment_Summary-LR.pdf

11 Patt A., R. J.T. Klein, A. de la Vega-Leinert (2005) Taking the uncertainty in climate-change vulnerability assessment seriously. External Geophysics, Climate and Environment. C. R. Geoscience 337 pp 411–424.

12 Gladwell, 2000. The Tipping Point: How Little Things Can Make a Big Difference. Little Brown and Company.

13 Lindsay, R.W. and J. Zhang, 2005. The thinning of Arctic sea ice, 19988-2003: have we passed a tipping point? Journal of Climate 18, 4879 - 4894

14 Russill, Chris and Zoe Nyssa, 2009. The tipping point trend in climate change communication. Global Environmental Change 19 (2009) 336 - 344

15 Lenton M.T., Hermann Held, Elmar Kriegler, Jim W. Hall, Wolfgang Lucht, Stefan Rahmstorf, and Hans Joachim Schellnhuber, 2008. Tipping elements in the Earth’s climate system PNAS 105 (6). 1786–1793.

16 Smith, J., Schnellnhubner, H.-J. and Mirza, M.Q.M., 2001. Vulnerability to climate change and reasons for concern: a synthesis. In: J.J. McCarthy, O.F. Canziani, N.A. Leary, D.J. Dokken and K.S. White (Editors), Climate Change 2001: Impacts, Adaptation, and Vulnerability. Cambridge University Press, Cambridge, UK.

17 Hare, W.L., 2003. Assessment of Knowledge on Impacts of Climate Change – Contribution to the Specification of Art. 2 of the UNFCCC, WBGU - German Advisory Council on Global Change, Potsdam, Berlin.

18 Hitz, S. and Smith, J., 2004. Estimating global impacts from climate change. Global Environmental Change Part A, 14(3): 201-218.

19 ISSC (2005). The International Symposium on Stabilisation of Greenhouse Gas Concentrations –Avoiding Dangerous Climate Change

20 Hanssen, 2005. Is there still time to avoid dangerous anthropogenic interference with global climate? A tribute to Charles David Keeling. AGU, San Fransisco December 6.

21 Deltares, 2008. Klimaatbestendigheid van Nederland Waterland: Knikpunten in beheer en beleid voor het hoofdwatersysteem. The climate resistance of Nederland Waterland: Tipping points in the management and policy for the main water system Compiled by J.Kwadijk, A.Jeuken and H. van Waveren; 2008. Interim project report T2447(in dutch). .

22 Van Beek, 2008, Managing Water under current climate variability. (In) Ludwig, Kabat, van Schaick and Van der Valk: Climate change adaptation in the water sector. The Netherlands.

23 Kwadijk, J.C.J , 2008. Climate, water management, supply and use in the Nile, a comparison. International Geographical Union Congress, August 2008, Tunis.

24 OECD (1993) Environmental indicators: basis concepts and terminology. Indicators for use in environmental performances reviews, Paris, France.

25 Nicholls, M.M.,1989. Sediment accumulation rates and relative sea-level rise in lagoons. Marine Geology 88 201-219..

26 Blum M.D. , and Roberts H.H., 2009. Drowning of the Mississippi Delta due to insufficient sediment supply and global sea-level rise. Nature Geoscience 2, 488 - 491 (2009)

27 Beets, D. J. & van der Spek, A. J. (2000) The Holocene evolution of the barrier and the back-barrier basins of Belgium and the Netherlands as a function of late Weichselian morphology, relative sea-level rise and sediment supply. Geologie en Mijnbouw / Netherlands Journal of Geosciences, 79 (1), 3-16

28 Van der Spek, A.J.F., 1995. Holocene sediment influxes in the coastal zone of The Netherlands and the North Sea as a function of sea-level rise and wave- and tide-induced sand transport. Report 40.017, Geological Survey of The Netherlands, Haarlem, 13 pp.

29 Van der Meulen, M.J., A.J.F. van der Spek, G. de Lange, S.H.L.L.Gruijters, S.F. van Gessel, B-L Ngyuyen, D. Maljers, J. Schokker, J.P.M. Mulder and R.A.A. van der Krogt, 2007a, Regional sediment deficits in the Dutch lowlands : implications for long-term land-use options, J. Soils Sediments 7 (1) 9-16

30 Waterbolk, H. T. (1988) Zomerbewoning in het terpen gebied. In BIERMAN, M. (Ed.) Terpen en Wierden in het Fries-Groningse kustgebied .Groningen, the Netherlands, 1989 (in dutch).

31 Van de Ven, G. P. (1993) Man-made lowlands a history of water management and land reclamation in the Netherlands. The Netherlands: Matrijs

32 Van Koningsveld, M., J.P.M. Mulder, M.J.F. Stive, L. van der Valk and A.W. van der Weck, 2008. Living with Sea Level Rise; a case study of the Netherlands. Journal of Coastal Research 24(2):367

33 Mulder, J.P.M.,and T. Louters, 1994, Changes in basin geomorphology after implementation of the Oosterschelde Project, Hydrobiologia, 282/283: 29

34 Louters, T., van den Berg J.H. and Mulder, J.P.M.,(1998) Geomorphological Changes of the Oosterschelde Tidal System During and After the Implementation of the Delta project, Journ of Coastal Research 14(3), 1134.

35 Ministerie van Verkeer en Waterstaat (1990), Coastal defence after 1990, a policy choice for coastal protection , 1st Coastal Policy Document, Ministry of Transport, Public Works and Watermanagement, The Hague NL.

36 Van Koningsveld, M. and J.P.M. Mulder, 2004. “Sustainable Coastal Policy Developments in the Netherlands. A Systematic Approach Revealed. ” Journal of Coastal Research. 20(2) 375-385.

37 Steetzel H.J., J,H. de Vroeg, L.C. van Rijn and J.M.T. Stam, 2000. Morphological modelling using a modified multi-layer approach. *Proceedings 27th ICCE, Sydney, Australia*.

38 Steetzel, H.J., Z.B. Wang and J.P.M.Mulder, 2004. Large scale sand balance of the Netherlands coastal system; modelling of a policy indicator. *Proceedings. 29th International congress Coastal Engineering 2004,* Vol.3: 2973-2984.

39 Steetzel H.J. and Z.B. Wang, 2004. A long-term morphological model for he whole Dutch coast; Model formulation and Application of the model. *Report Z3334/A1000 WL|Delft Hydraulics / Alkyon*, November 2004.

40 Stive, M.J.F., M. Capobianco, Z.B. Wang, P. Ruol and M.C. Buijsman, 1998. Morphodynamics of a tidal lagoon and the adjacent coast. In: J. Dronkers and M. Scheffers (eds.), Physics of estuaries and coastal seas, Balkema, Rotterdam, pp 397-407.

41 Stive, M.J.F. and Z.B. Wang, 2003, Morphodynamic modelling of tidal basins and coastal inlets, *In: C. Lakkhan (ed.) Advances in coastal modelling, Elsevier Sciences, pp. 367-392.*

42 Van Goor M.A., M.J.F. Stive, Z.B. Wang, T.J. Zitman, 2003, Impact of sea level rise on the morphological stability of tidal inlets, Marine Geology, Volume 202, issues 3-4, pp.211-227.

43 Kragtwijk, N.G, T.J. Zitman., M.J.F. Stive and Z.B. Wang, 2004, Morphological response of tidal basins to human interventions, *Coastal Engineering, 51 (2004) 207-221.*

44 Mulder,Jan P.M., Gertjan Nederbragt, Henk J. Steetzel, Mark van Koningsveld, Zheng B. Wang, (2007), Different implementation scenarios for the large scale coastal policy of the Netherlands, Proc. 30th Int.Conf.Coast.Eng, San Diego USA, Vol. 2 (1705 – 1717).

45 Van der Lee, W.T.B. (2009). Practical experiences in monitoring and dynamic preservation of the Dutch coast: a case study. St Fergus Symposium Proceedings 2009.

46 Eberle, M., Buiteveld, H., Wilke, K., & Krahe, P. (2005). Hydrological modelling in the river rhine basin part iii - daily hbv model for the rhine basin (Tech. Rep. No. BfG- 1451). Institute for Inland Water Management and Wase Water Treatment (RIZA) and Bundesanstalt fuer Gewasserkunde (BfG)).

47 Te Linde, A., 2007. Effect of climate change on the rivers Rhine and Meuse – Applying the KNMI 2006 scenarios using the HBV model. Report Q4286, WL | delft hydraulics, June 2007.

48 Leander, R., & Buishand, T. (2007). Resampling of regional climate model output for the simulation of extreme river flows. Journal of Hydrology, 332 , 487-496.

49 RIZA (2000). Een Sobek-model van het Noordelijk Deltabekken kalibratie en verificatie, RIZA werkdocument 2000.128X (in dutch). .

50 RIZA (2003). Een Sobek-model van het Noordelijk Deltabekken kalibratie en verificatie zoutbeweging Noordrand, RIZA werkdocument 2003.047X (in dutch). .

51 Rand / Goeller, B.F. et al. (1983). Policy Analysis of Water Management for the Netherlands, Vol. I, Summary Report, Rand R-2500/1.

52 Pulles, J.W. (1985). Beleidsanalyse van de waterhuishouding van Nederland - Witte Nota, Rijkswaterstaat, 's-Gravenhage (in dutch).

53 Haasnoot, M, J.A.P.H. Vermulst en H. Middelkoop. 1999. Impact of climate change and land subsidence on the watersystems in the Netherlands. NRP report, Waterdienst, Lelystad, the Netherlands.

54 Haasnoot, M. & Van De Wolfshaar, K. E. (2009) HABITAT: a Decision Support System for the implementation of the Birds, Habitat and Water Framework Directive. International Journal of River Basin Management.

55 Vellinga, P., C Katsman, A Sterl, J Beersma (eds) (2008). Exploring high end climate change scenarios for flood protection of the Netherlands. KNMI and Wageningen UR (Alterra, Earth System Science and Climate Change Group.

56 Flood Defense Act (1996), Wet op de Waterkering. (in Dutch). The Hague, the Netherlands: SDU Tweede Kamer der Staten-Generaal .

57 Lubbers B, De Heer J, Groenendijk J, Van Bockel M, Blekemolen M, Lambeek J, Steijn R. Evaluatie Derde Kustnota. Twynstra Gudde & Alkyon, 2007 (in dutch).

58 RIZA (2006). Aanvoerfrequenties verziltingsjaren t.b.v. Zoetwaterverkenning Midden-West Nederland. Projectnummer 6100.016.36 (in dutch). .

59 Ministerie van Verkeer en Waterstaat, 2008. Ontwerp nationaal waterplan. Ministerie van verkeer en waterstaat. The Hague, The Netherlands (in dutch)..

60 Delta Commission (Deltacommissie), 2008. Samen werken met water (Working together with water) Bevindingen van de Deltacommissie 2008. (Findings of the Delta Commission 2008) 134 pp. (http://www.deltacommissie.nl).

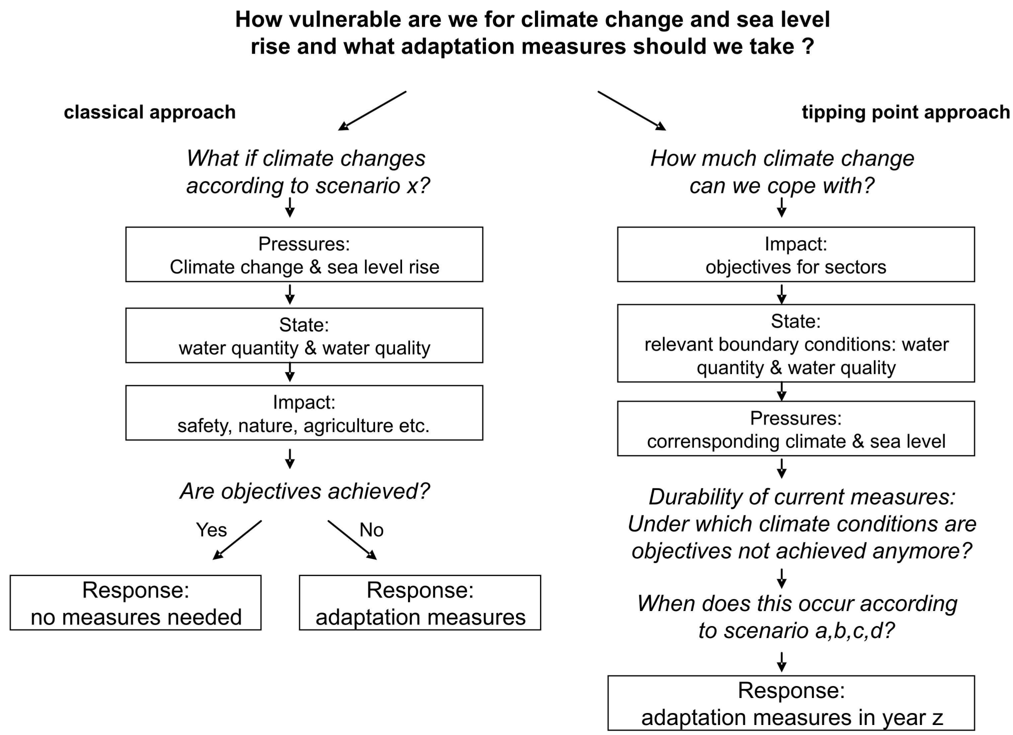
61 Kabat, P., Fresco, L. O., Stive, M. J. F., Veerman, C.P., van Alphen, Jos S. L. J., Parmet, B. W. A. H., Hazeleger, W. and Katsman, C. A. (2009) Dutch coasts in transition. Nature Geoscience 2, 450-452 (30 June 2009) doi:10.1038/ngeo572.

62 Haasnoot, M., H. Middelkoop, E. van Beek, W. P . A. van Deursen. (2009b) A method to develop sustainable water management strategies for an uncertain future. Accepted for publication in Sustainable Development.

Cross-References

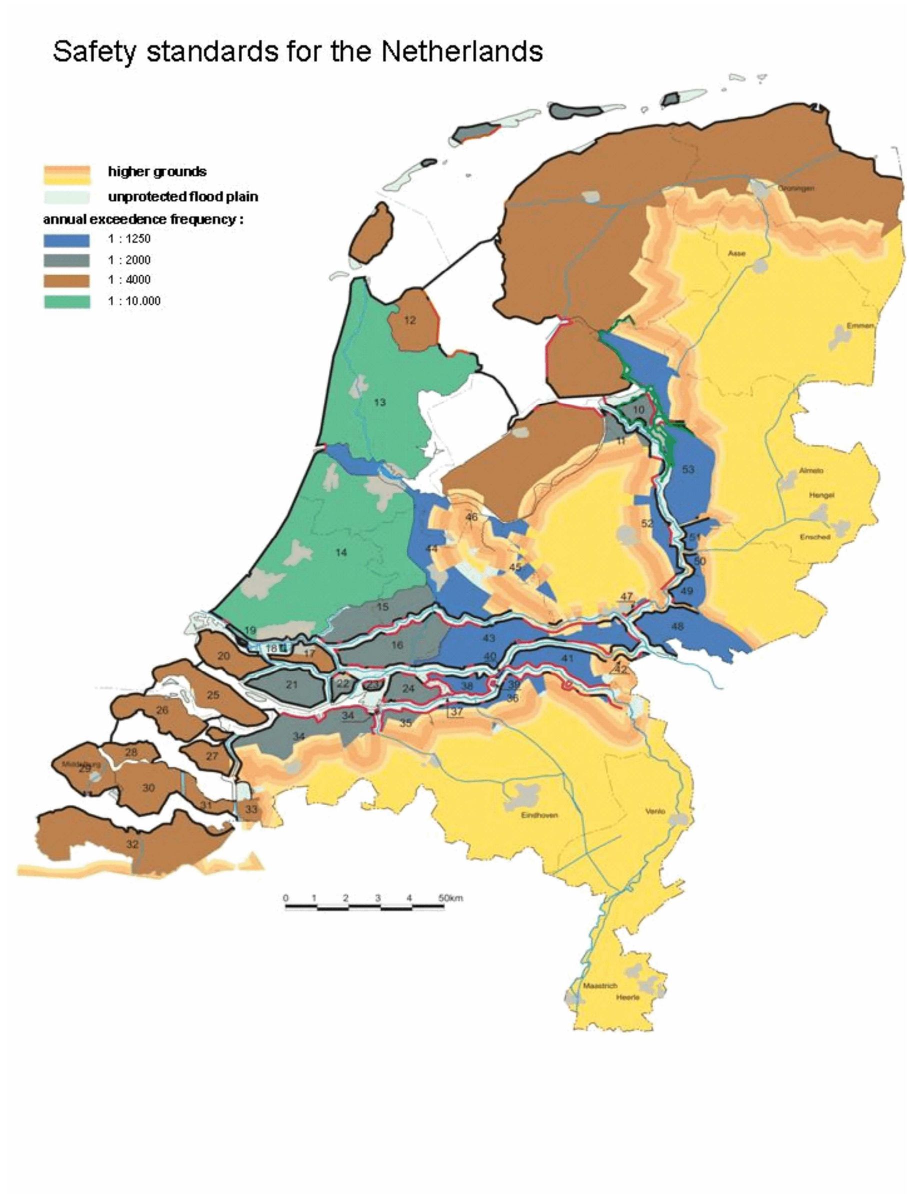
CC-0032: Sea-level scenarios for evaluating coastal impacts

CC-0226: Communicating adaptation (vs. mitigation)

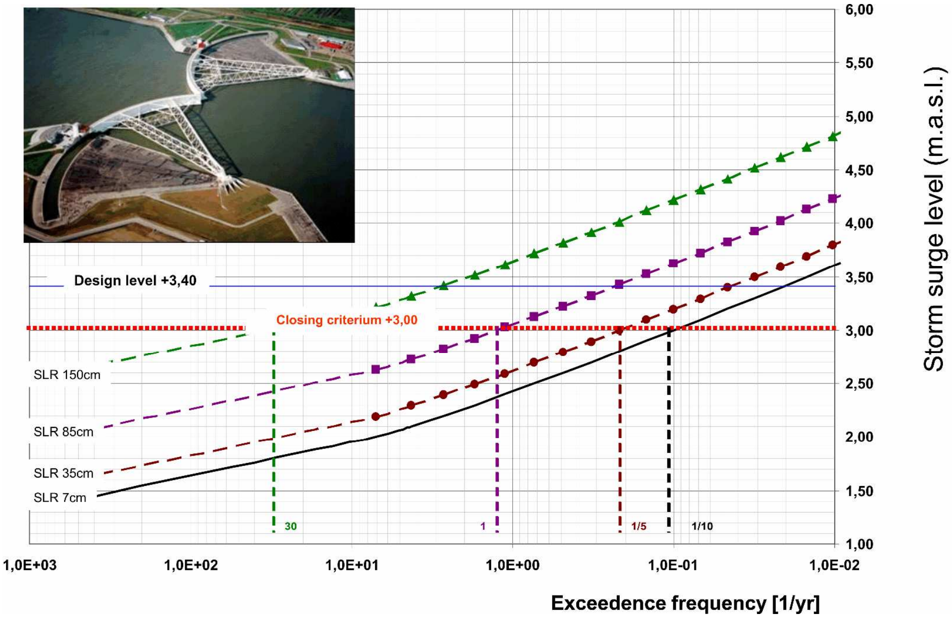


Classical 'top down' approach and Tipping point approach to develop adaptation measures
217x156mm (350 x 350 DPI)

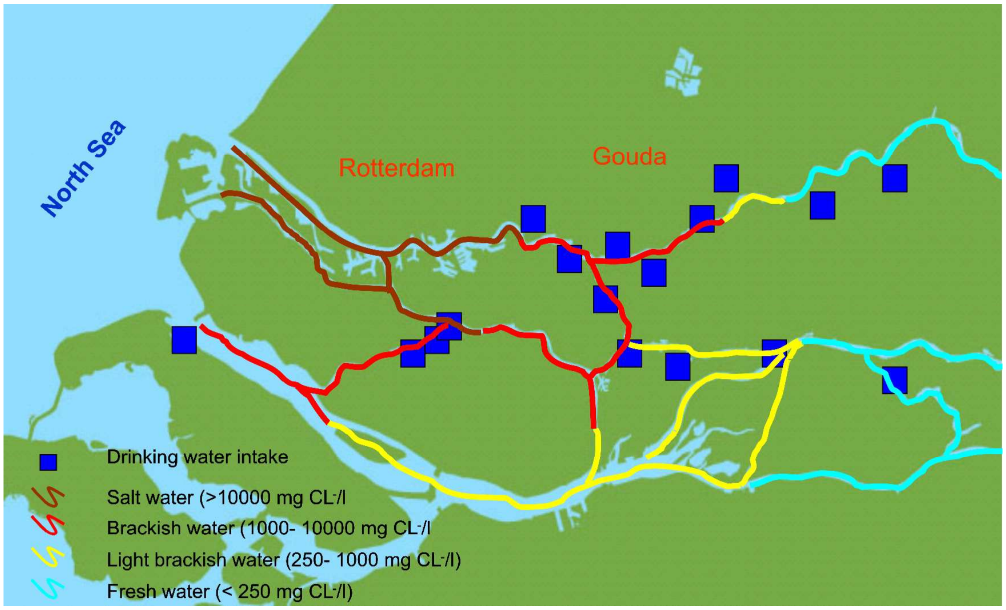
The Rhine - Meuse delta
165x204mm (350 x 350 DPI)



Flood safety standards in the Netherlands
190x253mm (350 x 350 DPI)



The storm surge barrier (Maeslant kering) to protect the Rotterdam Harbour and exceedence frequencies (year-1) of water levels in the Rotterdam Harbour assuming sea level rise between 0 and 150 cm [from 21].
247x151mm (350 x 350 DPI)



Chloride concentrations and drinking water intake points along the tidal rivers in SW Netherlands
253x153mm (350 x 350 DPI)