Spatial developments, subsidence and climate change: adding or multiplying?

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Abstract Lowland areas are vulnerable to inundations by extreme precipitation, as runoff may temporarily exceed the limited discharge capacity of drainage canals and pumping stations. This type of flooding is not life threatening, but can cause considerable economic damage. Moreover, it is likely that the frequency and damage of this type of flood event will increase in the future due to ongoing processes, e.g. climate change, subsidence, and intensification of land use by spatial developments. The research question addressed in this paper is: how do climate change, subsidence, and spatial developments increase the risk of flooding? To answer this question the case of the Flevo polder was studied. It will be shown that the risk increase of spatial developments, subsidence and climate change is simultaneously larger than the sum of the individual risk increase per category.

Key words climate change; continuous simulations; risk; spatial developments; subsidence

INTRODUCTION

The Netherlands has been created after centuries of land reclamation, water management, and drainage induced land subsidence in the Delta of three rivers: the Rhine, the Meuse, and the Scheldt. Large parts of the present landscape are below mean sea level and need protection from the sea by dunes and levees (Fig. 1). Furthermore, this lowland area is divided in to polders, and each polder area is equipped with a network of canals, weirs and pumping stations to discharge excess rainfall.

A polder water system is functioning well when it is able to withstand high outside water levels and discharge excess rainfall to the sea. The system fails when inundations occur by e.g. dike collapses or high (ground) water levels caused by extensive precipitation in combination with limited discharge capacities.

Rainfall induced floods occurred frequently in recent years in The Netherlands (1998, 1999, 2000, 2001, 2002, 2004). This type of flooding in polder areas is not life threatening, but can be extremely frustrating when the same farmer sees his harvest washed away in consecutive years. Furthermore, it is likely that in the future these types of flood events will happen more often, and cause more damage than they do now. The frequency of flooding is expected to increase because of climate change. In addition, the damage in the case of an event will increase due to an intensification of land use and shifts towards more expensive land use functions.

This (potential) sequence of events has started a discussion in The Netherlands on whether discharge capacities currently available should be reviewed and adapted. One of the problems recognized is that the improvement of existing systems is more difficult than adapting design rules for new water systems. The need is determined

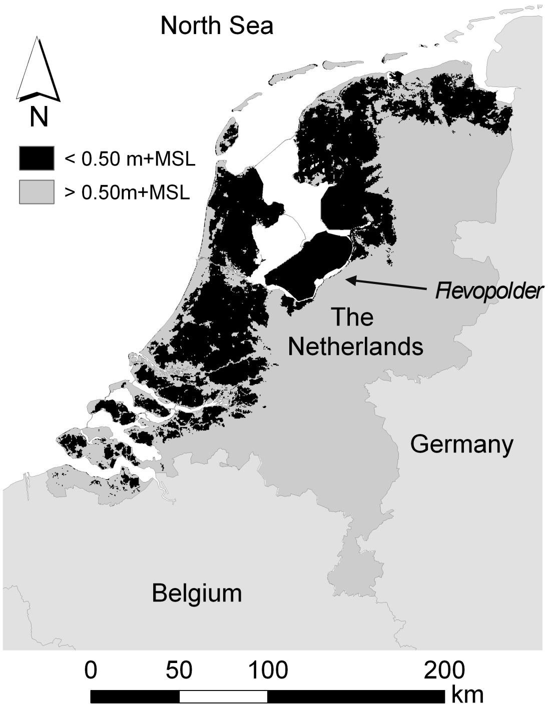

Fig. 1 The Netherlands: in black the areas below 0.50 m + mean sea level.

by the robustness of the present system, the potential damage to be prevented, and the financial possibilities of water authorities to invest in mitigation measures.

The research question addressed in this paper is whether there is any need to improve the water system with respect to climate change, subsidence and spatial developments. To answer this question we need to know what the increase in damage will be and whether it is worthwhile to invest in measures to reduce the risk of flooding. Perhaps these measures themselves are more expensive than the damage in the case of flooding.

To answer this question, a detailed case study was conducted for the 97 000 ha Flevo polder. This polder is the largest in The Netherlands; it was selected because land use in the polder is diverse and changing rapidly compared to other locations in The Netherlands. For this area a detailed risk assessment was made, using a combination of hydrological models, Geographical Information Systems (GIS) and depth–damage functions.

FLOOD RISK

In an optimal water system there is equilibrium between costs and benefits. In other words, flooding causing damage may occur now and then in this system, but will not be a real problem as long as extra costs for measures for a better system are equal or larger then the damage prevented by these measures (please note again that this paper discusses flooding caused by extensive rainfall, which does not result in human casualties). If a too-extraordinary meteorological event is used to design the dikes, canals and pumping stations, a too-expensive water system will be the result. So, there is always a certain risk of flooding that we have to accept. This risk is defined as the probability of a flood multiplied by the consequences in case of failure, and is equal to the expected annual damage (EAD) (USACE, 1996; Penning-Rowsell *et al.*, 2003). The exact procedure to determine the risk of flooding depends on the type of water system studied. In general, flooding risks for river and sea systems have been studied regularly (Vis *et al.*, 2003; Apel *et al.*, 2004). Polder systems in relation to extensive rainfall are much less studied.

To evaluate the Flevo polder water system a detailed lumped rainfall–runoff model of the water system was made. With this model, 188 years of historic (hourly!) rainfall and daily evaporation records were introduced to determine 188 years of water levels. Such long-term simulations are still uncommon for most Dutch polder water systems, as until not long ago computation times to determine the probability distribution functions by continuous simulations were considerable (weeks!). However, present data availability, available computer simulation models and the possibility to have computers performing parallel calculations make long-term continuous simulations applicable on a large and detailed scale. The probability distribution functions were determined by fitting an Extreme Value Distribution through the annual maxima of water levels for each location in the model.

To estimate the damage for all possible floods, a unit-loss model was made. In our model only direct, first order damage was assessed, which is caused by physical contact with water. Higher order, indirect and intangible damage was neglected, as it is usually small compared to direct damage for small-scale inundations. Furthermore, it is relatively difficult to estimate indirect damage as these depend on more factors than high water levels (Penning-Rowsell *et al.*, 2003).

A unit-loss model counts items categorized in terms of relevant units. The relevant units were defined according to the land use functions of Table 1 in raster cells of 25 × 25 m. The maximum damage per item was based on data from the Dutch Agricultural Economics Research Institute. The fraction of damage assigned to every item was calculated with depth–damage functions (Fig. 2).

CASE STUDY OF FLEVO POLDER

The Flevo polder is a 97 000 ha large polder situated in the IJsselmeer lake in the centre of The Netherlands (Fig. 1). The polder was constructed in two phases. The 54 000 ha north-east part of the Flevo polder was constructed in the 1950–1957 period; the second 43 000 ha south-east part was realized between 1959 and 1968.

Table 1 Maximum damage per land use class.

Land use class	Damage function	Maximum damage (€ ha^{-1})
Pastures	II	1 000
Arable crops	I	2 500
Horticulture, flower bulbs	I	25 000
Orchards	I	100 000
Main (rail) roads	III	100 000
Residential buildings	III	225 000
Industrial areas	III	500 000

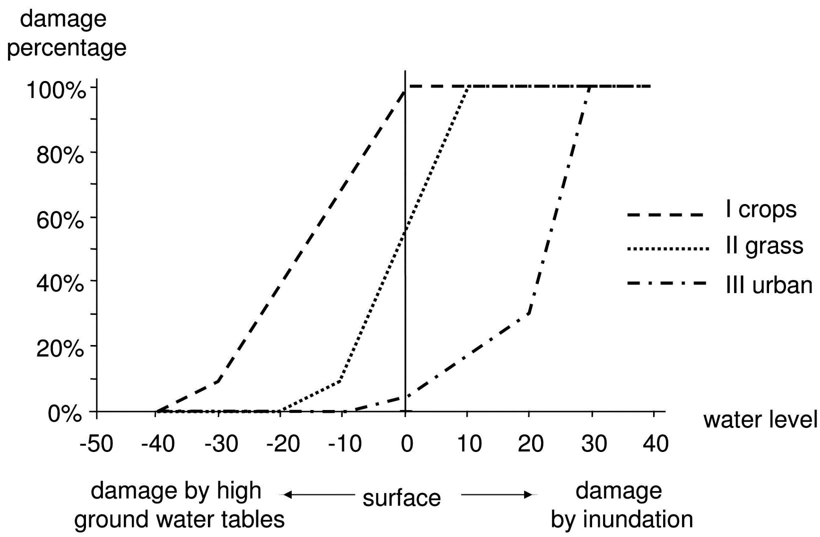

Fig. 2 Depth damage functions.

The polder area includes two cities for which the first houses were built in 1976. Lelystad was founded in 1980 (currently with 72 000 inhabitants) and Almere was founded in 1984 (180 000 inhabitants). It is a national policy that the city of Almere may build 45 000 houses until 2030. Furthermore, a famous wetland area of 60 km^2 is located in the polder. This area accommodates, amongst others, some 30 rare bird species and a game population of 3000 animals.

CLIMATE CHANGE

The Earth's average temperature is slowly increasing due to increased emission of greenhouse gases in the last decades. The exact consequences of this temperature rise are uncertain, but worldwide climatologists agree upon possible severe changes in climate. For The Netherlands it is expected that the future will bring warmer summers, increased precipitation in winter, and more severe and frequent precipitation events. To be able to analyse the potential impacts of climate change, the Royal Dutch Meteorological Institute has formulated climate change scenarios for temperature rises of 1, 2 and 4°C (Table 2). All water boards in The Netherlands agreed to use a climate scenario in which the average temperature will rise by 1°C in 2050. For our simulations we adapted the rainfall and evaporation series according to changes in Table 2.

Table 2 Expected consequences of a global temperature rise (Können, 2001).

	ΔT = 0.5°C	ΔT = 1°C	ΔT = 2°C
Yearly precipitation	+1.5%	+3%	+6%
Summer precipitation	+0.5%	+1%	+2%
Winter precipitation	+3%	+6%	+12%
Intensity in showers	+5%	+10%	+20%
Evaporation	+2%	+4%	+8%
Sea level rise	+10 cm	+25 cm	+45 cm

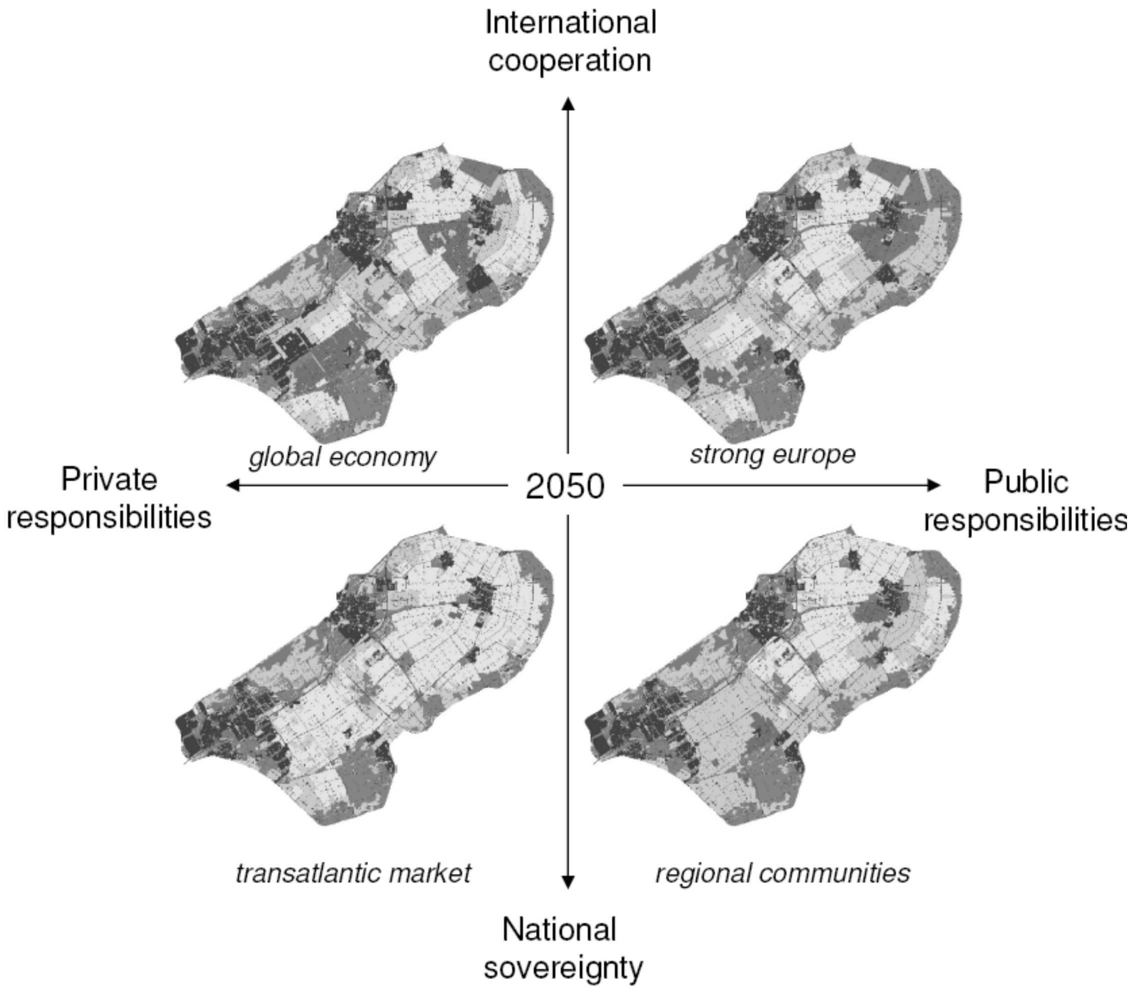

Fig. 3 Four future spatial maps of Flevo polder.

SPATIAL DEVELOPMENTS

The damage in the case of flooding over time is influenced by spatial developments. For example, the potential damage increases when an agricultural area is changed to horticulture. Furthermore, a change in spatial planning may—besides potential damage—also increase the probability of flooding. An increase of the paved surface by urbanization will decrease the possibility of rainfall to infiltrate and increase the rapid runoff to surface water, which may alter the flood extent in the case of extreme precipitation.

In the case study, four maps each showing a possible future economic scenario (Global Economy, Transatlantic Market, Strong Europe, and Regional Communities) were used to estimate the influence of future developments in the Flevo polder on the risk of flooding (Fig. 3). The bases of these scenarios were developed by The Netherlands Bureau for Economic Policy Analysis; they describe four futures of Europe (CPB, 2003). The National Institute for Public Health and the Environment (RIVM) has included sustainability aspects of the four scenarios, and translated to spatial impressions maps for The Netherlands in 2040 (RIVM, 2005). The translation to the Flevo polder was done by combining the RIVM data with maps from the Dutch National Mapping Agency (TOP10NL), Centre for Geo Information (LGN), and maps of the Municipalities.

According to these scenarios, both the rural and urban environment will change thoroughly during the next decades. Each scenario shows a deterioration of present arable areas and an expansion of built-up areas, depending upon the degree of government protection assumed in a scenario (see Table 3). Fairly large areas of arable farming will be superseded by horticulture in the Global Economy scenario. In total, agriculture (meadows, arable land, and horticulture) will remain dominant, but the expectation is, to stay ahead of East-European competitors, the more expensive crops will have to be cultivated more closely together. A large lake in the Flevo polder is foreseen in the Strong Europe scenario.

Table 3 Surface in km^2 of different types of land use per scenario in year 2040.

	Present land use	Global Economy	Strong Europe	Transatlantic Market	Regional Communities
Water	50	60	100	50	50
Nature	240	260	260	250	260
Meadows	90	180	230	120	260
Arable land	460	200	180	390	210
Horticulture	20	80	30	–	30
Built-up areas	110	190	170	160	160
Total	970	970	970	970	970

Table 4 Expected annual damage in M€ yr^{-1} per scenario in the Flevo polder.

Spatial scenario	Present climate (2005)		Δt = +1°C (2050)	
	present elevation	+ subsidence	present elevation	+ subsidence
Present land use	1.0	3.2	1.7	5.2
Global economy	1.6	7.3	2.6	11.3
Strong Europe	1.5	6.6	2.2	9.2
Transatlantic market	1.6	5.9	2.6	9.7
Regional communities	1.9	7.5	3.0	11.0

SUBSIDENCE

The surface of the Flevo polder is located at –4.4 m MSL. At the time of construction it was already known that the surface would descend several cm as a result of the sudden drop in groundwater tension. To compensate for this surface subsidence at the same target levels, all canals were constructed deeper than necessary. To analyse the effect of subsidence on the expected annual damage, the calculations were repeated with an adapted digital elevation model of the polder that incorporated the expected subsidence in the coming 50 years. The subsidence is considerable because of the relatively young age of the polder. The expected lowering of the surface until 2050 totals 2–12 cm in the northeastern part of the polder. In the southwestern part the lowering totals 20–35 cm.

RESULTS AND DISCUSSION

The results of simulated scenarios are summarized in Table 4. The risk in the Flevo polder amounts to nearly M€ 1.0 a year in the present situation (taking into account land use, elevation and climate). The results show that the increase in risk due to climate change (Δt = 1° in 2050) was estimated at M€ 1.7 a year (70%), whereas the expected increase of the rainfall intensities was only about 10% (see Table 4). The larger increase of risk can be explained by the fact that the return periods of heavy rainfall events (and floods) decrease by more than the 10% change in intensity; extreme events will happen more frequently. Analyses of the data show that this risk increase is not homogeneous and shifts particularly to less robust areas within the polder.

An increase in built-up areas and shifts in agriculture (not taking into account climate change and subsidence) causes an increase in risk from M€ 1.0 to M€ 1.5 up to M€ 1.9 depending on the scenario, as damage for similar events becomes larger. This increase is of the same order of magnitude as the increase in risk due to climate change (Δt = 1° in 2050).

The simulations show that the increase in risk due to subsidence is dominant in comparison with climate change and spatial developments. The main explanation for this result is that when the surface subsides, target water levels are maintained at present levels, as these are defined in relation to MSL and not to land surface levels (which was the reason to construct extra deep canals some 40 years ago). In practice, subsidence will never end, as target levels have to be revised at a minimum of once every 10 years by law.

The combined effect of spatial developments and climate change is worse than the sum of their separate effects. To take one example, the shift from present land use towards regional communities combined with climate change and subsidence shows this combined effect:

– The risk increase by climate change, at present land use and elevation, amounts M€ 0.7 $year^{-1}$;
– The risk increase by spatial development from present land use towards regional communities, at present climate and elevation, is M€ 0.9 $year^{-1}$;
– The risk increase by subsidence, at present land use and climate, is M€ 2.2 $year^{-1}$.

So the sum of their separate effects (M€ 0.7 $year^{-1}$ + M€ 0.9 $year^{-1}$+ M€ 2.2 $year^{-1}$) is M€ 3.8 $year^{-1}$. When simulated together, the increase in risk amounts to M€ 10.0 $year^{-1}$, which is larger. This effect of a larger risk increase when combining processes is visible in all scenarios studied. The cause of the influence of combining effects is the multiplication of probability and consequences.

CONCLUSION

This paper has outlined a method for estimating the risk of flooding due to precipitation under different scenarios. The case study of the Flevo polder showed that the impact of climate change will increase the risk significantly, but that, depending on the scenario, changes in land use may have more influence. However, the increase caused by subsidence is dominant.

Although the results of this study are based on future scenarios, which do not show the "real" future, the case study clearly shows the feasibility of this type of analysis. An important result of this study is that it is vital to take into account the combined risks of future developments. It was clearly shown that the sum of the individual risks of the three categories of climate change, land use and subsidence was lower than the combined risks when taking into account all three categories simultaneously, in all scenarios. Thus, despite all uncertainties, it is certain that any decision-making process concerning future water management aimed at risk reduction should not be based on separate tracks of analysis, as this will tend to underestimating risks.

Limitations of the methodology presented are the influence of uncertainties in the data used and taking into account only direct damage. Ignoring indirect damage may become a problem, as avoiding these risks may increase the benefit of spatial developments. For this reason it is recommended to include risk analyses only as a part of decision-making procedures, to prevent mitigation measures that are absolutely infeasible.

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