Research Articles

Regional Sediment Deficits in the Dutch Lowlands: Implications for Long-Term Land-Use Options

Michiel J. van der Meulen[1]*, Ad J.F. van der Spek[1,2], Ger de Lange[1], Stephan H.L.L. Gruijters[1], Serge F. van Gessel[1], Buu-Long Nguyen[1,3], Denise Maljers[1], Jeroen Schokker[1], Jan P.M. Mulder[4,5] and Rob A.A. van der Krogt[1]

[1] TNO Built Environment and Geosciences – *Geological Survey of the Netherlands*, PO Box 80015, 3508 TA Utrecht, Netherlands
[2] Delft University of Technology, Faculty of Civil Engineering and Geosciences, PO Box 5048, 2600 GA Delft, Netherlands
[3] Currently at: Royal Boskalis Westminster, PO Box 43, 3350 AA Papendrecht, Netherlands
[4] RIKZ – National Institute for Coastal and Marine Management, PO Box 20907, 2500 EX Den Haag, Netherlands
[5] University of Twente, Department of Water Engineering and Management, PO Box 217, 7500 AE Enschede

---

* **Corresponding author** (michiel.vandermeulen@tno.nl)

DOI: http://dx.doi.org/10.1065/jss2006.12.199

Abstract

Background, Aim and Scope. Coastal and river plains are the surfaces of depositional systems, to which sediment input is a parameter of key-importance. Their habitation and economic development usually requires protection with dikes, quays, etc., which are effective in retaining floods but have the side effect of impeding sedimentation in their hinterlands. The flood-protected Dutch lowlands (so-called dike-ring areas) have been sediment-starved for up to about a millennium. In addition to this, peat decomposition and soil compaction, brought about by land drainage, have caused significant land subsidence. Sediment deficiency, defined as the combined effect of sediment-starvation and drainage-induced volume losses, has already been substantial in this area, and it is expected to become urgent in view of the forecasted effects of climate change (sea-level rise, intensified precipitation and run-off). We therefore explore this deficiency, compare it with natural (Holocene) and current human sediment inputs, and discuss it in terms of long-term land-use options.

Materials and Methods. We use available 3D geological models to define natural sediment inputs to our study area. Recent progress in large-scale modelling of peat oxidation and compaction enables us to address volume loss associated with these processes. Human sediment inputs are based on published minerals statistics. All results are given as first-order approximations.

Results. The current sediment deficit in the diked lowlands of the Netherlands is estimated at 136 ± 67 million m^3/a. About 85% of this volume is the hypothetical amount of sediment required to keep up with sea-level rise, and 15% is the effect of land drainage (peat decomposition and compaction). The average Holocene sediment input to our study area (based on a total of 145 km^3) is ~14 million m^3/a, and the maximum (millennium-averaged) input ~26 million m^3/a. Historical sediment deficiency has resulted in an unused sediment accommodation space of about 13.3 km^3. Net human input of sediment material currently amounts to ~23 million m^3/a.

Discussion. As sedimentary processes in the Dutch lowlands have been retarded, the depositional system's natural resilience to sea-level rise is low, and all that is left to cope is human countermeasure. Preserving some sort of status quo with water management solutions may reach its limits in the foreseeable future. The most viable long-term option therefore seems a combination of allowing for more water in open country (anything from flood-buffer zones to open water) and raising lands that are to be built up (enabling their lasting protection). As to the latter, doubling or tripling the use of filling sand in a planned and sustained effort may resolve up to one half of the Dutch sediment deficiency problems in about a century.

Conclusions, Recommendations and Perspectives. We conclude that sediment deficiency – past, present and future – challenges the sustainable habitation of the Dutch lowlands. In order to explore possible solutions, we recommend the development of long-term scenarios for the changing lowland physiography, that include the effects of Global Change, compensation measures, costs and benefits, and the implications for long-term land-use options.

Keywords: Climate proofing; Global Change; land subsidence; land use; lowlands; sea-level rise; sediment budgets; sediment deficits; sediment management; spatial planning; The Netherlands; water management

Introduction

Coastal and river plains host some of the world's largest population concentrations and economic centres. In geological terms, they are the surfaces of sediment bodies that accumulate between the continental and marine domains. While the overall setting is determined tectonically, their natural development is largely climate-driven, through combinations of terrestrial and marine processes and conditions (e.g. run-off, sediment transport, vegetation coverage, sea-level variation, tides, and storm, wave and currents action). Each of these act and vary on timescales ranging from geological to human. Over the last few years, a general feeling of control over some of these factors has been replaced with concern, due to expected effects of climate change such as sea-level rise and higher precipitation intensities. As recently shown by the flooding of New Orleans, coastal and river plains are vulnerable, and new strategies for their sustainable habitation and economical development are called for.

Natural sedimentary processes, such as periodical flooding or channel shifting, are restricted or prevented altogether in inhabited lowland areas. Usually, the effects of this restriction on sediment distribution are recognised only at places where active sedimentation can still occur, for example in or next to river channels. Deposition rates tend to be high when sedimentation space is confined, and when this imposes a problem, it is mostly solved by dredging. In contrast, the fact that water management also inevitably results in areas of non-deposition is generally underappreciated, as are the potential consequences. Governed by the aforementioned processes, natural lowlands essentially develop in a steady-state equilibrium between supplies of sediments and the accommodation space for their deposition. In such a system, retarded sediment inputs should in principle be regarded as sediment deficits, rather than as some sort of standstill.

This article explores sediment deficiency in the diked, sediment-starved parts of the Dutch lowlands. For this purpose, we present estimates of: (1) the hypothetical amount of sediment that would be required to keep up with the predicted sea-level rise, (2) volume losses associated with peat oxidation and compaction, and (3) human inputs of sediment material. The sum of these volumes is compared with the net natural sediment inputs in the recent geological past. We discuss the resulting sediment deficit in terms of long-term land-use options, with special reference to sediment and water management.

1 Materials and Methods

The Geological Survey of the Netherlands manages the Dutch national database for geological data, which contains about 380,000 borehole descriptions, and it carries out a national geological mapping programme. Both data and mapping results provide the natural reference for the sediment balance of our study. Recent progress in large-scale forward modelling of peat oxidation and compaction enables us to address the volume losses associated with these processes. Finally, human inputs are based on published statistics. More details of the data and methods used are outlined below for each component in the sediment balance.

Sediment inputs and losses, present and past, are given as first-order approximations. We feel this solution level to be sufficient for the purpose of this study, which is to discuss whether or not problems associated with sediment starvation are manageable. The main effort has been put in presenting pertinent processes in terms of the sediment volumes involved. Rates of sedimentation, compaction and peat oxidation are usually given one-dimensionally, e.g. in cm/a, while a volume approach is required for a full appreciation of the impacts of these processes, as well as for comparisons between one another. Note that ages are given in calendar years BP rather than C14 years.

2 Results

2.1 The Holocene as a natural frame of reference

The Holocene is distinguished as a composite lithostratigraphic unit in the Dutch geological survey's mapping programme (De Mulder at al. 2003, TNO 2006a). It consists of (1) coastal, back-barrier and estuarine deposits, (2) fluvial deposits of the Rhine and Meuse rivers, and (3) a variety of local deposits such as brook sediments and peat, all of which were deposited after the most recent glaciation, i.e. from 11,500 years BP onwards. The mapping programme has resulted in a national 2.5D stacked grid model of the boundary surfaces of all Quaternary and Tertiary formations. The model, which has a grid-cell size of 250 by 250 m, has been constructed by interpolating ~22,000 interpreted boreholes in the entire country. **Fig. 1** shows a map of the distribution and thickness of the Dutch Holocene deposits, thickness having been obtained by subtracting the Holocene base from a digital terrain model with equal resolution. Rather than the coastline, we use the 20 m isobath, which approximately corresponds to the base of the shoreface (Van Alphen & Damoiseaux 1989), to distinguish the Holocene coastal and terrestrial deposits of interest from their open marine equivalents.

The Dutch Holocene deposits (including sub-aquatic coastal sequences) has a surface area of 29,858 km^2, and a total volume of ~275 km^3. The average net accumulation of sediment over the last 11,500 years is ~24 million m^3/a. Based on facies architecture and a proposed correlation of sedimentation rate to sea-level rise, Beets & Van der Spek (2000) estimate about 60% of the Dutch coastal sediments to have been deposited between 8850 and 5750 years BP, 30% between 5750 and 3150 years BP, and 10% from 3150 years BP to date. Their definition of coastal sediments includes the western and northern 226 km^3 of Holocene sediments, i.e. the bulk of the entire series. Erkens et al. (2006) report a different trend for the Holocene floodplain deposits of the river Rhine; recalculating their rates to sediment-input estimates for the aforementioned time slices results in proportions of 31%, 29% and 41%, respectively. We have upscaled these values to the entire terrestrial Holocene volume, i.e. the remaining 49 km^3, and combined them with the results of Beets and Van der Spek (2000). The resulting net sediment inputs for the three time slices are 49 million m^3/a, 31 million m^3/a and 14 million m^3/a, respectively. Van der Spek (2004) shows that sub-millennial and regional variation in early Holocene sedimentation rates is considerable: the highest rate observed is ~40 times the average for that period.

2.2 Non-deposition as a result of water management

19,439 km^2 (56%) of the Dutch land surface is encompassed in so-called 'dike rings' (*dijkringen*), i.e. protected by closed rings of primary dikes (including sluices), and natural flood barriers such as dunes or higher grounds. 'Dike-ring areas' (*dijkringgebieden*) are compartmented by secondary dikes, that mainly separate different drainage subsystems but may offer additional flood protection. Diking started as early as ~1000 AD (e.g. Middelkoop 1997), and the subsequent, ever-increasing control over water eventually resulted in the current flood-protection system. The flood barriers of each dike ring are dimensioned to provide legally defined safety levels, expressed as flooding chances that vary between 1 / 10,000 years in the coastal area to 1 / 1,250 years elsewhere.

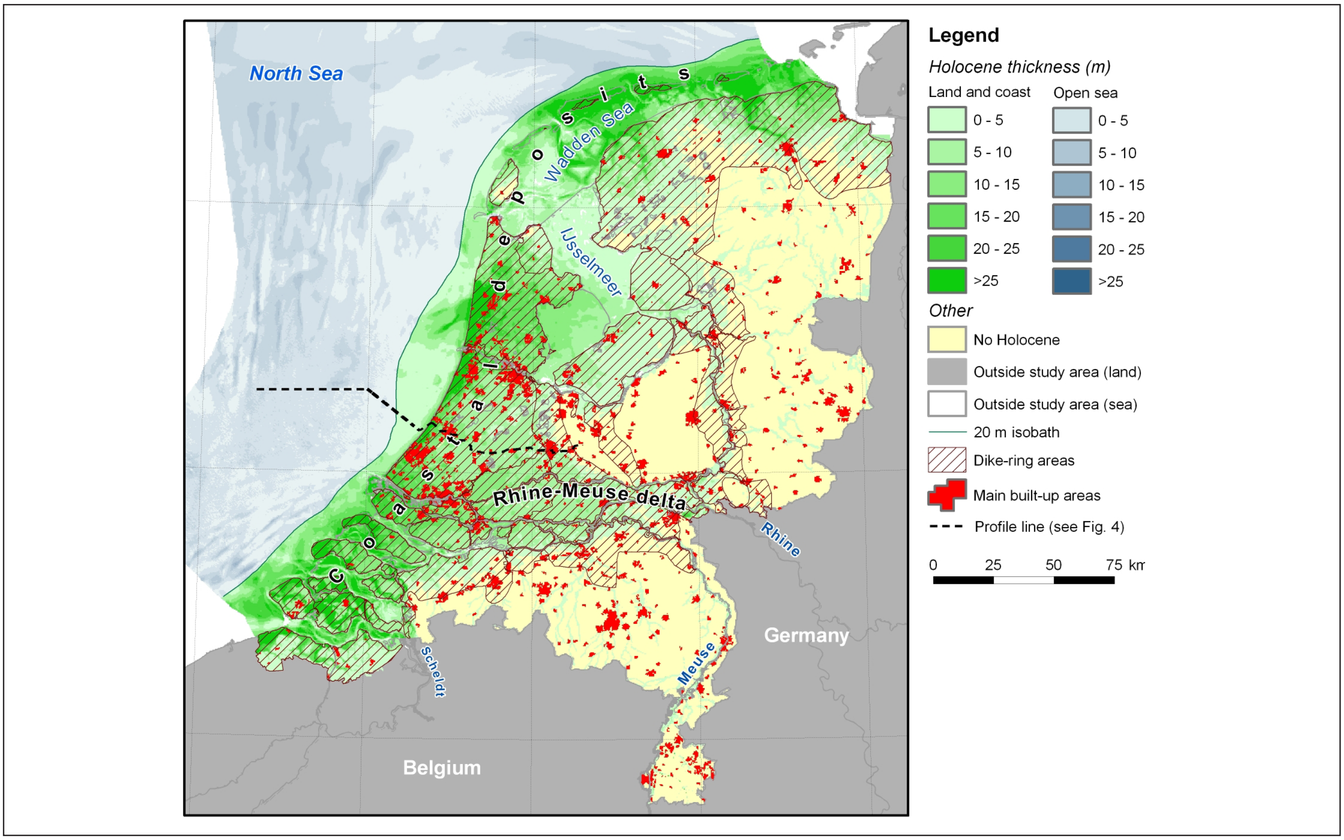

Fig. 1: Map of the Netherlands showing the thickness and extent of the Holocene deposits, and the so-called dike-ring areas, where sedimentation has been suspended. Holocene terrestrial and coastal sediments (green shading) show a west- and northward thickening. Their marine equivalents (blue shading) are not taken into account in the present study. In the eastern and southern uplands (mainly Pleistocene of age), Holocene sedimentation is limited to the valleys of brooks and small rivers. See text for further explanation

Dike-ring areas cover almost the entire onshore Holocene surface (see Fig. 1). Not only have these areas been cut off from the main sources of clastic sediment, their drainage and cultivation have put an end to peat formation. Peat has been fundamental to the development of the Dutch lowlands. Raised bogs, i.e. peat accumulations with a positive, dome-shaped topography, have reached heights up to ~4 m above base level, and closed the larger part of the coastal plain for clastic depositional systems in mid Holocene times. Peatlands were exploited for fuel (turf) and salt, and cultivated from mediaeval times onwards. Collapse of bog domes, peat extraction and suspending peat formation have significantly increased potential sediment accommodation space in the Dutch lowlands.

The total volume of Holocene sediments in the dike-ring areas' subsurface is about 145 km^3, which implies that the currently sediment-starved lowlands used to receive a net average of 13 million m^3/a of sediment during the Holocene, or 14 million m^3/a when assuming sediment starvation from mediaeval times onwards. Analogous to the above estimates for the entire Holocene series, net sediment inputs would have been 26 million m^3/a from 8850 to 5750 years BP, 17 million^3/a from 5750 to 3150 years BP, and 10 million m^3/a from 3150 to 1000 years BP.

Van der Meulen et al. (2005) have presented national aggregate resource estimates, based on a 3D lithological voxel model. The model was upgraded, as part of the follow up of this minerals work, the main improvements being the resolution (250 by 250 by 1 m, instead of 1000 by 1000 by 1 m), and the use of nationally mapped formation boundaries as interpolation constraints (TNO 2006b). We used the upgraded model version to estimate the proportions of various lithologies within the Holocene deposits (**Fig. 2**; onshore sequences only). The predominant component is sand and gravel (59.5%), clay and peat amount to 33.0 and 7.5%, respectively. In the dike-ring areas, these proportions are 49.7%, 40.3% and 10.0%, respectively. The value of peat is underestimated, as both the amounts that have been extracted, and the volume losses due to collapse and decomposition are not represented.

The only active sedimentation taking place within the confinement of the dike rings is redeposition of sediment material, or the deposition of algae, micro-organisms and other organic matter (e.g. dy or gyttja) in ponds, lakes, drainage canals, etc. We neglect the latter organic sedimentation types for two reasons. First, the surface of open water within the dike-ring areas amounts to only 1 to 2%. Hence, organic deposition volumes are likely be low (especially when considering the fact that sedimentation is partly countered with dredging), and fall within the error margins of this study. Secondly, from the lithological model discussed above, it is clear that only peat formation at the aforementioned scale

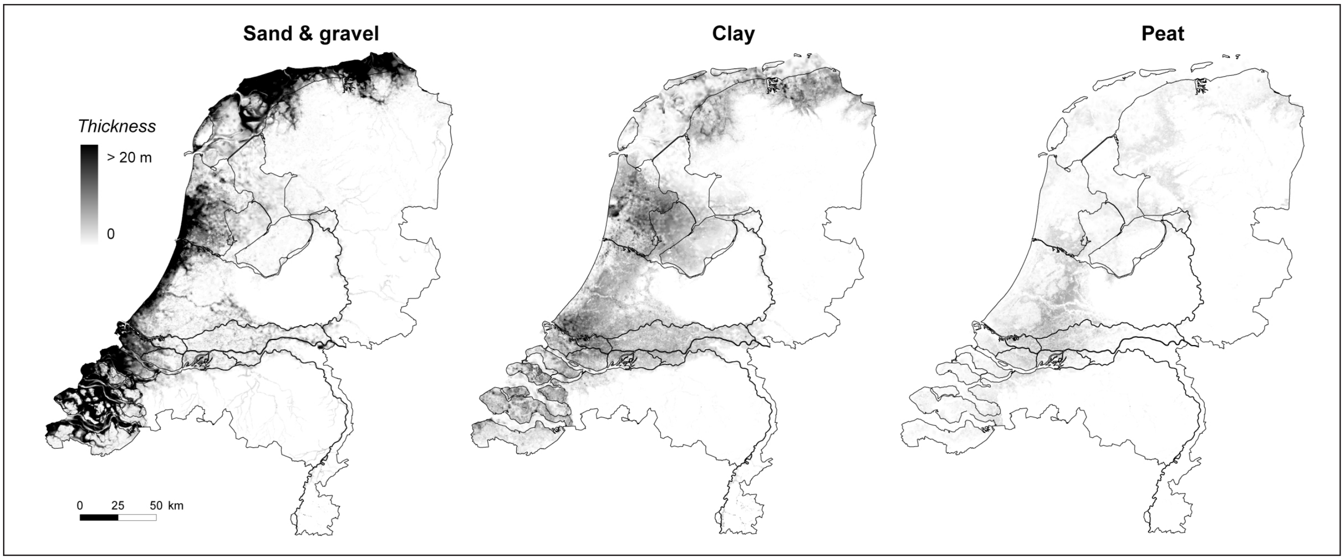

Fig. 2: The occurrence of sand and gravel, clay, and peat in the Holocene (onshore only), given as cumulative thicknesses. Sand predominantly occurs in the coastal zone; clay in the fluvial and coastal plains. Peat has been deposited in coastal swamps; the distribution patterns clearly shows the effect of pre 20th century peat extraction

has contributed significantly to the Dutch Holocene sediment volume. As atmospheric and aeolian inputs are currently negligible as well, we consider the dike rings to be completely sediment-starved in this study.

2.3 Keeping up with sea-level rise?

The recently updated climate scenarios of the Dutch Meteorological Institute (KNMI) include sea-level rise forecasts. The rise until 2100 is expected to range between 35 and 85 cm, at an average rate of 0.4 to 0.9 cm/a. In the long term, this is expected to have consequences for the coastal flood-barrier systems, and it may force increased drainage efforts in the coastal areas, as groundwater will rise with sea level. A crude estimate of the amount of sediment that would, hypothetically, be required to keep up with sea-level rise can be obtained by multiplying the sedimentation area with the rise forecasts. The dike rings encompass some areas without Holocene sediments (see Fig. 1): depending on whether these are excluded or included, the minimum sediment requirement would be 59 or 72 million m^3/a, respectively. The corresponding values in the maximum scenario are 141 and 175 million m^3/a. Note that this particular sediment volume has no practical meaning, it has been calculated to estimate sediment deficiency using a sedimentation surface in equilibrium with sea-level (as outlined above) as a plane of reference. Also note that compaction (of new deposits and their substrate) has not been taken into consideration.

The response of the Dutch Holocene sedimentary system to prior phases of high sea-level rise provides a frame of reference to assess the effects of the forecasted rise. Sustained sea-level rise of more than 0.6 cm/a, which occurred up till 6000 BP, appears to have been too high for compensation by sediment supply, as evidenced by coastline retreat (Beets and Van der Spek 2000). Just as for sediment budgets, however, comparisons between past and predicted processes should be made cautiously, at appropriate timescales, and with proper reference to the difference between past natural and future constraining conditions.

2.4 Volume loss due to compaction and peat oxidation

Developed lands that have surfaces at or below sea level require drainage. So-called 'water boards' (*waterschappen*, the oldest democratic institutions in the Netherlands, that also manage flood-protection systems) are responsible for water-table management. For this purpose, some 7.6 km^3/a of water is extracted from Dutch ground- and surface-water bodies (Dufour 2000). This is accomplished with systems of drainage canals and pumping facilities, most of which dating back centuries. In open country, mostly agricultural area, water-table management has become aimed primarily at crop optimisation (De Bakker & Van den Berg 1982).

Aeration of the soil results in the oxidation of its organic components, and in former peat swamps, now mostly grassland, this decomposition process has lead to significant land subsidence (e.g. Van Huissteden et al. 2006). Groundwater levels, defined relative to Dutch ordnance datum (*NAP*), are periodically adapted in order to maintain the desired unsaturated zone depths, exposing more and more peat to oxygen. In addition to this, drained soils compact as a result of pore-tension reduction. In this way, land subsidence has come to be self-perpetuating, having rates up to 5 cm/a and resulting in cumulative displacements of up to several meters. Note that we will not discuss salination, another problem for agriculture associated with drainage, and probably aggravated by sea-level rise.

Over the last years, agricultural interests are weighed against water-management policies to avoid land subsidence. For this purpose, the Geological Survey of the Netherlands has recently developed a method to assess the effects of water-management measures in terms of the resulting subsidence.

It involves a 3D subsurface model, water-management scenarios, and the calculation of subsidence using empirically obtained process rates (see De Lange et al. 2004 for a full methodological account). Compaction is calculated using (1):

$$\frac{\Delta h_t}{h} = \left(\frac{1}{C_p} + \frac{1}{C_s}\log\frac{\Delta t}{\Delta t_d}\right)\ln\left(\frac{\sigma_i' + \Delta\sigma'}{\sigma_i'}\right) \qquad (1)$$

where h and Δh_t are the layer thickness and thickness reduction at time t, respectively, C_p and C_s are the empirically obtained hydrodynamic and creep coefficients, respectively, Δt_d is the time interval of the compaction coefficient, and σ_i' and $\Delta\sigma'$ are the effective initial stress and stress increments, respectively. The effect of peat oxidation is modelled using (2):

$$\Delta h_t = h_{dry} \cdot (1 - e^{(-V_{ox} \cdot \Delta t)}) \qquad (2)$$

where Δh_t is the layer thickness reduction at time t, h_{dry} is the unsaturated zone thickness, V_{ox} is the empirically obtained peat oxidation rate (15 mm per metre of unsaturated soil per year), and Δt is the oxidation time.

Numerical solutions of (1) and (2), applied to geological voxel models, allow us to predict subsidence for each vertical stack of cells. This method was first applied to the central western province of Zuid-Holland, in order to classify the area in terms of subsidence susceptibility (Anonymous 2006). Because of a lack of measured subsidence data, we employed the same method to estimate current and future yearly volume losses in the dike-ring areas. The aforementioned upgraded geological model (see Fig. 2) was used as input, and we modelled subsidence for a period of 100 years. A maximum estimate was obtained with an initial unsaturated zone of 50 cm and a two-yearly adjustment to subsidence; a minimum subsidence estimate was calculated without this periodic adjustment (**Fig. 3**). 50 cm is a fair approximation of the average current practice in water-table management. As a starting point for our subsidence modelling, it is a more or less arbitrary value: the extent to which adjustment to subsidence is carried through is far more significant. As this extent is unknown, we have chosen to model the range between no adjustment and frequent adjustment throughout. The resulting volume loss for the dike rings is estimated between 9.4 and 28 million m³/a.

2.5 Human bulk material inputs

Building in the Dutch lowlands requires bulk amounts of filling sand as a foundation, to stabilise the building substrate and to create (or keep) sufficient elevation with respect to groundwater. Dutch use of filling material is about 57 million m³/a (average over the period 1999-2003; e.g. Van der Meulen et al. 2003, 2006a). This includes 45 million m³/a of sand, the remaining amount is secondary (i.e. recycled) fill and foundation material.

There are no statistics available as to where these materials are extracted and used, but provincial minerals-supply data allow for an approximation (Dumoulin 2004). The coastal provinces of Friesland, Groningen, Noord-Holland, Zuid-Holland and Zeeland, and the central provinces of Utrecht and Flevoland coincide, more or less, with the joint dike-ring area. **Table 1** shows that filling-sand consumption in these provinces amounts to 68% of the Dutch total (31 million m³/a in 1999–2003), while the share in the national production is 18% (8.1 million m³/a). This implies that some 23 million m³/a of filling sand is imported to the Dutch lowlands, most of which is derived from marine resources.

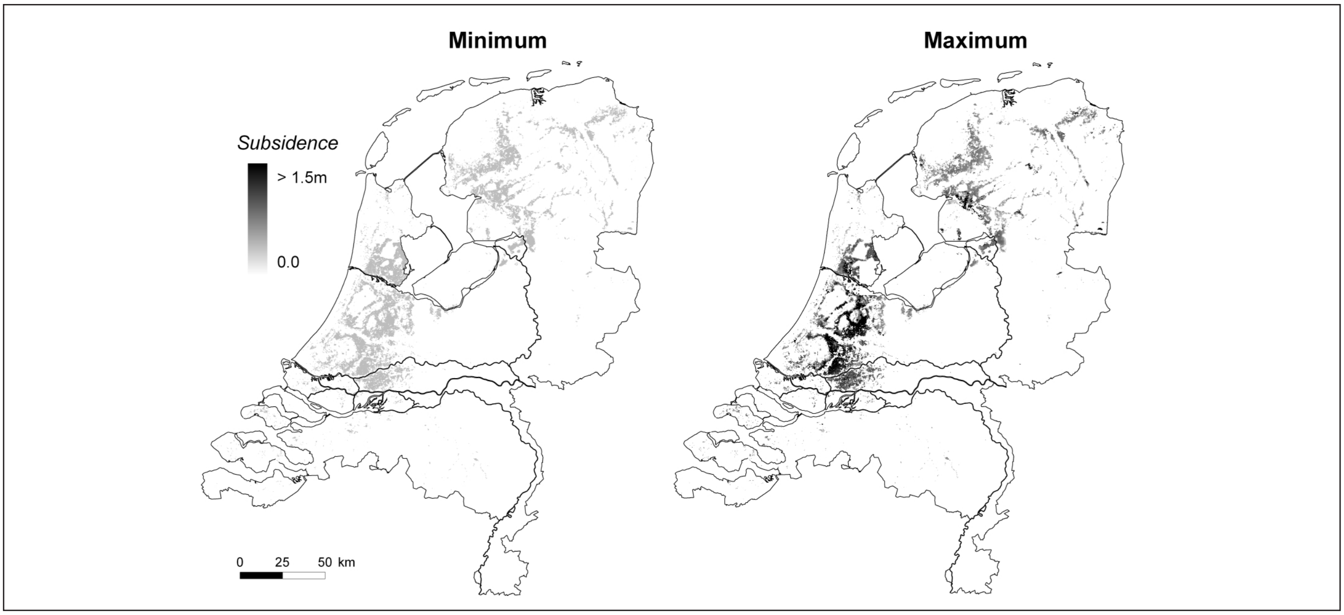

Fig 3: Subsidence associated with land drainage, caused by a century of modelled peat oxidation and compaction, in two scenarios. The minimum scenario is the response to a uniform initial, unadjusted unsaturated zone of 50 cm. The maximum scenario has the same starting point, but includes a two-yearly adjustment to subsidence. See text for further explanation

Table 1: Provincial filling-sand supply data for 2001–2002 (Dumoulin 2004), that allow for the estimation of human sediment inputs to the dike-ring areas (see text for explanation). Provincial production statistics are for land-based extraction only, and exclude sand extracted in the State Waters (mainly from the North Sea). The consumption statistics include all sand

	Province	Production (million m^3)	Consumption (million m^3)	Production share	Consumption share
Predominantly Lowlands ~ dike ring area	Flevoland	0.0	10.8	0.0%	10.1%
	Friesland	3.6	5.9	3.3%	5.5%
	Groningen	2.8	4.4	2.6%	4.2%
	Noord-Holland	2.5	16.4	2.3%	15.4%
	Utrecht	3.3	9.0	3.0%	8.5%
	Zeeland	0.0	14.7	0.0%	13.8%
	Zuid-Holland	6.6	10.8	6.0%	10.1%
	Total 2002–2003	**18.8%**	**72.1%**	**17.7%**	**67.7%**
Predominantly uplands	Drenthe	4.9	4.1	4.5%	3.8%
	Gelderland	11.4	12.4	10.5%	11.7%
	Limburg	2.8	2.5	2.6%	2.3%
	Noord-Brabant	8.1	8.9	7.5%	8.4%
	Overijssel	2.3	6.6	2.1%	6.2%
	Total 2002–2003	**29.6%**	**34.4%**	**27.8%**	**32.3%**

2.6 Historical sediment deficits

Processes and conditions that cause sediment deficiency and land subsidence, related to flood-protection and groundwater management, have been acting for about a millennium. Drainage was less efficient and pervasive in the early phases of this period and, accordingly, the associated subsidence has probably been much lower than presently observed. In contrast, peat extraction, which started out at the same approximate period but is presently virtually non-existent, has resulted in substantial historical volume losses.

The cumulative effect of all of this is the well-known sub-sea-level topography of the Dutch lowlands. Without going into the details and reconstruction of the governing processes, we approximate the cumulative effect of historical sediment deficiency with the negative difference between land surface and Dutch ordnance datum (~base level). The resulting volume, which is basically unused sediment accommodation space, is about 13.3 km^3. Its order of magnitude (billions of m^3) is in agreement with a millennium of sediment deficiency in the order of millions of m^3/a. For a reference, the volume of the IJsselmeer lake is about 5.2 km^3 (Ministry of Transport, Public Works and Water Management, The Hague, unpublished statistic; see Fig. 1).

3 Analysis and Discussion

3.1 Summary and inferences

Our results, summarised in **Fig. 4**, allow for the following inferences and observations:

- Impeding sedimentation in the dike-ring areas results in a predicted sediment deficit of 136 ± 67 million m^3/a, deficit being defined as the sum of the hypothetical sediment amounts required to keep up with the forecasted sea-level rise, and drainage-induced volume losses (due to peat oxidation and compaction).
- To some extent, human inputs of filling sand (~23 million m^3/a) can be considered a compensation for this: a mere 17% in the total sediment balance, but locally substantial when taking into account the fact that fill is applied on a fraction of the dike-ring surface area.
- Volume losses due to peat oxidation and compaction (19 ± 9 million m^3/a) and human inputs (sand filling) seem to be more or less in balance, but obviously do not coincide geographically.
- Keeping up with sea-level rise, for any scenario, would require more sediment than the net inputs observed in the recent geological past (10 million m^3/a). From this

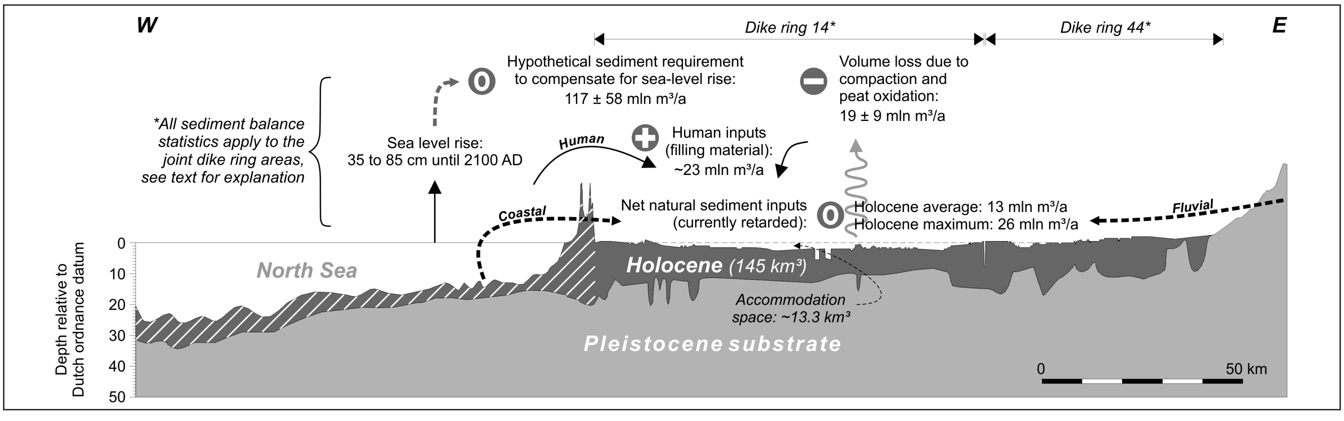

Fig. 4: Cross section (see Fig. 1 for profile line) and summary of the sediment balance for the dike-ring areas. White hatching indicates Holocene sediments outside the study area. (+), (–) and (0) refer to positive, negative, and zero or retarded contributions to the Dutch sediment balance, respectively

observation, the habitation of the Dutch lowlands would seem to be unsustainable. Even though higher sedimentation rates in the early Holocene may seem to suggest the opposite, the resilience of the sedimentary system in its current state is low, as its constituting processes have been retarded, and all that is left to cope with sea-level rise is human countermeasure.

- Compensation of the annual sediment deficit by means of human inputs would quantitatively seem to be within reach, as the sediment requirement for this has the same order of magnitude as filling-sand consumption. The same applies to compensating the back-lag volume of 13.3 km^3, provided that sufficient time is allowed for this (e.g. one century). However, raising developed lands obviously presents practical difficulties, and requires a planned effort.

3.2 Implications of sediment deficiency

The Dutch approach to the habitation of the lowlands is an elaborate flood-protection and drainage system, that allows for a more or less free choice in the allocation of land-use functions. However, the resulting regional sediment deficits have rendered the country vulnerable to some of the predicted effects of climate change: rising sea and groundwater levels, and higher peak river discharges, precipitation intensities and storm (surge) frequencies. The increased risks associated with the disperse accumulation of population and wealth behind the Dutch flood-defence system have come to be well-acknowledged.

In response to this, Dutch water management is in the process of changing from defence- towards adaptation-oriented (Tielrooij et al. 2000). The best example of this is the choice to increase the discharge capacities of the rivers Rhine and Meuse rather than raising the dikes (Van der Meulen et al. 2006b). However, while measures such as these can essentially be accommodated in the existing layout of the country, a full solution to the problems outlined above probably cannot. Hence, widening the time horizon for water management and land-use planning may significantly change the views on living with water in the Netherlands, or on living in the Netherlands altogether.

It seems inevitable that, in the long term, some wettening of the lowlands is going to have to be accepted as a matter of fact, whether it be to accommodate excess water, or in order to avoid further subsidence of peatlands. The question is what the consequences are for land use. To whatever extent and frequency water will be allowed to enter the dike rings, it basically implies abandoning the concept of uniform flood protection for each dike ring. And in whatever configuration water will be allowed to enter (designated flood-buffer zones, wetlands, lagoons, lakes, etc.), built-up areas will probably need additional water protection if they are to be maintained.

The aforementioned New Orleans example shares some similarities with the Dutch situation, as both areas have a subsea-level topography that is in part the result of human intervention with sedimentary systems. The main difference is the flood protection level: 200–300 years for New Orleans and 10,000 years for the Dutch coastal area. In that respect, failure of New Orleans' flood defence system is not surprising, but it serves to illustrate that flood resistance strategies may obscure the need to consider resilience. While hurricanes are the most important, imminent threat to New Orleans, the Dutch face a combination of extreme events and more gradual deterioration. The higher current protection levels present more favourable conditions for the development of adaptive strategies.

3.3 Anticipation and adaptation

There are several ways to anticipate on the trends and changes discussed here. Most importantly, it would seem to be logical that lowland areas that are to be built up anyway, especially the deepest polders, should be raised higher than in current practice. For new urban and industrial zones, this would be aimed at providing not only a firm building substrate, but also longer-lasting flood-protection possibilities. Raising parts of the main infrastructure (e.g., as part of road-building or reconstruction projects) has the potential of offering additional compartmentation of dike-ring areas, which would reduce the flooding extent in case of a disaster. For road and railway infrastructure in lowland areas, the use of excess amounts of filling sand is in fact common practice, aimed at the enhanced and accelerated compaction and stabilisation of the underlying soil. Excess fill, however, is now removed and reused.

Building on higher-raised grounds should in principle be affordable, even if it would double or triple filling-sand consumption. The costs of this are roughly estimated at 0.5 to 1 G€/a (c.f. Van der Meulen et al. 2006a), i.e. ~2% of total current Dutch building investments (note that this does not include the costs of additional provisions for building on raised grounds). For a reference: tripling the use of filling-sand would add ~120 million m^3/a to the lowlands ($3 \cdot 45$ million m^3/a minus filling sand use in the uplands), and approximately equate the expected annual sediment deficits. 100 years of tripled supplies (12 km^3) would approximately equate the back-lag deficiency volume. Hence, a strategic, properly prioritised land-raising programme would have the potential of compensating up to one half of the Dutch sediment-deficiency problems in a century. Given the fact that less than half of the lowlands will be built-up by that time, this is more than sufficient. Marine sand is the most appropriate resource for this purpose, and the supply-infrastructure for this material is already in place. Note that this idea is not new. Beach and coastal nourishment as a compensation for sediment deficiency in the Dutch coastal system has been common practice since 1990; it involves ~12 million m^3 of sand per year (Van Koningsveld & Mulder 2004). Living on raised grounds (on mounds; *terpen*) has been common practice in the northern provinces up till mediaeval times.

Obviously, adaptation to climate change and sediment deficiency involves more than bringing in bulk amounts of sand. In the lowlands, for example, open country is now mostly agricultural while nature is concentrated on the higher grounds; this long-established general zoning has been consolidated in the most recent National Spatial Plan (Anonymous 2004). In view of the above, however, partial transfer of these functions may be called for: wetland nature instead of farmland between raised built-up areas in the lowlands, and (more) agriculture or other forms of development instead of nature on the higher grounds. An interesting aspect of wetlands is the potential to reinstate peat formation, which would (1) offer some additional compensation for sediment deficiency, and (2) act as carbonate sink. Underground construction, that is currently promoted as a means of more efficient land use in the densely populated country (e.g. COB 2000), may also require some reconsideration. Constructions such as tunnels are expensive and usually have relatively long life cycles, possibly within the time range of the deteriorating conditions discussed here (higher flooding risks, increased hydrostatic pressure, etc.). An interesting alternative is to build such structures at the surface, prior to land raising. A further discussion of such planning considerations, as well as the interesting design options presented by building on higher-raised grounds, falls outside the scope of the present paper.

4 Conclusions, Recommendations and Perspectives

Sediment deficiency in the Dutch lowlands renders the country vulnerable to Global Change. We have quantified this deficiency in first-order approximation, and argue that it could in principle be compensated by a sustained land-raising programme. Tripling the current use of filling sand would seem to be affordable, and effective in about one century.

Further research will have to focus on the urgency and feasibility of such an undertaking: politically, economically and practically. It would first require policy and decision makers to adopt a wider planning horizon than the current one for water management and land-use planning. As to economical and practical feasibility, we recommend the development of long-term scenarios for the changing physiography of the Dutch lowlands, that include the impacts of climate change on water systems, sediment deficiency, possible compensation measures, costs *and* benefits, and the implications for long-term land-use options. Apart from the obvious water-management and engineering considerations, such scenarios require a strong focus on sediments – system analyses, resources, management issues – in order to be meaningful (see Brils 2002, Brils & De Deckere 2003, Owens 2005).

Acknowledgements. This paper was inspired by the Dutch Sediment Forum, a discussion group founded by Hanneke Gieske (Delfland Water Board). The authors wish to thank Meindert van den Berg and Ipo Ritsema (TNO), Gilles Erkens, Albert van der Meulen and Roy Frings (Utrecht University), and Albert Oost (RIKZ National Institute for Coastal and Marine Management) for discussions and suggestions. Phil Owens and an anonymous reviewer are thanked for helpful suggestions.

References

Anonymous (2004): Nota Ruimte (National Spatial Plan, in Dutch). Ministry of Housing, Spatial Planning and the Environment, The Hague, Netherlands, 206 pp

Anonymous (2006): Bodemvisie Zuid-Holland (Policy document on the subsurface in spatial planning in the Province of Zuid-Holland, in Dutch). Province of Zuid-Holland, The Hague, Netherlands, 108 pp

Beets DJ, Van der Spek AJF (2000): The Holocene evolution of the barrier and the back-barrier basin of Belgium and the Netherlands as a function of Late Weichselian morphology, relative sea-level rise and sediment supply. Netherl J Geosci 79 (1) 3–16

Brils J (2002): The SedNet Mission. J Soils Sediments 2 (1) 2–3

Brils J, De Deckere E (2003): SedNet – An Evolving Network Aimed at Sustainable Sediment Management. J Soils Sediments 3 (3) 127–128

COB – Netherlands Centre for Underground Construction (2000): Planologische visie ondergronds ruimtegebruik, verslag van een deltasessie (in Dutch). CUR/COB, Gouda, Netherlands, 42 pp

De Bakker H, Van den Berg MW (1982): Proceedings of the symposium on peat lands below sea level. ILRI publication 30, Wageningen University, Wageningen, Netherlands, 296 pp

De Lange G, Van der Linden W, Veldkamp JG, Bremmer CN (2004): Modelling time-dependent compaction and oxidation in a stochastically derived top layer system with a modified IBS-3 package. Proceedings of the International Conference on Finite-Element Models, Modflow, and more, Karlovy Vary, Czech Republic, 13–16 September 2004, Digital publication on CD-ROM, 11 pp

De Mulder EFJ, Geluk MC, Ritsema I, Westerhoff WE, Wong TE (2003): De ondergrond van Nederland (The Dutch subsurface, in Dutch). Wolters Noordhof, Groningen, Netherlands, 379 pp

Dufour FC (2000): Ground water in the Netherlands – Facts and Figures. TNO Built Environment and Geosciences – Geological Survey of the Netherlands, Utrecht, Netherlands, 96 pp

Dumoulin P (2004): Monitoring ophoogzand (Monitoring of filling sand, in Dutch). Publicatiereeks Grondstoffen 2004/08, Road and Hydraulic Engineering Institute, Delft, Netherlands, 55 pp

Erkens G, Cohen KM, Gouw MJP, Middelkoop H, Hoek WZ (2006): Holocene sediment budgets of the Rhine Delta (The Netherlands): A record of changing sediment delivery. In: Rowan JS, Duck RW, Werritty A (eds), Sediment Dynamics and the Hydromorphology of Fluvial Systems. IAHS Publ 306, 406–415

Middelkoop H (1997): Embanked floodplains in the Netherlands; Geomorphological evolution over various time scales. PhD thesis Utrecht University, Utrecht, Netherlands, 352 pp

Olsthoorn AA, Van der Werff PE, Bouwer LM, Huitema D (2005): Neo-Atlantis: Dutch Responses to Five Meter Sea Level Rise. Hamburg University and Centre for Marine and Atmospheric Science, Hamburg, Working paper FNU-75, 20 pp

Owens PN (2005): Conceptual Models and Budgets for Sediment Management at the River Basin Scale. J Soils Sediments 5 (4) 201–212

Tielrooij F, Van Dijk J, De Blécourt J, Van den Ende A, Oosterbaan GA, Overbeek HJ (2000): Waterbeleid voor de 21e eeuw (Water policy for the 21st century, in Dutch). Commissie Waterbeheer 21e eeuw, The Hague, Netherlands, 50 pp

TNO (2006a): Dinoloket (Internet portal for Geo-Information): <http://dinolks01.nitg.tno.nl/dinoLks/DINOLoket.jsp>

TNO (2006b): Delfstoffen Online (Minerals Online): <http://dinolks01.nitg.tno.nl/dinoLks/delfstoffen/index.html>

Van Alphen JSLJ, Damoiseaux MA (1989): A geomorphological map of the Dutch shoreface and adjacent part of the continental shelf. Netherlands J Geosci 68 (4) 433–443

Van Huissteden J, Van den Bos R, Marticorena Alvarez I (2006): Modelling the effect of water-table management on CO_2 and CH_4 fluxes from peat soils. Netherlands J Geosci 85 (1) 3–18

Van der Meulen MJ, Koopmans TPF, Pietersen HS (2003): Construction raw materials policy and supply practices in Northwestern Europe. In: Elsen J, Degryse P (eds), Industrial Minerals – Resources, Characteristics and Applications. Aardk Mededel 13, 19–30

Van der Meulen MJ (2005): Sustainable mineral development: Possibilities and pitfalls illustrated by the rise and fall of Dutch mineral planning guidance. In: Marker BR, Petterson MG, McEvoy F, Stephenson, MH (eds), Sustainable Minerals Operations in the Developing World. Geol Soc Spec Publ 250, 225–232

Van der Meulen MJ, Van Gessel SF, Veldkamp JG (2005): Aggregate resources in the Netherlands. Netherlands J Geosci 84 (3) 379–387

Van der Meulen MJ, Broers JW, Hakstege AL, Pietersen HS, Van Heijst MWIM, Koopmans TPF (2006a): Surface mineral resources. In: Wong TE, Batjes DAJ, De Jager J (eds), Geology of the Netherlands. Royal Netherlands Academy of Arts and Sciences (KNAW), Amsterdam, Netherlands (in press)

Van der Meulen MJ, Rijnveld M, Gerrits LM, Joziasse J, Van Heijst MWIM, Gruijters SHLL (2006b): Handling sediments in Dutch river management: The planning stage of the Maaswerken river widening project. J Soils Sediments 6 (3) 163–172

Van der Spek AJF (2004): Sediment accumulation in Atlantic back-barrier basins in the Netherlands: fine-grained infilling under high rates of sea-level rise. In: Bartholdy J, Pedersen JBT (eds), Tidalites 2004, 6th International Conference on Tidal Sedimentology, August 2–5, University of Copenhagen, Denmark, pp 167–170

Van Koningsveld M, Mulder JPM (2004): Sustainable Coastal Policy Developments in the Netherlands – A Systematic Approach Revealed. J Coastal Res 20 (2) 375–385

Received: September 18th, 2006
Accepted: December 18th, 2006
OnlineFirst: December 19th, 2006