Geologie en Mijnbouw **72**: 237–249, 1994.

Modelling of potential effects of long-term fluvial dynamics on possible geological storage facilities of nuclear waste in the Netherlands

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Received 4 March 1993; accepted in revised form 29 October 1993

Key words: finite state modelling, geological barrier-system, OPLA, Rhine, Meuse

Abstract

Within the programme of investigation for suitable safe geological sites (such as salt diapirs) for long-term storage of radioactive waste (OPLA), a modelling study of long-term effects of fluvial dynamics was carried out. The model used, FLUVER, allows long-term simulations of the combined effects of climatic change, tectonism, sea level and initial relief on fluvial erosion. As an exercise, landscape development scenarios of a Rhine-Meuse type system with climate and base-level dynamics related to Milankovitch's astronomical theory, during stable, uplifting, and subsiding tectonic scenarios, are simulated and discussed. Under the assumptions that climate and base-level changes can be described with Milankovitch's theory and that tectonic activity in the Netherlands will not change considerably during the next hundred thousands of years, it can be concluded provisionally that the maximum fluvial erosion depth in the next few hundred thousand years is unlikely to exceed 100 metres and to reach a salt diapir.

Introduction

Safe storage of radioactive waste poses an increasing problem. In the Netherlands this has led to a programme of investigation for suitable safe geological sites for long-term storage of radioactive waste (OPLA 1984). This programme is executed under subcontract to the 'Commission on Disposal on Land (OPLA)'. From the Dutch safety point of view, salt occurrences seem the most promising long-term storage facilities. The GEO-1A project is mainly focused on the natural isolation capacity of the rock types in, above and around potential geological storage facilities. Together, these rock types form the so-called 'geological barrier-system'. The GEO-1A research programme is divided into five fields of interest, of which geology is one. The Geological Survey of the Netherlands (RGD) executed one of the research projects in this field. This project is mainly aimed at a description of the actual and long-term future conditions of geological barrier-systems. Because a suitable site should isolate the stored waste for more than 100000 years (100ka), i.e. at least one glacial-interglacial cycle, the stability of the geological barrier must be reviewed for such a time span.

Previous OPLA research by the Geological Survey of the Netherlands concluded that several geological processes determine the long-term stability and state of salt structures. In addition to salt dissolution, subglacial erosion, halokinesis and diagenesis, fluvial erosion is one of the dominant pro-

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cesses able to affect a potential storage facility (Wildenborg et al. 1990). Fluvial systems have played an important role in the Quaternary geological history of the Netherlands. Large quantities of sediments were eroded, transported and deposited by large fluvial systems such as the Rhine, Meuse and Scheldt (Brunnacker & Boenigk 1983; De Groot et al. 1992). The net erosional effects of these fluvial systems do not seem very spectacular, but after a glacial-interglacial cycle they could have considerable impact on any Dutch geological barrier-system under consideration. The deepest known Quaternary fluvial incision in the Netherlands is found in South Limburg where the Meuse eroded a valley of approximately 150 m in an uplifting region (Van den Berg 1992). Should such an erosional event take place in the northeastern Netherlands, then it could easily expose the most shallow salt diapirs (Wildenborg et al. 1990).

Because one of the goals of the OPLA-1A project is to give indications of the long-term stability of potential radioactive waste disposal facilities, it was decided to attempt modelling the long-term effects of fluvial erosion with special emphasis on the long-term dynamics (100–500ka) of vertical erosion. Because fluvial dynamics in the Netherlands have been mainly determined by the combined effects of climatic change, tectonism and sea level changes (De Groot et al. 1992), these effects have to be incorporated in a model simulating fluvial erosion effects. Because an existing fluvial terrace formation model (Veldkamp & Vermeulen 1989; Veldkamp 1991) met most formulated requirements it was selected as main model. A tuned version for the Meuse (Veldkamp & Van den Berg, in press) was adapted and applied to model potential long-term effects of fluvial erosion in the Netherlands. In order to assess the maximum potential fluvial erosion, fluvial dynamics similar to those of the two largest Dutch fluvial systems, the Rhine and Meuse, were simulated.

Model description

The model used to simulate FLUVial ERosion (FLUVER) is a discrete 'finite state' model with time steps of 2 ka. Model construction, organization, operation and testing are extensively described in previous papers (Veldkamp & Vermeulen 1989; Veldkamp 1992) and will only be summarized. Interactions between the two entities, LANDSCAPE and RIVER, are defined as erosion and sedimentation processes acting in time steps of 2 ka. In Fig. 1, a schematic flow chart of the FLUVER model is given, with inputs, model variables and states. During a simulation, the volume eroded or deposited by the RIVER in the LANDSCAPE is calculated for each time step. These calculations are followed by state determinations and boundary calculations within which LANDSCAPE changes take place. The LANDSCAPE is changed by modifying grid cell elevations in response to the acting process. The changed LANDSCAPE is stored in a geographical information system (GIS). The way erosion and sedimentation processes act in the LANDSCAPE is determined by decision rules based on calculated conditions which are extracted from general literature on hydrology (Leopold et al. 1964; Schumm 1977). More details on these decision rules and the way they were extracted are given in a previous paper (Veldkamp 1991).

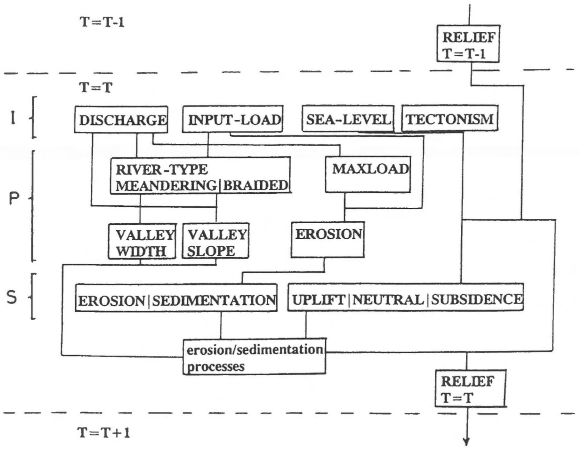


Fig. 1. Flow chart of FLUVER. (I) = model inputs, (P) = model parameters, (S) = model states.

These model processes are long-term and large-scale analogies of real erosion and sedimentation processes which react to changes in the 2 ka climate-controlled discharge-sediment load equilibrium. When sediment input load exceeds the sediment transport capacity the difference is deposited, and in case transport capacity exceeds the input load the difference is eroded in the simulated system. The zone with active erosion migrates headward along the longitudinal profile, while the sedimentation zone migrates in downward direction. Changes in the floodplain width of a meandering RIVER during the simulation cause the headward moving erosional zone to change in effective width. The resulting irregular bank erosion has a similar effect as caused by a meandering system. Except for changes in climate the simulated system also reacts to changes in base-level and vertical crustal movements. In case of uplift or base-level lowering, the fluvial system will strive to compensate by erosion, which is not always possible since climatic conditions may be such that the simulated system tends to deposition. A similar relationship applies for subsidence and base-level rise which will stimulate sedimentation in the simulated system.

Model inputs

A first and well-known generalization about changes in fluvial dynamics due to changes in an external factor can be found in 'Huntington's principle' (Huntington 1907), which related fluvial response to climatic change. Later, other major generalizations were formulated, also taking into account the effects of base-level and tectonism (McGregor & Green 1978; Starkel 1983; Gregory et al. 1987). In FLUVER these three factors are used as input variables. In addition to climate, tectonism and base-level, initial relief is also an input variable, an often neglected factor which can strongly determine the effects of fluvial erosion.

Climate

Quaternary climatic changes have been global and synchronous. The waxing and waning of continental ice caps and climatic zones have been satisfactorily correlated to the astronomical parameters of Milankovitch's theory as evidenced from calibration procedures carried out on both continental (Kukla 1987) as well as deep-sea records (Imbrie et al. 1984; Shackleton et al. 1990). Continental ice caps and related sea-ice fields in the northern hemisphere strongly influenced the ocean-continent heat transfer and the jet-stream-related depression tracks (COHMAP members 1988), thus affecting northwest European climate. The relationship between climatic behaviour and fluvial dynamics depends on the nature of climatic change and the effect of such changes on discharge distribution and sediment load (Lowe & Walker 1984). Fluvial system response is usually out of phase with temperature changes which are satisfactorily described by Milankovitch's theory. For FLUVER, the following generalizations about climatic conditions and average 2 ka discharge and 2 ka sediment load are used. During *Glacial* episodes the southward expanding high pressure areas forced the depression tracks and the vegetation belts towards lower latitudes. The shift of the vegetation belts lead to a vegetation type (tundra) in the northwest European drainage basins which was particularly sensitive to high-frequency changes in the climatic system and caused an increase of sediment supply to the fluvial systems like Rhine and Meuse. The southward shift of the depression tracks lead to more continental and drier conditions (Guiot et al. 1989; Raymo et al. 1989; Ruddiman et al. 1989) causing relatively low mean discharges in the rivers during these periods. *Interglacials* yielded an opposite picture, an increase in the mean discharge and a complementary decrease in sediment supply to the simulated system. These changes in mean discharge and sediment supply did not occur simultaneously. Discharge can be seen as a direct result of precipitation, but sediment supply is a function of vegetation cover, a factor which needs time to adjust to a change in climatic conditions. The climate-related changes in mean sediment supply and discharge are thus out of phase, with mean sediment load lagging behind mean discharge.

Model simulations require a climatic input with a constant reliability during the simulated time span. Therefore, a simplified Milankovitch curve was proposed as basic climatic input, applied in a similar way as in previous model versions (Veldkamp & Vermeulen 1989; Veldkamp 1991), whereby the change in general climatic conditions is related linearly to fluvial input variables. It is hereby assumed that mean discharge is approximately 2 ka (one time step) out of phase with changes in mean temperature. Consequently, discharge, Equation (1), is simulated as the sum of three sinus (SIN) functions and input load, and input load, Equation (2), as the sum of three cosinus (COS) functions, of the earth-orbit parameter periods of 23000, 42000 and approximately 100000 years, as found in $d^{18}O$ curves by Hays et al. (1976) and in palynological records by Guiot et al. (1989).

$$\text{DISCHARGE} = \text{DAVE} + \text{DAMP} \times [\text{SIN}(2\pi \times \text{TIME}/100) + \text{SIN}(2\pi \times \text{TIME}/42) + \text{SIN}(2\pi \times \text{TIME}/23)] \tag{1}$$

$$\text{INPUT-LOAD} = \text{INLAVE} + \text{INLAMP} \times [\text{COS}(2\pi \times \text{TIME}/100) + \text{COS}(2\pi \times \text{TIME}/42) + \text{COS}(2\pi \times \text{TIME}/23)] \tag{2}$$

with:

DISCHARGE	: Discharge	(m^3 s-^{1})
DAVE	: Average discharge	(m^3 s^{-1})
INPUT-LOAD	: Input load	(m^3 s-^{1})
INLAVE	: Average input load	(m^3 s^{-1})
DAMP	: Discharge amplitude	(m^3 s-^{1})
INLAMP	: Input load amplitude	(m^3 s-^{1})
TIME	: Time	(ka)

Tectonism

The importance of lithospheric stresses (basin uplift and subsidence) on sedimentation or erosion has been demonstrated by models developed by Cloetingh et al. (1986). Such model studies show that second-order (1–10 million years (Ma)) data can be validated by stratigraphical studies in basins and fission-track chronologies in uplifting areas. Rates of vertical crustal movement are inferred only in a general way, averaged over at least 1 Ma. However, measurements of actual uplift rates through repeated levelling in basins and mountains often indicate much greater uplift or subsidence rates for this century than calculated Cenozoic averages. If uplift rates of 10-20 mm/year as measured, for example, in the Caucasus and New Zealand and subsidence of 10-20 mm/year such as in Venice (Lilienberg 1985) are maintained through 1 Ma, unrealistic amounts of vertical crustal movements must result. Therefore, vertical crustal movements during the Quaternary were probably not uniform in time, but very little is known on the actual discontinuity of such movements. Resolution in basin stratigraphy and fission-track chronology is often insufficient to single out datable events on shorter time scales.

Geomorphological and sedimentological information, especially the study of marine and fluvial terraces, can lead to a refinement of the history of vertical crustal movements. This is because terrace formation closely records third-order (0.1 Ma, Milankovitch type) climatic and sea level variations in uplifting areas. A first reconstruction on regional uplift rates in South Limburg (the Netherlands) seems to support this preliminary conclusion (Van den Berg 1992). An analysis of basin fills using dynamic models may give more clues about the variation in subsidence rates in basins. As only very few of such detailed reconstructions have been carried out for the Quaternary time scale, we will use average Quaternary crustal movement rates as input in FLUVER. Only average uplift or subsidence rates will be used. The effect of using crustal movements in FLUVER is that the simulated fluvial system will always try to compensate any crustal change by erosion or sedimentation whenever the system state allows it.

Base-level

Throughout the Phanerozoic, eustatic sea level changed many times, affecting directly and indirectly erosion and sedimentation processes (Vail et al. 1977). During the Quaternary, global sea levels changed even more often and more dramatically in response to episodes of glaciation and deglaciation (Pirazzoli 1991). Lowering of the sea level during glacials is thought to be due to the storage of large water quantities in ice masses on land. Sea level rise during warmer interglacials is caused when water is restored to the oceans (King 1972; Bloom et al. 1974; Pirazzoli 1991). This theory is strongly supported by deep-sea sediment records and flights of marine terraces. Climate is thus assumed to be the dominant steering factor of sea level changes. To obtain a general base-level curve input, a simplified version of the widely accepted Milankovitch curve is also proposed as an input function, describing climatic changes in the Quaternary as a result of astronomical parameters (Bradley 1985). Consequently, sea level is simulated as the sum of three sinus (SIN) functions of the earth-orbit parameters precession, obliquity and eccentricity respectively. The sea level curve is, of course, also out of phase with the mean temperature curve as it takes time for the earth system to respond to climatic changes.

The following generalized relation between time (simplified insolation curves) and mean sea level is incorporated in FLUVER.

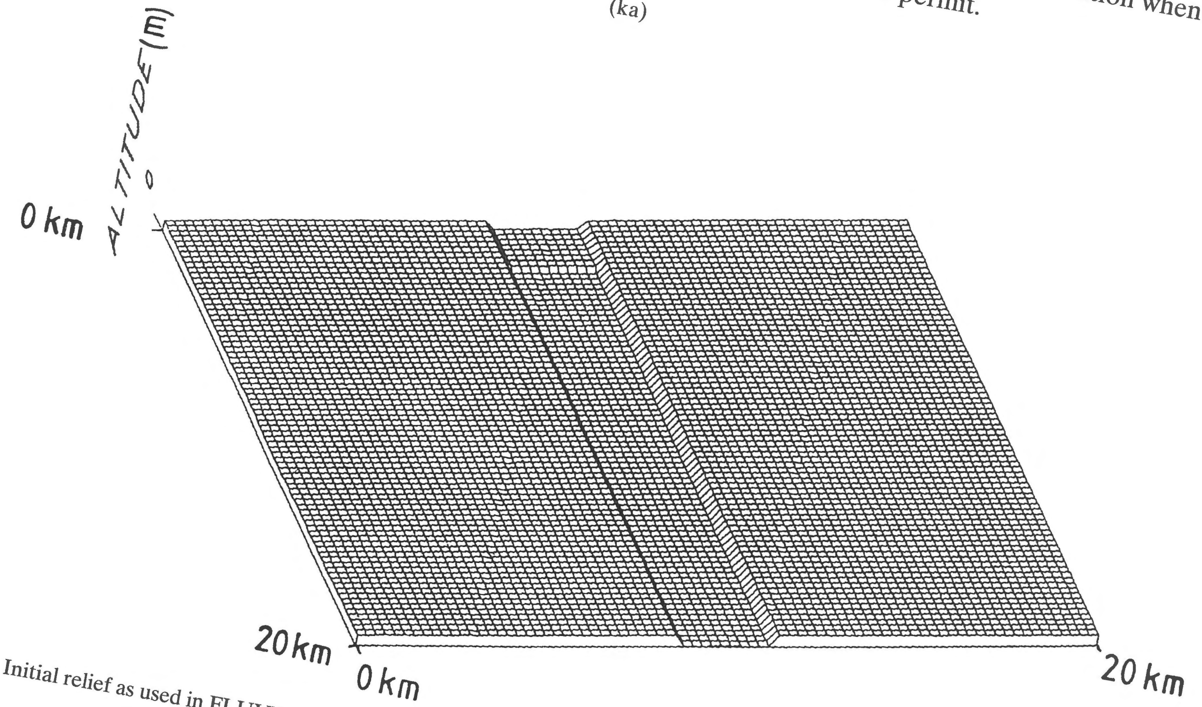
$$\text{SEA-LEVEL} = \text{SEALEVEL-AVE} + \text{SEALEVEL-AMP} \times (\text{SIN}(2\pi \times \text{TIME}/100) + \text{SIN}(2\pi \times \text{TIME}/42) + \text{SIN}(2\pi \times \text{TIME}/23)) \tag{3}$$

with:

SEA-LEVEL	: Sea level	(m)
SEALEVEL-AVE	: Average sea level	(m)
SEALEVEL-AMP	: Sea level amplitude	(m)
TIME	: Time	(ka)

The SEALEVEL-AVE is a chosen level be tual sea level and the SEALEVEL-AMP i and derived from literature (Milliman & 1968; Bloom et al. 1974).

Sea level always acts as the ultimate base-lev any fluvial system. The effects of base-level cha are not uniform throughout the whole fluvial tem; base-level effects decrease upstream along longitudinal profile. In the Dutch situation, baselevel effect during the last two glacials w more than 100 m at the continental shelf edge, 20 at the actual coast line, and 10 m at the Dutch-Ger man state border (Smith 1985; De Groot & D Gans, in press). In order to allow realistic FLUVER simulations for the Netherlands, it is assumed that the maximum base-level effect is 20 m. This value is selected because several salt diapirs occur below the southern North Sea and the northern Netherlands. The basic assumption by using base-level changes in FLUVER is that the simulated fluvial system will always try to compensate any base-level change by erosion or sedimentation whenever system conditions permit.



g. 2. Initial relief as used in FLUVER; relief area is 20 × 20 km^2. The initial valley is 5 m deep.

Table 1. Used domains of attributes of model entities as used during simulation examples discussed.

A. Time	1: < Time	< 500 (ka)	(Time steps of 2 ka)	
B. Entities				
1. Entity: RIVER				
Attributes	Domain			
1.1 Discharge	: 2×10^{12}	< Discharge	< 3×10^{13}	(m^3/2 ka)
1.2 Input-load	: -1.2×10^{9}	< Input-load	< 2.8×10^{8}	(m^3/2 ka)
1.3 Form	: meandering or braided			(–)
1.3.1 Flood-plain-width	: 0.3	< Fl-pl-width	< 19.7	(km)
1.3.2 Maxload	: 7.05×10^{-5}	< Maxload	< 4.5×10^{-3}	($m^3 s^{-1}$)
1.4 Erosion	: -2.1×10^{-3}	< Erosion	< 4.5×10^{-3}	($m^3 s^{-1}$)
2. Entity: LANDSCAPE				
Attributes	Domain			
2.1 Quplift	: − 0.5	< Quplift	< 0.5	(m/ka)
2.2 Quplift-unequal	: 0	< Quplift-unequal	< 0.05	(m/ka)
2.3 Base-level-effect	: − 10	< Base-level	< 10	(m)
2.4 Relief x,y,z	: 150	< x	< 15000	(m)
	150	< y	< 15000	(m)
	1	< z	< 500	(m)
2.4.1 Valley-depth	: − 150	< Valley-depth	< 500	(m)
2.4.2 Stratigraphy	: 0	< Stratigraphy	< 500	(ka)
2.5 Valley-width	: 0.3	< Valley-width	< 19.7	(km)

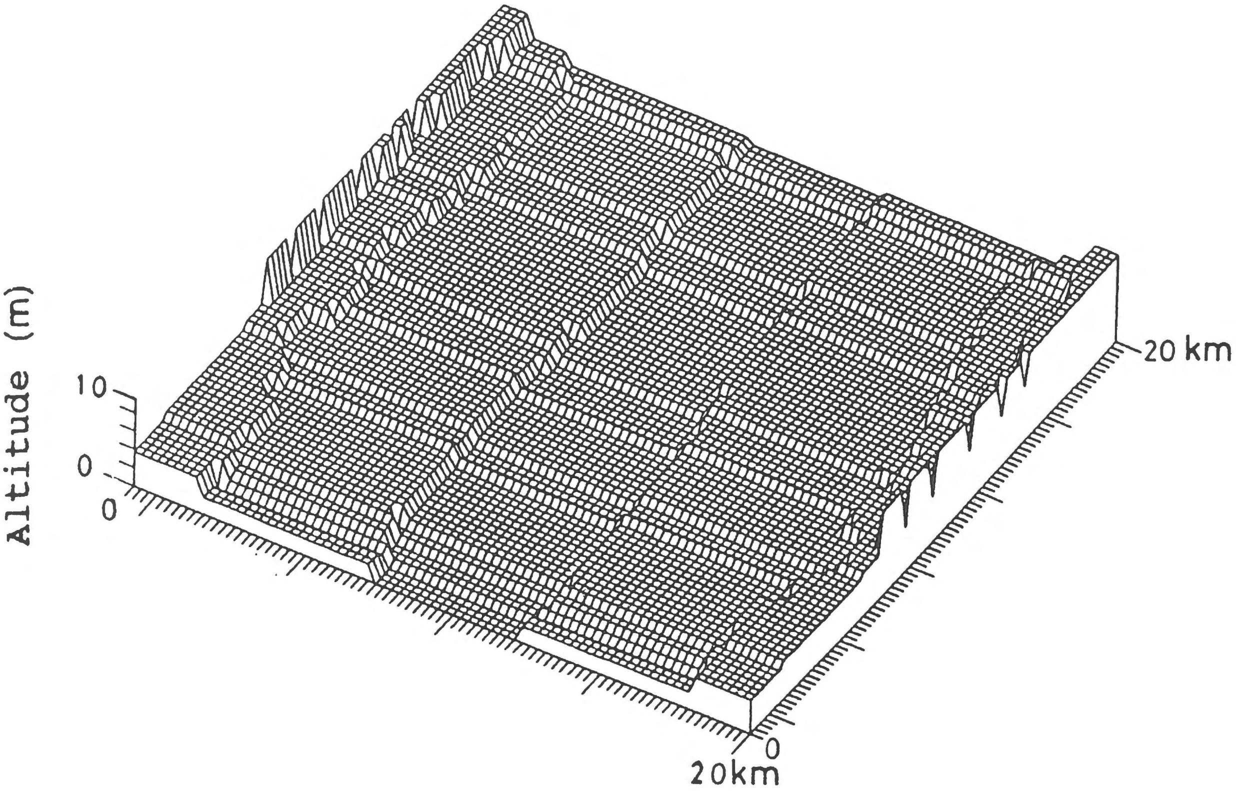


Fig. 3. Relief (20×20 km^2) after 500 ka in simulation of a stable tectonic scenario.

Initial relief

As initial relief, a strongly simplified relief is used which the simulated fluvial system can easily reshape. The chosen initial relief has a surface of 400 km^2 (20 * 20 km), a maximum altitude of 500 m and a minimum altitude of – 150 m (Fig. 2). The initial relief consists of a valley with a width of 2000 m and a depth of 5 m only. Fluvial stratigraphy displays only age 0 indicating that no fluvial sediments occur in the initial LANDSCAPE. The lithology of the simulated landscape has a low resistance against erosion processes, a characteristic only valid for unconsolidated sediments.

Model outputs

At each time step, 3-D pictures can be made of the simulated landscape (x,y,z). Series of these three-dimensional pictures (Figs 3, 6, 9), showing the relief morphology, can demonstrate the erosional dynamics of the simulated fluvial system. The X-axis is the cross-sectional direction, the longitudinal direction coincides with the Y-axis and the Z-axis gives the altitude of the relief. A visualization of the dynamic properties of the simulated example is shown in Figs 4, 7 and 10, which show the fluvial dynamics in one cross section at y = 9 km, during the simulated time span of 500 ka. The development of one cross section in time visualizes the pulsating (alternating erosion and sedimentation) character of the simulated Rhine-Meuse-type system in the Netherlands. The stratigraphy of this same cross section (y = 9 km) after the simulated 500 ka is given in Figs 5, 8 and 11. Sediment 'ages' are given in deposition time during the simulation. In the drawn cross sections, sediments of 'age' class 0–100 (ka) are the oldest and those deposited during the last 100000 simulated years (400–500 ka) the youngest.

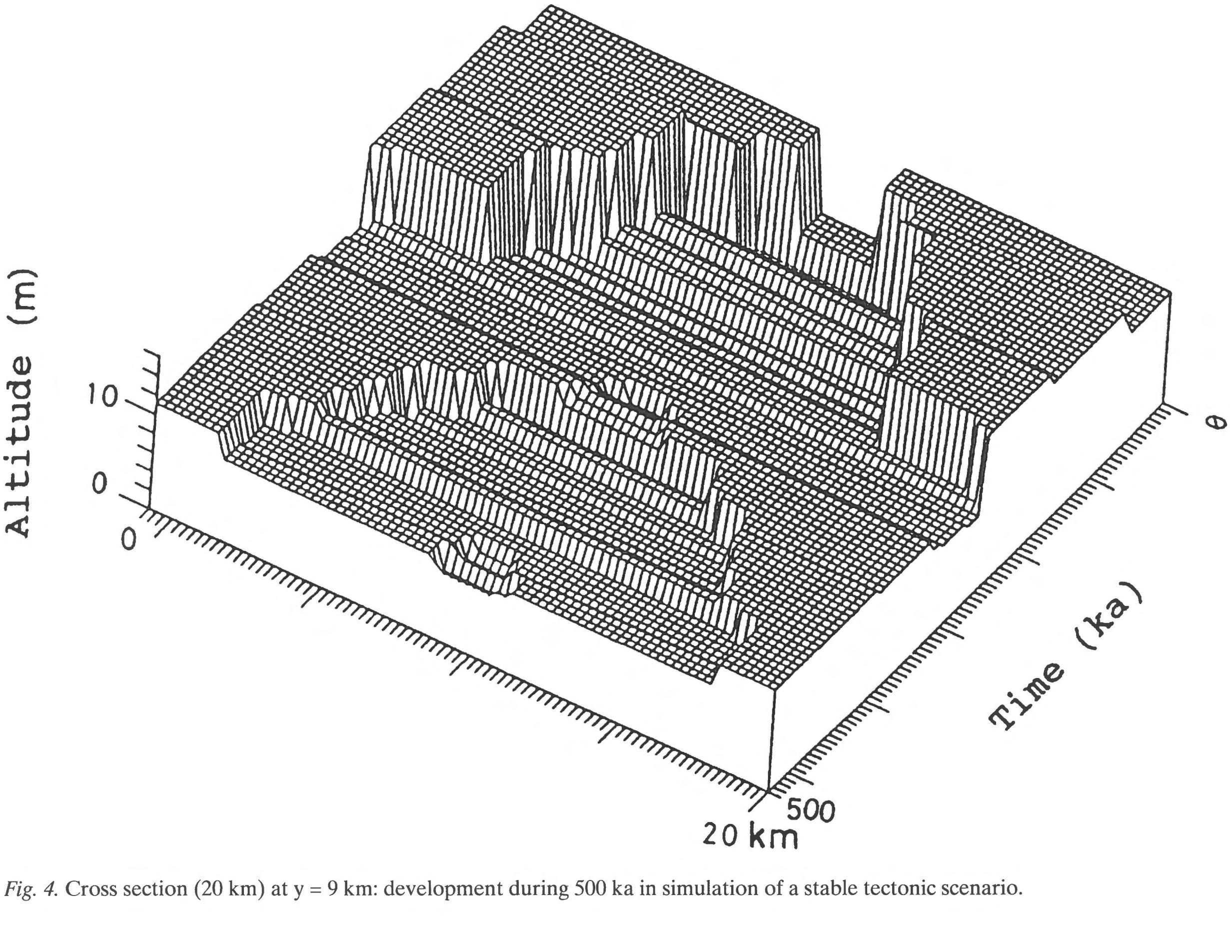


Fig. 4. Cross section (20 km) at y = 9 km: development during 500 ka in simulation of a stable tectonic scenario.

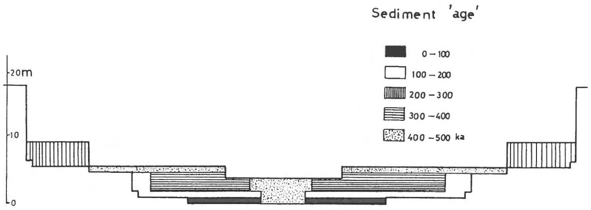


Fig. 5. Cross section (20 km) at y = 9 km: stratigraphy after 500 ka simulation of a stable tectonic scenario. Sediment 'ages' are given in deposition time during the simulation. Sediments of 'age' class 0–100 ka are oldest and sediments during the last 100000 simulated years (400–500 ka) are youngest.

Results

Three different tectonic settings were simulated in order to demonstrate the effects of the known tectonic extremes for the Netherlands. These simulations represent an uplifting, a subsiding and a relatively stable tectonic setting. For each simulation the same climatic and base-level inputs are used as described in Table 1.

A stable tectonic scenario

To evaluate the effects of only changing climate and base-level in time, a simulation was run without any tectonic change, demonstrating a stable tectonic setting. The simulated time span of 500 ka is used to visualize the impacts of several glacial-interglacial cycles. The relief after the simulated time span shows a relatively shallow and broad valley with two extended terraces (Fig. 3). The relatively high ridges along the edge are relicts of the initial relief and have no realistic value. These relicts find their origin in the fact that the initial relief and the sim-

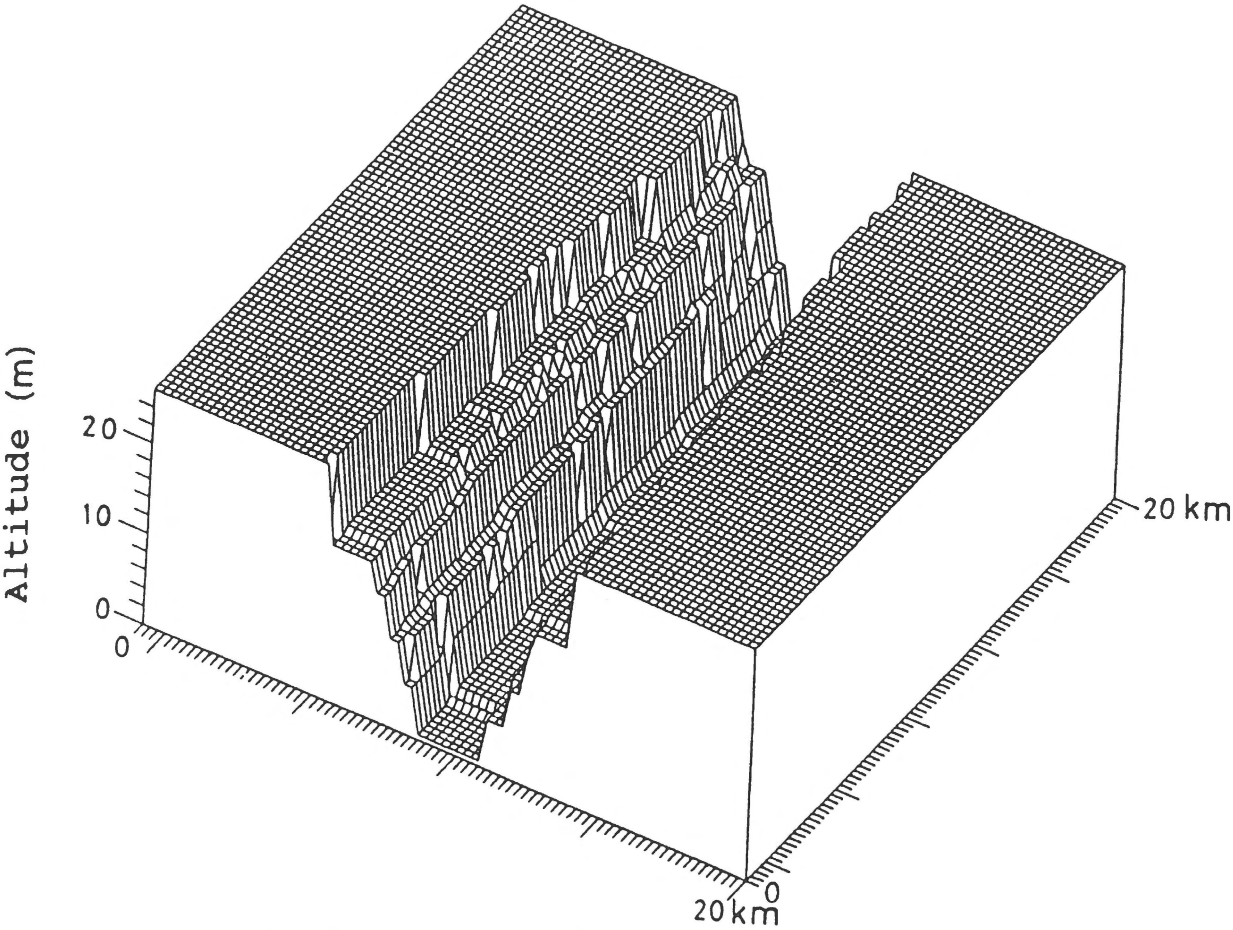


Fig. 6. Relief (20 × 20 km^2) after 500 ka in simulation of an uplifting tectonic scenario.

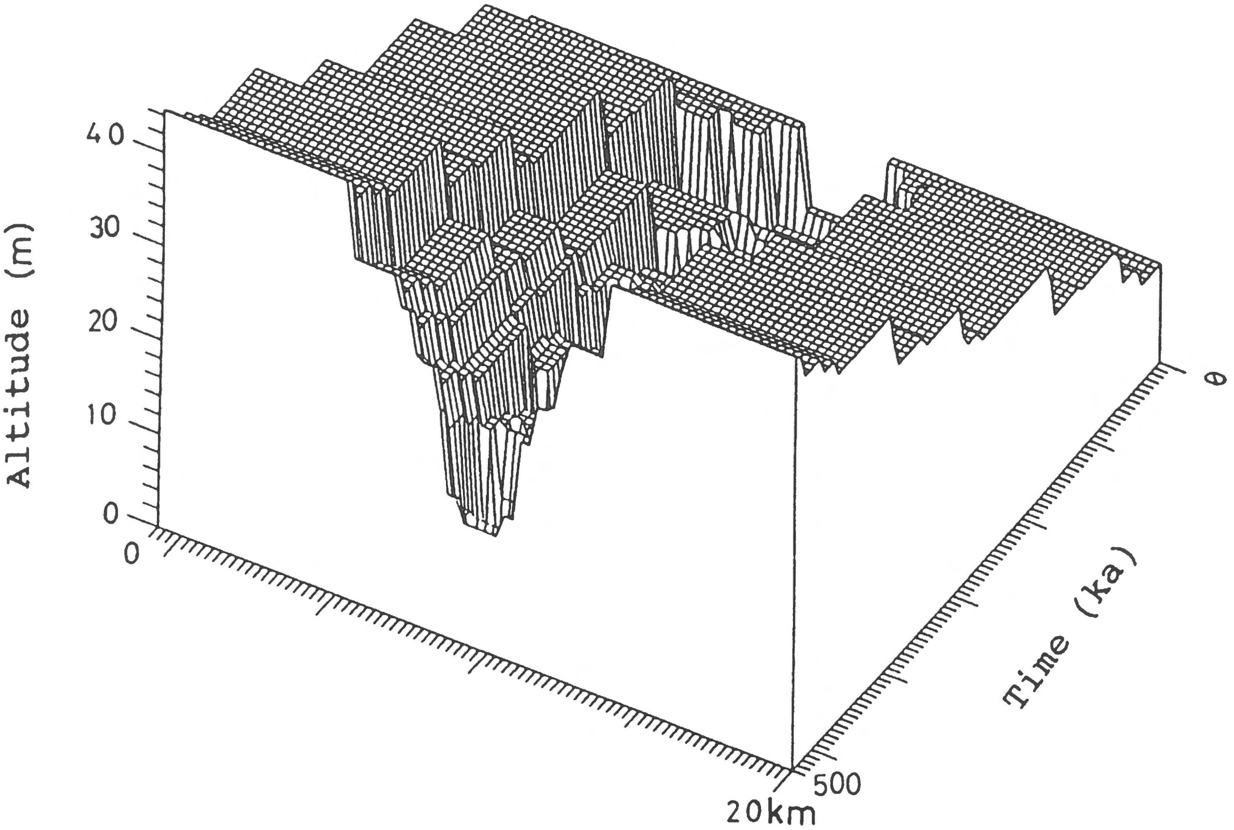


Fig. 7. Cross section (20 km) at y = 9 km: development during 500 ka in simulation of uplifting tectonic scenario.

ulated fluvial system are not well matched. Cross-section development (at y = 9 km) is shown in Fig. 4. The irregularities in the valley edge in time are caused by base-level changes and lateral fluvial erosion. During the simulation, due to disequilibrium of the initial relief and the simulated system, an initial incision occurs after which the simulated fluvial system widens the incised valley by alternating erosion and sedimentation. This fluctuating character of the simulated system can also be visualized easily by a cross-section stratigraphy (at y = 9 km) of the end relief (Fig. 5). The valley stratigraphy as indicated by sediment age in time steps (ka) has registered the repeated incision followed by valley widening. The net fluvial erosion during the simulation is only 10 m; a relatively small value over such a long time span.

An uplifting tectonic scenario

In order to assess the potential effects of regional uplift, a scenario was run with the fastest average uplift rate reconstructed for the Quaternary in the Netherlands, viz. 0.1 m/ka (Van den Berg 1992). Climate and base-level changes are similar to those in the previous simulation. Landscape relief after the simulated time span shows a valley approximately 40 to 50 m deep with at least four different terrace levels (Fig. 6). The cross-section (y = 9 km) development in time shows the interaction of base-level changes and continuous uplift by the irregular landscape edge and by the fluvial dynamics (Fig. 7). End relief stratigraphy as displayed in Fig. 8 has a typical terrace sequence with oldest sediments, deposited during the first hundred thousands of years (0–100 ka), found in the highest terrace bodies and with the younger sediments in increasingly lower

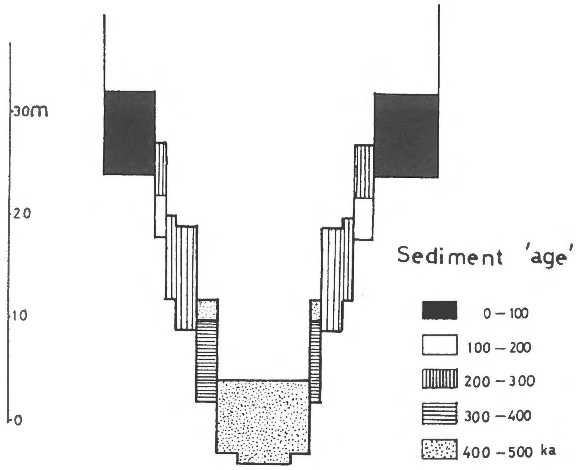


Fig. 8. Cross section (20 km) at y = 9 km: stratigraphy after 500 ka simulation of an uplifting tectonic scenario. Sediment 'ages' are given as in Fig. 5.

terrace bodies. The simulation results display a qualitative similarity with simulation results which were performed specifically for the Meuse system near Maastricht where no base-level effect was incorporated (Veldkamp & Van den Berg, in press).

A subsiding tectonic scenario

To evaluate the effects of tectonic subsidence a simulation was run with a subsidence rate of 0.04 m/ka. This simulation with a typical tectonic setting for the Netherlands, results in a flat, slightly sloping fluvial relief (Fig. 9). The only typically morphological property is the increase of landscape gradient upstream. The net fluvial erosion is negative (i.e. there was deposition) as was to be expected for a subsiding area. Fluvial dynamics are clearly visualized in Fig. 10 where the cross-sectional (y = 9 km) development in time shows an initial incision followed by valley widening due to disequilibrium of the initial landscape and the simulated system. After equilibrium is reached, the fluvial system alternatingly erodes and deposits, demonstrating a limited base-level effect. The resulting stratigraphy at cross section y = 9 km, shows a simple sequence with younger sediments overlying older sediments with several erosional boundaries in between due to base-level lowering in time (Fig. 11).

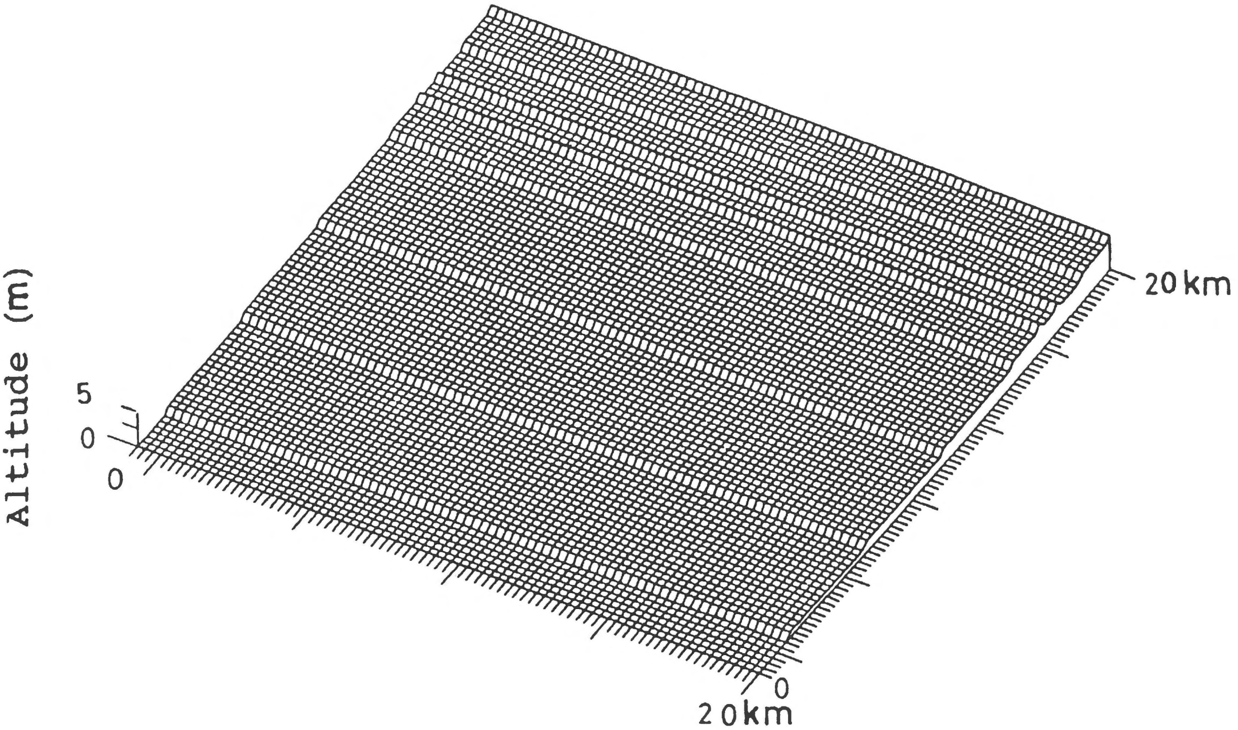


Fig. 9. Relief (20×20 km^2) after 500 ka in simulation of a subsiding tectonic scenario.

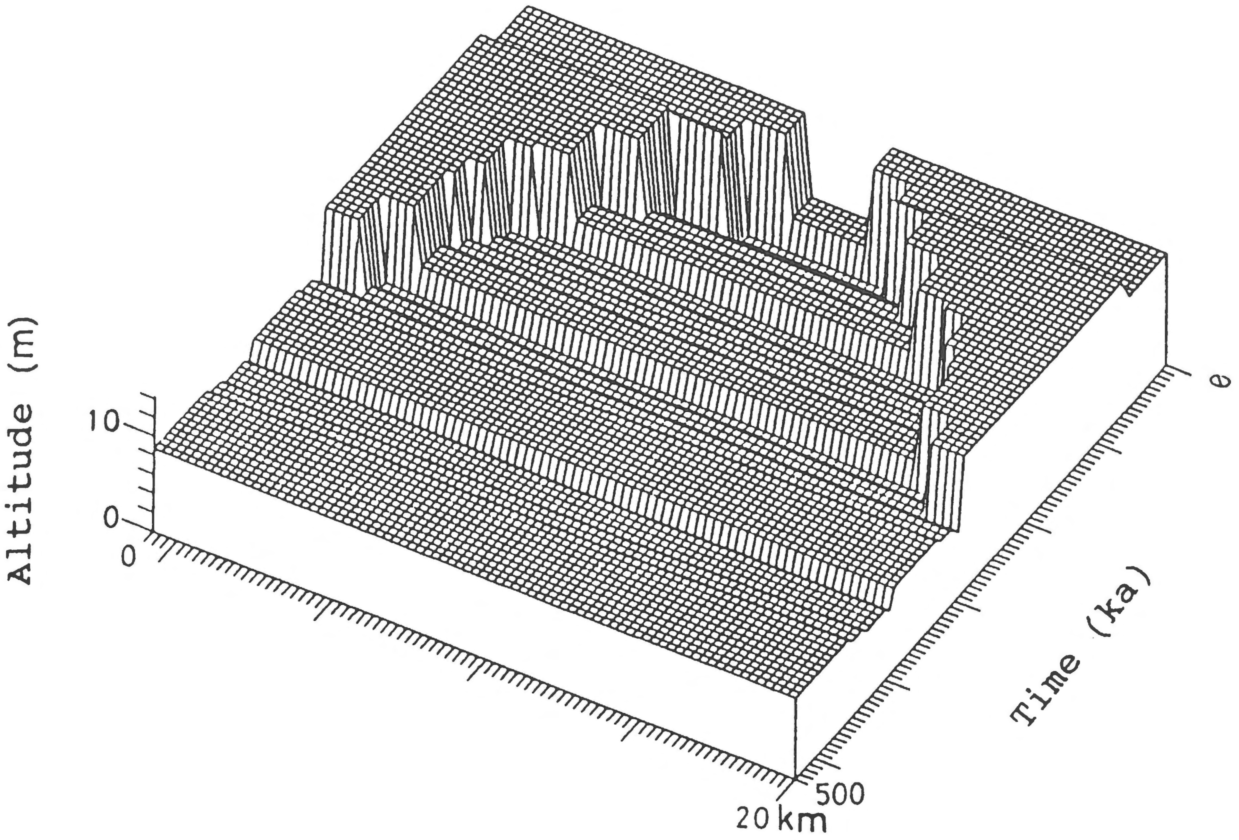


Fig. 10. Cross section (20 km) at y = 9 km: development during 500 ka in simulation of a subsiding tectonic scenario.

Discussion

Under the assumptions that climate and base-level changes can be satisfactorily described with Milankovitch's theory, that tectonic activity in the Netherlands will not change considerably, and that no larger fluvial systems than the Rhine or Meuse will enter the Netherlands, it can be tentatively concluded that it is unlikely that during the next few hundred thousand years fluvial erosion shall exceed the hundred meters needed to expose the shallowest salt diapirs. It should be noted, however, that deeper incisions can be expected along the edge of the continental shelf where the low sea level stands during glacials are known to have caused major incisions (De Groot & De Gans, in press). By choosing a base-level effect of approximately 20 m, the FLUVER simulations are mostly valid for the zone near the actual coast. The more landinward zone of the fluvial system will have a more limited base-level effect, but regional tectonic settings like rift grabens and shoulders can cause considerable tectonic differences over relatively short distances.

Model extensions

Although reliable long-term input for future conditions is lacking and FLUVER simulations have

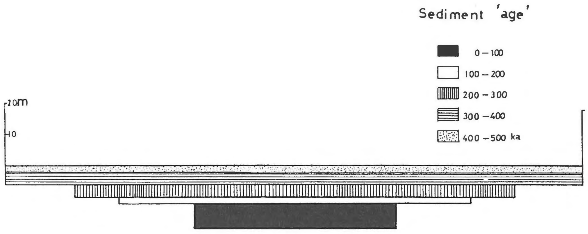


Fig. 11. Cross section (20 km) at y = 9 km: stratigraphy after 500 ka simulation of a subsiding tectonic scenario. Sediment 'ages' are given as in Fig. 5.

conceptual validity only, FLUVER can demonstrate potential long-term fluvial erosion effects. An aspect of fluvial systems which may be worth adding to FLUVER is the mechanism which determines the diversion of floodplain course in time.

For the construction of FLUVER, qualitative and descriptive knowledge was also used, since suitable long-term quantitative knowledge and data are lacking. To permit a more quantitatively reliable model in the future it will be necessary to collect more quantitative data. Since this model study is mainly based on general data, a comparison and evaluation with actual field data could also improve model validity. Extended and well-dated fluvial records of subsiding and uplifting regions like fluvial basin infills and fluvial terraces may serve as a primary data set to which FLUVER could be calibrated. Because FLUVER needs much more validation and regional tuning, for which unfortunately no reliable data are available, FLUVER has no reliable quantitative forecasting status.

Geological barrier-system

Because FLUVER has no links with and inputs of other processes determining geological barrier-system stability at salt structures, the simulation results will certainly have to be reevaluated when these interactions and effects are incorporated in a more sophisticated barrier-system model. It could well be possible that fluvial erosion and sedimentation have effects on, for example, the overburden of a diapir and can indirectly affect diapirism. On the other hand diapirism (uplift) could directly or indirectly determine potential erosion effects. More interdisciplinary efforts are necessary to develop such an integrated barrier-system model. A main problem which has to be solved is the unravelling of the hierarchy of processes and factors on different spatial and temporal scales.

Conclusions

A conceptual fluvial erosion model, FLUVER, simulating the long-term effects of climate, base-level and tectonism on a fluvial system, is shown. It demonstrates that fluvial erosion can be modelled for a long time span in such a way that after fine tuning and validation it may support research on the long-term stability of geological barrier systems at possible storage facilities of nuclear waste. More interdisciplinary efforts are necessary to develop a geological barrier-system model which can be applied for any specific site.

Acknowledgements

This research was carried out in the OPLA-lA project at the Geological Survey of the Netherlands. Thanks are due to C. Staudt, director of the Geological Survey of the Netherlands. A.F.B. Wildenborg, E.F.J. de Mulder and many other colleagues in the OPLA project are thanked for their cooperation and stimulation of our research. Critical review of the manuscript by Th. A. M de Groot is gratefully acknowledged.

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