Prepared for:

Rijkswaterstaat RIZA

Voorspelinstrument duurzame vaarweg

Case study: Fixed layer and sediment nourishment in the Bovenrijn

Report

April 2008

WL | delft hydraulics

Q4357.30

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Case study: Fixed layer and sediment nourishment in the Bovenrijn

Mohamed Yossef, Migena Zagonjolli, Kees Sloff

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Abstract:

The DVR programme calls for a prediction tool to evaluate the proposed intervention measures. Accordingly, WL | Delft Hydraulics was commissioned the task of developing an advanced 2-D morphodynamic model of the Rhine system in the Netherlands (Van Vuren et al., 2006). The model contains several innovative, recently developed aspects (Yossef et al., 2006). We refer to this model as "DVR model". Using this model we can evaluate measures that are planned to maintain the navigability of the Rhine. The bed degradation in the Bovenrijn (Upper Rhine River) between km 859 and km 867 during the period of 1970 to 2000 amounted up to 3 cm/year on average (RIZA, 2005). This is equivalent to a yearly-averaged sediment shortage of 70,000 m^3 in this branch. Predictions (RIZA, 2005) indicate that this trend will continue in the coming decades. One of the proposed measures to counteract this effect is the application of fixed layers and a sediment nourishment strategy.

Here we evaluate the combined effect of these measures by conducting a case study using the graded-sediment model of the Bovenrijn. Firstly, we evaluate the effect of the fixed layer without nourishment. Secondly, we evaluate the combined effect of the fixed layer and a one-time nourishment. Finally, we evaluate the effect of repeated nourishment.

The results indicate that using a fixed layer improves the navigation channel width and that the morphological effect of the fixed layer is dominant over the effect of nourishment. The local morphological effect of the fixed layer reaches a state of dynamic equilibrium after nearly two years. In the inner bend of the fixed layer erosion develops and just downstream of the erosion area, a deposition ridge forms that contributes to filling the designated nourishment area. The behaviour of the nourishment material indicates that its effect on the bed level is small and it hardly affects the sediment size at the bifurcation point. The interval of 2 years for repetitive nourishment appears to be short, as accumulation of nourishment material was observed in the case of repetitive nourishment. Using a coarser material causes additional accumulation of material in the nourishment area whereas using a finer composition leads to less accumulation in the nourishment area. This means that the time required to repeat the nourishment increases when using coarser material. The effect of the applied measures was small both on the water level near the upstream boundary and on the sediment distribution at the Pannerdensche kop.

References: RI-4737 "Vervolg Bouw morfologisch model DVR"

Ver	Author		Date	Remarks	Review		Approved by
1.0	dr. Mohamed Yossef		20 December 2007		ir. Frans van der Knaap		dr. A.G. Segeren
2.0	dr. Mohamed Yossef				ir. Frans van der Knaap		dr. A.G. Segeren
3.0	dr. Mohamed Yossef		25 March 2008		dr.ir. Erik Mosselman		dr. A.G. Segeren
3.1	dr. Mohamed Yossef		25 April 2008		dr.ir. Erik Mosselman		dr. A.G. Segeren

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Samenvatting:

Het DVR-programma vraagt om een voorspelinstrument om de voorgestelde maatregelen te evalueren. WL | Delft Hydraulics had de opdracht om een geavanceerd 2D morfodynamisch model te ontwikkelen van het systeem van de Rijn in Nederland (Van Vuren e.a., 2006). Het model bevat verscheidene innovatieve, recent ontwikkelde aspecten (Yossef e.a., 2006). We duiden dit model aan als "DVR-model". Met dit model kunnen we maatregelen evalueren die gepland zijn om de bevaarbaarheid van de Rijn te onderhouden. De bodemdaling in de Bovenrijn tussen km 859 en km 867 bedroeg in de periode van 1970 tot 2000 gemiddeld 3 cm/jaar (RIZA, 2005). Dit komt overeen met een jaargemiddeld tekort aan sediment in deze tak van 70.000 m3. Voorspellingen (RIZA, 2005) wijzen erop dat deze trend in de komende decennia zal doorzetten. Een van de maatregelen om dit effect tegen te gaan is de toepassing van vaste lagen en een strategie van sedimentsuppletie.

Hier evalueren we het gecombineerde effect van deze maatregelen door een casestudy uit te voeren met het gegradeerd-sedimentmodel van de Bovenrijn. Allereerst evalueren we het effect van de vaste laag zonder suppletie. Vervolgens evalueren we het gecombineerde effect van de vaste laag en eenmalige suppletie. Tenslotte evalueren we het effect van herhaalde suppleties.

De resultaten wijzen uit dat het gebruik van een vaste laag de vaargeulbreedte verbetert en dat het morfologische effect van de vaste laag het effect van suppletie overheerst. Het lokale morfologische effect van de vaste laag bereikt een toestand van dynamisch evenwicht na bijna twee jaar. In de binnenbocht van de vaste laag ontwikkelt zich erosie en meteen benedenstrooms van het erosiegebied vormt zich een afzettingsrug die bijdraagt aan het opvullen van het aangewezen suppletiegebied. Het gedrag van het suppletiemateriaal wijst uit dat het effect daarvan op de bodemligging klein is en nauwelijks de sedimentgrootte op het splitsingspunt beinvloedt. Het interval van 2 jaar voor herhaalde suppleties blijkt te kort, aangezien accumulatie van suppletiemateriaal werd waargenomen in geval van herhaalde suppleties. Het gebruik van een grover materiaal veroorzaakt aanvullende accumulatie van materiaal in het suppletiegebied, terwijl het gebruik van een fijnere samenstelling leidt tot minder accumulatie in het suppletiegebied. Dit betekent dat de benodigde tijd voor herhaling van de suppletie toeneemt wanneer grover materiaal gebruikt wordt. Het effect van de toegepaste maatregelen was klein voor wat betreft zowel het niveau van de waterspiegel bij de bovenrand als de sedimentverdeling op de Pannerdensche Kop.

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Contents

1 Introduction

1.1 Background

The Rhine is the most navigated inland waterway in Western Europe. Due to its advantageous location in the Rhine delta, the inland waterways in the Netherlands form a natural access to the continent of Europe. As a consequence of climate change and morphological changes in the Rhine system an increasing number of nautical bottlenecks are expected in the coming years. In order to meet the demands for navigation also in the future, Rijkswaterstaat introduced the programme Duurzame Vaardiepte Rijndelta (DVR) (Sustainable Navigation Depth for the Rhine Delta). Within the DVR programme, river intervention measures are defined and are to be evaluated to maintain and improve the navigability of the Rhine.

The DVR programme calls for a prediction tool to evaluate the proposed intervention measures. Accordingly, WL | Delft Hydraulics was commissioned the task of developing an advanced 2-D morphodynamic model of the Rhine system in the Netherlands (Van Vuren et al., 2006). The model contains all kinds of innovative, recently developed aspects, amongst which domain decomposition, sediment transport over non-erodible layers and functionality for sediment management to assess dredging and dumping strategies (Yossef et al., 2006). In this report, we refer to this model as “DVR model”.

The advanced DVR model can be used to assess the long-term large-scale evolution of the Rhine system. As the model incorporates also complex time-dependent multi-dimensional phenomena, such as curvature-induced point bar and pool patterns in bends, assessment is also possible at the meso-scale, which is the scale of alternate bars and cross sectional-profile evolution (De Vriend, 1999). For a detailed description of the model, reference is made to Van Vuren et al. (2006), Yossef et al. (2006), and Mosselman et al. (2007).

Using this model we can evaluate measures that are planned to maintain the navigability of the Rhine. The bed degradation in the Bovenrijn (Upper Rhine River) between km 859 and km 867 during the period of 1970 to 2000 amounted up to 3 cm/year on average (RIZA, 2005). This is equivalent to a yearly-averaged sediment shortage of 70,000 m^3 in this branch. The predictions (RIZA, 2005), indicate that this trend will continue in the coming decades. One of the proposed measures to counteract this effect is the application of fixed layers and sediment nourishment strategy(s).

To evaluate this measure, we carry out a case study using the graded-sediment model of the Bovenrijn. The same model was used before to evaluate the behaviour of nourishment material in the Bovenrijn for a test case (Mosselman et al., 2007). Based on the knowledge gained, this case study is designed aiming at the evaluation of the effects of the application of a sediment nourishment strategy combined with the construction of a fixed layer in the Bovenrijn.

1.2 Assignment

The project includes three primary tasks:

1- Reducing the computational time;

2- Improving the model;

3- Case study of fixed layer and nourishment in the Bovenrijn (*this report*);

4- Improving the model's physical concepts;

In this report we evaluate the application of a fixed layer and nourishment in the Bovenrijn, We undertake the following tasks activities:

- Additional calibration of the graded-sediment Bovenrijn model

  The model developed earlier (Mosselman et al., 2007) exhibits large-scale deposition downstream the Bovenrijn branch in a period of 10 years. Thus, a calibration of the model was found to be necessary in order to improve its performance and to facilitate the implementation of the appropriate measures.

- Implementation of a fixed layer

  The fixed layer is designed to stabilise the outer bend of the Bovenrijn reach from km 858.3 to km 861.7 with a top level 4.5 m below the low water reference level (OLR – 4.50 m). The implications of the fixed layer on the morphological behaviour of the whole reach during 15 years period are evaluated. The performance of the fixed layer is depicted for different schematisations in terms of 1D and 2D morphological response.

- Implementation of a fixed layer and one time nourishment

  The sediment nourishment takes place at the left (south), outer-bend of the Bovenrijn reach from km 861 to km 864 downstream of the fixed layer. The nourishment is applied gradually during the low water period after the end of the first year, with a nourishment material volume of 60,000 m^3.

- Implementation of a fixed layer and repetitive nourishment

  The last objective is to simulate the repetitive nourishment process instead of one time nourishment of the degraded area behind the fixed layer. The nourishment is conducted once every two years during a ten year period. The implications of the repetitive nourishment along with the effect of the fixed layer are discussed and depicted at the end of this project report.

The work has been carried out within the agreement RI-4737 "Vervolg Bouw morfologisch model DVR", (in English: Continued construction of morphological model for DVR). The project is known in WL | Delft Hydraulics as Q4357.00.

1.3 Organisation

This report is the third in a series of three within this project. The team contributing to the project consisted of: Migena Zagonjolli, Chris Stolker, Anke Hauschild, Sanjay Giri, Willem Ottevanger, Saskia van Vuren, Kees Sloff, Erik Mosselman, Bert Jagers, Frans van der Knaap and Mohamed Yossef. The later was the project leader and the editor of this report. Arjan Sieben managed the project on behalf of Rijkswaterstaat RIZA

2 Morphological calibration

2.1 Background

The graded-sediment model of the Bovenrijn domain which is part of the DVR model is used in this case study (Figure 2.1). That model was roughly calibrated in an earlier study (Mosselman et al., 2007). During test simulations, for a period of 10 years and more, at the start of this study, it became evident that the model behaviour is not satisfactory for the purpose of this case study. Though a calibration of the model is not part of the scope of work of this project, it appeared that additional calibration needs to be carried out. Accordingly, an additional rough calibration was carried out; it is presented in this chapter.

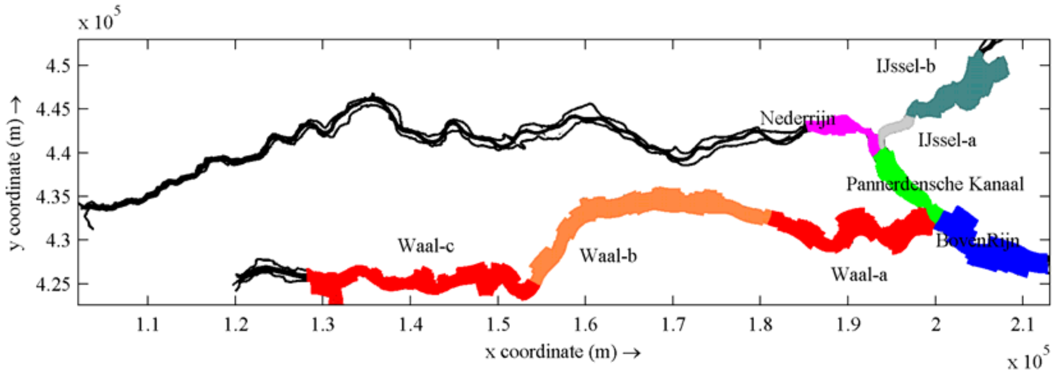


Figure 2.1 Overview of the complete model grid with indication of the different model domains.

2.2 Model setup

2.2.1 Schematisation

Baseline version 3.31 was used to set up the model, viz. the bed topography, the hydraulic roughness, the schematisation and location of weirs (groynes, summer levees, and steep obstacles), and thin dams (van Vuren et al., 2006 and Mosselman et al., 2007). The multi-beam soundings of 1997 were used for creating the topography while the multi-beam measurements for the years 1999-2005 were considered for calibration.

For the most upstream part of the model domain (German part of the Bovenrijn) no multi-beam measurements are available, thus, the uncertainty related to the accepted topography for that section contributes to further changes of the bed level later on during the project. Due to discrepancies observed during the first stage of the case study, the initial bed level is lowered by 40 cm in the German part of the river from km 853.310 to km 857.456 compared to the bed level used in previous simulations.

The hydraulic condition at the upstream boundary is a discharge hydrograph (Figure 2.2) while the downstream boundary condition is water levels deduced from a rating curve. The morphological boundary condition at the upstream boundary is a gradually degrading bed level to simulate autonomous lowering of the bed level. To account for the degradation of the downstream bed level, a gradual lowering of the water level at the downstream boundary was imposed.

The bed composition consists of graded-sediment with the grain size distribution presented in Figure 2.3. The grain size distribution has been used previously in the DVR case studies (Mosselman et al., 2007). The active-layer thickness (*ThTrLyr*) is taken as 1.5 m, see Mosselman et al. (2007).

In Delft3D the morphological factor M*orFac* takes into consideration the time development of morphological processes in relation to hydrodynamic development. For each discharge value we choose a different *MorFac* value, namely a value 5 for the high discharges of 4,400 m^3/s and 6,000 m^3/s and a value 10 for the low discharges of 1,500 m^3/s and 2,954 m^3/s.

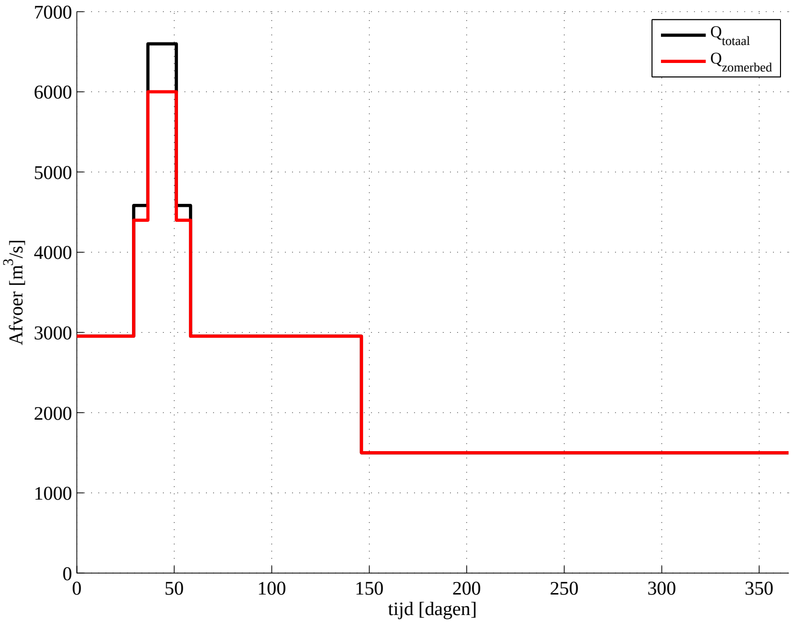


Figure 2.2 Discharge hydrograph used as upstream boundary condition.

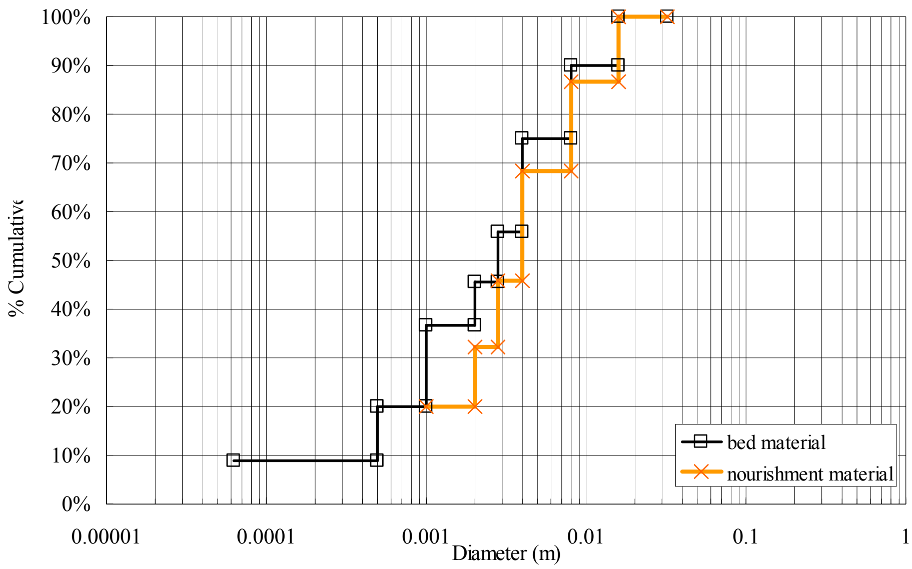


Figure 2.3 Sieve curves for bed material and nourishment material.

2.2.2 Sediment transport formula

The modified Meyer-Peter & Müller sediment transport formula for non-uniform sediment has been used for the computations because of good experiences in previous modelling studies for the Boven Rijn (Sloff, 2006, Mosselman et al., 2007). The transport formula is written per sediment fraction *i* as follows:

$$s_{b,i} = p_i \alpha D_i^{3/2} \sqrt{g\Delta} \left(\mu\theta_i - \xi_i\theta_{cr}\right)^{3/2}$$

where:

α	=	coefficient [-]
p_i	=	fraction of grain class *i* in the mixture [-]
D_i	=	mean grain size fraction *i* [m]
g	=	gravitational acceleration [m/s^2]
$s_{b,i}$	=	sediment-transport rate per unit of width for fraction *i* [m^2/s]
Δ	=	relative density $(\rho_s - \rho_w)/\rho_w$ [-]
μ	=	ripple factor, taken equal to 0.7 [-]
θ_i	=	Shields parameter [-]
ξ_i	=	and exposure factor for the sediment fraction *i* [-]

The Shields parameter θ_i is given by

$$\theta_i = \frac{u^2}{C^2 \Delta D_i}$$

where u is the depth-average flow velocity, and C is the Chézy coefficient estimated as follows:

$$C = 18 \log\left(\frac{12h}{k_s}\right)$$

in which h is the water depth and k_s is the roughness height.

2.3 Calibration parameters

The calibration procedure follows two consecutive steps. The first step focuses on 1D morphological behaviour and the second step focuses on 2D morphological behaviour (see Yossef et al., 2007, for details). As it is a graded sediment model, in both steps the bed composition is an important variable as the bed levels.

2.3.1 1D morphology

The calibration of one-dimensional morphology focuses on the reproduction of width-averaged bed-level variations and large-scale morphological characteristics.

The relevant aspects are:

- The time-scale of 1D morphological changes (e.g. the propagation speed of sand waves) is proportional to the transport rate, but in non-uniform sediment approaches it is also affected by the ratio between bed composition and composition of the transported sediment. The observed celerity of sand waves in the Boven Rijn is in the order of 1 km/yr.
- The yearly transport rate in the Boven-Rijn is dependent on a combination of bed composition, transport formula settings, and discharge hydrograph. The actual transport rate should be roughly in the order of 500,000 m^3/year.
- The Boven-Rijn is lowering with an average rate of about 3 cm/year (reach average value), which implies that there should be a gradual increase of sediment-transport rate along the branch (in downstream direction). The effect is introduced into the model by a continuous lowering of the bed-level at the upstream boundary and the water-level at the downstream boundary.

The settings of the original Boven-Rijn model of Mosselman et al. (2007) did not lead to the expected trends in long-term morphology as indicated above. Long-term simulations (more than 10 years) showed that eventually the lower reach of the model (near the nourishment location) is silting up, instead of degrading. The 1D bed-slope along the entire reach appeared to decrease as a manifestation of erosion in the upstream part and deposition in the downstream part of the Bovenrijn. Therefore, additional calibration step was carried out:

- Apply water-levels at the lower boundary that were taken from the official stage-discharge relation at the Pannerdense Kop (data year 2000), instead of the water levels computed using the full Delft3D model for all branches. The differences are in the order of decimetres, but the effect on bed levels in the lower reach is in the order of centimetres. The water levels were described as a time-series that takes into consideration the large-scale degradation, i.e. the water level is gradually reducing with a rate of 3 cm/yr.
- Modification of roughness values to affect the morphological equilibrium condition. The roughness affects flow velocity as well as the Shields values and ripple factor in the model. An increase of roughness is expected to lead (in case of uniform flow) to an increased bed slope. This option is studied to counteract the decrease in bed slope that develops in time in the simulation. Variation of roughness is allowed as far as the errors in water-surface slope allow such a modification.
- As mentioned before, due to the observed discrepancy in the initial bed levels in the German part of the Boven-Rijn, the bed levels in that reach have been adjusted (lowered by 0.4 m). This improved the results significantly as the model responded to this error by significant erosion in this reach followed by a deposition of this material in the lower reach (explaining the decrease in slope). After lowering the bed this net erosion in the upper reach has been diminished significantly.
- For the calibration of the model the transport formula has been adjusted: the factor α and the critical mobility parameter θ_{cr} have been adjusted in several steps (see Table 2.1). The values range $\alpha = 2.2 – 5.6$ (Sloff, 2006) and $\theta_{cr} = 0.025 – 0.047$.
- The thickness of the active-layer was taken from the earlier model and was not changed during the calibration procedures (ThTrLyr = 1.5 m).

Table 2.1 Different combinations for the Meyer-Peter & Müller formula.

No.	θ_{cr}	α
1.	0.025	2
2.		5.6
3.	0.030	2
4.	0.035	3
5.	0.040	3
6.	0.045	4

The Nikuradse roughness height k_s used for the Chézy coefficient estimation is also part of the calibration procedures. Therefore the calibration parameters of the Van Rijn roughness predictors have been adjusted; k_s ranged from 0.10 to 0.04.

Section 2.4 presents more information on the calibration steps, outcomes and choices, as well as the shortcomings.

2.3.2 2D morphology

For a correct reproduction of the 2D bar-pool patterns, the following two factors are important:

- the spiral motion due to the curvature of the flow, and
- the effect of the transverse bed slope.

In Delft3D these are represented by two calibration parameters:

- E_s: affecting the spiral flow intensity
- A_{sh}: influencing the transverse slope effect.

The coefficients A_{sh} and E_s are subject to calibration. The combinations of E_s and A_{sh} values analysed are given in Table 2.2. Note that in the simulation conducted by Mosselman et al. (2007), the combination of $E_s = 1.0$, and $A_{sh} = 0.9$ has been found to be an optimal combination while the simulations were carried for a constant discharge of 2,500 m^3/s.

Table 2.2 Different combination of E_s and A_{sh} values.

No.	E_s	A_{sh}
1.	1	0.5
2		0.9
3.		1.5
4.	1.5	0.9

Note that in the case of graded sediment model, the bed composition is an important variable in addition to the bed levels. Reproduction of the grain size distribution across bend is an important aspect of the model. The bed composition is not a calibration parameter in this case but rather a result of the model. As bed composition adapts to the hydrodynamic conditions, starting simulations from any initial bed composition that is different from the 'equilibrium' bed composition would anyhow converge to an equilibrium composition. Important calibration parameters in this case are the active-layer thickness and bed slope effect.

2.4 Results

Figure 2.4 presents the annual sediment transport volume in the Bovenrijn. The calculated volume is in accordance with the estimated volume from the global model calibration presented by Yossef et al. (2007).

Figure 2.5 presents the temporal development of the cross-sectional-averaged bed level for the model of Van Vuren et al. (2006). We can observe large erosion in the upstream part of the river and large deposition in the downstream part. This leads to a significant reduction of the river slope over 10 years. Such behaviour cannot be substantiated from the field observations. In Figure 2.6, the same result from the calibrated model is presented; it shows smaller changes in the longitudinal profile of the river, see also Figure 2.7.

In Figure 2.8 the bed elevations at the end of the 5th and the 10th year are shown for the left and right banks of the river. The 2D bar-pool pattern for a relatively long period corresponds well with the measured bed levels. Accordingly, we were able to conclude that the combination of E_s = 1.0 and A_{sh} = 1.5 provides optimal results in terms of 2D pattern.

In search of the cause of the aggradations pattern along the river, different hydraulic and morphological parameters are changed. For the selected combination of E_s and A_{sh} the roughness height k_s was varied from 0.04 m to 0.1 m (see Figure 2.9). A roughness height of 0.06 m was chosen to be used for further analysis.

As it can be noted from Figure 2.8 erosion at the upstream part of the river reach is followed by deposition downstream of the river reach. Due to the discrepancy observed in comparison to the bed level at the German side of the river, the bed level upstream is updated by subtracting 40 cm from the initial bed level (Yossef et al. 2007).

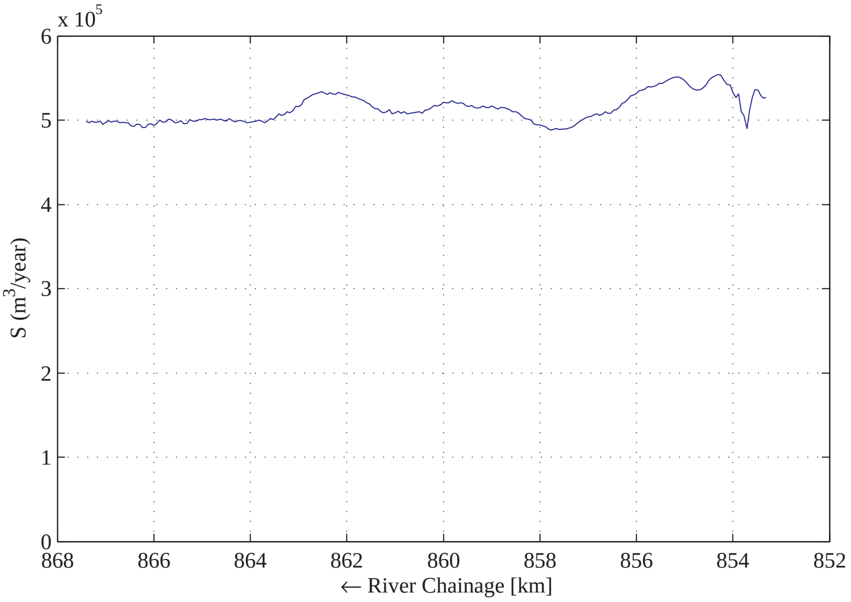


Figure 2.4 Calculated yearly sediment transport in the Bovenrijn.

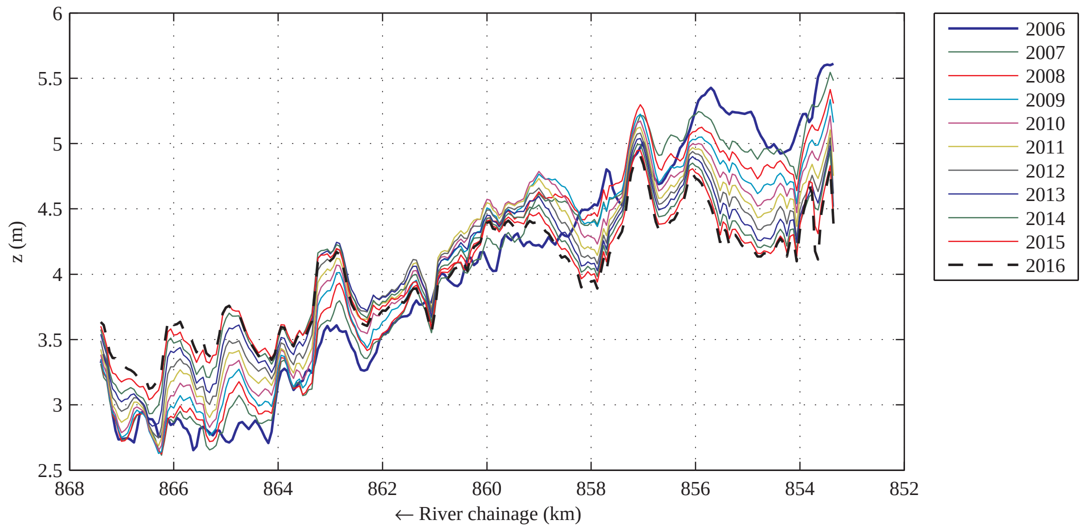


Figure 2.5 Temporal development of cross-sectional-averaged bed level for the original model.

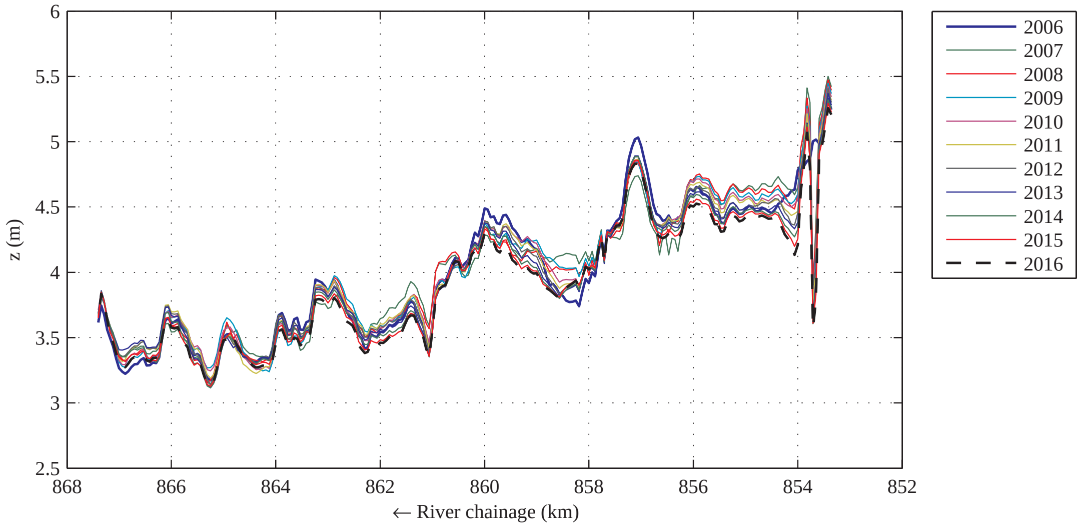


Figure 2.6 Temporal development of cross-sectional-averaged bed level for the model after calibration.

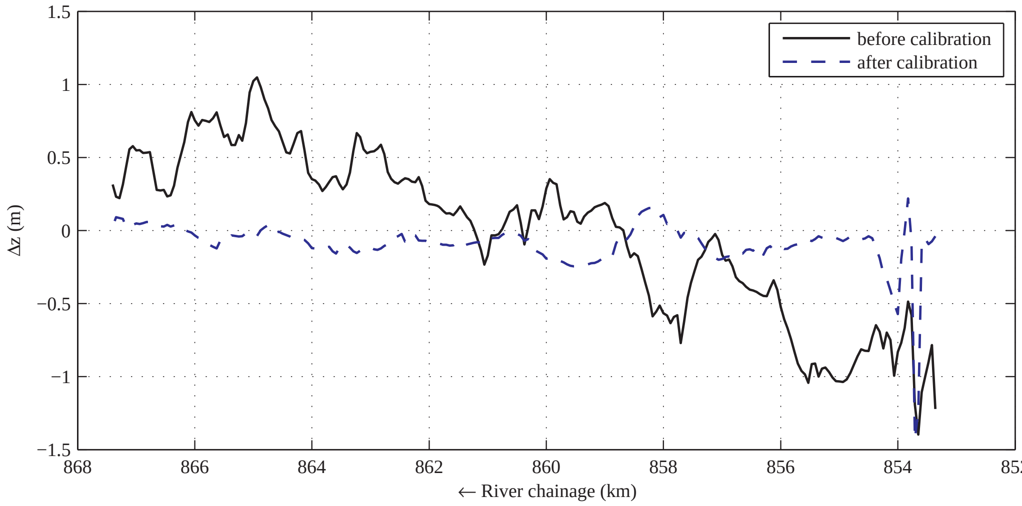


Figure 2.7 Comparison between the change in cross-sectional-averaged bed level (after 10 years) for the model before and after calibration.

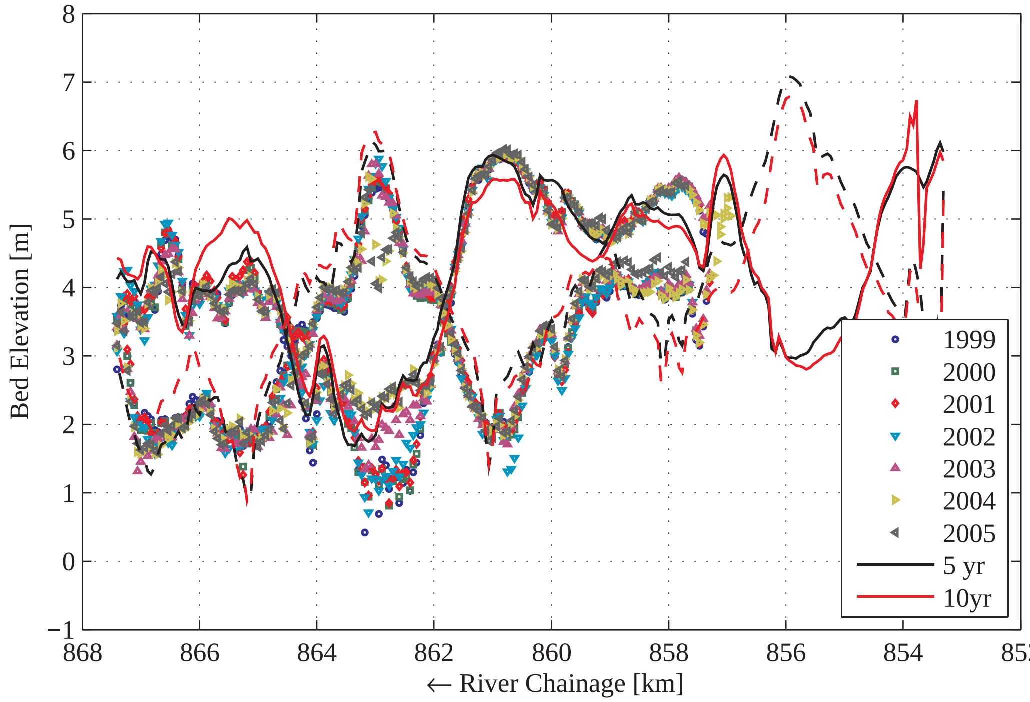


Figure 2.8 Longitudinal profile along left and right banks for the chosen combination of (E_s and A_{sh}; E_s = 1.0 and A_{sh} = 1.5); continuous line: left/south bank, dashed line: north/right bank.

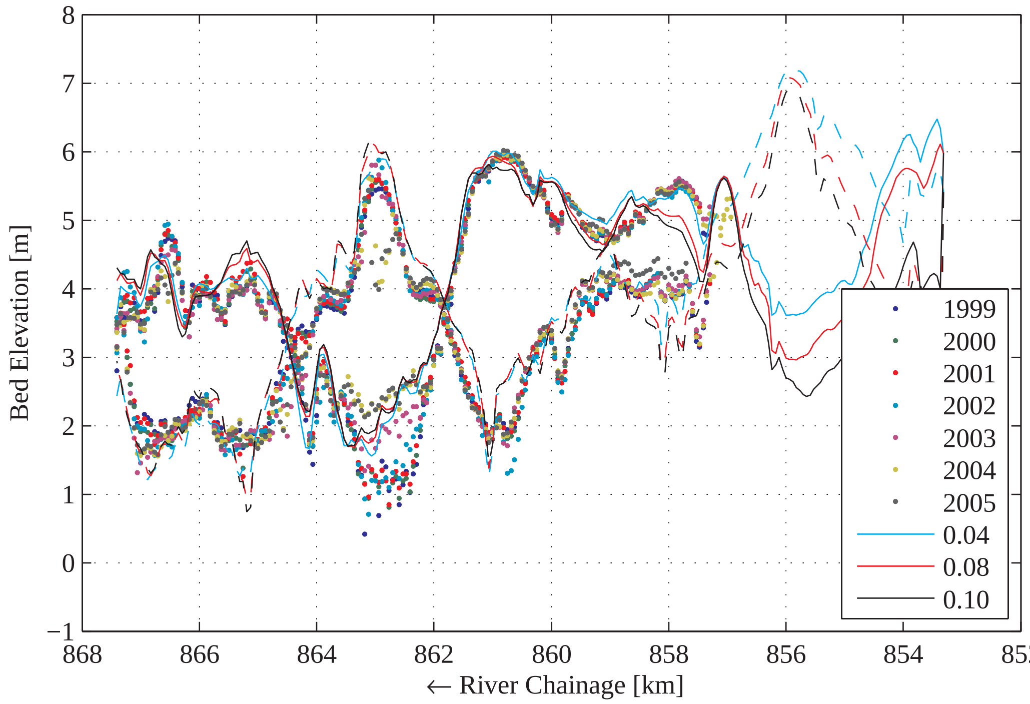


Figure 2.9 Longitudinal profile along left and right banks for different roughness height values at the end of the 5th year (left/south bank represented by the continuous line and the north/right bank represented by the dashed line).

The ten-year bed evolution for the modified bed level has lower rates of sediment erosion and deposition than the evolution for the old initial bed elevation despite the high deposition rates at the downstream side (see Figure 2.10). The lowering of the flow velocity at the upstream part of the river contributes to the decrease in sediment erosion rates.

For the selected roughness height k_s the parameters of the sediment transport formula are tested for different combinations of α and θ_{cr}. The results of the trial combinations presented in Table 2.1 are not shown in this report, but instead the results for the optimal combination of $\alpha = 5.6$ and $\theta_{cr} = 0.025$. The bed level development on the river axis exhibits high deposition rates at the downstream part of the Bovenrijn (see Figure 2.11).

From the results of the calibration simulation, no significant changes in the bed levels were observed after the 7th year. Based on this, and since the main purpose of this case study is to identify the impact of certain measures, the bed elevation at the end of the 7th year of simulation was decided to be used as initial bed for the simulations with fixed layer and nourishment. The bed level of the 7th year (Figure 2.12) of simulation is used as initial bed while the sediment composition of the bed is kept as originally assumed.

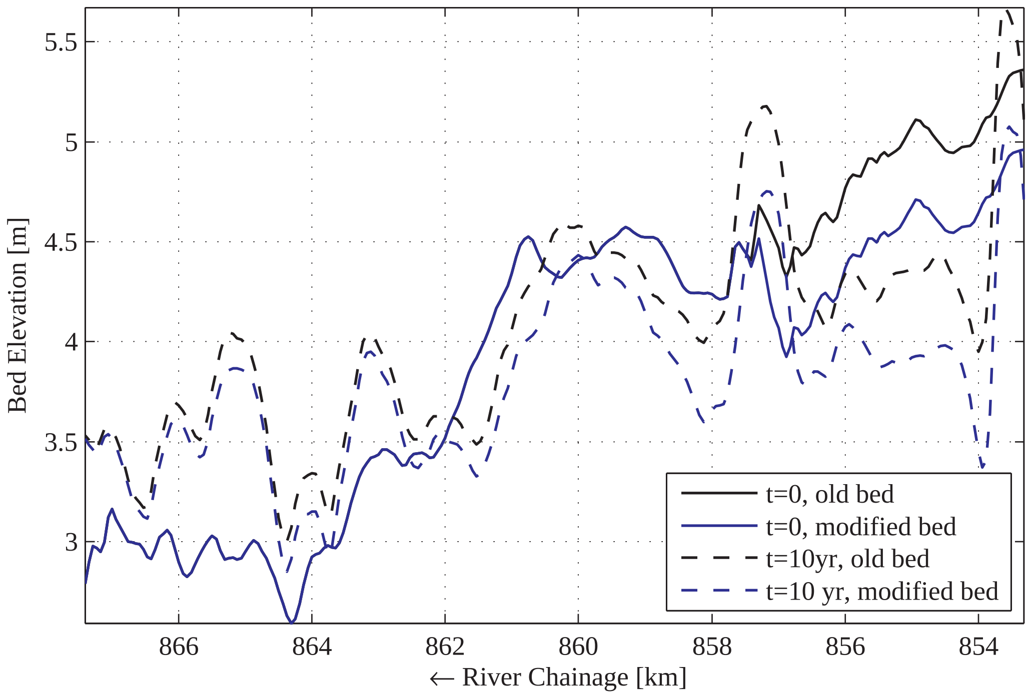


Figure 2.10 Bed elevation on the 10th year for two different initial bed upstream part of the river ($k_s = 0.06$ and $\alpha = 5.6$).

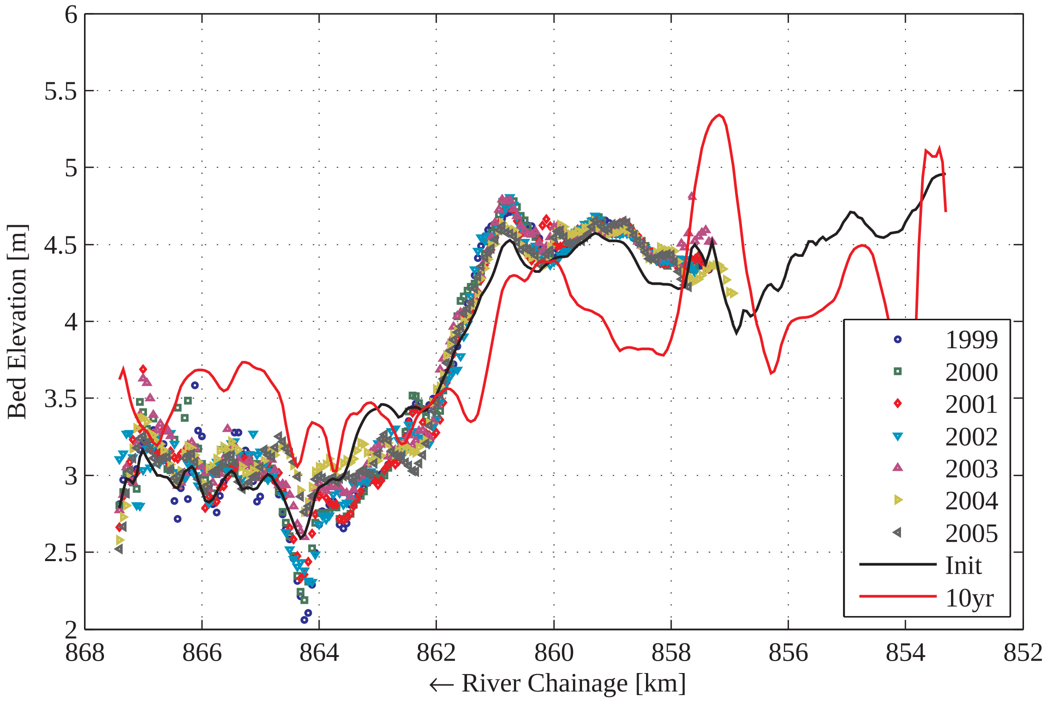


Figure 2.11 Longitudinal evolution of the river bed in its axis ($k_s = 0.06$ and $\alpha = 5.6$).

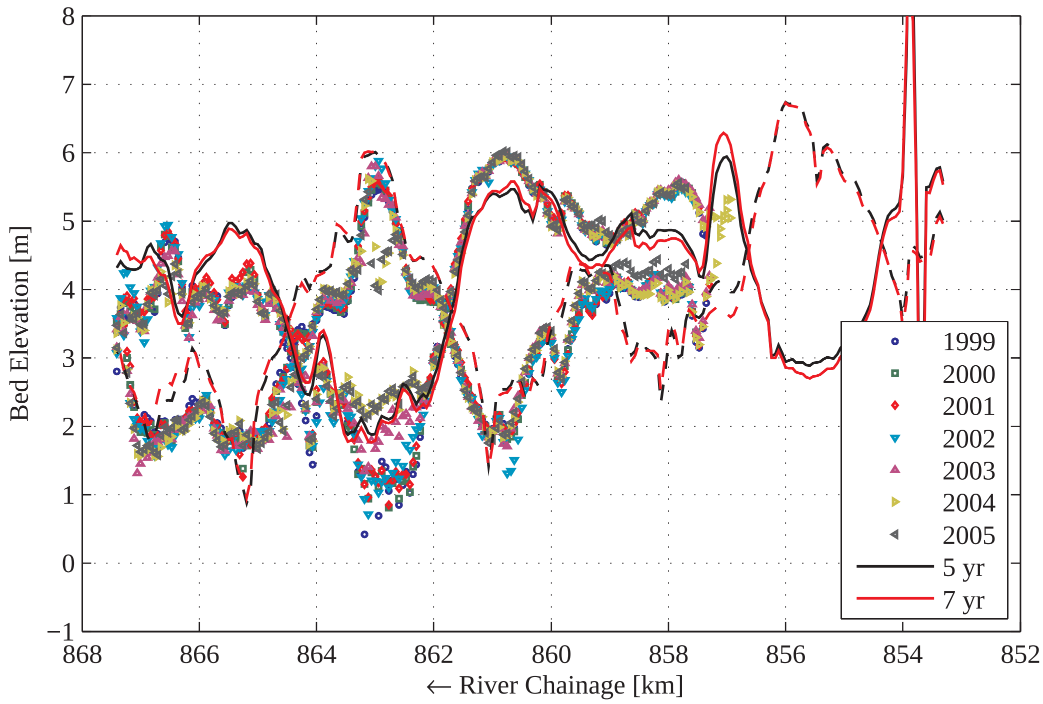


Figure 2.12 Longitudinal profile of bed level for roughness height $k_s = 0.06$ and $\alpha = 5.6$ at the end of the fifth and seventh year (left/south bank represented by the continuous line and the north/right bank represented by the dashed line).

2.5 Discussion and Conclusion

In the previously developed model (Mosselman et al., 2007), large deposition rates were observed in the downstream reach of the Bovenrijn by the end of the 5^{th} year. Since this result was not supported by measurements, the need for further calibration was evident. In this case study we roughly calibrated the previously developed model and improved its performance in relation to the overall morphological behaviour of the river for a relatively long period (15 years).

The model was calibrated using a variable discharge rather than constant discharge. Changing the parameters that affect the spiral flow, roughness height, and sediment transport calibration parameters (Meyer-Peter & Müller formula) was part of the calibration process. As no significant changes in the bed levels were observed after the 7^{th} year, the bed level at the end of the seventh year of simulation of the calibrated model was considered as initial bed level on the river for further simulations. For the purpose of this case study, these settings are considered acceptable for the behaviour analysis of the fixed layer and sediment nourishment.

It is important to mention here that at this stage the model use is limited to analysing the behaviour of this case study. As the behaviour of the model indicates large deposition in the downstream reach that has not been observed in the field, additional calibration for the 1D large-scale morphology remains to be carried out.

3 Setup of the case study

3.1 Background

One of measures within the framework of the DVR project to maintain a sustainable navigation channel is the application of sediment nourishment strategy(s) in areas affected by bed degradation. Herein, we present the functional design for a case study in which we evaluate the application of a sediment nourishment strategy combined with the construction of a fixed layer in the Bovenrijn.

3.2 Functional design of the case study

3.2.1 Base scenario

We establish a base scenario that represents the situation without interventions, i.e. with neither a fixed layer nor nourishment. The settings for the base scenario are chosen during the calibration phase described in Chapter 2. The initial bed elevation and arithmetic mean of grain size along the river reach are presented in Figure 3.1 and Figure 3.2. The sediment composition is based on the earlier model (Mosselman et al., 2007), where it was deduced from a long simulation where bed composition was left to reach equilibrium.

Additional simulations with trenches were carried out to estimate bedform celerity. This provides an indication of the speed at which morphodynamic changes occur. Three trenches of 50 cm deep were created along the river.

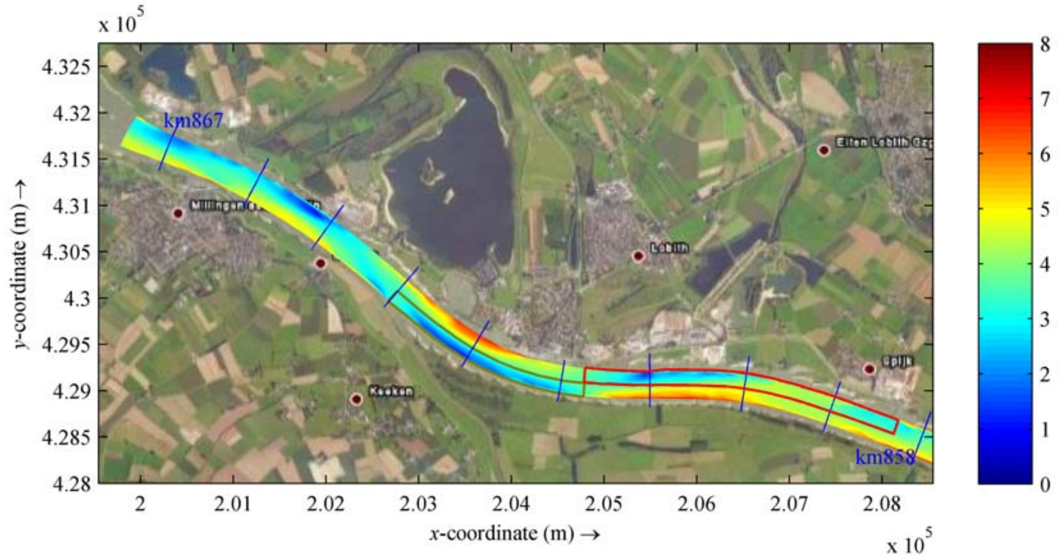


Figure 3.1 Initial bed level with indication to the fixed layer and nourishment areas.

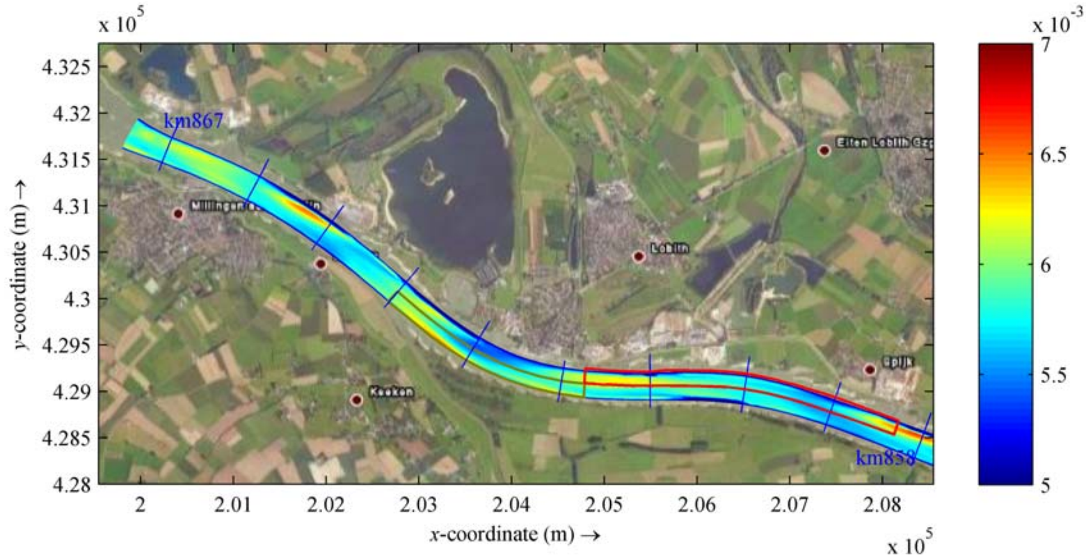


Figure 3.2 Initial mean grain size distribution.

3.2.2 Fixed layer

Nourishment is planned to take place at the left (south), outer-bend of the Bovenrijn reach from km 861 to km 864. At the upstream bend, a fixed layer is proposed to be constructed. The fixed layer is designed to cover the outer bend of the Bovenrijn reach from km 858.3 to km 861.7 (see Figure 3.4) with a top level 4.5 m below the OLR level, (OLR – 4.5 m).

Different schematisations of the fixed layer are evaluated in this study. The fixed layer as schematised in Figure 3.4b leads to an increase of the bed level of the deep part of the outer bend to reach the design level of the fixed layer top, while in the overlap area the bed level is reduced (dredged to place the fixed layer). In the second schematisation (Figure 3.4c), the fixed layer takes the same width as in the previous schematisation. However, the bed level in the shallow part of the bend is not reduced, only the sediment thickness is reduced. This is equivalent to placing a fixed layer under the existing bed (practically means dumping back sediment on top of the fixed layer). In the third schematisation (Figure 3.4d), the fixed layer is similar to the second one with an extended width to cover the full river width.

A fixed layer with a top level of 3.5 m below OLR is tested and its performance is compared versus the base design of OLR – 4.5 m. The comparison of morphological impact of different fixed-layer schematisation, and different settings for the active-layer thickness and threshold sediment layer thickness are analysed.

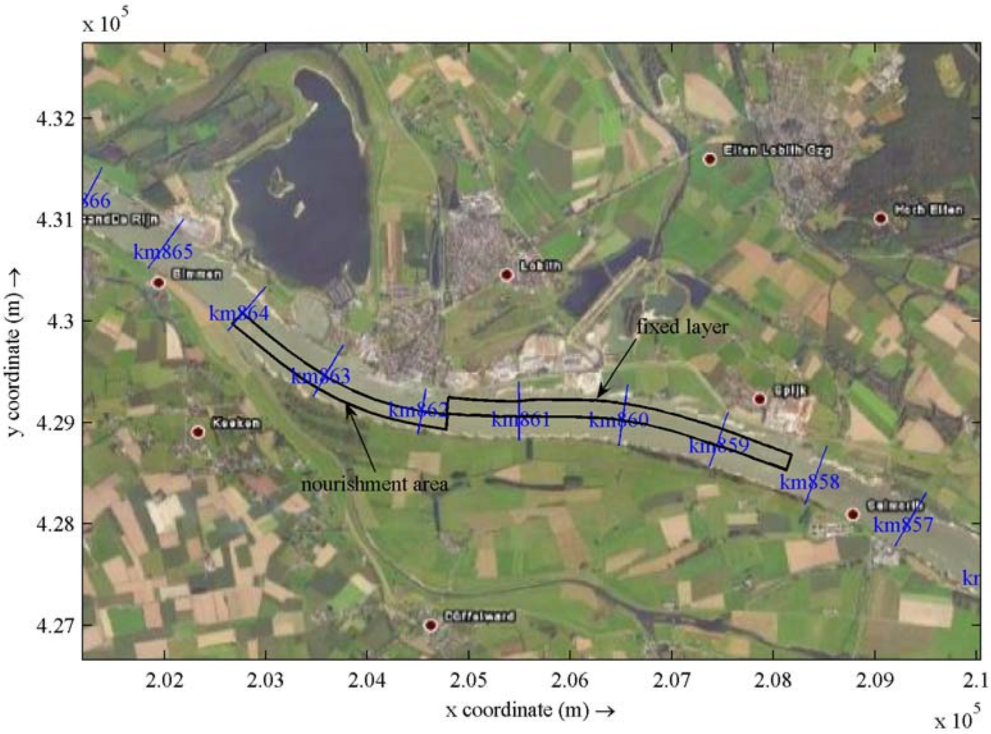


Figure 3.3 Satellite image with indication of the locations of the fixed layer and the nourishment area, (image source: Google Earth)

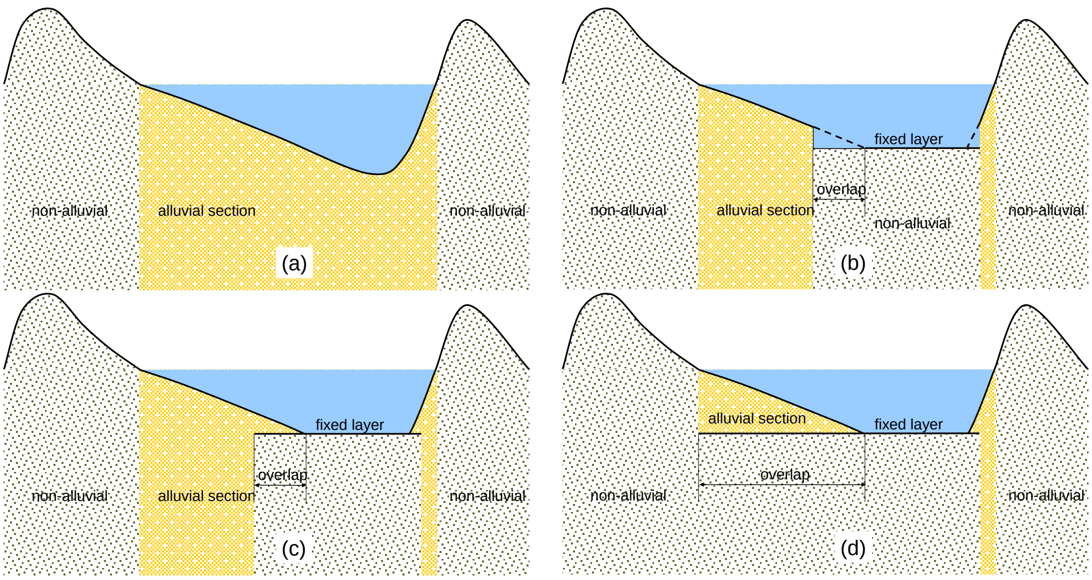


Figure 3.4 Cross profile of a river bend (a), with three different schematisations for a fixed layer (b, c & d).

3.2.3 Nourishment

Nourishment is simulated to take place in the outer bend of the reach between km 861 and km 864. Because the fixed layer extends to km 861.7, the nourishment will start from km 861.7 located downstream of the fixed layer, as depicted in Figure 3.3. The nourishment area is 150 m wide measured from the left normal line of the river.

The planned implementation is to apply the nourishment once every two years during low flow conditions with a total yearly volume of 60,000 m^3 distributed evenly over the low flow period. The maximum dump level should not exceed OLR-3.5 m. Herein, we evaluate the morphological response to one-time nourishment as well as nourishment once every two years.

The aim is to use a nourishment material similar to the material found in the outer bend of the nourishment reach. As a nourishment material we use material similar to the bed material, with slight coarsening to match the coarser material in the outer bend and test the results with two other materials that are coarser and finer than the original material (see Table 3.1). The number of fractions varies according to the test case while volume is kept constant at 60,000 m^3.

Table 3.1 Overview of the grain size distribution for the different nourishment materials

Fraction number	Grain Size (mm)		Nourishment Material (%)		
	Min	Max	Original	Coarser	Finer
1	1	2	19.9	-	22.6
2	2	2.8	12.3	10.8	14.9
3	2.8	4	13.5	12.0	16.2
4	4	8	22.5	26.5	25.1
5	8	16	18.6	28.1	21.2
6	16	32	13.2	22.6	-

3.3 Parameters settings

For different cases we evaluate the relevant parameters that affect the performance of the simulation. Some modelling parameters that have an effect on the fixed layer are evaluated, namely the effect of the active-layer thickness and the threshold depth, referred in this report as *ThTrLyr* and *Thresh* respectively.

For the schematisation depicting combined effect of the nourishment and the fixed layer we evaluate the effect of nourishment time interval and material. The effect of the gradation of the nourishment material is evaluated by using three types of nourishment material. A list of the evaluated parameters is presented in Table 3.2.

Table 3.2 Variation of parameter settings for different schematisations

No.	Case specifications	Nourishment		Fixed layer	Active-layer
		ate	Composition	Threshold Depth [m]	Thickness [m]
1.	Base case	-	-	-	0.5
2.					1.5
3.					f(Q)
4.	Fixed layer	-	-	1	0.5
5.					1.5
6.					f(Q)
7.				0.1	1
8.				0.5	
9.	Fixed layer and nourishment	once	as designed	0.1	1.5
10.				0.5	
11.				1	
12.			as designed	1	0.5
13.					f(Q)
14.			Coarser	1	1.5
15.			Finer		
16.		5 times	as designed	1	0.5
17.					1.5
18.					f(Q)
19.			Coarser	1	1.5
20.			Finer		

4 Results

4.1 Base scenario

The base scenario (no measures taken) has been chosen after the calibration carried out in Chapter 2. The cumulative erosion deposition pattern is presented in Figure 4.1 and the cross-section averaged bed level changes are presented in Figure 4.2. These two figures indicate that the considered river reach is rather stable with changes mainly in the 2D morphological pattern. These changes are elaborated further in Figure 4.3 and Figure 4.4, where we can see a comparison between the measured and calculated longitudinal bed profiles of the left and right banks. The cross-section averaged bed level changes given in Figure 4.2 indicate the presence of a relatively slow large-scale degradation; note that the morphological boundary condition at the upstream side is 3 cm/yr bed level degradation. The reach averaged bed level degradation is around 1 cm/yr which is comparable to the measured data that was used in the calibration of the uniform sediment model (Yossef et al., 2007).

Changes in bed composition are presented in Figure 4.5. We can see that the changes reach some 2 mm in several locations. The changes in grain size distribution correspond to the morphological changes with alternating coarsening and fining following the erosion and deposition pattern.

Note that the bed level fluctuations at km 854 in Figure 4.2 are thought to be due to numerical instabilities and they do not affect the analysis of the following results.

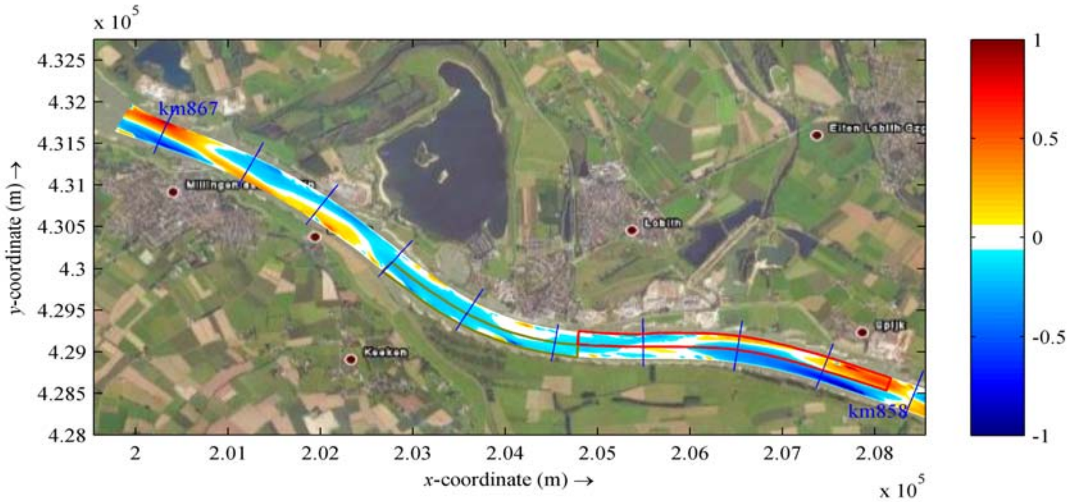


Figure 4.1 Bed level changes after 10 years.

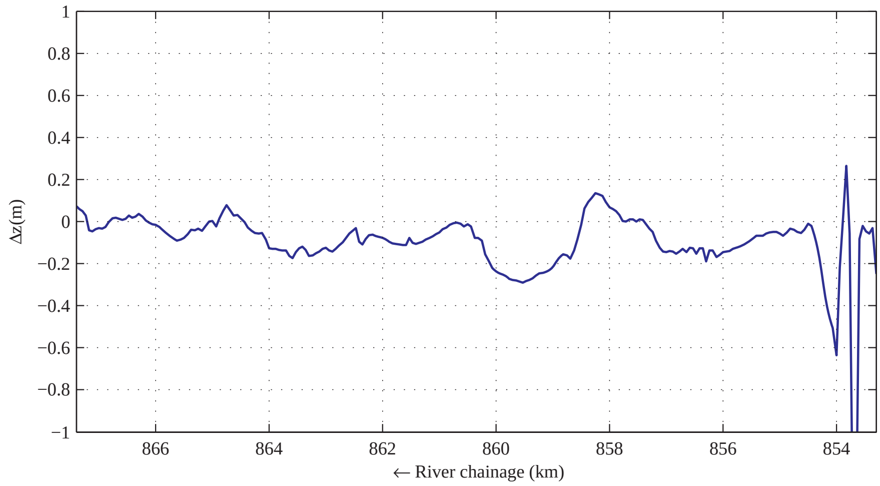


Figure 4.2 Cross-section averaged bed level changes after 10 years.

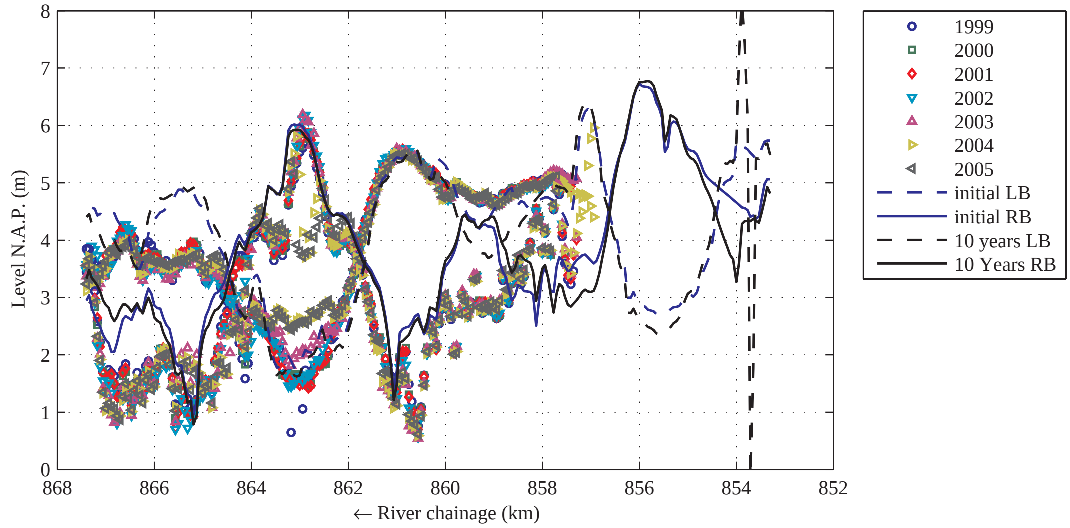


Figure 4.3 Longitudinal profiles of the left and right banks initially and after 10 years; comparison with the measured data.

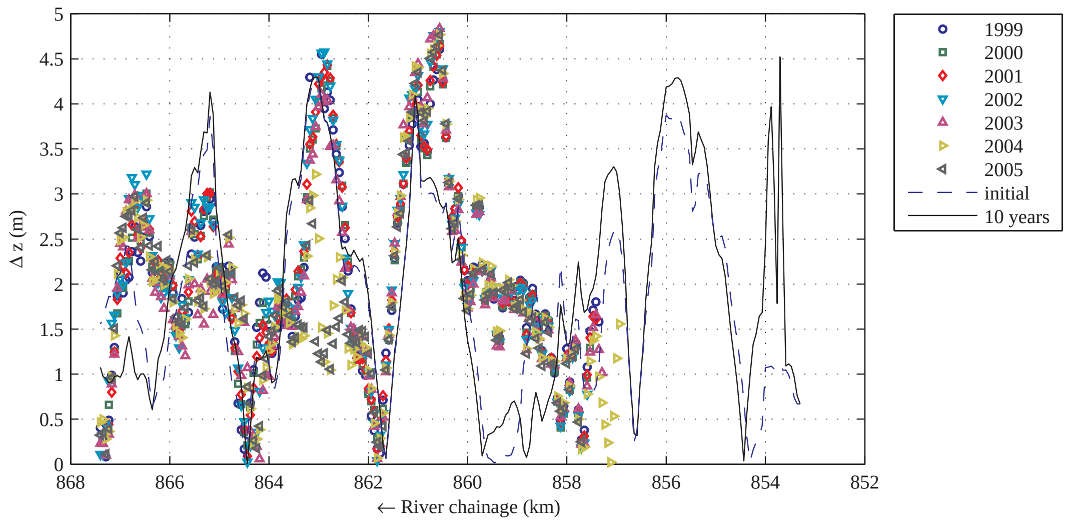


Figure 4.4 Bed level difference between the left and right banks initially and after 10 years; comparison with the measured data.

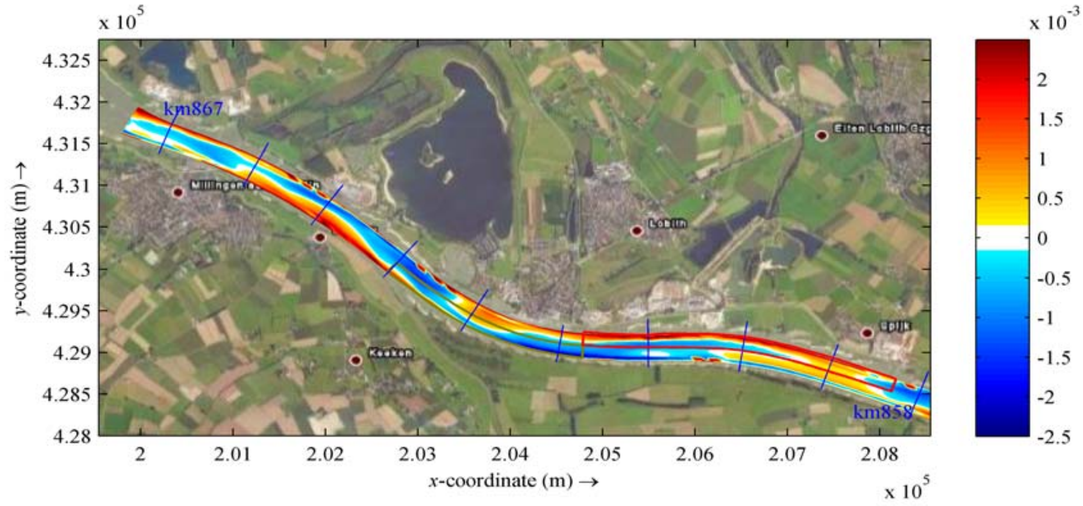


Figure 4.5 Changes in mean sediment diameter after ten years.

4.2 Effect of fixed layer

The effect of the fixed layer is given in Figure 4.6. The upper panel shows the initial difference in bed level between the case with a fixed layer (schematisation: b in Figure 3.4) and that without fixed layer. The figure shows the direct effect of implementing a fixed layer, the erosion means that the bed is dredged to construct the fixed layer and the deposition means that the bed is filled to reach the design level of the fixed layer. The middle and lower panels of Figure 4.6 gives to snapshots in time after five and ten years. We can see that the inner bend opposite to the fixed layer the bed is eroding. Just downstream of the fixed layer, a scour hole develops and just downstream of the inner bend, deposition ridge develops. The erosion in the inner bend is around 0.5 m, the depth of the scour hole is around 2 m and the deposition ridge amounts up to 1.5 m.

The temporal developments of some selected locations in the vicinity of the fixed layer are given in Figure 4.8. The figure reveals temporal changes that take place on three different time scale levels. The largest of these scales shows the large-scale behaviour of the river reach which is relatively slow; the second scale level covers the local changes due to the implementation of the fixed layer that takes around two years to reach a state of dynamic equilibrium; the third scale level covers the seasonal changes due to discharge variations and is a direct manifestation of the effect of high–low flow variations. The smaller scales are superimposed on larger-scales, viz. the scale of the local effect of the fixed layer is superimposed on the large-scale river trend and the seasonal variations are superimposed on both larger-scales. Needless to mention, the local morphological effect of the fixed layer affect the large-scale river morphological behaviour of the river (cf. Mosselman and Sloff, 2006). From that figure we can conclude that the morphological effect of the fixed layer takes around two years to reach a state of dynamic equilibrium.

Note that the long-term behaviour of point C in Figure 4.8 the difference in bed level between the case with fixed layer and the reference case appears as sedimentation after the initial large erosion. This might be explained by the behaviour of the reference case where there is long-term erosion at this point that stops after implantation of the fixed layer.

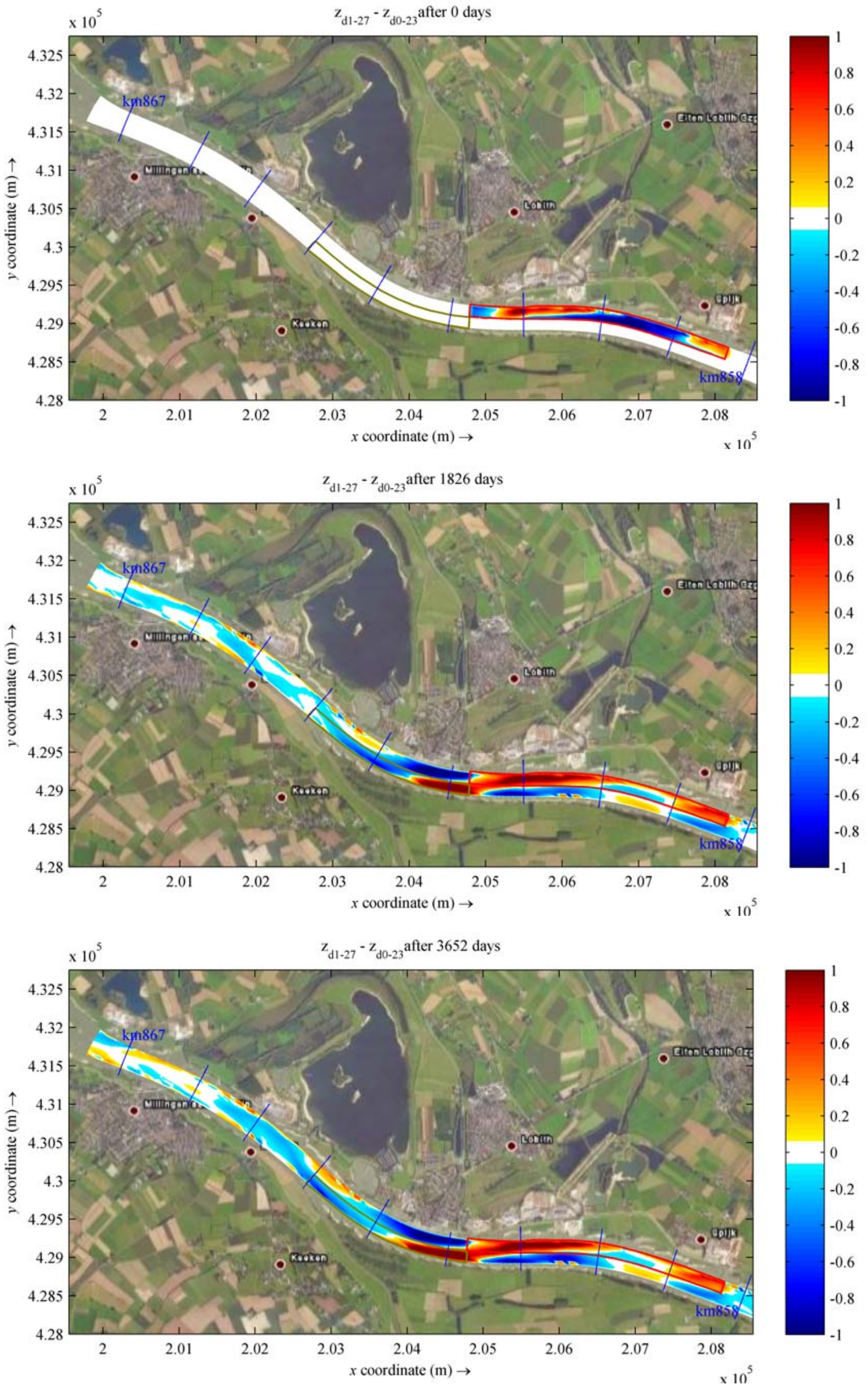


Figure 4.6 Difference in bed levels between the simulation with the fixed layer (schematisation: b) and that without fixed layer; initially, after 5 years and after 10 years.

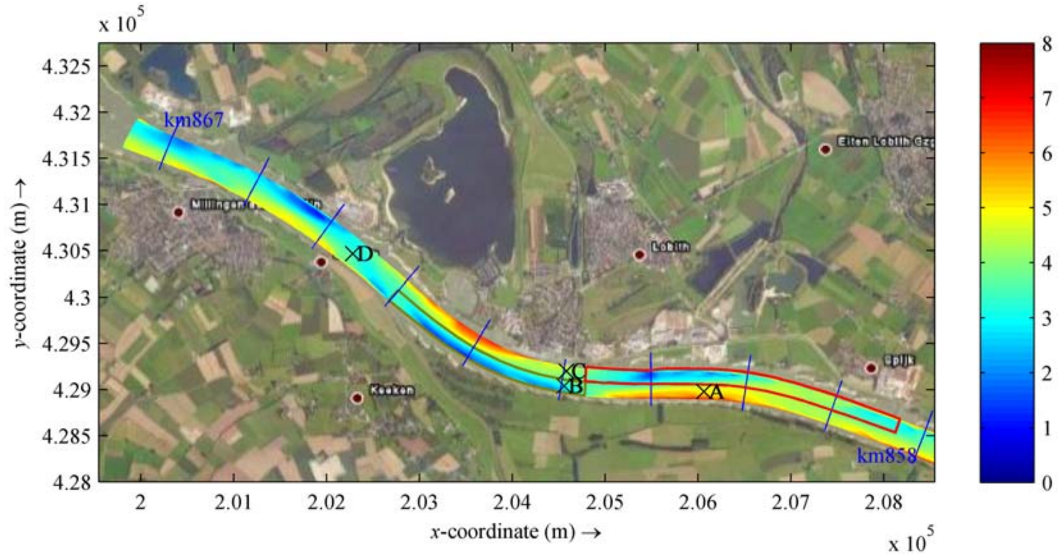


Figure 4.7 Identification of some selected locations in the vicinity of the fixed layer.

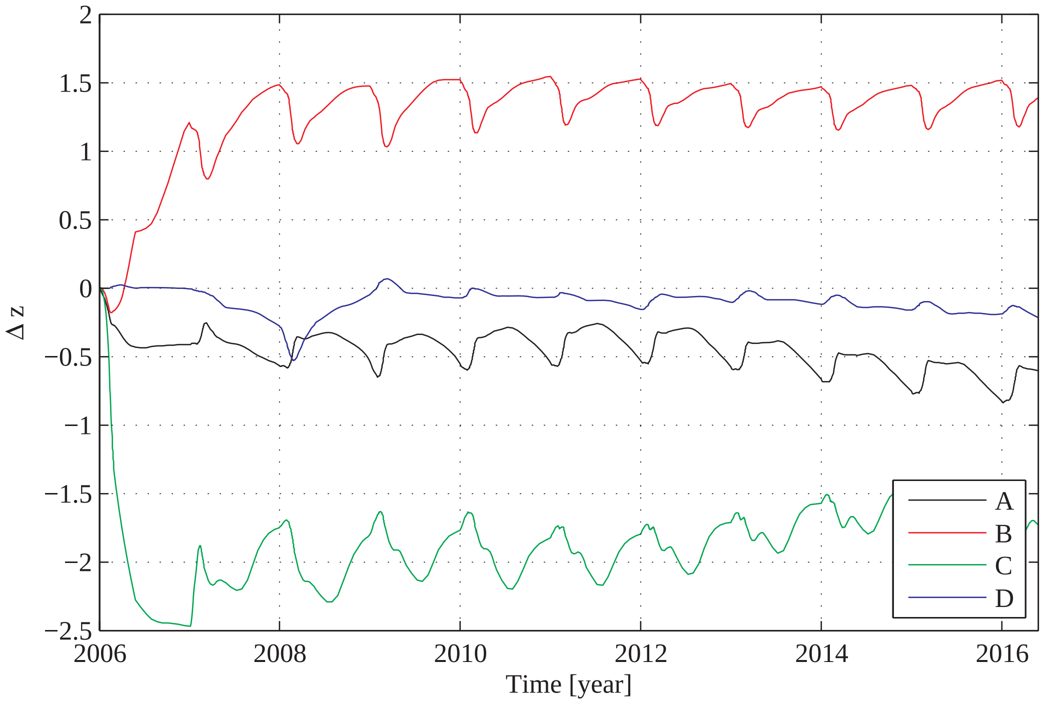


Figure 4.8 Temporal development of the difference in bed levels between the simulation with the fixed layer (schematisation: b) and that without fixed layer for some selected points.

4.2.1 Effect of schematisation

The effect of different schematisations of the fixed layer is shown in Figure 4.9 to Figure 4.11. The schematisations are referred to as (b), (c) and (d) as depicted in Figure 3.4. At the end of the 10th year the differences between different schematisations are minor. However, schematisation b with the higher design level (top level = OLR – 3.5 m) given in Figure 4.11 gives rise to additional erosion in the inner bend, deeper scour hole downstream of the fixed layer and a higher deposition ridge downstream of the inner bend.

For the locations given in Figure 4.7 the temporal development of bed levels for the simulations with and without fixed layer are given in Figure 4.8. The effect of the fixed layer vanishes at location D further downstream of the fixed layer. For the locations A, B, and C equilibrium is reached at the end of the second year. Higher erosion and deposition levels are observed for the schematisation (b) with (OLR – 3.5 m) in comparison to the one with (OLR – 4.5 m). Both schematisations have no effect further downstream (location D).

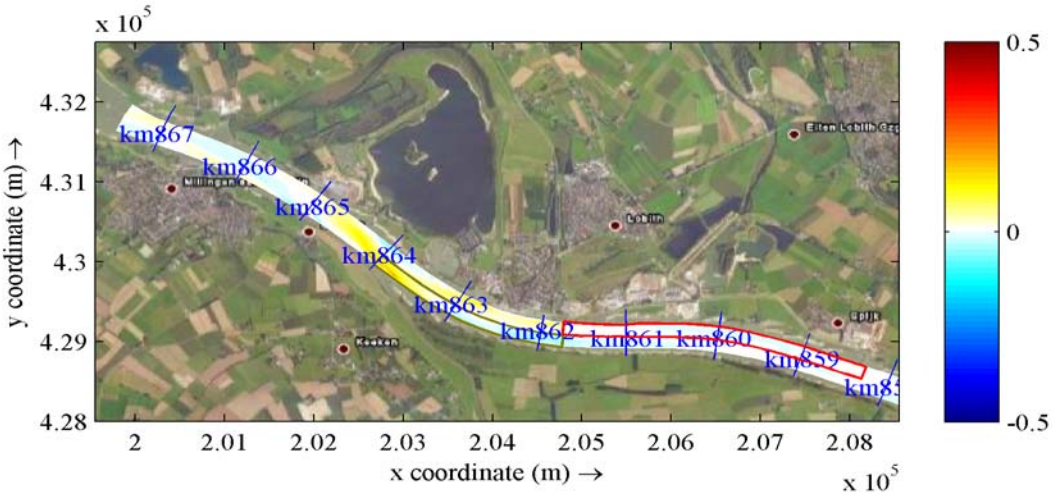


Figure 4.9 Difference in bed levels at the end of the 10th year between the simulation with the fixed layer of the half (schematisation: c) with respect to the fixed layer schematisation b.

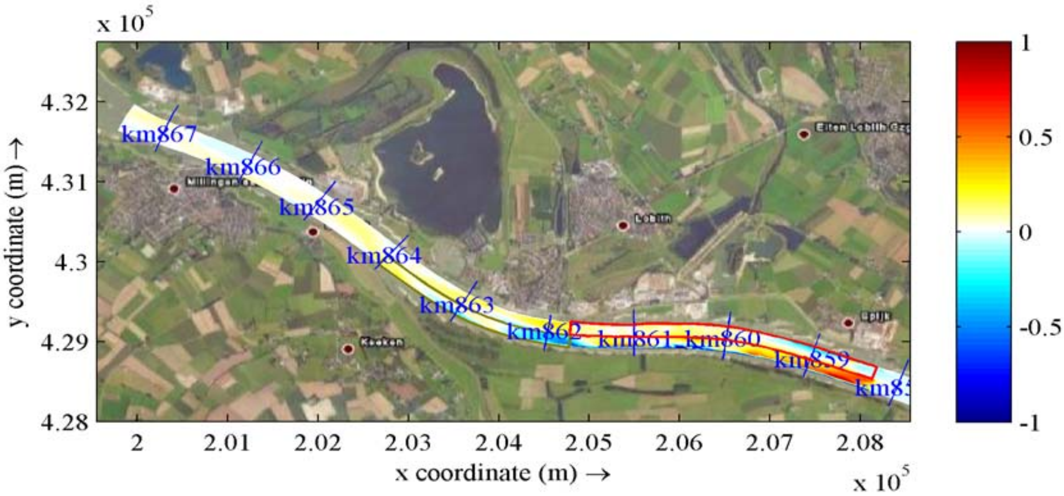


Figure 4.10 Difference in bed levels at the end of the 10th year between the fixed layer of the full width (schematisation: d) with respect to the fixed layer schematisation b.

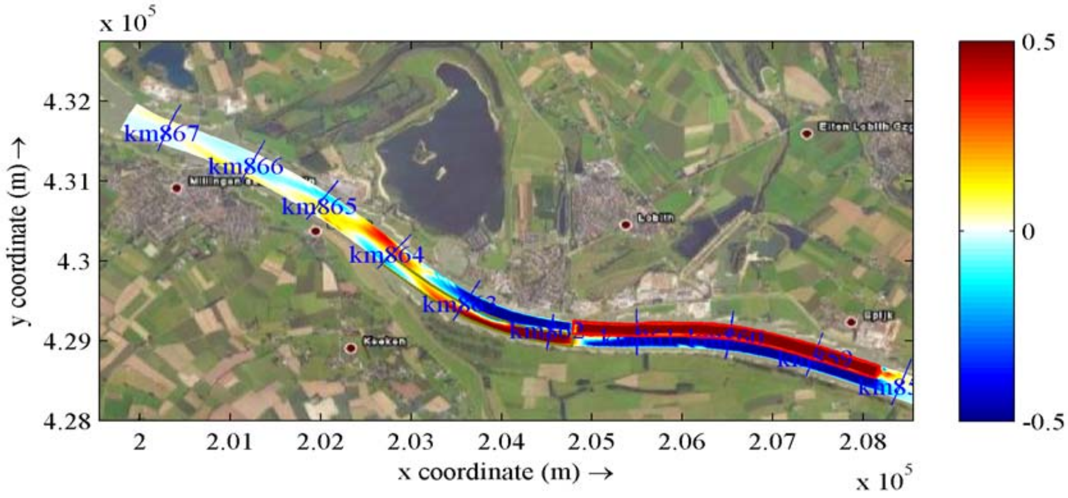


Figure 4.11 Difference in bed levels at the end of the 10th year between the simulation with the fixed layer schematisation b with increased design level (top level = OLR-3.5 m), with respect to schematisation b.

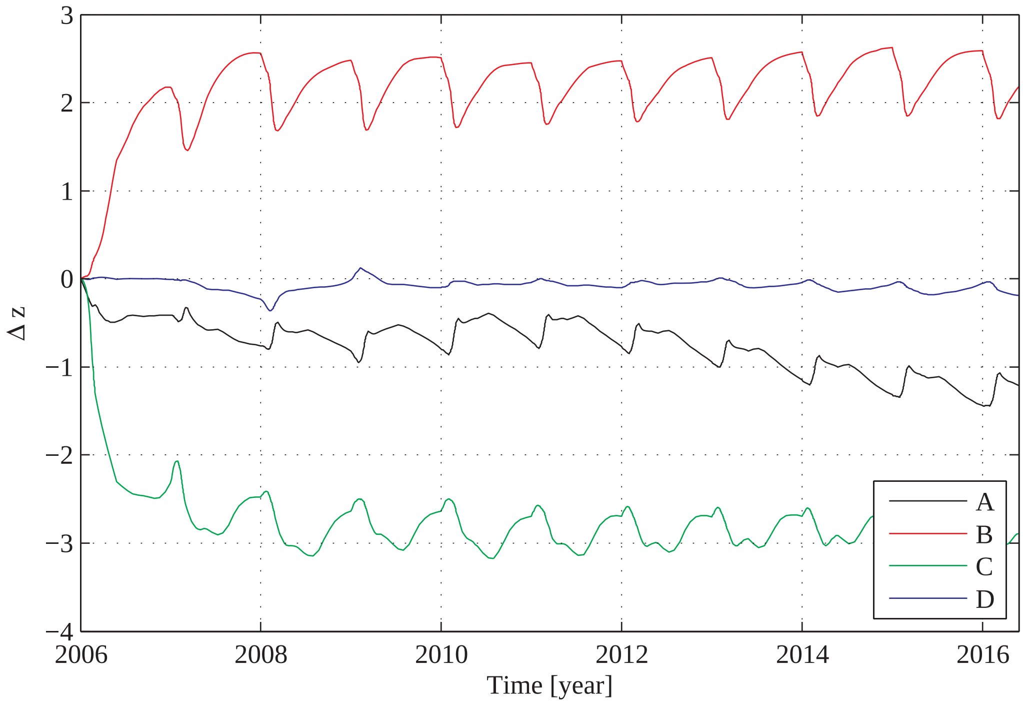


Figure 4.12 Differences in bed level for the simulation with fixed layer (schematisation (b) with a design level of OLR-3.5 m) and the base case scenario in some selected locations.

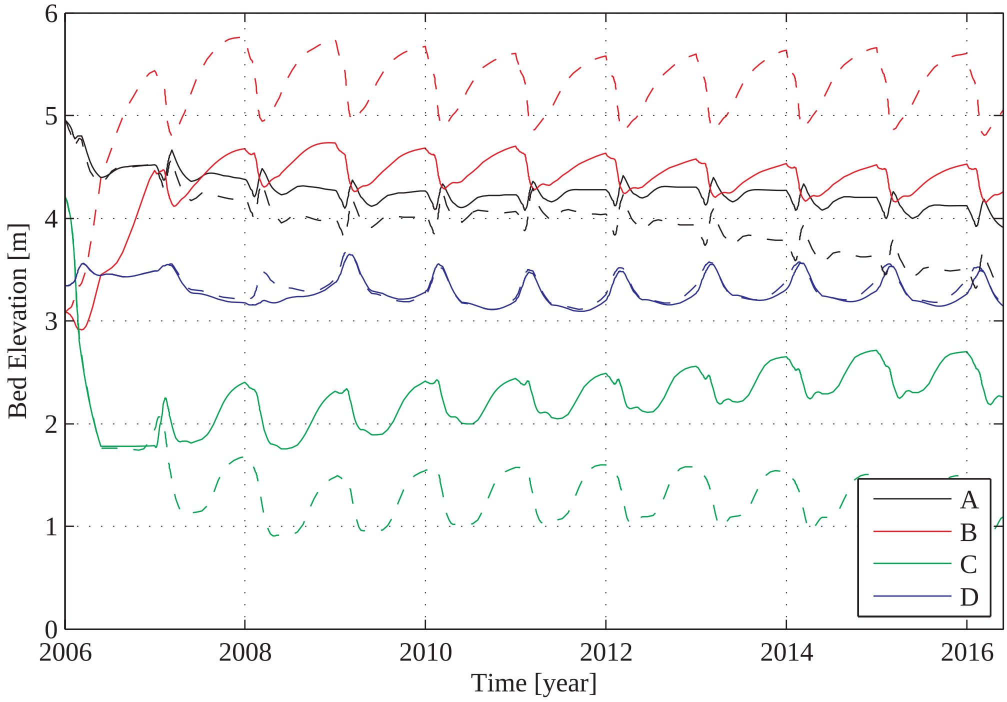


Figure 4.13 Temporal bed level development for the simulation with fixed layer (OLR-4.5 m) continuous lines and (OLR-3.5 m) dashed lines.

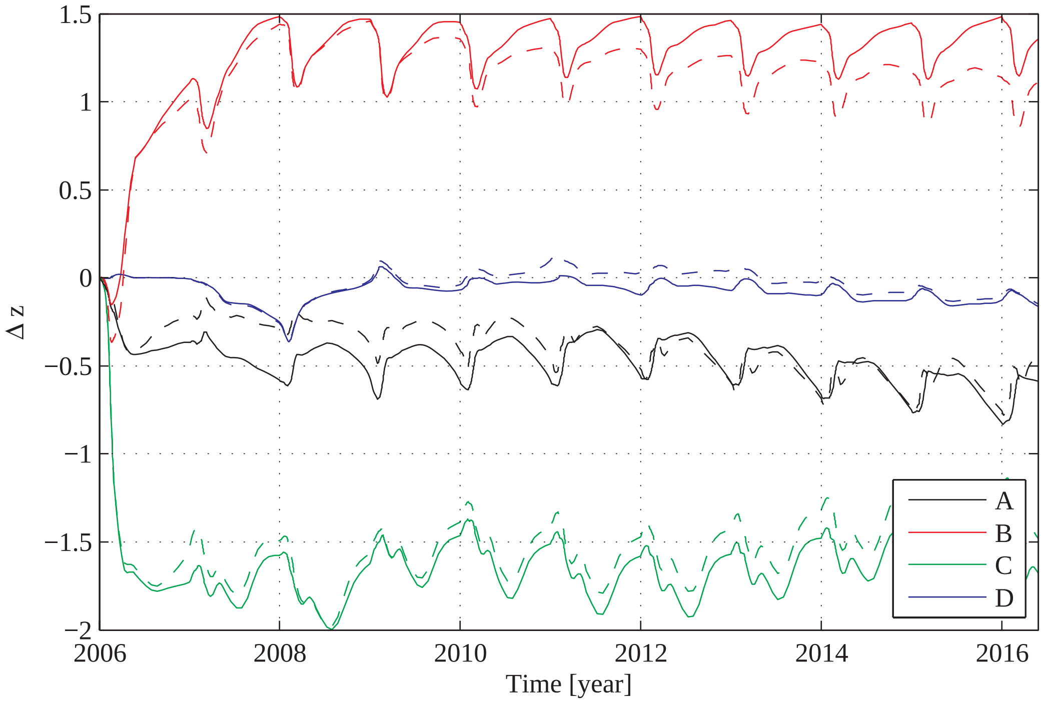


Figure 4.14 Differences in bed level of the simulation (Figure 3.4c) with fixed layer of half width (continuous lines) and simulation (Figure 3.4d) with fixed layer of full width (dashed lines) versus base case scenario.

Figure 4.15 and Figure 4.16 present the difference in mean sediment diameter between the case with a fixed layer and the base scenario. Note that there is sediment fining on top of the fixed layer. This is due to transport of fine material on top of the fixed layer. The fixed layer simulation starts with no sediment on top of the fixed layer (schematisation: b). The figures indicate that initially some coarsening takes place just downstream of the fixed layer Figure 4.15. After five years this material becomes finer. Changes in mean grain size diameter are in the order of ±1 mm.

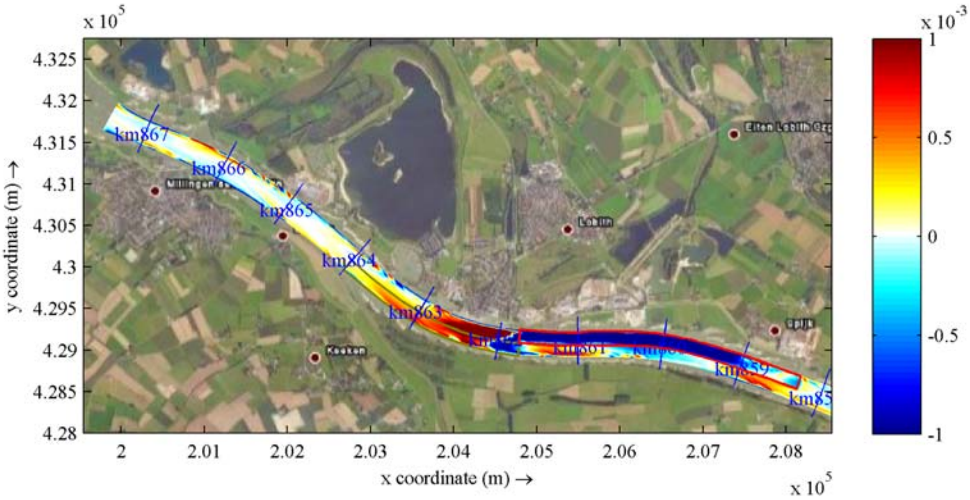


Figure 4.15 Difference in grain size distribution D_m at the end of the 1st year between schematisation (b) and the base case scenario, scale is in meters.

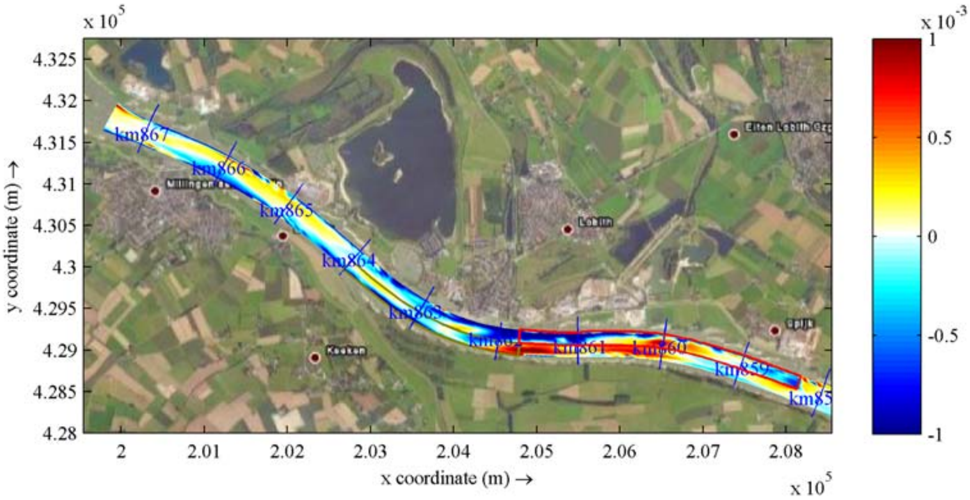


Figure 4.16 Difference in grain size distribution D_m at the end of the 5th year between schematisation (b) and the base case scenario, scale is in meters.

4.2.2 Effect of threshold sediment thickness (δ_a) for fixed layer effect

The model concept for fixed layers has been defined in the early 1980s, and is based on a correction of bed-load transport capacity. The model concept was subsequently implemented in Delft3D. The theoretical backgrounds and experimental verification of this approach have been presented by Struiksma (1999). In this approach, the fixed layer is modelled as an area where the thickness of the alluvium is limited (usually with no sediment at the start of the simulation). The model concept of Struiksma (1999) accounts for the transport limitations on fixed layers through a reduction of the active-layer thickness on the bed. In this concept the volumetric sediment transport per unit width (s_f) is reduced with a correction factor (ψ) to obtain the actual sediment transport per unit width (s) over the non-erodible layer (including pores) such that:

$$s = \psi\left(\frac{\delta}{\delta_a}\right) s_f$$

and,

$$\psi = \frac{\delta}{\delta_a}\left(2 - \frac{\delta}{\delta_a}\right) \quad \text{for} \quad \frac{\delta}{\delta_a} < 1$$

(as implemented in Delft3D)

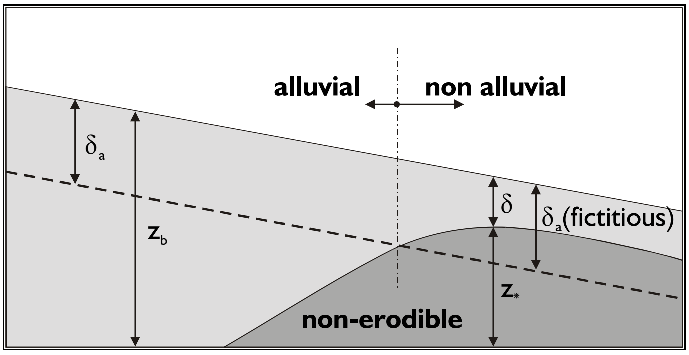


Figure 4.17 Definition sketch (after Struiksma, 1999)

where δ is the thickness of alluvium on the non-erodible bed, and δ_a is the threshold thickness of alluvium at which the fixed layer affects the sediment transport, see Figure 4.17 for more details.

The effect of the threshold depth δ_a was evaluated by using two additional settings for δ_a in addition to the reference case. The three tested values for δ_a were 1.0 m (reference case), 0.5 m, and 0.1 m. The effect of the different settings is presented in Figure 4.18 and Figure 4.19.

The figures indicate that using a smaller threshold value for the fixed layer effect primarily reduces the amount of sediment depositing on top of the fixed layer (as could be expected). This in turn affects the morphological pattern in the direct vicinity of the fixed layer causing less scour downstream of the fixed layer (right bank) and less deposition as well at the side opposite of the scour (left bank). At the left bank, opposite of the fixed layer, there is generally more erosion (more navigation depth) in comparison to the reference fixed-layer case. The effect extends in downstream direction causing higher bed levels in comparison to the reference case (the largest δ_a). At the upstream side of the fixed layer, the effect is limited.

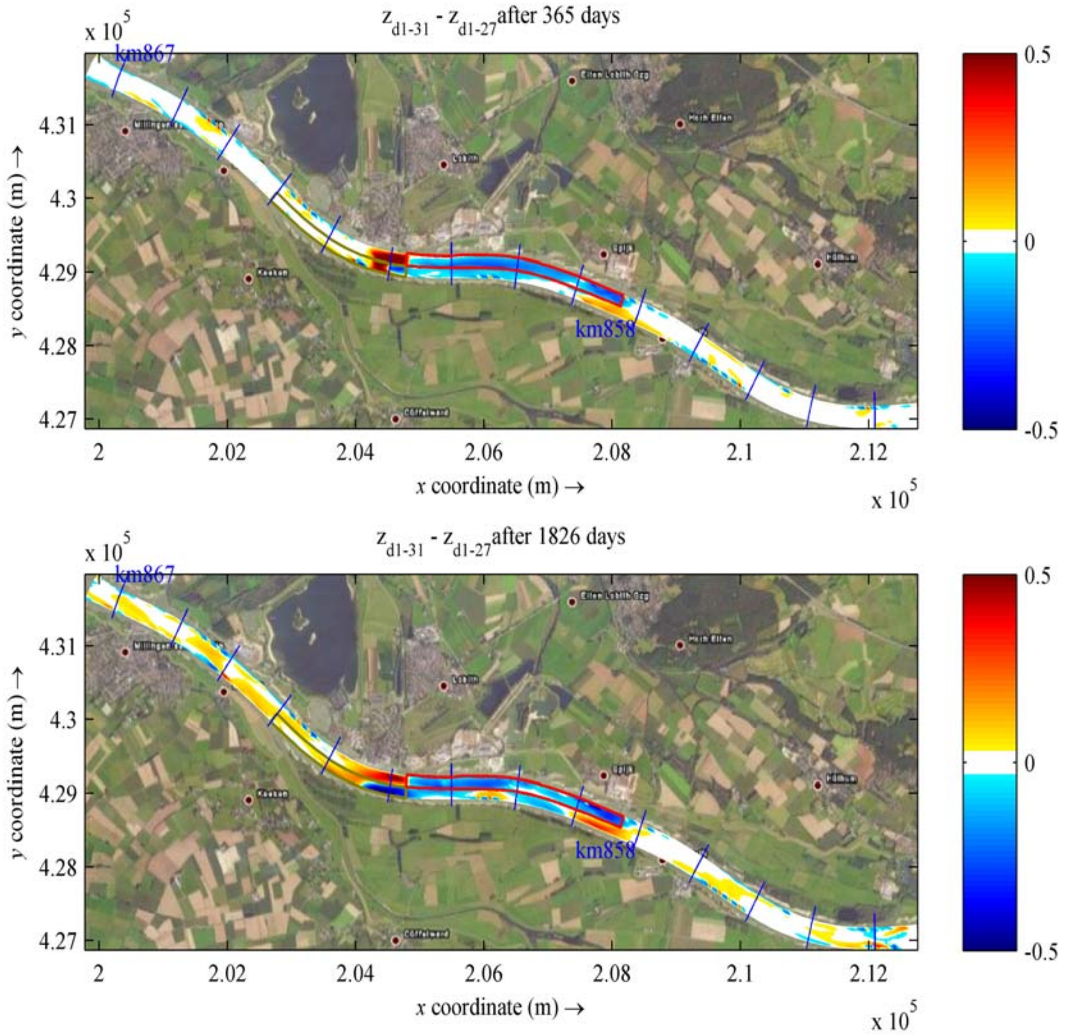


Figure 4.18 Difference in bed levels at the end of the 1st year (upper panel) and 5th year (lower panel) between the case with a fixed layer of (δ_a = 0.5 m) and the reference fixed-layer case (δ_a = 1.0 m).

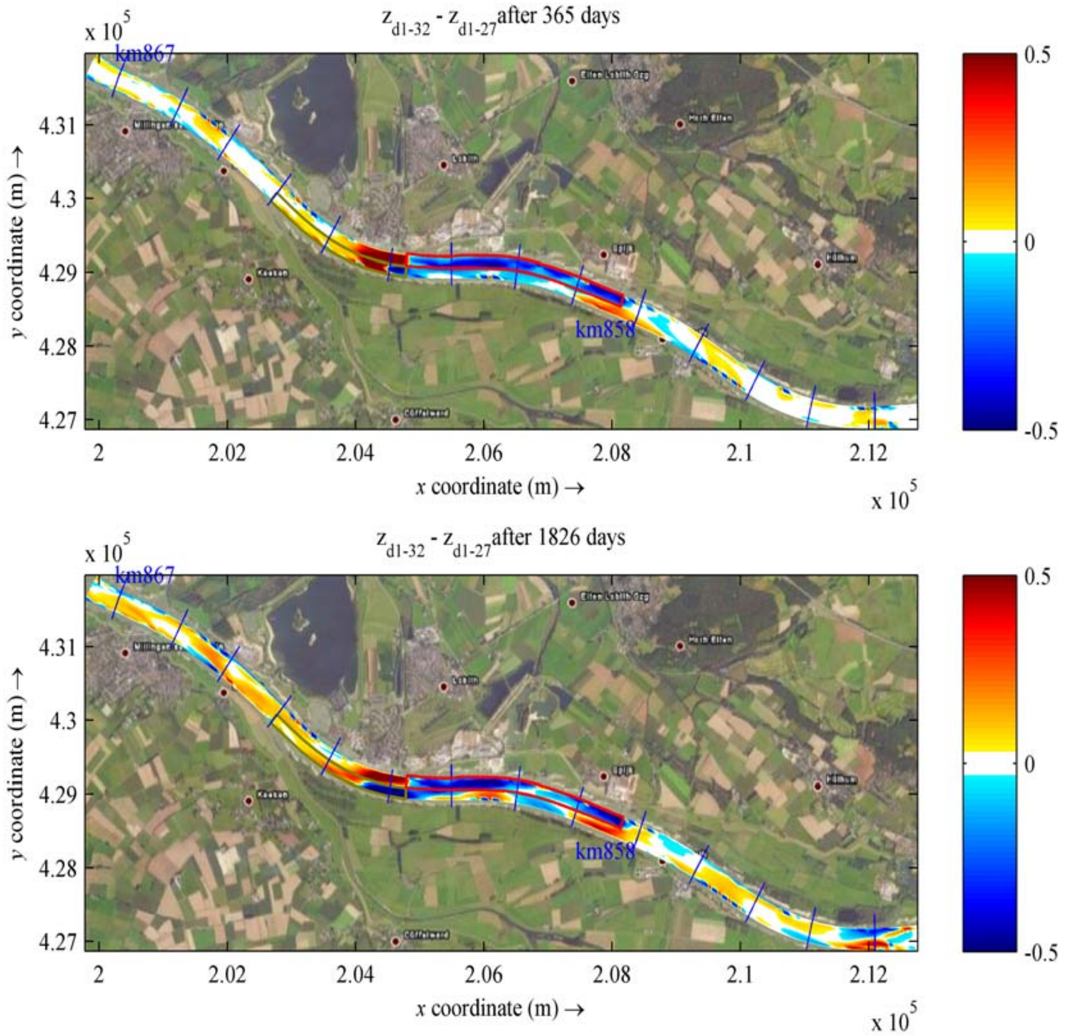


Figure 4.19 Difference in bed levels at the end of the 1st year (upper panel) and 5th year (lower panel) between the case with a fixed layer of (δ_a = 0.1 m) and the reference a fixed layer case (δ_a = 1.0 m).

4.3 Effect of nourishment

4.3.1 One-time nourishment

The nourishment was applied after the implementation of the fixed layer in the manner explained in Section 3.2.3. The result of the combined effect of the nourishment and the fixed layer for the first three years after nourishment is given in Figure 4.20. A comparison with the case including only the fixed layer indicates that the effect of the fixed layer dominates the behaviour of the downstream reach of the Bovenrijn (Figure 4.21 and Figure 4.22).

Figure 4.21 shows that the bed level in the nourishment area increases, with respect to the case with a fixed layer, by the end of the nourishment period; the increase amounts to 0.5 m and it is more pronounced in the deeper part of the bend. After two years have passed, the effect on the bed level is still present in the nourishment area, though with less magnitude.

The effect extends in downstream direction affecting the bed levels in the outer bend at km 865 with an increase in bed level less than 0.2 m. After five years the effect is reduced and nearly disappears after 10 years (Figure 4.22). In comparison to the reference case, introducing the nourishment after the construction of the fixed layer has a minor effect.

The net effect on the navigation channel is depicted in Figure 4.23. We can see that the shallow area in the inner bend opposite to the fixed layer, still, did not fulfil the navigation requirement for the full width. The effect of the fixed layer after three years leads to a slight increase of the navigation channel width in km 858.3-km 861.7. In the nourishment area, the available navigation channel is not affected. In the downstream reach, there is hardly any effect on the navigation channel.

The effect of nourishment on the sediment size can be seen in Figure 4.24 and Figure 4.25. The figures indicate that the changes in the sediment mean diameter D_m are in the order of 0.5 mm. The effect near the bifurcation point is minimal. Note that the changes in the grain size are affected by the morphological changes.

Figure 4.26 to Figure 4.28 show the percentage of the tracer material in the bed composition after one, three and five years. The figures highlight the difference in propagation speed between the finest and the coarsest tracers. The propagation speed of the finest material is more than 1 km/yr, the coarsest tracer has a propagation speed less than 1 km/yr. From Figure 4.27 we can see that after three years the tracer materials are still within the model domain.

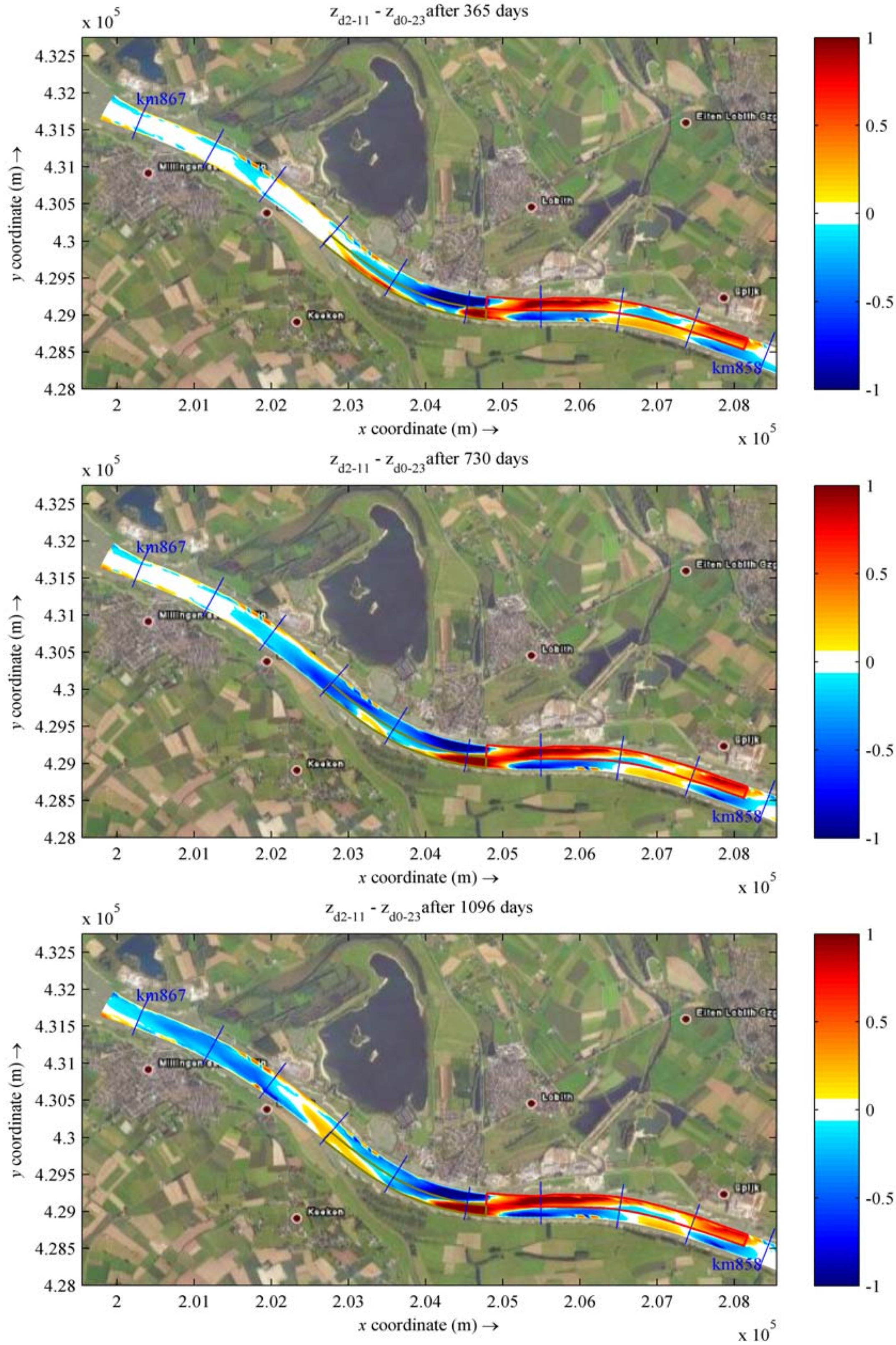


Figure 4.20 The combined effect of the fixed layer and nourishment; difference in bed level with respect to the base scenario at the end of the 1st, 2nd and 3rd years.

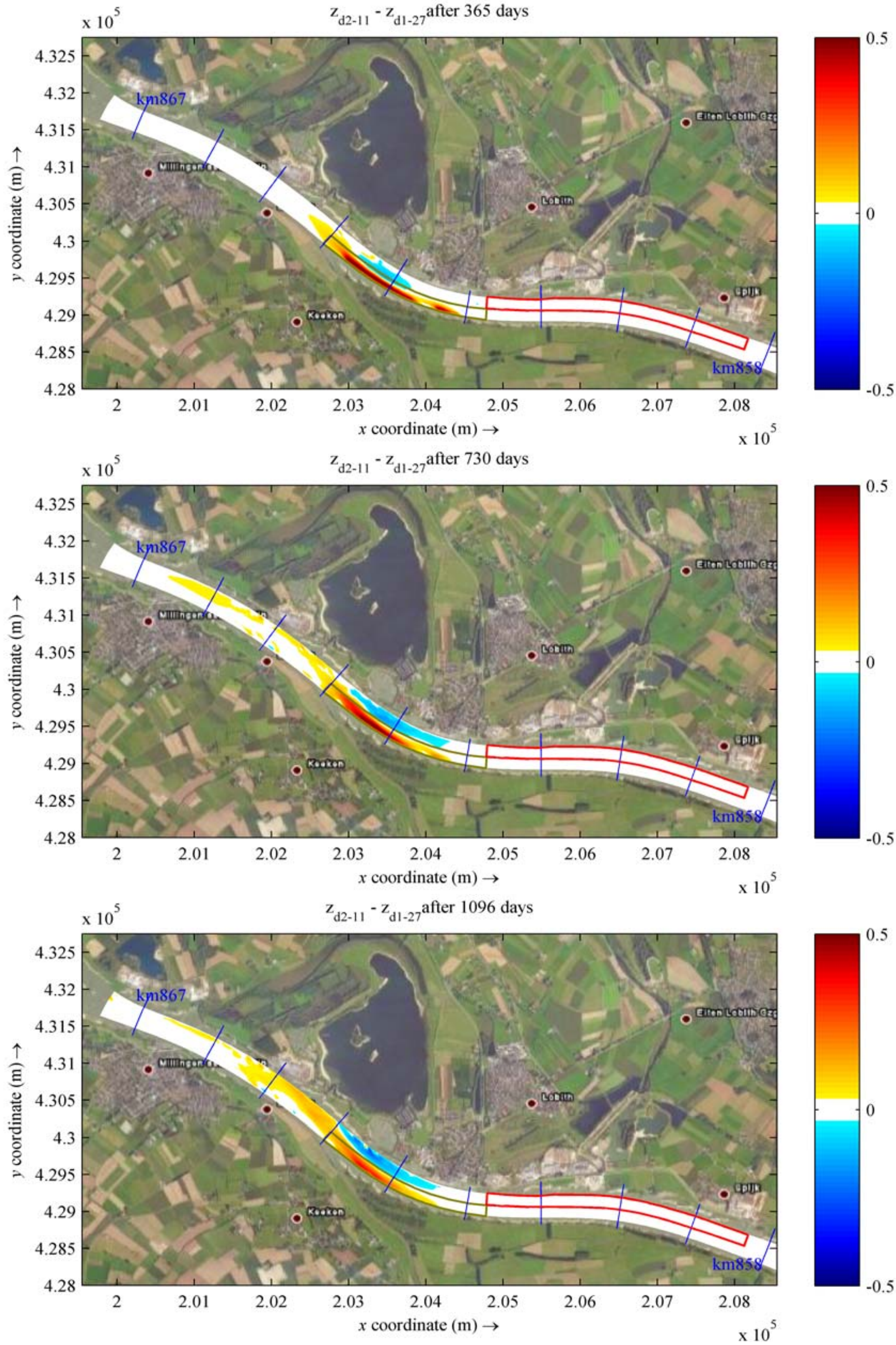
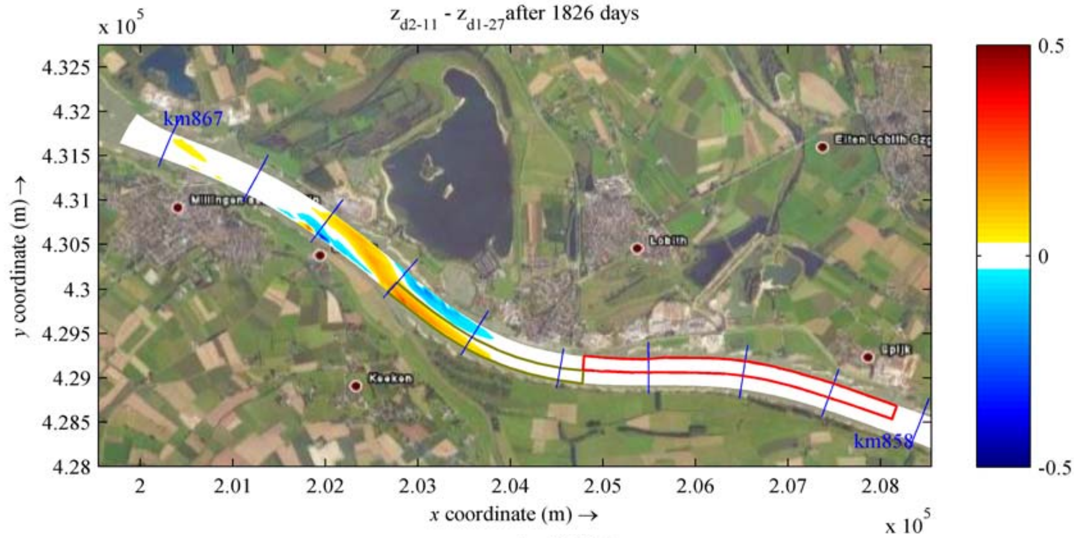


Figure 4.21 The effect of one-time nourishment; difference in bed level with respect to the case with fixed layer (schematisation b) at the end of the 1st, 2nd and 3rd years.



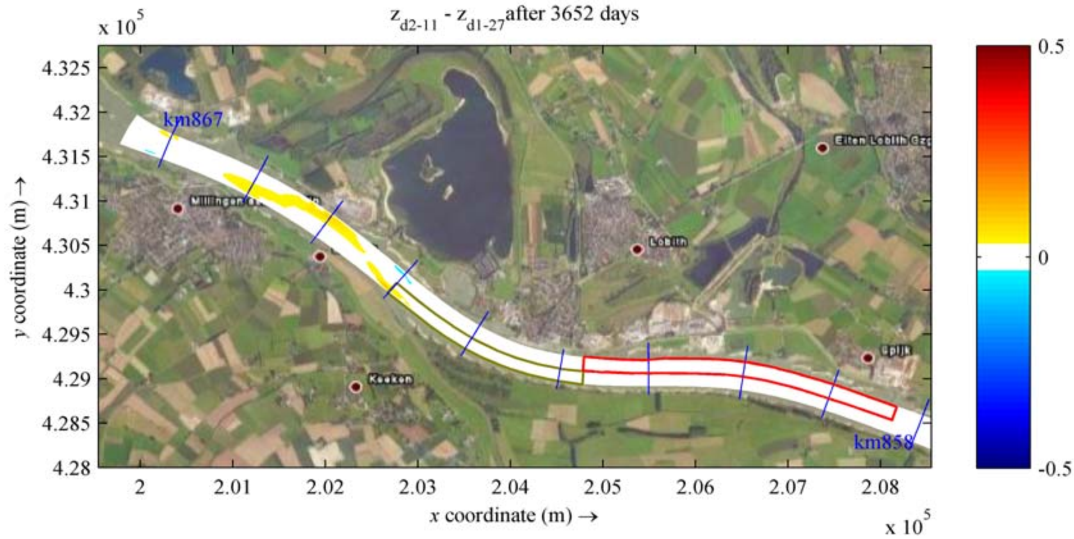


Figure 4.22 The effect of one-time nourishment; difference in bed level with respect to the case with fixed layer (schematisation b) at the end of the 5th and 10th years.

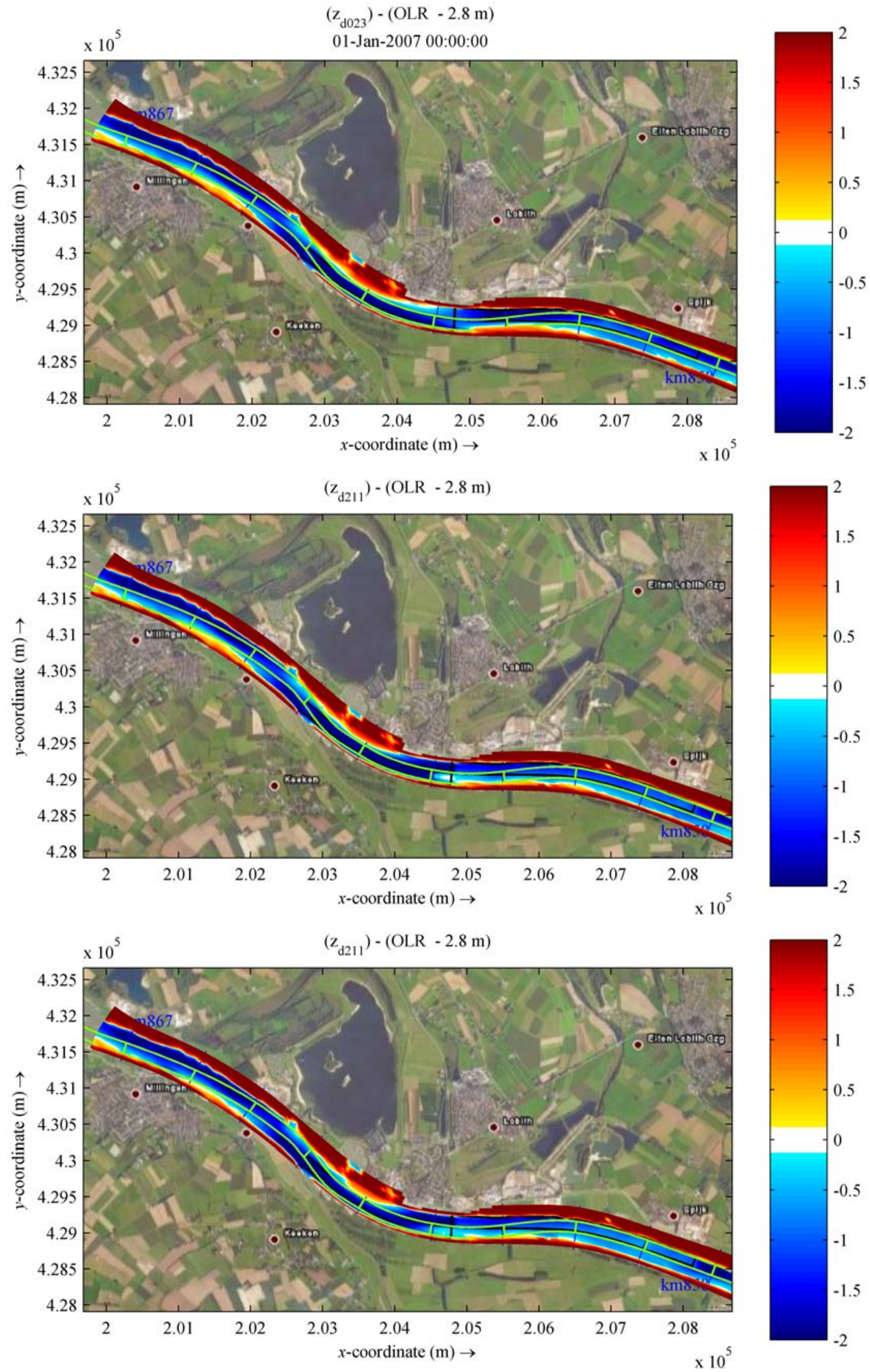


Figure 4.23 Available navigation depth (z – (OLR – 2.8)); upper panel: 1st year reference case, middle panel: case with nourishments and fixed layer 1st year, and 3rd year (lower panel).

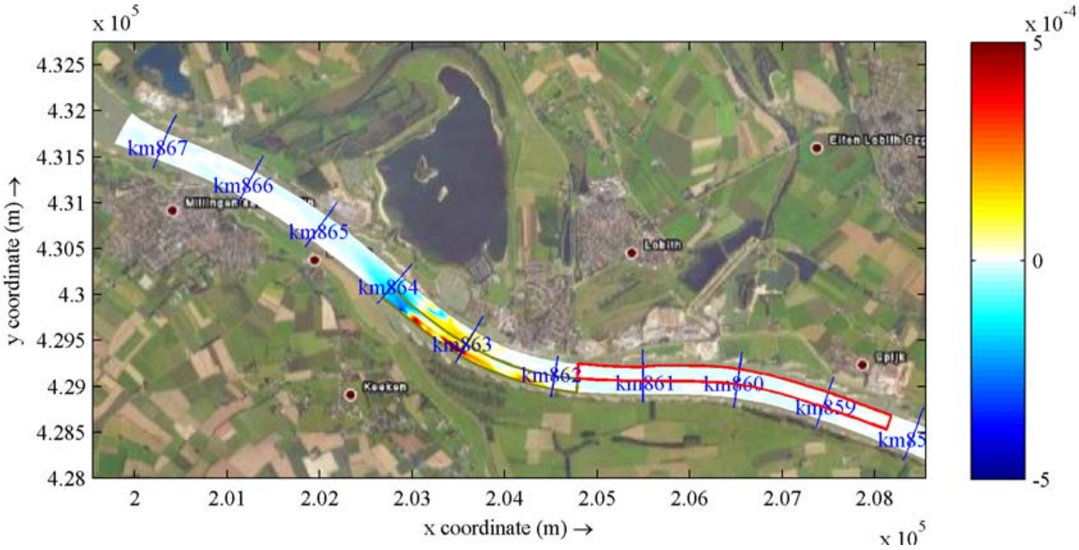


Figure 4.24 The effect of one time nourishment; difference in mean sediment diameter D_m with respect to the case with fixed layer (schematisation b)) at the end of the 1st year.

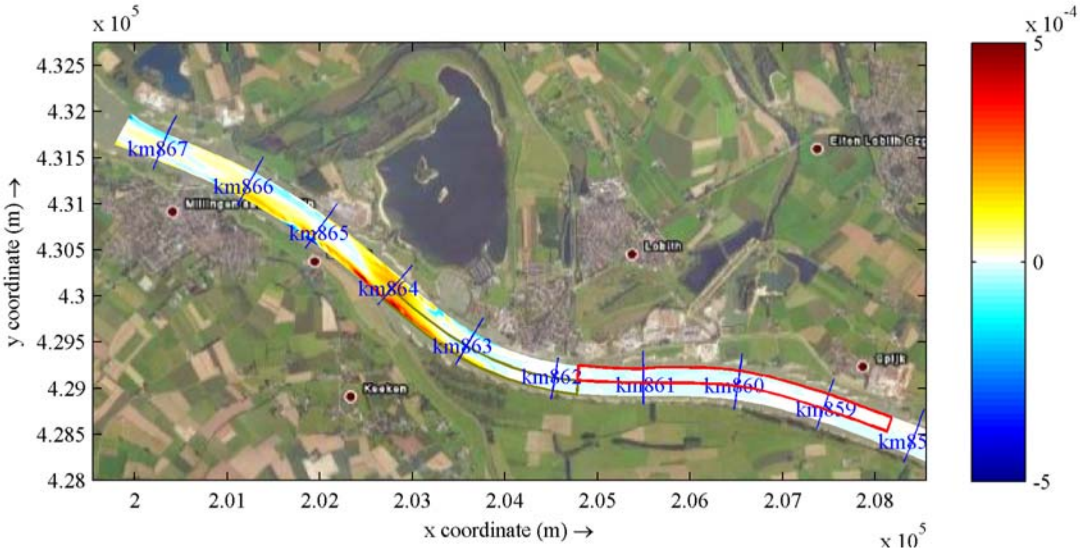


Figure 4.25 The effect of one time nourishment; difference in mean sediment diameter D_m with respect to the case with fixed layer (schematisation b) at the end of the 5th year.

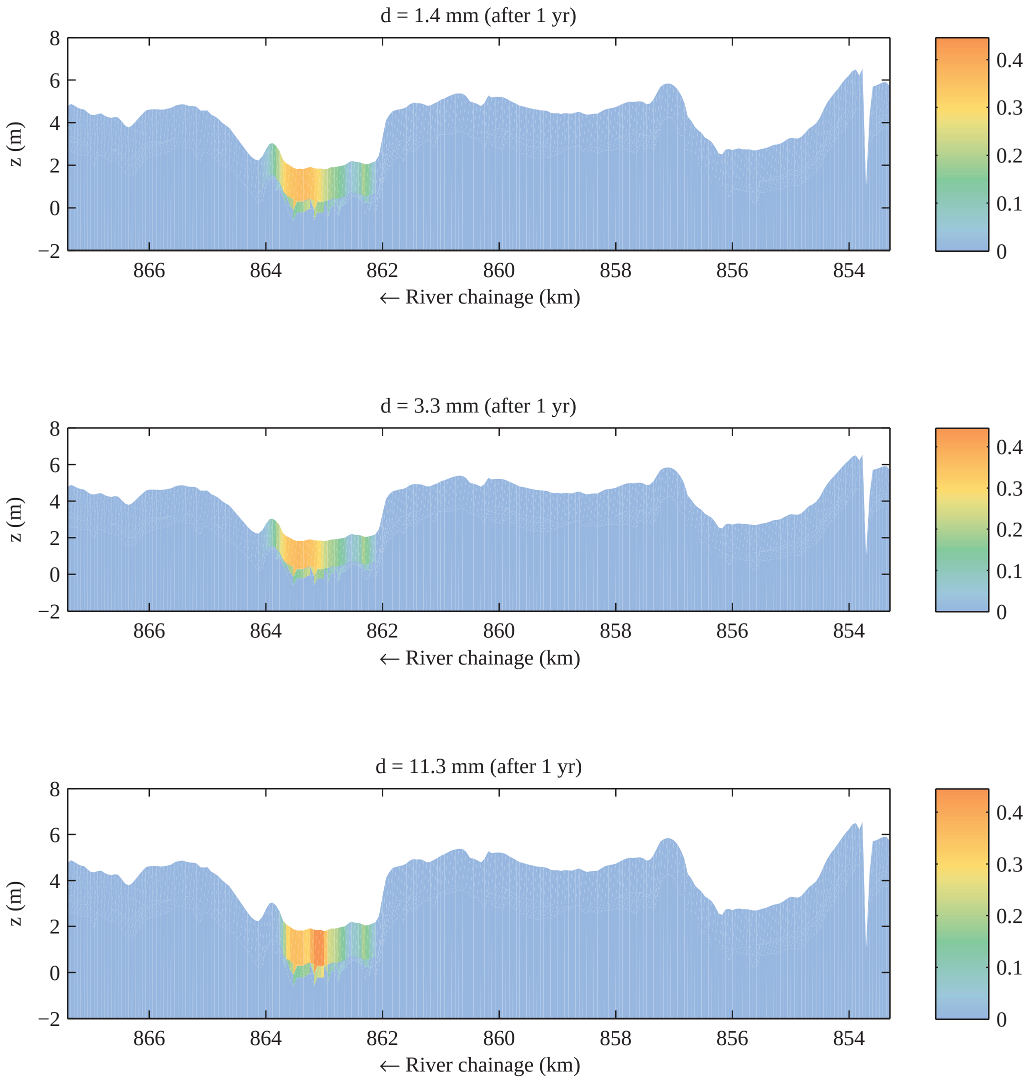


Figure 4.26 Percentage of tracer material in the bed composition along the left bank at the end of the 1st year.

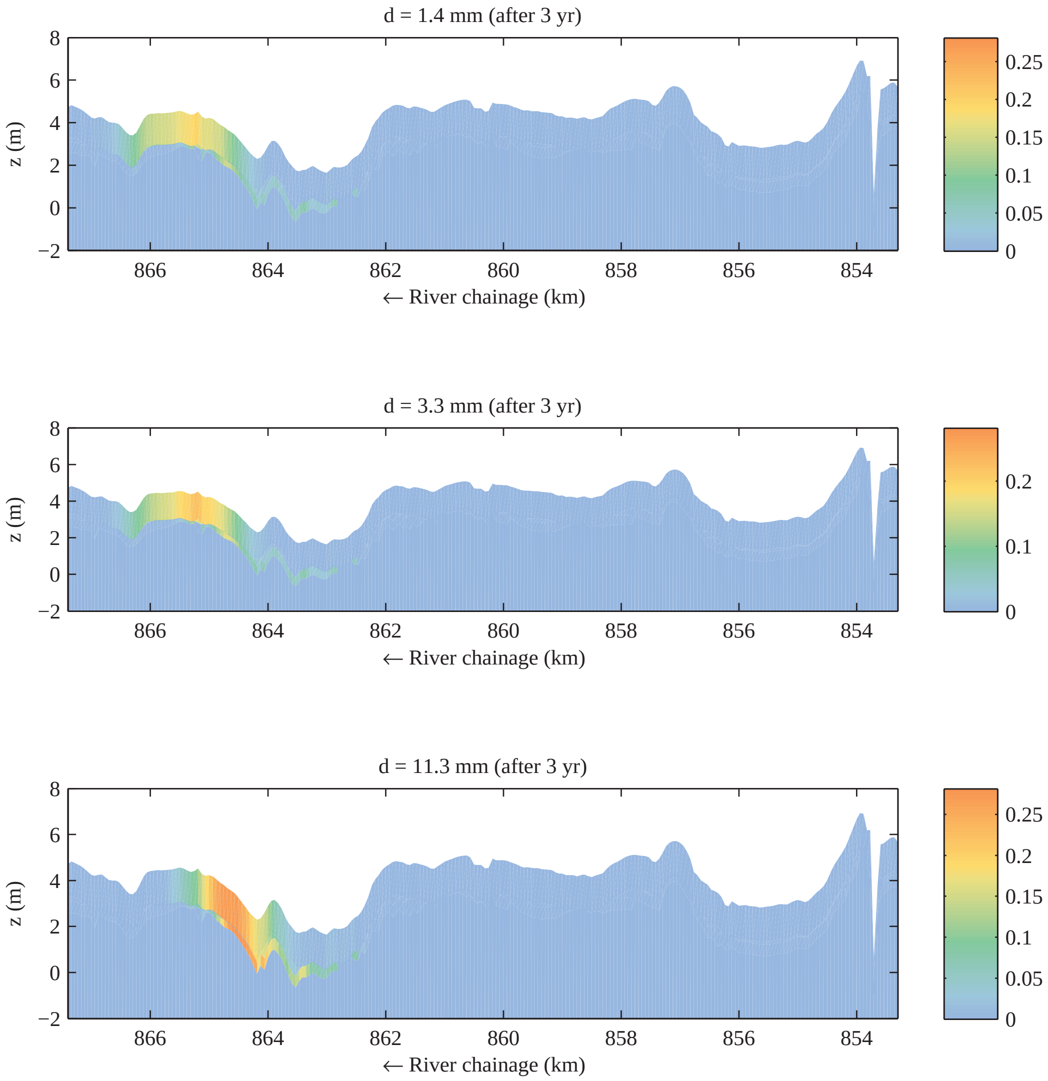


Figure 4.27 Percentage of tracer material in the bed composition along the left bank at the end of the 3rd year.

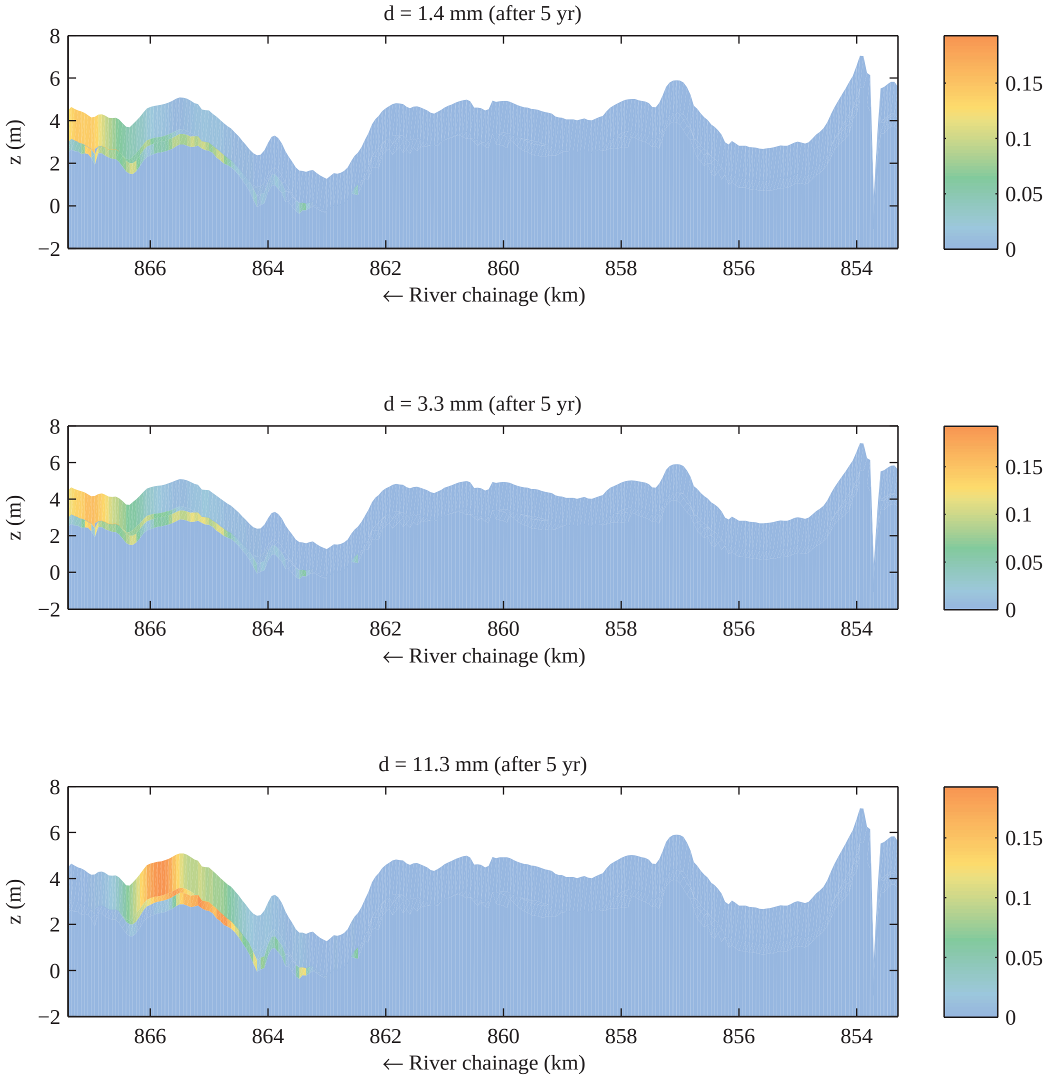


Figure 4.28 Percentage of tracer material in the bed composition along the left bank at the end of the 5^{th} year.

4.3.2 Repetitive nourishment

The difference in morphological behaviour between repetitive nourishment every 2 years (years 1, 3, etc.) and one-time nourishment (year 1) is given in Figure 4.29. The behaviour during the first three years is identical as the 2nd nourishment has not been applied yet. After the 2nd nourishment (year 3 given in Figure 4.29 upper panel), the bed level in the nourishment area increases further, as the effect of the 1st nourishment is still present (cf. Figure 4.21 lower panel). After one more year has passed the bed level in the nourishment area decreases. However, after five years when nourishment is carried out once more, the bed level increases further (Figure 4.29 lower panel). Apparently, the interval of two years is not enough for the effect of nourishment to vanish. This is also clear from the behaviour of the one-time nourishment case.

Figure 4.30 to Figure 4.33 show the percentage of the tracer material in the bed composition after one, two, three and five years. The figures highlight the difference in propagation speed between the finest and the coarsest tracers. It is clear from the figures as well that the nourishment material introduced in the 3rd and 5th years is accumulating the nourishment material in the downstream reach of the Bovenrijn.

Because the nourishment material is chosen to be similar to the existing material in the river, the changes in the median grain size due to nourishment are limited. Figure 4.34 and Figure 4.35 give the effect on sediment size. The comparison shows a slight coarsening, around 1 mm, in the downstream direction. However, near the bifurcation point, the effect is minimal.

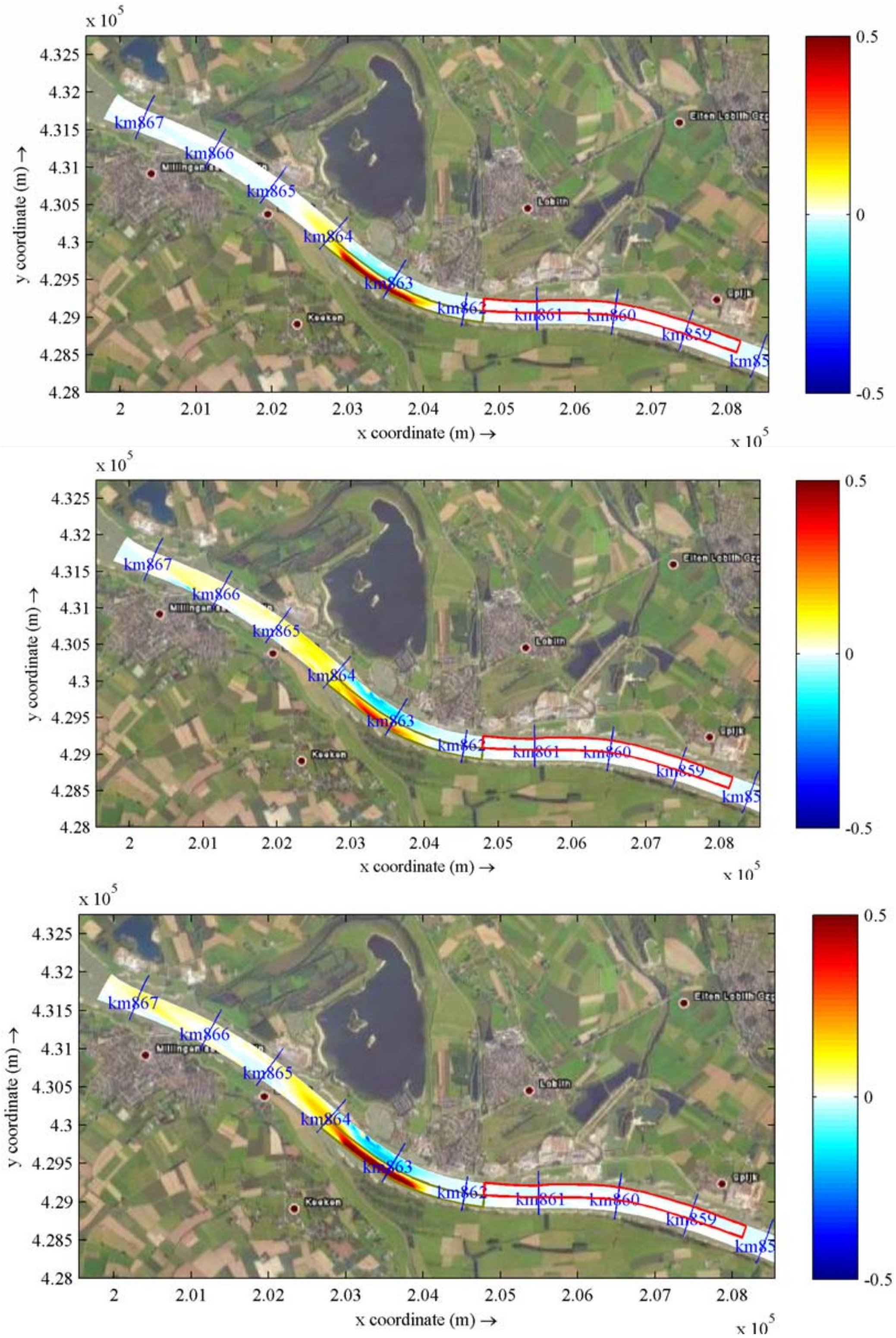


Figure 4.29 The effect of repetitive nourishment (once every 2 years); difference in bed level with respect to the case with one-time nourishment; upper panel: end of the 3rd year, middle panel: end of 4th year, lower panel: end of 5th year.

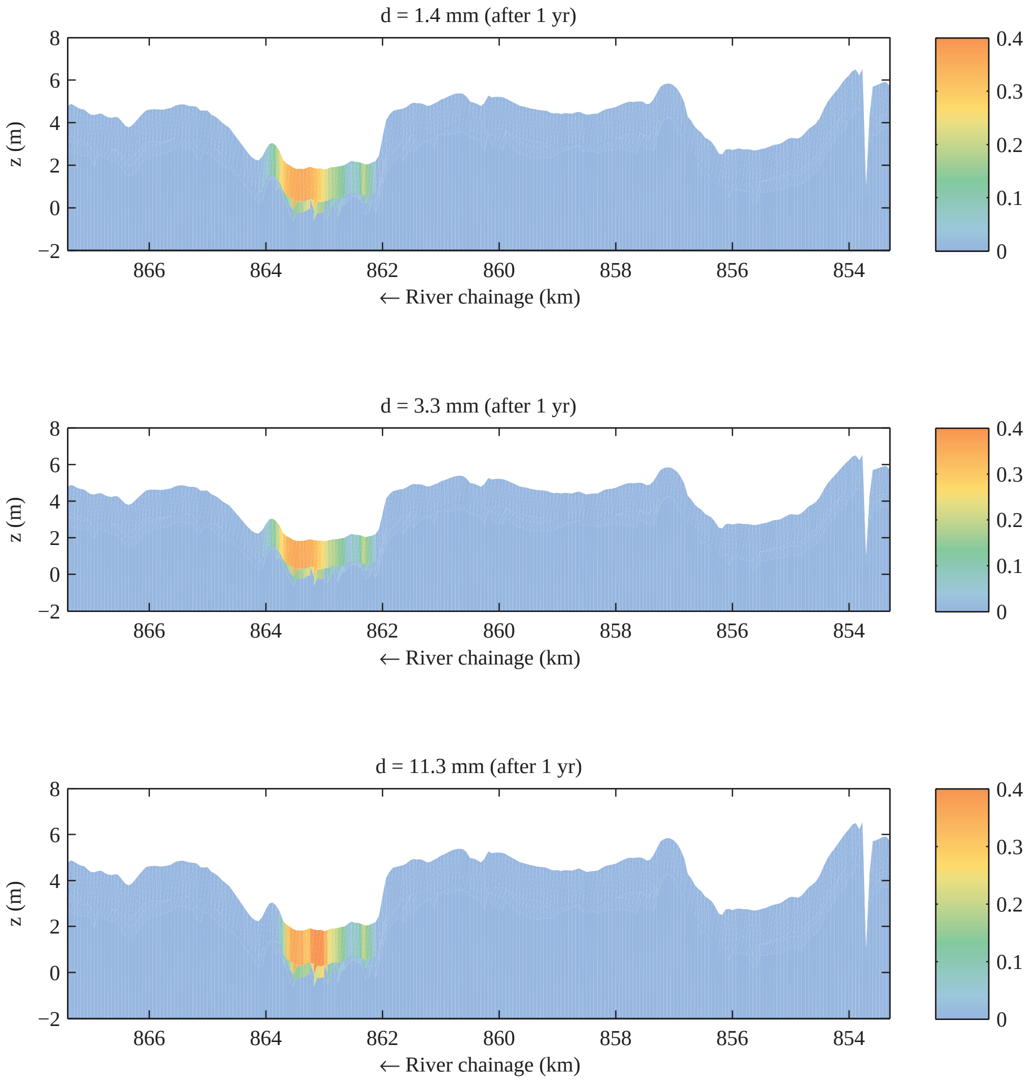


Figure 4.30 Percentage of tracer material in the bed composition along the left bank at the end of the 1st year.

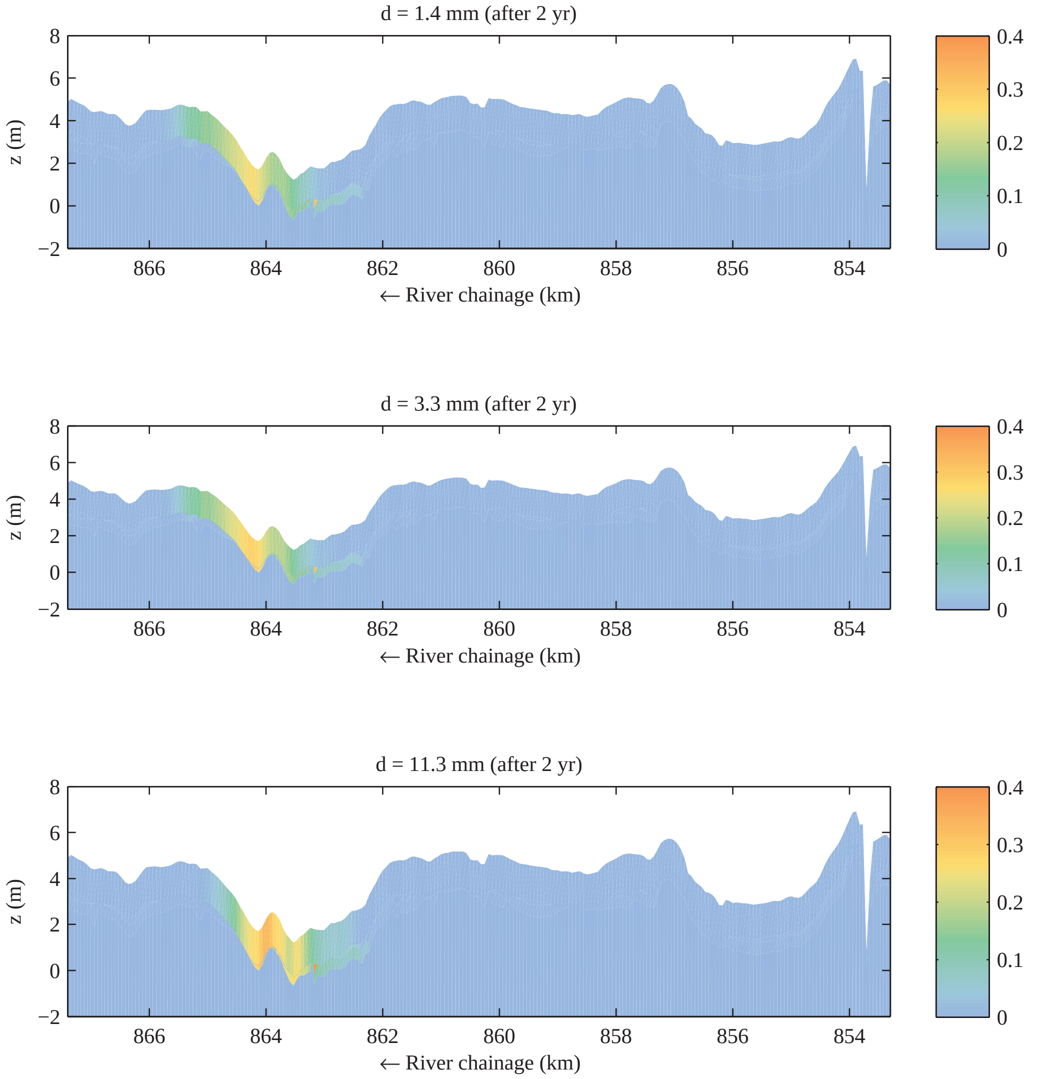


Figure 4.31 Percentage of tracer material in the bed composition along the left bank at the end of the 2nd year.

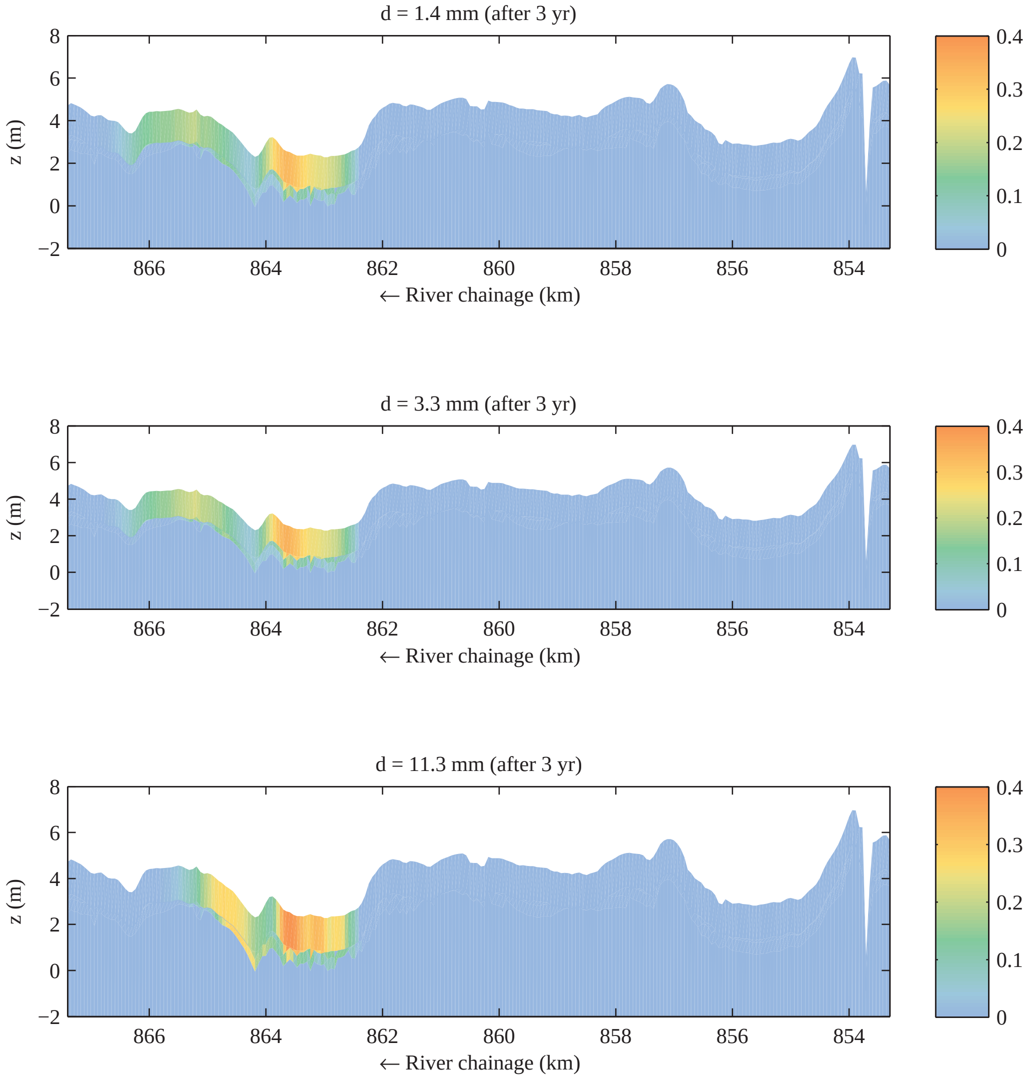


Figure 4.32 Percentage of tracer material in the bed composition along the left bank at the end of the 3rd year.

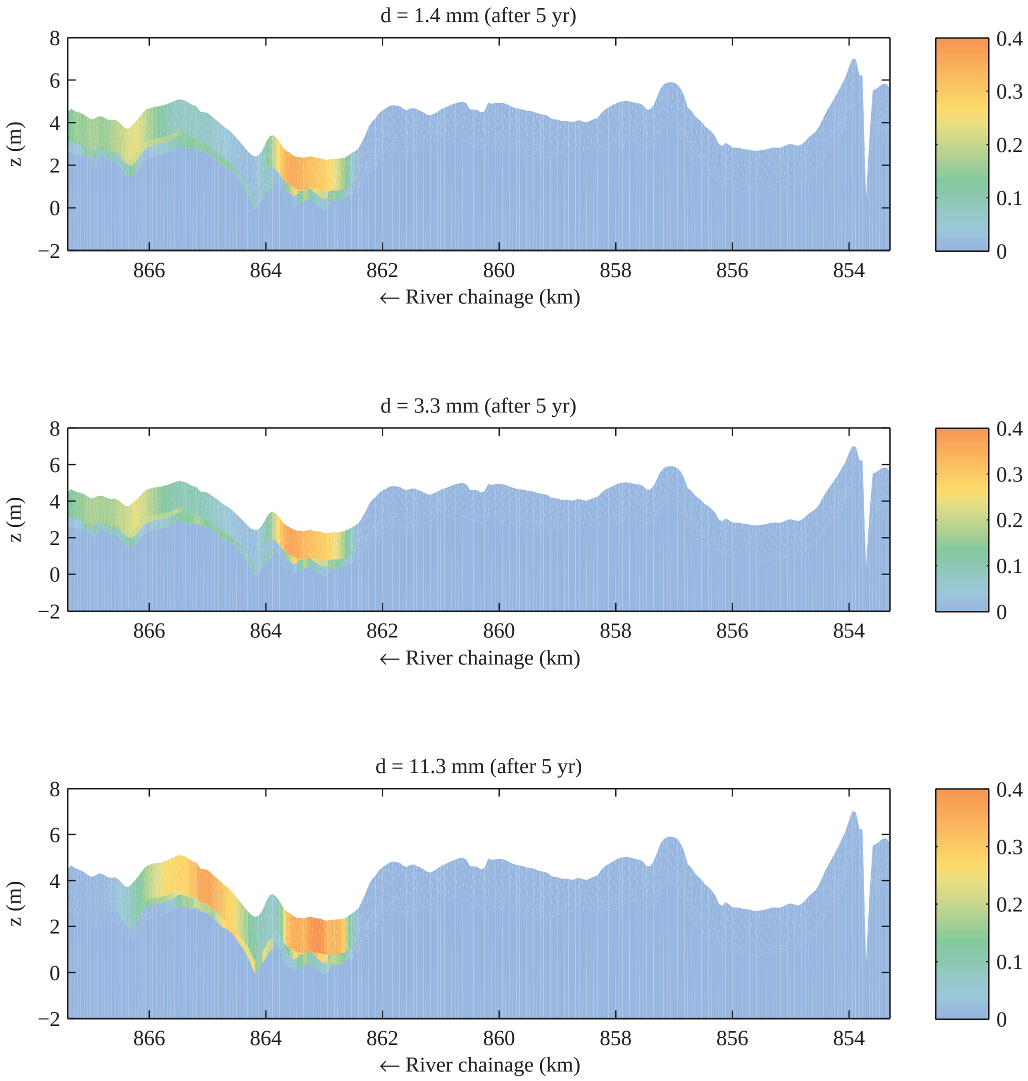


Figure 4.33 Percentage of tracer material in the bed composition along the left bank at the end of the 5^{th} year.

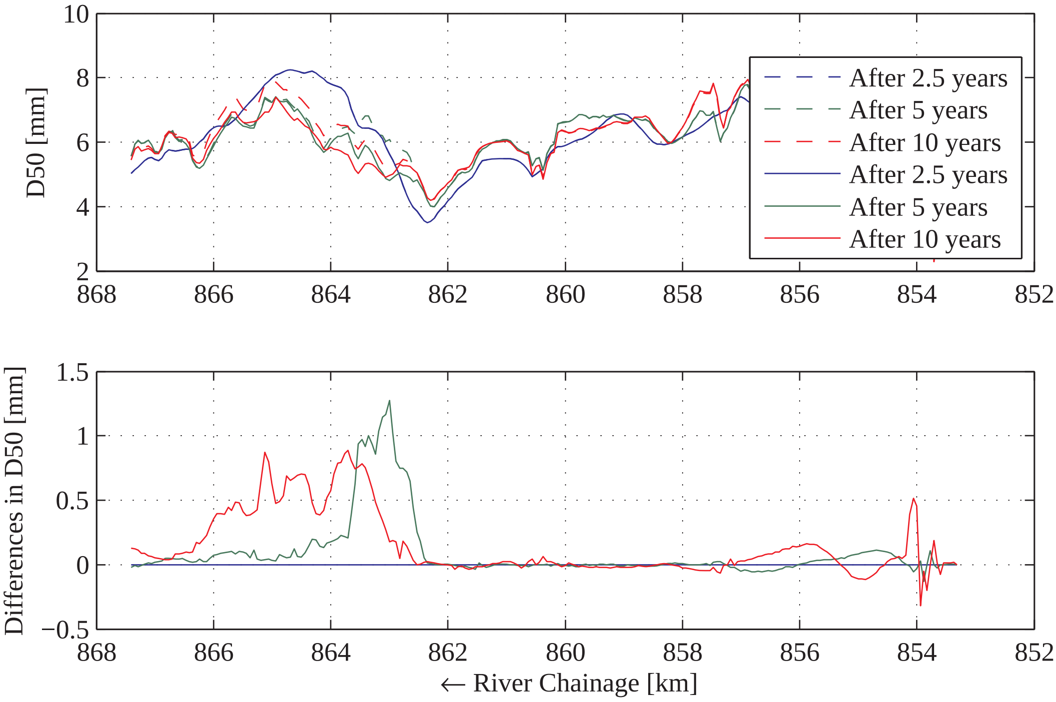


Figure 4.34 D50 and the absolute difference of the D50 for the simulations with repetitive nourishment (dashed lines) and one time nourishment (solid lines) for the left/south bank.

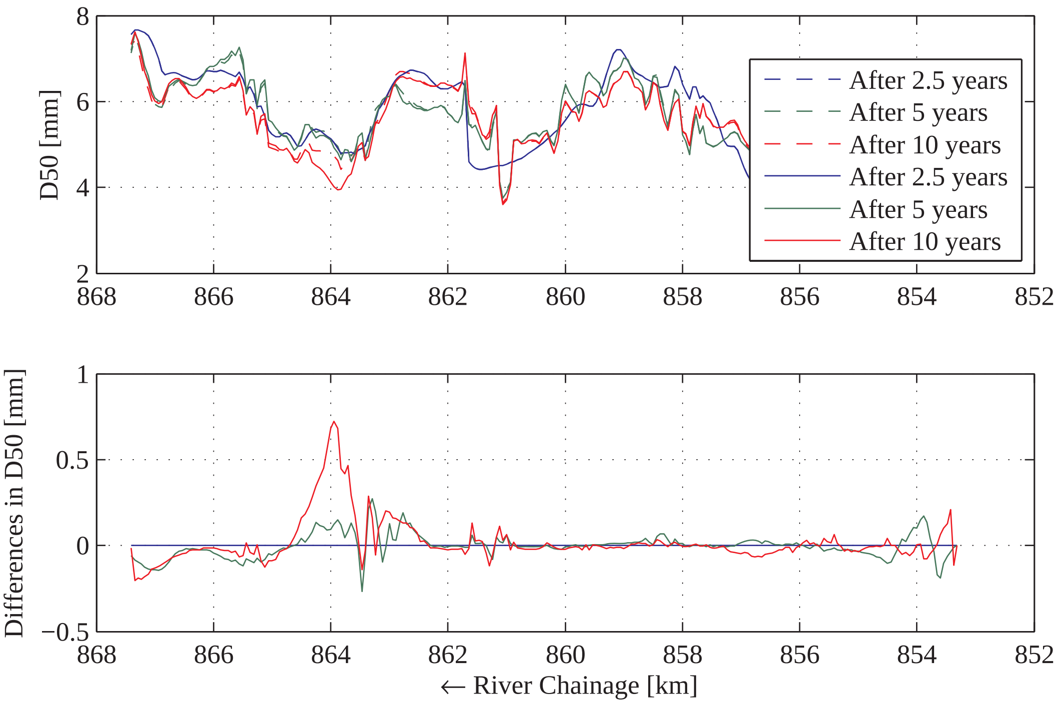


Figure 4.35 D50 and the absolute difference of the D50 for the simulations with repetitive nourishment (dashed lines) and one time nourishment (solid lines) for the right/north bank.

5 Detailed analysis

5.1 Sediment distribution at the Pannerdensche kop

In this section we try to analyse the effect of nourishment on the sediment distribution at the bifurcation point between the Pannerdensch Kanaal and the Waal.

Figure 5.1 gives the sediment distribution at the Pannerdensche kop for the base case scenario. The upper panel shows the cross-section profile of sediment transport upstream of the bifurcation point with indication of the part going into the Waal and that going into the Pannerdensch Kanaal. The plot shows that the amount of sediment going into the Waal increases gradually over the simulated 10 years. Figure 5.1 lower panel shows that the sediment transport into the Pannerdensch Kanaal is nearly constant over the 10 years; whereas the transport into the Waal increases by 30% over 10 years (see Table 5.1).

From Figure 5.2 we can see that, for the case with a fixed layer, the sediment transport out of the Bovenrijn is nearly constant during the first 5 years. It even reduces in the fourth year. The change in the cross-section distribution due to the effect of the fixed layer is given in Figure 5.5. After 10 years, the net effect of the fixed layer on the sediment distribution at the end of the Bovenrijn is rather small (see Table 5.1).

The nourishment causes an increase in the total amount of sediment transported out of the Bovenrijn. The effect of single-time nourishment can be evaluated from Figure 5.3 and Figure 5.6 where we can see that the increase in sediment transport from the Bovenrijn intensifies in years 3 to 5. The distribution between the two branches stays nearly the same. The effect of multiple nourishments can be evaluated from Figure 5.4 and Figure 5.7 where we can see that there is a continuous increase in sediment transport from the Bovenrijn intensifies. Again, the distribution between the two branches stays nearly the same.

The effect of the nourishment material composition on the sediment distribution between the Waal and the Pannerdensch Kanaal is given in Figure 5.8 and Figure 5.9. Using a coarser material leads to a slight reduction of the transport into the Waal and a small increase of the transport into the Pannerdensch Kanaal. The finer material causes an increased transport into both branches. Nevertheless, these changes are rather small.

Table 5.1 Sediment distribution at the Pannerdensche kop.

yr	**Base case scenario (d0-23)**					**Fixed layer (d1-27)**				
	S_t (m^3/yr)	S_{pk} (m^3/yr)	S_{wl} (m^3/yr)	S_{pk}	S_{wl}	S_t (m^3/yr)	S_{pk} (m^3/yr)	S_{wl} (m^3/yr)	S_{pk}	S_{wl}
1	471879	173000	298878	37%	63%	452156	166459	285697	37%	63%
2	498474	168928	329547	34%	66%	482911	161976	320935	34%	66%
3	512832	167416	345416	33%	67%	487804	151302	336502	31%	69%
4	531915	176532	355383	33%	67%	425919	131362	294558	31%	69%
5	542028	178665	363363	33%	67%	481964	155258	326706	32%	68%
6	555935	179525	376410	32%	68%	532212	167482	364729	31%	69%
7	564574	177914	386660	32%	68%	547827	167115	380712	31%	69%
8	583058	180107	402952	31%	69%	560002	169756	390246	30%	70%
9	583312	179263	404049	31%	69%	564082	172097	391985	31%	69%
10	584842	179647	405195	31%	69%	570694	174589	396106	31%	69%
yr	**Single-time nourishment (d2-11)**					**Multiple nourishment (d3-10)**				
	S_t (m^3/yr)	S_{pk} (m^3/yr)	S_{wl} (m^3/yr)	S_{pk}	S_{wl}	S_t (m^3/yr)	S_{pk} (m^3/yr)	S_{wl} (m^3/yr)	S_{pk}	S_{wl}
1	451957	166367	285590	37%	63%	451957	166367	285590	37%	63%
2	482824	161997	320826	34%	66%	482824	161997	320826	34%	66%
3	496140	153990	342151	31%	69%	495912	153924	341987	31%	69%
4	430762	133837	296926	31%	69%	429250	133348	295902	31%	69%
5	491037	159879	331158	33%	67%	500885	163576	337309	33%	67%
6	533517	168949	364568	32%	68%	544490	173975	370516	32%	68%
7	548695	167978	380717	31%	69%	559817	173061	386757	31%	69%
8	560068	170612	389457	30%	70%	574616	177222	397393	31%	69%
9	564507	172688	391819	31%	69%	579355	178723	400632	31%	69%
10	569144	174235	394909	31%	69%	585360	181437	403924	31%	69%

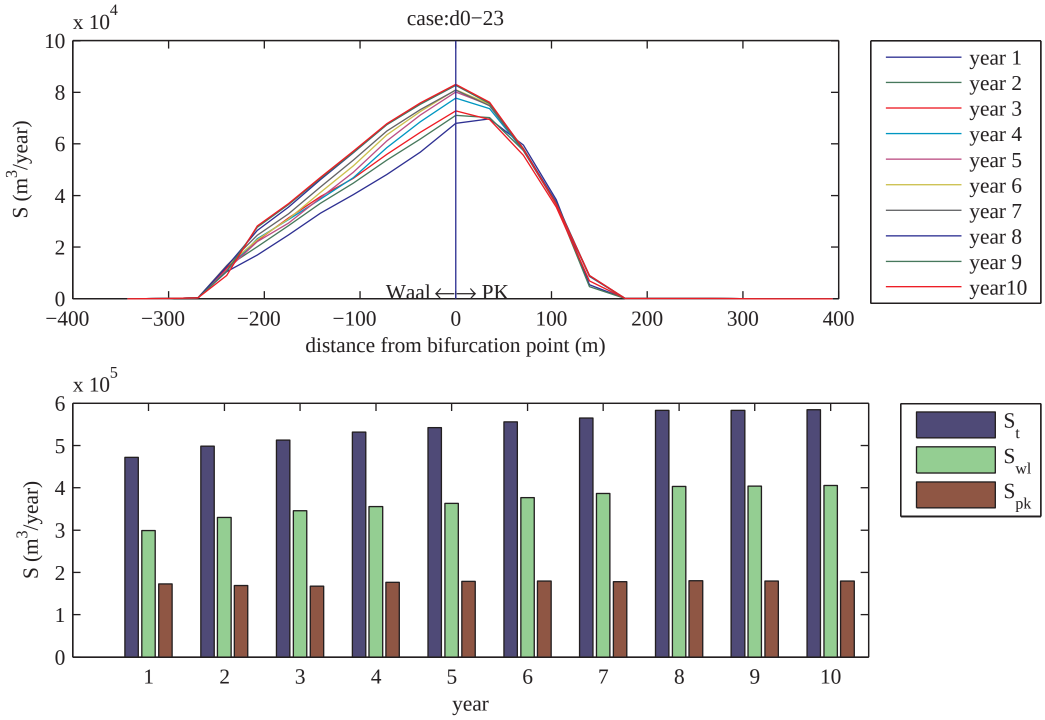


Figure 5.1 Sediment distribution between the Pannerdensch Kanaal and the Waal for the base case scenario; upper panel: cross-section profile of sediment transport upstream of the bifurcation point, lower panel: yearly sediment transport from the Bovenrijn (S_t) into the Waal (S_{wl}), and Pannerdensch Kanaal (S_{pk}).

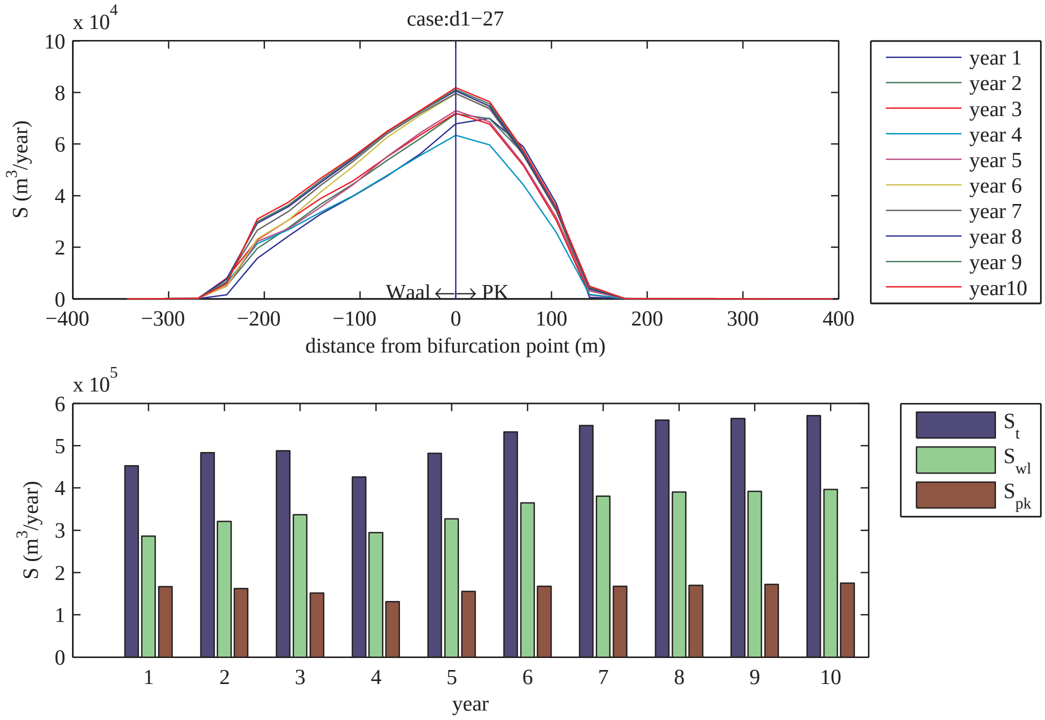


Figure 5.2 Sediment distribution between the Pannerdensch Kanaal and the Waal for the case with fixed layer; upper panel: cross-section profile of sediment transport upstream of the bifurcation point, lower panel: yearly sediment transport from the Bovenrijn (S_t) into the Waal (S_{wl}), and Pannerdensch Kanaal (S_{pk}).

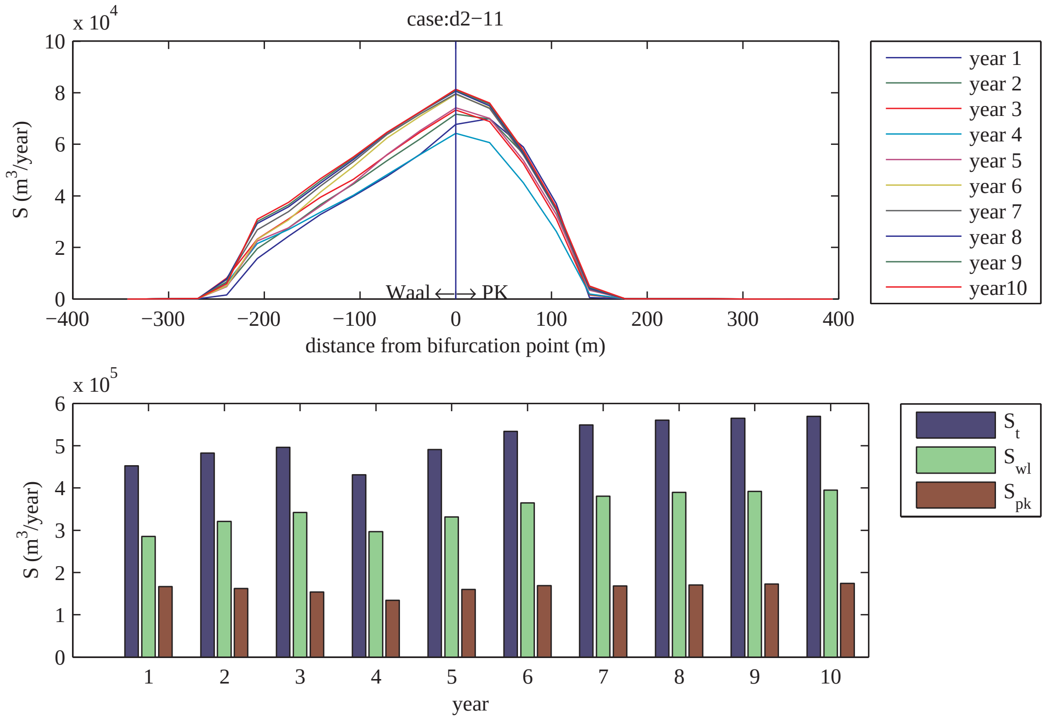


Figure 5.3 Sediment distribution between the Pannerdensch Kanaal and the Waal for the case with one time nourishment; upper panel: cross-section profile of sediment transport upstream of the bifurcation point, lower panel: yearly sediment transport from the Bovenrijn (S_t) into the Waal (S_{wl}), and Pannerdensch Kanaal (S_{pk}).

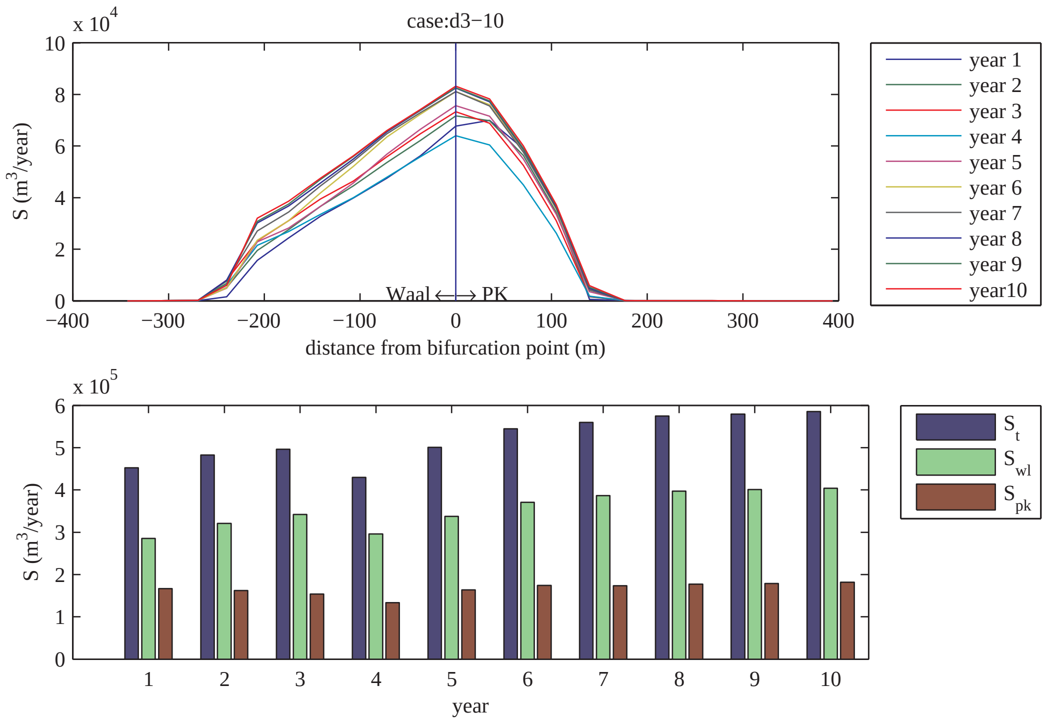


Figure 5.4 Sediment distribution between the Pannerdensch Kanaal and the Waal for the case with multiple nourishment; upper panel: cross-section profile of sediment transport upstream of the bifurcation point, lower panel: yearly sediment transport from the Bovenrijn (S_t) into the Waal (S_{wl}), and Pannerdensch Kanaal (S_{pk}).

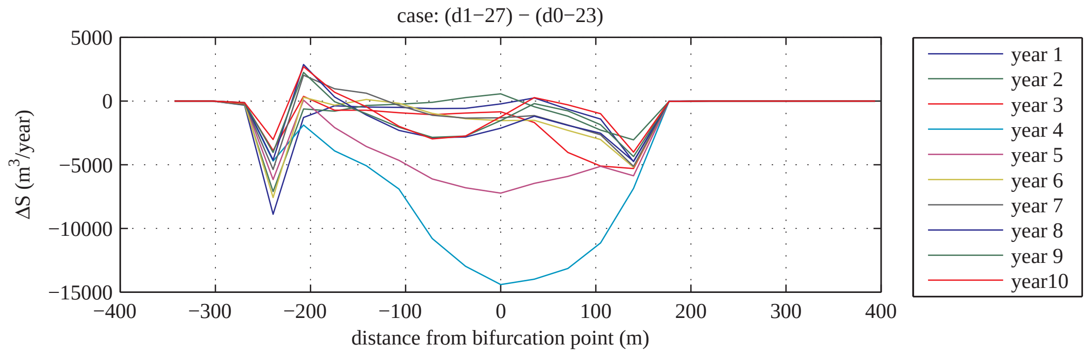


Figure 5.5 Change in sediment distribution at the Pannerdensche kop (base case with a fixed layer).

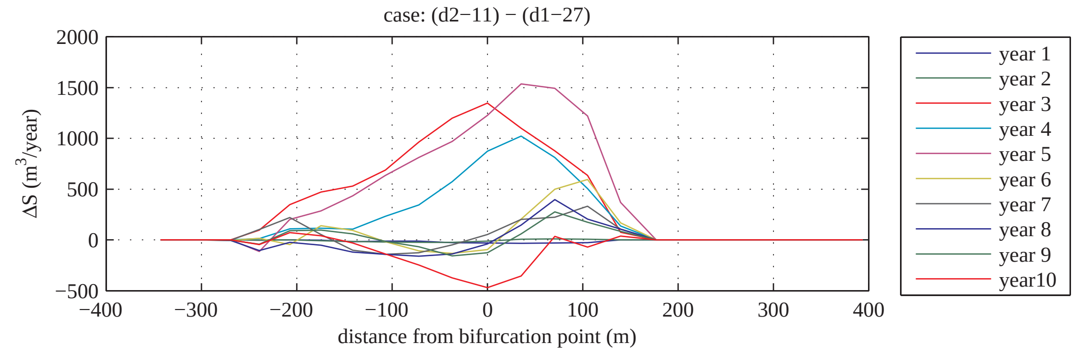


Figure 5.6 Change in sediment distribution at the Pannerdensche kop (case with one time nourishment and fixed layer).

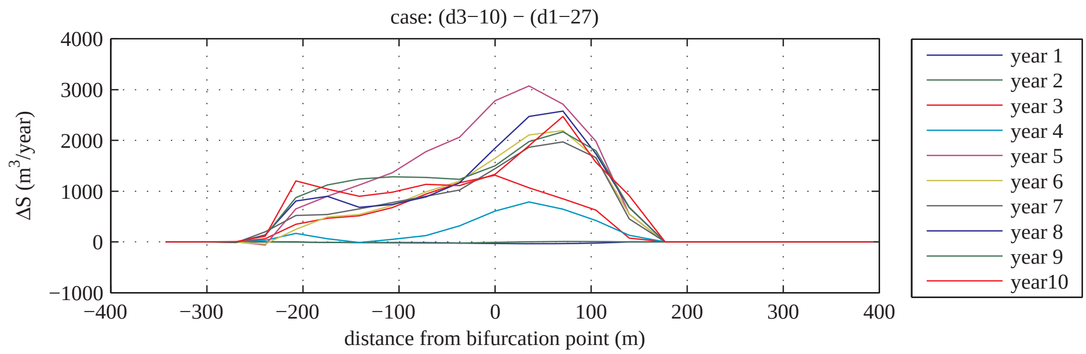


Figure 5.7 Change in sediment distribution at the Pannerdensche kop (case with multiple nourishment and fixed layer).

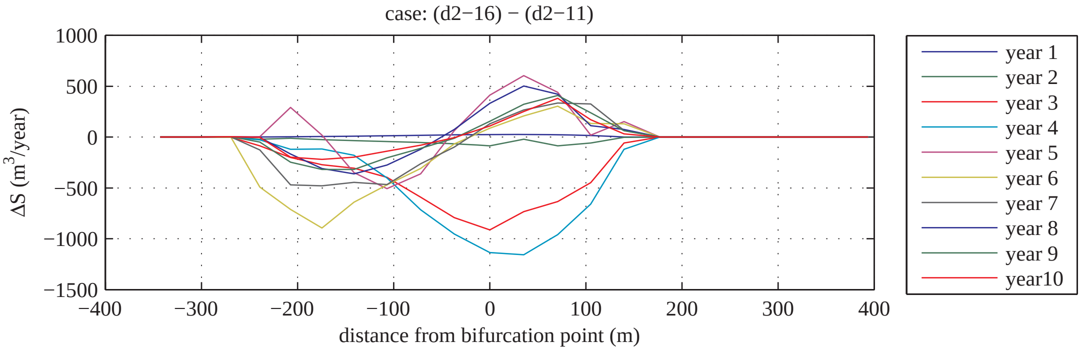


Figure 5.8 Change in sediment distribution at the Pannerdensche kop (effect of coarser nourishment material).

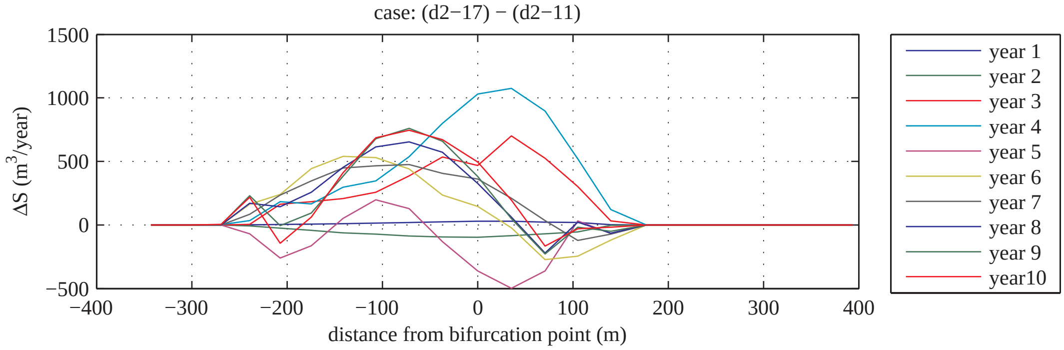


Figure 5.9 Change in sediment distribution at the Pannerdensche kop (effect of finer nourishment material).

5.2 Changes in water level

The effect of nourishment on water levels can be evaluated by looking at the net change in water level due to the application of nourishment. Figure 5.10 gives the net effect of the fixed layer (upper panel), the fixed layer and single-time nourishment (middle panel), and the fixed layer and multiple nourishment (lower panel). We can see from the figure that there is hardly any difference between the upper and middle panels; viz. the effect of the fixed layer dominates the effect of single-time nourishment.

The net effect of single-time nourishment is small (around 1 cm). The effect of multiple nourishments compared to single-time nourishment is given in Figure 5.11, where we can observe an increase in water level in the upstream side of the nourishment area. Nevertheless, the differences are small. In general the effect of applying a fixed layer and nourishment is rather small (around 5 cm).

The temporal changes in water level for a point near the upstream boundary are given in Figure 5.12. The figure indicates that the long-term effect of the one time nourishment is similar to that of the fixed layer, i.e. the effect of the single-time nourishment vanishes rather quickly. The effect of the multiple nourishments is somewhat more. The differences in water levels are higher during low discharge and smaller during high discharges.

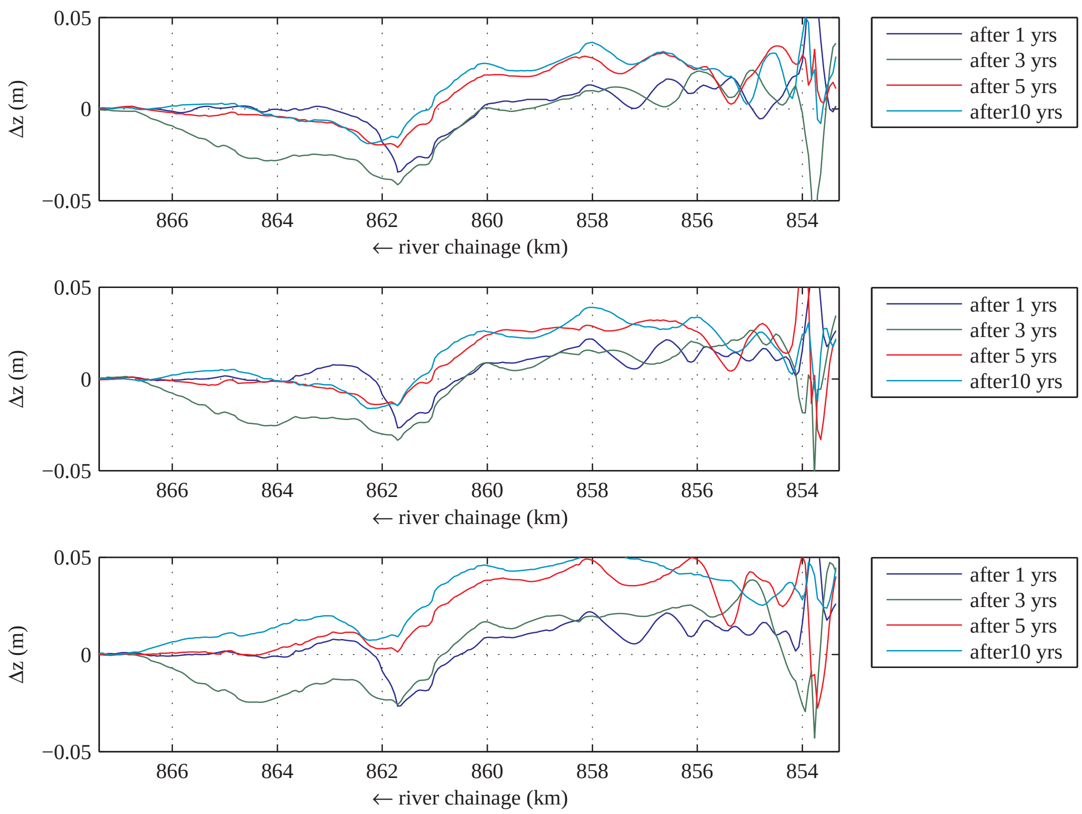


Figure 5.10 Longitudinal profile of the change in water level with respect to the base case; upper panel: effect of fixed layer, middle panel: effect of fixed layer and one-time nourishment, lower panel: effect of fixed layer and multiple nourishment.

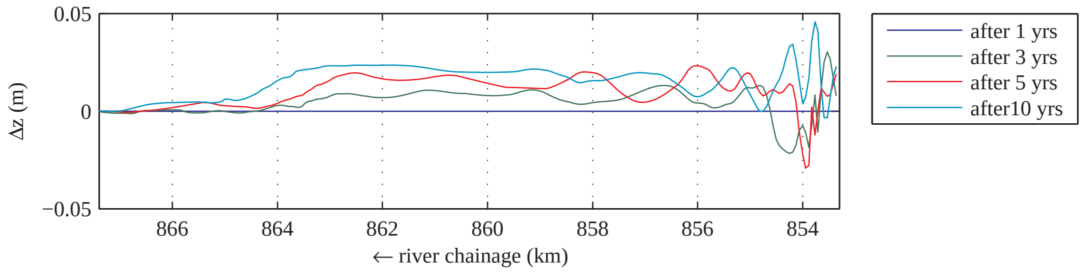


Figure 5.11 Longitudinal profile of the change in water level, difference between multiple nourishment and single-time nourishment.

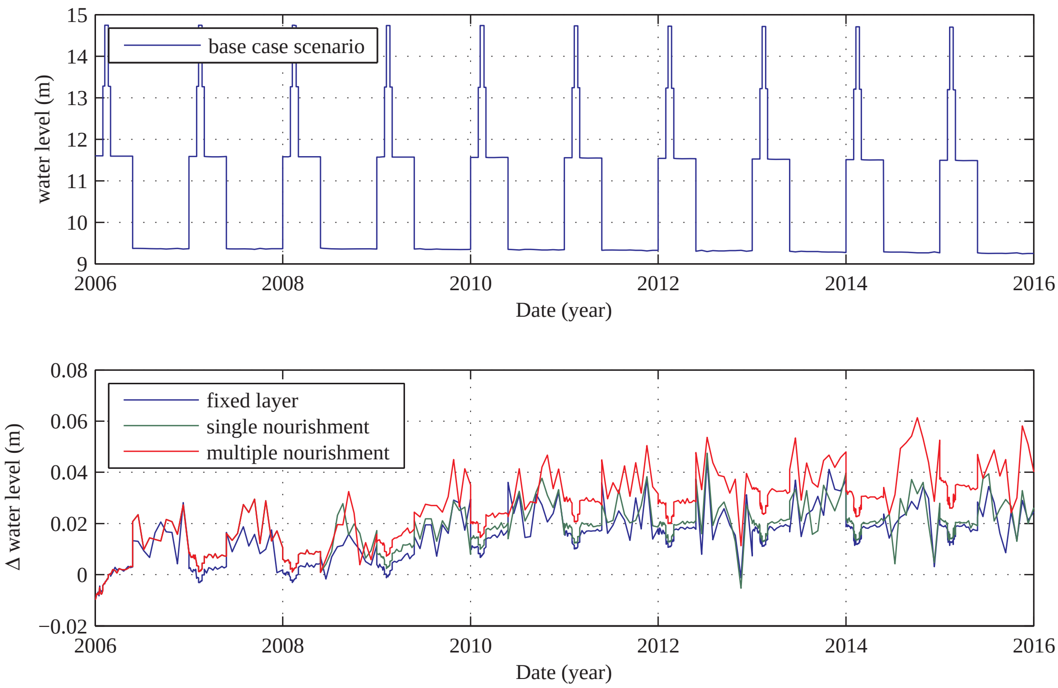


Figure 5.12 Temporal changes in water level at a point near the upstream boundary; upper panel: water level for base case scenario, lower panel: difference in water level between the cases indicated and base case scenario.

5.3 Changes in median sediment diameter

The initial median sediment diameter along the left and right banks for the base cases scenario is given in the upper panel of Figure 5.13 and the changes during the simulation period are given in the lower panel. The median diameters are around 6 mm and changes with ±2 mm during the simulation.

The changes in median sediment diameters due to the different scenarios are presented in Figure 5.14 to Figure 5.18. In general changes take place downstream of the fixed layer and nourishment area. Some disturbances that are thought to be numerical are observed near the upstream boundary.

Figure 5.14 gives the changes in median sediment diameter due to the implementation of a fixed layer. From that figure we can see that the changes are localised in the area where the fixed layer is implemented. The changes could amount up to ±4 mm. The maximum changes take place in the most downstream side of the fixed layer where the scour and deposition are maximum. Near the left bank on top of the fixed layer gradual fining takes place.

Figure 5.15 gives the changes in median sediment diameter due to nourishment. These changes are superimposed on the fixed layer. From that figure it is clear that the nourishment application causes an increase in the median sediment diameter in the nourishment area and along the left bank in the downstream direction. The increase in the median sediment diameter is less than 1 mm and decays after the 1st year while migrating downstream.

When applying a coarser nourishment material, the increase in median sediment diameter is more pronounced, a similar temporal decaying pattern can be observed as well (see Figure 5.16). The finer nourishment material causes a behaviour opposite to that of the coarse nourishment material (see Figure 5.17).

Figure 5.18 gives the changes in median sediment diameter due to repetitive nourishment. These changes are superimposed on the changes due to the fixed layer. After the second nourishment has been applied (3rd year), there is an additional 1 mm increase in the median sediment diameter. Due to the continuous supply of nourishment material this increase is maintained in the nourishment area with a slight increase over the years.

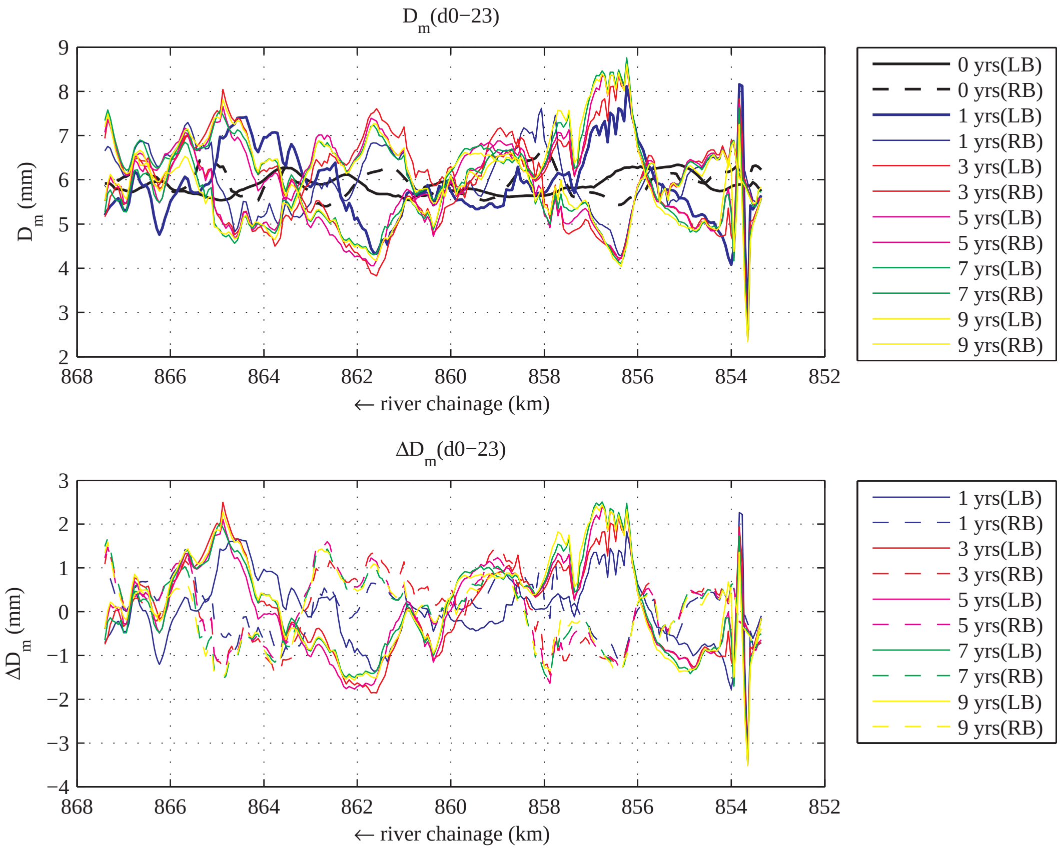


Figure 5.13 longitudinal profile of the median sediment diameter for the base case scenario (upper panel), and changes with respect to initial values (lower panel).

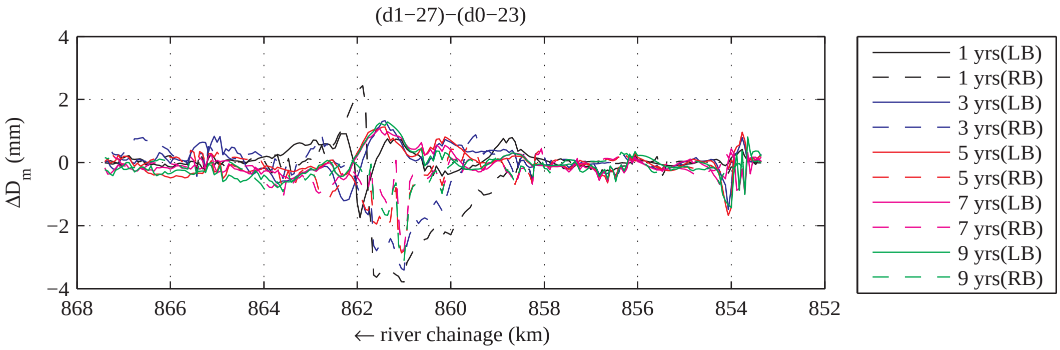


Figure 5.14 Changes in median sediment diameter because due to the fixed layer (with respect to Base case scenario).

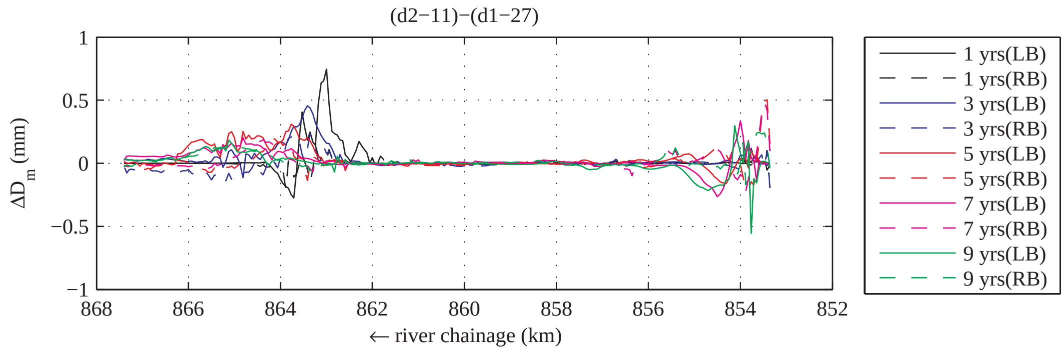


Figure 5.15 Changes in median sediment diameter due to one time nourishment (with respect to case with fixed layer).

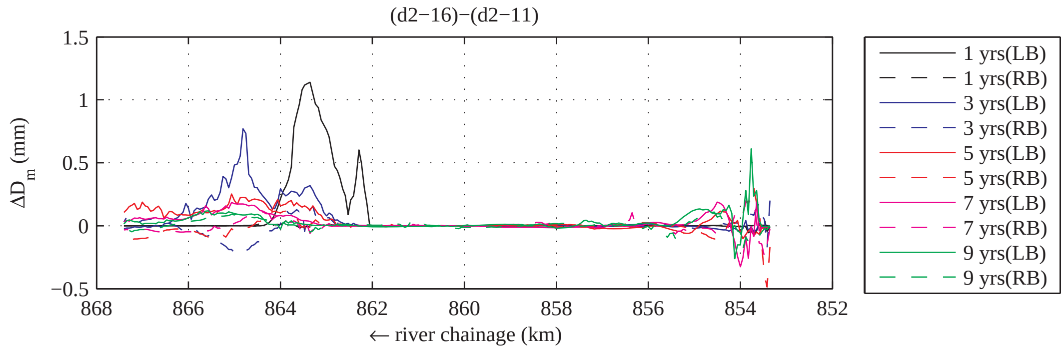


Figure 5.16 Changes in median sediment diameter due to the use of coarser nourishment material (with respect to original composition).

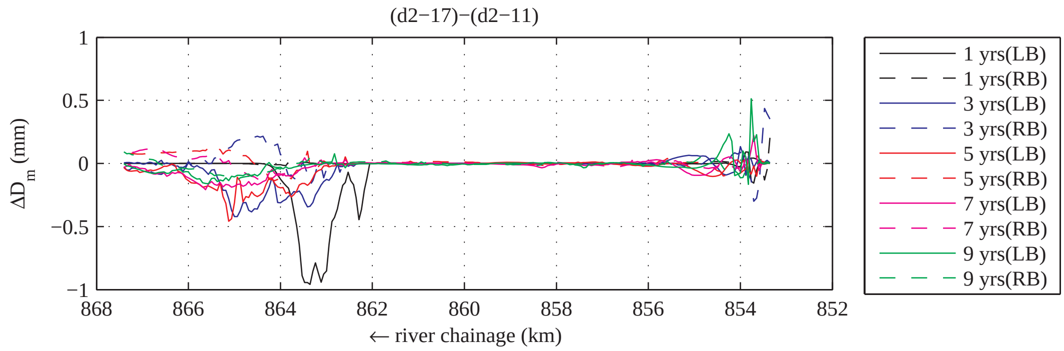


Figure 5.17 Changes in median sediment diameter due to the use of finer nourishment material (with respect to original composition).

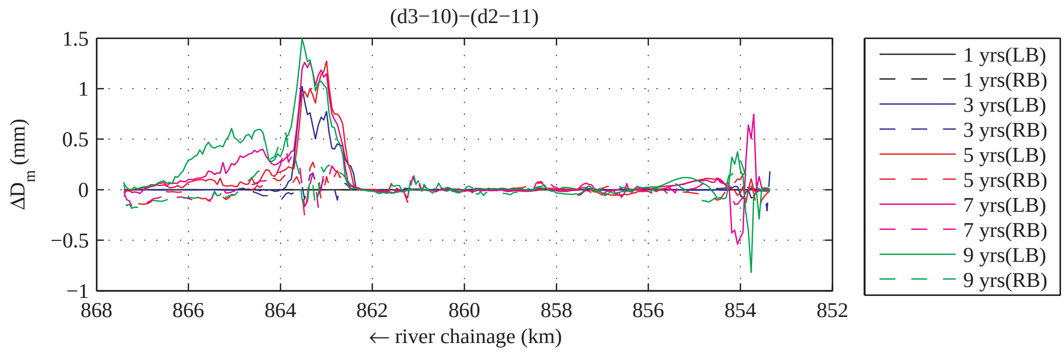


Figure 5.18 Changes in median sediment diameter due to repetitive nourishment (with respect to single-time nourishment).

5.4 Effect of active-layer thickness

The effect of the active-layer thickness was evaluated by testing the model with three different settings for the value of the active-layer thickness. The reference case had an active-layer thickness of 1.5 m. A smaller value of 0.5 m was tested and an additional settings of variable active-layer as a function of the discharge was tested. Values of 0.1 m, 1.5 m, 2.5 m, and 3.0 m for the discharges of 1500 m^3/s, 2954 m^3/s, 4400 m^3/s, and 6000 m^3/s were used respectively.

The general behaviour of the model in terms of erosion and deposition patterns is different in each of these three cases. Figure 5.19 and Figure 5.20 give the effect of the active-layer thickness on the bed development with respect to the reference case. The figures indicate a significant effect of the active-layer thickness on the morphological behaviour of the model. Apparently, using an active-layer thickness that is proportional to the discharge yields an increase in the transverse slope at the end of the Bovenrijn. This is manifested in the reduction of bed level in the deeper outer (right/north) bend and the increase in bed level in the shallow inner (left/south) bend, see Figure 5.21. This same behaviour is observed in some but not all bends, with no clear reason. The model with a smaller active-layer yielded an opposite behaviour at the end of the Bovenrijn. The reasons of such behaviour are not fully comprehended. Generally speaking, adaptation of bed composition reduces changes in bed level. Hence, the more a bed composition can adapt to hydraulic conditions, the lesser the bed level responds. Analogously, the transverse bed level slope that develops due discharge variation of a hydrograph is reduced by coarsening of the outer bend and fining of the inner bend. Since the adaptation rate of bed composition is determined by the layer thickness, the smaller the layer thickness, the quicker the adaptation of bed composition and, subsequently, the smaller the bed level response

The behaviour of the nourishment material in response to changing the active-layer thickness can be analysed by evaluating the temporal behaviour of tracer materials presented in Figure 5.22 to Figure 5.27.

When reducing the thickness of the active-layer, the composition of bed material in the nourishment area directly after nourishment corresponds better to the composition of the supplied material; this is due to the way that nourishment material is introduced to the model. In the current model, full mixing between nourishment material and bed material takes place upon the application of nourishment; thus, leading to a new composition that is a weighted average between the nourishment material and bed material.

In the case of a small active-layer thickness, the nourishment material quickly moves to the sub-layer (see Figure 5.25). This behaviour in the case of the variable active-layer thickness causes extra spatial spread of the nourishment material. Material in the top layer (active-layer) has a higher celerity than the material left in the sub-layer. The material in the active-layer has a higher celerity as the active-layer thickness reduces. After sufficient time, the nourishment material available in the active-layer disappears. However, in the case of a small active-layer thickness, more tracer material is found in the under layers than in the case with a large active-layer thickness.

This behaviour can be used in the analysis of monitoring data. Accordingly, information about the location of tracer materials both in the longitudinal and vertical directions coupled with the percentage in the total composition are required to have a complete overview of the behaviour of nourishment material.

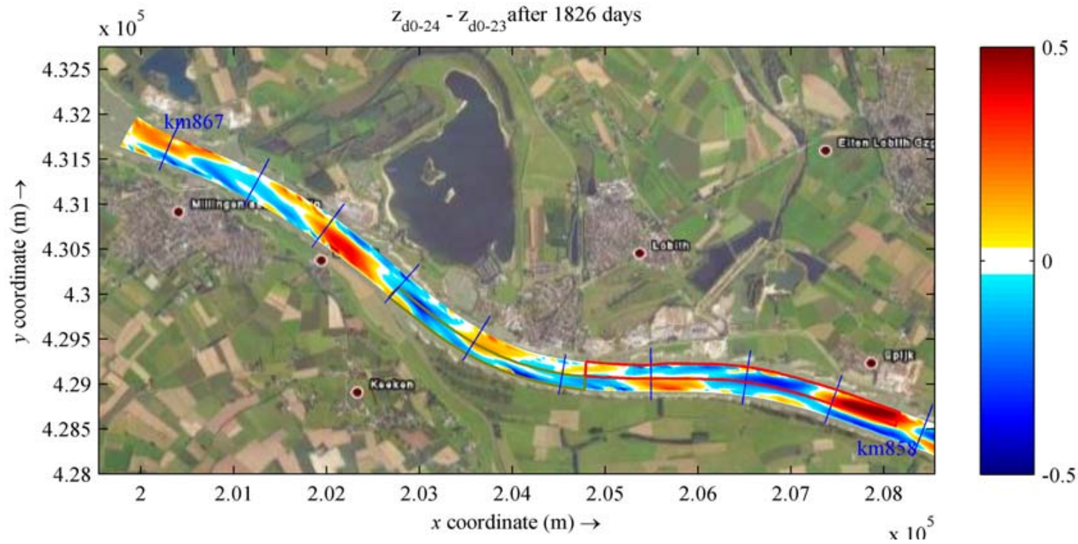


Figure 5.19 Difference in bed level between case with (ThTrLyr = 0.5 m) and case with (ThTrLyr = 1.5 m) base case scenario – after 5 years.

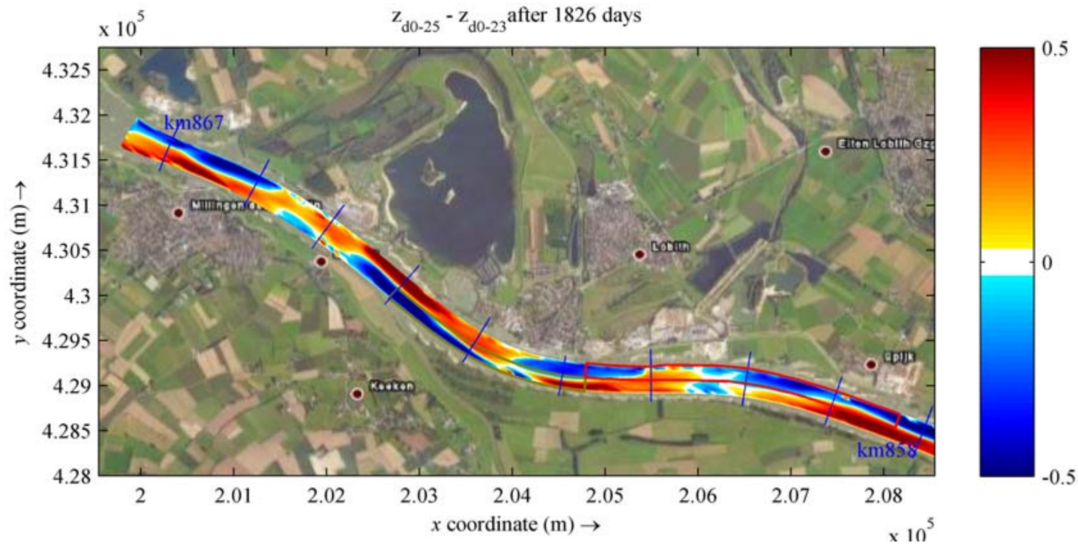


Figure 5.20 Difference in bed level between case with (ThTrLyr = *f(Q)*) and case with (ThTrLyr = 1.5 m) base case scenario – after 5 years.

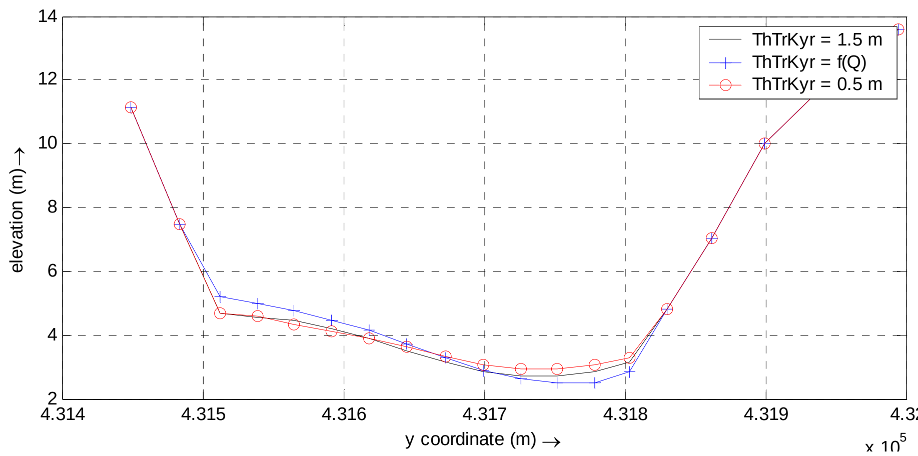


Figure 5.21 Cross section profiles at km867 after 5 years, showing the effect of the active-layer thickness.

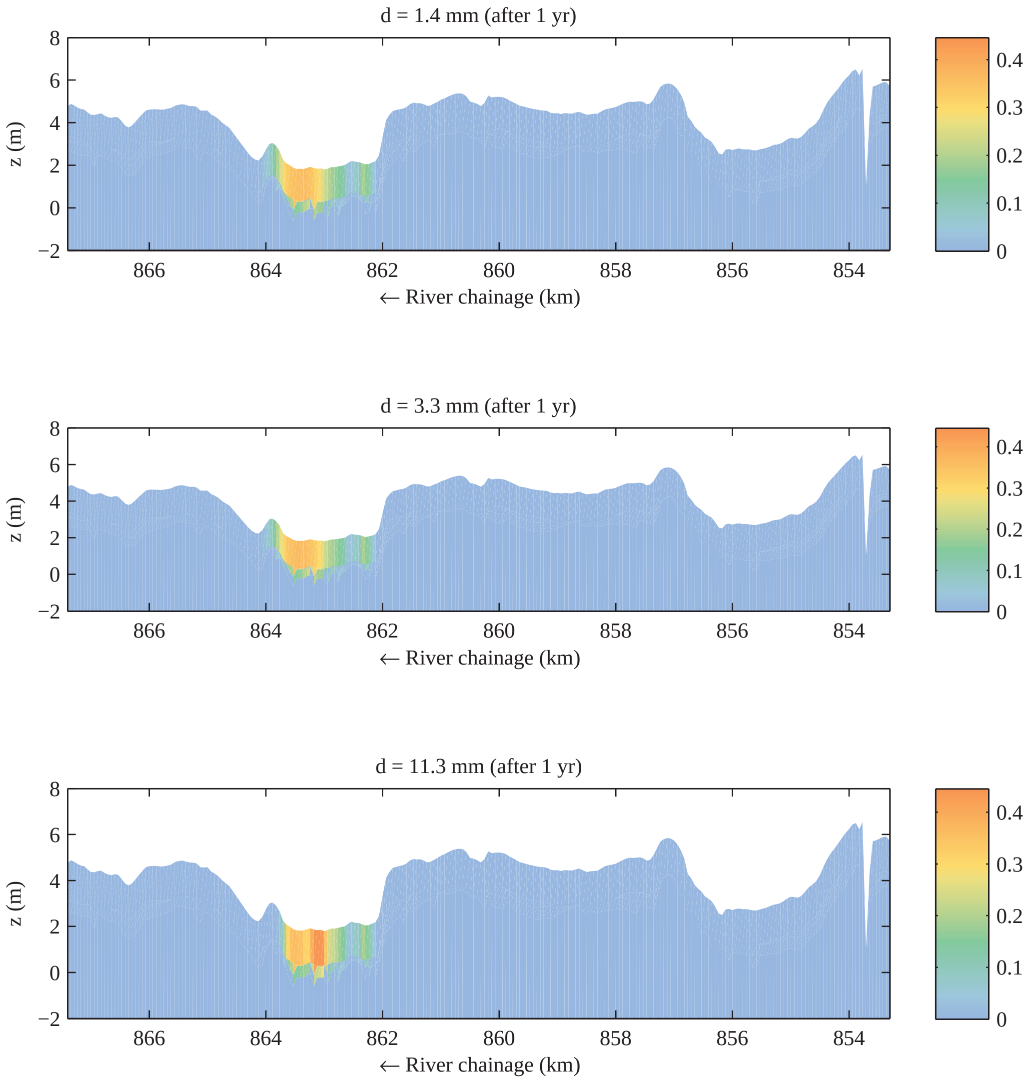


Figure 5.22 Percentage of tracer material in the bed composition along the left bank at the end of the 1st year; reference case (ThTrLyr = 1.5 m).

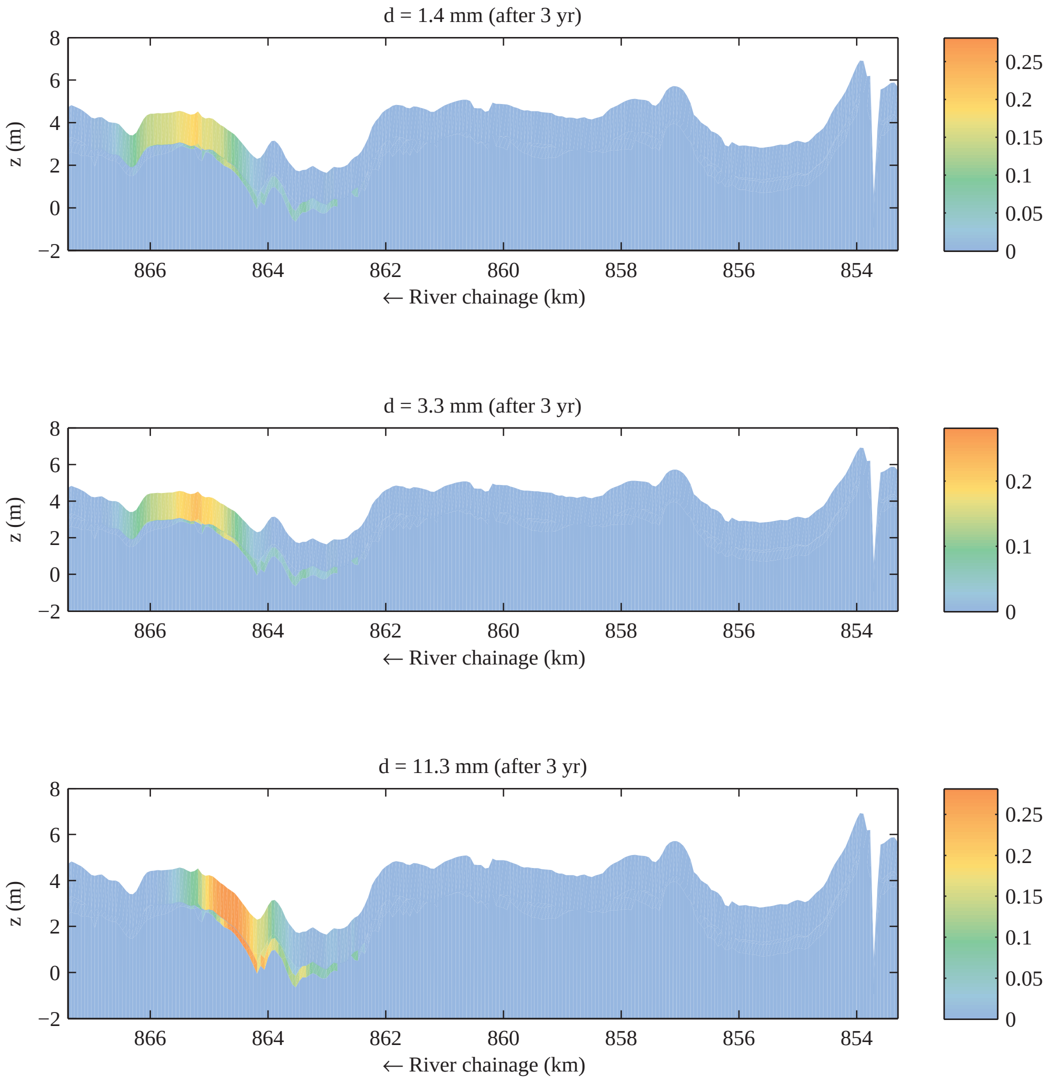


Figure 5.23 Percentage of tracer material in the bed composition along the left bank at the end of the 3rd year; reference case (ThTrLyr = 1.5 m).

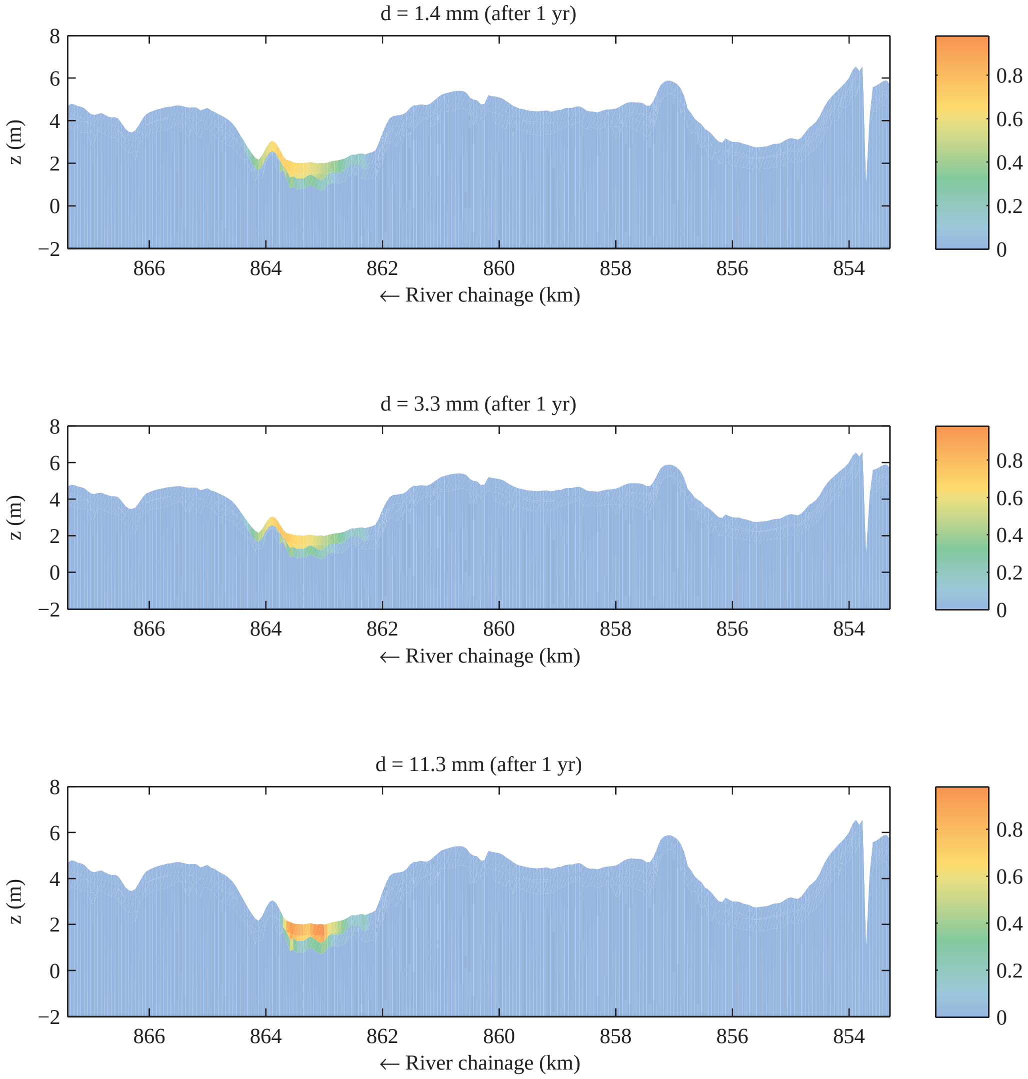


Figure 5.24 Percentage of tracer material in the bed composition along the left bank at the end of the 1st year; (ThTrLyr = 0.5 m).

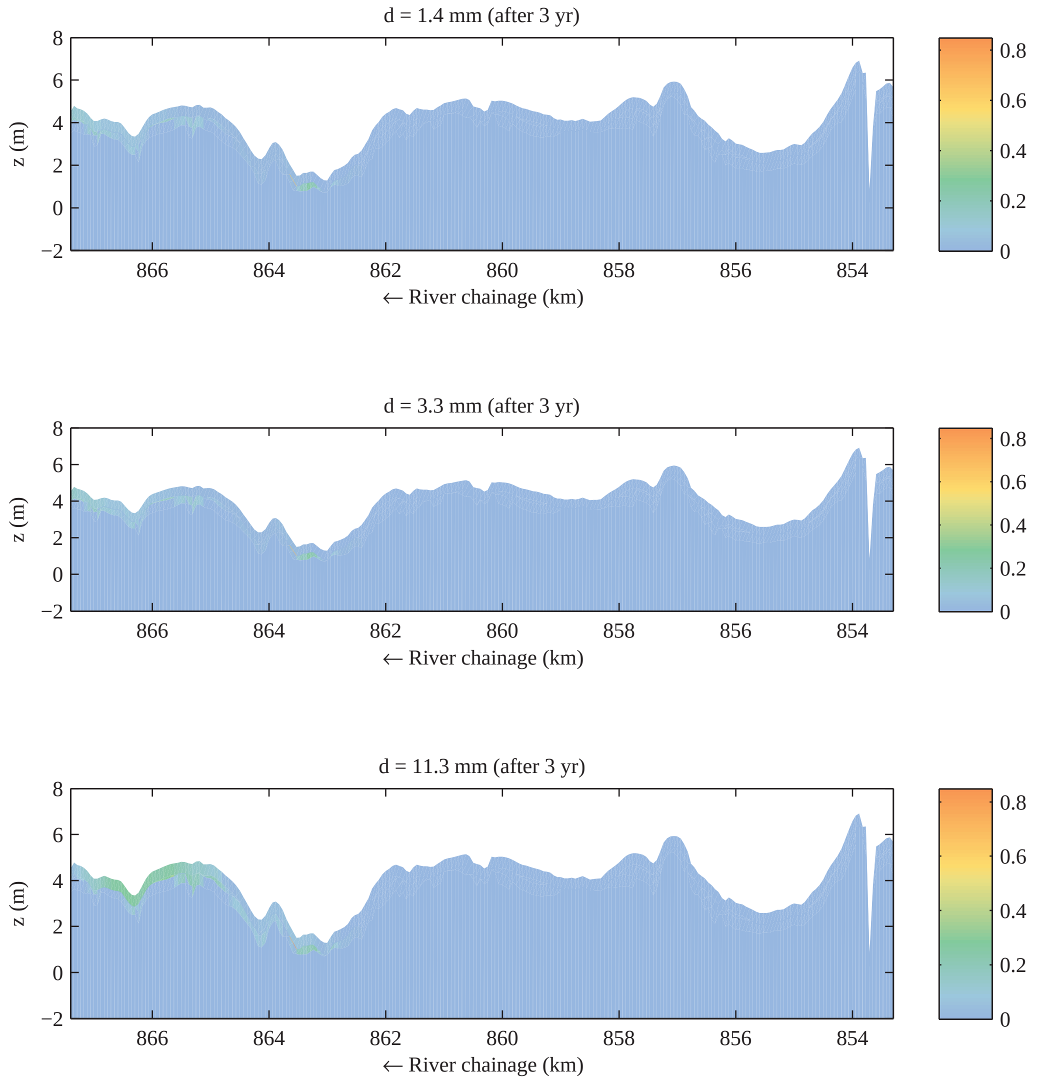


Figure 5.25 Percentage of tracer material in the bed composition along the left bank at the end of the 3rd year; (ThTrLyr = 0.5 m).

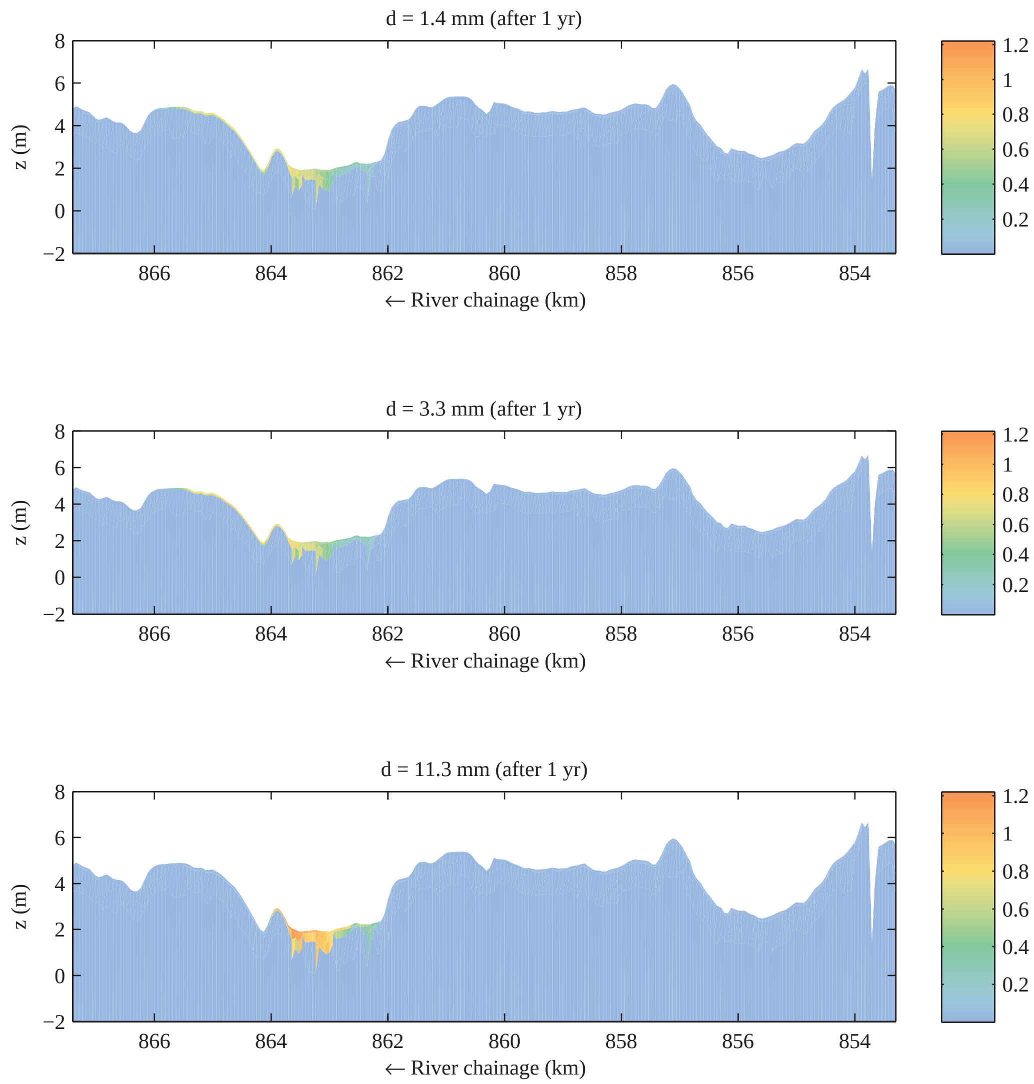


Figure 5.26 Percentage of tracer material in the bed composition along the left bank at the end of the 1st year; (ThTrLyr = *f(Q)*).

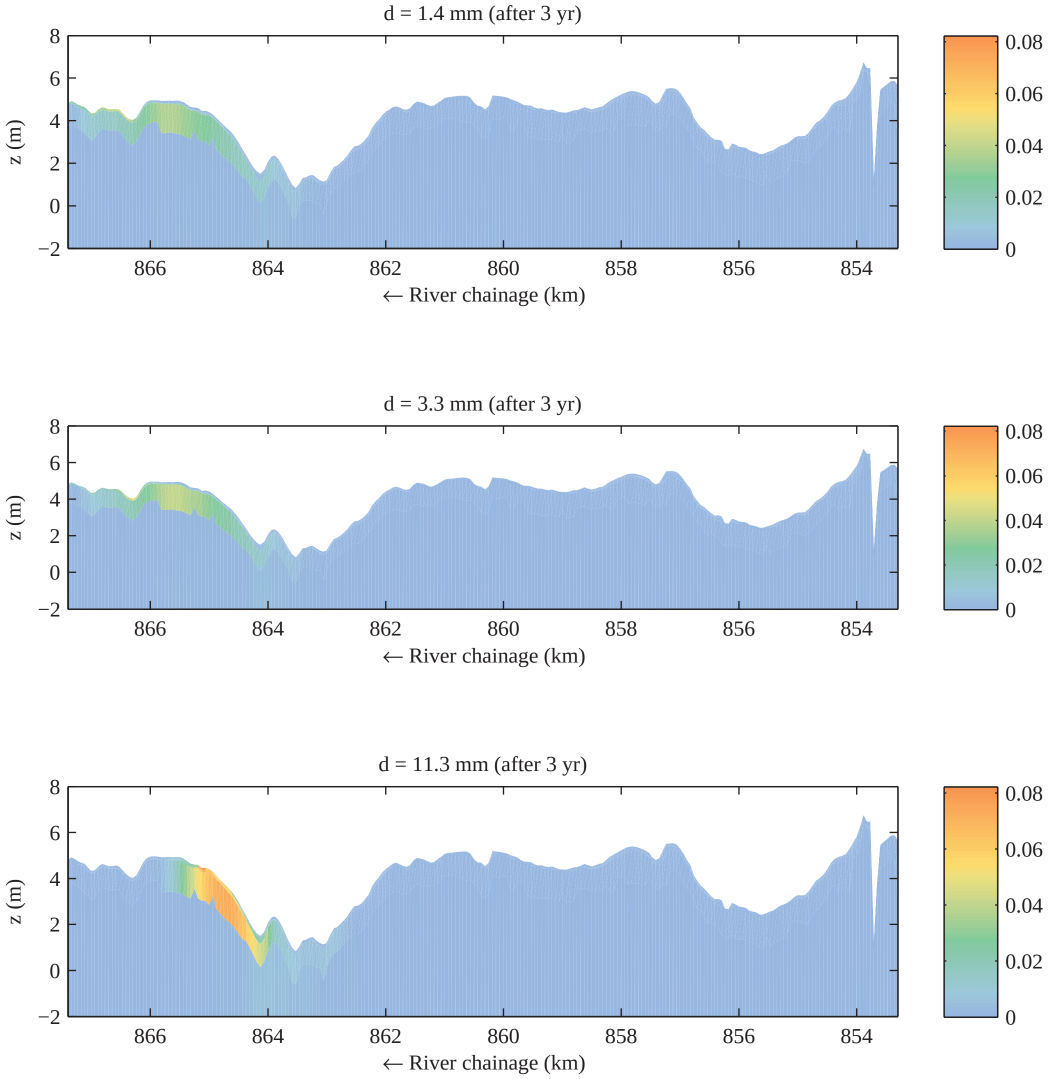


Figure 5.27 Percentage of tracer material in the bed composition along the left bank at the end of the 3rd year; (ThTrLyr = *f(Q)*).

5.5 Effect of gradation of nourishment material

The effect of the gradation of the nourishment material was evaluated by using two additional sediment compositions, one finer and the other coarser. By removing the finest fraction from the original nourishment material, the coarser composition is created. Likewise, the finer composition is created by removing the coarsest material from the original composition. Both compositions yielded different results.

Figure 5.28 to Figure 5.31 give the difference in bed level between the cases with coarser and finer nourishment materials with respect to the original nourishment material. The figures indicate that using a coarser material would cause an additional accumulation of material in the nourishment area, whereas, using a finer nourishment composition would lead to less accumulation in the nourishment area. From the same figures we can further conclude that the tested gradations had nearly no effect on the bed level near the bifurcation point. These figures should be considered in conjunction with Figure 4.20 and Figure 4.21.

The propagation speed of the tracer materials can be inferred from Figure 5.32 to Figure 5.35. Except for the difference in concentration of tracer material, the figures hardly indicate any difference in the location of the tracer materials implying that, for the tested material compositions, the tracer materials behaves in a similar manner.

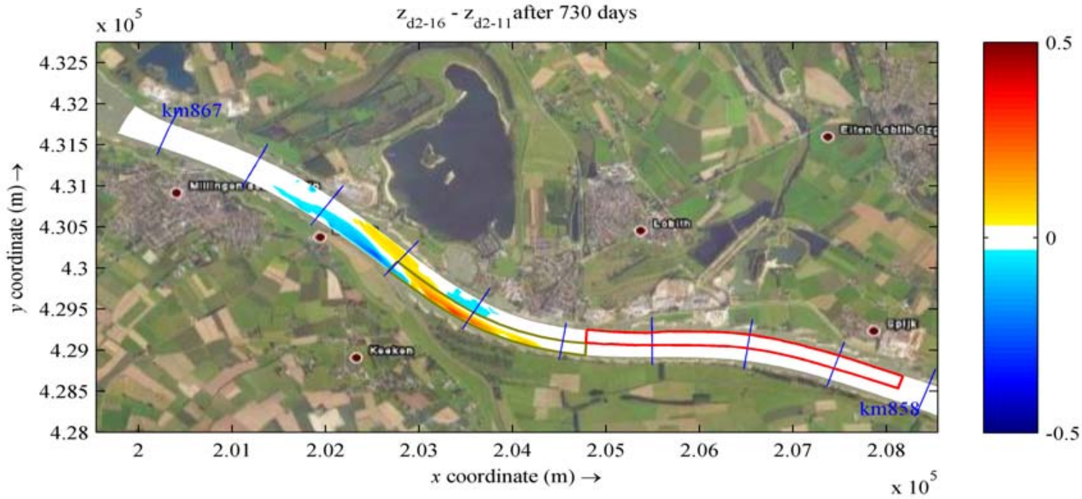


Figure 5.28 Difference in bed level at the end of 2nd year; effect of coarser nourishment material.

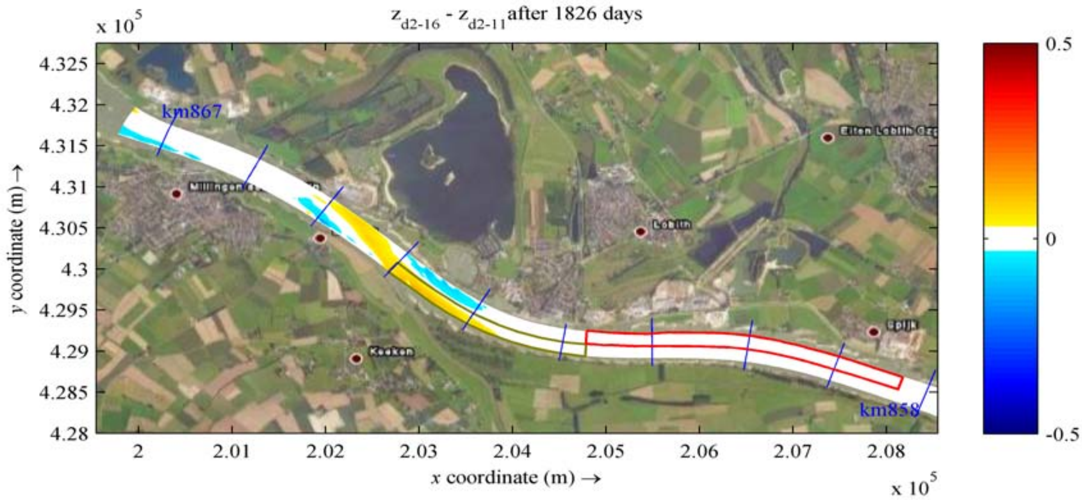


Figure 5.29 Difference in bed level at the end of 5th year; effect of coarser nourishment material.

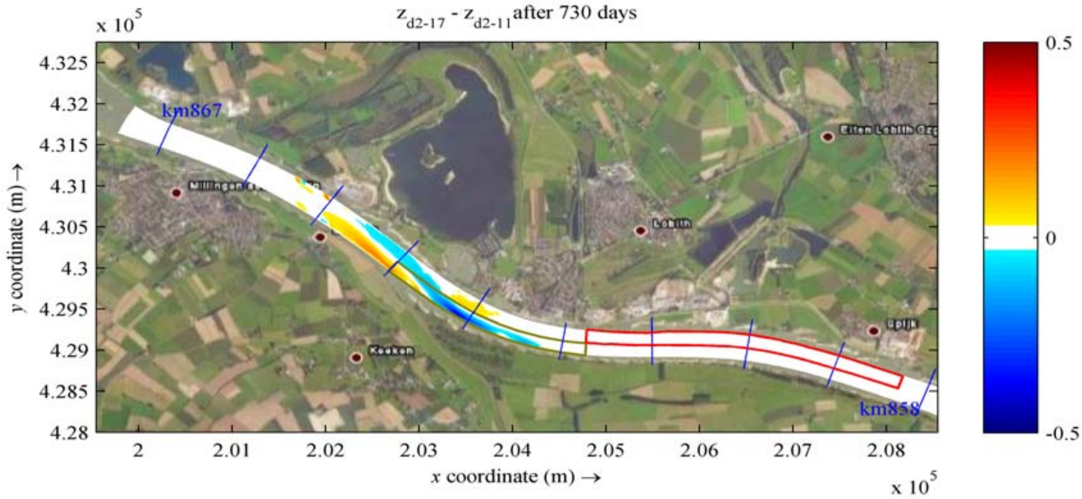


Figure 5.30 Difference in bed level at the end of 2nd year; effect of finer nourishment material.

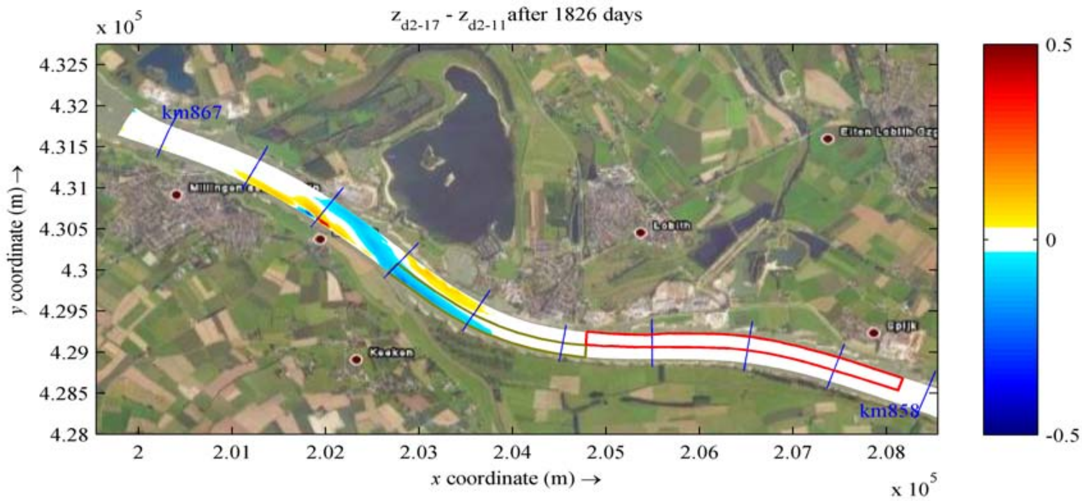


Figure 5.31 Difference in bed level at the end of 5th year; effect of finer nourishment material.

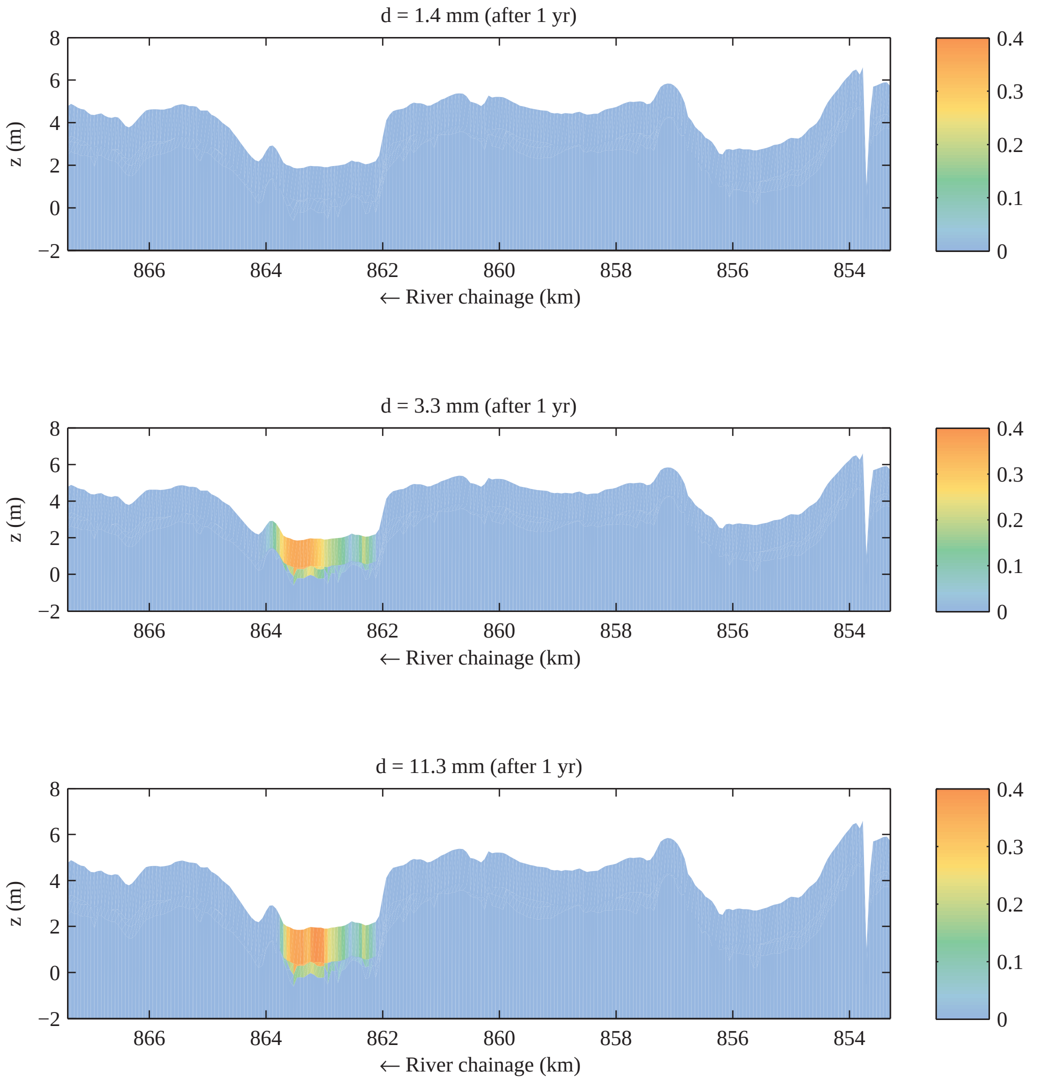


Figure 5.32 Percentage of tracer material in the bed composition along the left bank at the end of the 1st year; coarser material.

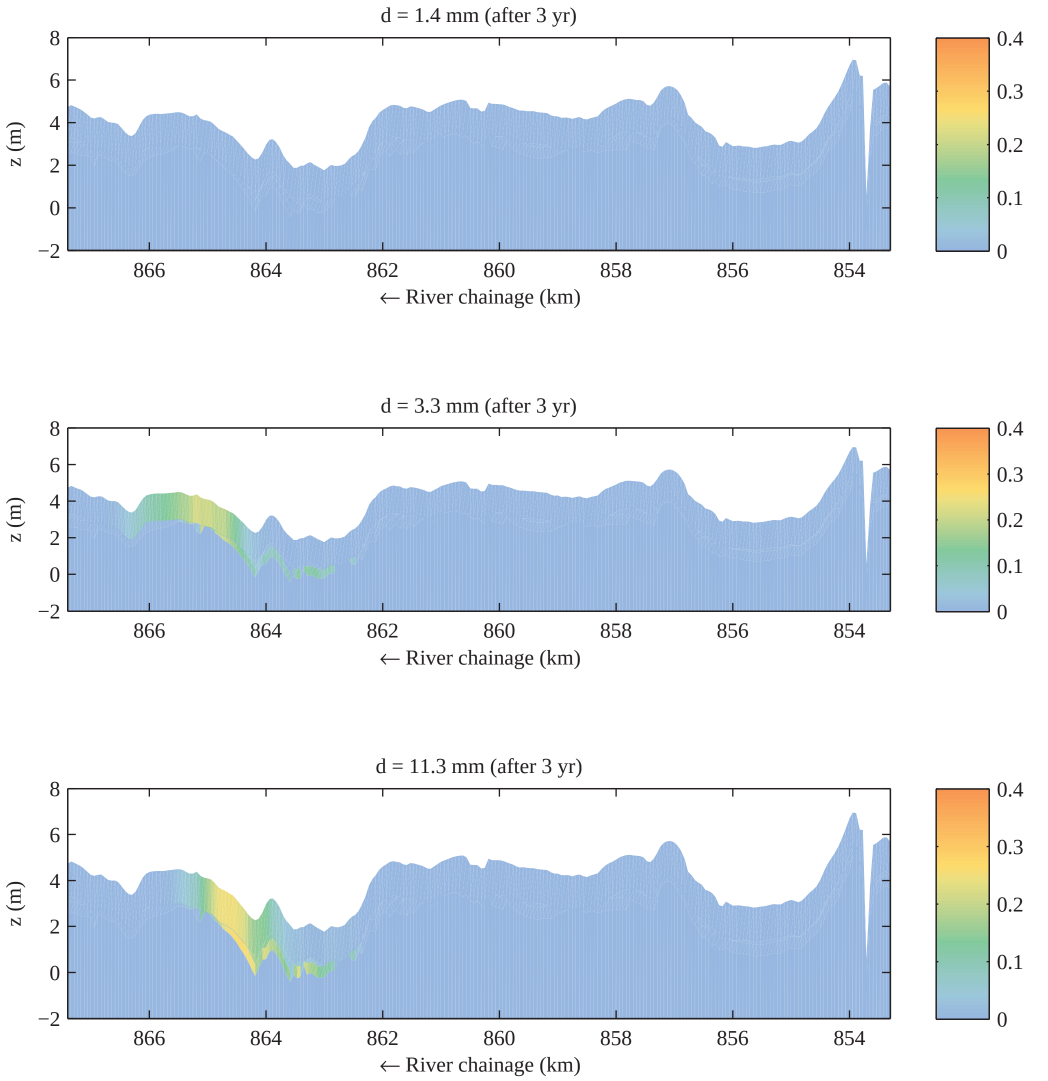


Figure 5.33 Percentage of tracer material in the bed composition along the left bank at the end of the 3rd year; coarser material.

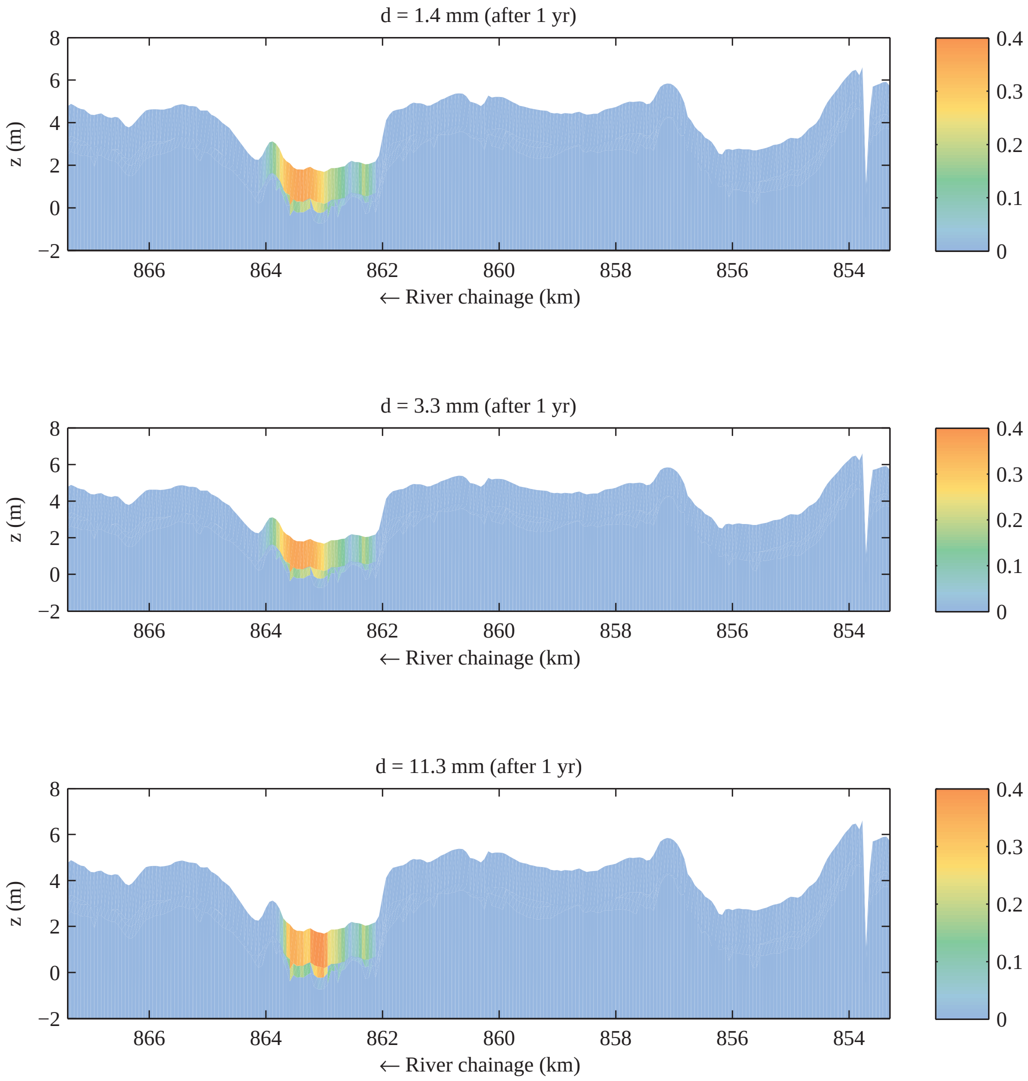


Figure 5.34 Percentage of tracer material in the bed composition along the left bank at the end of the 1st year; finer material.

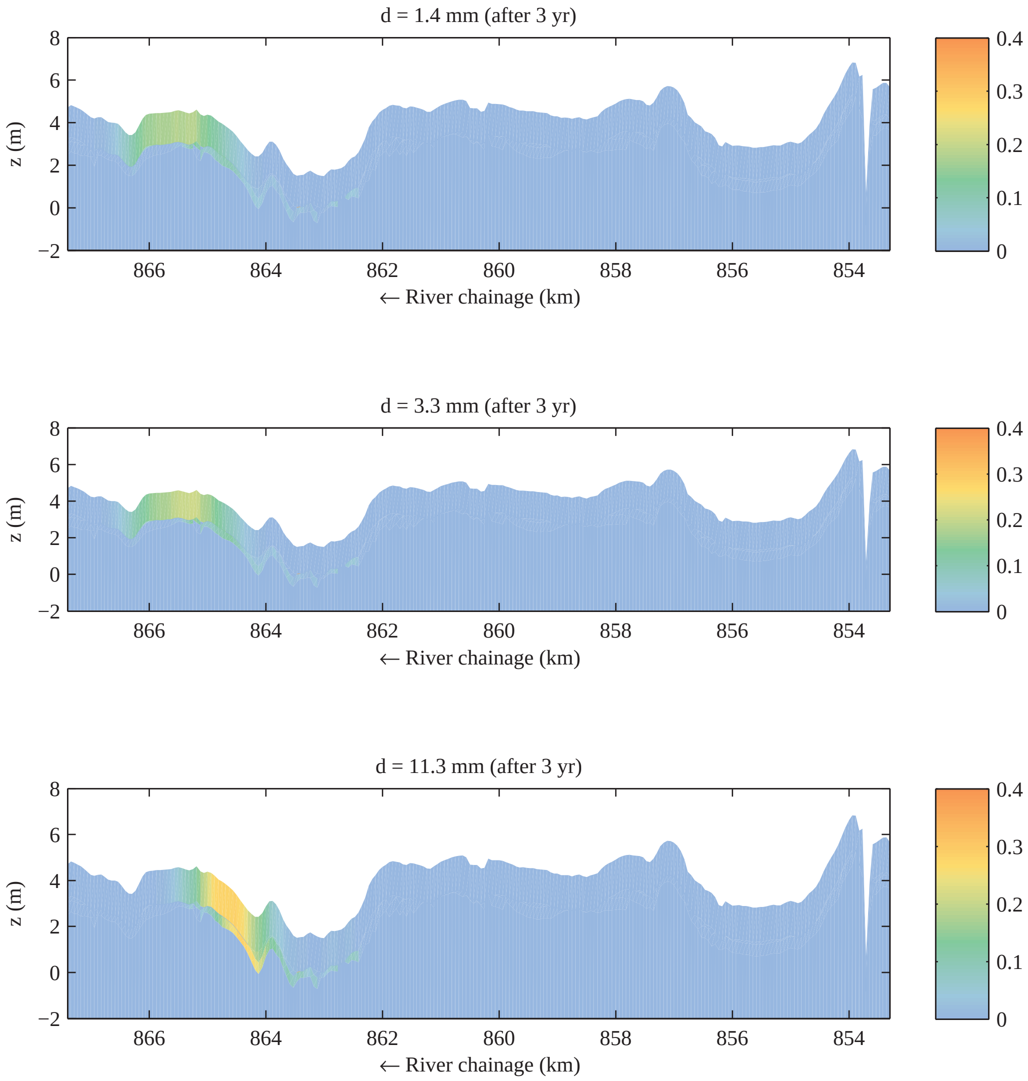


Figure 5.35 Percentage of tracer material in the bed composition along the left bank at the end of the 3rd year; finer material.

5.6 Effect on navigation channel

The effect on the navigation channel is evaluated by comparing the bed level to the navigation depth criteria of OLR – 2.8 m. Note that the navigation depth is affected by bed forms, hence a representative reference level should take this into consideration which is not done at this stage. The results are given in Figure 5.36 to Figure 5.39 where the boundaries of the 170 m-wide navigation channel are indicated by the green lines. We can infer that the implementation of the fixed layer slightly improves the navigability in the area where it is implemented. Note that the shallow area in the navigation channel near km 861 in the base case scenario given in Figure 5.36 has disappeared in the case with fixed layer given in Figure 5.37. The nourishment does not affect the navigation channel.

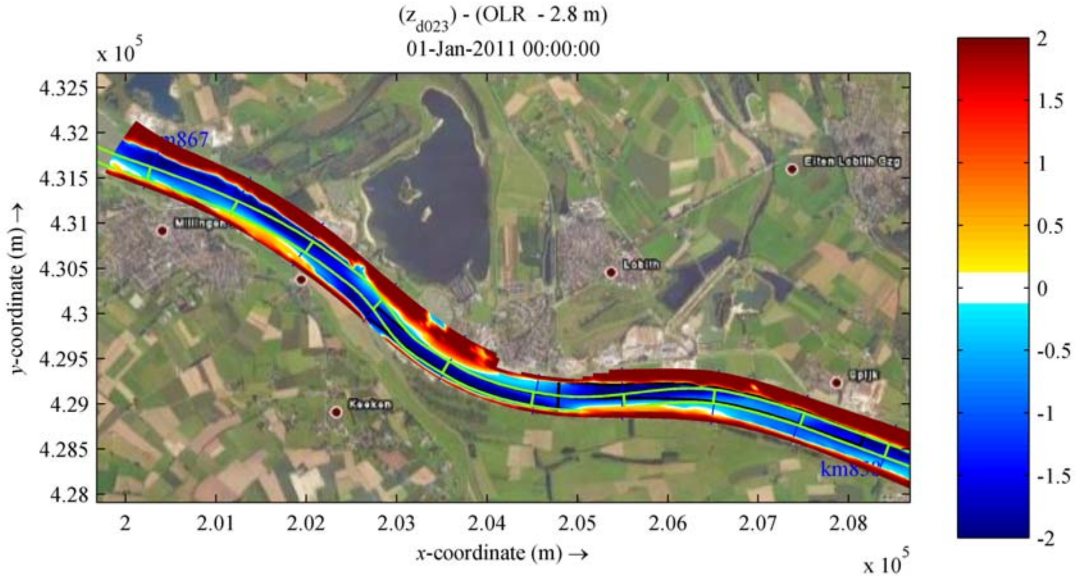


Figure 5.36 Difference between bed level and minimum navigation depth (OLR – 2.8 m) after 5 years of simulation (base case scenario).

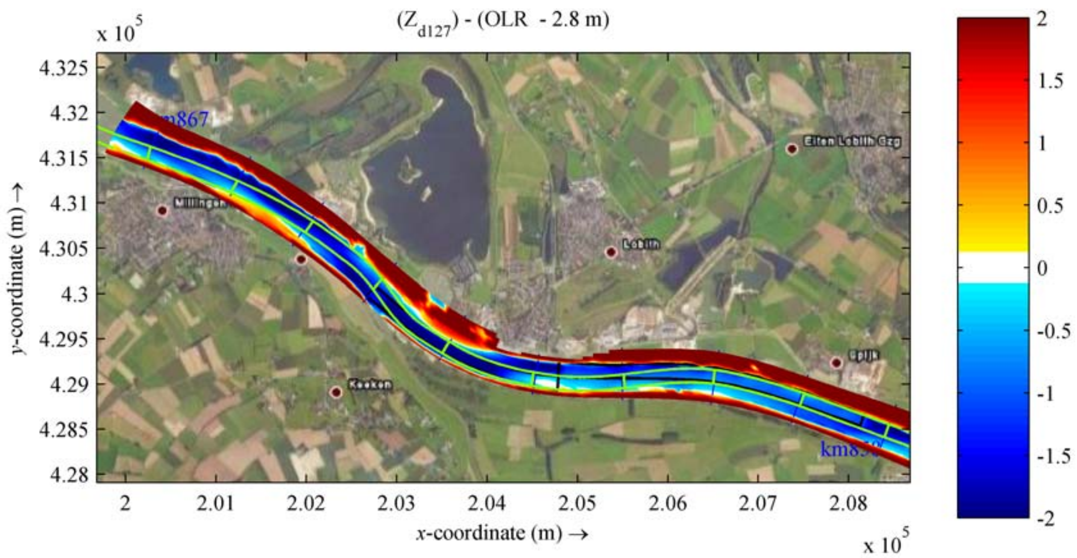


Figure 5.37 Difference between bed level and minimum navigation depth (OLR – 2.8 m) after 5 years of simulation (fixed layer case).

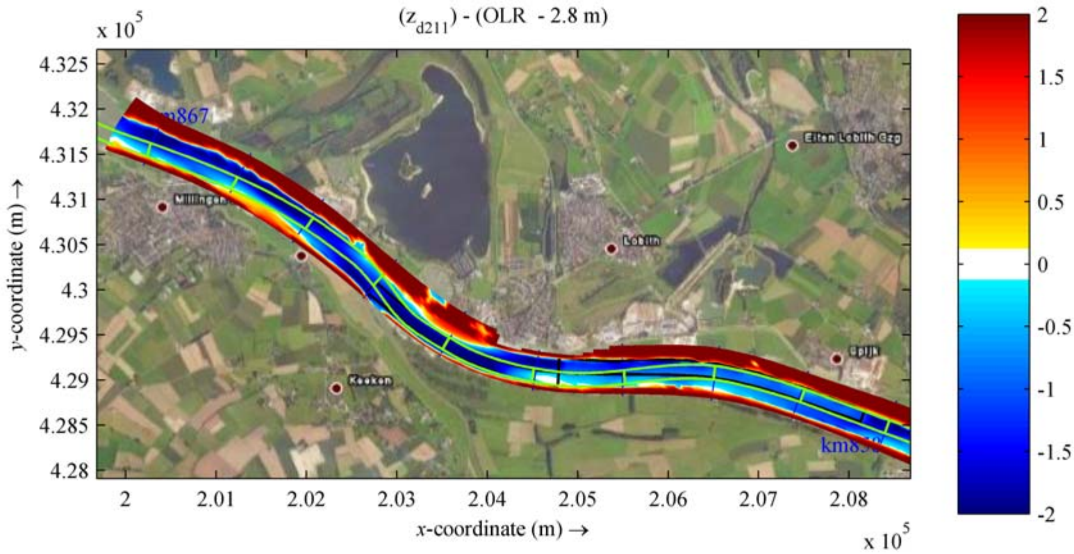


Figure 5.38 Difference between bed level and minimum navigation depth (OLR-2.5 m) after 5 years of simulation (one time nourishment).

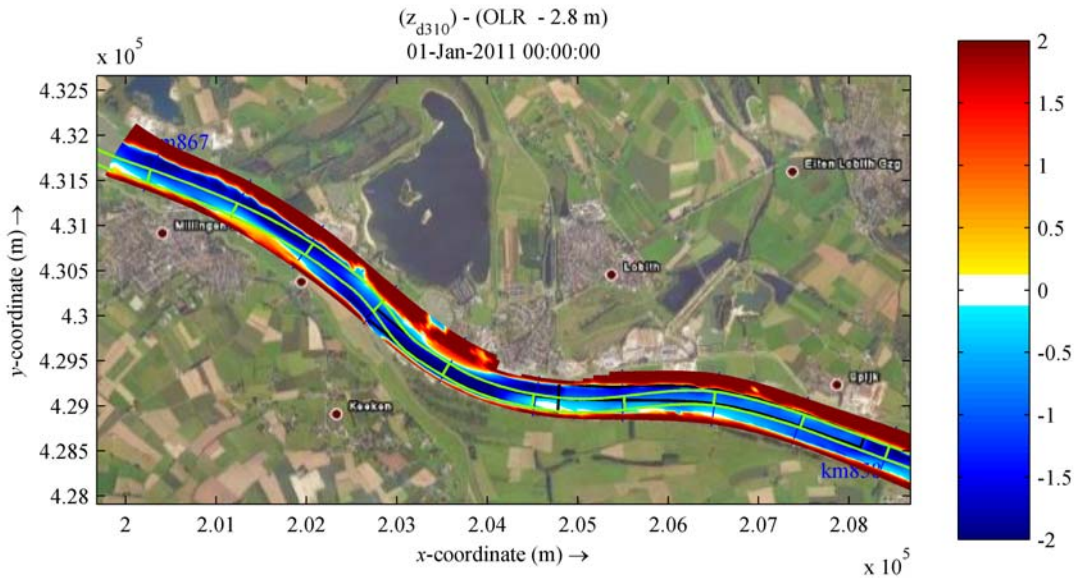


Figure 5.39 Difference between bed level and minimum navigation depth (OLR – 2.8 m) after 5 years of simulation (multiple nourishment).

6 Reflections, conclusions and recommendations

6.1 Reflections

- The analyses, conclusions and recommendations of this case study are subject to the current state of knowledge. The gap in the current knowledge in relation to graded-sediment requires more research that addresses some fundamental questions in relation to the transport and mixing process of graded-sediment.
- The model results indicated significant temporal changes in the sediment distribution at the bifurcation. This indicates that there are some uncertainties in the calibration of the graded-sediment model of the Bovenrijn.
- In terms of mixing of nourishment material with bed material, in the current implementation in Delft3d, nourishment material is treated as bed material. This means that the composition of the nourishment material changes upon entering the model. It is largely affected by the bed composition and the active-layer thickness.
- The local morphological impact of the fixed layer in terms of scour and deposition in its direct vicinity requires a different analysis tool; be it an empirical scour prediction formula, a physical model or a finer and more detailed numerical model.
- When discussing the behaviour of graded-sediment transport, the issue of transverse sorting comes into the picture. Some reports indicate that some differences between sediment size along north and south banks could be attributed to the significant difference between the characteristics of ships sailing either directions. Ships sailing upstream from Rotterdam to Germany are generally loaded, whereas they sail downstream generally empty; this leads to a significant difference in the underwater volume between ships sailing in either direction. The effect on transverse sediment sorting has not been addressed (or confirmed) until now. The effect of navigation on transverse sorting needs to be further discussed.
- Monitoring after implementation of the fixed layer and nourishment is an integral part of the project. Attention should be paid to the planning and execution of monitoring campaigns. Special attention should be paid to the monitoring of the behaviour of nourishment material. Besides the possibility of taking an action in relation to the maintenance of the navigation channel, monitoring is expected to help improve our knowledge about the process governing graded-sediment transport in general and behaviour of nourishment material in particular.
- In operational models that engineering decisions are going to be taken based on their results, it is important to carry out uncertainty analysis. The importance of uncertainty analysis in presenting results of morphological models has been indicated by Van Vuren et al. (2005) and Van der Klis (2003). For a more complete overview of the performance and impact of engineering measures that are to be applied in the DVR project uncertainties needs to be analysed and communicated with the river manager.

6.2 Conclusions

A case study that evaluates the effect of a fixed layer and nourishment in the Bovenrijn was carried out using the graded-sediment model of the Bovenrijn. The same model was used earlier to evaluate the behaviour of nourishment material in the Bovenrijn for a test case (Mosselman et al., 2007). The first set of simulations in this project indicated that additional calibration of the model was required. Accordingly, it was carried out. We have evaluated the effect of implementing a fixed layer in the outer bend of the reach from km 858.3 to km 864 and nourishment in the outer bend of the reach from km 861.7 to km 864.

The following conclusions can be made:

- The results from the case study presented in this report indicate that the morphological effect of the fixed layer is dominant over that of nourishment. In the inner bend of the fixed layer erosion develops and just downstream of the erosion area a deposition bar forms. Just downstream of the fixed layer a deep scour hole forms.
- The implementation of the fixed layer slightly improves the navigation channel in the area where it is applied. The nourishment did not cause an adverse effect on the navigation channel.
- The time dependent morphological results indicate that the local morphological effect of the fixed layer reaches a state of dynamic equilibrium after nearly two years.
- The fixed layer appears to be inadequate to stop large-scale bed level degradation. With a continued bed level degradation the relative height of the fixed layer increases, hence the local impact intensifies. Thus, the construction of the fixed layer in the Bovenrijn is sustainable if coupled with additional bed stabilisation measures, e.g. nourishment.
- The formation of a deposition ridge in the left bank downstream of the fixed layer contributes to filling the designated nourishment area. Hence, the location of nourishment might shift or nourishment could be distributed over two (or more) locations to match the required supply volume.
- The morphological impact of the fixed layer is largely affected by the choice of the threshold sediment thickness (δ_a), whereas the effect of the schematisation has little effect on the resulting morphological pattern.
- The design level (relative height) of the fixed layer has a large impact on the local morphological pattern compared to a rather small impact on locations away from the fixed layer.
- Attention has to be given to monitoring the morphological development after implementation of the fixed layer. The following two issues are of special importance:
  - The deposition ridge developing near the left bank downstream of the fixed layer could hinder navigability in this reach and could necessitate dredging after implementation of the fixed layer.
  - The development of a scour hole downstream of the fixed layer could lead to toe failure and might require supply of additional stabilising material.

- Two years after introducing the nourishment material there is still an effect on the bed level that appears as an increased bed level downstream of the nourishment area. When the following nourishment is introduced after 2 years, it adds up to this effect and leads to an additional increase in bed level. The interval of 2 years for repetitive nourishment appears to cause an accumulation of nourishment material in the nourishment area. The final decision on when to repeat the nourishment should be left subject to the results of the monitoring of the behaviour of the 1st nourishment.

- As the nourishment material in the model was chosen to be close to the existing bed material, the effect on the sediment size distribution at the bifurcation point is relatively small.
- The analysis of the behaviour of the coarser and finer nourishment materials indicates that:
  - using a coarser material causes additional accumulation of material in the nourishment area, whereas
  - using finer composition leads to less accumulation in the nourishment area.
  - This means that the time required to repeat the nourishment increases when using coarser material.

- The results of the model provide information on water level changes at the upstream boundary (Emmerich). The effect of the tested measure on the water level is around 4 cm increase in water level; 2 cm can be attributed to the fixed layer, 2 additional cm are attributed to repetitive nourishment. The effect is highest during low discharges.
- The analysis of the sediment distribution between the Waal and the Pannerdensch kanaal indicated that:
  - In the base case scenario, there is a 30% increase in the sediment into the Waal over the simulated 10 years. This indicates the need of further calibration. The sediment discharge into the Pannerdensch kanaal remains constant.
  - The effect of the fixed layer is small on the sediment distribution between the Waal and the Pannerdensch kanaal.
  - The nourishment causes an increase in the total amount of sediment transported out of the Bovenrijn yet the distribution between the two branches stays similar to the base case scenario. Using a coarser material leads to a slight reduction of the transport into the Waal and a small increase of the transport into the Pannerdensch Kanaal. The finer material causes a slight increased transport into both branches.

- Analysis of the changes in median sediment diameter indicated that:
  - In the base case scenario (no measures), changes of up to ±2 mm (around 30%) were observed, with the largest changes near the crossings between bends.
  - Changes due to the fixed layer are limited to its direct vicinity with changes that could amount to 4 mm.
  - The nourishment causes an increase in the median sediment diameter in the nourishment area and along the left bank in the downstream direction. The increase in the median sediment diameter due to single-time nourishment is less than 1 mm and decays with time. Coarser nourishment material causes an additional increase and a finer nourishment material causes an opposite behaviour.
  - The repetitive nourishment causes an additional increase in the median sediment diameter. Due to the continuous supply of nourishment material this increase is maintained in the nourishment area.

- In conformity to the finding from the study of Mosselman at al. (2007), the morphological behaviour of the model largely depends on the thickness of the active-layer. Similarly, the behaviour of the nourishment material depends on the active-layer thickness in addition to the material composition. The nourishment material dumped along the left bank follows the left bank of the river.
- Additional analysis of the effect of the active-layer thickness indicated that:
  – Using a variable thickness for the active-layer yields a significant reduction of the transverse slope in all bends along the Bovenrijn. The smaller thickness of the active-layer yields an opposite behaviour yet it is less pronounced. The reason behind this behaviour is not fully comprehended yet and further analysis of this specific behaviour is required.
  – In the case of a small active-layer thickness, the nourishment material quickly moves to the sub-layer.
  – This behaviour in the case of the variable active-layer thickness causes extra dispersion of the nourishment material (apparent diffusion). Material in the top layer (active-layer) has a higher celerity than the material left in the sub-layer. The celerity of the material in the active-layer increases as the active-layer thickness reduces. After sufficient time, the nourishment material available in the active-layer disappears. However, in the case of a small active-layer thickness, more tracer material is found in the under-layers than in the case with a large active-layer thickness.
  – Such behaviour can be used in the analysis of monitoring data. Accordingly, information about the location of tracer materials both in the longitudinal and vertical directions coupled with the percentage in the total composition are required to have a complete overview of the behaviour of nourishment material.

6.3 Recommendations

- With respect to the application of repetitive nourishment and to avoid accumulation of nourishment material, it is recommended to apply a flexible nourishment strategy that is possible to adapt in terms of location and volume in response to the situation created by previous nourishment(s). Such a strategy implies further study and we recommend using numerical simulations to analyse it. The strategy comprises the following:
  – Every second year, the required volume of nourishment is determined (updated) by the integrated two-year change in bed level of the Bovenrijn. The maximum volume of nourishment applied as estimated earlier is 70 000 m^3.
  – A nourishment area is identified between Emmerich (Dutch border) and km 865, only in areas with bed levels below OLR-3.5 m.
  – The average raise in bed level in a nourishment area should not exceed 0.3 m.
- It is recommended to implement in Delft3D a different mixing procedure (bookkeeping) when applying nourishment; the mixing should consider the thickness of the nourishment layer in comparison to the active-layer thickness, in cases with a nourishment thickness larger than or equal to the active-layer thickness, mixing should not take place. Currently mixing takes place first in any case.

- It is recommended to further calibrate the graded-sediment Bovenrijn model in such a way that extra attention is paid to the 2D morphological pattern and sediment distribution at the bifurcation.
- With respect to improving our knowledge about graded transport in general and behaviour of nourishment material in particular, it is recommended to collect data about the following during the monitoring campaign:
  - Spread of tracer material in the longitudinal direction,
  - Presence of tracer material in the inactive sub-layers.
  - Changes in the transverse slopes.
  - Changes in transport rate and material composition at the bifurcation.
- It is recommended to carry out an uncertainty analysis for the effect of the applied measures. Possible parameters to include in the analysis are: hydrograph schematisations, bed composition, active-layer thickness, and the effect of model schematisation of applied measures.

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