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Modelling of the Bovenrijn nourishment

Comparison of two different transport layer approaches

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Summary

After centuries of river training in the Dutch Rhine, the river has developed to a waterway which conveys water downstream very efficiently. Moreover, the corridor Waal-Bovenrijn-Niederrhein has developed into a main shipping route between the port of Rotterdam to the German hinterland. Decades of monosectoral projects (e.g., focussing on flood safety only), have rendered the river the way it is today. Dealing with climate change and other current needs have shifted the paradigm towards multisectoral projects, such as Integral River Management (IRM), which look at the wishes of different stakeholders. One of the measures, which is adaptive and is considered within the context of IRM, is performing large scale nourishments. This is expected to reduce the bed level degradation seen in the downstream Bovenrijn and Upper Waal. Reducing this bed degradation is expected to raise water levels during the low water periods, which has a benefit for nature and shipping. A pilot nourishment was performed in 2016, with a follow-up nourishment in 2019.

The bed level development is the key indicator in such intervention and an important parameter controlling bed level changes is grain size (of the parent material and the nourished sediment). This research was set to compare the bed level development using two different approaches for modelling changes in bed composition, namely the state-of-the-art Hirano concept and the novel HANNEKE concept.

The novel concept was successfully applied to the nourishment in the Bovenrijn. This shows that the modelling concept can be applied at a field scale. Analysis of the results showed comparable behaviour using both approaches. Unfortunately, a one-to-one comparison proved to be troublesome, as errors were found in both results. Nevertheless, the results are encouraging as the analysis have guided us to issues which need to be improved in the software.

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1 Introduction

The Bovenrijn has shown a long term erosion trend, eroding in the order of 2 meters over the past 90 years (Figure 1.1). To counteract the bed level degradation, a pilot nourishment in 2016 and follow-up nourishment in 2019 were done. Their goal is to raise water levels and keep the bed level above a critical value which is necessary for the stability of river infrastructure, such as pipes, tunnels, constructions and entrances to harbours.

This year the evaluation of the nourishment pilot is being carried out by Deltares and HKV. One of the difficulties in modelling nourishments, or river morphodynamics in general, is that at certain times a large proportion of sediment may be immobile and the state-of-the-art model for mixed-size sediment (Hirano, 1971) cannot capture the fixed-layer behaviour occurring under these circumstances. Struiksma (1999) formulated a concept to deal with fixed layers as a lack of sediment. This approach, however, cannot model the fact that part of the time the river can be considered to be alluvial and at other times the river can be considered to be non-alluvial. In Chavarrías *et al.* (2022), the HANNEKE (HirANo does Not havE the Key Exchange) concept is introduced, which includes a coarse layer below the transport layer. This coarse layer, when filled with immobile sediment allows for the limited transport according to the concept of Struiksma (1999). At higher discharges, this coarse layer may become mobile again, and subsequently the material can be part of the transport layer such that it can be transported. In this limit the behaviour is the same as the Hirano (1971) approach.

Previously, The HANNEKE concept was applied to the experiment of Struiksma (1999) showing good and expected results. Following this, the concept was applied in the Struiksma (1999) limit, by applying it to the fixed layer at Nijmegen Chavarrías *et al.* (2020). Next both the Struiksma (1999) and the Hirano (1971) limits were tested in flume experiment of Blom *et al.* (2003) (cf. Chavarrias and Ottevanger, 2021), and to a test nourishment simulation in the Boven Waal (cf. Becker, 2021).

In this report, the HANNEKE concept is applied to the nourishments in the Bovenrijn. The aim is to analyse what the added value is of the HANNEKE concept in comparison to the Hirano concept at alluvial regions, and the Struiksma concept at fixed layers).

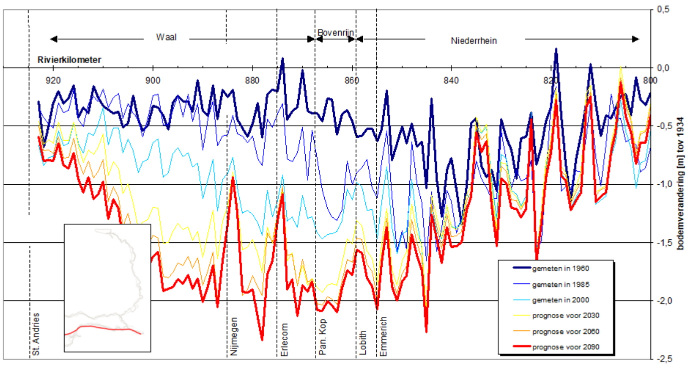


Figure 1.1 Bed level trend in the Rhine (courtesy Arjan Sieben).

2 Model setup

2.1 Model schematisation

2.1.1 Extent

The model is a shortened version of the one used by Becker (2021). Here the domain covers the Niederrhein from Xanten until the Pannerdensche Kop. For an assessment of the nourishment propagation over the first years it is not necessary to model the Waal and the Pannerdensch kanaal, and reducing the model extend also reduces simulation time.

2.1.2 Boundary conditions

At the upstream boundary (Xanten, Germany) the hindcast discharges of the Pannerdensche Kanaal are used. To obtain the water level values at the Pannerdensche Kop (i.e., the downstream boundary condition), the water levels from the flow restart fields of Becker (2021) are used. These are shown in Figure 2.1.

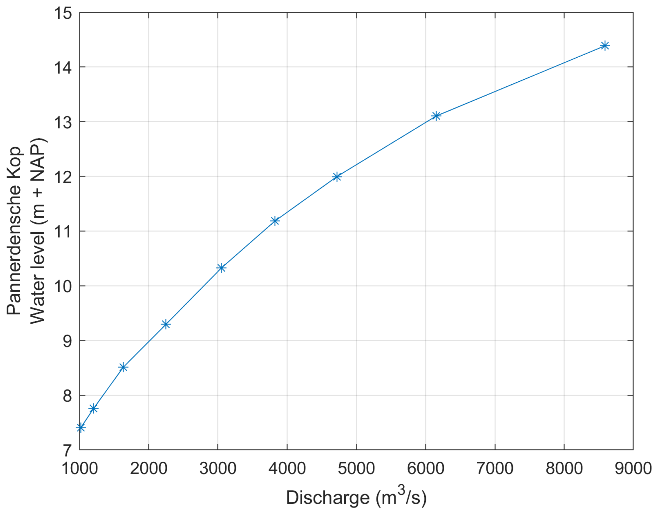


Figure 2.1 Waterlevel at the Pannerdensche Kop as obtained from the steady state flow simulations.

2.1.3 Sediment properties

The sediment properties are included as done by Becker (2021). The original bed material includes 10 sediment fractions ranging in size from 63 µm to 6.4 cm.

The difference with the simulations in Becker (2021) is that the base layer of sediment (below the top active layer), was subdivided into 0.5 m thick additional layers near the surface, and the number of underlayers was increased accordingly. This was necessary to reduce mixing with the thick base sediment layer. In previous simulations, any sediment from the thinner underlayers below the transport layer which mixed with this base-layer got instantly diluted so strongly, that it is expected that its propagation could no longer be tracked accurately.

The initial nourishment was conducted on the 1st of April 2016 between river kilometer 862 and 864.3 at the left of the river. The most upstream and downstream parts of the nourished sediment had a different background radiation than the parent sediment in the river bed and the rest of the nourished sediment (cf. Figure 2.2). In the simulations this has been implemented using 10 additional fractions, with identical properties to the first, yet having a different label. This enables the tracking of the sediment which was added from outside the system.

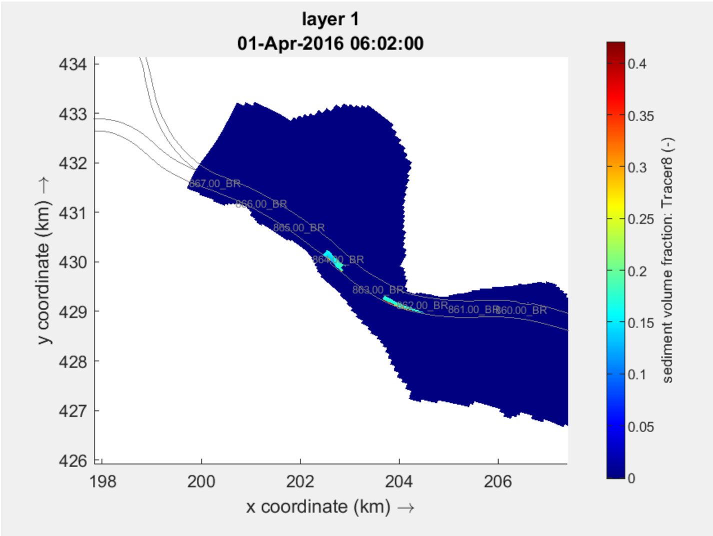


Figure 2.2 Tracer material in the simulation after the 2016 nourishment.

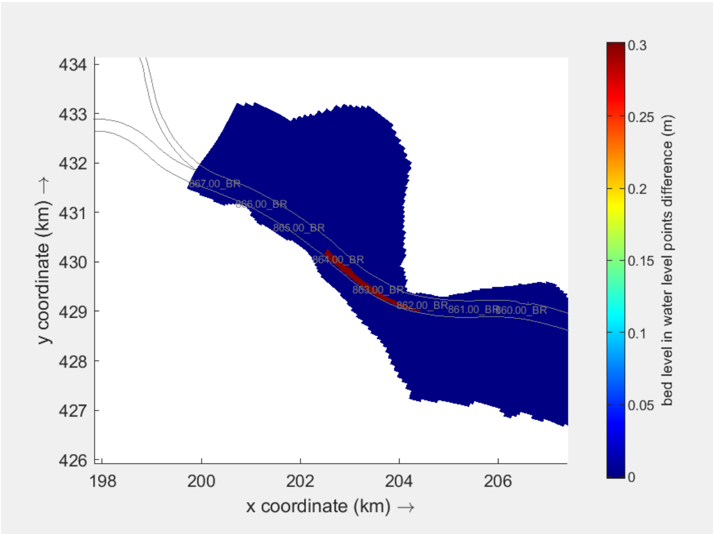


Figure 2.3 Difference in the bed level before and after the nourishment.

Similarly, the 2019 nourishment was added using another 10 tracer fractions. This enables the tracking of the second nourishment. The second volume of 70 000 m^3 is nourished to the bed level on the 13th of June 2019. Here no tracer fraction was applied in the field. In addition, to enable the comparison between the behaviour of the two modelling concepts, the material as added with a uniform layer thickness of roughly 53 cm. For details on how the second nourishment was executed in reality, see Becker *et al.* (2021).

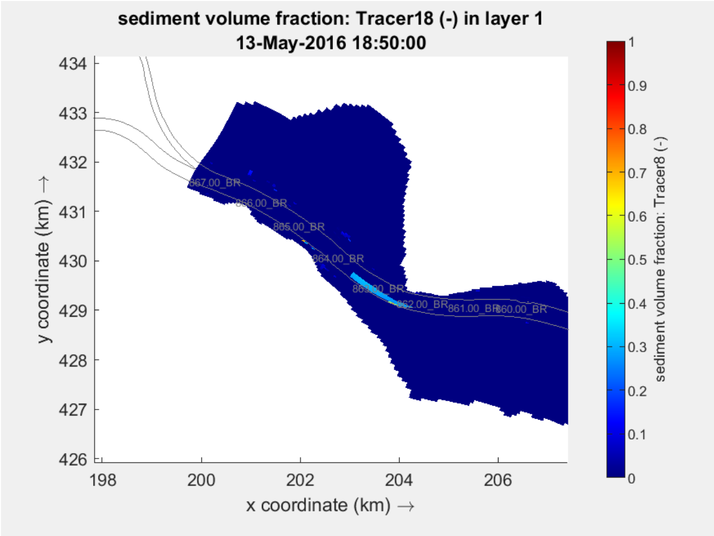


Figure 2.4 Tracer material in the simulation after the 2019 nourishment.

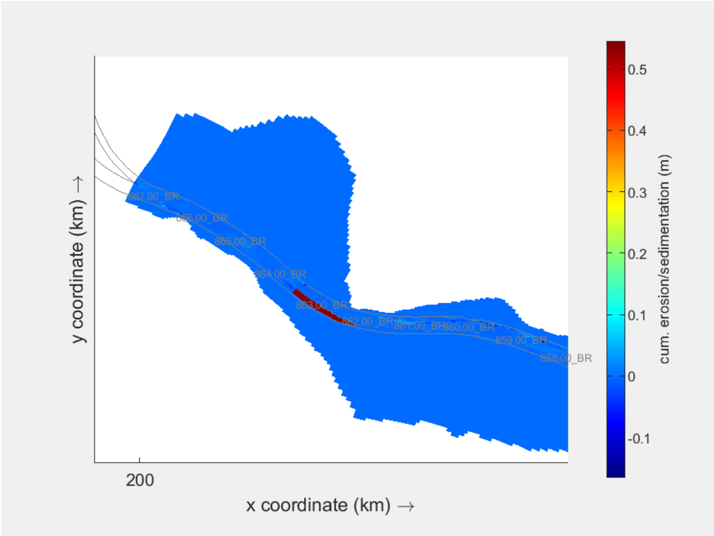


Figure 2.5 Difference in the bed level before and after the nourishment in 2019

2.2 Modelling concepts

The different methods which are available for use are summarised in the Table 2.1. The different approaches are explained in short. For a detailed explanation, please refer to Chavarrías *et al.* (2022).

The Struiksma concept concerns a reduction of the sediment transport over fixed layers. This concept is shown to work well in the flume experiment by Struiksma, although in reality the material was immobile but not truly fixed. This option is good to use considering that coarse layers are truly not mobile, and as such cannot model the break-up of a coarse layer.

The Hirano concept includes the concept of an active layer, which is the top layer of the sediment. This top layer can typically contain both mobile and immobile material. A drawback of this method is that immobile sediment can be artificially moved upwards under aggradational conditions. This method allows the implicit modelling of the break-up of a coarse layer.

Model	Transport over a coarse layer	Coarse-layer break-up	Explicit coarse-layer formation	Software package
Struiksma	yes	no	no	Delft3D, ELV
Hirano	no	yes	no	Delft3D, ELV
ILSE	yes	yes	no	ELV
HANNEKE	yes	yes	yes	Delft3D

Table 2.1 Model capabilities (from Chavarrías *et al.* (2022)).

The ILSE (ImmobiLe Sediment Exchange) flux exchanges immobile material to the substrate first, and just like Hirano (1971), allows for coarse immobile sediment to be present in the active layer. Hence, modelling of the break-up of a coarse layer is also done implicitly.

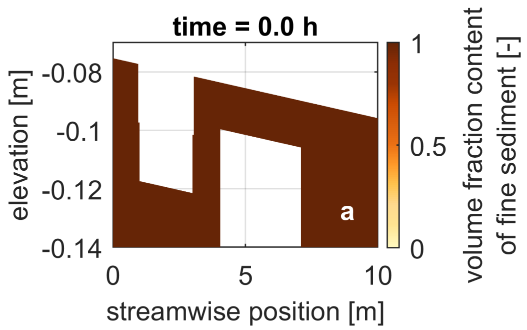
The HANNEKE model sorts coarse immobile sediment to the substrate, resulting in an active layer with solely mobile material. The coarse material no longer influences the transport of the fines. It is debatable whether this assumption always holds. The underlying reason is that although coarse material might be immobile, it still influences the boundary layer of the flow which in turn influences the shear velocity acting on the finer material. If the mixture is not well graded, e.g. a bimodal mixture, transport may be occurring through the pores, which again may influence the sediment transport closure model which is being used.

The behaviour of the different modelling concepts is illustrated in Figure 2.6 and Figure 2.7 for low and high flows, respectively. The experiment with low flow, originally performed by Struiksma (1999), shows the passage of a trench over a coarse patch of sediment located between 4 and 6 m from the start of the flume. The low flow corresponds to the situation where the coarse sediment is immobile and the high flow (a thought experiment) is the situation of full mobility of all the sediment fractions.

For the low flow situation (Figure 2.6) it is shown that the Struiksma concept works to limit the bed level over the coarse layer as the trench passes, with a return to the equilibrium slope after the trench has passed. The Hirano concept also shows a reduction of the bed level as the trench passes over the coarse layer. At this stage, coarse sediment enters the active layer. As the trench passes and aggradation occurs, coarse sediment moves upwards. The presence of coarse sediment in the active layer implies a reduction of the amount of fine material in the active layer. Hence, the equilibrium condition is reached with a higher bed level over the coarse layer (i.e., higher velocity) such that it compensates for the reduction of volume fraction content of fine sediment in the active layer. The ILSE model, uses a similar approach to Hirano, but uses preferential deposition to the subsurface and also results in the equilibrium slope at the end of the simulation. The HANNEKE model shows a combination of both, with limiting of the fine transport according to the Struiksma (1999) concept and including a separate layer which stores the coarse immobile sediment. The ILSE and HANNEKE models both show the limit behaviour of the Struiksma transport reduction, as when the active layer thickness reduces below a certain threshold (typically the alluvial active layer thickness), the transport is reduced according to Struiksma (1999), even when there is sediment available below the active layer.

For the high-flow situation (Figure 2.7), the Struiksma concept shows a swift passage of the trench over the fixed layer. Using the Hirano and the ILSE concepts show a similar pattern, with coarse sediment removed at the upstream end of the coarse patch, and a mixed substrate downstream of it. The HANNEKE concept also shows erosion at the upstream end of the coarse patch, a mixed substrate above the coarse patch and mixing of the substrate at the downstream end. Unfortunately, the experiment was not performed under high-flow conditions, so it cannot be determined what the real result should be, but the results indicate that both the ILSE and the HANNEKE models show the limit behaviour of the Hirano concept.

The ILSE model could not be used directly, as it only exists within the research model Elv (Chavarrías *et al.*, 2019). The current report discusses the differences and similarities between the standard Delft3D 4 options and the HANNEKE model.



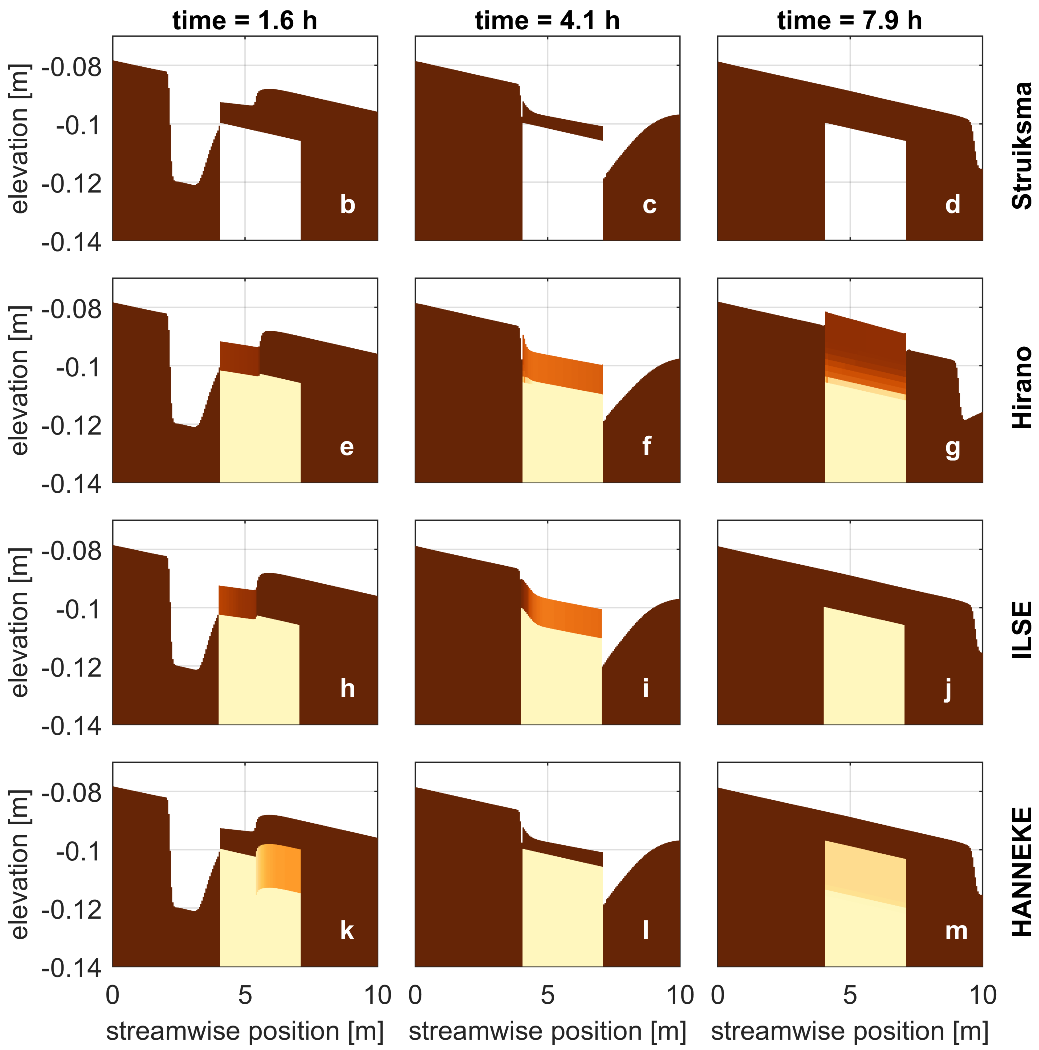


Figure 2.6 Initial condition (**a**) and model results at different times (in columns) applying the model by Struiksma (top row), the model by Hirano (second row from above), the ILSE flux (third row from above) and the HANNEKE model (fourth row from above) to a case in which coarse sediment is immobile (from Chavarrías *et al.* (2022))

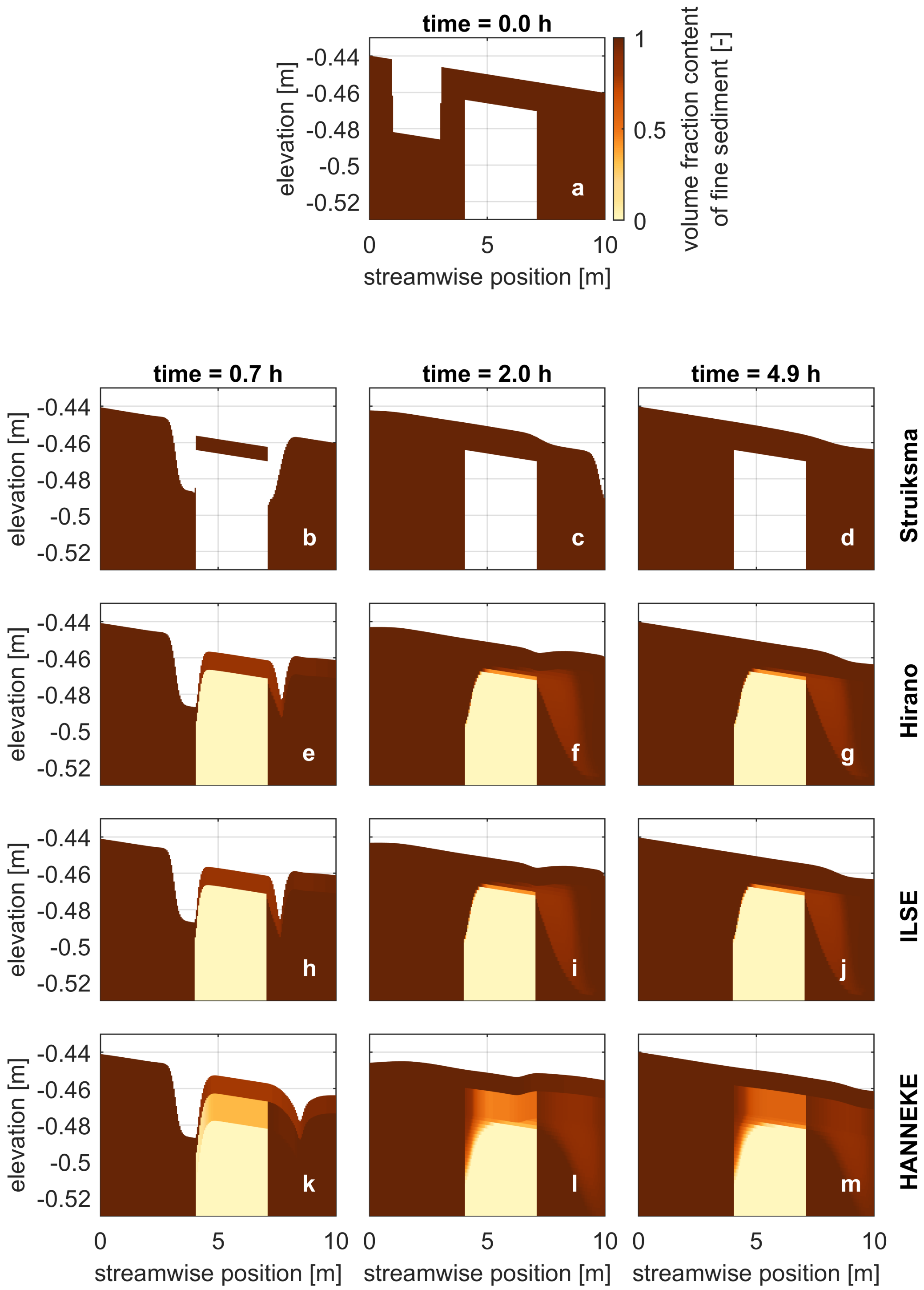


Figure 2.7 Initial condition (**a**) and model results at different times (in columns) applying the model by Struiksma (top row), the model by Hirano (second row from above), the ILSE flux (third row from above) and the HANNEKE model (fourth row from above) to a case in which coarse sediment is mobile (from Chavarrías *et al.* (2022))

2.3 Simulations

In this report, the first application of the HANNEKE model to a real field case is shown. The results of the model are compared to those of the standard modelling approach (Hirano-Struiksma). A summary of the simulations is given in Table 2.2.

Simulation	Model concept	Nourishment
1	Hirano	no
2	HANNEKE	no
3	Hirano	yes
4	HANNEKE	yes

Table 2.2 Overview of the simulations performed.

2.3.1 Active-layer thickness

The active part of the bed is modelled as in the nourishment simulations by Niesten *et al.* (2017), in which the alluvial active layer thickness is equal to 12 % of the water depth, with a minimum of 0.5 m. When the active layer has a thickness of 0.7 m or less the transport reduction by Struiksma (1999) is activated.

For the models, which use the HANNEKE concept, the following settings are used as well. The maximum thickness of the coarse layer is set to 0.5 m, the inverse probability of deep troughs, which defines a rate at which sediment is exchanged with the substrate, is set to 1. Furthermore, during a single time step, the maximum fraction of material that can be moved to the coarse layer is set to 60 %. The hiding-exposure is computed based on the sediment in both the active and coarse layer. The mobility computation in the HANNEKE concept follows from a condition related to a critical Shields' parameter of 0.047. When the active layer reduces below the threshold of 0.7 m, the Stuiksma transport reduction is activated, even when the coarse layer contains sediment.

3 Results

3.1 Simulation times

Table 3.1 shows the simulation time for the different simulations. The HANNEKE model computes slightly faster than the Hirano model. Furthermore the simulations including a nourishment take about 60 % longer than the reference simulation. The reason for the difference in computational time between the HANNEKE module and the Hirano module is not immediately clear, can could be researched further. It could be caused by a chance difference in the processing speed of the cluster, or possibly the fact that the HANNEKE module was compiled with a more recent compiler. This should be investigated further. The difference between the simulation with and without nourishment could possibly be explained by the activation of the dredging module. Although it is only used during the 2019 nourishment, this seems to be the only possible difference which could explain this. It is recommended to research this further.

Simulation	Model concept	Nourishment	Run time [days]
1	Hirano	no	4.6
2	HANNEKE	no	4.3
3	Hirano	yes	7
4	HANNEKE	yes	6.8

Table 3.1 Overview of the simulations performed.

3.2 Evolution of bed level

The difference in the autonomous (i.e., without nourishment) bed level evolution is shown for the two modelling concepts in Figures 3.1 (absolute values) and 3.2 (relative to the initial bed level). The bed level shown is the average bed level in the summer-bed averaged over 250 m distance. The simulations show the reference behaviour in the case of the simulation using the standard approach for modelling graded sediment (i.e., the active-layer model by Hirano (1971)) and the new approach using the HANNEKE model.

The model results show differences in the evolution compared to the initial bed level. In the reach 855 to 857 the Hirano model degrades much slower than the HANNEKE model. In the reach 860-863 the Hirano model shows degradation, whereas the HANNEKE model shows aggradation. The relative difference in bed level between the HANNEKE and the Hirano concepts is shown in Figure 3.3. Possibly the substrate sediment which gets mobilised at high discharge, under degradational conditions, in the HANNEKE model is different.

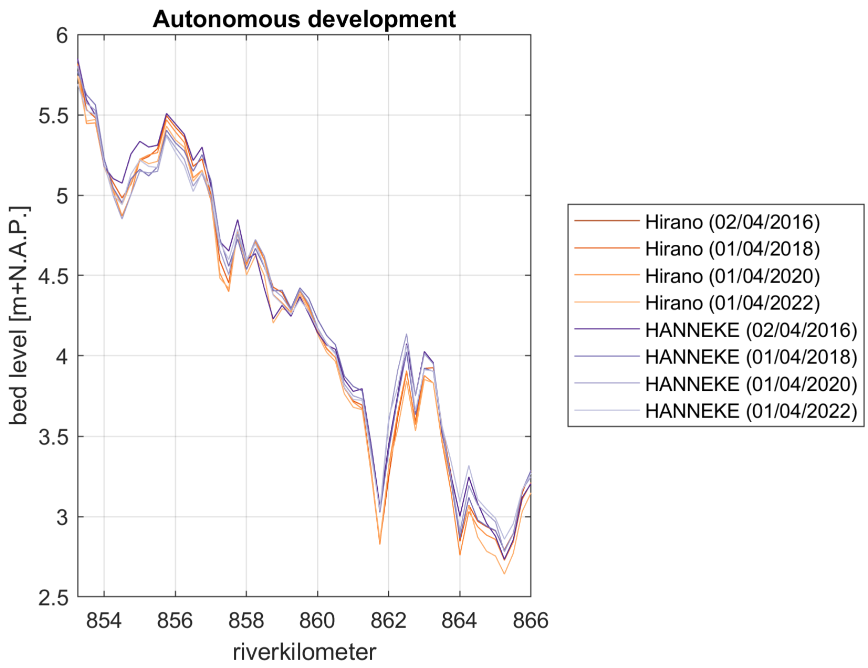


Figure 3.1 Autonomous development in the bed level for the reference situations excluding a nourishment using the Hirano and HANNEKE concepts.

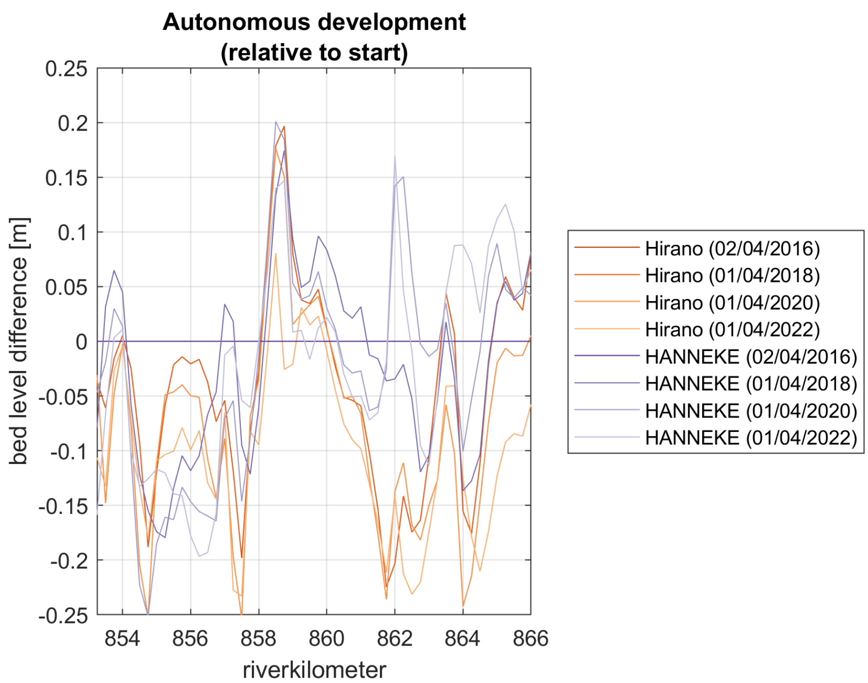


Figure 3.2 Autonomous development in the bed level for the reference situations excluding a nourishment using the Hirano and HANNEKE concepts relative to the start.

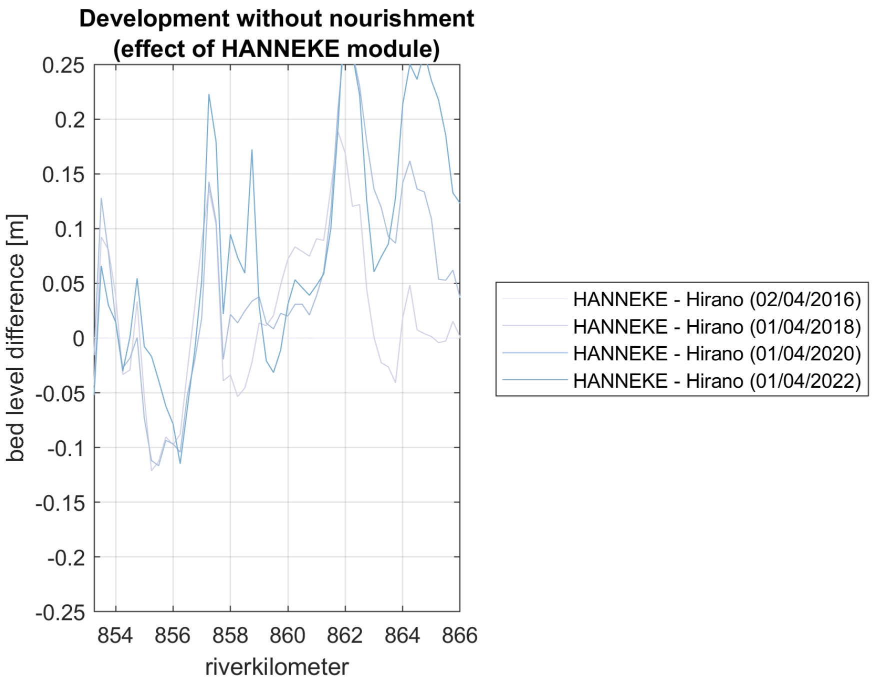


Figure 3.3 Autonomous development in the bed level for HANNEKE module in comparison to the Hirano bed level evolution.

3.3 Evolution of nourishment

Following modelling of the autonomous behaviour, the nourishment was included using both types of model. The bed level evolution relative to the initial bed prior to the nourishment is shown for the two modelling concepts in Figure 3.4.

In both models, the response to nourishment is similar. At the upstream end of the nourishment (rkm 862) erosion occurs. Midway the nourishment (rkm 863), initial degradation and final aggradation occurs. The Hirano concept shows more sedimentation than the HANNEKE concept. Downstream of the nourishment, initial aggradation and final degradation are observed.

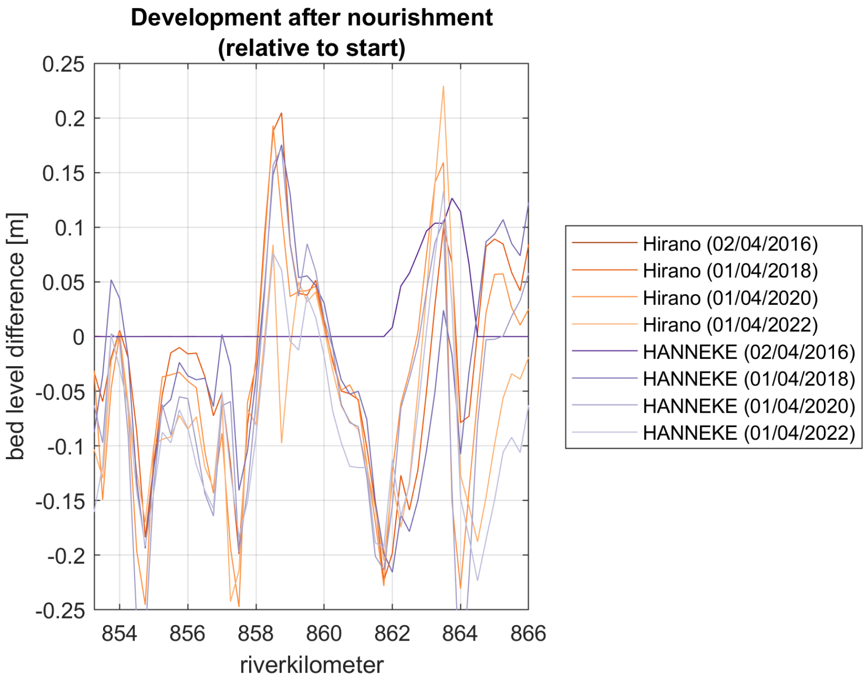


Figure 3.4 Development in the bed level including a nourishment using the Hirano and HANNEKE concepts relative to the initial bed level.

In Figure 3.5 we compare the evolution of the nourishment with respect to the reference model development (each model against their own reference). The Hirano model shows hardly any variation upstream of the nourishment, whereas the HANNEKE model does show this. This evolution, may indicate a transition to a more non-linear behaviour than in the Hirano model. It could also point to an instability in the HANNEKE model. This is also visible and locations 862 and 864, where the nourishment leads to degradation relative to the reference (which shows aggradation locally, cf. Figure 3.2).

The relative difference in bed level between the HANNEKE and the Hirano concepts is shown in Figure 3.6. Strikingly, the difference in the bed level development between the HANNEKE and Hirano concepts is smaller after the addition of a nourishment compared to the reference situation in Figure 3.3.

Another possibility to evaluate the evolution of the nourishment is to compare the tracer propagation in either case. Starting from the tracer material as depicted in Figure 2.3, its evolution considering the Hirano model is shown in Figure 3.7. The same figure, but then using the alternative model, is shown in Figure 3.8. The Hirano model tends to transport the tracer material slightly faster than the HANNEKE model.

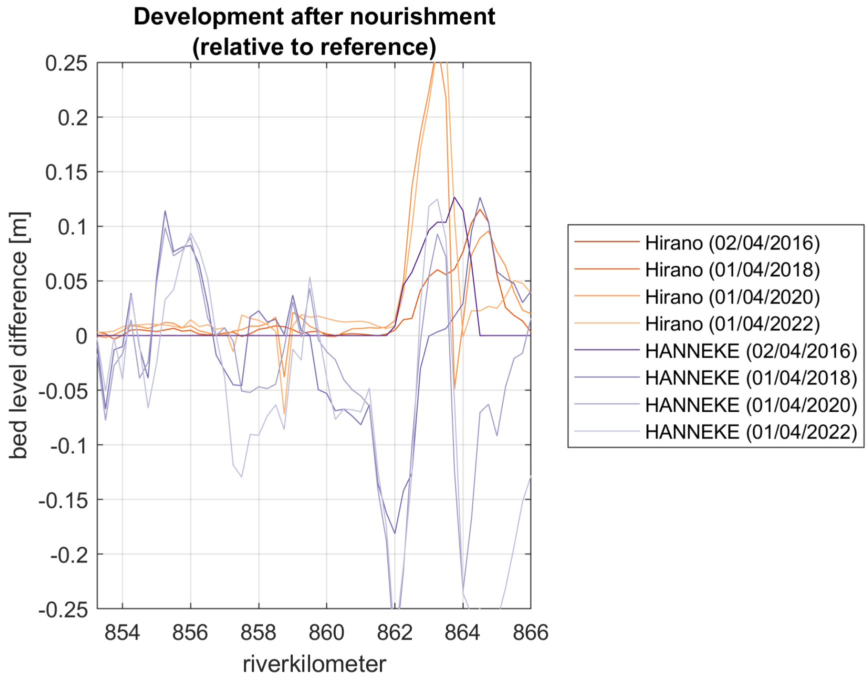


Figure 3.5 Development in the bed level including a nourishment using the Hirano and HANNEKE concepts relative to the reference.

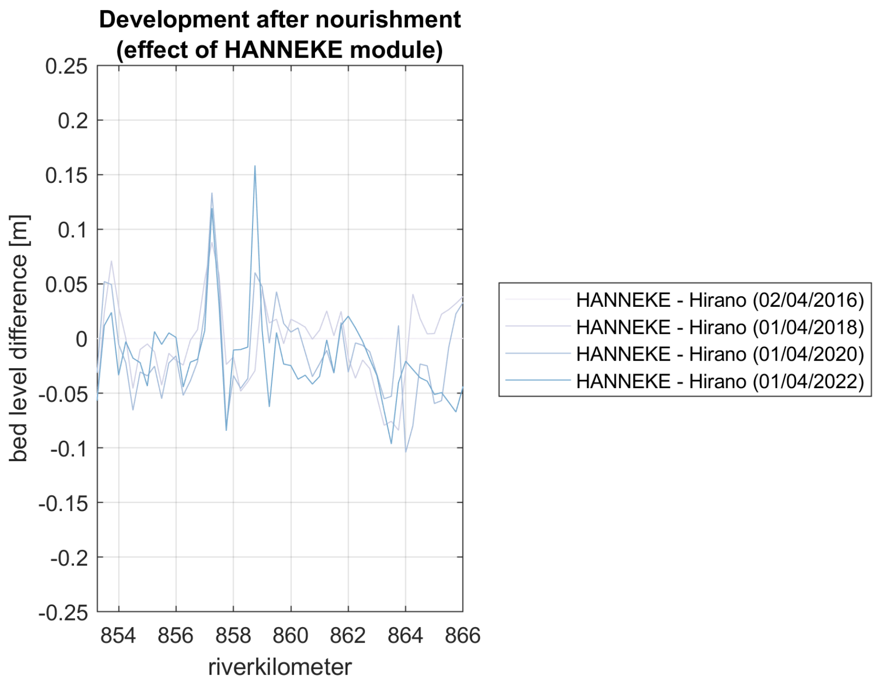


Figure 3.6 Development in the bed level including a nourishment for the HANNEKE module in comparison to the Hirano nourishment simulation.

A strange artefact appears in the Hirano result, namely that some tracer material appears in the right side of the channel (cf. Figure 3.7). This behaviour is not seen when using the HANNEKE module.

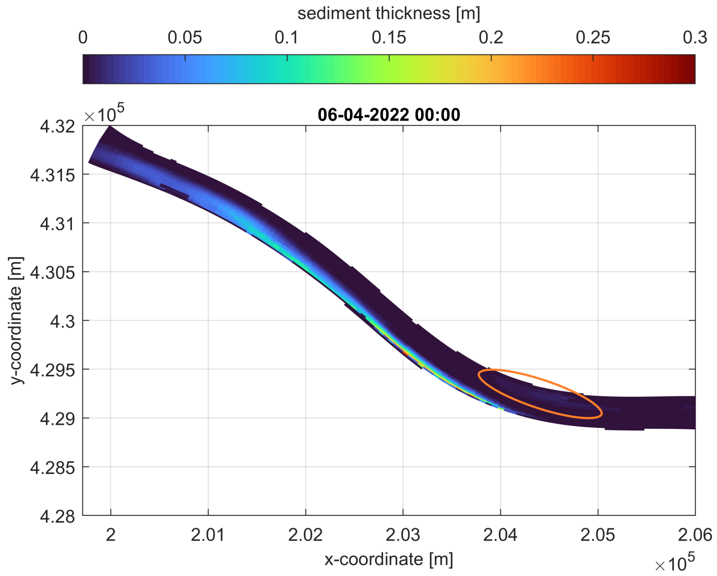


Figure 3.7 Thickness of the 2016 tracer material in 2022 using the Hirano concept. The orange ellipse shows the presence of tracer at an unlikely location.

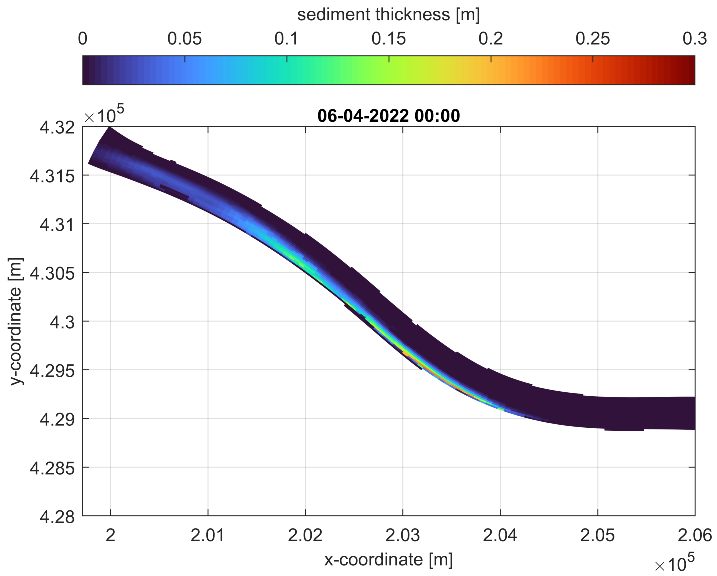


Figure 3.8 Thickness of the 2016 tracer material in 2022 using the HANNEKE concept

In 2019 a second nourishment was performed. The material was evenly distributed to the location shown in Figure 2.5. In 2022 the material had moved downstream, and the resulting location for both modelling concepts is shown in Figure 3.9 and Figure 3.10 for the Hirano and HANNEKE models, respectively. The propagation of the second nourishment is similar in both cases.

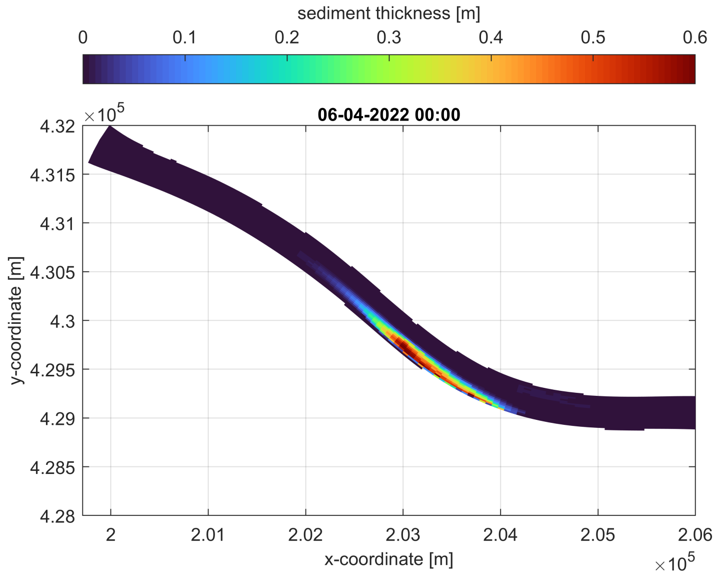


Figure 3.9 Thickness of the 2019 tracer material in 2022 using the Hirano concept

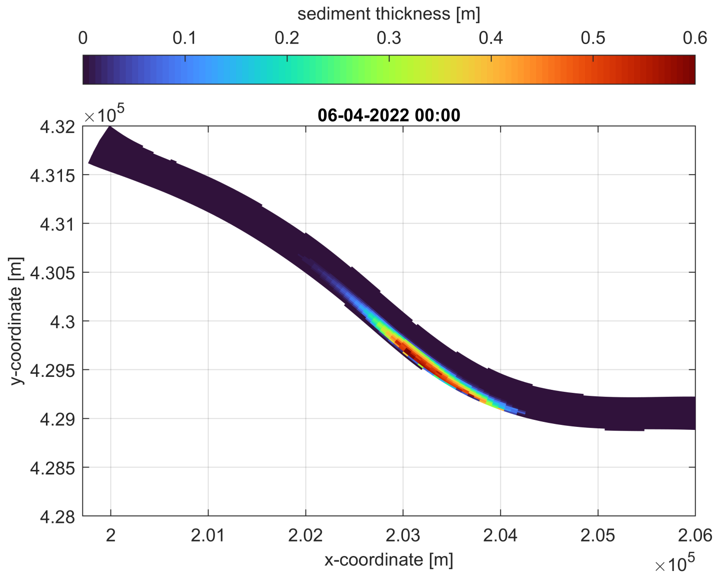


Figure 3.10 Thickness of the 2019 tracer material in 2022 using the HANNEKE concept

Figure 3.11 shows the initial thickness of sediment with a grainsize larger than 8 mm. The propagation using the Hirano and HANNEKE model are shown in Figure 3.11 and Figure 3.13, respectively. The results show that coarse material moves less far downstream when using the HANNEKE module compared to the Hirano module.

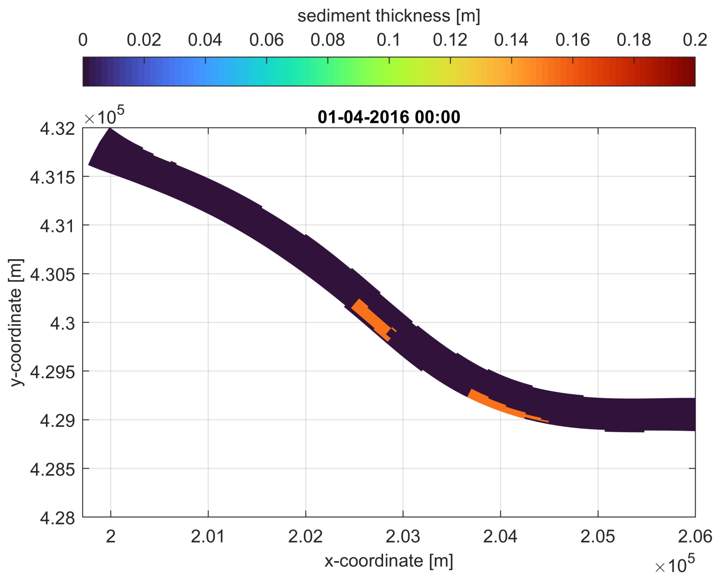


Figure 3.11 Initial sediment thickness of fractions coarser than 8 mm.

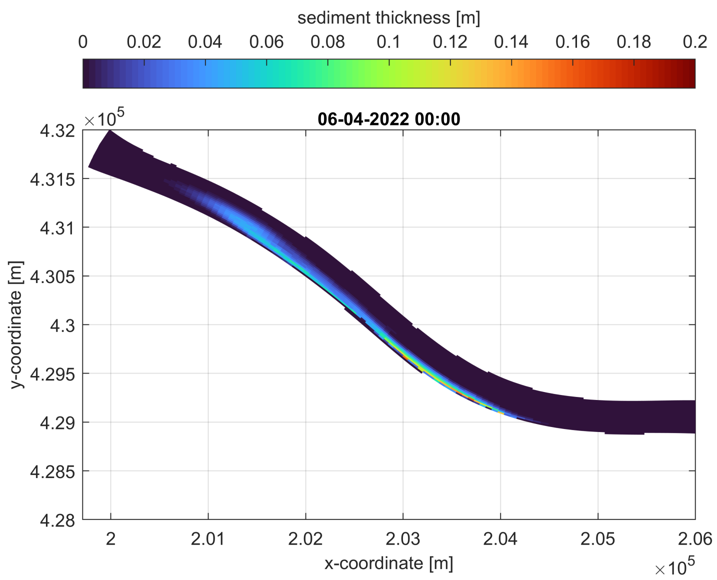


Figure 3.12 Sediment thickness of fractions coarser than 8 mm using the Hirano module on the 1st of April 2022.

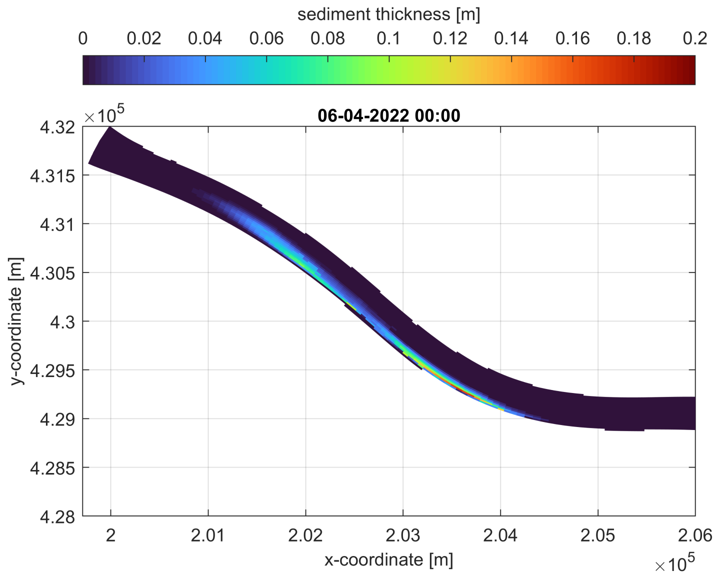


Figure 3.13 Sediment thickness of fractions coarser than 8 mm using the HANNEKE module on the 1st of April 2022.

This behaviour is assessed further by taking a slice along a transect of the nourishment. Figure 3.14 shows the initial fraction content of the 2016 tracer material. The vertical distribution after six years in 2022 is shown in Figure 3.15 and Figure 3.16 for both modelling concepts. The results show that using the HANNEKE module relatively more nourished material ends up deeper in the substrate. The same analysis for material coarser than 8 mm shows a similar behaviour. Upon closer inspection of the software, the HANNEKE model contained a hard-coded Shields' threshold of mobility of 0.047, whereas in the Hirano model a value of 0.025 is prescribed. This implies that relatively more sediment is considered immobile when using the HANNEKE model.

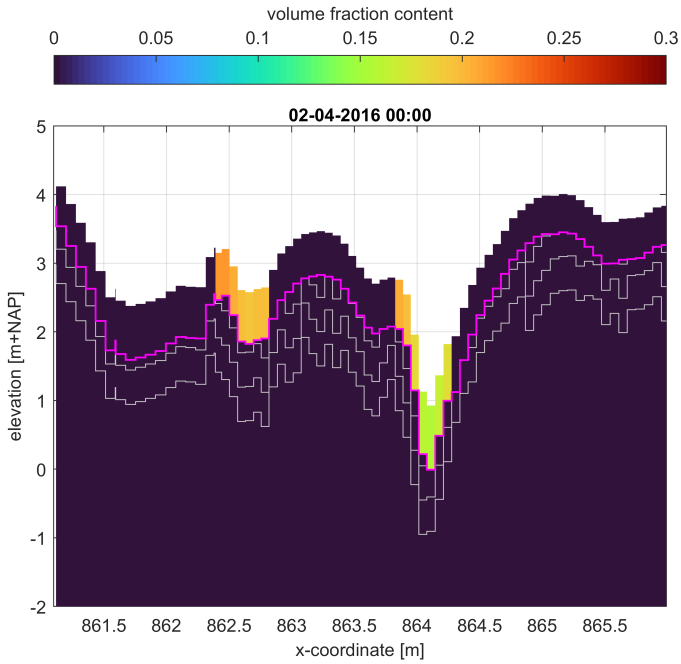


Figure 3.14 Sediment fraction of fractions finer than 8 mm using the Hirano module on the 2nd of April 2016 along the transect of the nourishment.

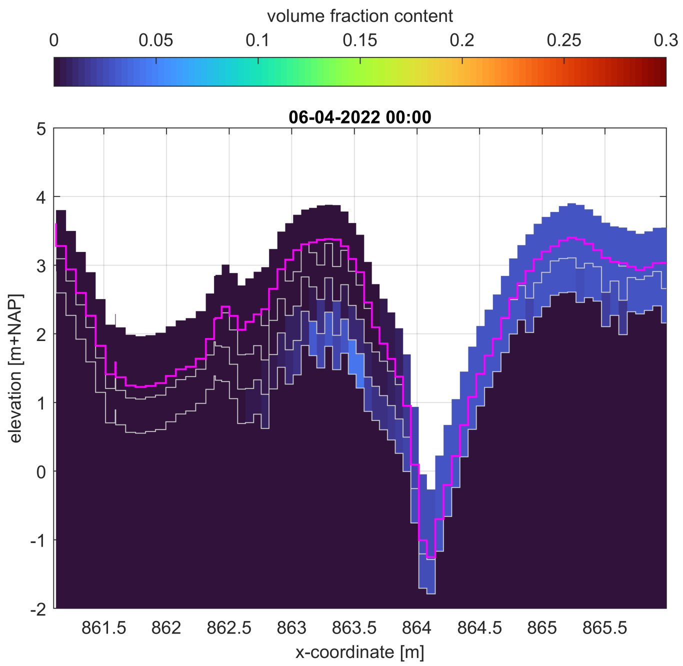


Figure 3.15 Sediment fraction of fractions finer than 8 mm using the Hirano module on the 1st of April 2022 along the transect of the nourishment.

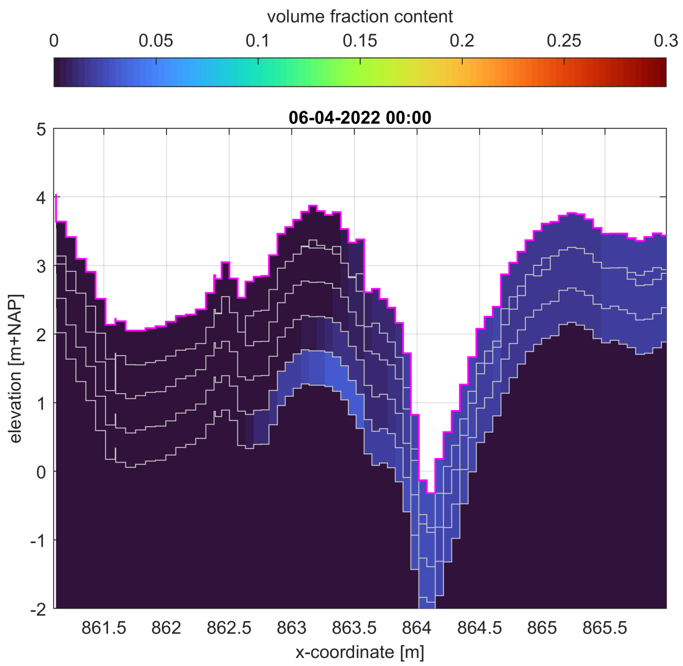


Figure 3.16 Sediment fraction of fractions finer than 8 mm using the HANNEKE module on the 1st of April 2022 along the transect of the nourishment.

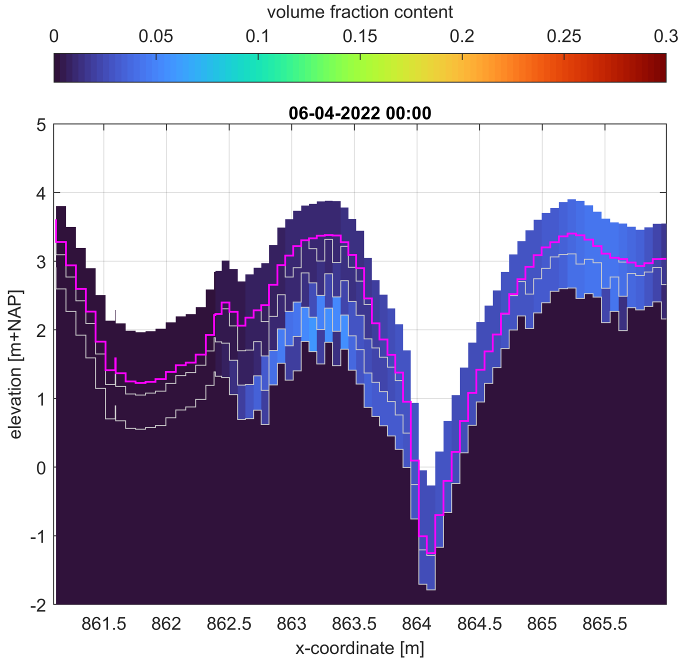


Figure 3.17 Sediment fraction of fractions coarser than 8 mm using the Hirano module on the 1st of April 2022 along the transect of the nourishment.

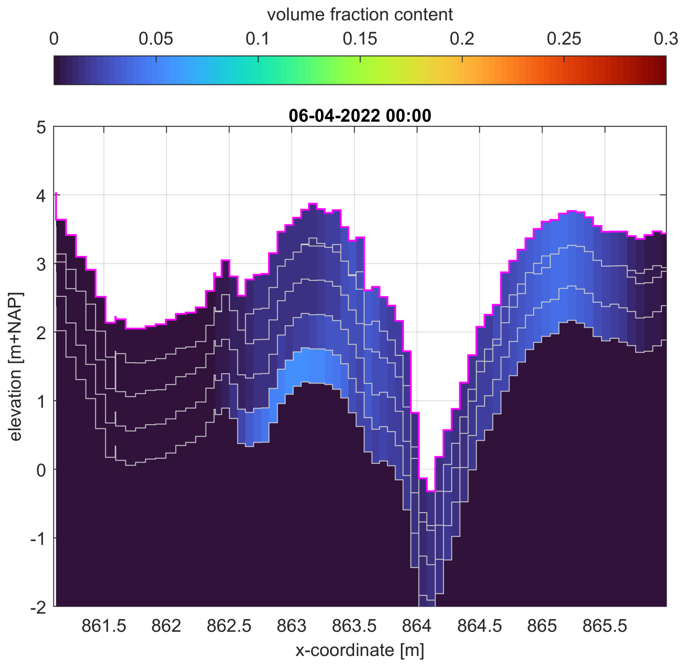


Figure 3.18 Sediment fraction of fractions coarser than 8 mm using the HANNEKE module on the 1st of April 2022 along the transect of the nourishment.

3.4 Fixed layer at Spijk

At Spijk a fixed layer is present in the Bovenrijn (river kilometres 860.5 - 862.0). This is modelled as a real fixed layer, and therefore lacks sediment below the surface. The bed level evolution for both modelling concepts is shown in Figure 3.19 and Figure 3.20, respectively. The difference in bed level evolution between the two concepts is shown in Figure 3.21. The HANNEKE concept shows a slight sedimentation trend compared to the standard Hirano approach. The sedimentation is likely because there is relatively more immobile sediment in the HANNEKE model. We expect that by reducing the Shields stress to the value used in the transport model, will lead to similar results between the different models.

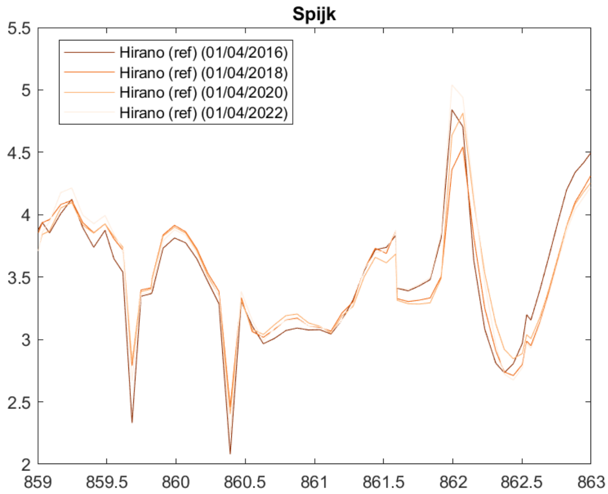


Figure 3.19 Evolution of the bed level at Spijk using the Hirano approach

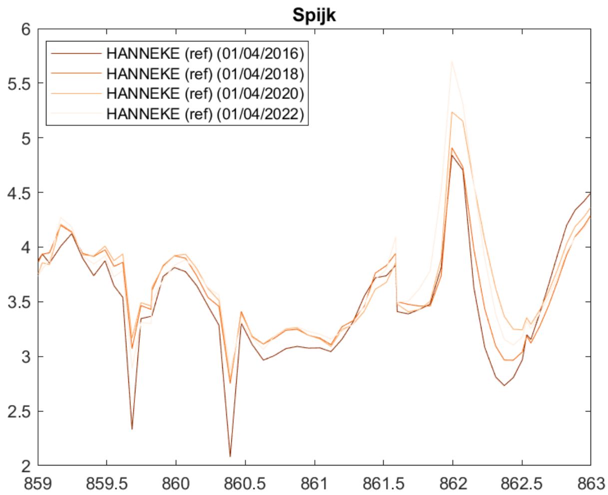


Figure 3.20 Evolution of the bed level at Spijk using the HANNEKE approach

The fraction of sand for the Hirano and the HANNEKE model is shown in Figure 3.22 and Figure 3.23. The behaviour of both models is shown to be similar, yet the top layer has more sand in the HANNEKE concept compared to the Hirano approach.

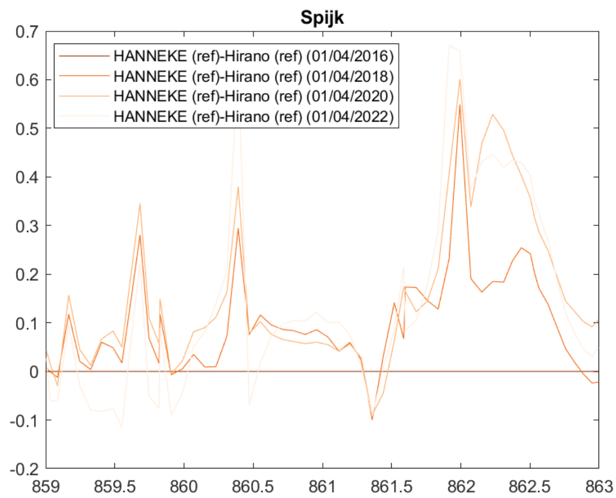


Figure 3.21 Difference in bed level evolution between the HANNEKE and Hirano approaches.

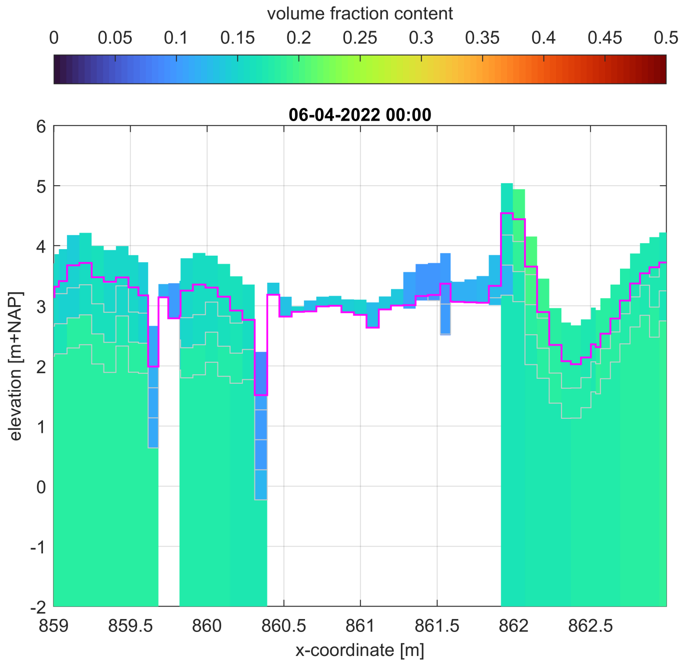


Figure 3.22 Sand fraction on the 1st of April 2022 using the Hirano approach.

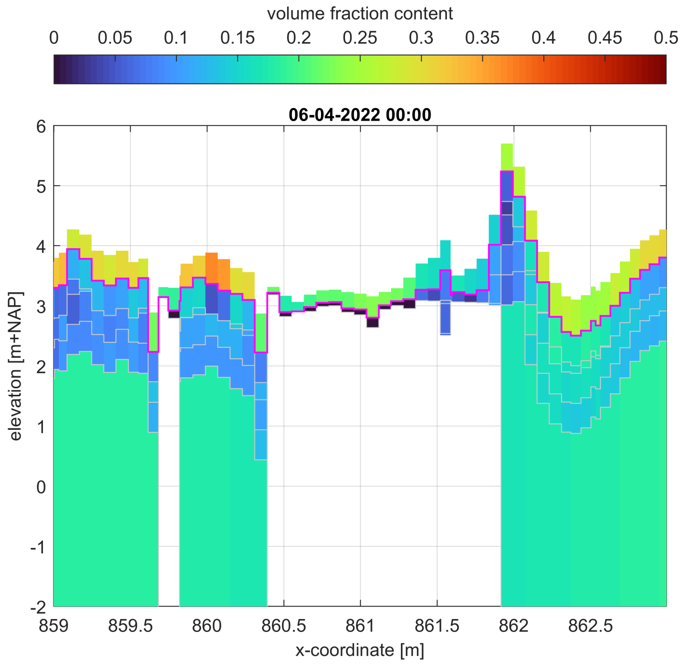


Figure 3.23 Sand fraction on the 1st of April 2022 using the HANNEKE approach.

4 Discussion

The HANNEKE module is applied to a real-world-situation nourishment and compared to the Hirano model. The simulation which runs slightly faster than the standard Hirano module completes the full run without crashing. The reason for the increase in speed may be explained by the more recently compiled executable for the HANNEKE module. It is recommended to evaluate the evolution of the Hirano module using the recently compiled executable of the Hirano module too. Furthermore, inclusion of inactive dredging to have the 2019 nourishment may be the reason for the increase of simulation time with respect to the nourishment. It would be be good to verify there is no extra overhead if the dredging is switched on but not being used.

The autonomous bed level development not considering a nourishment shows a relative sedimentation when the HANNEKE model is used compared to the Hirano model (cf. Figure 3.3). Two main reasons can be identified for this. The first is that, upon closer inspection of the source code of the HANNEKE module, a hard coded critical Shields' stress of 0.047 is found for discerning between mobile and immobile sediment for exchange with the coarse layer, although the sediment transport rate is computed with a critical bed shear stress equal to 0.025 (as when applying the Hirano model). This presumably implies that intermediate-size sediment can be transported under reduced transport conditions, and as a temporal effect will have a portion which gets moved downwards into the coarse layer. An hypothesis is that this combination leads to relative aggradation. This is however not easy to verify using a field scale model.

Secondly, but likely of less importance, is that the transport during low flows is computed slightly differently. In the Hirano case the transport of fine sediment is limited by its relative portion in the active layer. In the case of the HANNEKE model the transport computed by the relative availability in the active layer is further limited by the Struiksma (1999) factor (which is defined as the ratio of the active layer thickness and the alluvial active layer thickness). It is recommended to use the critical shields stress based on the transport formula in the HANNEKE module, rather than the hard coded value. In the case of a sediment formula lacking a threshold of motion, the application of the HANNEKE module should result in exactly the same behaviour as the Hirano module.

Often, simulations with a measure can be compared to a reference simulation not including the measure. It appears that the HANNEKE concept leads to a more non-linear evolution, than in the Hirano case. Due to this non-linearity the differences between the simulation including the measure and the simulation without are larger. The reason for this is not immediately apparent. It may also be linked to the transport, but further investigation is necessary. The role of the fixed layer and the growth rate of bars may also be important to consider here.

The evolution of the tracer shows a slightly slower propagation velocity of the tracer material. The reason for this is again linked to the difference in the computed transport.

The discretisation of the subsurface also requires further attention. Both models show that (cf. Figure 3.15 and Figure 3.16) the tracer material is already filled into all the included subsurface layers. The thicker base layer may also include this material, but due to the thickness, tracer information may diluted so strongly it does not appear in the figures. The HANNEKE module appears to have a tracer material available at a deeper level than the Hirano model, but this is probably caused by the fact that the HANNEKE module includes an extra subsurface layer to keep track of the coarse immobile material. It is recommended to further increase the number of the subsurface layers, such that tracer material does not mix with the base layer.

In the simulation with the Hirano concept, tracer material appears upstream of the nourishment. This is not seen in the HANNEKE models. It is not understood what causes this, but this should be investigated thoroughly. The fact that this is seen in the Hirano model and not in the HANNEKE model, may also be linked to the way in which transport is computed at the inflow boundary.

5 Outlook

The current model results were obtained after many iterations, where finally still improvements are required to make the next step. Currently, an unknown appearance of tracer material, and a hard coded value of the critical Shields' stress make it illogical to continue with a further parameter testing in the HANNEKE module. In this outlook we provide steps to further improve the application of the HANNEKE module to a real field case.

The first step is too make a Delft3D 4 issue to investigate the behaviour of the phantom tracer material. In parallel the implementation of the hard-coded critical Shields parameter of 0.047 in the HANNEKE module should be set to a parameter dependent on the transport formula.

When these two issues are out of the way, a comparison of the application using both modelling concepts, using the calibrated settings of Becker (2017), but with more subsurface layers should be performed. When the reference behaviour in the HANNEKE and Hirano models can be explained, we can proceed with the next steps.

Subsequently, it is advised to understand what causes the large differences upstream of the nourishment in the HANNEKE model. This is a location which should not be affected as much as it is in the current simulations.

Another thing which is good to test is the behaviour of the HANNEKE module during only high flow and only low flow in comparison to the Hirano module. For example, during high flow, both modules should provide similar results. It is advised to check whether that is really the case.

When these fixes and checks have been completed, the next steps could be done by conducting a sensitivity analysis varying the parameters of major importance in the HANNEKE and Hirano concepts. These include substrate discretisation, active layer thickness, coarse layer thickness, and various sorting parameters. Upon running these variations, the similarities and differences between both approaches can be properly judged.

It may be interesting to introduce limited sediment availability, by adding relatively more coarse material at certain locations according to a derived parameter analysis (similar to what was done for the Maas, cf. Sieben (2022)). The approach would be to apply a limited sediment availabilty (Hirano) or a relatively coarse substrate, but still including a small part of fine material (HANNEKE) at locations which show smaller bed forms.

Finally, a reanalysis of the data in the study by Gruijters *et al.* (2001) on the grain size distribution at the Pannerdensche Kop, may offer valuable information for further describing the subsurface material at the Pannerdensche Kop accurately. Imposing this sediment information may, however, lead to an ill-posed model behaviour Chavarrías *et al.* (2018) when fine material is present below coarse material at the surface. In this case, it may be worthwhile to extend the research, by including a set of model runs using a regularisation strategy Chavarrías (2019) and the Hirano model, or by adjusting the model input so that it does not get to this ill-posed behaviour.

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A Bed level development (Hirano)

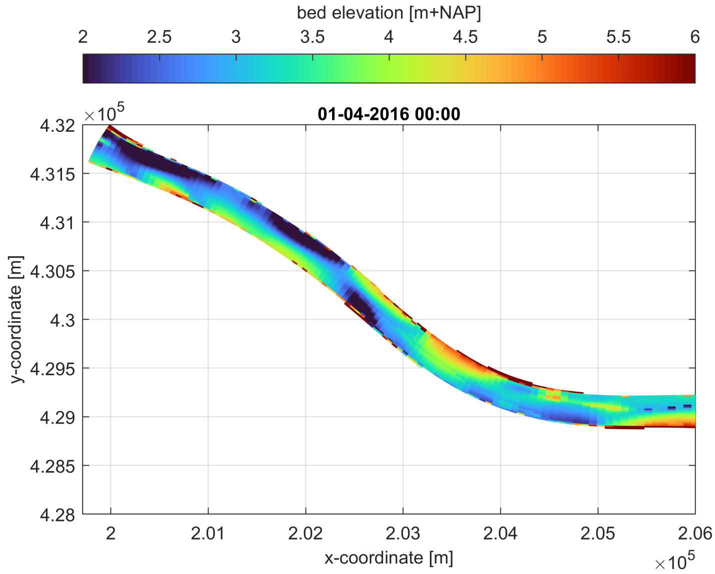

Figure A.1 Bed level at the start of the simulation including a nourishment using the Hirano model

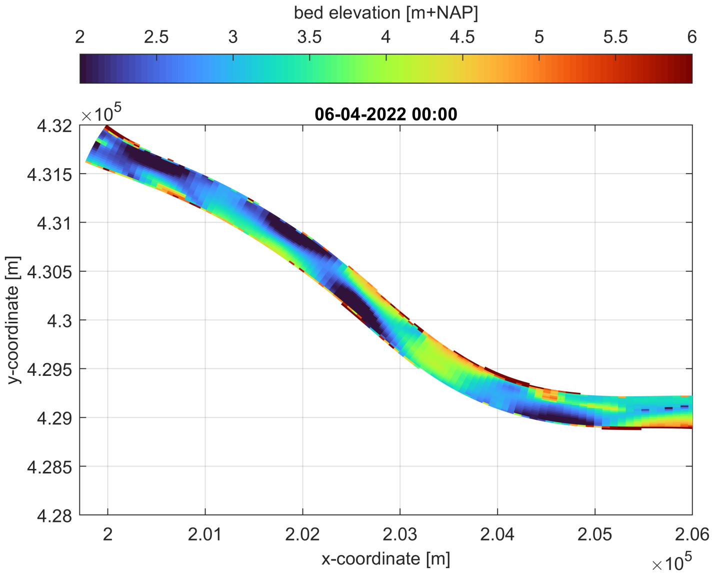

Figure A.2 Bed level at the end of the simulation including a nourishment using the Hirano model

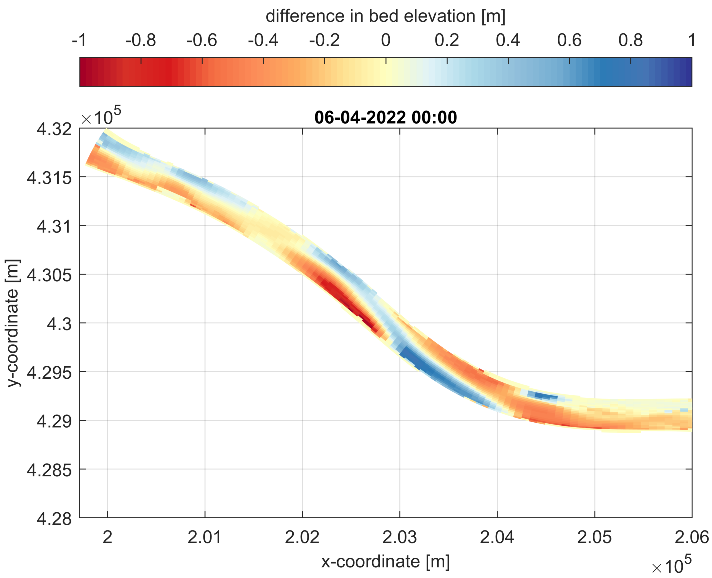

Figure A.3 Final erosion and sedimentation for the simulation including a nourishment using the Hirano model

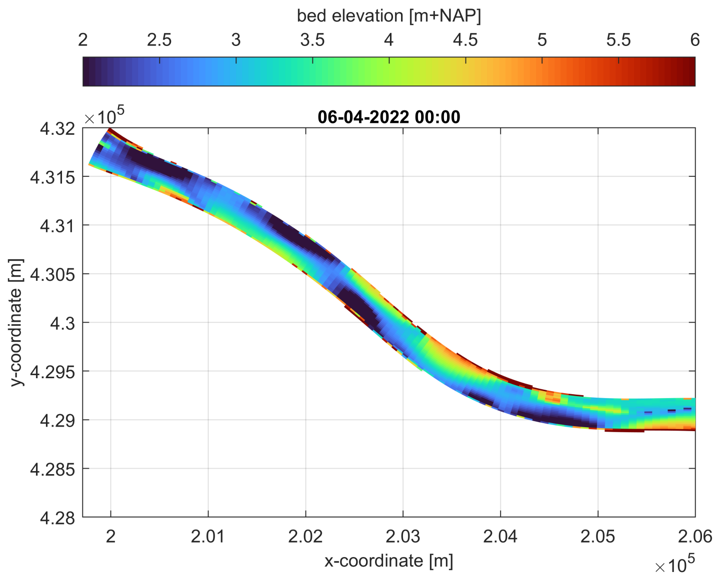

Figure A.4 Bed level at the end of the reference simulation using the Hirano model.

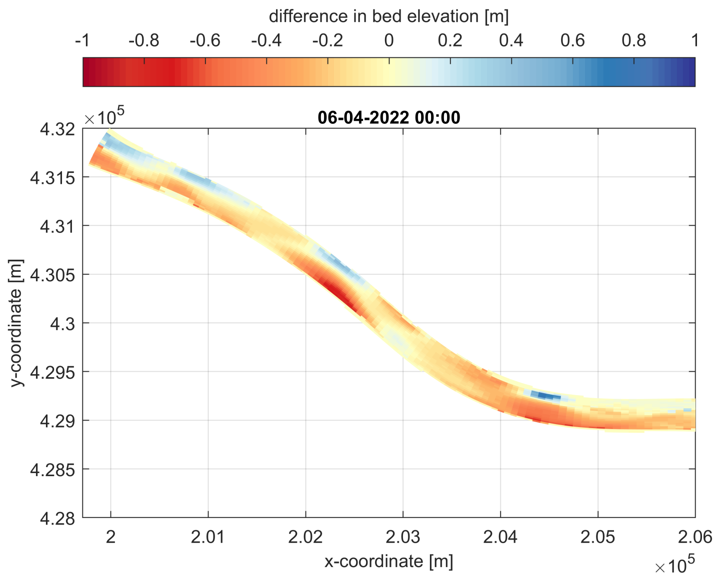

Figure A.5 Final erosion and sedimentation for the reference simulation using the Hirano model

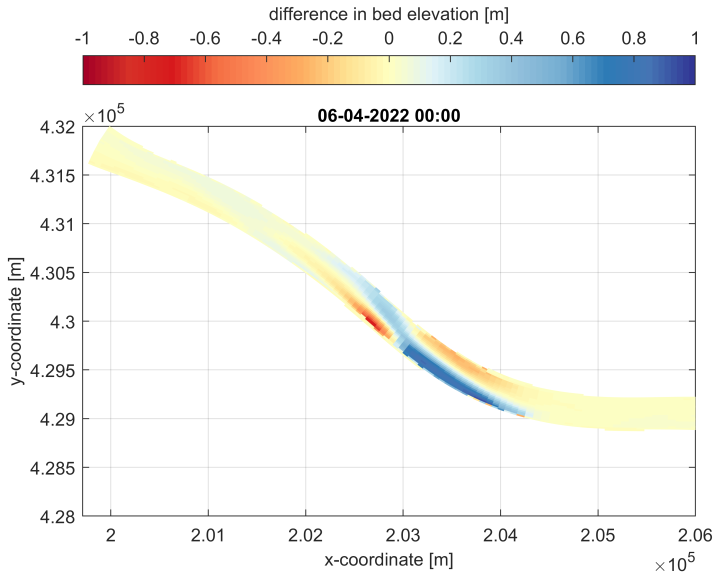

Figure A.6 Final relative bed level change in the simulation including a nourishment using the Hirano model against its reference

B Bed level development (HANNEKE)

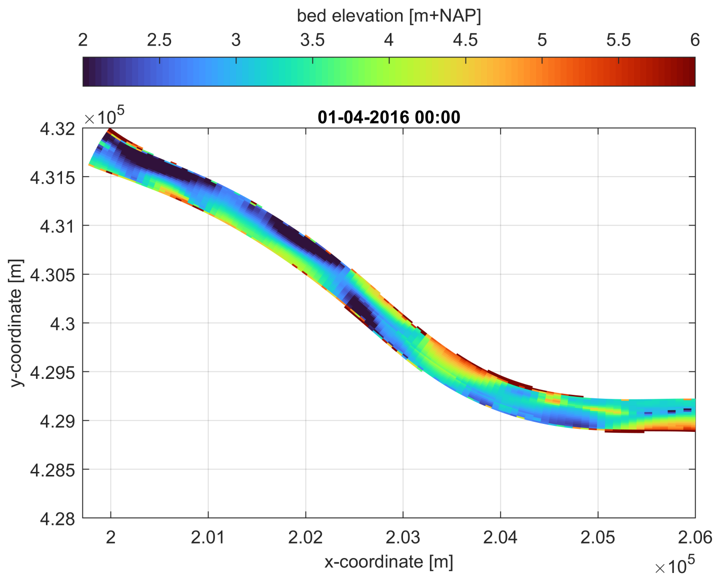

Figure B.1 Initial bed level at the start of the simulation including a nourishment using the HANNEKE model

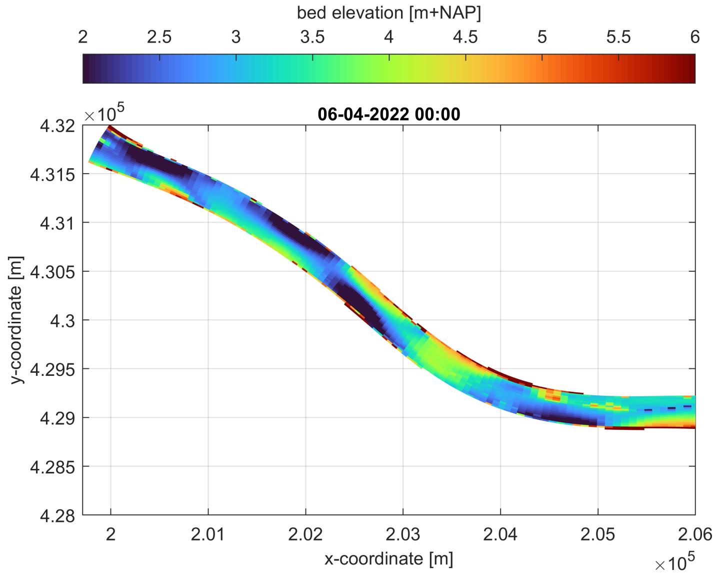

Figure B.2 Final bed level at the end of the simulation including a nourishment using the HANNEKE model

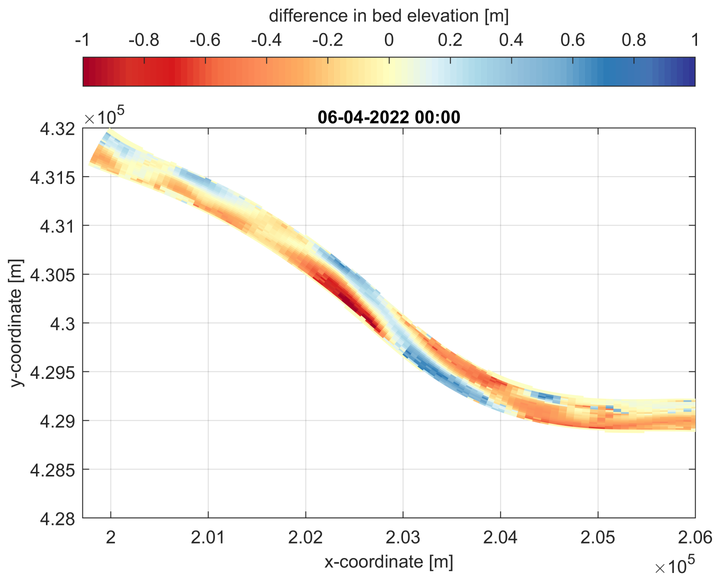

Figure B.3 Final erosion and sedimentation for the simulation including a nourishment using the HANNEKE model

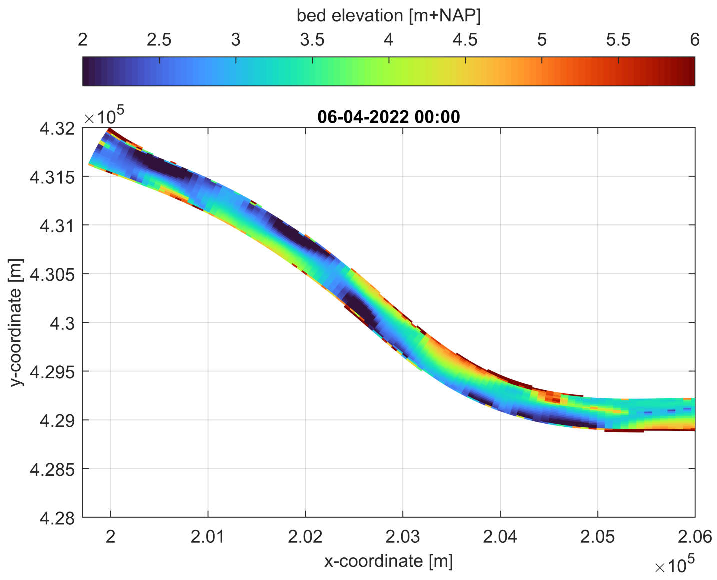

Figure B.4 Bed level at the end of the reference simulation using the Hirano model.

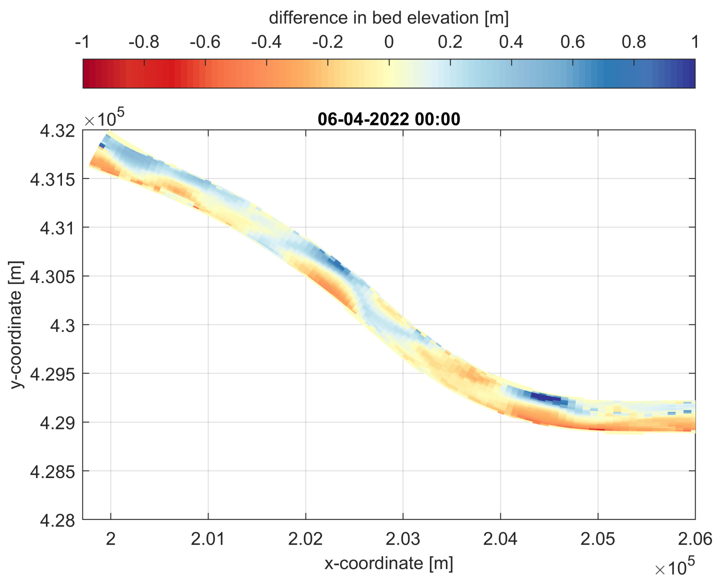

Figure B.5 Final erosion and sedimentation for the reference simulation using the HANNEKE model

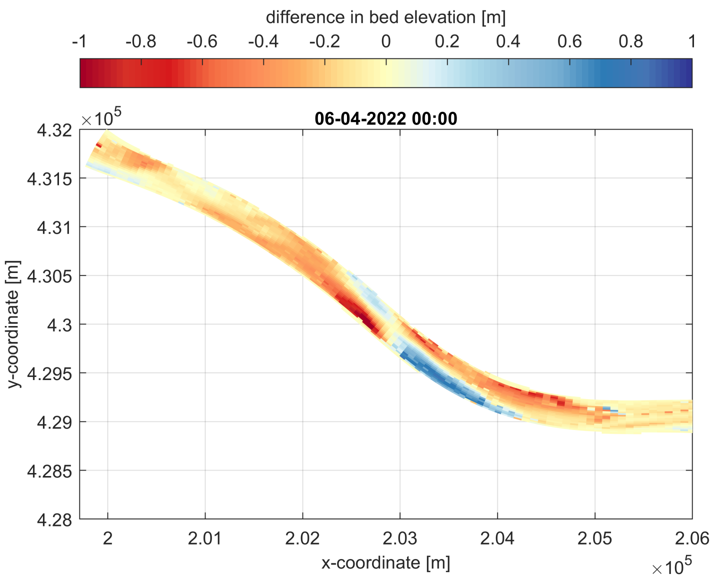

Figure B.6 Final relative bed level change in the simulation including a nourishment using the HANNEKE model against its reference

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