# Modelling the morphological effects of longitudinal dams in the Midden-Waal

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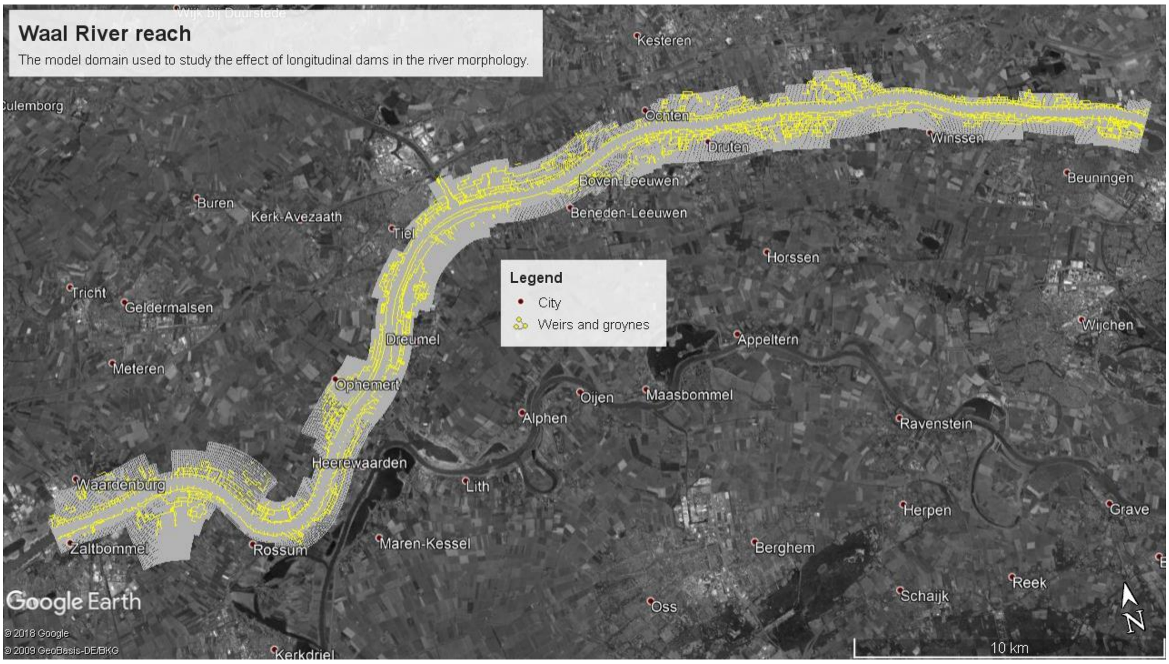

Deltares

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Modelling the morphological effects of longitudinal dams in the Midden-Waal

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**Summary**
The longitudinal Dams have been constructed in the Waal River as a new river training measure to sustain its ecosystem services, navigability and provide more room for the river. In this study, we investigate the effects of the longitudinal dams on the river morphology. Long-term morphological simulations (for 30 years) have been conducted. Many variants have been considered in this study. The main variants are modelling the river reach with and without the dams. Furthermore, variants are defined to investigate the effects of the side channel inlet opening on the flow distribution and river morphology.

The study displays that the longitudinal dams are able to maintain the main channel navigability. However, the current design provides local deposition, in the main channel, downstream km 912, around km 918 and between km 919 to km 921. This deposition may need to be verified and investigated further. The study also shows that the inlet opening influences the morphological changes in main channel and the side channels, especially for the Dreumel and Ophemert reaches. Despite the valuable insights from these results, for more detailed investigation and evaluation of the longitudinal dams in the Midden Waal, some further investigations are recommended.

**References**
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| 1.0 | Nov. 2019 | Amgad Omer | | Kees Sloff | | Gerard Blom | |
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# Contents

# 1 Introduction

## 1.1 Background

Rijkswaterstaat has constructed longitudinal dams in the Waal River. The dam construction was finished at the end of 2014. The longitudinal dams are subdivided into three parts as shown in Figure 1.1 (Wamel, Dreumel and Ophemert). This kind of intervention has an impact on the river hydraulics, ecology and morphology.

In this study, we investigated further the impacts of the dams to the river hydraulics and morphology, based on the study of 2018 (Omer et al, 2019a). The priority is to identify differences with and without the existence of the dams and explain them by analysing of the results. In this study, we focus on setting up and improving the morphological model and perform simulations for validation scenarios. Pinpointing the exact reasons and possible causes of the differences are too complex and extensive to fit in this project. Possible causes are defined based on expert judgement. Many simulations and comparison will be implemented within the “evaluation project”. This evaluation project is a separate project to evaluate the overall performance of the longitudinal dams pilot project in 2020.

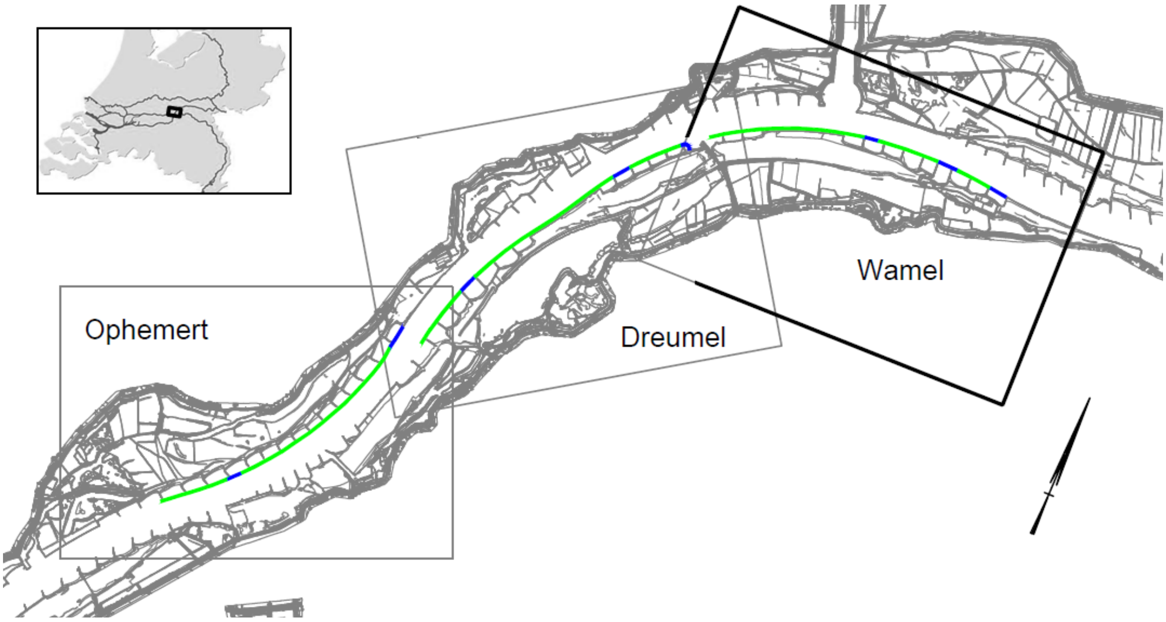



*Figure 1.1 Plan View depicts the study area. The model domain is expected to be from Nijmegen to Zaltbommel.*

This study focuses on the effects of the longitudinal dams to the main channel (zomerbed). Their influence on the riverbed, water level and water depths are examined. It is expected that the morphological effects of the dams need many years to show a considerable effect. Therefore, numerical modelling will be used to predict that.

The model application concerns estimating the effect of longitudinal dams and the potential effect of other factors is expected to be touched or known through model simulations. The most interesting areas are upstream and downstream of longitudinal dams. The Waal model developed last year (Omer et al, 2019a) is a good practical choice to continue the modelling work for these dams.

## 1.2 Objectives

The study provides information and numerical model which can be used for further investigation and scenarios to finalise the evaluation of the performance of longitudinal dams as a pilot project in 2020.

In addition, the study provides scenarios that helps to assess the operation of the longitudinal dams and their impacts over a period of 30 years to:

1 Understand the effects of the longitudinal dams to the change of bed level, water level and the maintenance of the navigation channel.
2 Evaluate the differences with and without the longitudinal dams with respect to a) Hydrodynamic factors (e.g. water levels, discharge distributions), b) Morphological factors (e.g. bed level changes, local sediment deposition).
3 Give insight into the performance of the inflow openings of the side channels.

## 1.3 The approach

To Investigate the morphological effects of the longitudinal Dams, the following steps are considered:

1. The Waal model of Delft3D4 (Omer et al, 2019a) is used in this study. Delft3D4 has the simulation management tool (SMT) which allows us to provide the 30 years morphological results in acceptable computation time. Nevertheless, Delft3D4 has only the Tabellenboek to simulate the weirs, while Delft3D-FM has other approaches, in addition to the Tabellenboek, like the analytical solution or the Villemonte empirical approaches for the simulation of weirs. Those are not available in Delft3D4 software. Given the study approach, the possibility to use SMT is more important than the weir approach as the focus is more on the long-term behaviour of the river bed next to the longitudinal dams rather than the detailed hydrodynamic behaviour of groynes. Therefore, the Delft3D 4 model is used for this assignment.
2. Model Improvement: The model is improved as follows
   I. The model grid is refined to improve its performance to capture more detailed features. This is implemented where is needed within the model domain to execute the steps below. However, reasonable computation time is always a constraint, the refinement is bounded to that.
   II. The model is extended to include sediment. The spatial sediment distribution $d_{50}$ used is like the distribution presented in Omer et al, 2019a. This spatial sediment distribution is a result of the calibration process implemented for the DVR-model (Yossef et al, 2008b). The morphological parameters are tuned to improve model performance. Spin-up model of ten years is conducted to provide the model with an initial bed topography that suits its schematization. The resulted bed after 5 years is used as initial bed of the simulations since the local bed variations have more or less stabilised after that. The “Modified Van Rijn 1984” transport formula is used in this study.
3. After the model was improved, four main variants were simulated:
   a. **V0**: a morphological simulation without the longitudinal dams for 30 years of simulation time. This model has the schematization of the river reach before the dam construction (e.g. the replaced groynes). The scenario includes the bed topography of the spin-up simulation. The schematization is generated using the baseline Rijn_j14_5-v1.
   b. **V1**: a morphological simulation with the longitudinal dams for 30 years of simulation time. This scenario is used to generate the reference case of the longitudinal dams’ variant. The initial bed and the boundaries are like V0. The openings of the side channels and the schematization are obtained from the baseline Rijn_j18_5-v1.

c. **V2**: This simulation is like V1, but with completely closed inflow inlets openings to the side channel.
d. **V3:** This simulation is like V1 except for the inflow openings to the side channel. They are obtained from the as-built survey of longitudinal dams that is implemented directly after their construction.
e. **V4**: This scenario is like V1 but includes river maintenance (dredging and dumping). The current management regulations of the river bed level are included in this simulation, to ensure the required water depth along the navigation channel. In RHDHV simulations of the Waal river, an assumption is made that if the depth of water at a location is less than 2.8 m then the model dredges this location to obtain the depth of 2.8 m. However, this assumption might not be considered by the dredger in reality. Because in most of the time, the dredger may dredge to a deeper depth (overdiepte) to make sure that he does not have to return the next time step in case bed-levels recover quickly. The dredged materials are dumped (by the model) within 1 km upstream or downstream of the location. If there is no deeper location within the 2 km, then the model dumps the dredged materials outside the model domain.

4. Based on the above-mentioned scenarios, analyses are conducted to understand the impact of the longitudinal dams of the Waal River reach. The analyses provide information about water and bed levels changes and their impact on the navigation of the main channel and-or the channel maintenance. The exchange of discharge between the side and the main channels is useful for various environmental reasons. However, with respect to minimizing the side-channel discharge, it might be beneficial to navigation if discharge is kept in the main channel during the low flow season.

## 1.4 Outlines

This report discusses the outcome of a subproject within the 'KPP Rivierkunde' project. The main aim of this project is to prepare a suitable model that can be used for the final evaluation of the longitudinal dams' project in 2020.

Chapter 1 discusses the introduction, chapter 2 provides information about the hydrodynamic model. Chapter 3 displays the morphological model setup and the spin-up simulation. The results of the morphological simulations have been discussed in Chapter 4. The findings are deliberated in Chapter 5 and in chapter 6 some conclusions and recommendation are provided. The project is executed under KPP program of 2019. Anke Becker acts as a project leader from Deltares side.

# 2 Hydrodynamic modelling

## 2.1 Model setup

### 2.1.1 Grid refinement

The model grid is refined to improve the model resolution around the longitudinal dams. The new grid is shown in the upper plot of Figure 2.1. The model domain starts around Nijmegen and ends at Zaltbommel (from rkm 887.95 to rkm 934.7). The grid has been refined to a resolution of (5 × 20) m at the longitudinal dam area. The resolution gradually increases further away from the area of interest. This grid has 136,382 cells (79 cells in M-direction×1406 cell in N-direction). It was decided not to reduce the grid size even further to limit the computation time to an acceptable and workable value. The resolution is sufficient to be able to reproduce the relevant morphological features and a realistic reproduction of the geometry of the dam and secondary channels.

### 2.1.2 Model schematization

In this study two bassline schematizations are used:

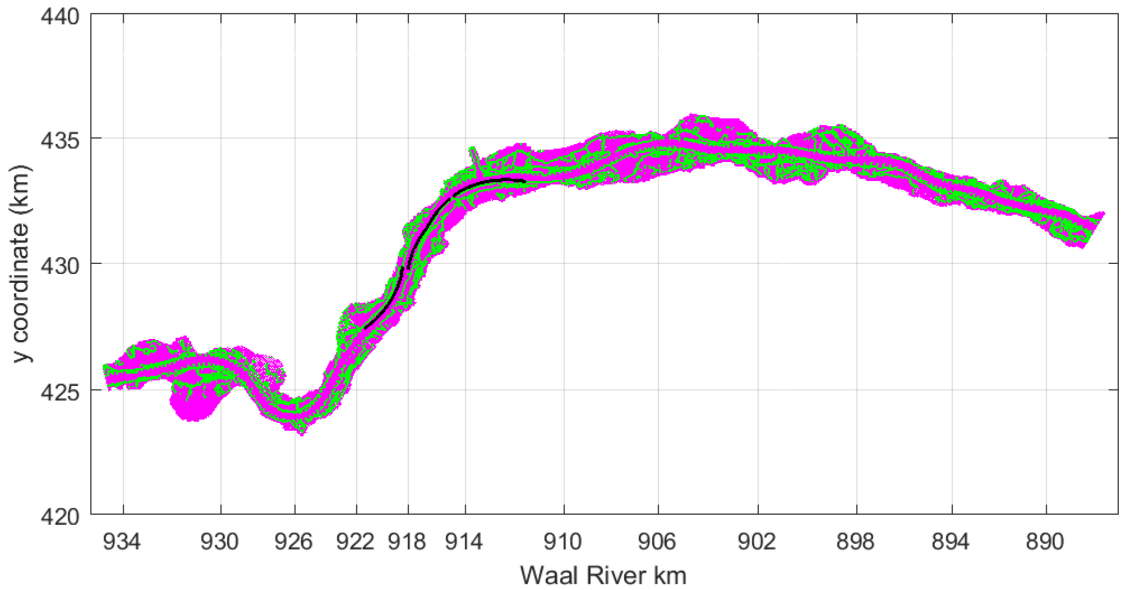
- Baseline Rijn-j14 is used to generate the model schematization of the simulation that represents the condition before building the longitudinal dams (V0).
- Baseline Rijn-j18 is used to generate the model schematization of the simulations that represent various conditions after building the longitudinal dams (V1 ~V4).

Figure 2.2, Figure 2.3 and Figure 2.4 illustrate cross-section profiles of the models topography at km 914 (it includes Wamel Dam), 918 (it includes Dreumel Dam) and 920 (it includes Ophemert), respectively. The figures show how the cross-sections of the dams are projected on the grid (V1~V4). They also depict the bed level before the longitudinal dams' implementation (V0).

### 2.1.3 Boundaries

*Upstream Boundary*

In order to simulate 30 years of morphological development within the model domain. The simulation management tool (SMT) is used to Facilitate that. SMT is a tool developed by Deltares to accelerate the morphological computation time using discrete discharge steps, a database with initial flow conditions for each discharge step, and acceleration with large morphological factors. To use the tool for the Rhine branches the unsteady river hydrograph (statistically average of the past decades) is converted to a step hydrograph as illustrated in Figure 2.5. Before using the SMT, a database file must be created that should include the initial hydrodynamic conditions of every discharge value (Q1, Q2, Q3, etc) from Figure 2.5. These initial files will be used by the SMT as "restart files" when the relevant discharge computation starts. These restart files are updated in the database while the model is running. The communication procedure between the sub-simulations controlled by the SMT is shown in Figure 2.6.



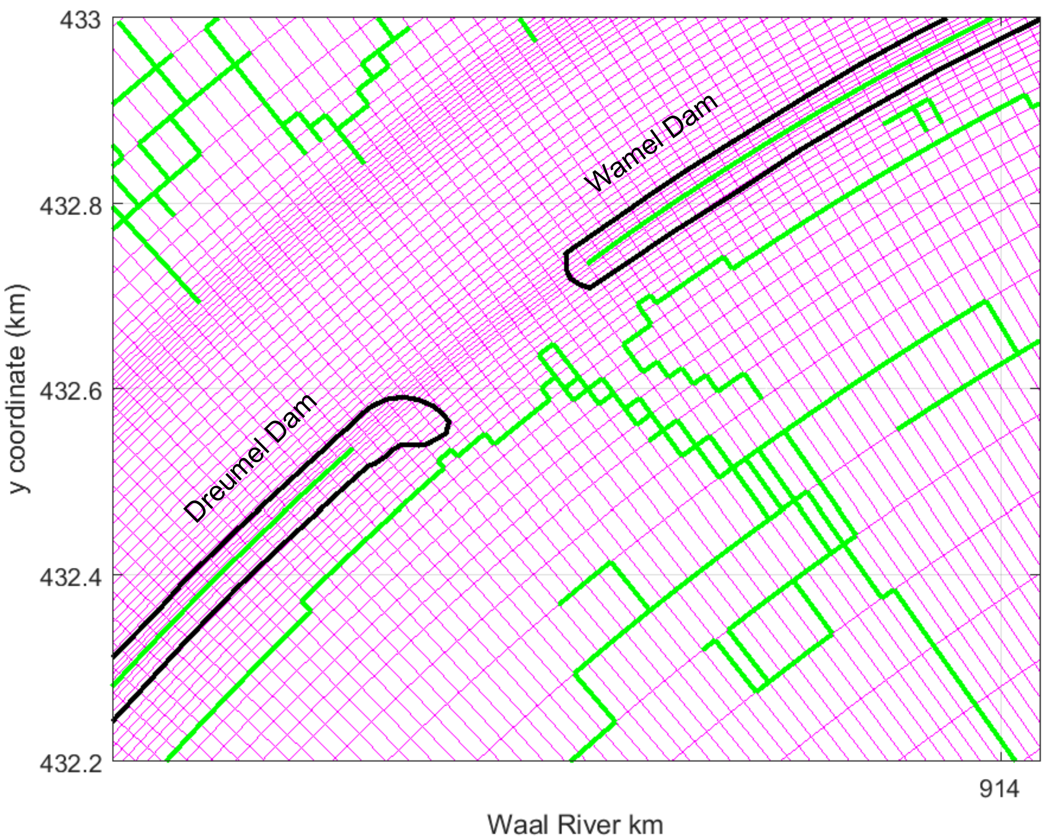




*Figure 2.1 The refined grid of the Waal river Reach. The upper plot shows the model domain grid, while the lower plot illustrates the grid resolution downstream at a location km 914. The blackline is the toe line of the dams. The green lines are the weirs.*

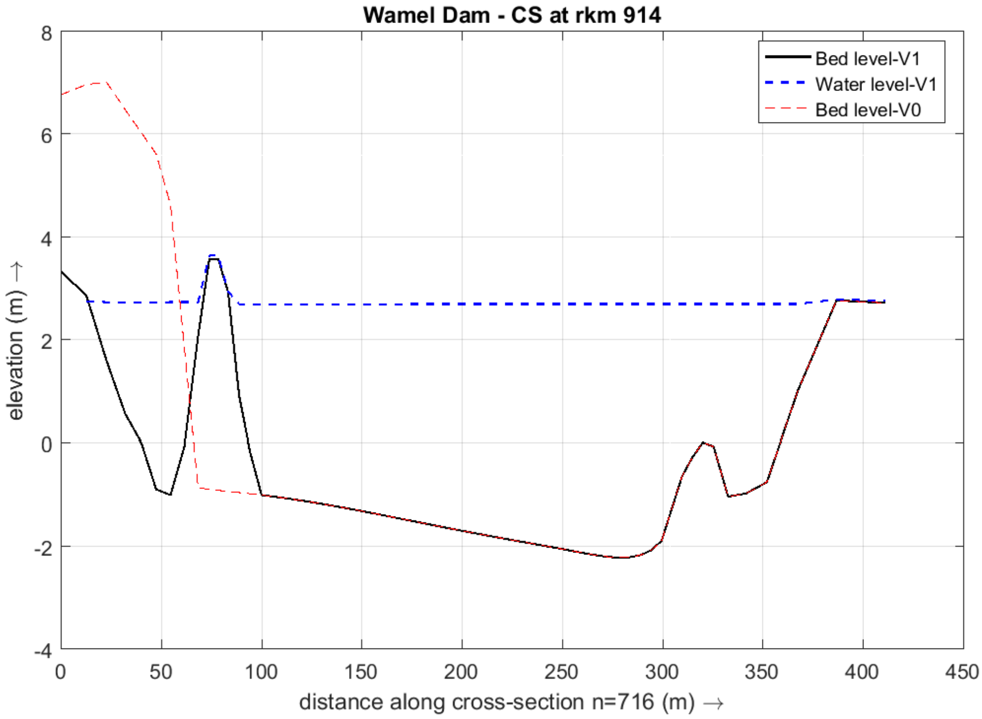



*Figure 2.2 The river cross-section at km 914 (see upper plot of Figure 2.1) in the model topography of V0 and V1.*

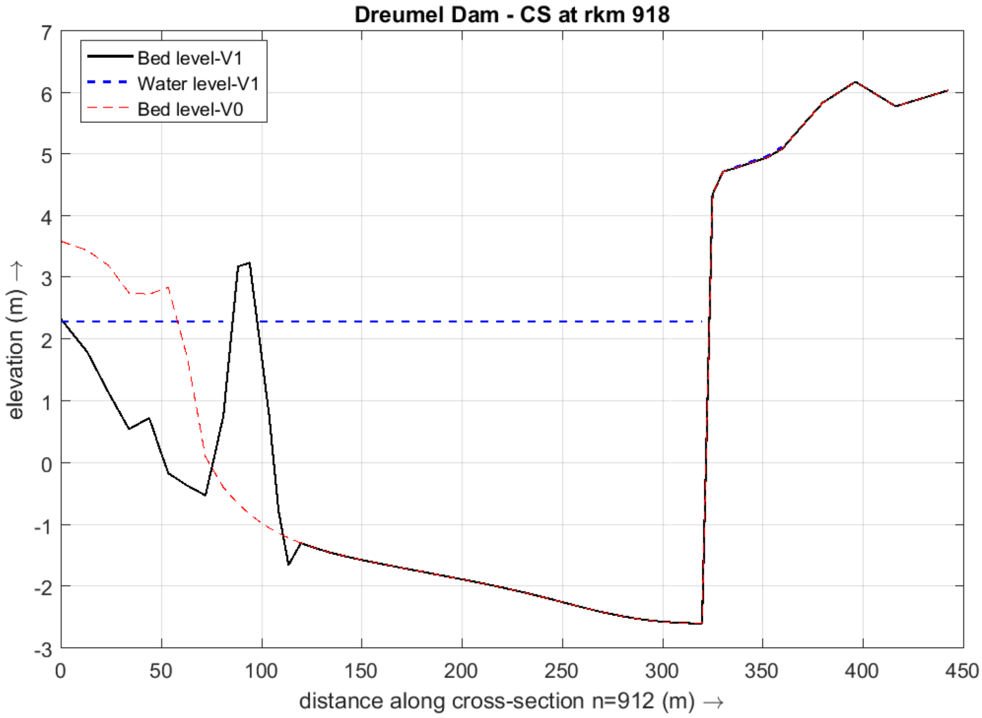



*Figure 2.3 The river cross-section at km 918 (see upper plot of Figure 2.1) in the model topography of V0 and V1.*

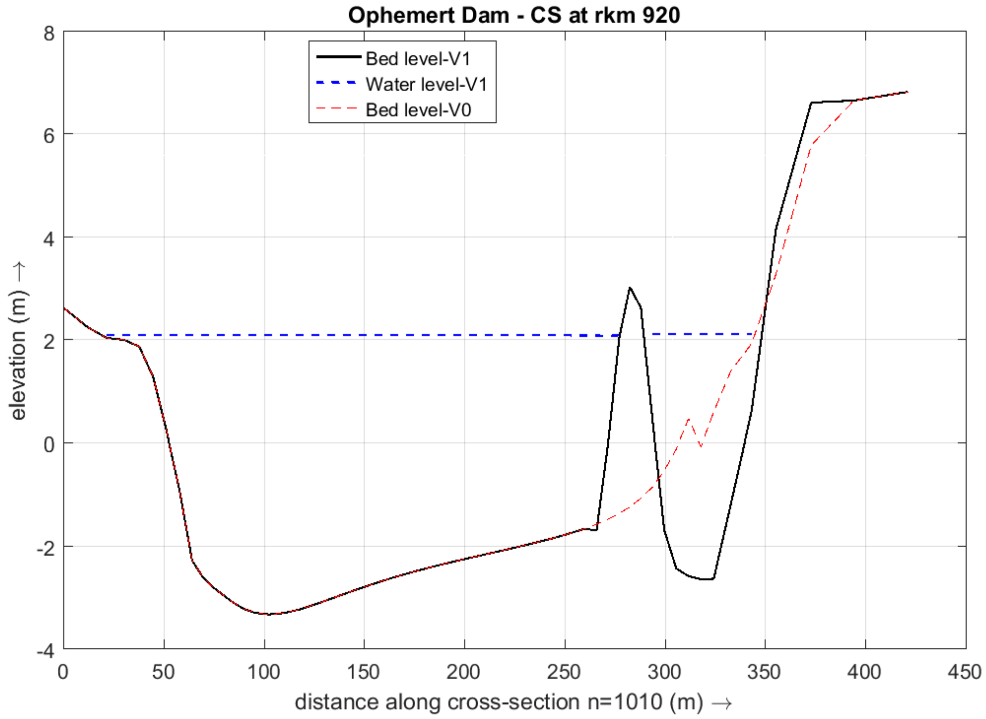



*Figure 2.4 The river cross-section at km 920 (see upper plot of Figure 2.1) in the model topography of V0 and V1.*

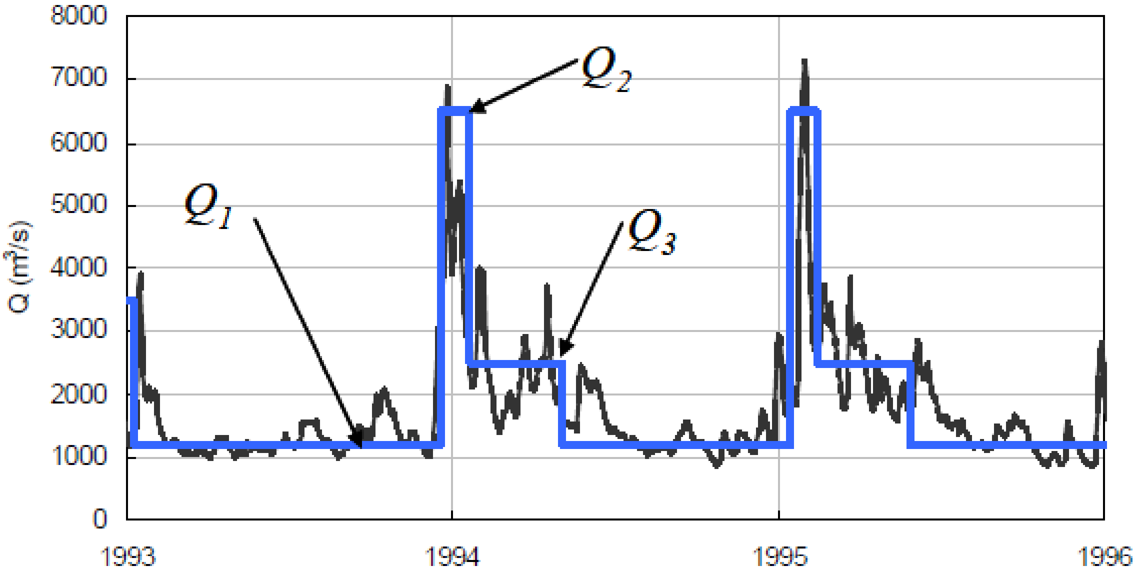



*Figure 2.5 The adaptation of a measured hydrograph to step hydrograph in order to be used by the SMT.*

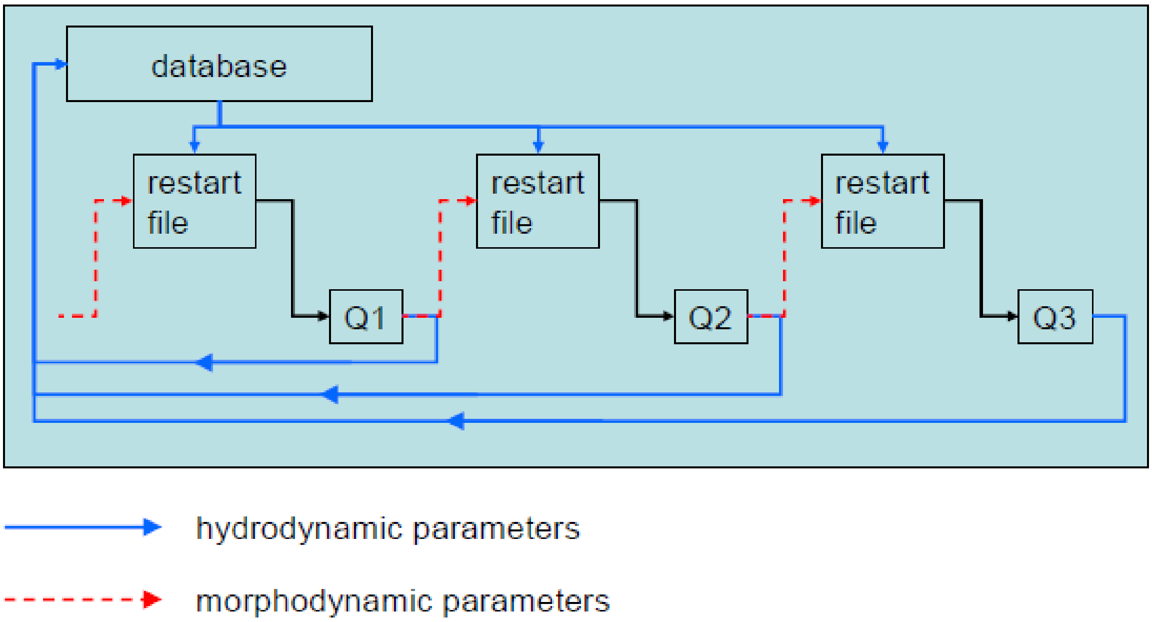



*Figure 2.6 The communication procedure between the sub-simulations and the database inside the SMT.*

In this assignment, we used the step hydrograph of the Waal River shown in Figure 2.7 as upstream inflow boundary. The step-hydrograph was constructed from the discharge duration curve which was derived from the Waal discharge time series of 1961 ~2001. An initial hydrodynamic spin-up run has been conducted for every discharge value in this step hydrograph to create the database file.

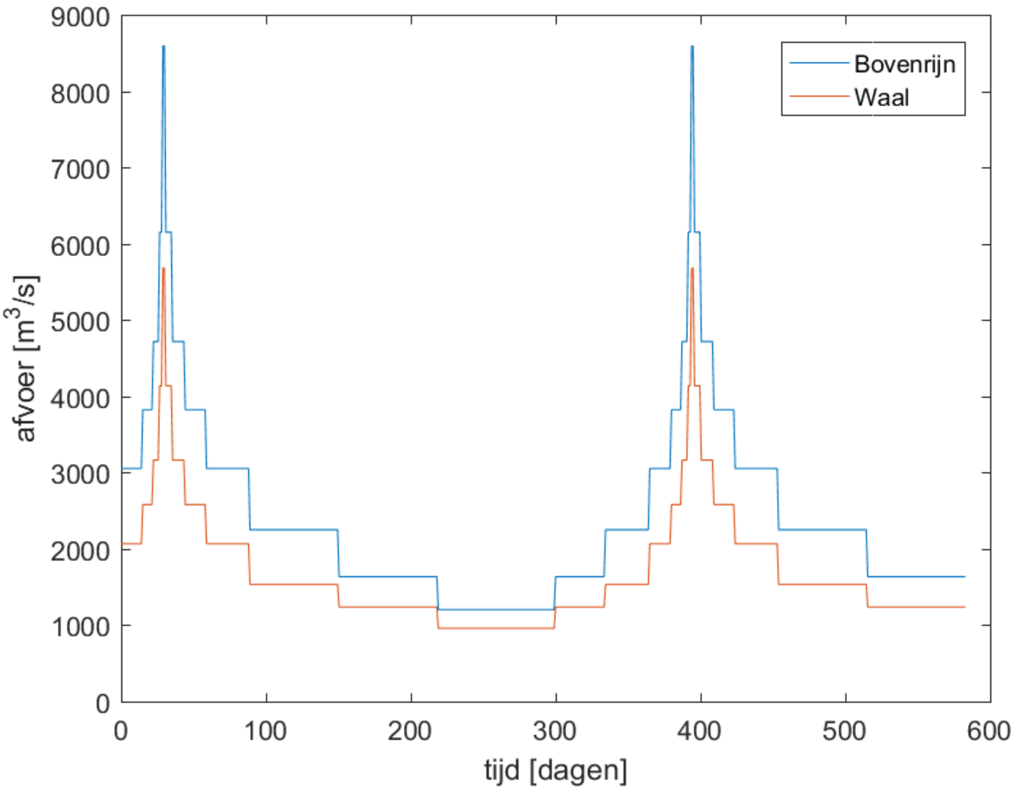



*Figure 2.7 The step hydrograph discharge of the Waal River and the Bovenrijn River.*

*Downstream Boundary*
*The downstream boundary used is the QH-relation of Zaltbommel (Omer et al, 2019a).*

The hydrodynamic model setup and roughness used in Omer et al (2019a) is applied in this model.

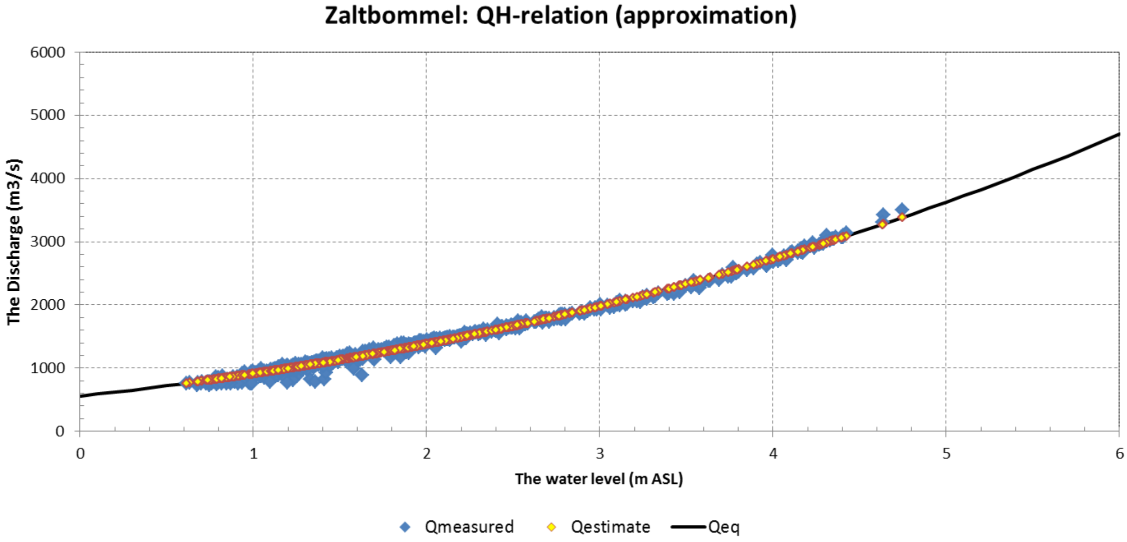



*Figure 2.8 The estimated QH-relation of Zaltbommel station (Omer et al, 2019a)*

## 2.2 Discharge distribution

*The model is used to validate the discharge distribution between the main channel and the side channels of the three longitudinal dams. Steady-state discharges of 1,039 m³/s and 2,592.5 m³/s are used as inflow boundary. At these discharges, some measurements are conducted in October 2017 and January 2018, respectively (Omer et al, 2019a). The results of the discharge distribution along the longitudinal dams are recorded during the simulations and shown in Figure 2.9 for Q1039 and in Figure 2.10 for Q2592.5. The figures display the discharge distribution between the main channel and the side channel at the longitudinal dams' reach. The dam' locations can be distinguished based on the river kilometre as shown in table 2.1.*

*Table 2.1 The longitudinal dams location based on the river kilometre*

| Longitudinal Dam Name | The dam location |
|---|---|
| Wamel | Between km 911.5 and km 914.5 |
| Dreumel | Between km 914.5 and km 918 |
| Ophemert | Between km 918.5 and km 921.5 |

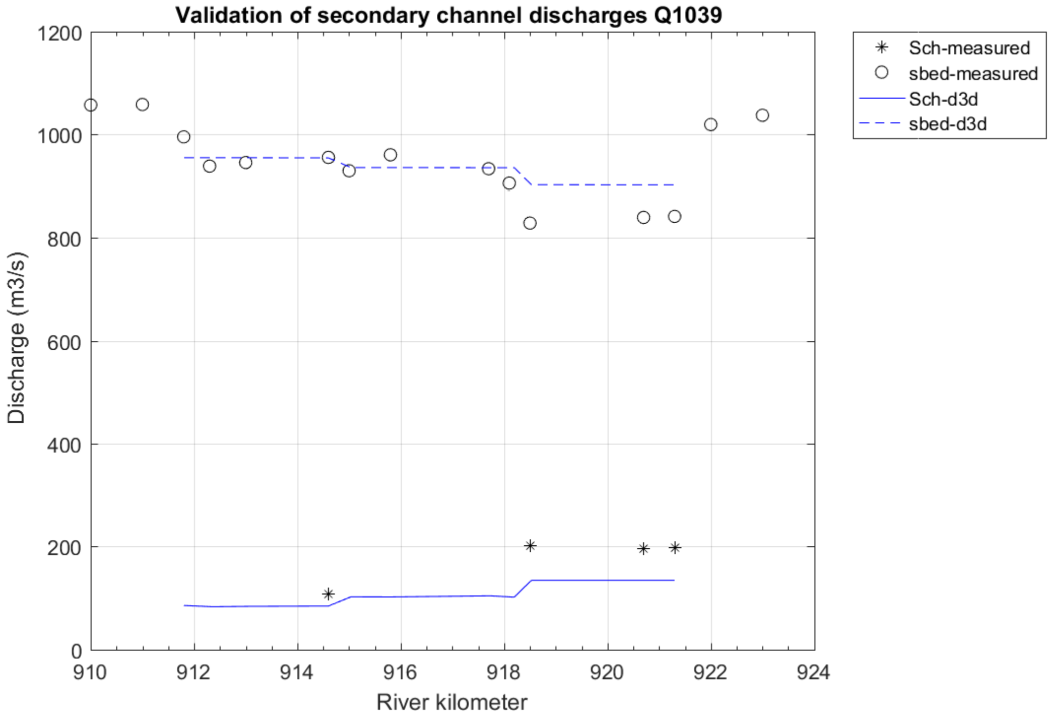



*Figure 2.9 The discharge distribution between the main and secondary channel for low water discharge (1039 m3/s). The "Sch" refers to the secondary channel, whereas "sbed" is the main channel*

In Figure 2.9, the results for the simulation with 1039 $m^3/s$ have been compared to the measured data. These are the low-flow conditions in which the dams are emerged, and inflow to the side channels is determined by the entrance geometry and weirs. The discharge distribution is considered relatively well simulated with respect to side channels of the dams at Wamel and Dreumel. However, the model underestimates the discharge passes to the side channel of the dam at Ophemert. This means further tuning is required to ensure a proper discharge passes through Ophemert channel during the low flow discharges.
However, since the long-term morphological trends are the main objective of the study, we decided to use the available resources on the morphological spin-up and tuning rather than the hydro-tuning of the model.

In Figure 2.10, the results for the simulation with 2539 $m^3/s$ have been compared to the measured data. The model is considered to provide a sufficiently good match of the simulated discharges to the measurements of the main channel and the side channel. This means the model performs well enough when discharges provide submerged condition for the dams (Bank-full discharge).

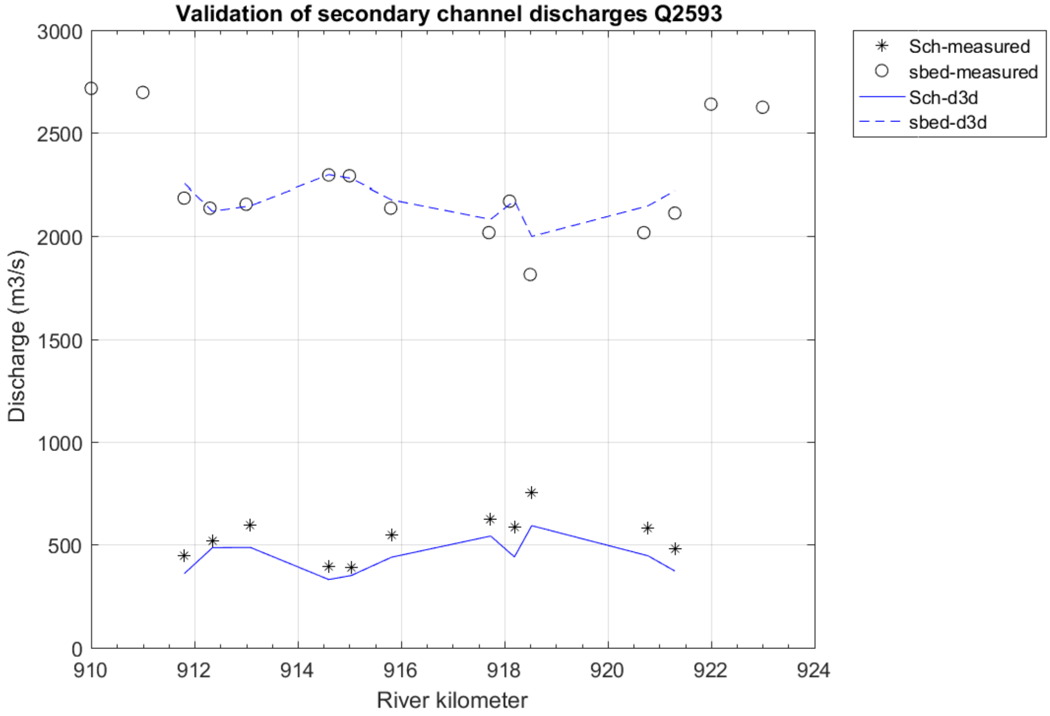



*Figure 2.10 The discharge distribution between the main and secondary channel for low water discharge (2592.5 m3/s). The “Sch” refers to the secondary channel, whereas “sbed” is the main channel.*

# 3 Morphological modelling

## 3.1 The morphological setup

The hydrodynamic model is extended to include sediment in the same way as used in the DVR models for this reach. One sediment fraction is used. The spatial distribution of d50 of the sediment used in the model (see Figure 3.1) is obtained from the DVR model. The spatial grain size (d50) is a result of the morphological calibration conducted in the study of 2008 (Yossef et al, 2008b). This sediment spatial distribution fraction is used in all simulations.

The initial bed composition of the sediment layer is shown in Figure 3.2. In this figure, the bed of the river main channel and the groyne fields are erodible (alluvial), while the river banks are schematized as being non-erodible. The model domain also includes the fixed layer located in the outer bend close to Sint Andries as indicated in the baseline Rijn_j14_5-v1. Non-erodible bed is schematised by using an initial sediment thickness of zero meter. Since we use two schematizations of for simulations (baseline j14 and j18, with and without the dams), the sediment thickness has a different schematization at the location where the longitudinal dams are located. Figure 3.4 illustrates the difference between the initial sediment thickness for the simulation without the dams and the simulations with the dams, representing a different layout of the non-erodible parts. In figure, the following are indicated as fixed/non-erodible layer:

1 The longitudinal Dams
2 The groynes.
3 The bed protection over the cables in the secondary channel (Wamel, km 914).
4 The relicts of groynes in the secondary channels.

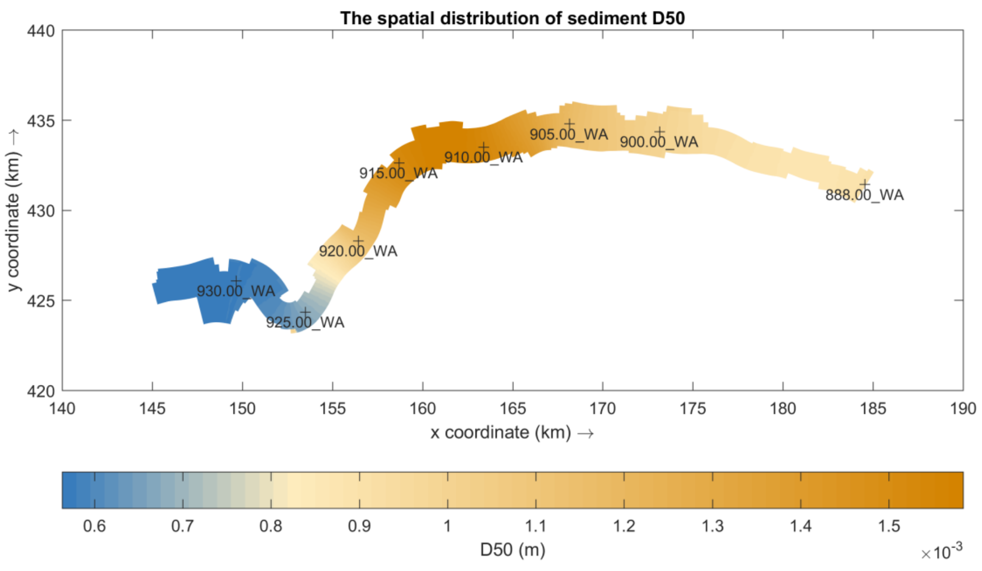



*Figure 3.1 The spatial varying of sediment (d50) within the model domain.*

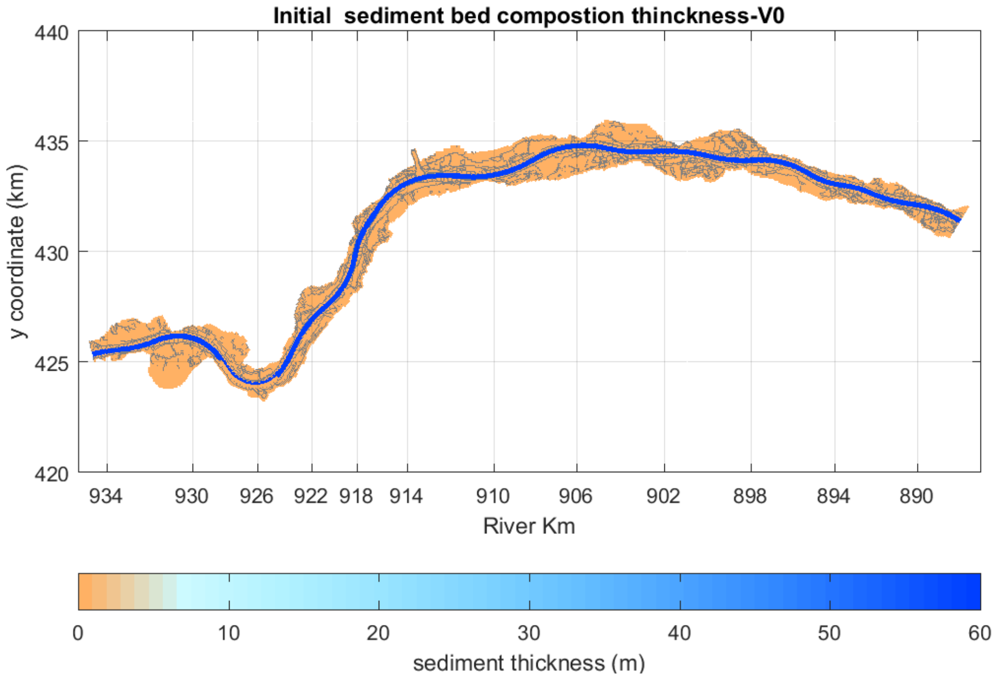



*Figure 3.2 The initial sediment bed composition at the model bed*

The Modified Van-Rijn 1984 sediment transport formula is used in these simulations. The morphological factor (Morfac) used depends on the discharge inflow (see Figure 3.3). In Figure 3.3. The Morfac varies between 120 during high water season to 1440 during the low flow season. These high values are acceptable since the hydrodynamics are approached as quasi-steady. Other morphological parameters of the model are obtained from the previous study (Omer et al, 2019a).

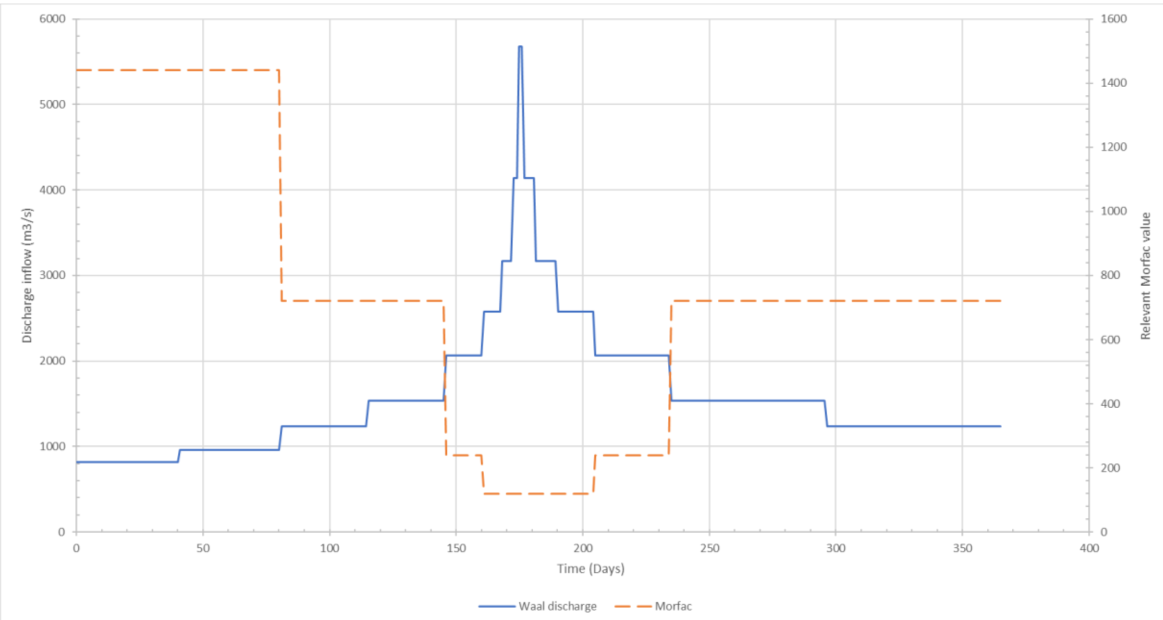



*Figure 3.3 The inflow discharge and the relevant morphological factor used in the simulation management tool for one typical year.*

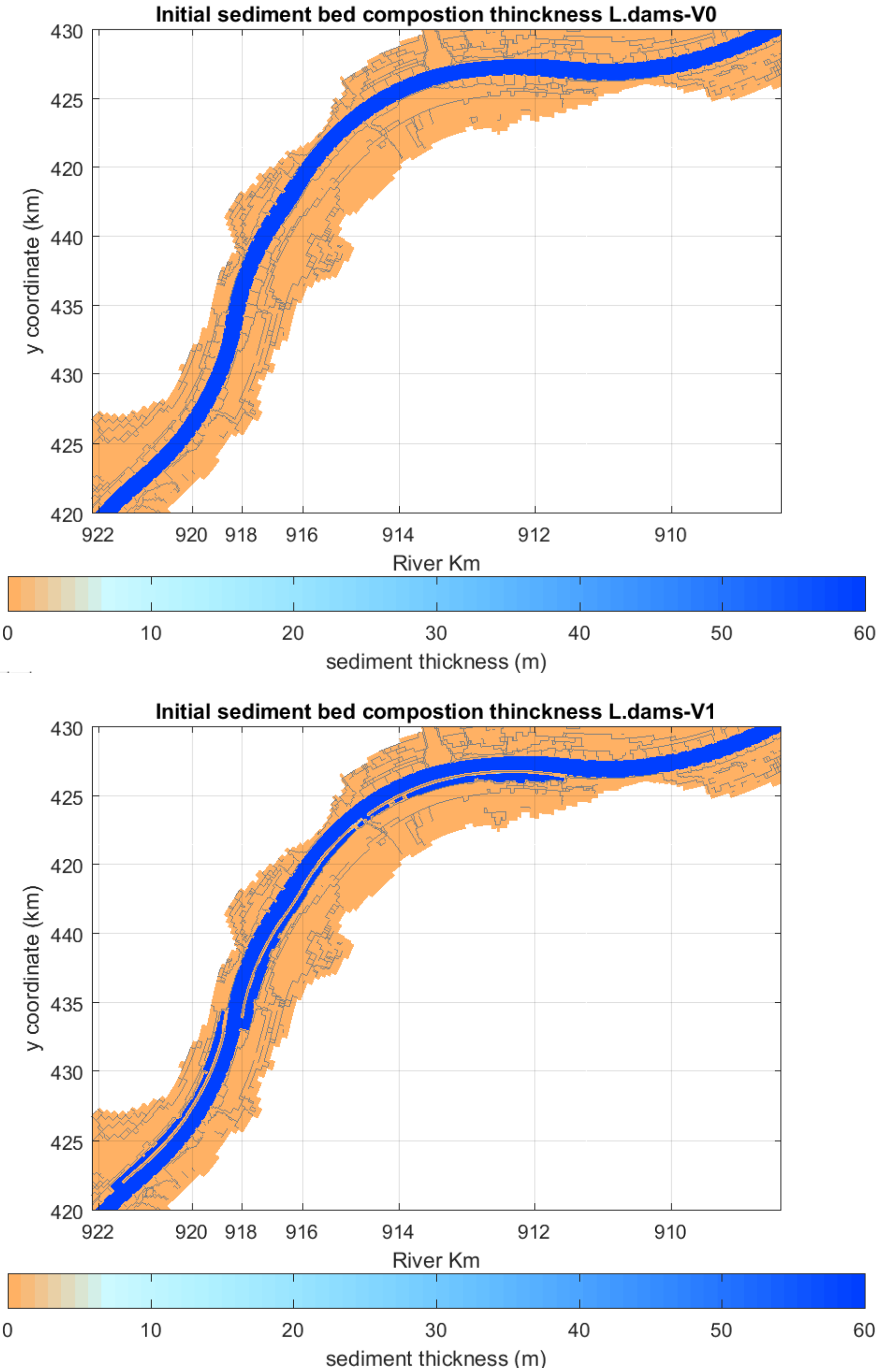



*Figure 3.4 The initial sediment thickness. The upper plot shows the thickness of V0 scenario, while the lower plot shows the thickness of the other scenarios (V1~V4).*

In order to produce a realistic performance of the morphological model, spin-up simulations are implemented. The spin-up is explained in the following section.

## 3.2 Spin-up simulations

The spin-up simulation is recommended in the previous study (Omer et al, 2019a) to provide a stable bed at the beginning of the model simulation, in which local features in the measurements that cannot be reproduced by the model can be dissipated. The spin-up continues until a stable (dynamic) condition develops that 'fits' the model schematisation and calibrated model settings. As explained before, V0 is built using Baseline Rijn-j14 while V1~V4 simulations use Baseline Rijn-j18. To conduct the spin-up run the following has been considered:

- Use of Baseline Rijn-j14 for a spin-up run of 10 years using the average discharge of the Waal river (1,500 $m^3/s$). The resulted bed topography can be used as input bed for V0.

- For V1~V4, we adjust the grid points at the dams and the side-channels locations with schematization and the topography of baseline Rijn-j18. We think the implementation of the dams; the side channels and the removal of the groynes can be considered as one measure (the measure). The impact of this measure is investigated in this assignment.

The morphological parameters used, initially, in this study are obtained from last year study (Omer et al, 2019a). The morphological adjustment focuses firstly on a reasonable reproduction of the average bed topography in the considered section. Secondly, an attempt is made to rectify the dynamic variations that have occurred in the section, which probably needs adjustment of sediment-transport rates. The morphological parameters resulted from the adjustment are also used in the morphological model scenarios.

The bed topography after the spin-up is not expected to have many changes compared to the initial (measured) topography, especially the morphological changes at bends. To achieve that, we may need to tune the model by changing Ashd and Espir. (length of point bar and the transverse slope). Some simulations are conducted to decide the best combination to be used for spin-up simulation.

As a result of the morphological tuning, some morphological parameters are altered like the transport formula. The modified Van Rijn 1984 (RIV-77) formula has been used in this study instead of Van Rijn 1984 which was used in the last year. The coefficient of the spiral flow effect (Espir) in the morphology input file has been increased from 1 to 1.25.

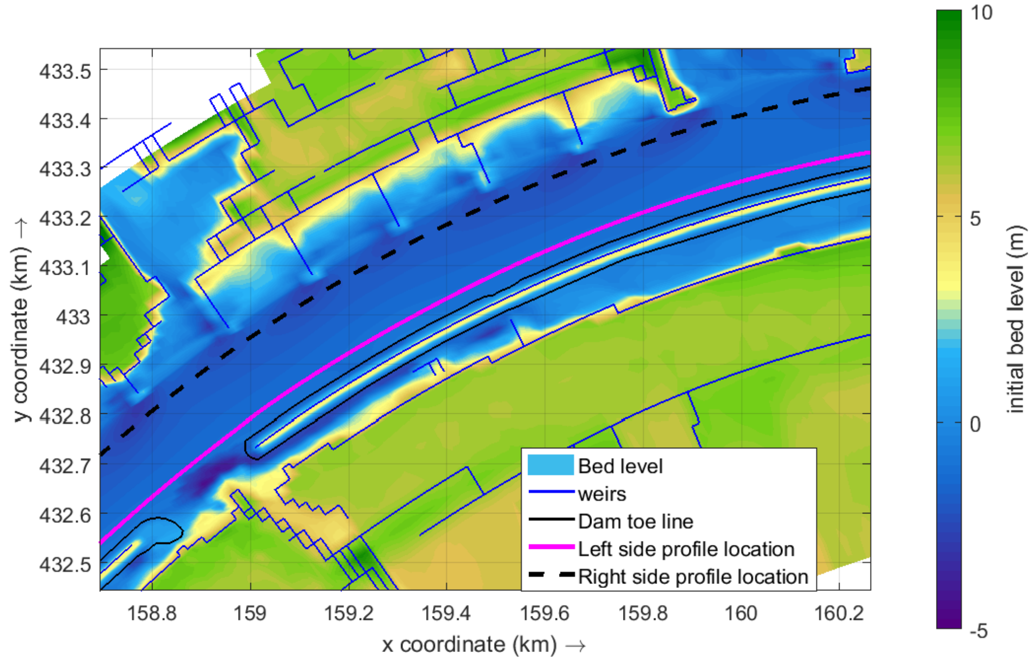



*Figure 3.5 The bed topography (Baseline rijn_j18) and the left and right-side lines, which are used to demonstrate the model output.*

The left and right bar-pool formations, at the start and end of the simulations, have been used to judge the simulated bed change. This approach used for all the spin-up trials. Below are the results of the spin-up simulation that was used to develop the morphology scenarios.

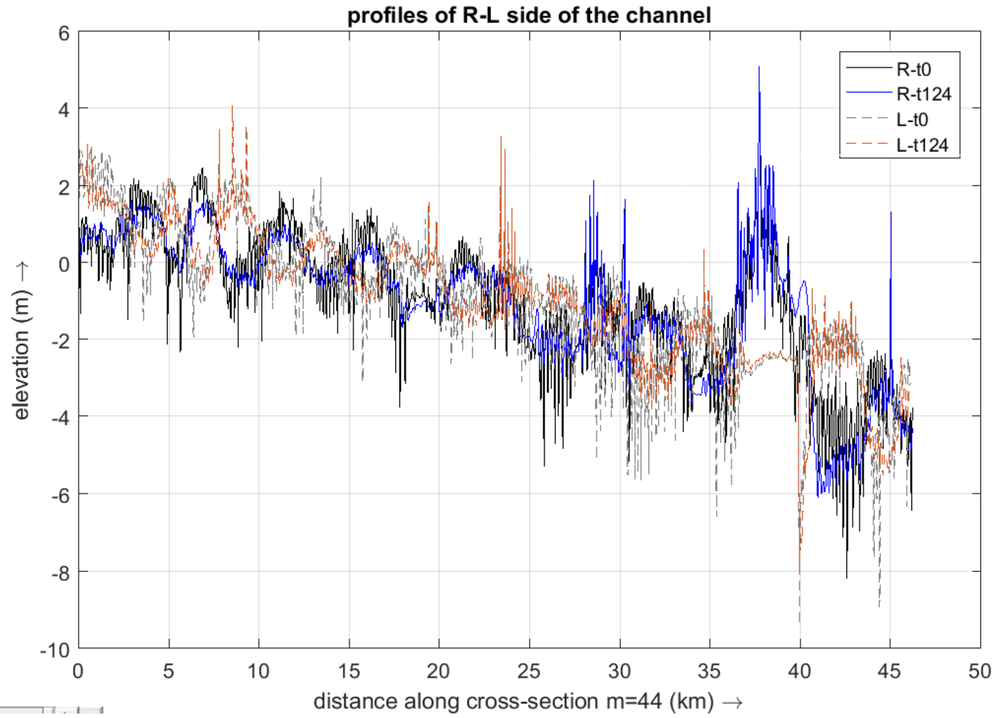



*Figure 3.6 The profiles of the right (R ) and left (L) side of the main river channel as shown in Figure 3.5. The initial condition is shown in the plot as t0, while the end-result of the bed level is illustrated as t124 (after 10 years of spin-up run).*

Figure 3.6 displays the forced bar and pool formation of the model after 10 years of the steady-state spin-up run. The results at the end of the simulation are following the same pattern of the bed at t0 (start time), since not much bed changes occurred in the last five years. The resulted bed level of the first 5 years is used as input bed for the variant scenarios. More detailed about the spin-simulations can be found in Appendix A. The 2D pattern of bars and pools and the long-term trend are considered to be reasonably well approximated by the model as shown in Appendix A. The following changes have been introduced to achieve the final spin-up results:

- The fixed layer around the edge of the groyne is extended 20 m towards the main-river centreline.
- The spiral flow factor (Espir) is set to 1.25.
- The roughness of the Sint Andries fixed layer bend is normalised to be like the alluvium river bed.

## 3.3 Simulations of the variants

The morphological model is used to simulate 5 scenarios for 30 years. The step hydrograph generated from the 40 years historical data of the Waal River is used. To simulate long-term morphological behaviour (of 30 years), the management simulation tool is applied. This helps to achieve sufficiently accurate and physically correct results in reasonable computation time (e.g. 2 weeks for 30 years).

The variants of scenarios are described below:

1. The first variant, scenario (**V0**), considers river schematization before the construction of the longitudinal dams (Baseline rijn_j14). The simulation has been executed for the period mentioned above to investigate the long-term morphological changes as if the longitudinal dams are not implemented.
2. The second variant, scenario (**V1**), considers the current situation of the model schematization including the longitudinal dams (Baseline rijn_j18). The results of this scenario are compared with V1 to find the difference between both cases. The scenario is also considered as a reference scenario and it is also used to judge the other four variants scenarios (V2~V4). This scenario differs from V0 only in the following:
   - 2.1 The model schematization is based on Baseline of rijn_j18 instead of rijn_j14.
   - 2.2 The grid cells of the bed level where the longitudinal dams are executed are replaced by the bed level of the baseline rijn_j18. This includes removing the groynes at those locations, projecting the dams in the topography and the side channels. It must be mentioned here that groynes had been replaced to construct the dams which means that the narrowing of the channel already existed before the dam implementation.
3. The third scenario (**V2**) has almost the same schematization as V1. The difference is that the openings of the side channels are fully closed. The adjacent dam crest level is extended to cover the inlet opening of each dam. In addition, the weir on the top of the dam is also extended.
4. The fourth scenario (**V3**) is like V1 except for the side channel openings. They are set open as it is shown in the as-built survey of the longitudinal dams. The sill-level and the inlet opening cross-sections of the three dams are quite different in the as-built survey compare to the Baseline Rijn-j18.
5. This may provide more insight into the sensitivity of the inlet opening to the river morphology. Figure 3.7, Figure 3.8 and Figure 3.9 illustrate the comparison between the inlet cross-section of the side channels of Wamel Dam, Dreumel Dam and Ophemert Dam, respectively.

6 The fifth scenario (**V4**) has the same setting as V1 but with the current bed level maintenance. In this simulation, the dredging and dumping approach used before by RHDHV is considered. For further details see section 1.3.

If there are any structural activities implemented (e.g. fixing bed, lowering flood plain, sediment nourishment, etc) on the modelled river reach, we may use them only for the analysis of the modelling results. The results of the simulations are compared to each other. From this addition, we can learn about the robustness of the model to predict future bed developments.

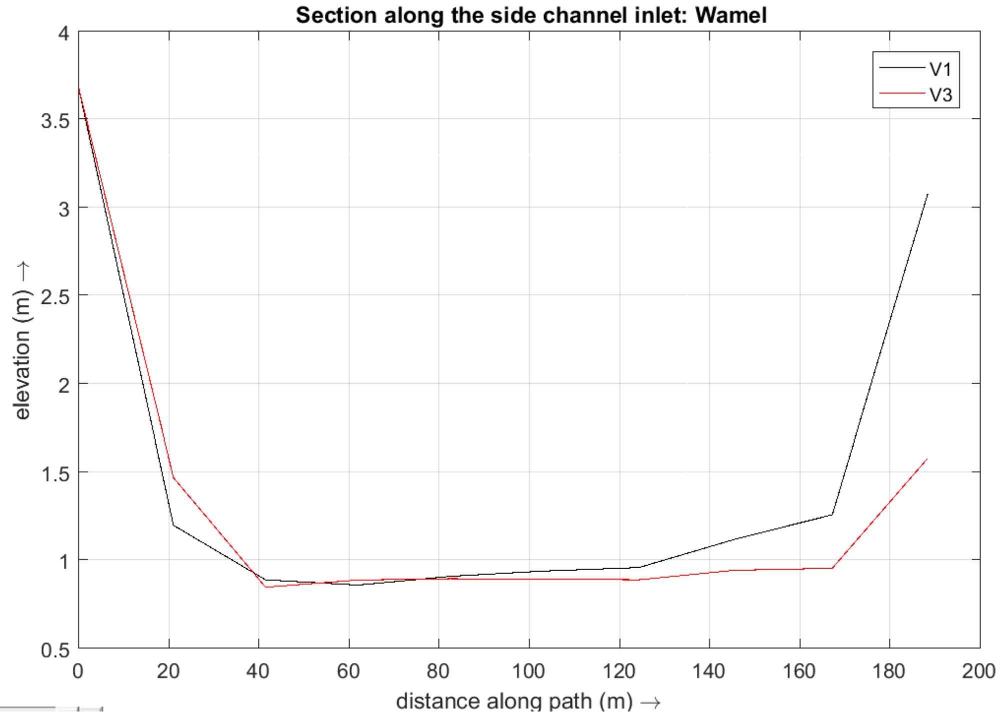



*Figure 3.7 The bed level at the inlet (the sill) of the side channel of the Wamel Dam (for V1 (j18 sill) and V3 (asbuilt sill) scenarios)*

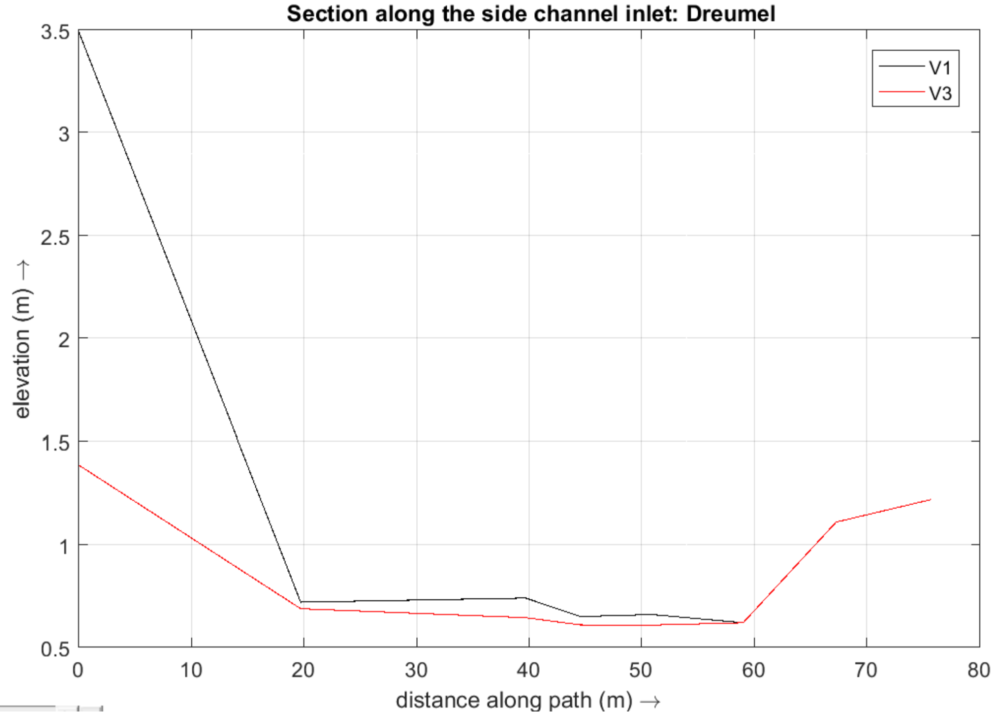



*Figure 3.8 The bed level at the inlet (the sill) of the side channel of Deumel Dam (for V1 (j18 sill) and V3 (asbuilt sill) scenarios)*

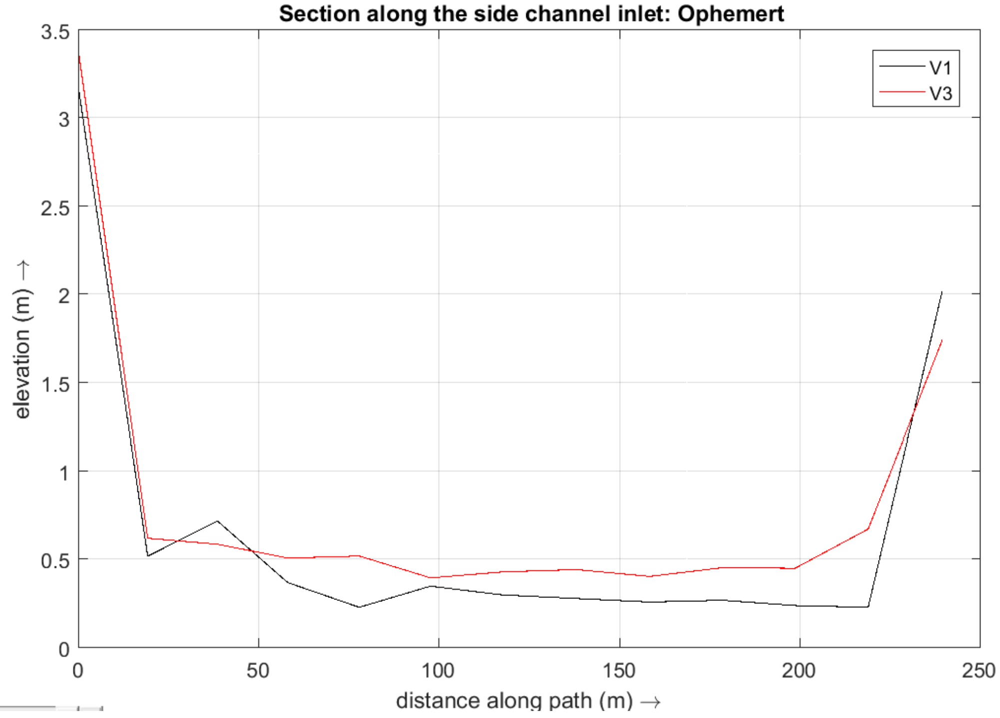



*Figure 3.9 The bed level at the inlet (the sill) of the side channel of Ophemert Dam (for V1 (j18 sill) and V3 (asbuilt sill) scenarios)*

# 4 Simulations results

In this section, the simulation results of every variant will be discussed. The scenarios are compared to the reference scenario (s) to understand more about the impact of every variant. The long-term impact of the variant on the water level is also presented here.

## 4.1 V0 (the variant without dams)

V0 scenario includes the schematization of baseline Rijn-j14_5-v1. It represents the situation before implementing the longitudinal dams. At the location of the longitudinal dams, there were many groynes in place. The groynes in this simulation and other simulations are represented using sub-grid weir approach.

The results of the morphological change of 30 years are shown in Figure 4.1. The lower plot in Figure 4.1 illustrates a tendency of deposition around km 912 and at the right side of the main channel between km 918 to km 919. The upper plot in Figure 4.1 also shows the bed is subjected mainly to erosion downstream of the fixed layer of the river bend at Sint Andries (between km 928 ~934). We zoom on the lower plot of Figure 4.1 to perceive the bed change around the longitudinal dams; as shown in Figure 4.1.

Figure 4.1. Illustrates also the alteration of bar and pool bed change pattern. This is well shown in Figure 4.2. Figure 4.2 depicts the right and left profiles along the river main channel. The increase in bar formation may hamper the navigation in the river, while the increase in pool depth may create instability in the bank. Based on Figure 4.2, there is an increase in both formations, however, it is in a magnitude of 0.5 m or less in 30 years. More details can be seen in Appendix E.

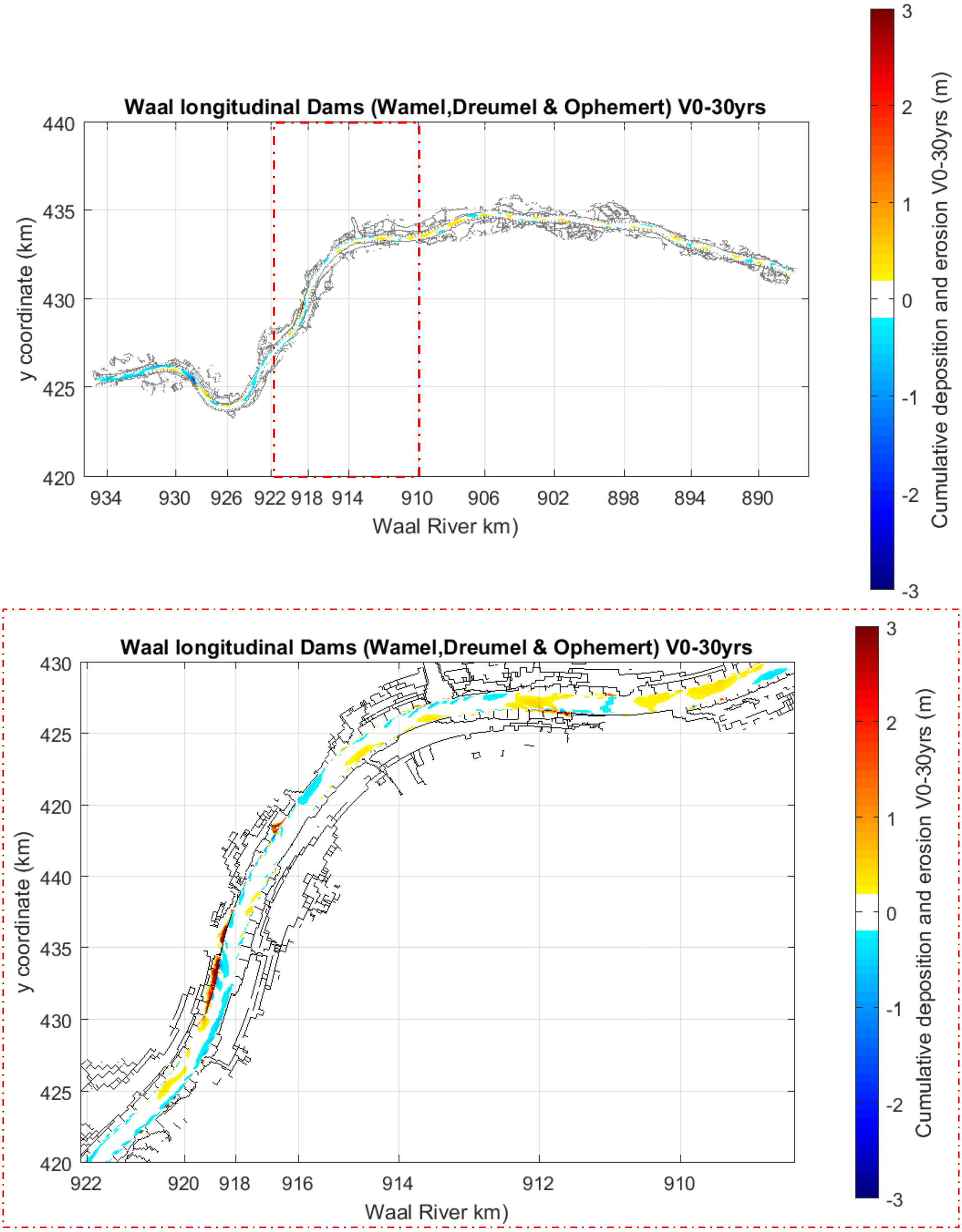



*Figure 4.1 The cumulative deposition and erosion of 30 years simulation of V0 (without the dams). The upper plot shows the whole model domain, while the lower plot displays the cumulative deposition at the location where the longitudinal dam are constructed.*

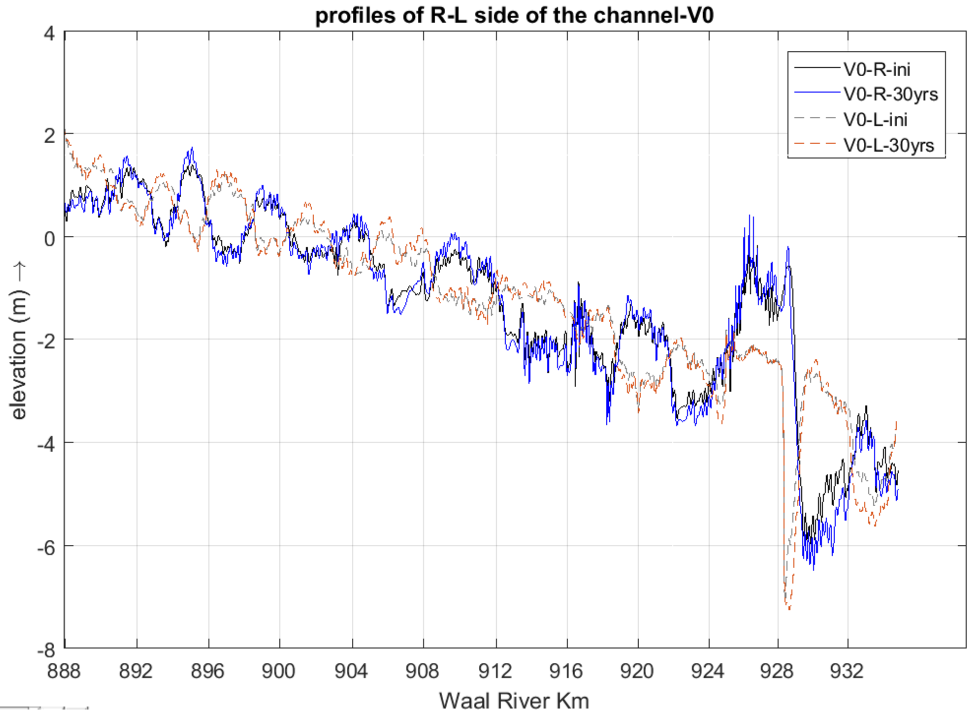



*Figure 4.2 The change of the bar-pool formation at both sides of the main channel of the model (V0)*

## 4.2 V1 (the variant with the dams)

V1 scenario includes the schematization of baseline Rijn-j18_5-v1. The sill levels of the inlets of the side-channels are obtained from the baseline (Sch_j18 sill levels). It represents the situation after the longitudinal dams' construction. The results of the morphological change of 30 years are shown in Figure 4.3

Figure 4.3 shows the cumulative deposition and erosion of the 30 years simulation of V1. The upper plot in Figure 4.3 depicts the whole model domain while the lower plot shows the longitudinal dams reach. The results show deposition upstream of Wamel Dam and just downstream of the Dreumel Dam. The model also shows deposition in the main channel parallel to Ophemert Dam. These patterns can be recognized with less magnitude in the 2 years topographical measurements difference shown in Figure 4.4. Figure 4.4 is obtained from the previous study (Omer et al, 2019a). The figure shows the topographical measurement of March 2018 is subtracted from the topographical measurement of May 2016.

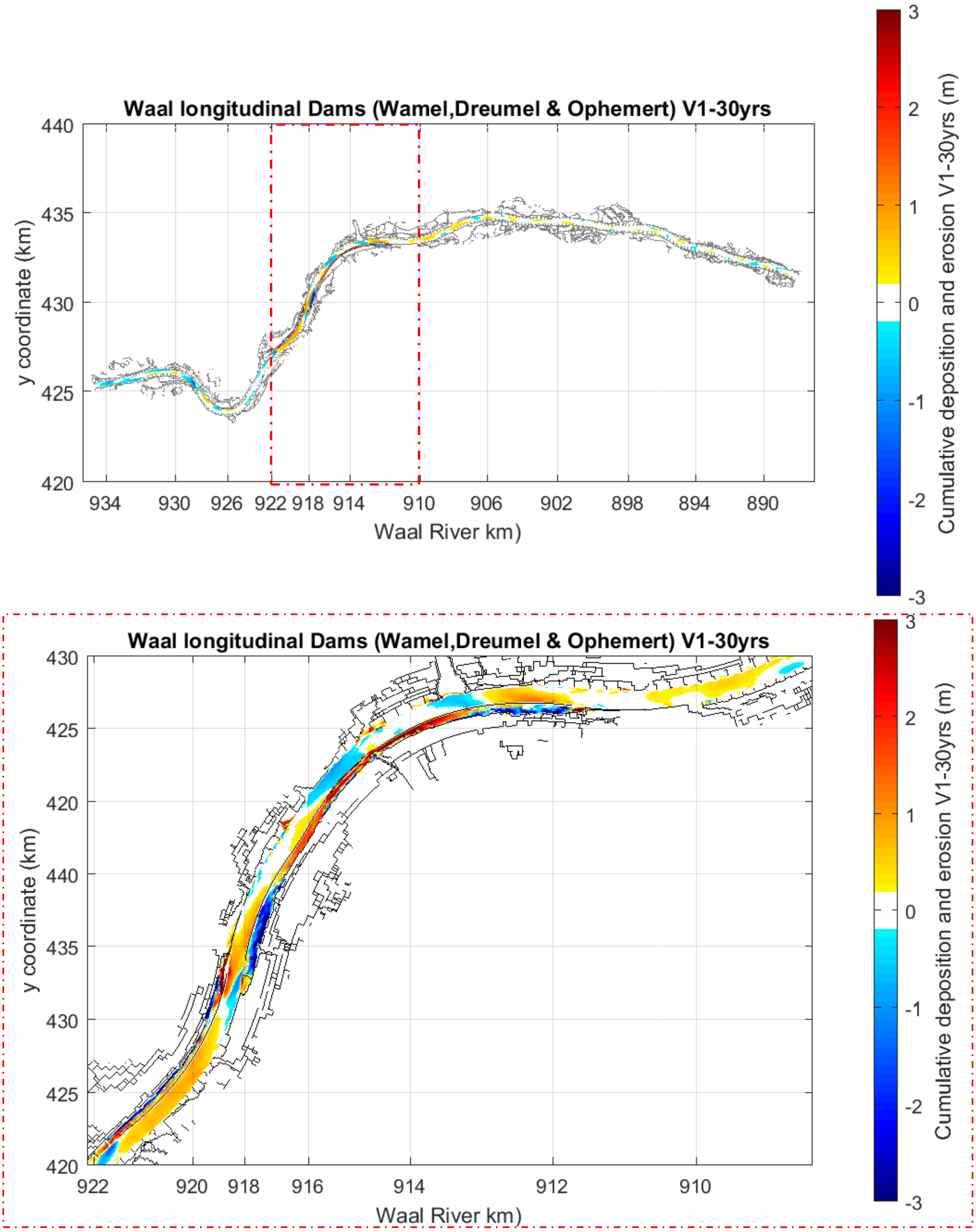



*Figure 4.3 The cumulative deposition and erosion of 30 yrs simulation of V0 (with the longitudinal dams and j18 Sch-inlets sills). The upper plot shows the whole model domain, while the lower plot displays the reach related to the longitudinal dams.*

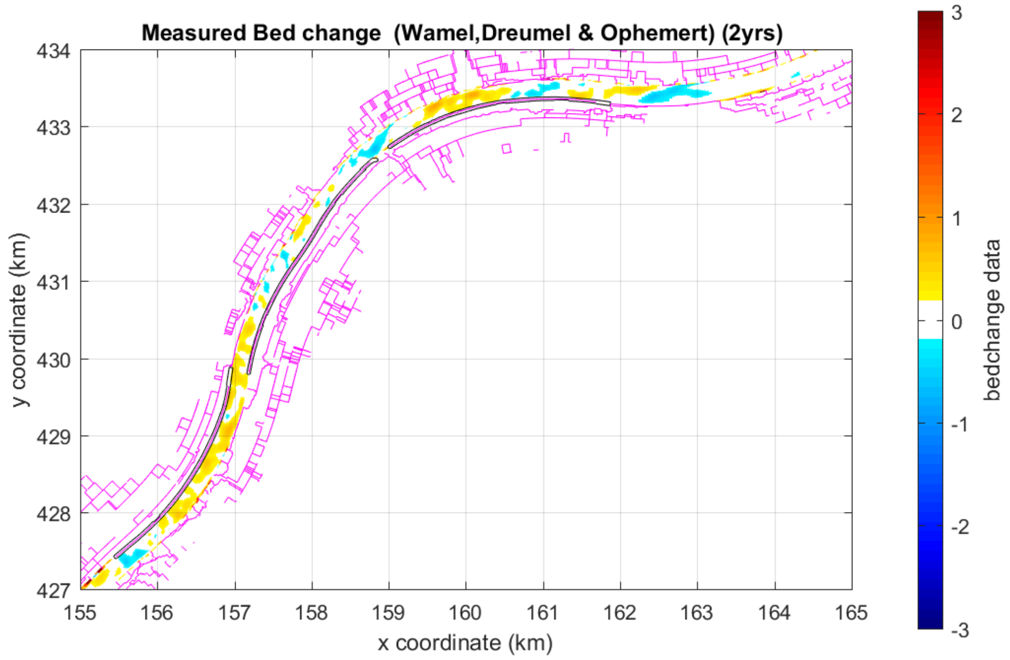



*Figure 4.4 The difference in topographical measurements of May 2018-May2016 (Omer et al, 2019a)*

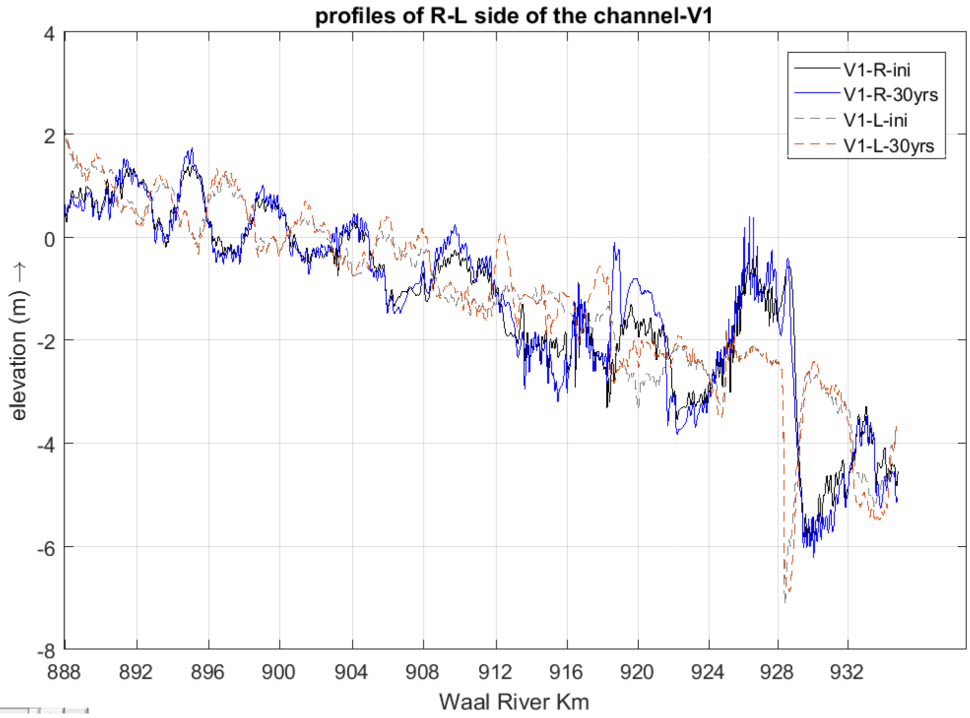



*Figure 4.5 The change of the bar-pool formation at both sides of the main channel of the model (V1). L is left side while R is the right side of the main channel*

Figure 4.5 presents the bar-pool development of V1 simulation. The alternating bar-pool pattern development through the 30 years is almost similar. The bar gets higher while the pool gets lower. However, the magnitude is relatively higher between km 912 and km 922 where the longitudinal dams are located. The increase in bar formations is in a magnitude of 1~1.5 m at km 912 after years. This can be seen clearer in Appendix E.

## 4.3 V2 (as V1 with closed inlets)

V2 scenario is like V1 but the side-channels inlets are closed to the level of the relevant dams. As the dam has a weir on the crest the weir is extended to include also the crest of the inlet. In addition to that, the extended dam is considered as non-erodible layer as shown in Figure 4.6. The crest of the dam initiated in the topography has a level of, 3.77 m,3.5 m and 3.18 m for Wamel Dam, Dreumel Dam and Ophemert Dam, respectively. These levels are similar to the level of the dam at their junction with the side channel inlets.

This scenario shows the expected morphological changes in case the side channels openings are fully closed. This means the exchange of water between the side channel and the main channel would be possible only during the high flows when water overtops the longitudinal dams. The results of the morphological change of 30 years for this variant are shown in Figure 4.7.

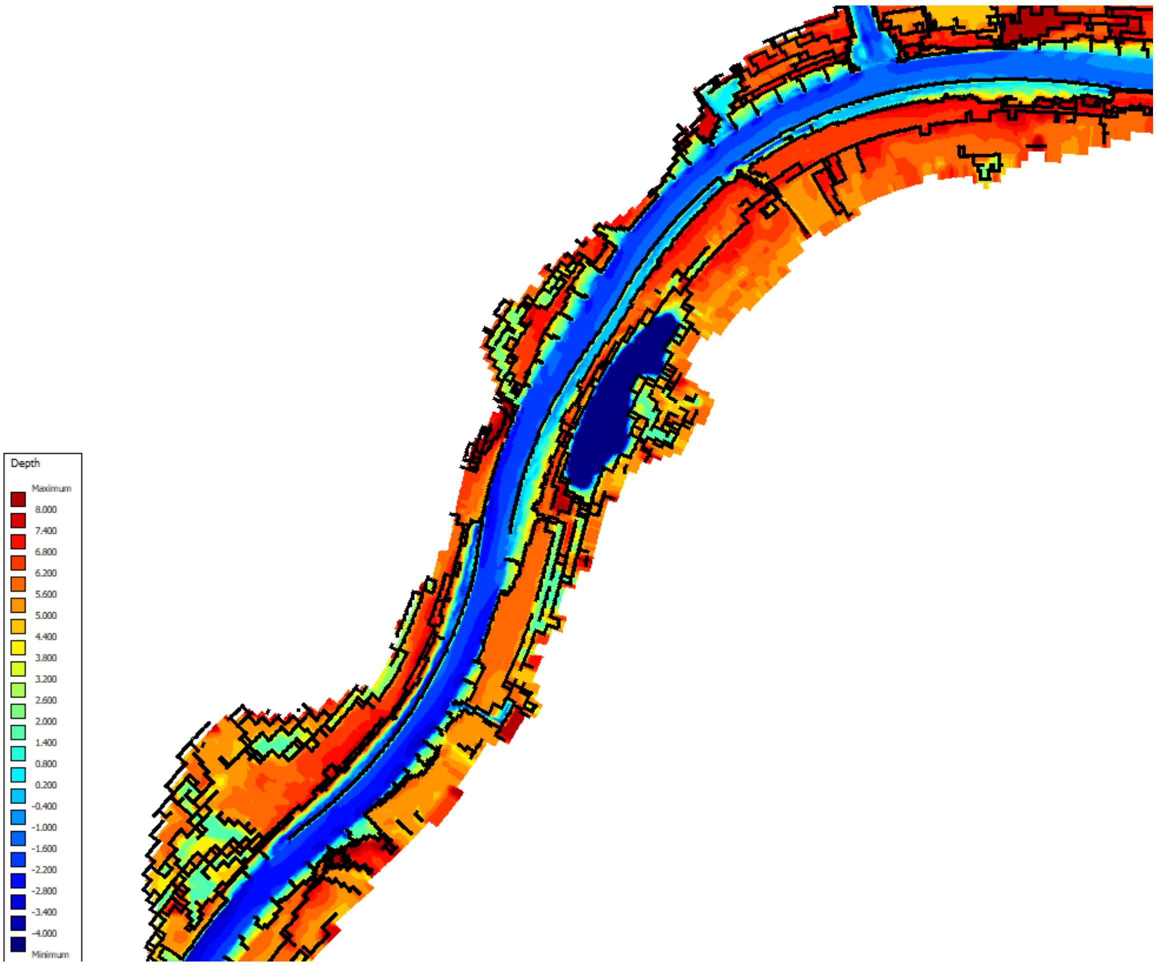



*Figure 4.6 The initial bed level of V3. In this figure, the longitudinal dams are extended to the bank. They are also considered as non-erodible layer with a weir on the top of them.*

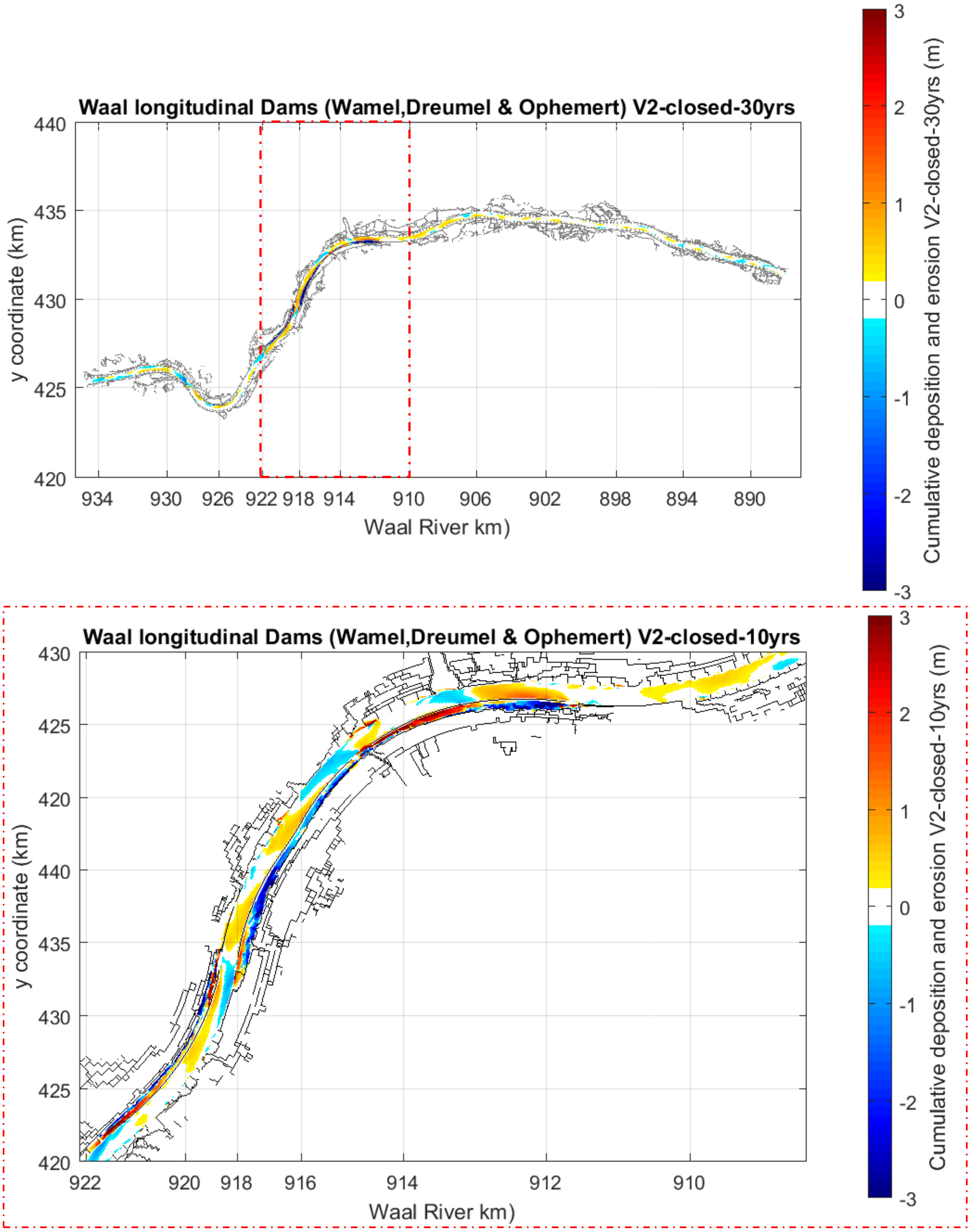



*Figure 4.7 The cumulative deposition and erosion of 30 yrs simulation of V2 ( as V1 but side-channel inlets are closed).The upper plot shows the whole model domain, while the lower plot displays the reach related to the longitudinal dams.*

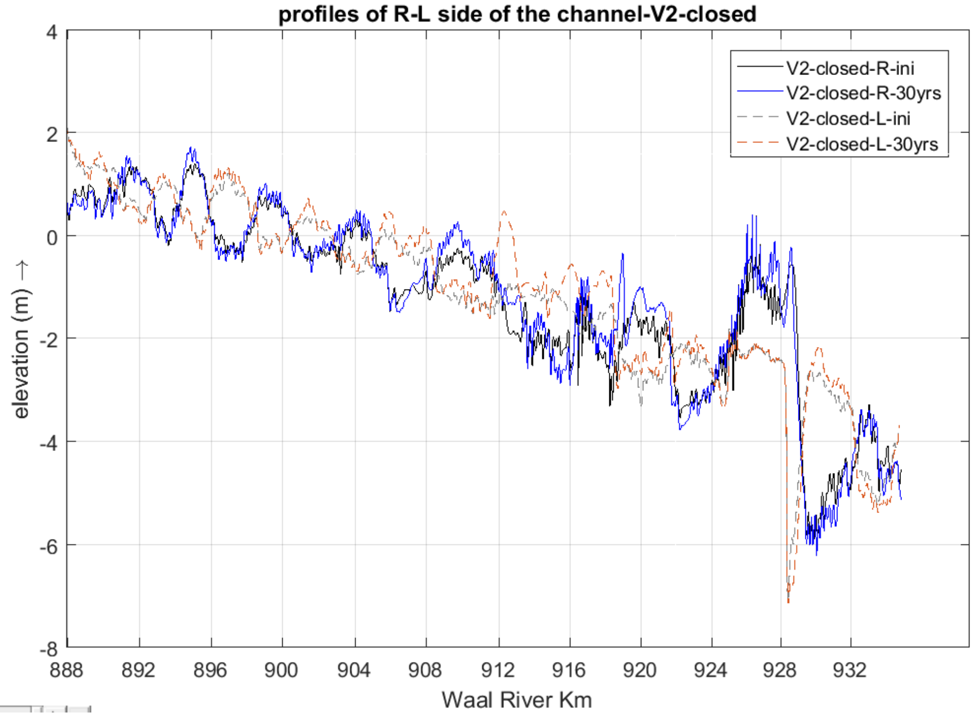



*Figure 4.8 The change of the bar-pool formation at the both sides of the main channel of the model (V2)*

The upper plot in Figure 4.7 illustrates cumulative deposition and erosion in the whole model domain, while the lower plot shows the bed change at the longitudinal dams' river reach. The lower plot in Figure 4.7 explains that the deposition magnitude in the main channel is less than V1 (see Figure 4.3), especially at the main channel parallel to Ophemert Dam. However, the model results show that the side channel of Dreumel Dam is more subjected to erosion in V2 than V1. This may make the side channel attracts more discharge during the high flow season.

Figure 4.8 depicts the bar-pool pattern of V2 simulation. The figure shows the changes on the right and left the side of the main channel for 30 years. It can be seen that the rate of the deposition or bar formation is more than pool formation. More details can be seen in Appendix E.

## 4.4 V3 (as V1 but with the as-built inlets sill)

V3 scenario is like V1 but the side-channels inlets have different sill levels. The sill level is obtained from the as-built survey of the longitudinal dams. As the dam has a weir on the crest the weir is extended to include also the crest of the inlet. As in V1, the inlets are non-erodible layers as shown in Figure 4.6. The sill-levels of the inlet for Wamel inlet, Dreumel inlet and Ophemert inlet are shown in Figure 3.7, Figure 3.8 and Figure 3.9, respectively.

In Figure 4.9, the upper plot illustrates cumulative deposition and erosion in the whole model domain, while the lower plot shows the bed change at the longitudinal dams' river reach. In Figure 4.9, the lower plot explains that the deposition magnitude in the main channel is less than V1 (see the lower plot of Figure 4.3 ), especially at the main channel parallel to Ophemert Dam.
However, the model results show that the side channel of Wamel Dam and Dreumel Dam is less subjected to deposition in V3 than V1. This may make the side channel attracts more discharge during the high flow season.

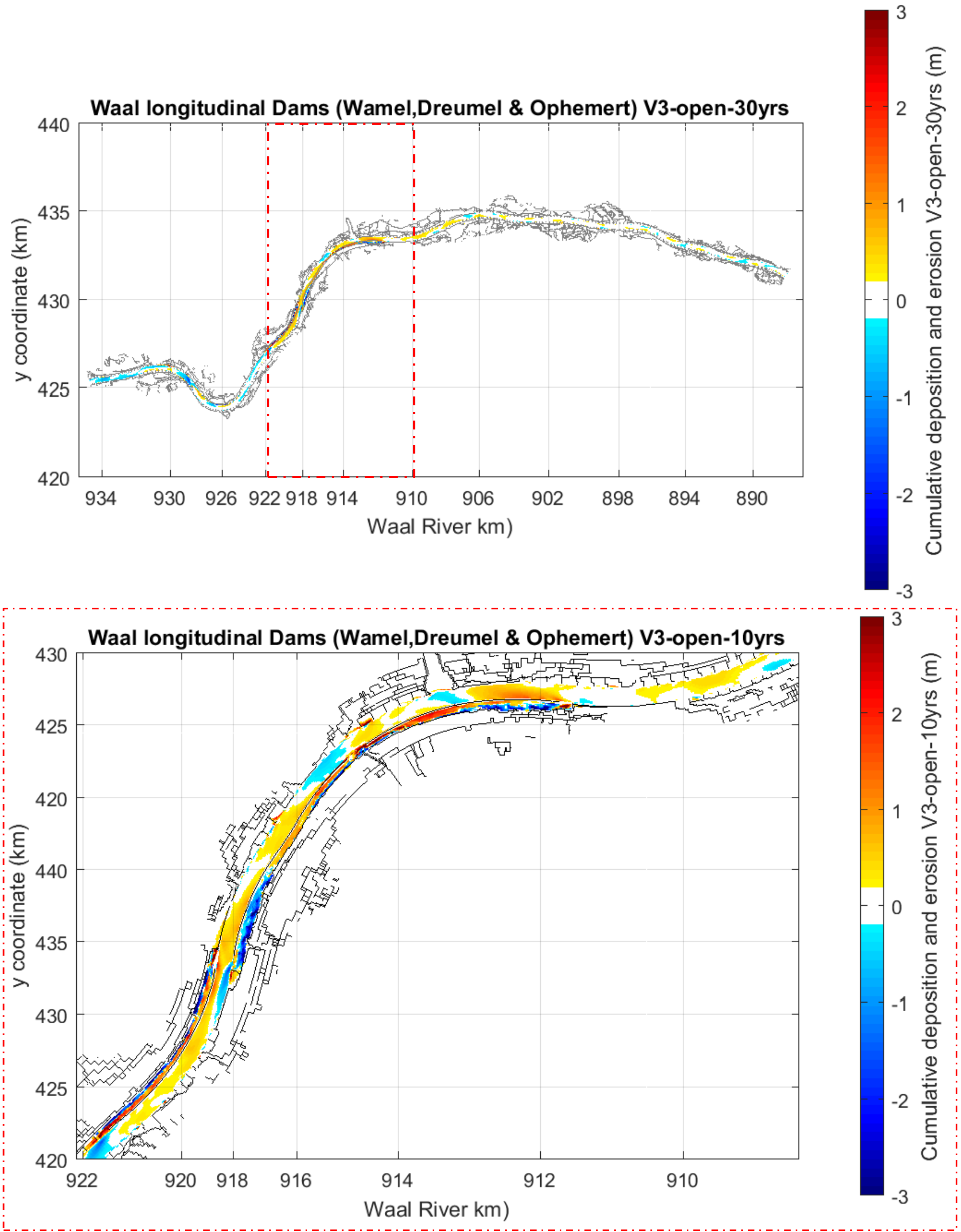



*Figure 4.9 The cumulative deposition and erosion of 30 yrs simulation of V3 (as V1 but with as-built Sch-inlets sill levels).The upper plot shows the whole model domain, while the lower plot displays the reach related to the longitudinal dams.*

Figure 4.10 depicts the bar-pool pattern of V3 on both sides of the main channel. The figure illustrates the alternating pattern; however, the magnitude of bar increase is relatively more than the erosion in the pool's areas. This can be observed between km 912 to km 922 where the longitudinal dams are located. This can be seen clearer in Appendix E.

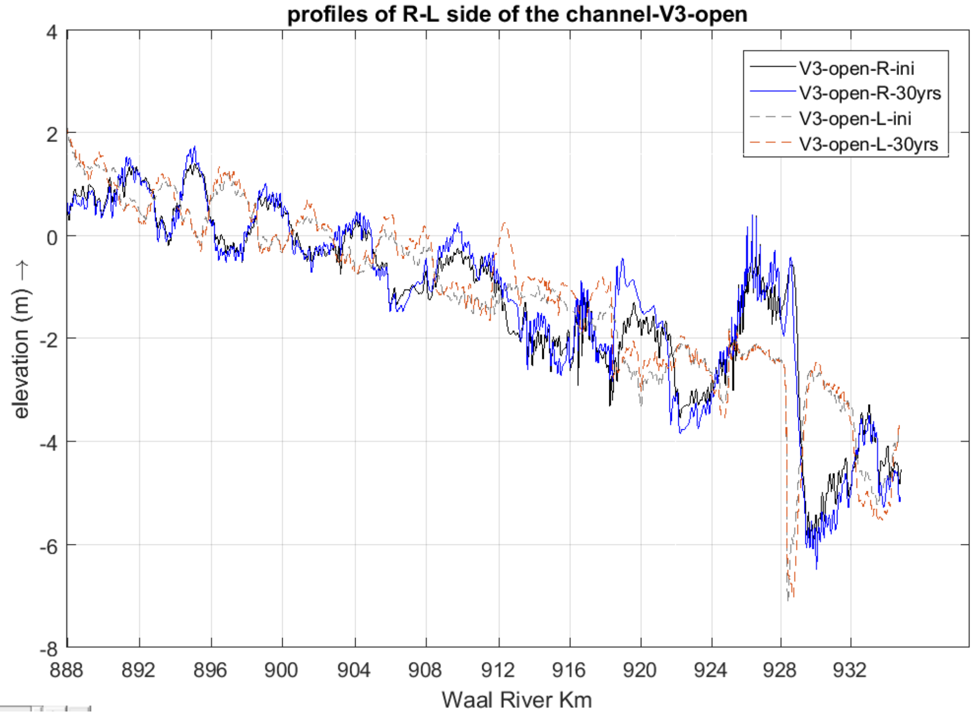
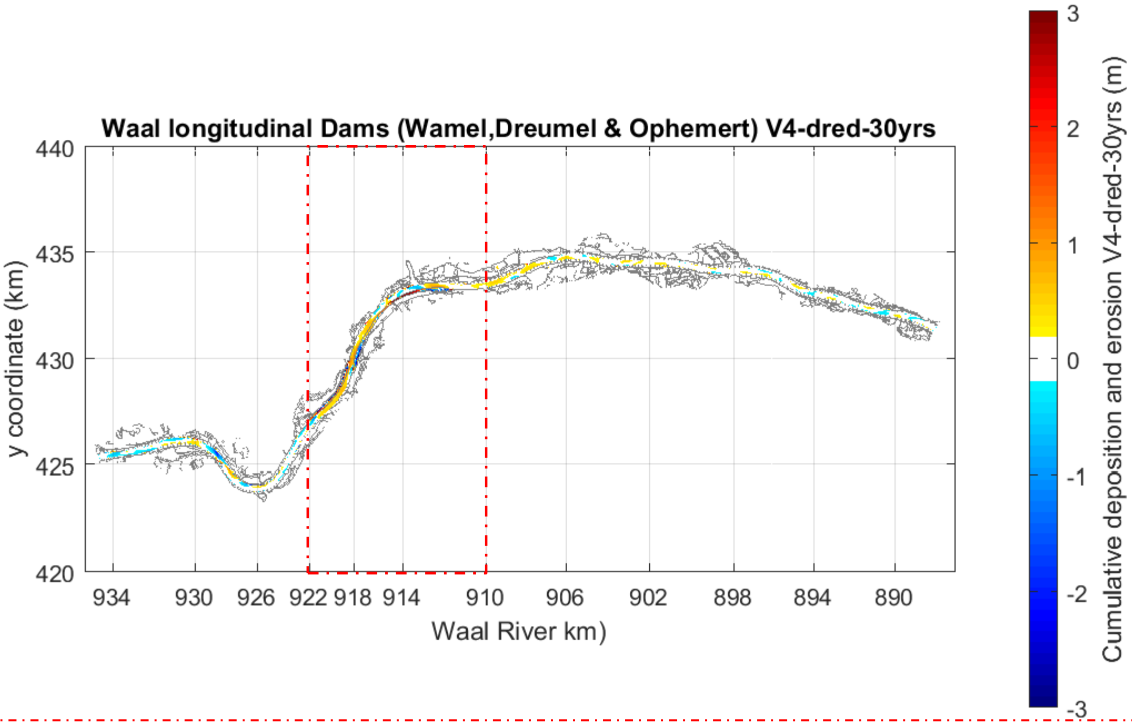



*Figure 4.10 The change of the bar-pool formation at both sides of the main channel of the model (V3)*

## 4.5 V4 (as V1 but with dredging and dumping)

V4 scenario is like V1 but includes river maintenance (dredging and dumping). The current management regulations of the river bed level are included in this simulation, to ensure the required water depth along the navigation channel. In RHDHV simulations of the Waal river, an assumption is made that if the depth of water below OLR (Agreed low water level) at a location is less than 2.8 m in the navigation channel then the model dredges this location to obtain the depth of 2.8 m below OLR. The OLR is derived from the OLA (Agreed low discharge). The OLA value is estimated to 1,020 $m^3$/s at Lobith and 820 $m^3$/s at Waal River (Sloff et al, 2014). This means dredging and dumping process is active mainly during the low flow season. The dredged materials are dumped (by the model) within 1 km upstream or downstream of the location. If there is no deeper location within the 2 km, then the model dumps the dredged materials outside the model domain. This approach is implemented in this scenario. Figure 4.11 shows results of V4.

In Figure 4.11, the upper plot illustrates cumulative deposition and erosion in the whole model domain, while the lower plot shows the bed change at the longitudinal dams' river reach. The lower plot of Figure 4.11 explains that the deposition magnitude in the main channel is similar to V1 at the Wamel dam Reach (see the lower plot of Figure 4.3 ). However, the deposition in the main channel of Dreumel Dam reach, of V4, is more than V1, while the deposition in the Dreumel side channel is of V4 is less compare to V1.
In Ophemert Dam reach the comparison results are adverse to Dreumel Dam reach. This simulation displays deposition at almost similar locations as V1 with a more spatially varying distribution. This can be seen in more details in Appendix B and C.



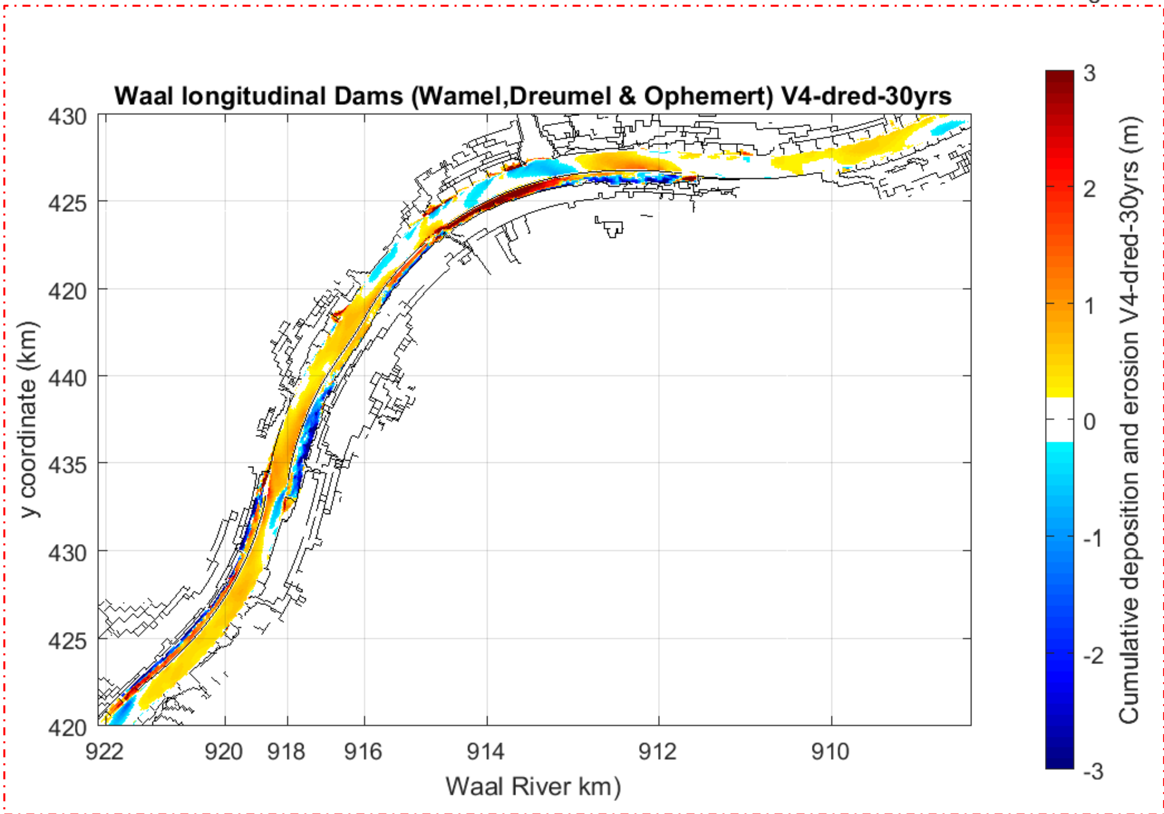




*Figure 4.11 The cumulative deposition and erosion of 30 yrs simulation of V4 (as V1 but with dredging and dumping). The upper plot shows the whole model domain, while the lower plot displays the reach related to the longitudinal dams.*

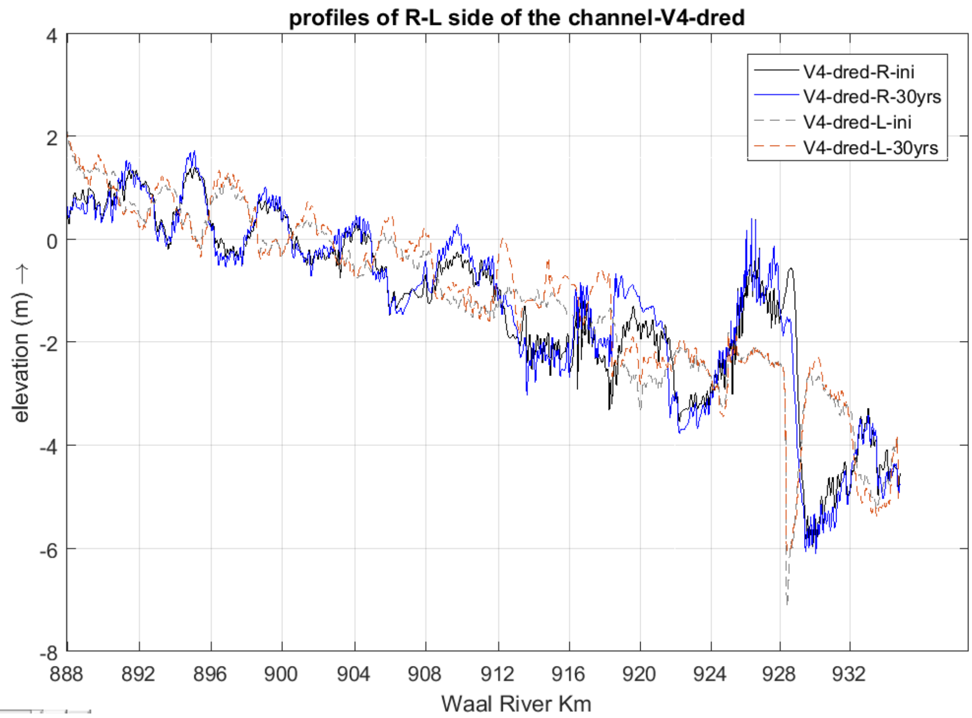



*Figure 4.12 The change of the bar-pool formation at both sides of the main channel of the model (V4). L indicates the left side of the main channel, while R indicates the right side of the main channel.*

Figure 4.12 illustrates the left and right longitudinal profiles of V4. The figure shows the pool-bar formation. Not many changes have been observed downstream of the longitudinal dams. However, the tendency of deposition in the longitudinal dam reach is more than the tendency of erosion. This might be because of the distribution of the dredge material within the model domain. This can be seen clearer in Appendix E.

## 4.6 V1 vs V0

To further investigate the impact of longitudinal dams, Figure 4.13 has been produced. The figure shows the difference in bed levels between V1 and V0 at the end of the simulation (30-years).

The result explains that the longitudinal dams provide more room for the river. However, the model results show a tendency to more deposition in V1, especially downstream of km 912 and around km 918 (km 917.5~918.5). The model also displays the tendency of deposition in the main channel that is parallel to Ophemert Dam.

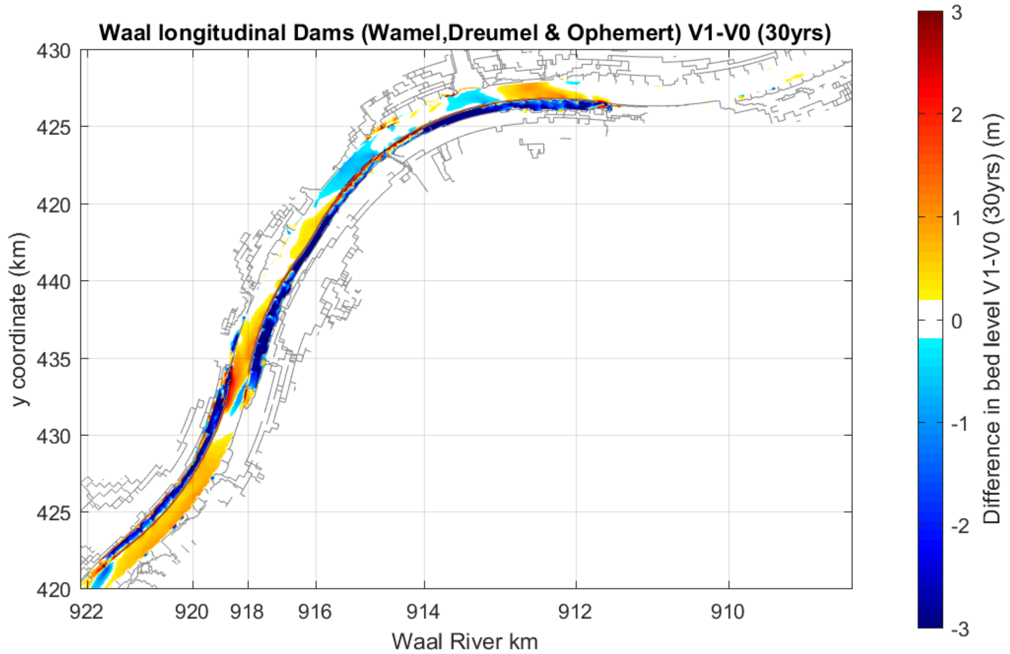



*Figure 4.13  The difference between V1 and V0 in the bed level resulted after 30 years.*

The result of the model in Figure 4.13 can be connected to Figure 4.14. Figure 4.14 depicts the velocity difference at the same time and discharge (1,233 $m^3/s$) between V1 and V0. The figure shows an increase in the velocity within the main channel. The increase is very much concentrated in the location where the deposition occurs in Figure 4.13. The rise of velocity inside the side channel is normal as the flow velocity in the groyne's fields in V0 is relatively small. The figure also displays an increase in the velocity at the main channel at this discharge (1,233 $m^3/s$). This might be due to the deposition that occurred during the floods' periods (e.g. for V1), In addition to the blockage impact of the river cross section by the dam at this discharge. The erosion occurs in the side channel of V1 makes the side channel attracts more water as there is more room behind.

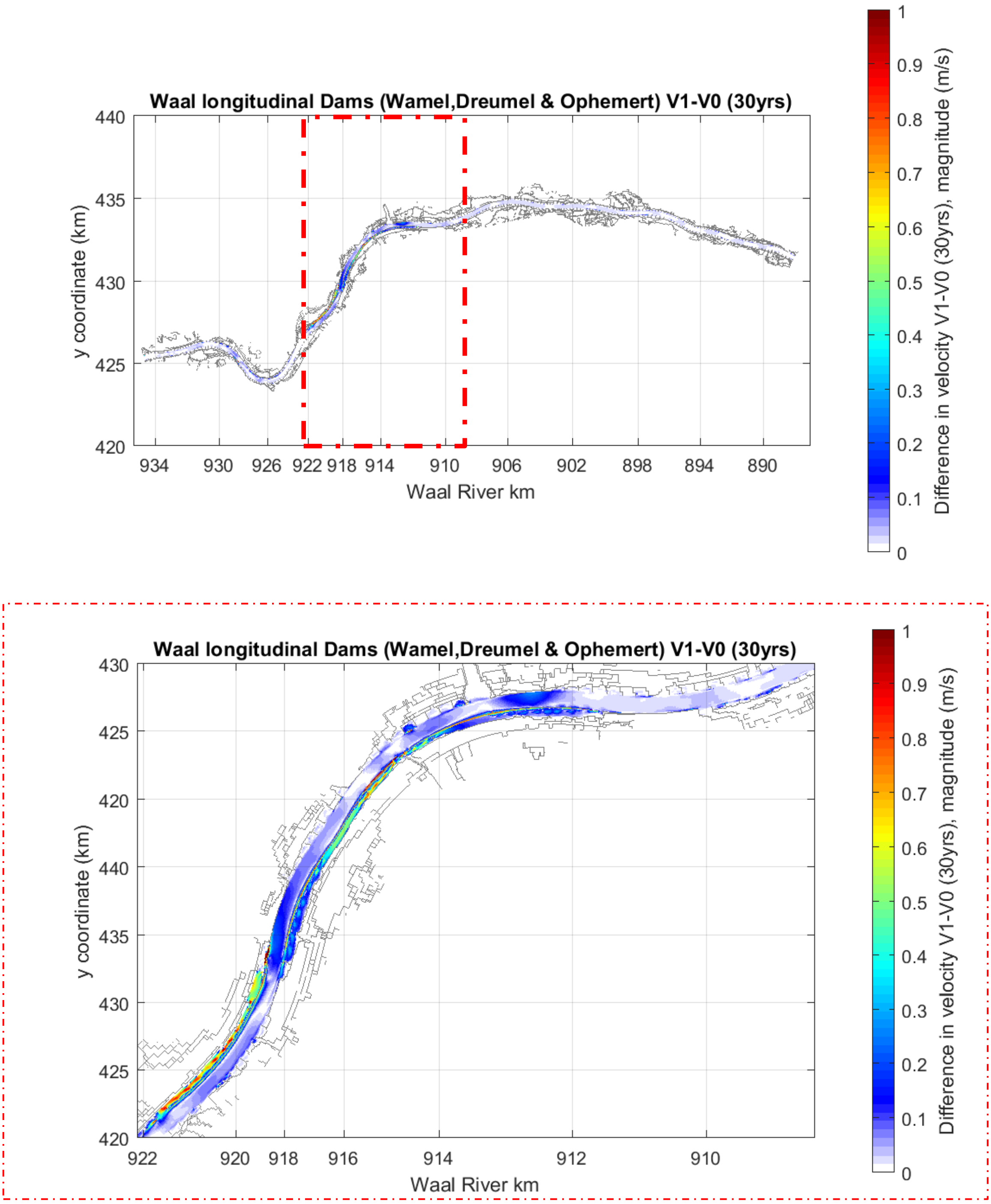



*Figure 4.14 The difference in velocity between V1 and V0 at the end of both simulations. The upper plot displays the map of the whole model domain while the lower plot zooms to the longitudinal dam reach.*

## 4.7 V2 vs V1

In the same manner, we compared the resulted bed level, after 30 years, of V2 to V1. In V2 the inlet to the side channel is closed, while the V1 is the reference case. In V1 the inlets of the side channel opening are obtained from the baseline Rijn-j18. The comparison result is shown in Figure 4.15. The model results illustrate that the closing of the inlet creates:

- A tendency for erosion in the side channel of Wamel and Dreumel.
- A tendency of minor deposition in the main channel parallel to Wamel and Dreumel Dams.
- A tendency of erosion in the main channel parallel to Ophemert Dam.
- A tendency to deposition and erosion.

The erosion in the side channel of Wamel and Dreumel seems to be attracting more discharge. This leads to less discharge and less velocity inside the main channel, which creates the tendency to deposition. On the other hand, the closing of Ophemert inlet and the tendency of the deposition in the first part of the side channel leads to divert more discharge in the main channel. As a result of that, the erosion may occur there.

The comparison between these two variants provides indicators about the expected bed tendency to deposition and erosion. However, V2 scenario includes a weir on the top of the inlet, while the V1 (reference scenario) does not have a weir at the inlet. This means the model considers the energy loss during the flood at the inlet for V2 and not for V1. Nevertheless, if the weir would be added on the top of the inlet-sill of V1 then energy loss will be considered also during low flow.

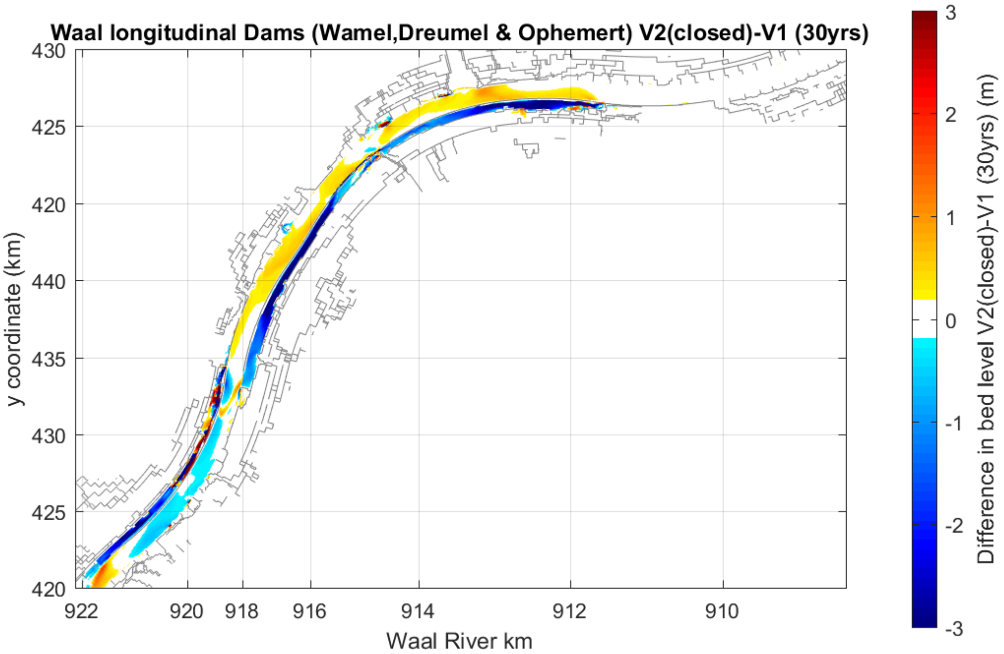



*Figure 4.15 The difference between V2 and V1 in the bed level resulted after 30 years.*

To recognise more morphological patterns of V2-V1, the velocity difference is depicted in Figure 4.16. Figure 4.16 shows that the velocity rises in the side channels. This is in-line with the resulted erosion of the side channels as shown in Figure 4.15.
In the main channel, the increase is less but in order of 0.2 m/s. This difference in velocity might be significant for sediment transport within the main channel at this discharge (1,233 $m^3$/s).

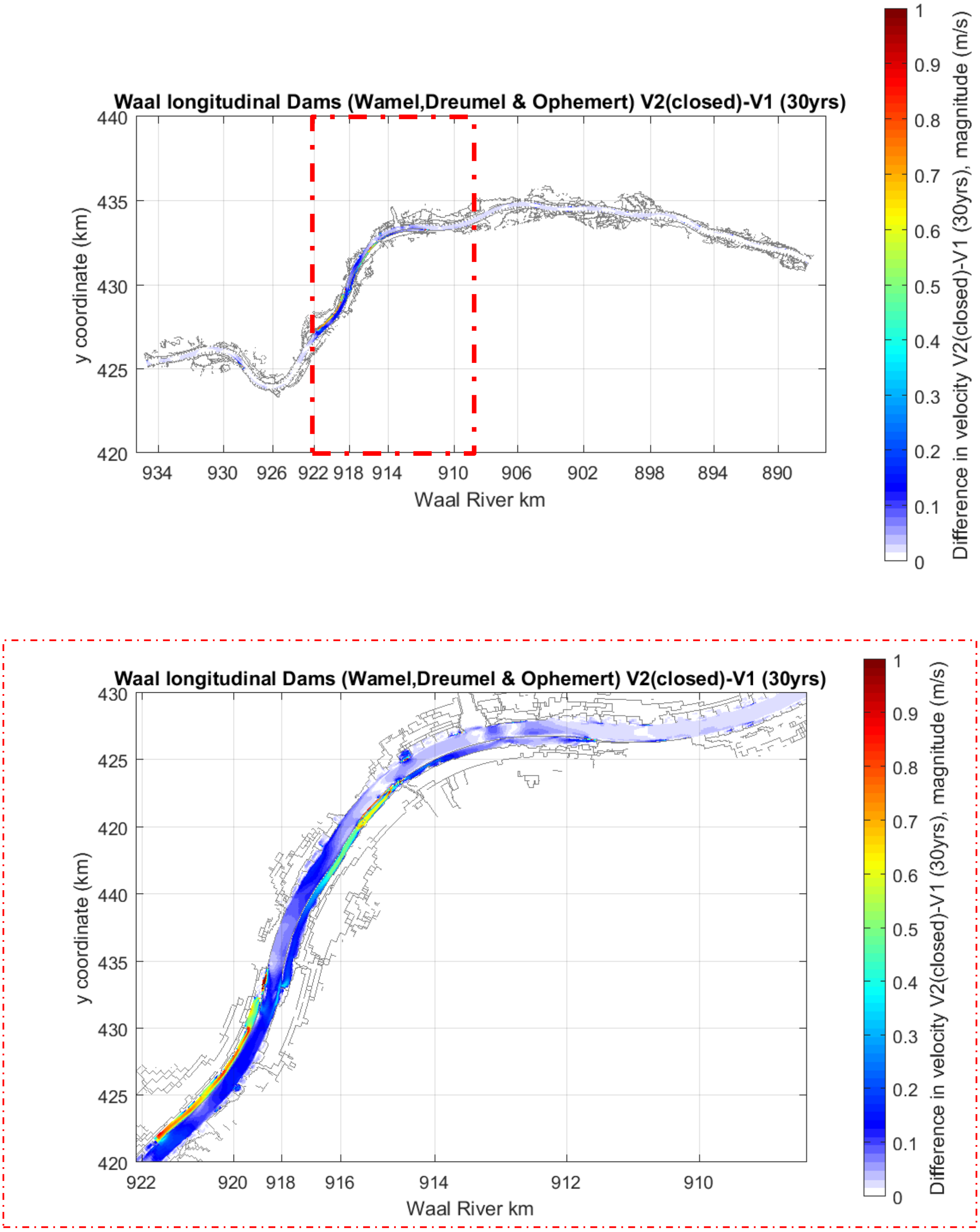



*Figure 4.16 The difference in velocity between V2 and V1 at the end of both simulations. The upper plot displays the map of the whole model domain while the lower plot zooms to the longitudinal dam reach*

## 4.8 V3 vs V1

We compare the resulted bed level, after 30 years, of V3 to V1. In V3 the inlet to the side channel is open according to the as-built survey of the longitudinal dams. In V1, the inlets of the side channels are open slightly differently compare to V3. The difference in the opening between the two variants is shown, for Wamel, Dreumel and Ophemert, in Figure 3.7, Figure 3.8 and Figure 3.9. Accordingly, it seems that the inlet cross-sections of Wamel and Dreumel Dams are enlarged while Ophemert inlet is reduced.

Figure 4.17 illustrates the difference in the end bed level of V3 to V1(different side channel inlet geometry). The model results display the following:

- For Wamel and Dreumel Dams reaches, a tendency for erosion at the inlet entrance of the side channels followed further by deposition. The effect of enlarging the inlet section provides a minor deposition in the main channels
- For Ophemert Dam reach; a tendency of deposition at the inlet of the side channel can be observed from the results. The effect of reducing the inlet section provides minor erosion in the main channel.

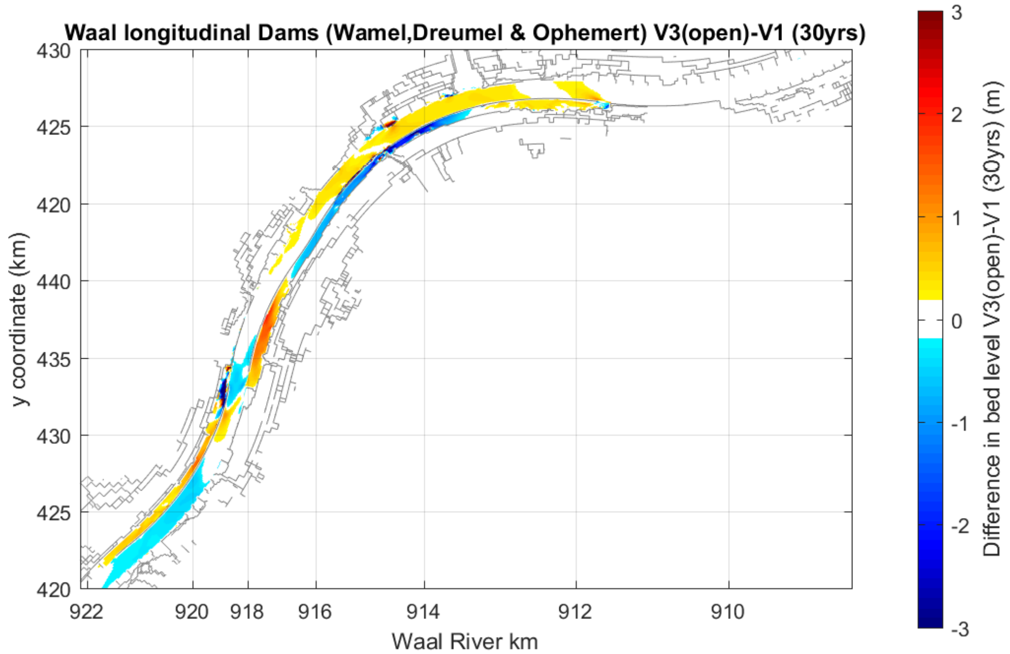



*Figure 4.17 The difference between V3 and V1 in the bed level resulted after 30 years.*

## 4.9 V4 vs V1

The resulted bed level difference, after 30 years, of V4 to V1. In V4 river maintenance (dredging and dumping) included, while the V1 is the reference case. Form Figure 4.18, the following can be observed:

- For Wamel Dam reach, the maintenance of the main channel bed does not have that much influence on the bed level. However, the side channel due to the maintenance become more subjected to deposition.

- For Dreumel Dam reach, a tendency of minor deposition can be seen in the main channel. However, the side channel is less subject to deposition and erosion in V4 compared to V1.
- For Ophemert Dam reach; more tendency of deposition at the side channel can be observed from the results. While less sedimentation is seen in the main channel.

These variants comparison cannot be explained due to maintenance intervention (dredging and dumping). Further details for intermediate differences of bed changes (10 years and 20 years) are shown in Appendix C. However, the results show that this level of deposition is still acceptable to fulfil the maintenance regulations requirements (OLR water depth). Nevertheless, the difference, between the two simulations (V4 & V1) shown in Figure 4.18, is remarkable and uncertain. Therefore, it may require further investigation in evaluation study.

This can be seen in Figure 4.19. Figure 4.19. illustrates the water depth at a discharge close to OLA (818 $m^3/s$) at the centreline of the main channel. The figure displays that all the water depth of all variants after 30 years fulfils the OLR criteria except at km 928. In this location only V4 fulfils the OLR criteria.

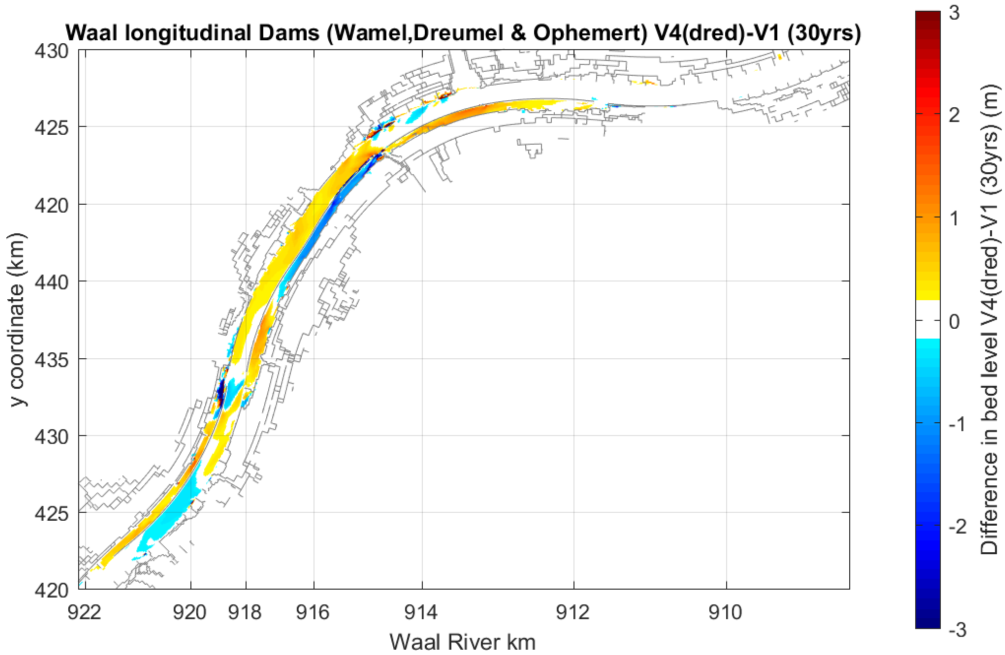
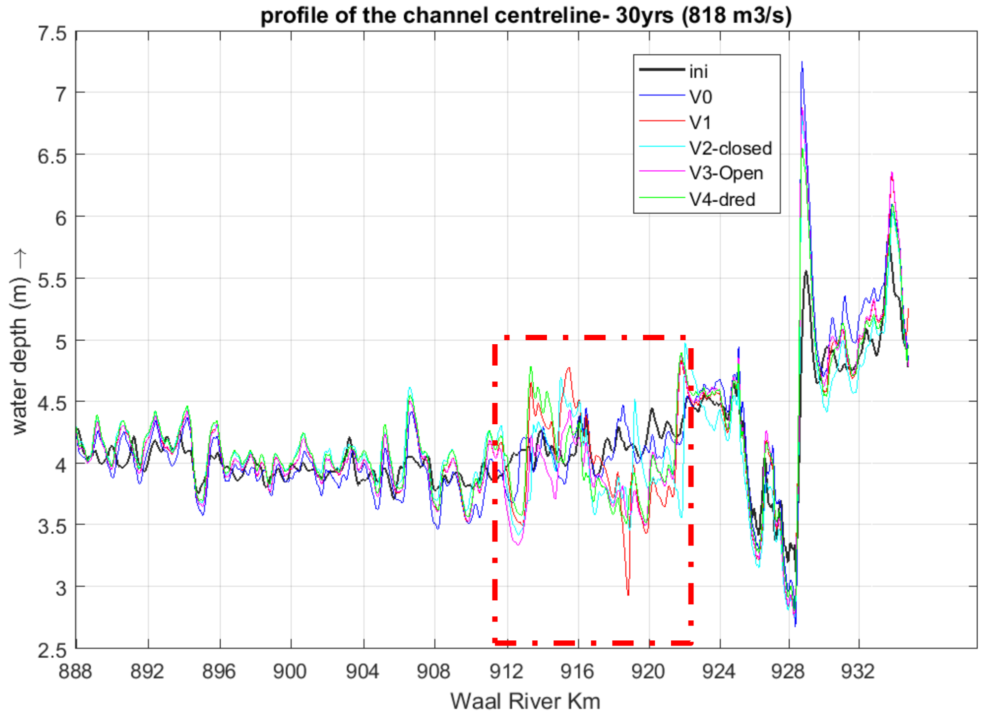



*Figure 4.18 The difference between V4 and V1 in the bed level resulted after 30 years.*



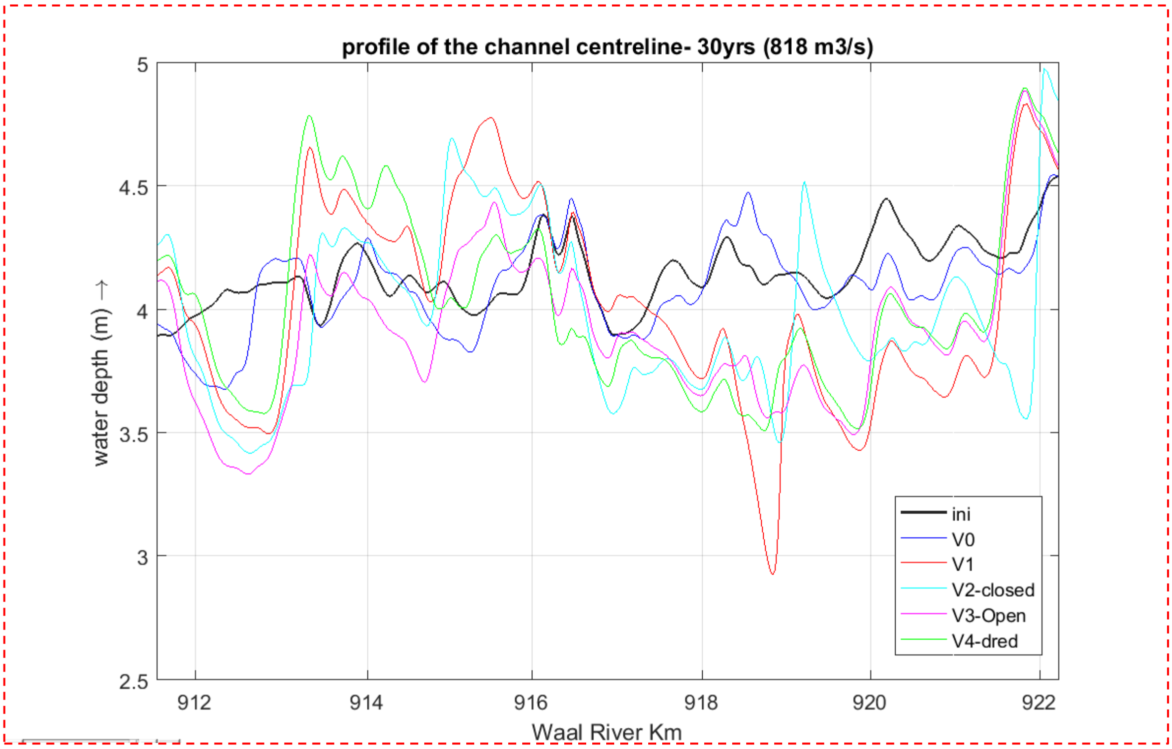




*Figure 4.19 The water depth at the centreline of the main channel at discharge of 818 m3/s. This discharge is close to the OLA of the Waal River (OLA = 820 $m^3$/s). The upper plot displays the water depth for the whole model domain, while the lower plot zooms to the longitudinal dam reach.*

## 4.10 Change in Water levels

Due to the morphological changes, the river water level is expected to change. In the figures below the results of the model for the variant without the dam (V0), the reference case with the dam including opened side channels inlets (V1) and the V2 with the longitudinal dams and closed inlets of the side channels.

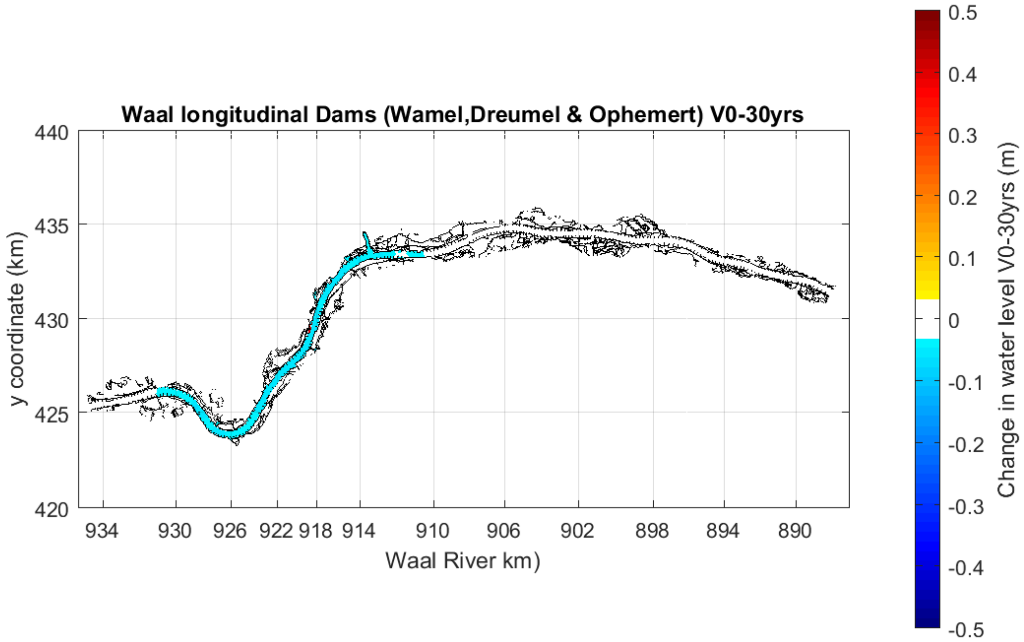



*Figure 4.20 The change in the water level after 30 years for V0 (Q = 1.233 m³/s).*

Figure 4.20, Figure 4.21 and Figure 4.22 show the change in the water level after 30 years, at same discharge value (1,233 $m^3/s$), for V0, V1 and V2, respectively. The presented changes in water-level are directly related to the computed changes in morphology over the period of 30 years. The model result displays that V0 with the groynes water levels downstream km 910 may lower slightly (See Figure 4.20 ). However, the use of longitudinal dams with open inlets to the side channels may lead to an increase in the water level upstream of Km 918 on the long term, while it water levels downstream of km 918 remain practically similar to the start condition (see Figure 4.21). When closing the inlets to the side channels, the rise of the water level (with larger magnitude) would extend further to the reach around km 921(see Figure 4.22).

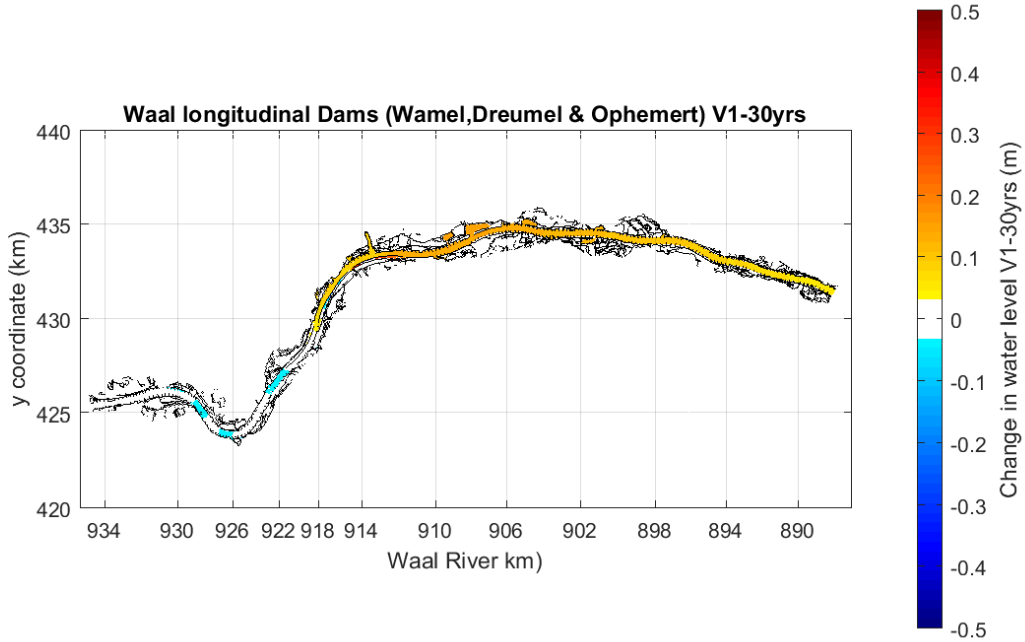



*Figure 4.21 The change in the water level after 30 years for V1 (Q = 1.233 $m^3/s$).*

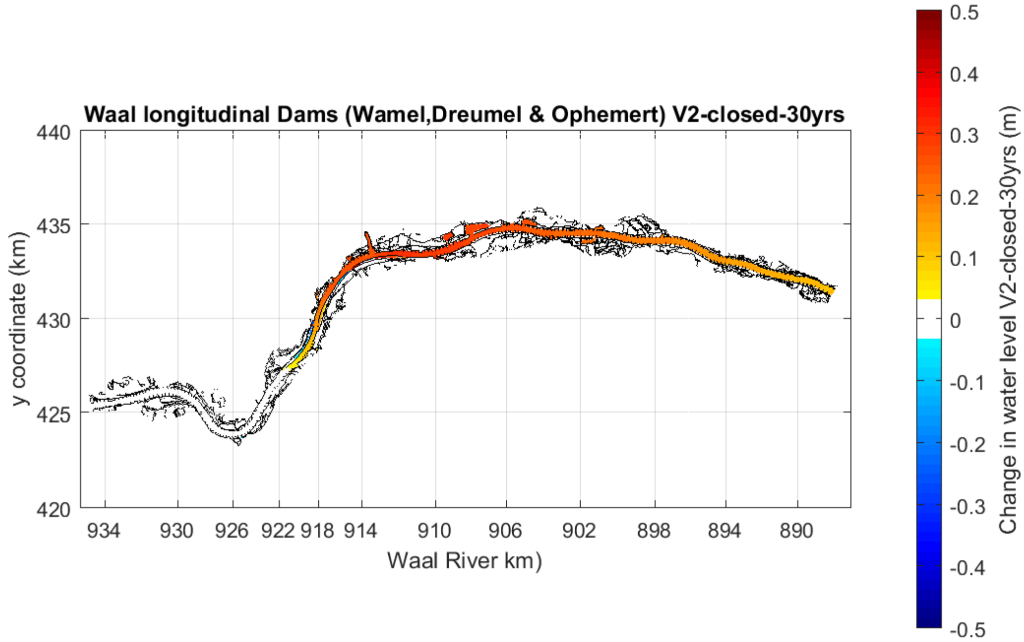



*Figure 4.22 The change in the water level after 30 years for V2 (Q = 1.233 $m^3/s$).*

# 5 Discussion

The study focuses on the impacts on river morphology due to the construction of longitudinal dams in the Midden Waal. The model has not been tuned in detail for hydrodynamics as its main purpose is to model the morphology. Nevertheless, some tuning of parameters and settings have been done during the morphological simulations for the spin-up, but this tuning focused mainly on the parameters for sediment transport and morphology. The hydraulic effects have very much added value to get a better understanding of the morphological changes. Hence, this has not been investigated profoundly in this study and might need to be well-thought-out in the future. It might be also useful for further analyses to join with the efforts exerted in the project of Rijn River flexible mesh schematization. In that way, the calibration efforts (and resulting schematisations and parameters, such as side-channel roughness and/or weir parameters of inflow openings) may contribute to these models as well.

Due to time and budget limitations, the morphologic adjustment is not optimal. The remaining tasks which can lead to proper calibration according to the calibration and verification protocol will be given as a recommendation.

The model setup of the reference case (V1) is built based on the schematization of baseline Rijn_j18. In this schematization, there is no weir included for the sill at the inlet of the side channel. When this inlet is closed in V2, the adjacent crest dam level is extended to close the whole inlet. The weir on top of every longitudinal dam crest is then also extended. This may create discrepancy when comparing V2 with V1 or V3. During high flows, energy losses are calculated at the closed inlet due to the sub-grid weir when the dams are overtopped, but not during the low flow when the dams are not overtopped. On the other hand, including weirs on top of the inlet sill for V1 and V3 (which is not the case in this study) provides energy losses during the low flow and high flow of these simulations.

The model is set-up and refined to fulfil the case study objectives. Further use of the model for different objectives may require a different level of resolution.

The study has the following limitation and restriction of the conclusion:

- The groynes in V0, at the location of the longitudinal dams, are represented using weirs only. These groynes are replaced by the longitudinal dams and side channels in the other scenarios (V1 to V4). The longitudinal dams are represented using the combination of bed topography change and weirs. This may create some discrepancies in the comparison.
- There is a level of uncertainty in the inflow (the step-wise hydrograph) used in the model. These discharges are the average discharges of the Waal River. It should be realised that 90% of the annual inflow discharge creates a water level higher than the longitudinal dam crest. This limits the low flow influence to the morphological results.
- The flow in the side channel interferes with the flow in the main channel. Morphological changes in the side channel will cause a redistribution of flow between main-channel and side channel which seems to have a major impact on morphology. However, the morphological change behind the dam is not calibrated and the large morphological changes in these side channels cannot be considered accurate. Interpretation should therefore be done with care.

- Based on the data, Baseline Rijn-j18 does not reflect the initial dam-geometry (e.g. inflow openings) and not the actual 2018 geometry (reduced openings). So, the variants are mainly meant for comparison to each other, rather than to be compared with the actual measurements. Thus, schematization creates uncertainty in the results.

# 6 Conclusion and recommendations

## 6.1 Conclusion

The study aims to gain a better understanding of the impacts of the longitudinal dams to the river morphology. In addition, it aims at providing a numerical model that can be used further to perform scenarios for the final evaluation of the longitudinal-dam pilot project in the Midden Waal. Five variants (simulations) are computed and their results are compared. Given that, the following could be concluded:

- Based on the Waal step-hydrograph used, more than 90 % of the time (annually), the longitudinal dams are submerged or overtopped partially. This means that the impact of closing the side channel on morphology is relatively small and might not be clearly distinguished.
- When comparing model results with measurements, the discharge distribution between the main channel and the side channels is found to be well simulated, except for the reach at the Ophemert Dam during low flow conditions. The model shows that less water passes through that side channel compared to the measurements. This might be caused by different bed levels in the main channel after the spin-up compared to the measurement, or by differences in the inlet opening used in the model (Baseline_rijn_j18) compared to the real opening at the time of the measurements (Oct 2017 and Jan 2018).
- The result of reference simulation V1 (the river reach with the dams) shows that the bed at the dam reach is very active morphologically compare to V0 (the river reach without the dams). This might be due to the fact that with the spin-up the V0 schematization results in a rather stable bed evolution, while in V1 the dams are implemented without a new spin-up. The dynamics in the first years of the V1 calculation are therefore the initial adjustments of the morphology to the measures.
- For V1 (the simulation with the measure) the model results show that:
  - The main channel shows deposition at the beginning of Wamel Dam reach (~km 912). This can be due to the fact the river cross-section becomes wider with two side channels.
  - The main channel shows deposition at the end of Dreumel Dam reach (~km 918). This can be caused by the local flow entering the main channel from the Dreumel outlet.
  - The main channel of Ophemert dam reach shows deposition (km 919~km921). This deposition can also be observed in the measurements. Nevertheless, the outflow of Dreumel side-channel might have an influence. Since its direction may lower the velocity of the main channel flow (local velocity retarding).
  - In most cases, when the main channel shows deposition, the side channel shows erosion and vice versa. The details of redistribution of flows between main channel and side channel appears to drive these processes. The model accuracy may benefit from a good and well validated computation of the distribution of flows between the main- and side channels.
- For V2 (as V1 but the inlet of side channels is closed to the dams’ crests), the model results show that:
  - Closing of Wamel side-channel inlet creates small changes in the flow redistribution and causes small changes in the main channel bed.
  - Closing of Dreumel side-channel inlet may have created more tendency to deposition in the main channel and erosion in the side channel. This might be because the erosion of the side channel attracts more discharge.

   – Closing of Ophemert side-channel inlet creates less deposition in Ophemert main channel. This also created tendency of deposition at and around the outlet of Dreumel and inside the Ophemert side channel. This redistributes more discharge to the main channel of Ophemert.
- For V3 (similar to V1 but the cross-sections of the inlets are different), the geometry of inlets is obtained from the as-built survey (implemented after dams' construction). These geometries are slightly different from the baseline Rijn_j18 inlet geometries. The simulation provides more insight into the sensitivity of the inlet opening to the flow distribution and morphology. Based on cross-sections comparison figures shown in section 3.3. The following table can be provided.

| **The dam** | **Inlet opening section** | **Effect on main channel deposition** |
|---|---|---|
| Wamel | V3 > V1 | The difference between both variants is minor |
| Dreumel | V3 > V1 | V3 has more deposition than V1 |
| Ophemert | V1> V3 | V1 has more deposition than V3 |

- For V4 (like V1 but includes the river dredging and dumping), the simulation maintains the minimum depth of channel navigability. This simulation displays deposition at almost similar locations as V1 with a more spatially varying distribution. Probably because of the dredging and dumping implemented in this variant within the model domain. This means despite the deposition tendency in V1 the main channel might be still very well navigable. The model results show that only the area around km 928 may need attention for maintenance. Nonetheless, this investigation made only for the centreline which is obtained from the Baseline -j18. Additionally, the comparison between V4 and V1 shows a remarkable difference. Therefore, further analysis might be needed to investigate more the impact of the channel maintenance.
  The model results display that the longitudinal dams provide more room in the river cross-section. The narrowing of the low-flow channel would be enough to minimize the deposition that occurs at high-flows when extra "room" is switched on (the side channel conveyance). Local deposition is occurred, mainly in three locations within the main channel (Ds-km 912, around km 918 and between km 919~km 921). Further investigation might be needed for the latter two locations as applying the measures mentioned above may mitigate the tendency of deposition there.
- The model shows, that after 30 years (in V1), the water level upstream of the dams and at the reach next to the dams may increase between 5-10 cm and 0-5 cm, respectively at high discharge of 1,233 $m^3/s$. The model also illustrates that water level in the scenario without the longitudinal dams may lead to lower water level at the dam reach and further downstream at high discharges of 1,233 $m^3/s$.

## 6.2 Recommendations

The results of the simulations show that the model provides a general insight in the processes that occur near the longitudinal dams that affect the long-term large-scale morphology of the river. The outcomes of this study are only valid for the Midden-Waal and should not be projected on future developments of longitudinal dams in other parts of the river without further careful interpretation and understanding.

The simulations do still not yet provide the full picture of the detailed performance of the longitudinal dams that can be used to optimise and evaluate them. Therefore, a few recommendations are added here to support further analysis:

- Examine the cross-section area of the flow at a number of cross-sections along the model domain; especially Between V1 and V0 or the difference in the conveyance (velocity (u) times depth(h)).
- The model results display that the morphological changes in the side channel are quite large and that this has an influence on the main channel bed changes and discharge distribution. Therefore, it might be useful to make further investigations to the full and partial fixation of the side channels beds.
- Base on the simulation results, the river morphology including longitudinal dams does not reach a (dynamic) equilibrium after 30 years. Extending the duration of the simulation period might be useful to investigate when the river will approach an equilibrium condition.
- It is recommended to include a weir on top of the inlet of the three side channels in the coming baseline schematization.
- Investigate the further possibility of performing structural measures to minimize the deposition tendency at km 918 and km919~km 921. It might be wise to do local investigation around the outlet of the Dreumel Side channel. For instance, removing or lowering the groyne just downstream of Dreumel outlet and modify the bank to ensure smooth confluence of Dreumel channels. The effect of these measures should be considered in combination with possible stabilisation of the bed of the side channels or the distribution of discharges between main channel and side channel over the top of the dams during high flows.
- The navigation maintenance setup of the model may need to be altered to cope with the actual maintenance that is used in the Waal river.
- In the simulations, only 10% of year the discharge is low enough to cause the water level to remain below the crest of the longitudinal dam. It is recommended to investigate further the opening and closing of the side channel during the low flow, as its impact seems to occur for short periods with low rates of sediment transport.
- It is recommended to investigate the sediment transport volumes inside the side channels based on different inlet opening. This was not conducted in this study due to the limitation of time and resources.

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# A Spin-up results

The spin-up is conducted for 10 years. Many runs have been performed to achieve the results below. The main changes in the final run used are:

- The Espir (spiral flow factor) used is 1.25.
- The fixed layer roughness is changed to be same as the alluvium bed.
- The fixed layer of the groyne has been extended towards the main channel centreline around 20 m from the edge of the groyne.

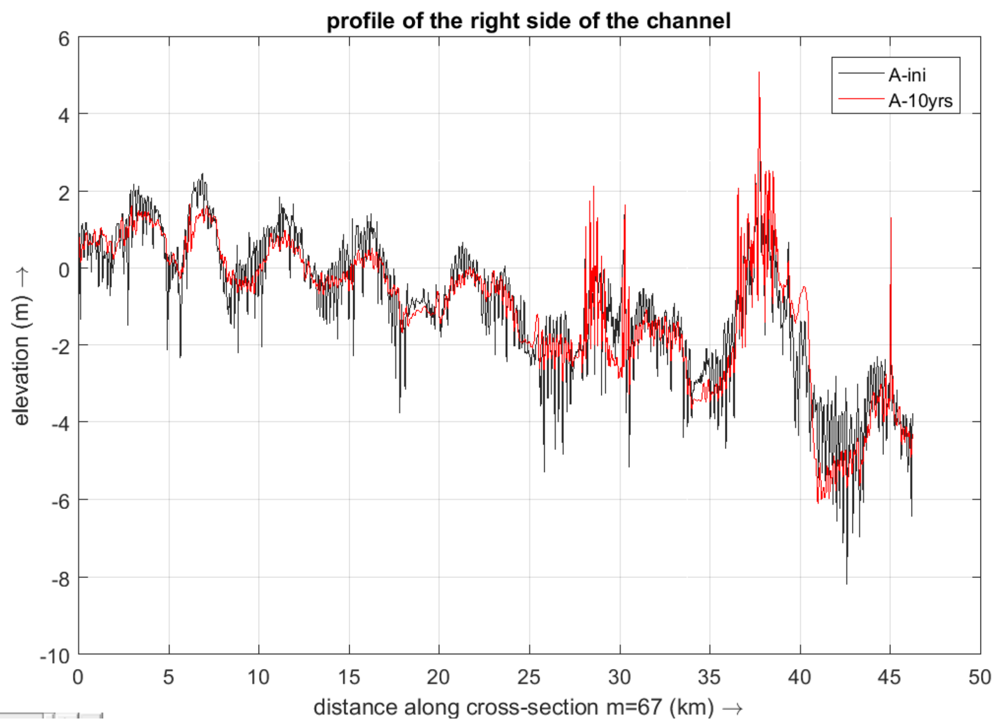


*Figure A.1 The bed level longitudinal profile of the right side of the main channel. The figure shows a comparison between the initial condition(A-ini) and after 10 years (A-10yrs)*

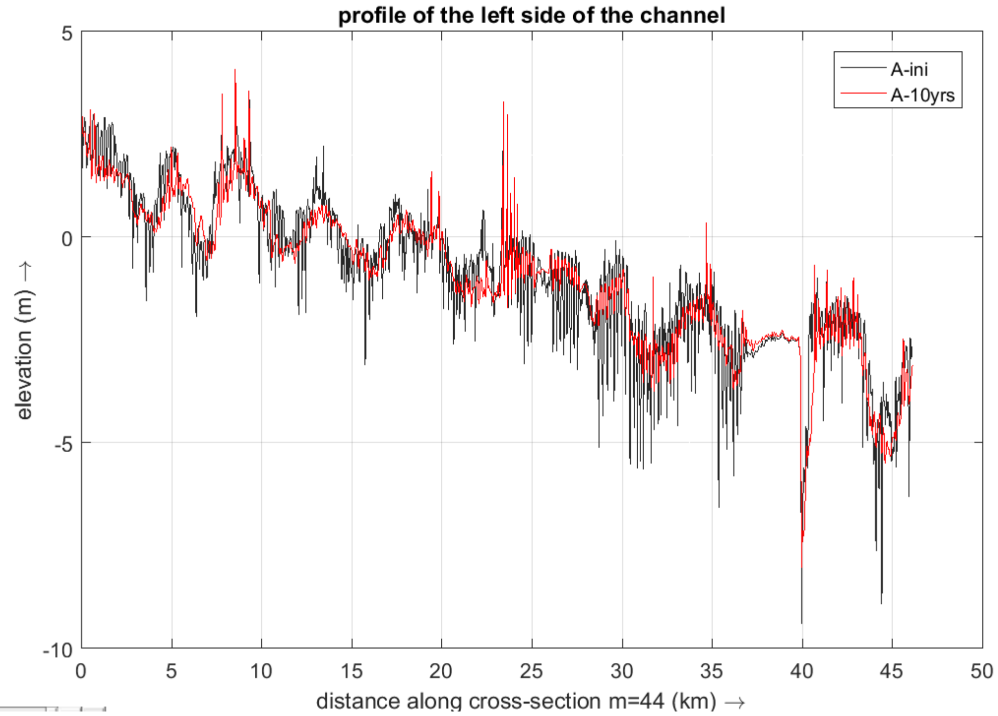


*Figure A.2 The bed level longitudinal profile of the left side of the main channel. The figure shows a comparison between the initial condition(A-ini) and after 10 years (A-10yrs)*

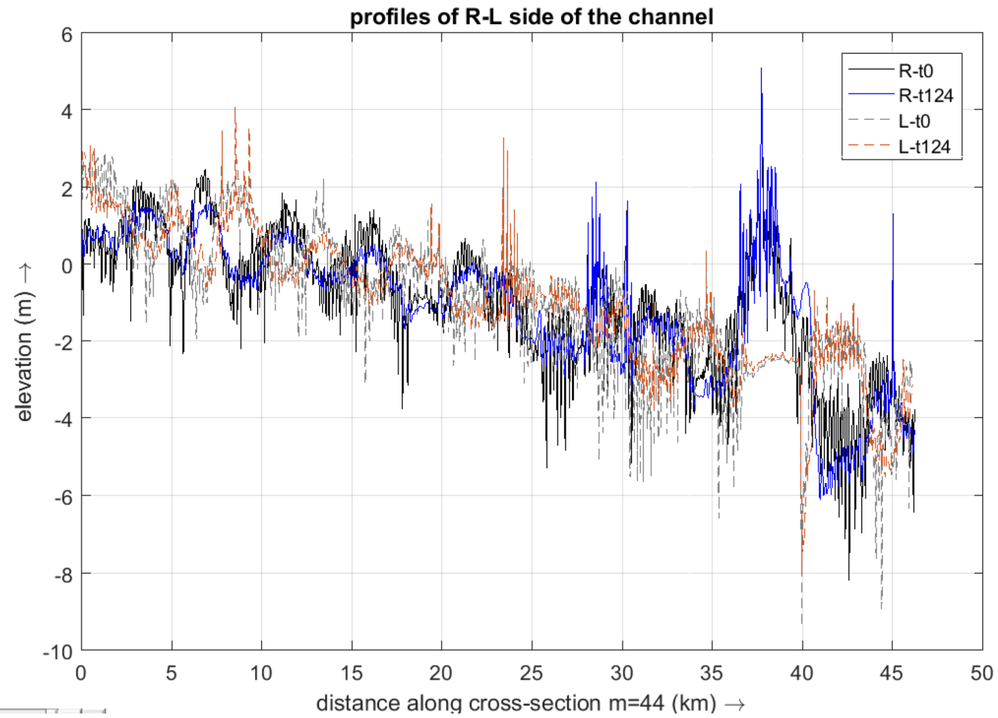


*Figure A.3 The bed level longitudinal profiles of both sides (left(L) and right (R)side) of the main channel. The figure shows comparison between the initial condition (R t0 and L t0) and after 10 years (R t124 and L t124).*

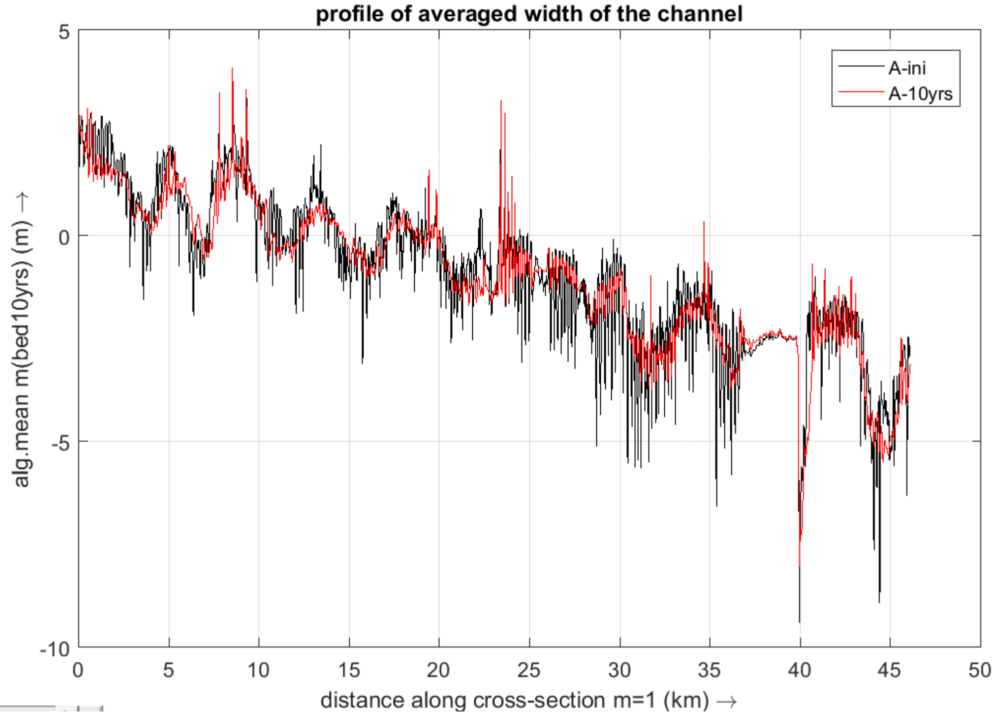


*Figure A.4 The average width bed level of the main channel. The figure shows a comparison between the initial condition(A-ini) and after 10 years (A-10yrs)*

# B Bed changes maps

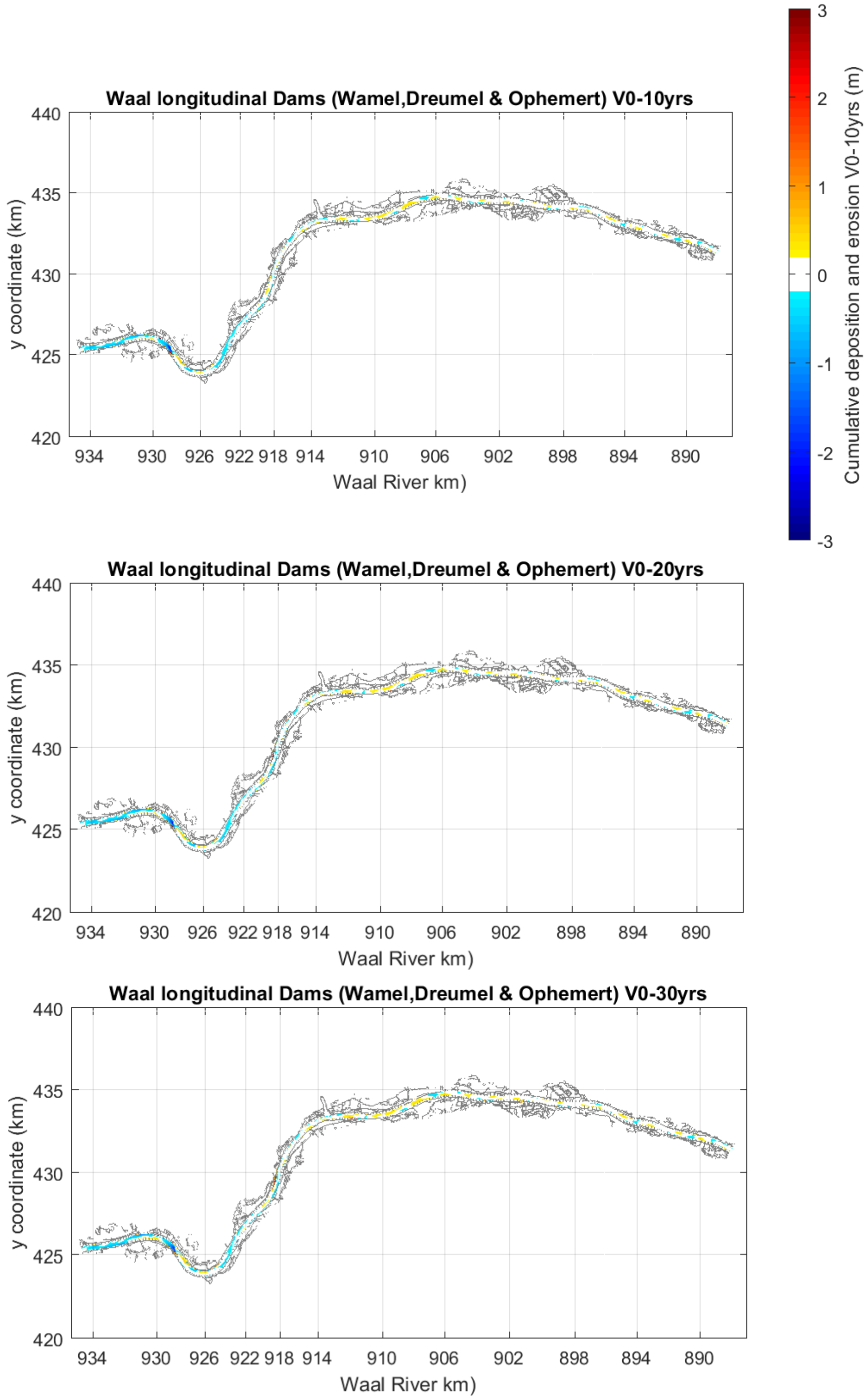


*Figure B.1 Maps of cumulative deposition and erosion of V0 after 10 years, 20 years and 30 years. The colour bar applies for all plots*

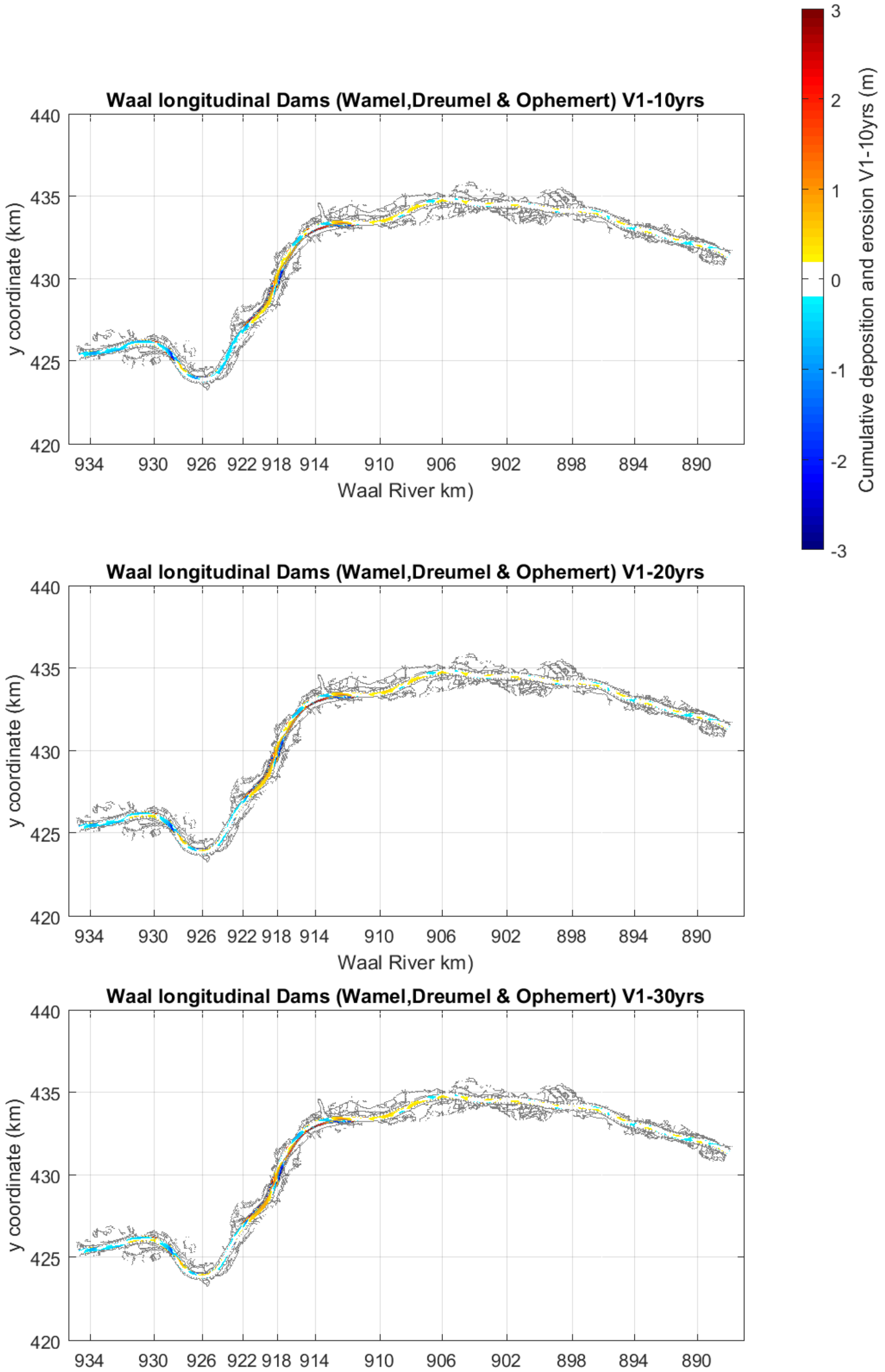


*Figure B.2 Maps of cumulative deposition and erosion of V1 after 10 years, 20 years and 30 years. The colour bar applies for all plots*

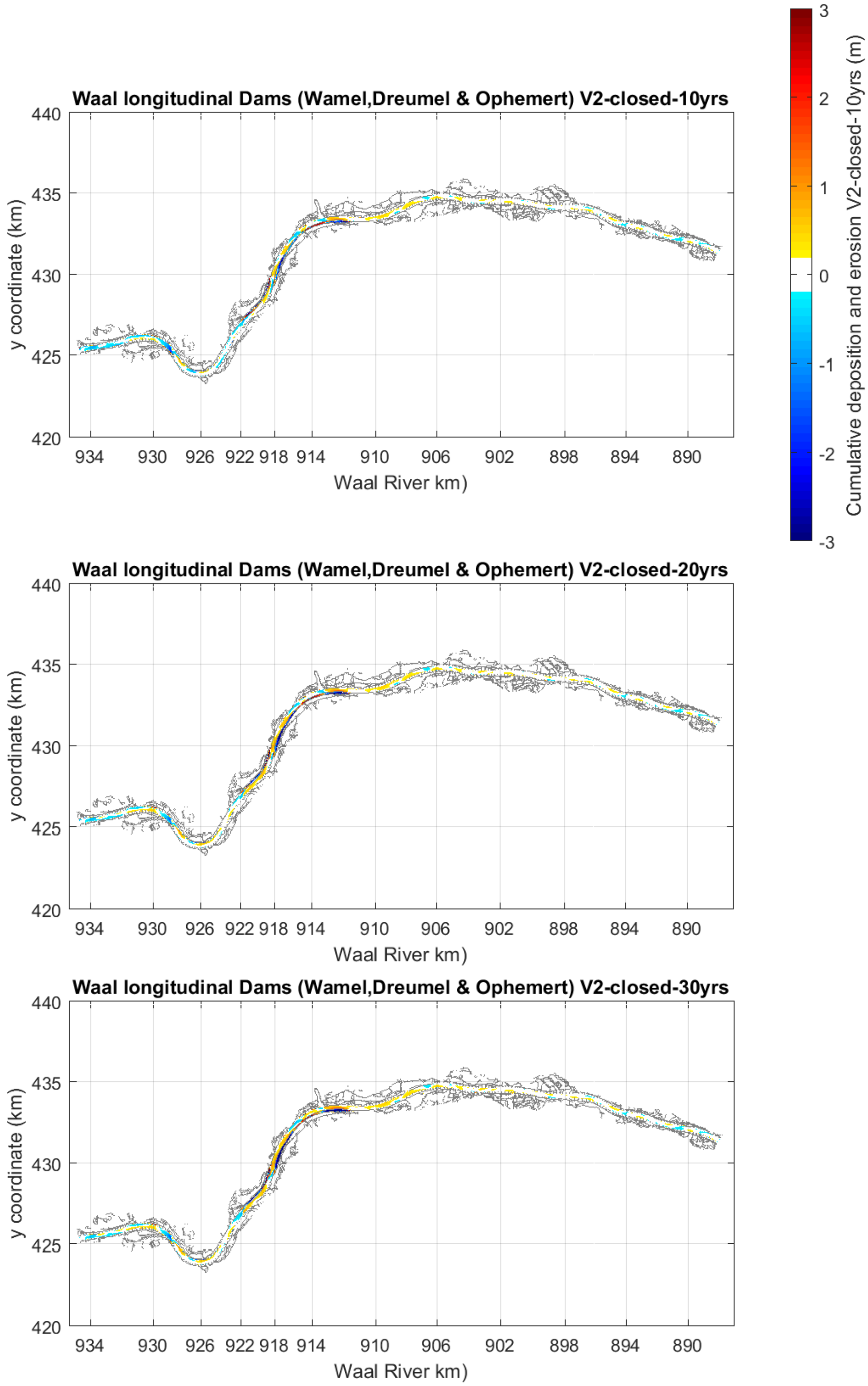


*Figure B.3 Maps of cumulative deposition and erosion of V2 after 10 years, 20 years and 30 years. The colour bar applies for all plots*

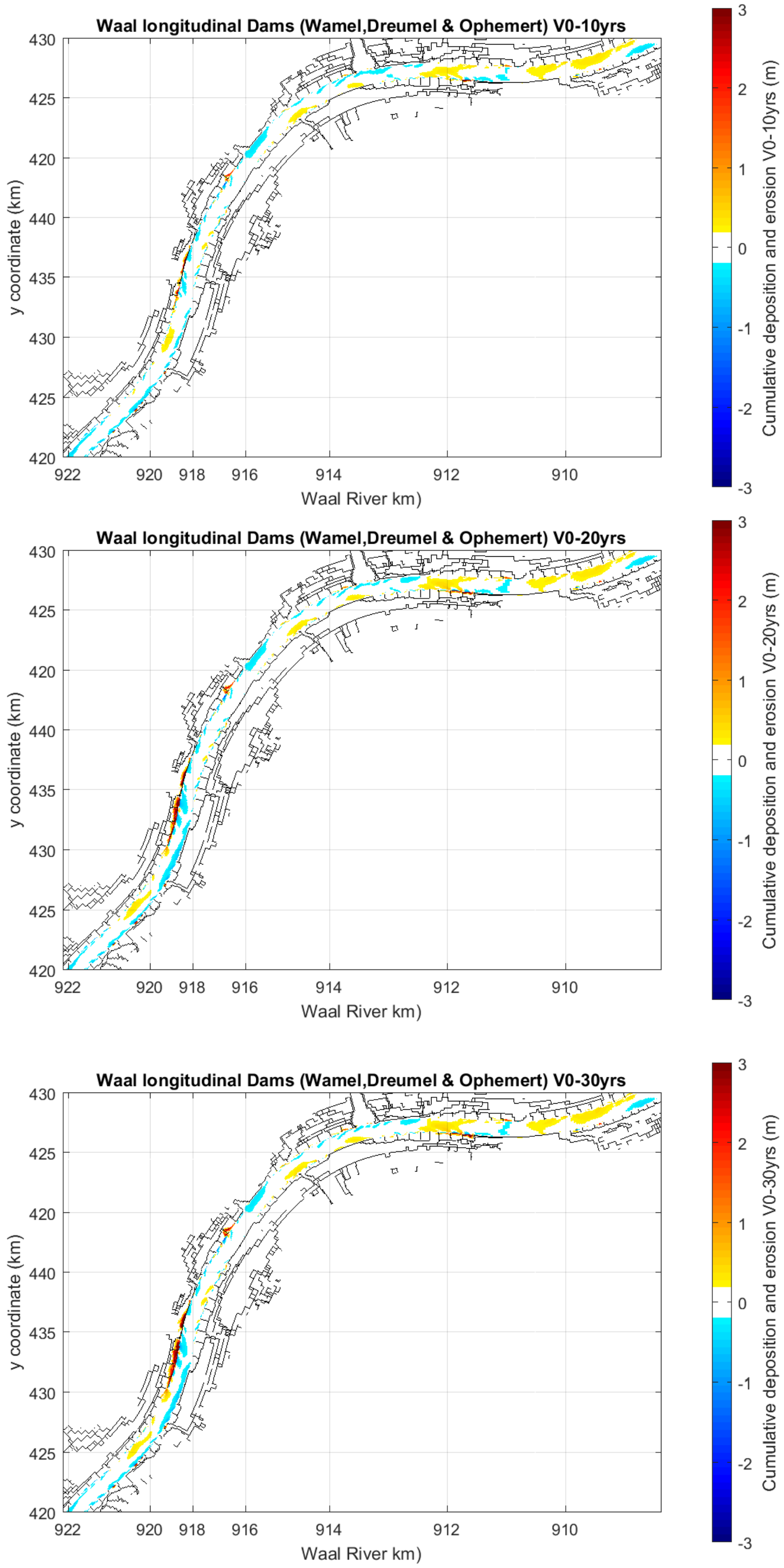


*Figure B.4 Maps of cumulative deposition and erosion of V0 after 10 years, 20 years and 30 years at the location where the dams are included in other simulations.*

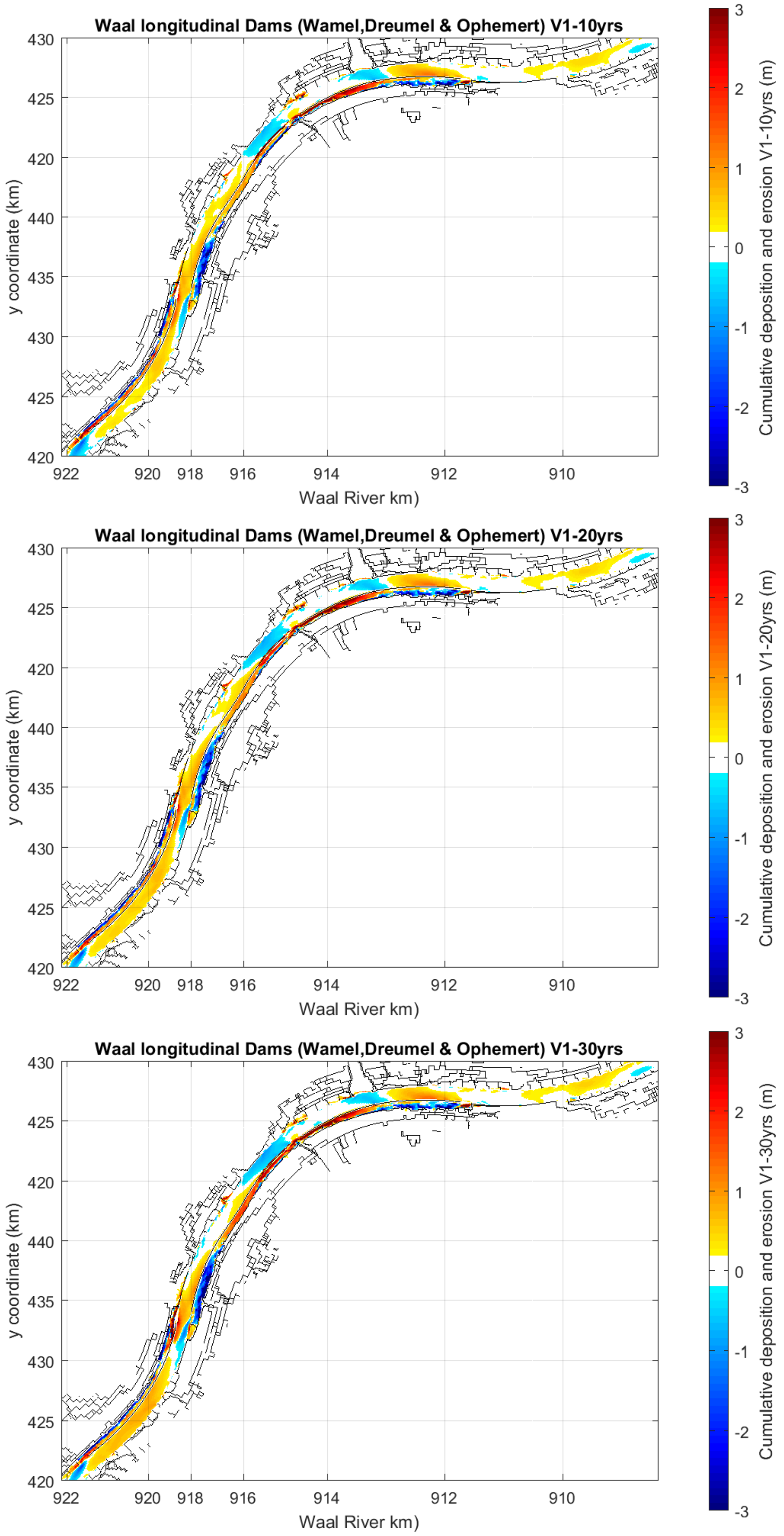


*Figure B.5 Maps of cumulative deposition and erosion of V1 after 10 years, 20 years and 30 years at the location of the longitudinal dams.*

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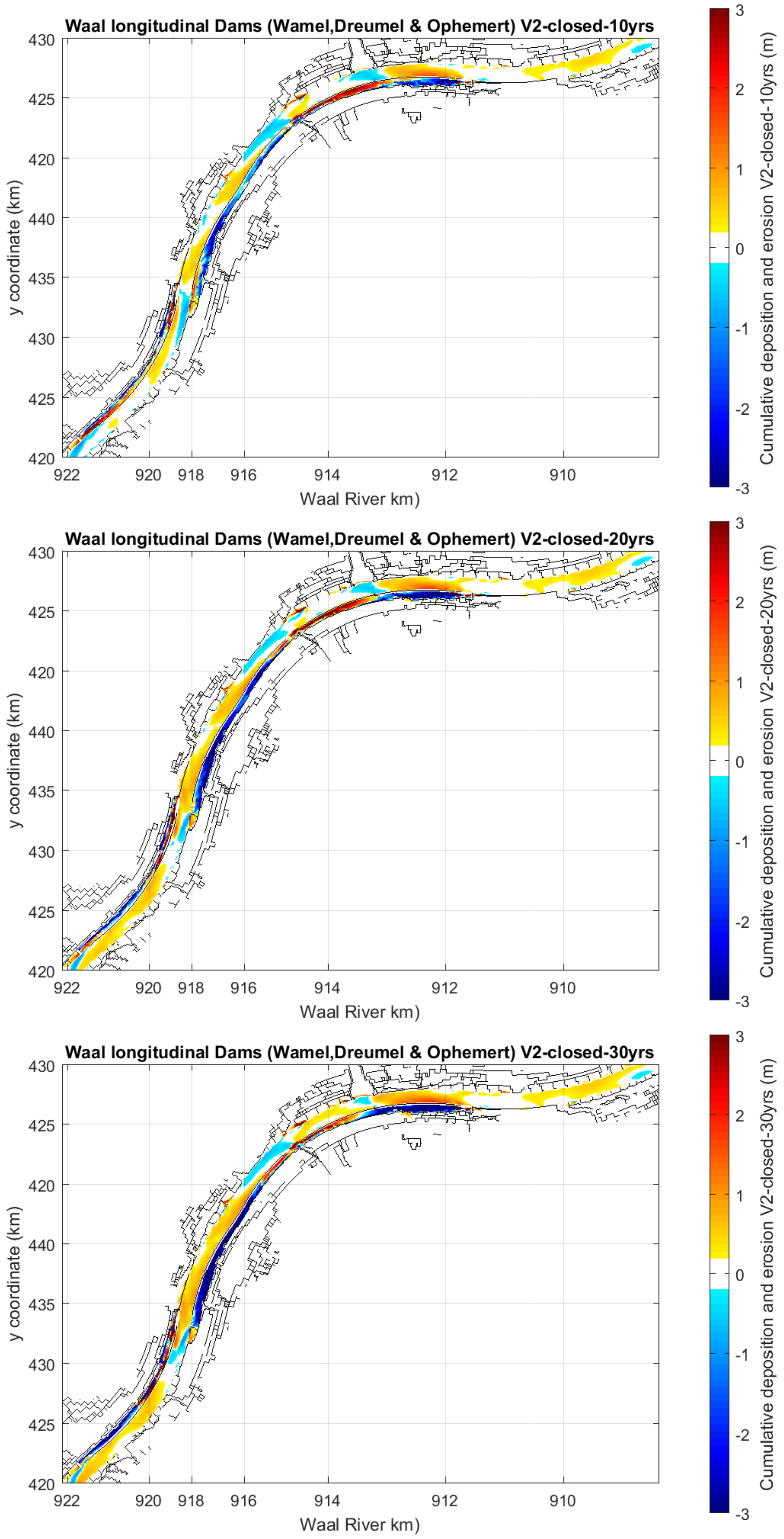



*Figure B.6 Maps of cumulative deposition and erosion of V2 after 10 years, 20 years and 30 years at the location of the longitudinal dams.*

# C Difference in bed levels

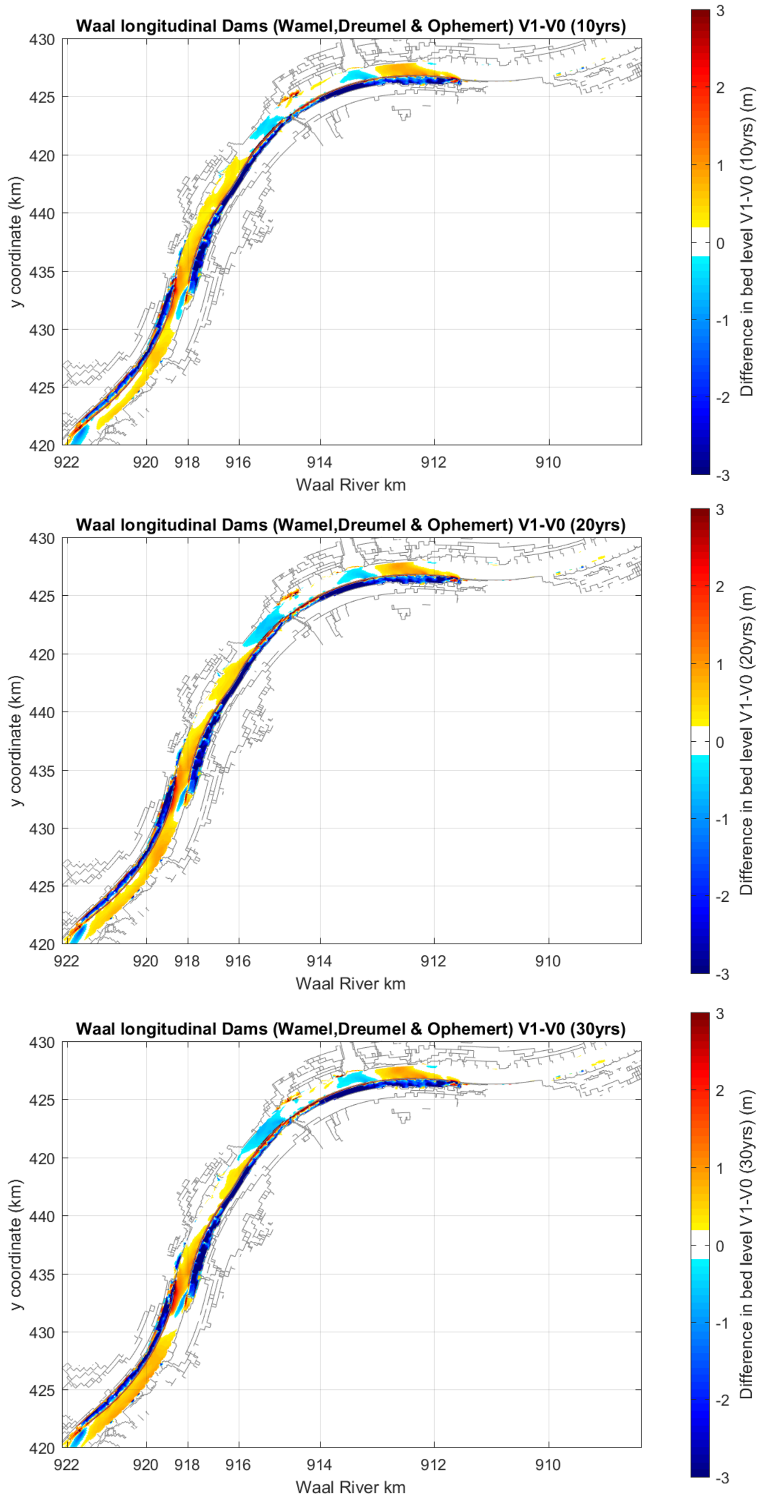



*Figure C.1 Maps of the difference in cumulative deposition and erosion of V1-V0 after 10 years, 20 years and 30 years at the location of the longitudinal dams.*

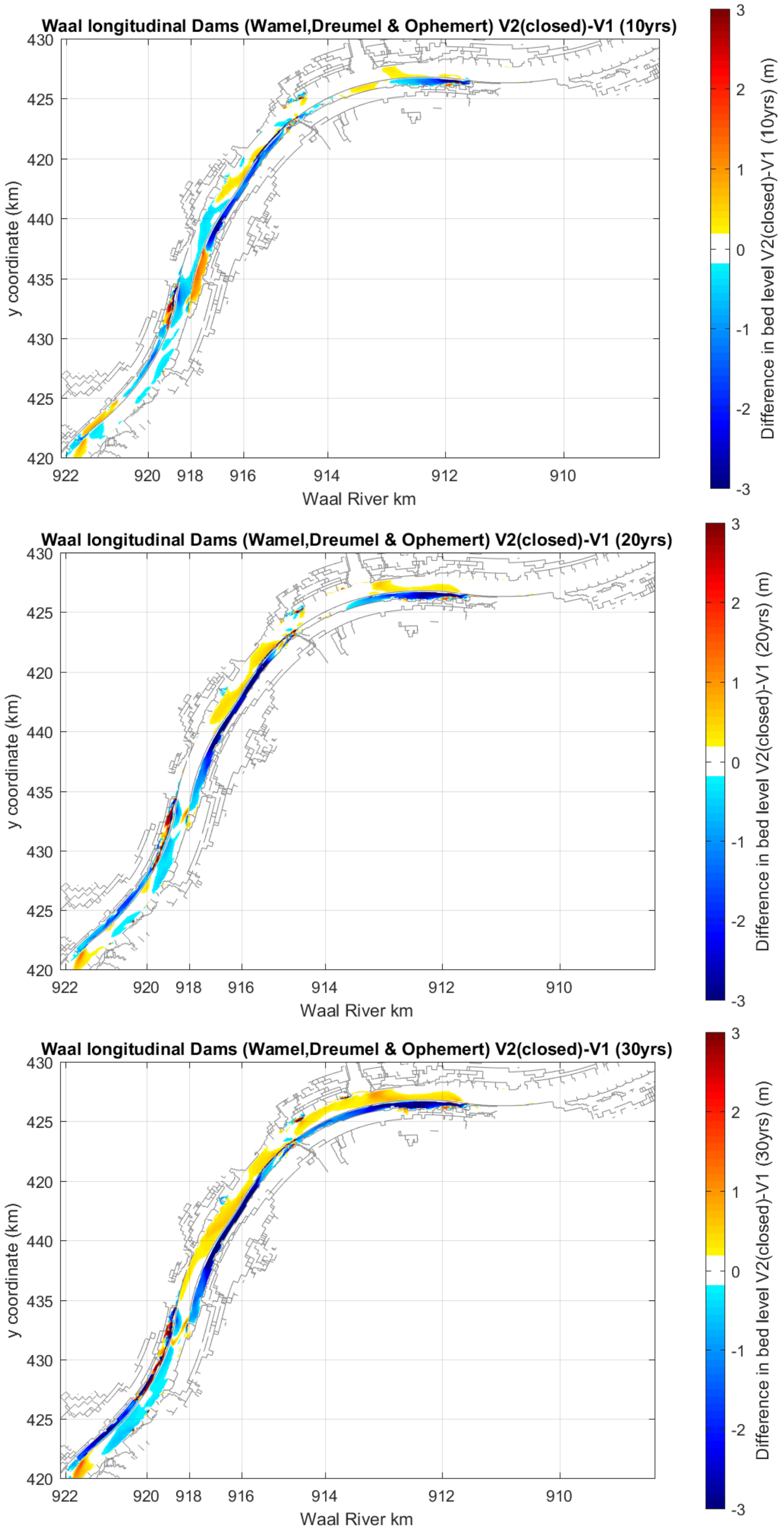



*Figure C.2 Maps of the difference in cumulative deposition and erosion of V2-V1 after 10 years, 20 years and 30 years at the location of the longitudinal dams.*

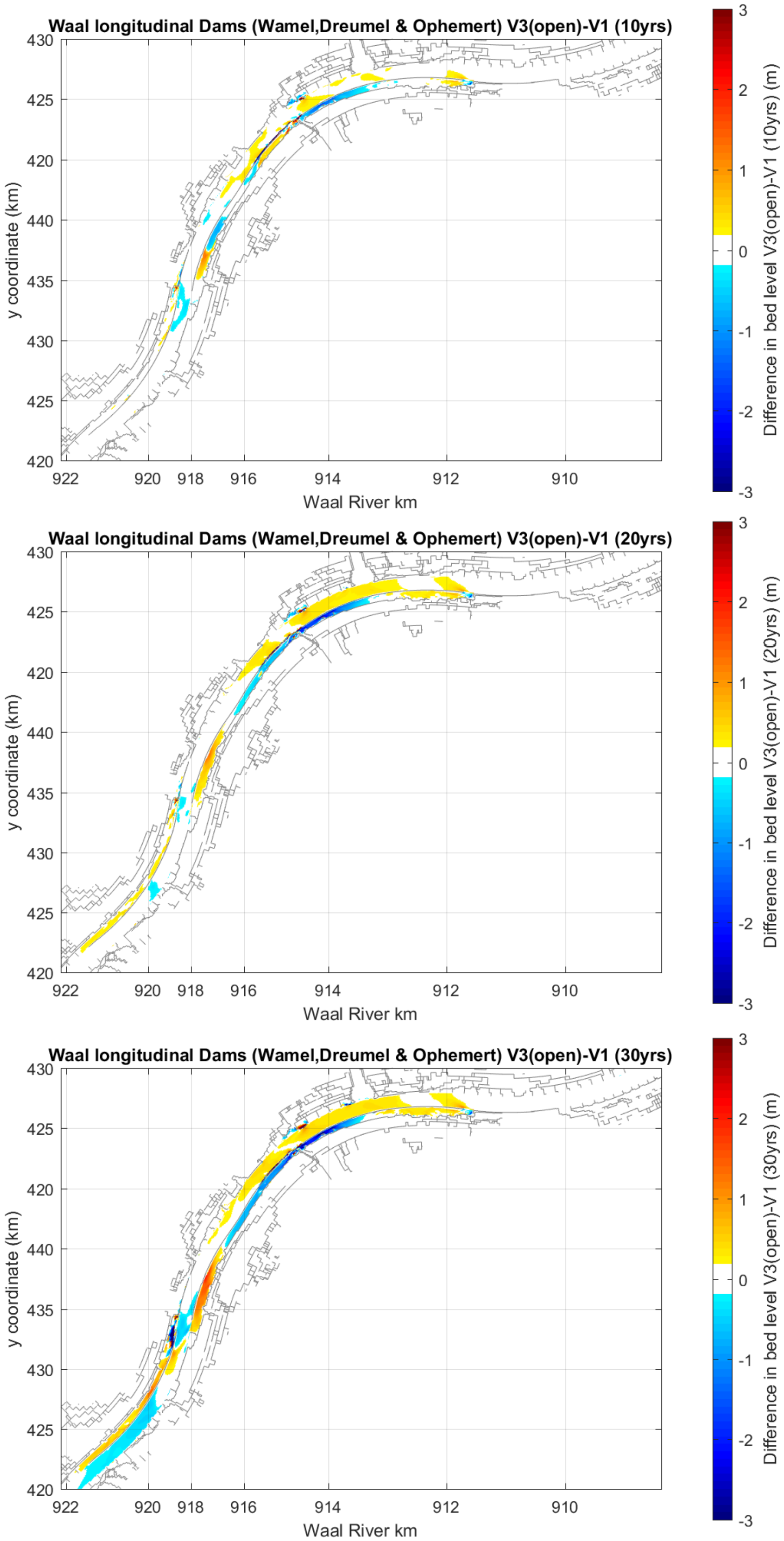



*Figure C.3 Maps of the difference in cumulative deposition and erosion of V3-V1 after 10 years, 20 years and 30 years at the location of the longitudinal dams. V3 side channels have the as-built inlet opening-shapes, while V1side channels have Baseline -j18 inlet opening-shapes*

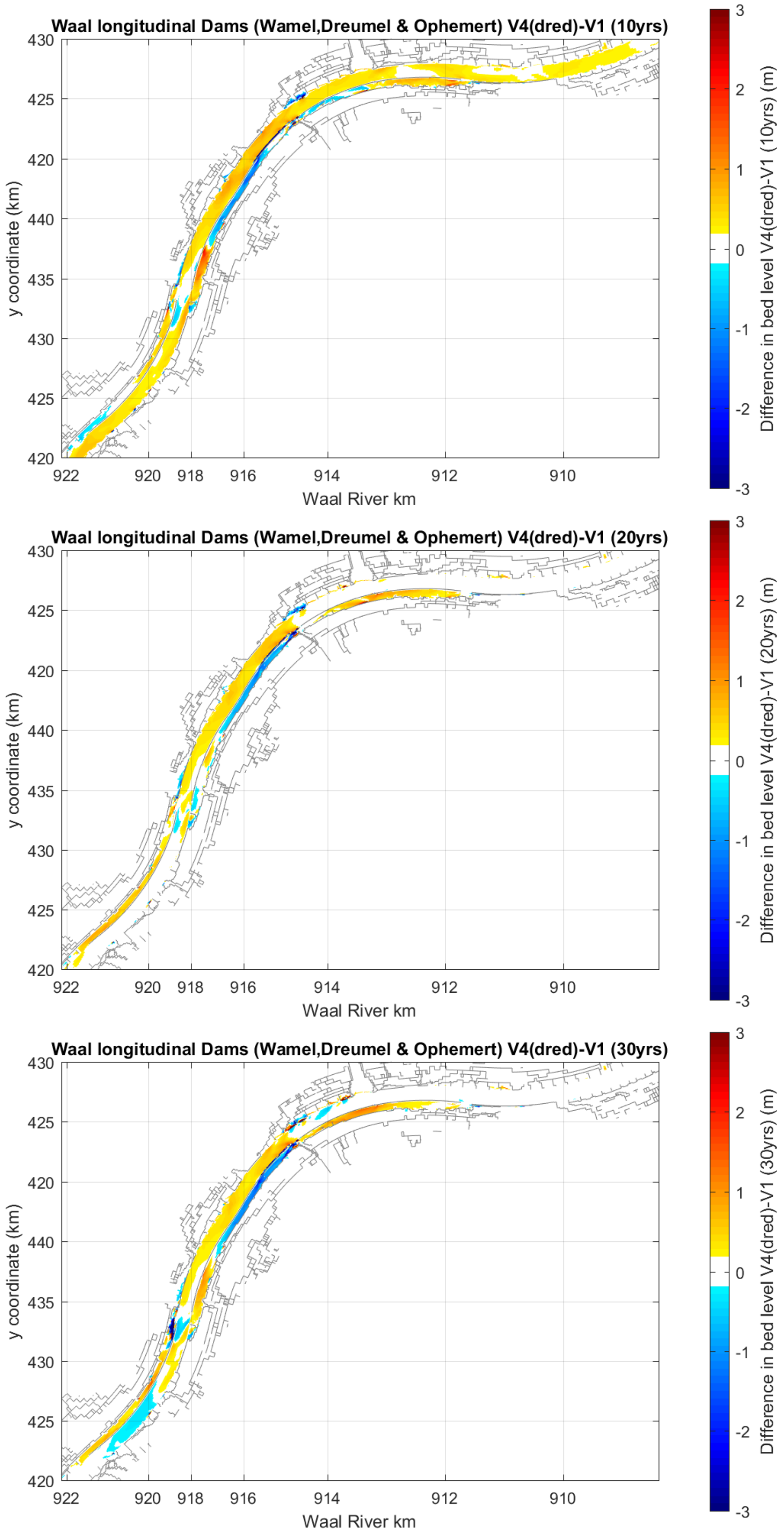



*Figure C.4 Maps of the difference in cumulative deposition and erosion of V4-V1 after 10 years, 20 years and 30 years at the location of the longitudinal dams.*

# D Difference in velocities

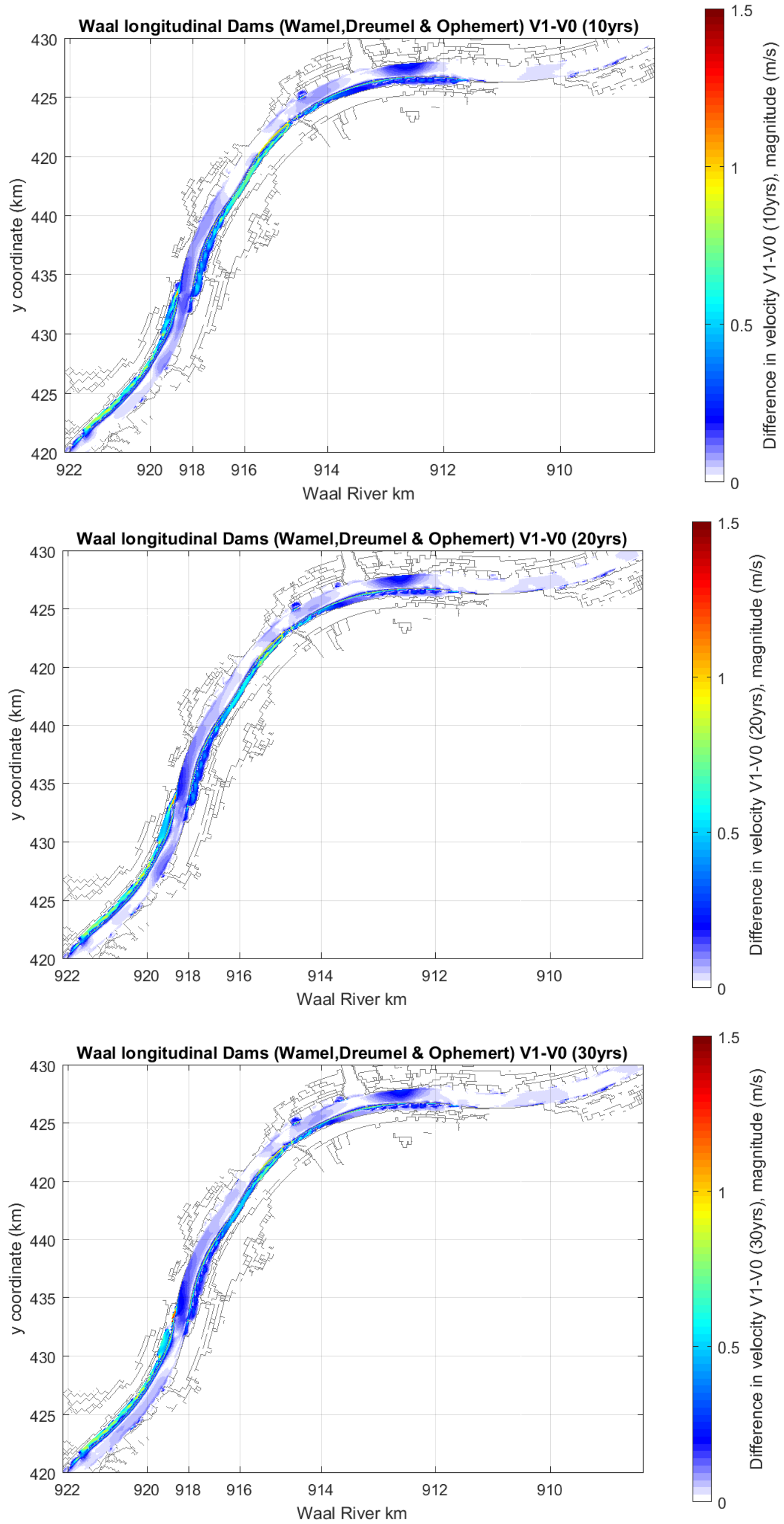



*Figure D.1 Maps of the difference in the magnitude of depth average velocity of V1-V0 after 10 years, 20 years and 30 years at the location of the longitudinal dams (1,233 $m^3/s$).*

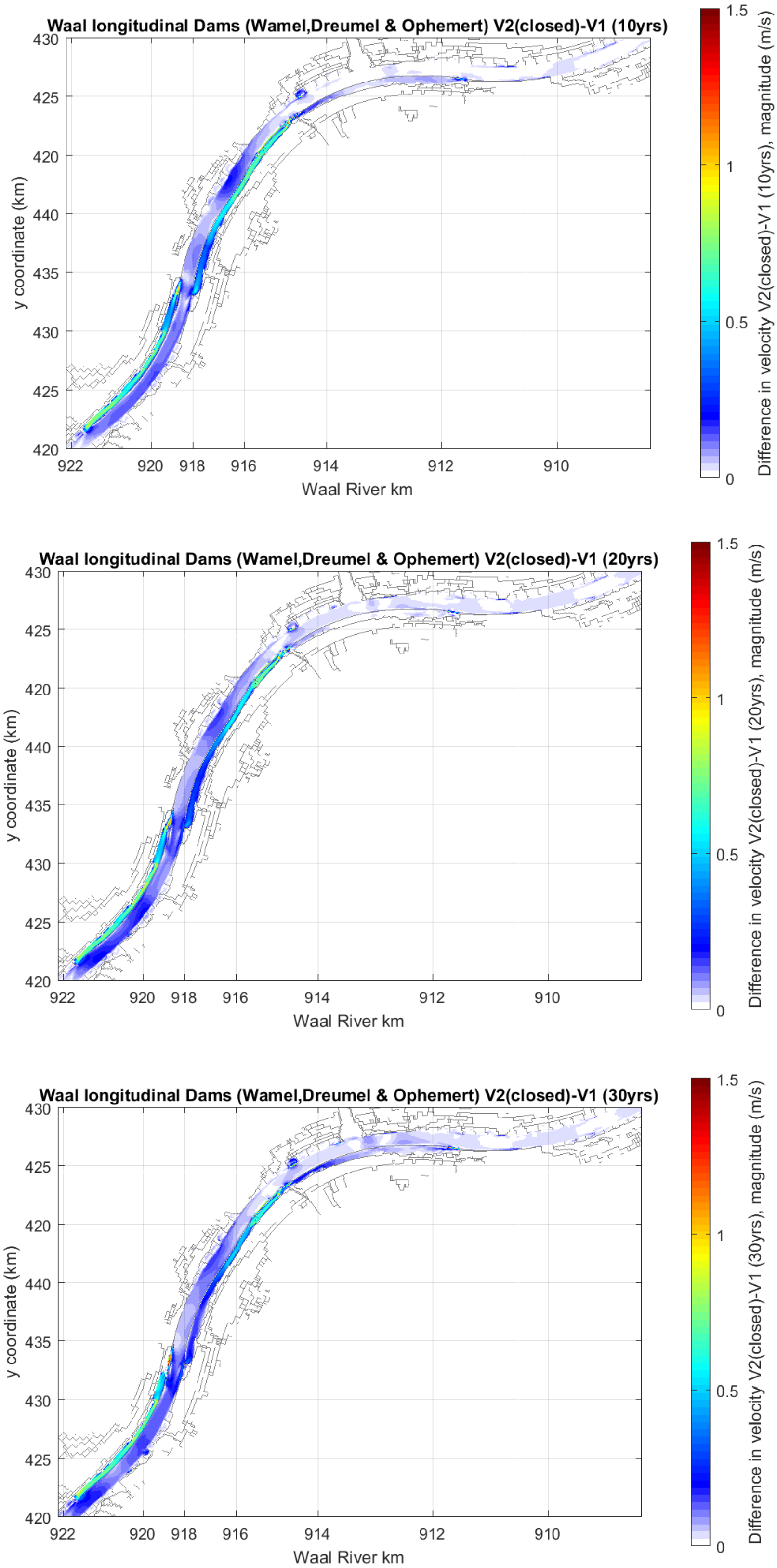



*Figure D.2 Maps of the difference in the magnitude of depth average velocity of V2-V1 after 10 years, 20 years and 30 years at the location of the longitudinal dams (1,233 $m^3/s$).*

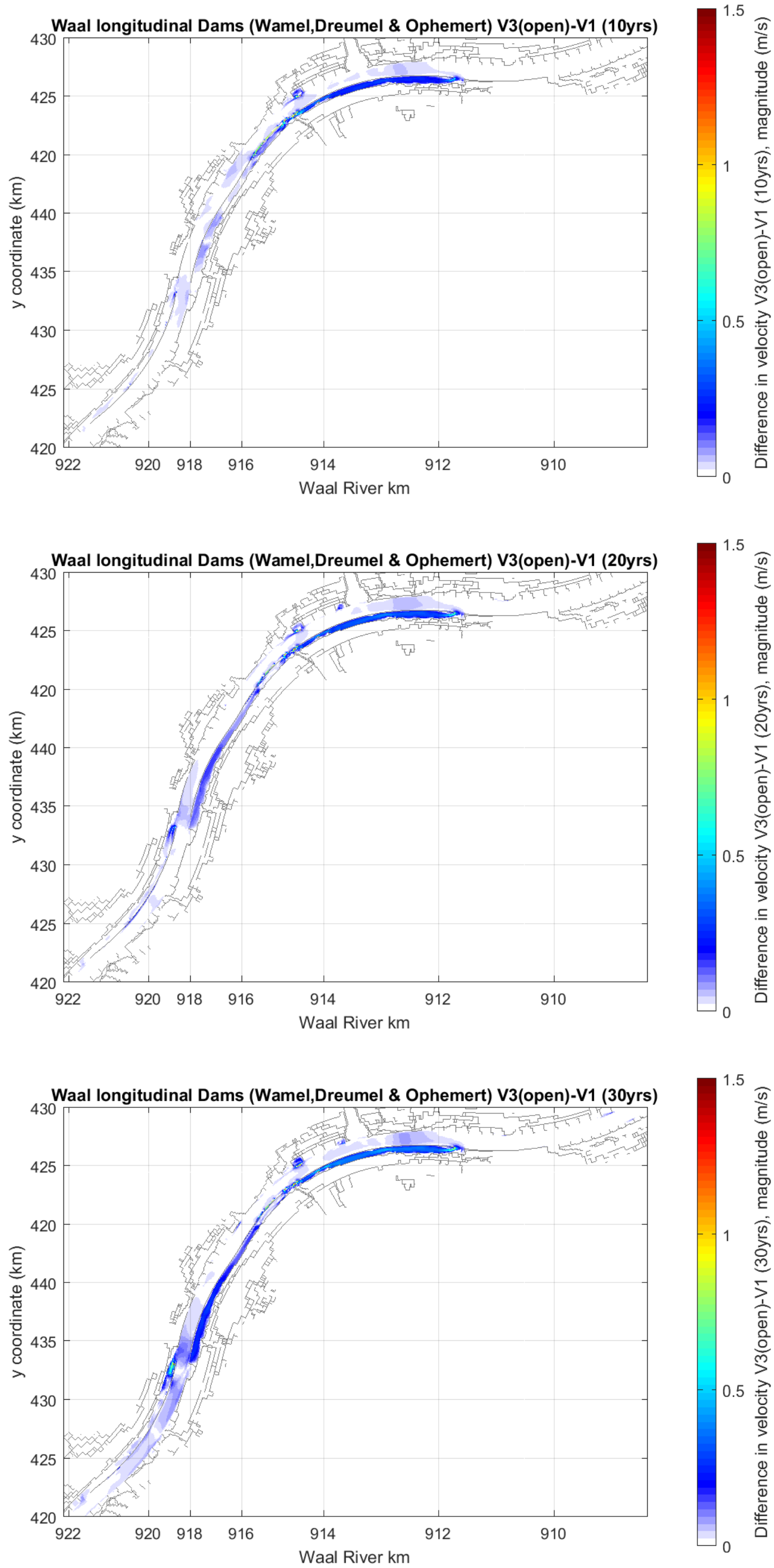



*Figure D.3 Maps of the difference in the magnitude of depth average velocity of V3-V1 after 10 years, 20 years and 30 years at the location of the longitudinal dams (1,233 $m^3/s$). V3 side channels have the as-built inlet opening-shapes, while V1side channels have Baseline -j18 inlet opening-shapes.*

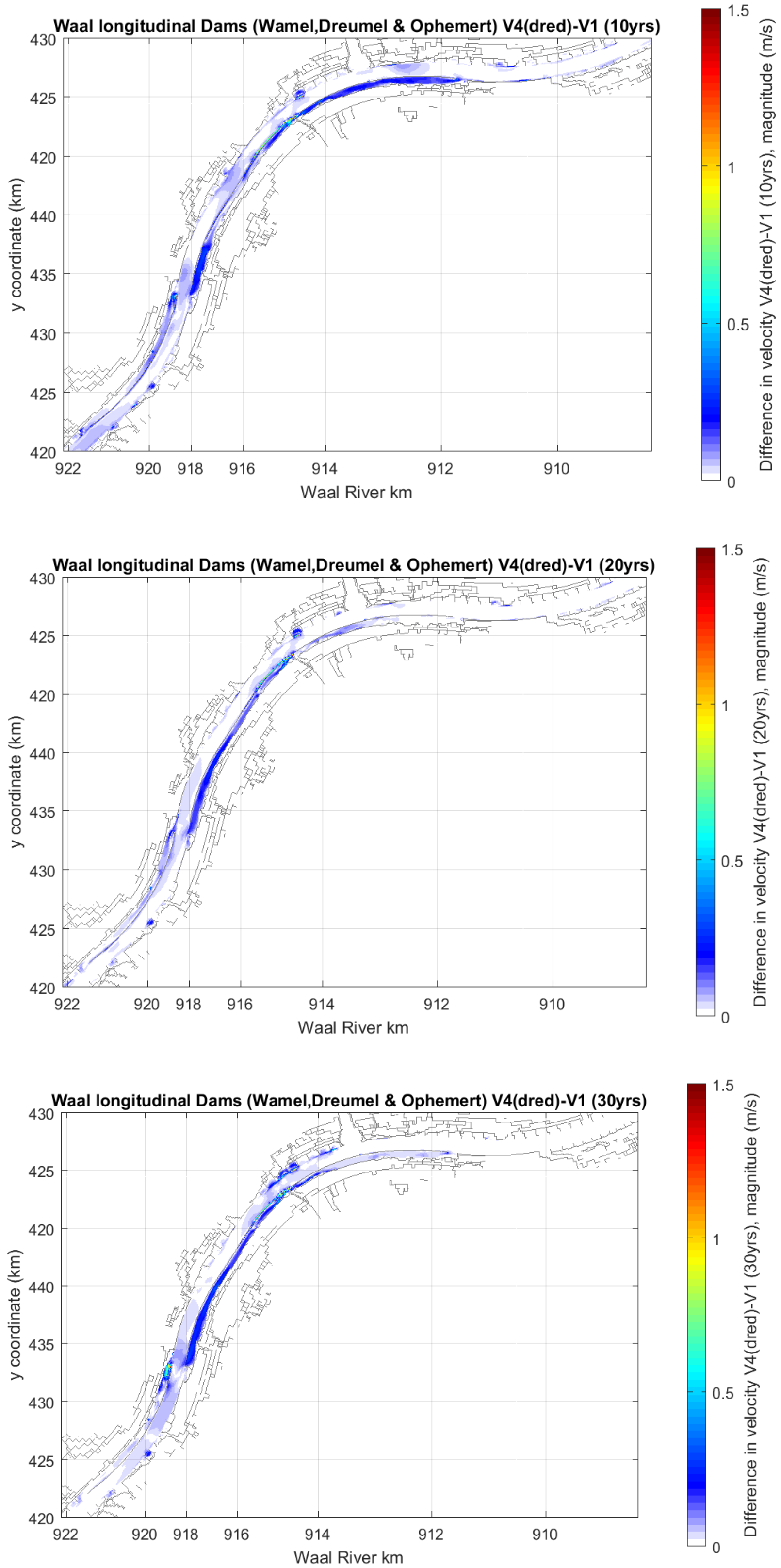
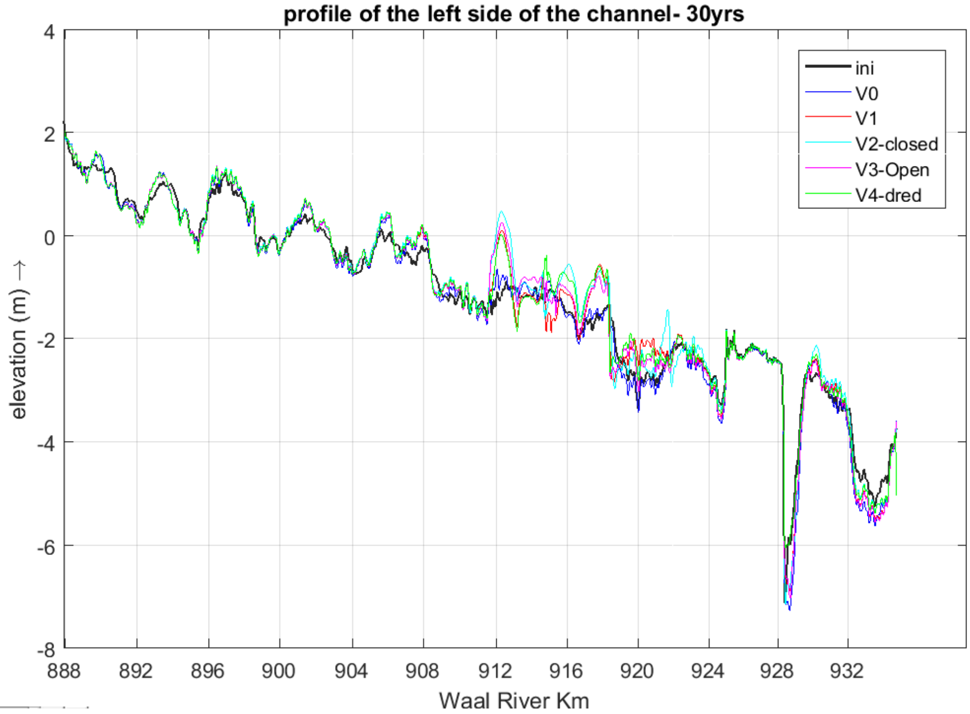



*Figure D.4 Maps of the difference in the magnitude of depth average velocity of V4-V1 after 10 years, 20 years and 30 years at the location of the longitudinal dams (1,233 $m^3/s$).*

# E Longitudinal profiles



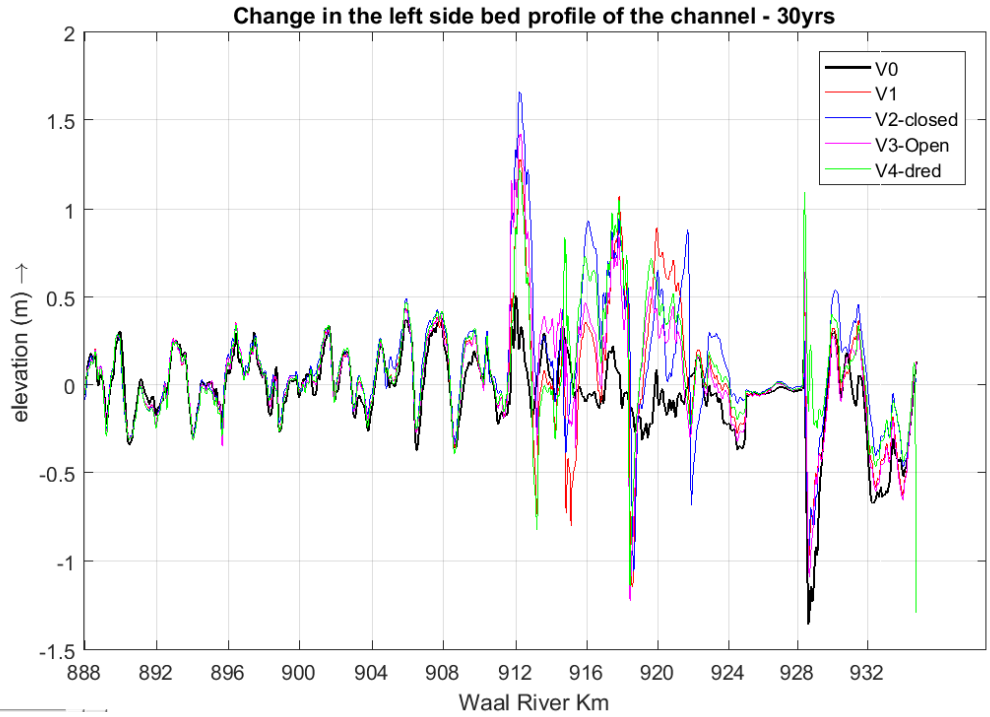
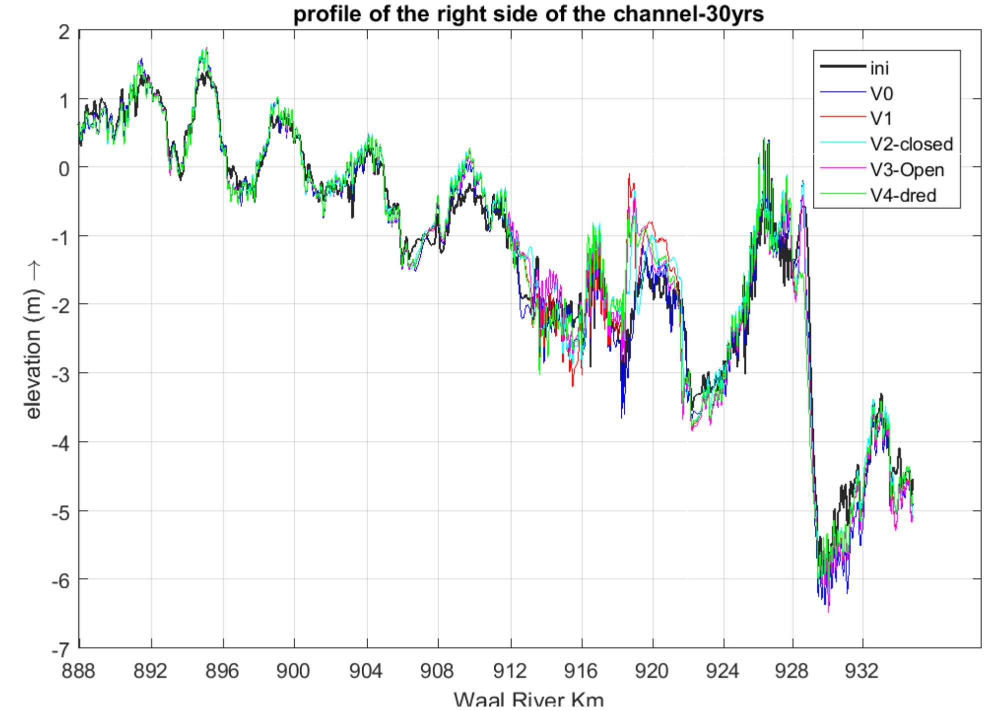




*Figure E.1 The upper plot displays the left side bed level of the main channel at the end of all simulations compared with the initial bed level (ini), while the lower plot compares the change in bed level of the same profile in the simulations. V3-Open side channels have the as-built inlet opening-shapes, while V1side channels have Baseline -j18 inlet opening-shapes.*



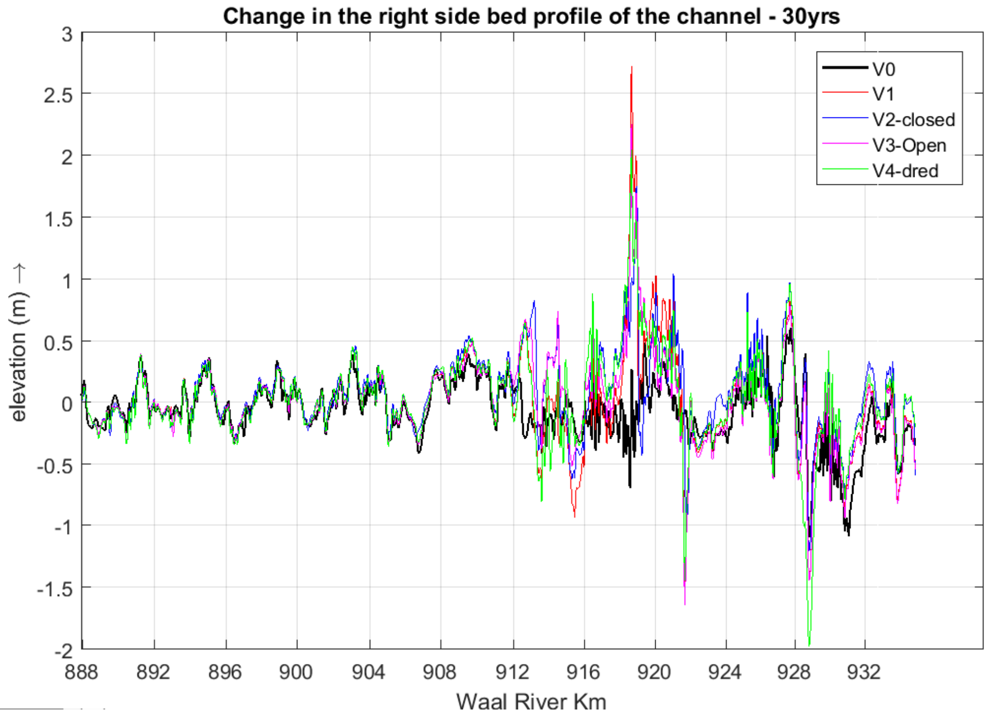




*Figure E.2 The upper plot displays the right side bed level of the main channel at the end of all simulations compared with the initial bed level (ini), while the lower plot compares the change in bed level of the same profile in the simulations. V3-Open side channels have the as-built inlet opening-shapes, while V1side channels have Baseline -j18 inlet opening-shapes*

# F Difference in Water level

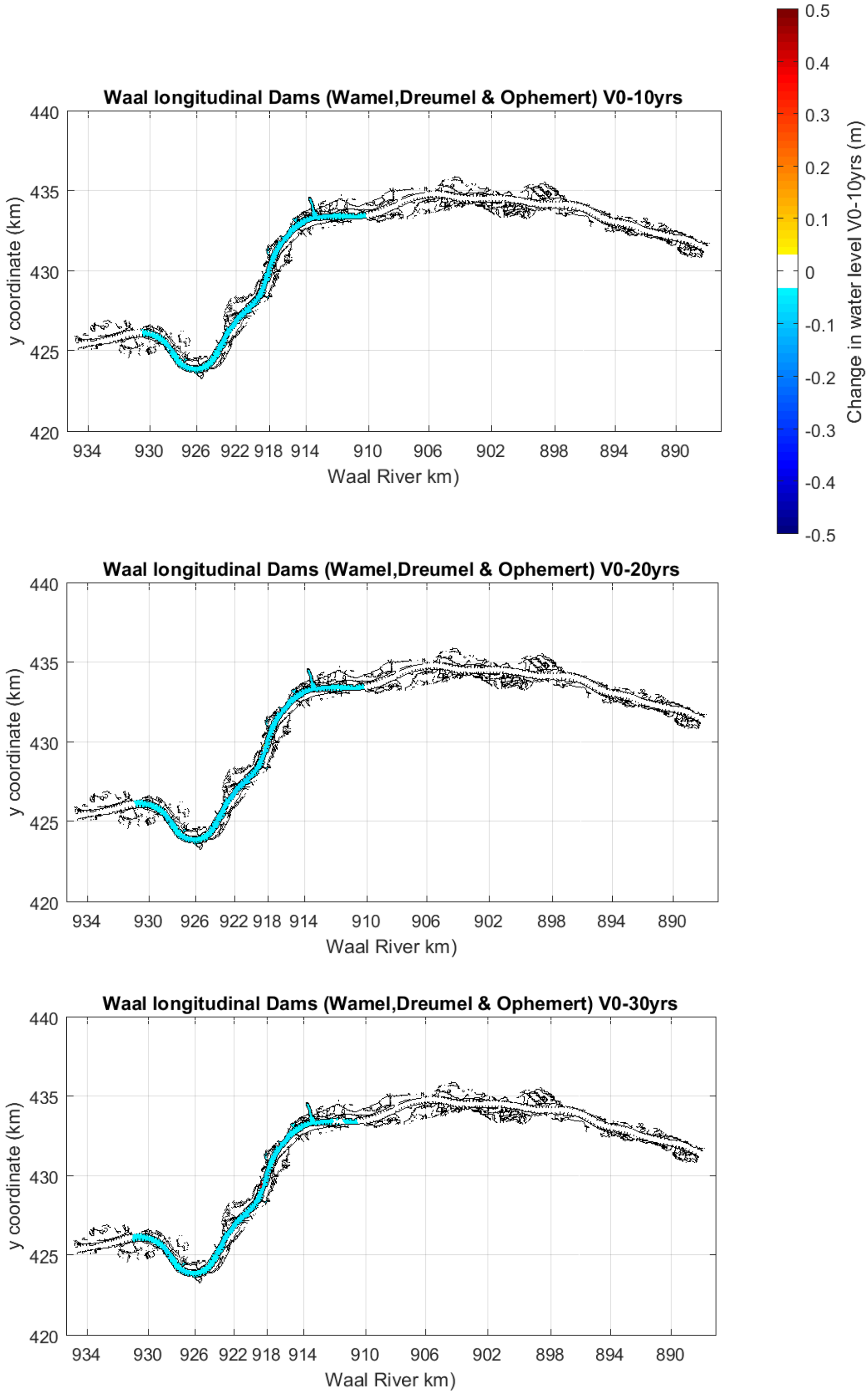



*Figure F.1 Maps of the difference in the water level of V0 after 10 years, 20 years and 30 years for the same discharge (1,233 m³/s). The colour bar applies for all plots*

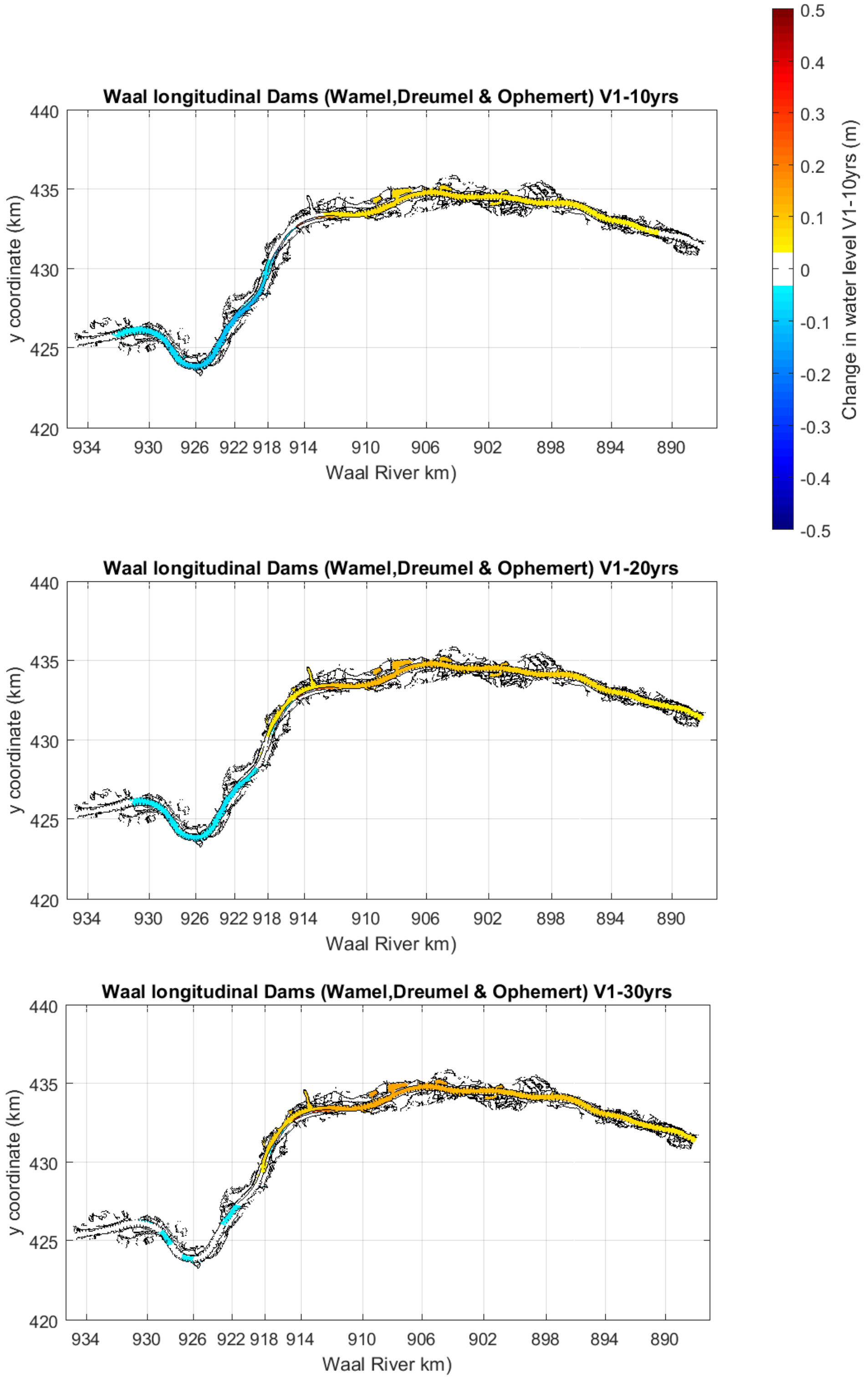



*Figure F.2 Maps of the difference in the water level of V1 after 10 years, 20 years and 30 years for the same discharge (1,233 $m^3/s$). The colour bar applies for all plots*

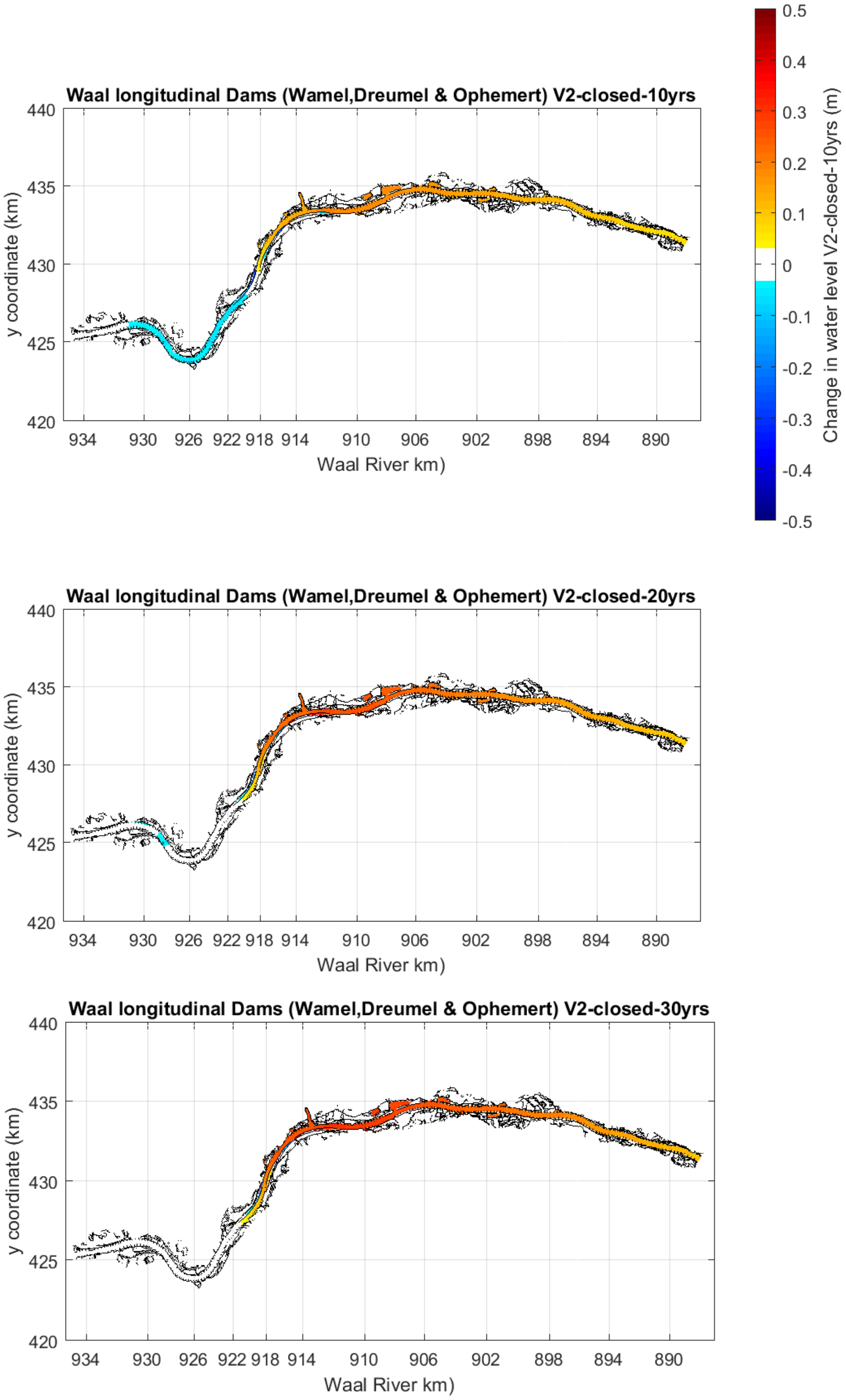



*Figure F.3 Maps of the difference in the water level of V2 after 10 years, 20 years and 30 years for the same discharge (1,233 $m^3/s$). The colour bar applies for all plots*

**Water level difference ($V_1 - V_0$):**
Figure F.4 shows the difference in water level (along the centreline of the main channel) at the start of the models (T = 0). The discharge is almost equal to the OLA. The figure shows that when the inlets of side channels are open (like Baseline_j18), the longitudinal dams provide almost similar water level in the main channel as the situation before the dams constructed. In case of fully closed inlets of side channels, the water level rises in the model to a maximum of 13 cm at Wamel Dam (see table 2.1) and then decreases when you go further downstream.

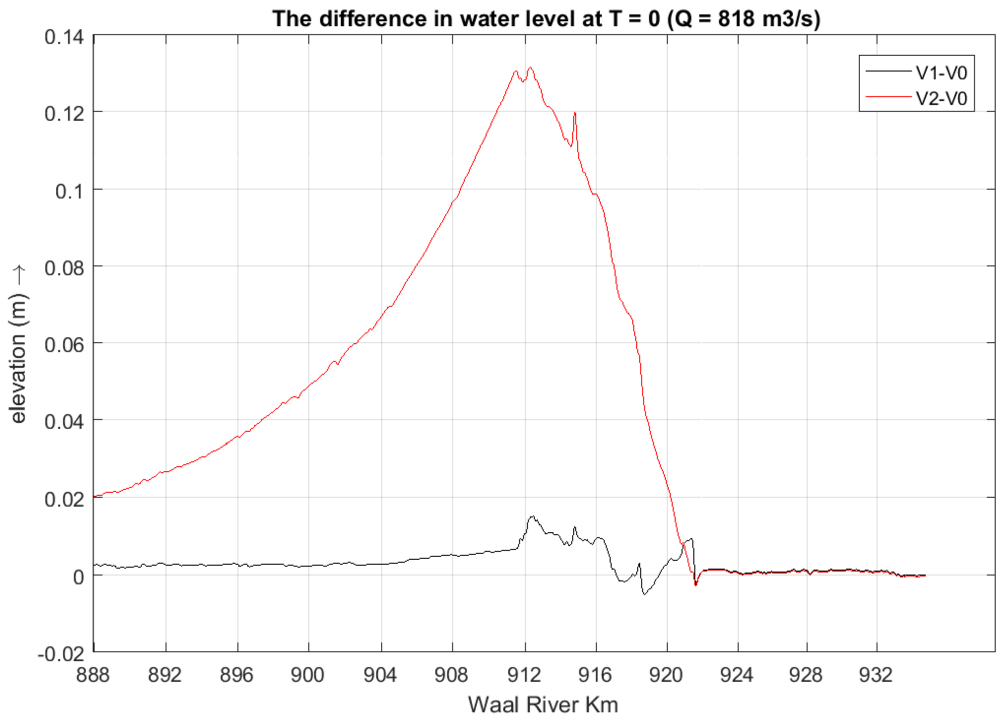
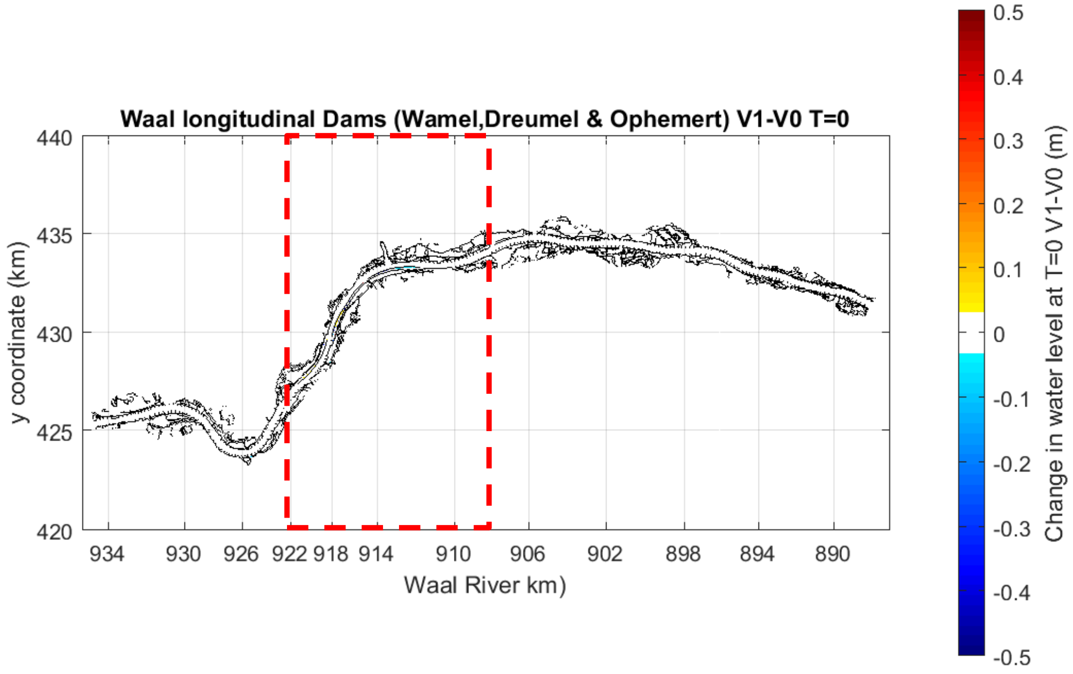



*Figure F.4 Difference in water level profile along the centreline of the main channel at T =0.*

Below are two figures of the difference in the water level of V1-V0 at time zero (Q = 818 $m^3/s$), and after 10 years, 20 years and 30 years for the same discharge (1,233 $m^3/s$).



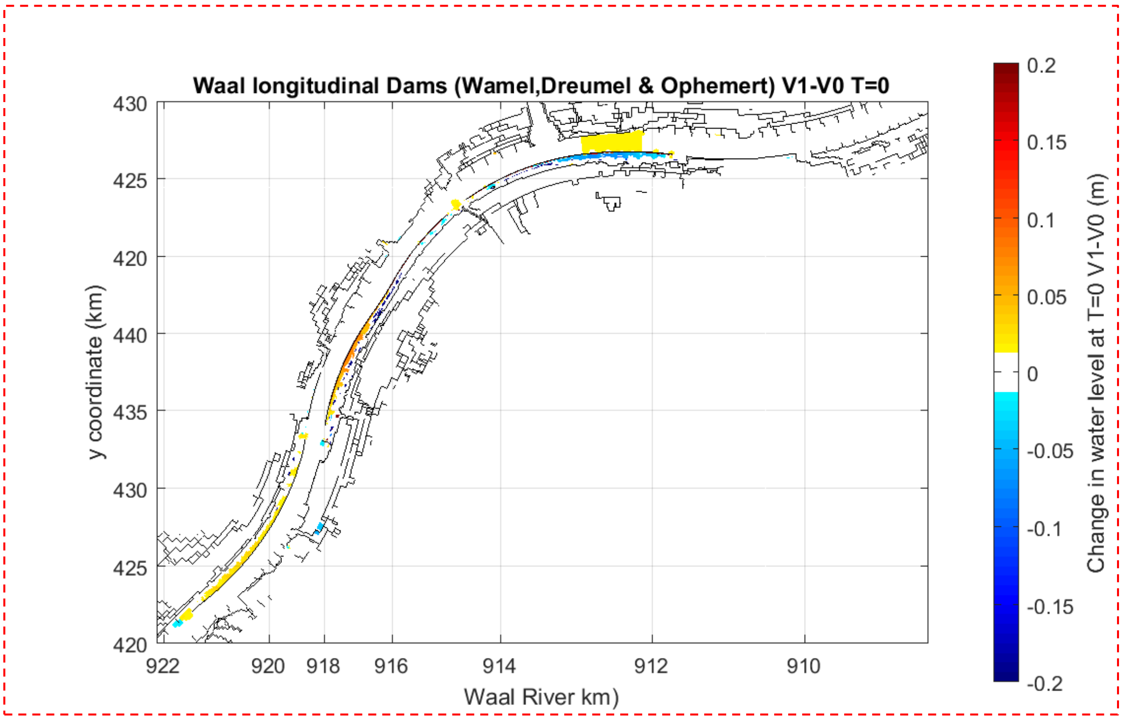




*Figure F.5 Maps show the difference in water level (V1-V0) at T = 0 (Q = 818 $m^3/s$). The upper plot for the whole model domain while the lower plot focuses at the longitudinal dams reach.*

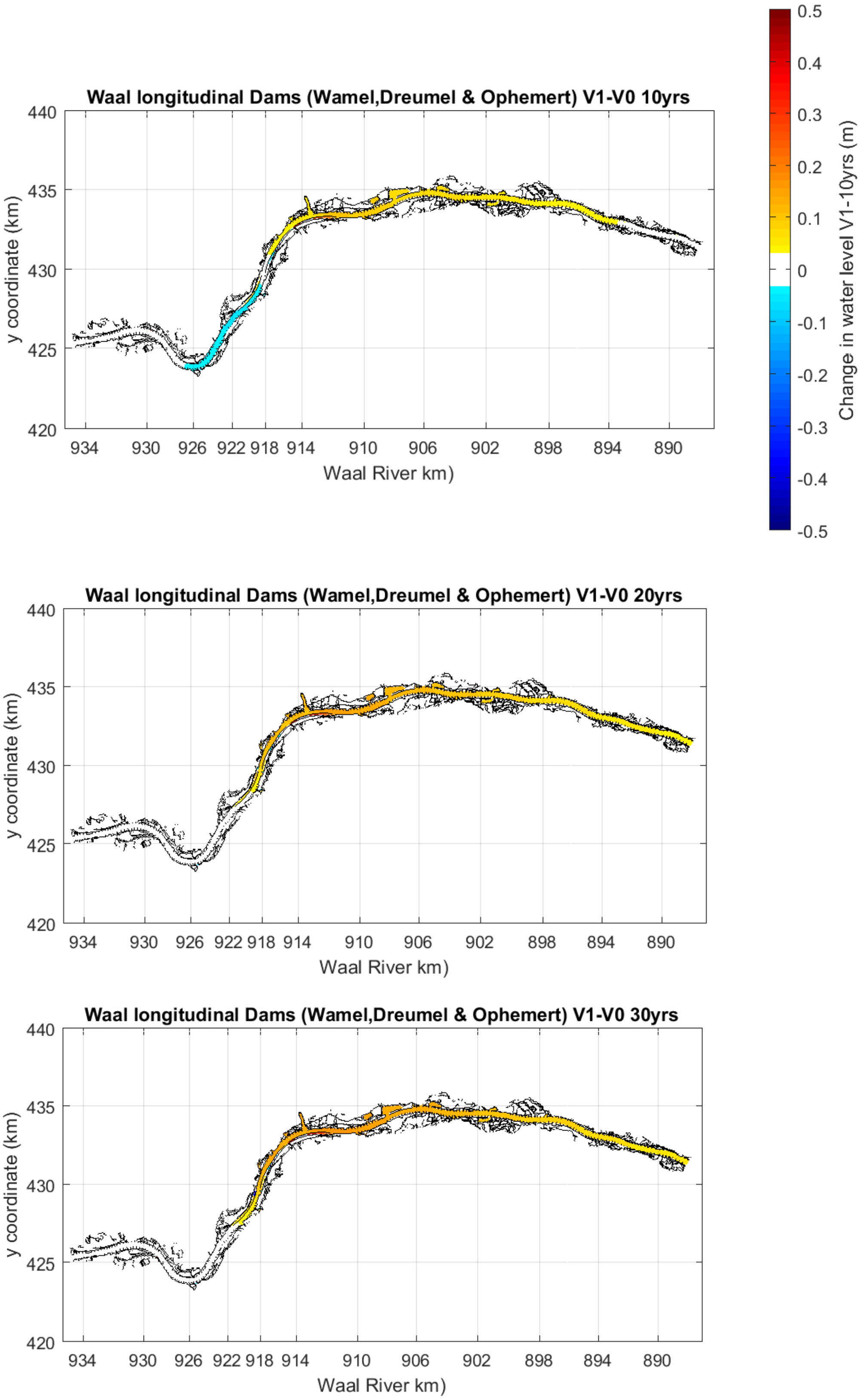



*Figure F.6 Maps of the difference in the water level of V1-V0 after 10 years, 20 years and 30 years for the same discharge (1,233 $m^3/s$). The colour bar applies for all plots.*

**Water level difference ($V_2 - V_0$):**
Below are two figures of the difference in the water level of V2-V0 at time zero and after 10 years, 20 years and 30 years for the same discharge (1,233 $m^3/s$).

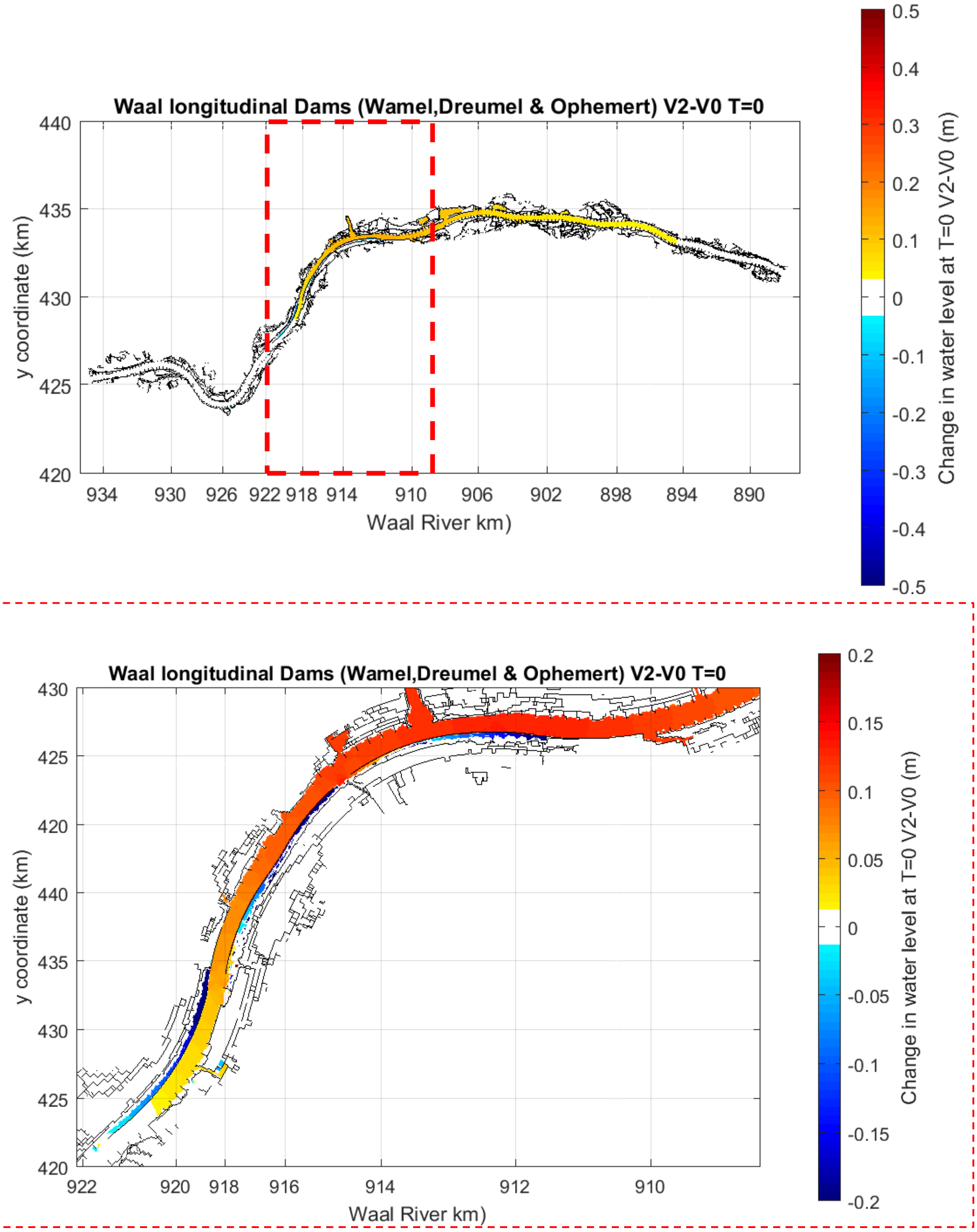



*Figure F.7 Maps explain the difference in water level (V1-V0) at T = 0 (Q = 818 $m^3/s$).The upper plot for the whole model domain while the lower plot focuses at the longitudinal dams reach.*

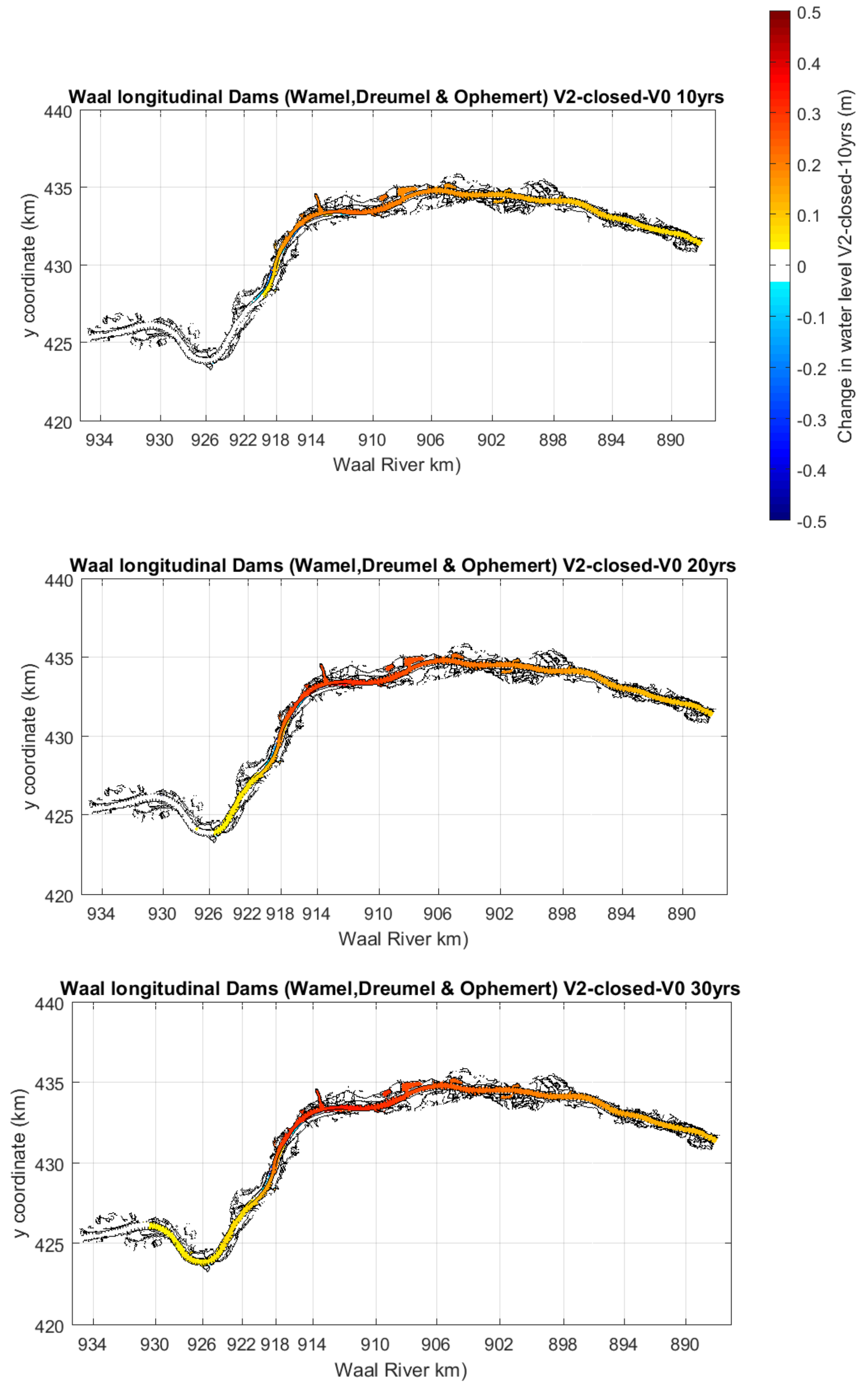



*Figure F.8 Maps of the difference in the water level of V2-V0 after 10 years, 20 years and 30 years for the same discharge (1,233 $m^3/s$). The colour bar applies to all plots.*