Morphodynamics of Tidal Systems

Sediment transport in a tidal basin

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1 Part 1: Sediment transport with Groen's model

Discuss and explain your results:

1. **Explain the sensitivity of the time delay between peak flow and peak sediment concentration to: (max 2 figures)**

   (a) **Fall velocity of the sediment**
   The fall velocity governs how fast the sediment mixed in a water column settles again and would therefore not available for transport anymore. The deposition of sediment to the bed is proportional to the squared fall velocity. At peak flow, because of the high velocity, the maximum of sediment is being separated from the ground into the water column. After peak flow, however, sediment is still added to the water column, just at a slower pace. At the same time, the settling velocity constantly removes sediment from the water column. As long as this removal rate is still lower than the addition rate due to the high velocities, the sediment concentration is continuing to rise even after peak flow has been reached. The peak sediment concentration is reached when sediment adding due to flow velocity equals the removal rate of sediment due to settling velocity. The time to reach this (shortlived) balance depends on the settling velocity. With higher settling velocities, more sediment is removed per time step and thus the peak sediment concentration is reached quicker after peak flow. The distinct relationship is shown in the plot of figure 1.

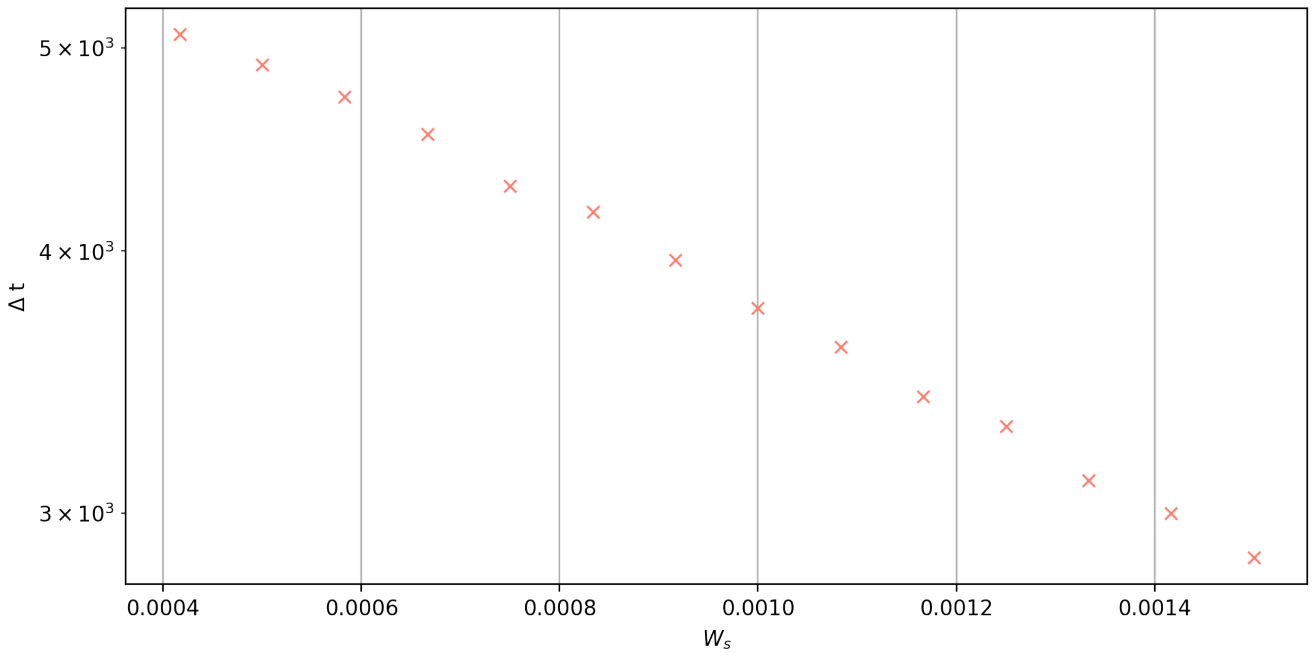

Figure 1: Time delay Δt between peak flow and peak sediment concentration as function of sediment fall velocity W_s. Note the logarithmic scale of the y-axis.

(b) **Eddy diffusivity**
The eddy diffusivity governs how quickly sediment is mixed within the water column. The deposition of sediment on the bed (D) is inversely related to the eddy diffusivity. This is because a high eddy diffusivity enables sediment that was removed from the bed move higher into the water column. This sediment then takes longer to be removed because of its higher distance to the bed. Thus, we would expect a lower D for higher eddy diffusivity which would consequently increase the time delay between peak flow and peak sediment concentration following the same argument as in 1a. Ultimately, this leads to an increase of the time delay with increased eddy diffusivity which can be seen in figure 2. The plot shows an approximately linear increase of the time difference with increased eddy diffusivity.

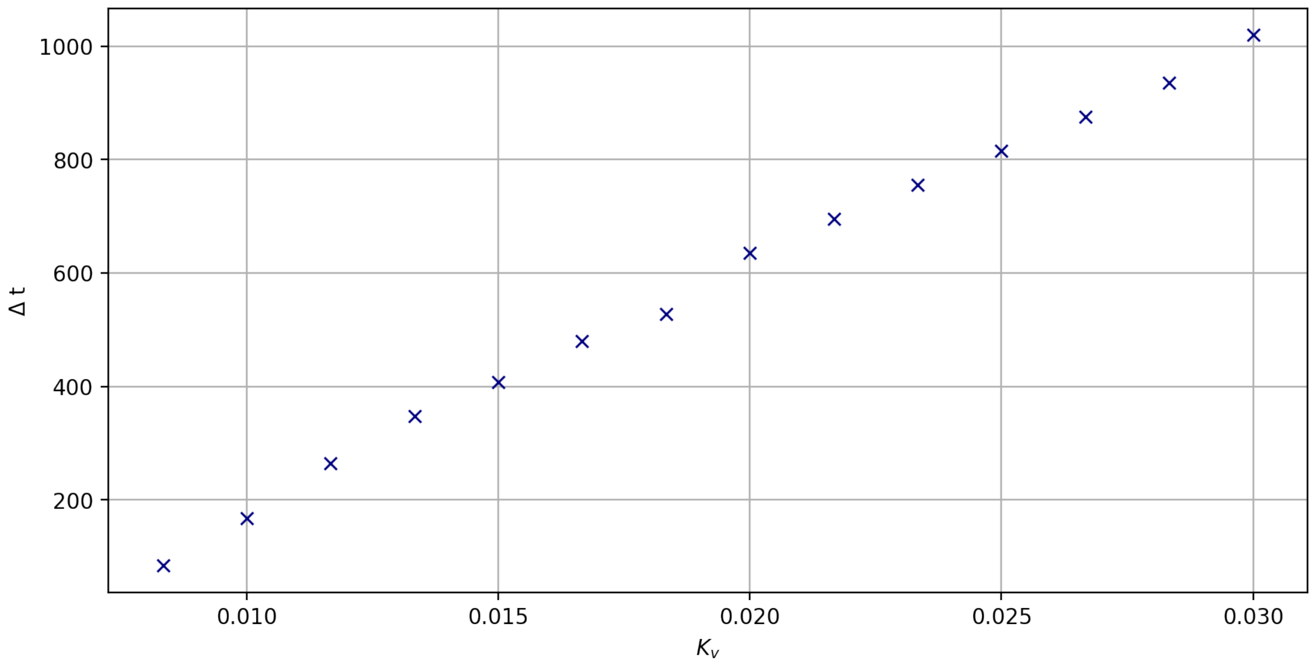

Figure 2: Time delay Δt between peak flow and peak sediment concentration as function of sediment fall velocity K_v.

2. **Explain the sensitivity of the (difference in) peak sediment concentration at ebb and flood to: (max 4 figures)**

   (a) **Relative phase difference between M2 and M4** Sediment concentration is expected to be dependent on the skewness and asymmetries of the velocity signal. Both of them are created through phase differences of the M2 and M4 tide. Generally, higher velocities can erode more sediment from the bed and thus a high concentration of sediment is expected shortly after the dominant phase for a phase difference of ±90 degrees. Compare that to figure 3 that shows the time series of the sediment concentration for different phase differences. For 90 degrees (yellow), peak flood flow removes a lot of sediment from the bed such that peak concentration is visible after at around 130 s. As the velocities are so low during ebb, the concentration then continuously drops and the ebb current can only decrease the magnitude of the negative slope. The opposite happens for 270 degrees (red), where the concentration is reaches its maximum shortly after the faster peak ebb flow.
   Another important mechanism influencing sediment transport, next to the just described velocity asymmetry, is the duration asymmetry. Suspended sediment, removed from the bed, takes some time to settle down again. Consequently, a fast change from one peak flow to the other peak flow can increase the concentration further while a slow change leaves enough time for a larger portion of the sediment to settle. This can be seen for 0 degrees (blue) and 180 degrees (green) in figure 3. Here, the concentration pattern shows first a low peak which is followed by a larger one. Thereafter, the concentration drops drastically, before the pattern repeats itself. This is a result of the duration asymmetry. First, sediment is suspended by the first phase, and the concentration is further increased after the quick change to the second phase of the flood. Then, a slow change of tidal phase takes place and the sediment concentration decreases as the sediment falls down to the bed.

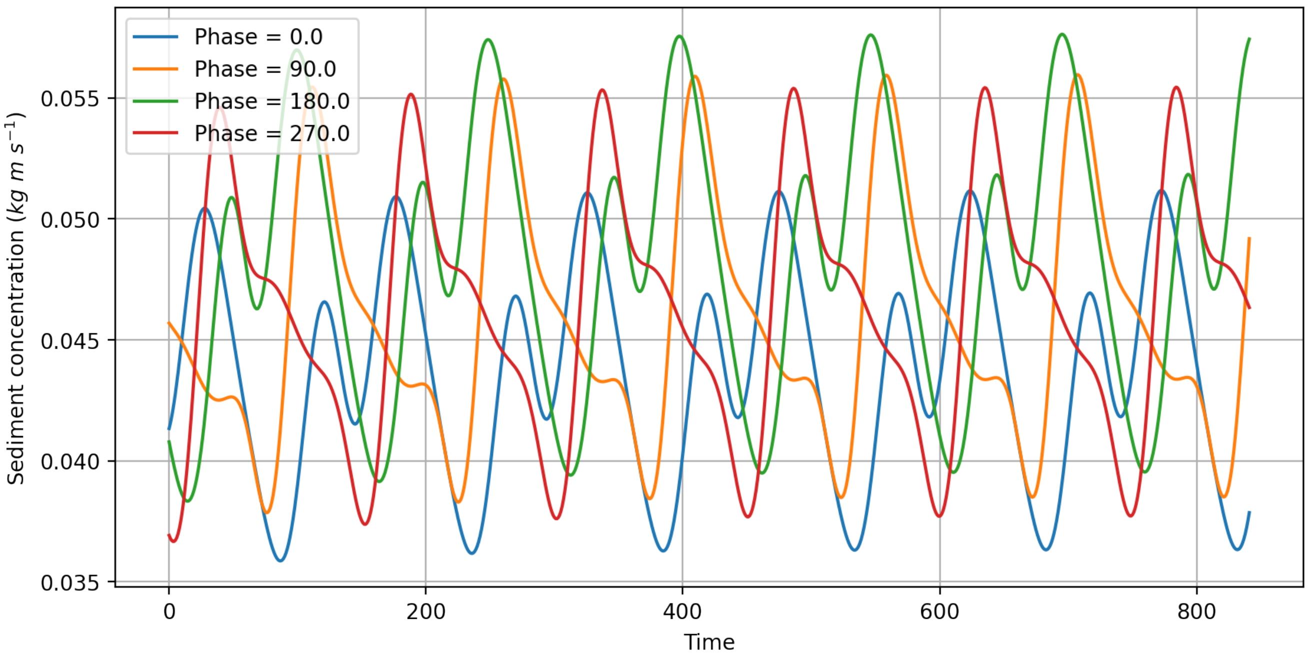

Figure 3: Time series of suspended sediment concentration for different phase differences between M2 and M4 SSH.

(b) **Fall velocity of the sediment** As discussed in 1a, an increased fall velocity increases the sediment deposition to the bed. Consequently, at high fall velocities, sediment added to the water column for instance during flood has been settled when the ebb starts. This ultimately increases the difference between in peak sediment concentration at ebb and flood. Conversely, a shorter fall velocity lets the sediment stay longer in the water column. This can also be seen in figure 4, which simulates sediment concentrations over time for different fall velocities at a phase difference between M2 and M4 of 0 degrees. Each cycle shows two peak concentrations, one belonging to ebb and one to flood. It is obvious that the difference between these concentrations increases with smaller fall velocities while the absolute concentrations generally increases for smaller fall velocities. The latter can be explained by the fact that the sediment concentration can built up over multiple cycles of ebb and flood as the removal rate is too slow initially. This can be seen in the increase of the blue line in the figure.

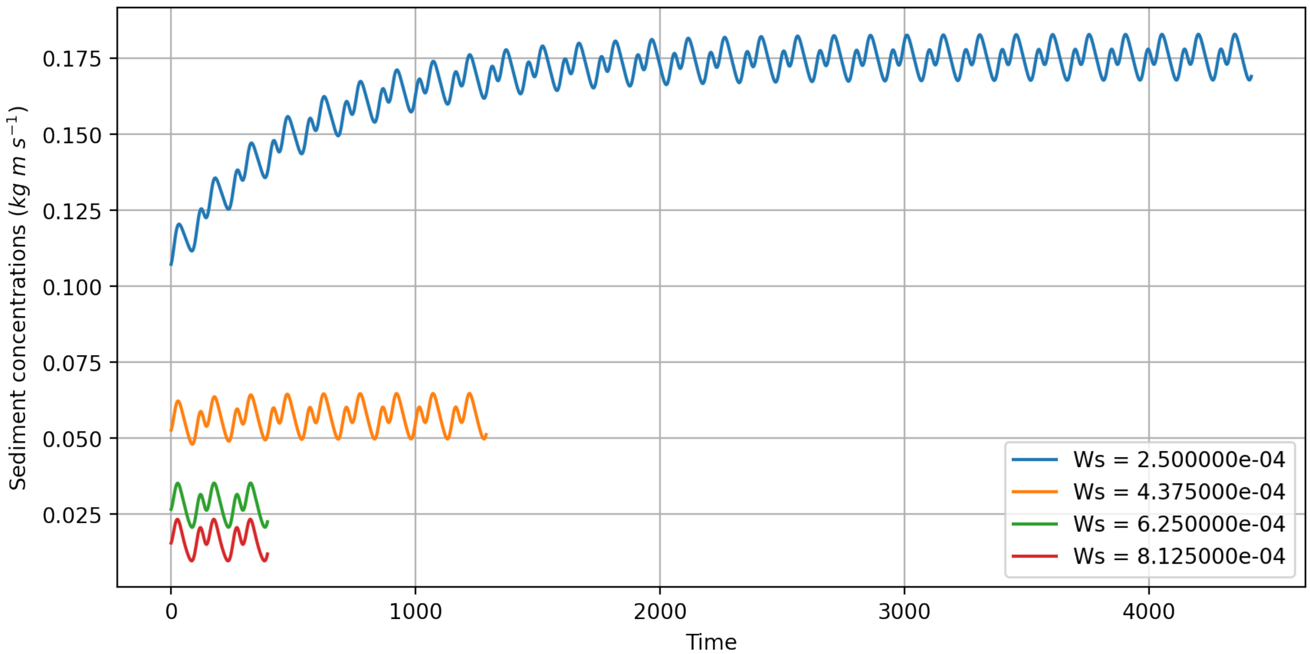

Figure 4: Time series of suspended sediment concentrations for different fall velocities.

(c) **Eddy diffusivity** Combining the arguments from 1b) and 2b) we expect to observe an increased difference in peak sediment concentration during ebb and flood for smaller eddy diffusivities. This is exactly what we can observe in figure 5. Once again, it is visible that the overall concentration level increases for higher eddy diffusivities as more sediment is brought to higher positions in the water column.

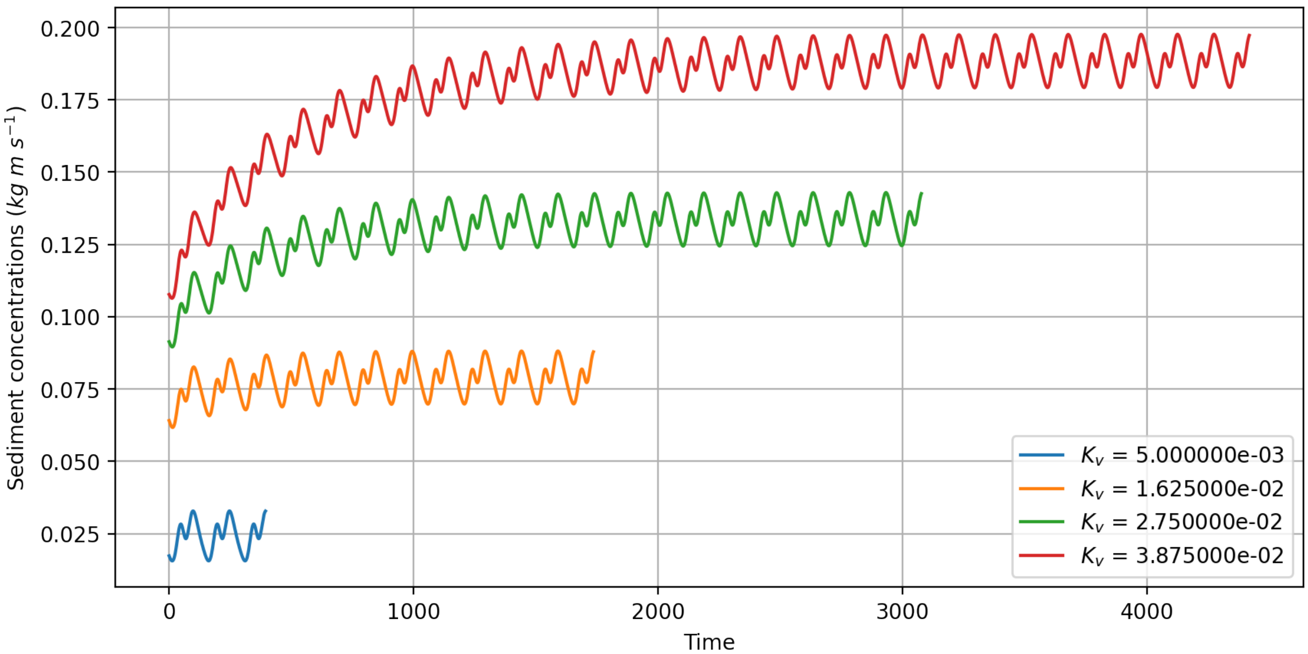

Figure 5: Time series of suspended sediment concentrations for different eddy diffusivities.

3. **Explain in your own words (including figures) the duration asymmetry mechanism and its sensitivity to the following parameters: (max 2 figures)**

   (a) **Fall velocity of the sediment**
   A duration asymmetry implies that the time between peak flood and peak ebb is different from the time between peak ebb and peak flood. It can occur when there is a phase difference between M2 and M4, which was set to 180 degrees in our simulation. This generated an asymmetry where the time from peak ebb to peak flood is shorter than the time from peak flood to peak ebb, while there is no velocity asymmetry. In figure 6 the implications of such a duration asymmetry on sediment flux is depicted for different fall velocities. It can be seen that, in general, the peak sediment flux is higher during flood than during ebb (absolute value). This translates to a net sediment transport in direction of the flood (landwards) which can be seen by integrating the flux over one tidal period. The physical reason for that is that sediment that was moved up in the water column during ebb is still available for transport during flood due to the quick change from peak ebb to peak flood. Between peak flood and peak ebb, however, the sediment has more time to settle and is thus not or to a lesser extend available for transport during ebb. The fall velocity controls the magnitude of this asymmetry. When it is high, the sediment falls almost instantaneously so that the duration asymmetry wont influence sediment transport. At slower fall velocities, however, the sediment is removed from the water column slower such that the duration asymmetry creates a net sediment transport.

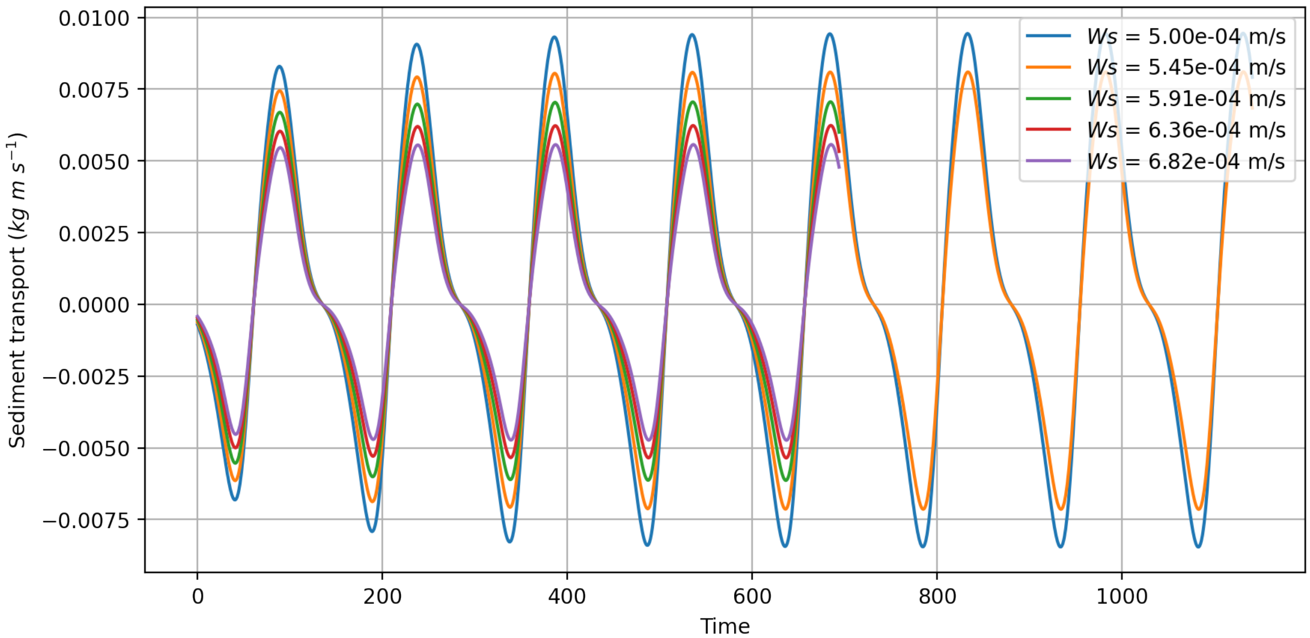

Figure 6: Time series of sediment transport for different fall velocities.

(b) **Eddy diffusivity**

Similarly, eddy diffusivity also influences the impact on duration asymmetry on sediment transport. At high diffusivity more sediment is transported in to higher layers of the water column. This sediment is then available for transportation for a longer time. Consequently, this increases the net sediment transport at constant duration asymmetry. This could be seen by integrating one period of the sediment flux in figure 7 for the different eddy fluxes. From the figure, it is also visible that there is a higher peak sediment flux during flood than during ebb.

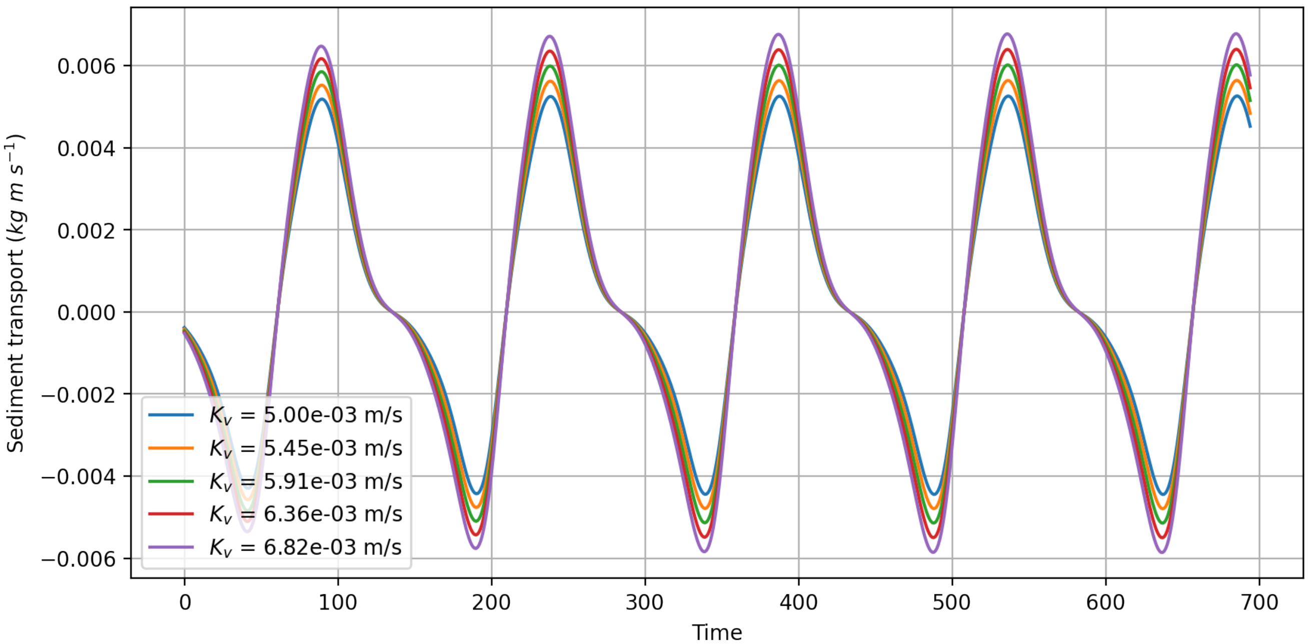

Figure 7: Time series of sedment transport for different eddy diffusivities.

4. **Explain the velocity-asymmetry mechanism: (max 1 figure)**

   Similarly to the duration asymmetry, velocity asymmetry has its origin in the phase difference of M2 and M4 tide and can be created by a phase difference of, ±90 for SSH. Then, the velocities of peak ebb and peak flood flow differ. Consequently, a net sediment transport develops in the direction of the dominant phase. If we have, for instance, flood dominance which implies faster peak flood velocities than peak ebb velocities, more sediment is being transported in that direction. This is because this asymmetry also implies a higher average velocity in which more sediment is removed (erosion quadratic with actual velocity) from the bed and also transported further (transport linear with actual velocity).

5. **Explain the sensitivity of tidally averaged sediment transport to the relative phase difference between M2 and M4. Use Ws =** $1\ \mathrm{mm/s}$ **and Kv =** $10^{-2}\ \mathrm{m^2/s}$**. Take steps of 45 degrees and vary from 0 to 315 degrees. (max 1 figure)** Figure 8 shows the sensitivity of tidally averaged sediment transport to the phase difference between M2 and M4. Note that these are phase differences between the respective velocities, not the respective water levels. For a phase difference of 0 degrees, M2 and M4 tide interfere constructively during flood and destructively during ebb which makes the system flood dominant (skewed signal). This thus induces a positive net sediment transport landwards as faster waters carry more sediment. Conversely, for 180 degrees, the system becomes ebb dominant with net sediment transport sear wards. Both is in agreement with the simulation as can be seen in dark blue and yellow in the plot.

   For 90 degrees and 270 degrees the interference of the M2 and M4 tides lead to an asymmetric signal, where the ebb and flood are temporally longer, respectively. While this does not change the peak velocities, more sediment can be transported in a longer time frame. Thus, for 90 degrees, we have negative net transport (green) while we have positive net transport for 270 degrees (purple). For all other phase differences, we have a mixture of both temporal and velocity effects. For 315 degrees (pink) for instance, we see the highest net transport. This is because, as it is close to 0 degrees, it is flood dominated. Additionally, as it is close to 270 degrees, flood is longer than ebb. This leads to the highest net sediment transport landwards. Similar arguments can be made for the rest of the plotted phase differences.

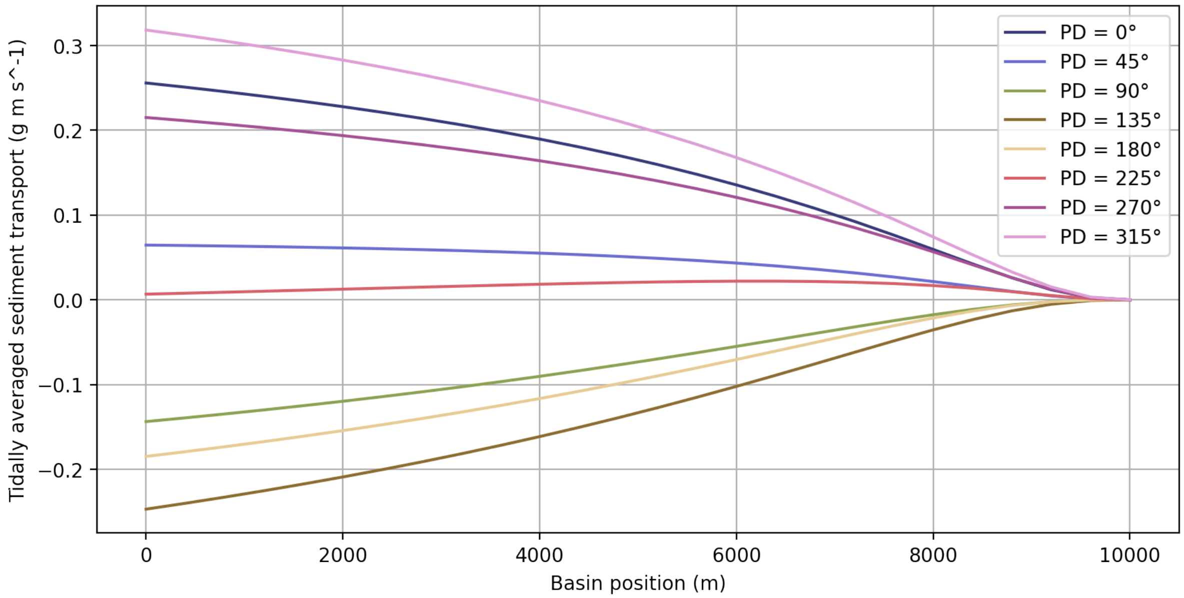

Figure 8: Net sediment transport as a function of distance in the basin from the sea for different velocity phase differences of M2 and M4.

2 Part 2: Spatial settling lag mechanism

Discuss and explain your results:

1. **Explain the spatial settling lag mechanism by explaining the differences in (i) predicted sediment concentrations and (ii) sediment transport between the 'full' model and 'Groen' model. Do this for a relative phase difference of zero and for 90 degrees. Use Ws =** $1\,\mathrm{mm/s}$ **and Kv =** $10^{-2}\,\mathrm{m^2/s}$. **(max 1 figure)**

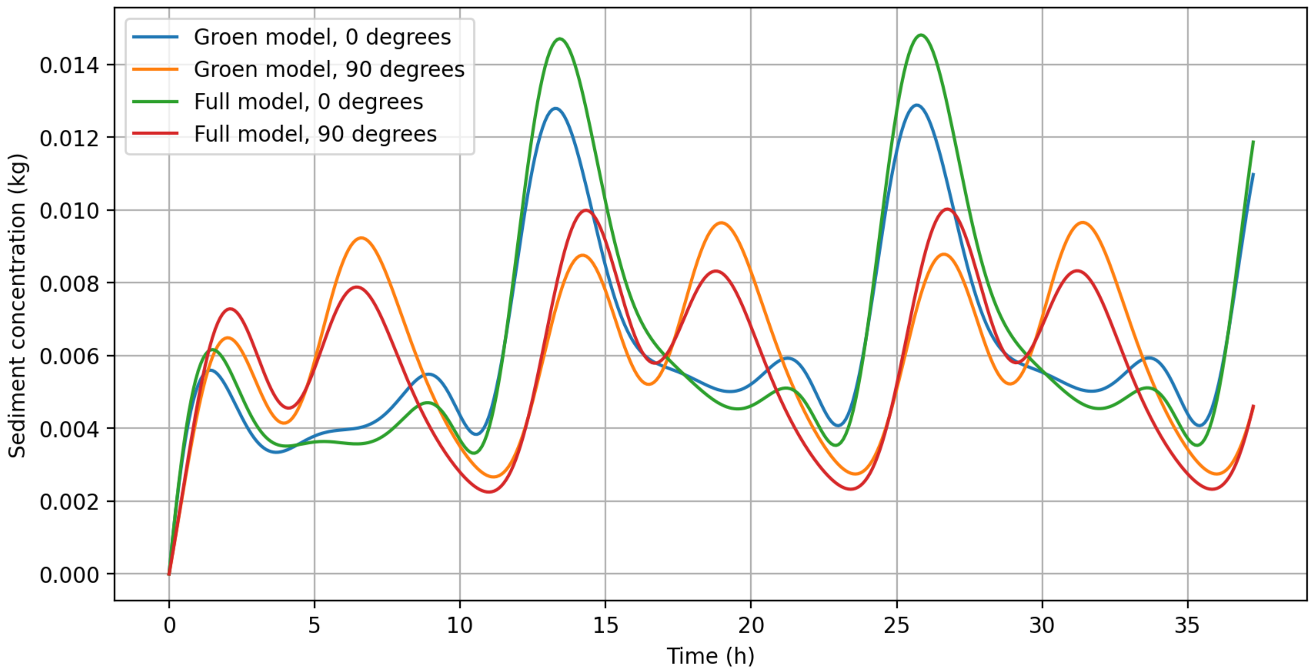

Figure 9: The sediment concentration as a function of time for both Groens model (withoud advection) and the Full model (with advection).

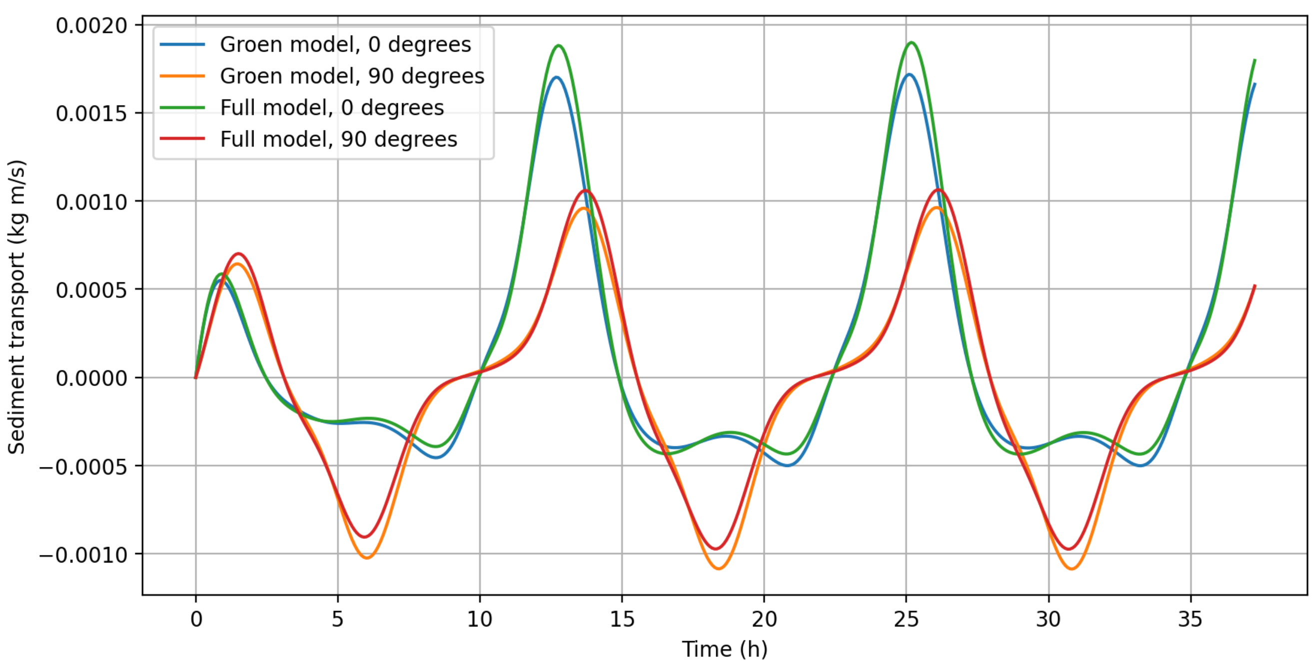

Figure 10: The sediment transportation as a function of time for both Groens model (withoud advection) and the Full model (with advection).

In figure 9 and figure 10 we see the sediment concentration and transportation. To explain the spacial settling lag mechanism, we look at the difference between Groens model and the Full model. The spacial settling lag mechanism is a result of advection which is only modelled in the Full model and was not considered in Groen Model. Advection implies a change of velocity with space. To explain what is happening we will first look at figure 9 explicitly.

We can clearly see that for both phase differences the peak concentration during flood is higher for the full model than the Groen model while it is exactly opposite for the peak concentration during ebb. This is a result of the spacial settling lag. As the velocity decreases landwards, more sediment comes from seaward direction (higher velocities) during flood than can come from landwards (lower velocities) during ebb. This changes not only the sediment concentrations but with that also the sediment transport as shown in figure 10.

Here, we see that the peak flood transportation for the Full Model is higher in both the 0° phase difference and the 90° phase difference than Groens model while the negative transportation is not as low as the Groens model. This is essentially the same trend that we also saw in the concentrations. It is actually visible now, more sediment is transported in during flood than is transported out during ebb. This is the spatial settling lag.

Another way this can be thought of is that when the tides turn from flood to ebb, the sediment still has a velocity in landward direction and only settles after it has travelled a bit further. In the other direction, during change from ebb to flood, this happens, too, but the sediment settles after a shorter path due to the lower velocities landwards. Combined, this means that there is an increased sediment transport during flood compared to ebb when advection is not negligible.

2. **Explain why with an M2 water level also M4 flows are generated and how this impacts the modeled sediment transport. So why do you get different results when you exclude M4 currents as well (using harmonic analysis)? (max 1 figure)**

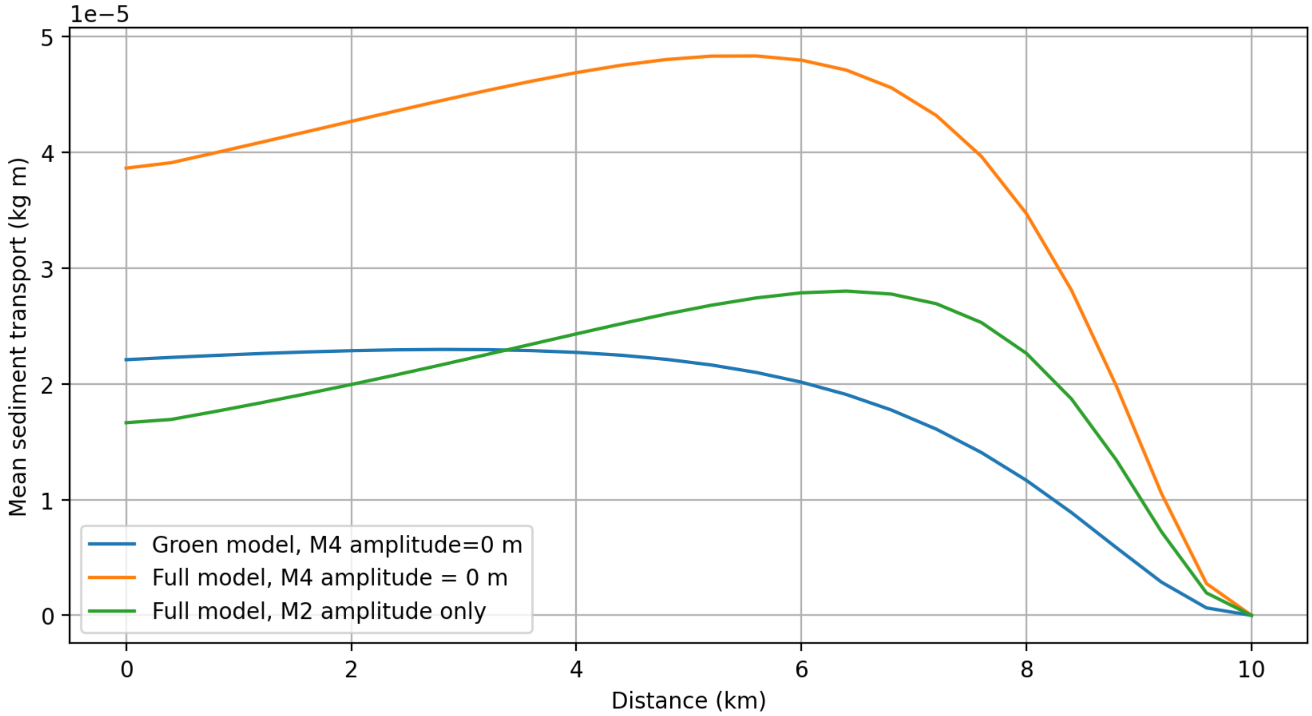

Figure 11: The mean sediment transportation

The M4 tide is a direct consequence from the M2 tide. This is, because the M4 constituent is a higher harmonic resulting from non-linearity of the underlying equation. It is not caused by gravitational interactions, but it exists because the M2 tide interacts with itself.

Net sediment is transported via three mechanisms.

(a) Mean flow

(b) Duration asymmetry & velocity asymmetry

(c) Spacial setting lag

Both the velocity and the duration asymmetry mechanisms depend on asymmetry. If there is no M4, the only modelled tide is M2. The M2 tide is symmetric, so therefore the sediment transportation via the asymmetries is not allowed. The spacial settling lag is only accounted for in the Full model, this explains why this simulation has higher mean sediment transportation than the Groens model. In the full model with only M2 amplitudes the net sediment transport is only due to mean flow. In the models where the M4 amplitude is zero the M4 flow velocities can still develop, still causing a slight asymmetry mechanism and causing net sediment transport. This is because the M4 wave was only set to zero at the entrance of the basin. Propagating into the basin, the M2 wave can still interact with itself in the model and thereby create a velocity M4 component. Reasons for that are non-linearities in the governing equations and changing water levels and cross sectional area.

3. **Discuss and explain the sensitivity of the spatial settling lag mechanism to the fall velocity. (max 1 figure)**

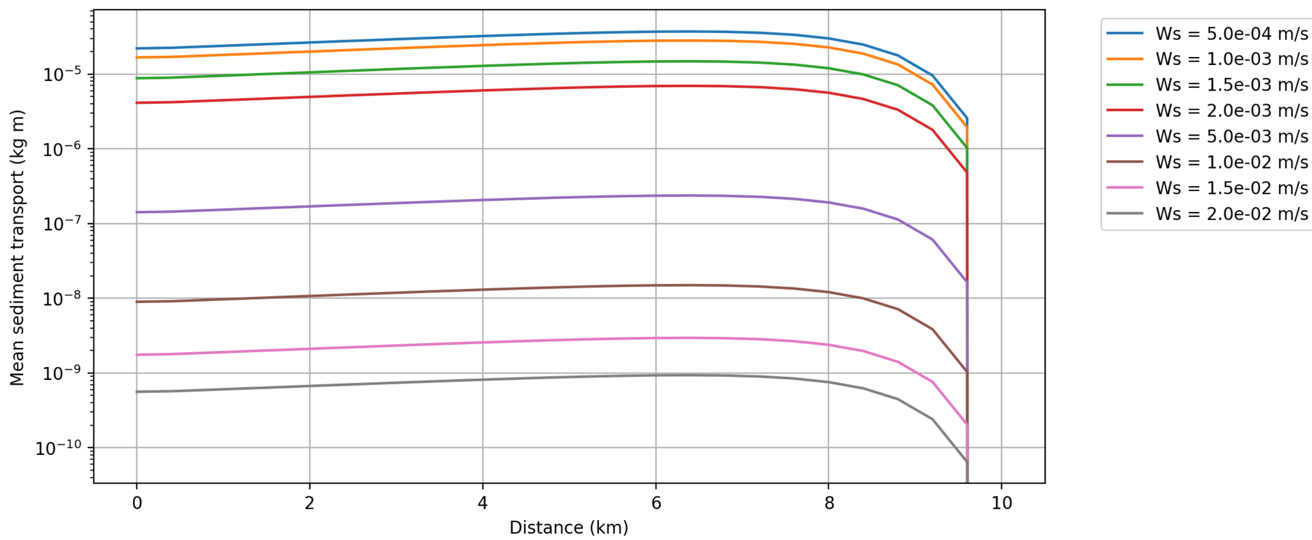

Figure 12: Mean sediment transportation as a function of distance to the sea for different fall velocities.

The spacial settling lag mechanism relies on the fact that particles that haven't settled yet get transported in the landward direction. This means, that for a higher fall velocity, we would expect less transportation since this means that there are less particles that have not settled yet and thus can be transported in the landward direction. We can see this clearly is the case in figure12.

3 Part 3: Sediment transport in your estuary

Discuss and explain your results:

1. **Explain the spatial patterns in tidally averaged sediment transport by discussing the transport by mean flows and by tidal asymmetry. Relate tidally averaged sediment transport to presence of mean flow, magnitude of tidal flows, generation of higher harmonics and phase difference between D2 and D4 flow velocities (=2*phaseD2-phaseD4). If you have diurnal tides it will be the relative phase difference between D1 and D2 tides. Discuss duration asymmetry and velocity asymmetry in your system. (max 4 figures)**

   In order to model the sediment transport in the Elbe estuary, Groen's model was used (without advection), combined with the flow velocities from the second project and the equilibrium depth of 8.69 m. An M2 tide with the amplitude of 1.45 m (corresponding to the average amplitude found in the first project) is forced at the mouth of the estuary. Until x_r a decreasing width is used and a fixed width after x_r to simulate the river. For simplicity no river flow is simulated in this model.

   In figure 13 the tidally averaged sediment transport is shown and the sediment transported by the M2 and M4 tide. In general most of the trends seem to be explained by the flow velocities shown in figure 14. This makes sense, since higher flow velocities lead to more erosion and thus also more sediment transport and vice versa.

   The phase difference seen in figure 15 changes quite a bit over the estuary, making it hard to give a single explanation of the relation between the sediment transport and the phase difference. We expect to see duration asymmetry with a phase difference of -90 or 90 degrees and velocity asymmetry with a phase difference of 0 or 180 degrees. The phase difference seen in figure 15 are not exactly in those modes, but somewhere in between. Therefore it is likely that we have a mix of duration and velocity asymmetry influencing the sediment transport.

   However, the phase difference is mostly around zero, indicating velocity asymmetry. For 0 degrees this indicates flood dominance, with peak flow velocities and sediment transport at flood, resulting in land-inwards sediment transport.

   The tidally averaged sediment transport is caused by the combination of the tidal asymmetry and the stokes return flow. The tidally averaged sediment transport is negative before x_r and positive behind x_r, indicating transport out of the estuary before x_r and transport into the estuary behind x_r. The tidally averaged flow velocities are negative before x_r and go to zero behind x_r, indicating a stokes return flow that decreases in strength behind x_r. Since the tidally averaged sediment is out of the estuary, the stokes return flow is probably dominant over the tidal asymmetry. This is corroborated by the phase-difference, which goes to zero between 25 and 50 km, leading to flood dominance. Over the same distance the sediment transport also decreases, meaning that the stokes return flow and the tidal asymmetry are in balance. Since the tidally averaged flow and thus also the stokes return flow behind x_r decreases, the tidal asymmetry becomes dominant, leading to positive sediment transport. Good to note that if river flow was present this would also influence the sediment transport, probably leading to negative sediment transport behind x_r.

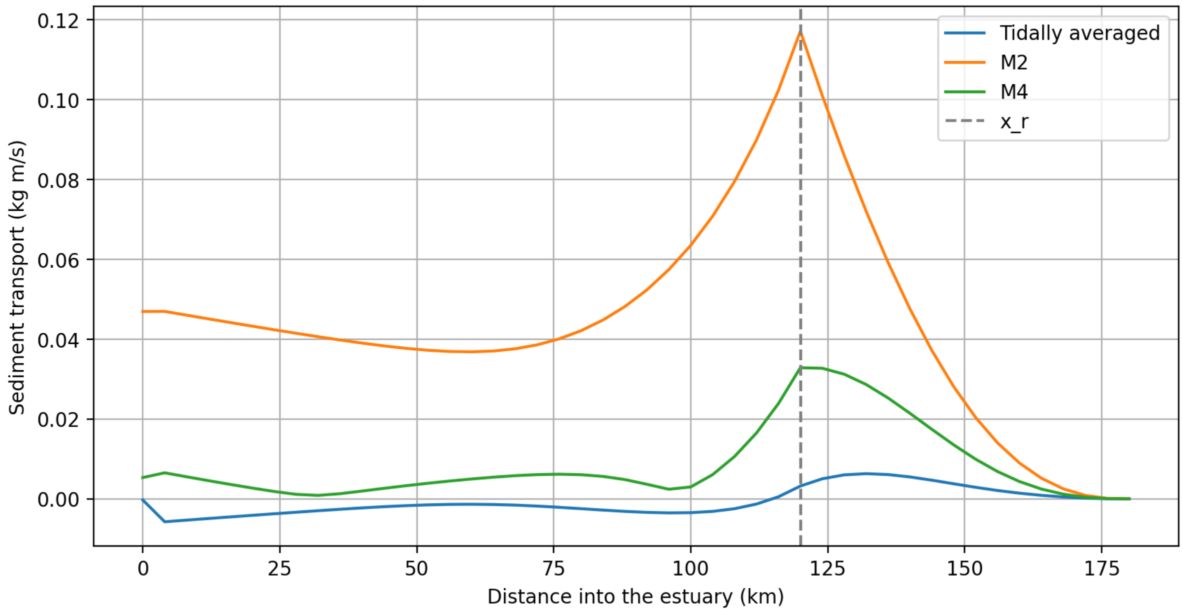

Figure 13: Tidally averaged sediment transport based on modelled flow velocities in the Elbe estuary for equilibrium depth. Furthermore also the sediment transport through the M2 and M4 velocities are shown. The grey line indicates where the estuary morphs into a river.

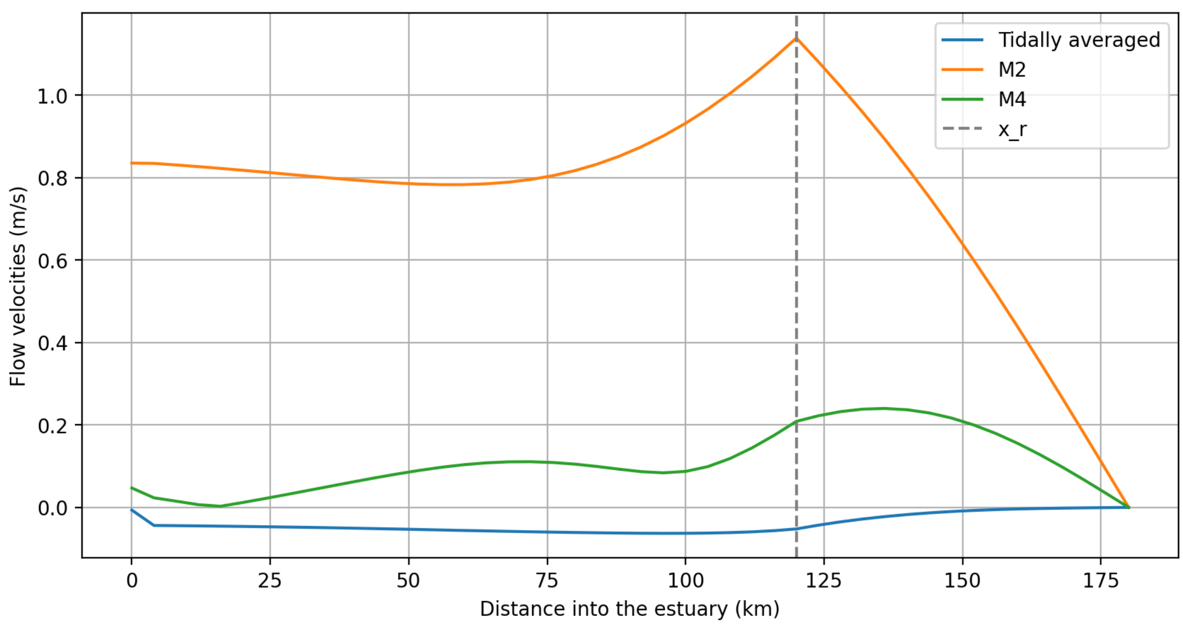

Figure 14: Tidally averaged flow velocities based on modelled flow velocities in the Elbe estuary for equilibrium depth. Furthermore also the M2 and M4 velocities are shown. The grey line indicates where the estuary morphs into a river.

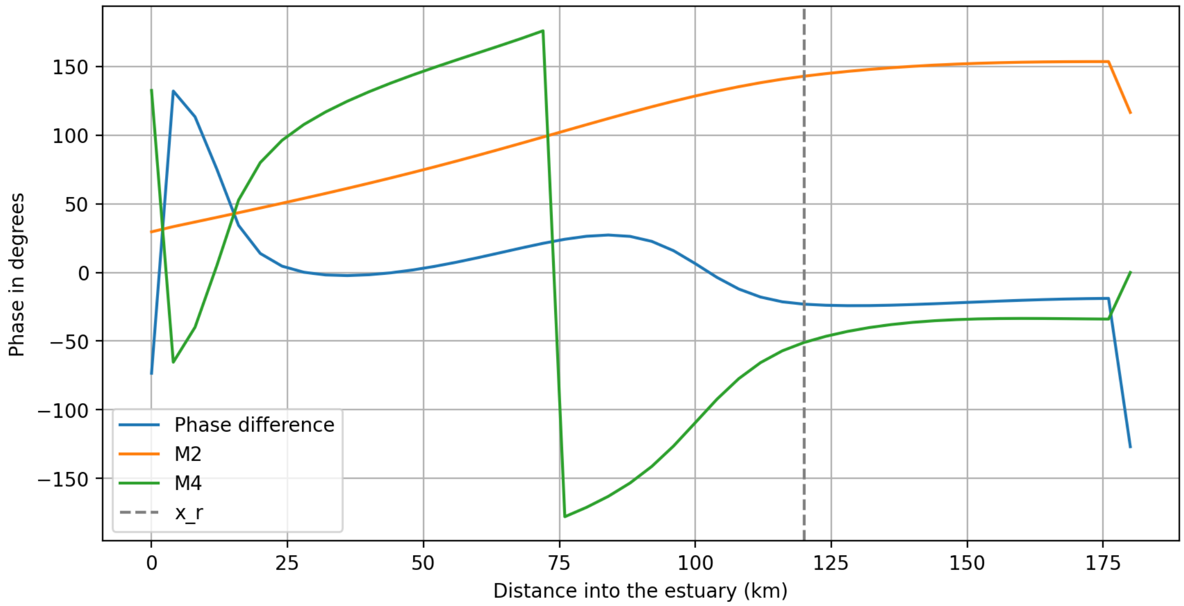

Figure 15: The phase difference of the M2 and M4 flow velocities in the Elbe estuary for equilibrium depth. Furthermore also the phase difference between M2 and M4 is shown. The grey line indicates where the estuary morphs into a river.