Change of mean tidal peaks and range due to estuarine waterway deepening

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Abstract:

The deepening of estuarine waterways enforces essential changes of mean tidal water level peaks and range. Legal requirements ask for their determination by preservation of evidence. A method has been established to evaluate these effects quantitatively by statistical tools for each measure, even in the case of subsequent deepenings.

Intruction

Deepening of estuarine waterways enforce there changes of tidal water levels. They start immediately after deepening but continue after execution of dredging for a certain period of time being necessary for the development of a new dynamical equilibrium between estuarine geometry and tides. The order of magnitude of changes of mean tidal water levels is particularly of importance for water management and ecological zonation but is also regarded as a primary indication for changes of tidal currents, salinity and storm surge levels. Therefore the quantitative determination of changes of mean tidal

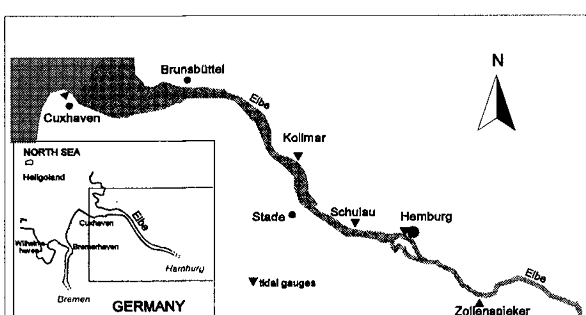

Fig.1: Elbe estuary, southern North Sea

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peaks and tidal range due to waterway deepening is given high priority in order to qualify its impacts. This is not only necessary for planning purposes but also for the environmental assessment studies and for the later preservation of evidence procedure due to legal requirements in Germany. Preservation of evidence gets increasingly difficult if subsequent deepenings have been carried out and their impacts are still continuing at the beginning of the successive one. An impressing example is the continuous increase of tidal range at the tidal gauge of Hamburg-St. Pauli since the beginning of this century whereas during the same period neither the tidal range at the island of Heligoland and in Cuxhaven at the estuarine mouth nor the fresh water discharge have experienced comparable changes (fig. 2).

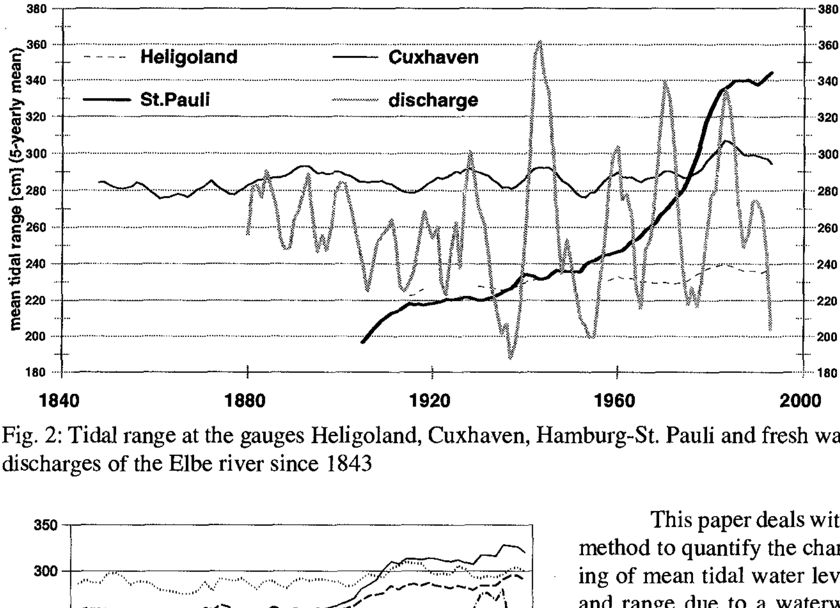

Fig. 2: Tidal range at the gauges Heligoland, Cuxhaven, Hamburg-St. Pauli and fresh water discharges of the Elbe river since 1843

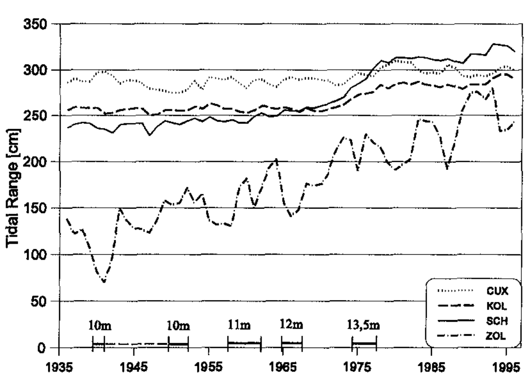

Fig. 3: Periods of sucessive waterway deepenings ↔ and time series of tidal range at estuarine tidal gauges Cuxhaven, Kollmar, Schulau and Zollenspieker (fig.1)

This paper deals with a method to quantify the changing of mean tidal water levels and range due to a waterway deepening in the Elbe estuary (fig. 1) for a navigational depth of 13,5 m below mean low spring tide water level (C.D.) during the years 1974 to 1976 being the fourth since 1949. The legal boundary conditions required a preservation of evidence procedure quantifying the singular effects occurring due to the specific deepening. The significant changes of mean tidal water levels for the last sixty years are documented here explanatory for the tidal range at four estuarine tidal gauges connected with the periods of the coincidently executed successive deepenings in the Elbe estuary. (fig. 3). The tidal range has increased relatively the more the further upstream the tidal gauge is located. Due to that effect the relations of local tidal range in the estuary have changed: E. g. at the gauge Schulau located immediately downstream of Hamburg it does therefore nowadays exceed that one at the gauges Kollmar and Cuxhaven. Before the intensive deepenings during the last decades tidal range decreased continuously from the estuarine mouth upstream (fig. 3); but meanwhile the maximum tidal range occurs in the central part of the estuary. The relatively largest increase has occured upstream of Hamburg where no dredging has been carried out. The development of tidal ranges during that period highligths two major effects: the changes are not only correlated to the period of dredging itself and the changes increase the more the gauge is further upstream located.

Basic effects of waterway deepening on mean tidal peaks

The deepening of an estuarine waterway leads to an extension of cross-sections allowing the propagation of a higher amount of tidal energy further upstream. The increase of the range of the tidal wave is symmetrically distributed to high and low water level peaks (fig. 4).The lowering of the bottom -generally increasing in upstream direction- creates additionally a lowering of the mean water level (fig. 5).

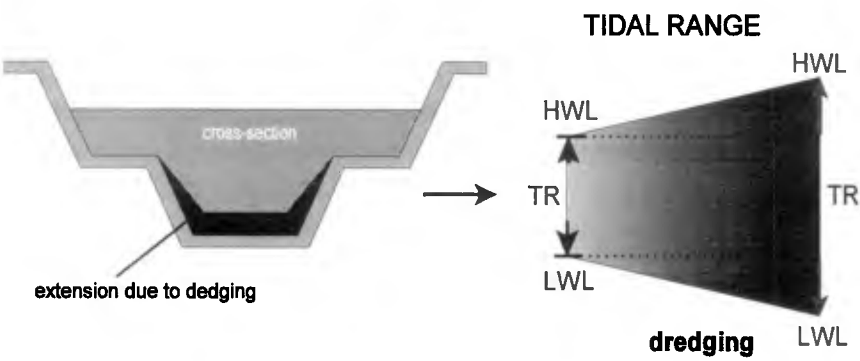

Fig. 4: Basic effect of cross-sectional extension on tidal range and peaks

The superimposition of both effects leads to a resulting relatively larger lowering of the tidal low peaks than heightening of the tidal high peaks (fig. 6). This phenomenon is well known from estuarine deepenings for the stretches of waterway deepening. Beyond there is only an increase of tidal range which is nearly evenly distributed to the high and low water level peaks.

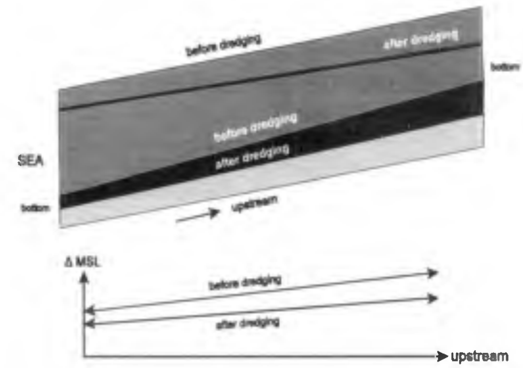

Fig. 5: Schematized lowering of estuarine mean water levels due the bottom lowering by estuarine deepening

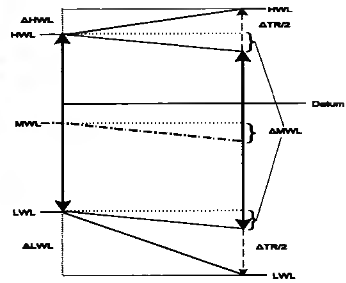

Fig. 6: Superimposed effects of cross-sectional extension and bottom lowering due to estuarine deepening on mean tidal water level peaks

Evaluation of suitable time series

In order to determine time series of mean tidal water levels which experienced only significant impacts due to the last deepening double-mass analysis [SEARCY & HARDYSON 1960] was applied to the time series as well of yearly mean high and mean low water levels as of mean tidal range in the downstream and central part of the estuary with respect to the same parameters at the offshore tidal gauge on the island of Heligoland (fig. 1) which was taken as base station representing the natural variation of tidal water levels in the southern North Sea. It is assumed that as far as offshore as the location of the island of Heligoland (fig. 1) no impacts of estuarine deepenings will occur. Further upstream the method has not been applied since ther the impacts of the fresh water discharge variations being not considered in the double-mass analysis would be to strong in order to allow a successful application of that method.

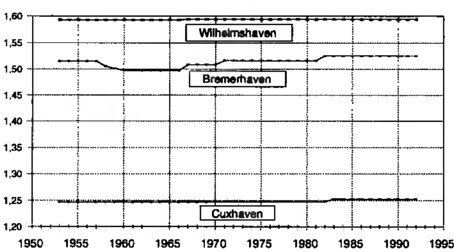

Fig. 7: Gradients of double-mass analysis for the tidal range at the gauges Wilhelmshaven (Jade), Bremerhaven (Weser) and Cuxhaven (Elbe) with correlation to that at the gauge on the island of Heligoland (fig. 1).

First a comparison was carried out for distinct tidal gauges at the German North Sea coast in order to check if there are general changes not related to impacts in the Elbe estuary itself in order to avoid any misinterpretation of effects being not specific for the Elbe estuary. The double-mass analysis of the tidal ranges at the gauges of Wilhelmshaven (Jade Bay), Bremerhaven (Weser estuary) and Cuxhaven (Elbe estuary) with respect to that one at the at the island of Heligoland makes evident that its variations differ locally at the German North Sea coast (fig. 7).

Exemplary for the analysis for the Elbe estuary here the results for the tidal range at the gauges Kollmar and Schulau are dicussed. In order to avoid the typical difficulties occuring by application of double-mass analysis no interpretation by visual observation of the double-mass curve itself has been carried out. The gradient of the double-mass curve was continuously computed and any change of more than 0,75 % is taken into consideration (fig. 7a + b). The results led to the conclusion to use the time series between 1970 and 1974 being representative for the situation before the deepening incorporating also the total effects of the previous deepening. The time series between 1977 and 1992 were used in order to determine the impacts of waterway deepening whereas 1975 and 1976 were regarded as a transition period between dredging and readaption .

Another check was carried out for the data of the tidal gauge Schulau (fig. 1): The gradient is changing for the whole period but with significant increase since about 1970 (fig. 8a). In order to gain results allowing a proper interpretation the tolerance for changes of the gradient of the double-mass curve was doubled to 1,5 %. The results of that analysis fit well with that carried out for the data of the tidal gauge Kollmar: during the period between 1970 and 1974 there is no change in the behavior of the tidal range at the gauge Schulau

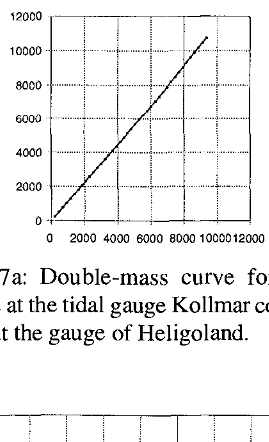

Fig. 7a: Double-mass curve for the tidal range at the tidal gauge Kollmar correlated to that at the gauge of Heligoland.

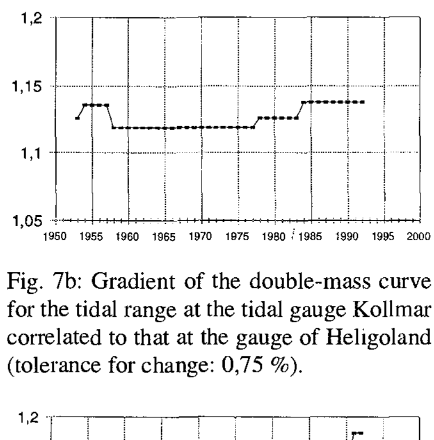

Fig. 7b: Gradient of the double-mass curve for the tidal range at the tidal gauge Kollmar correlated to that at the gauge of Heligoland (tolerance for change: 0,75 %).

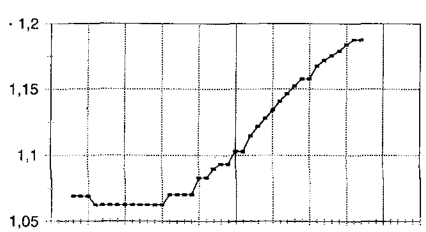

Fig. 8a: Gradient of the double-mass curve for the tidal range at the tidal gauge Schulau correlated to that at the gauge of Heligoland (sensivity for change: 0,75 %).

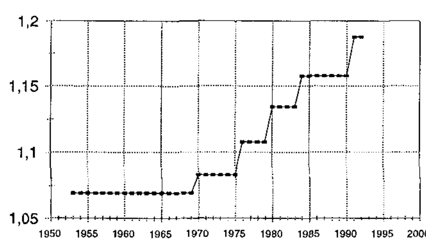

Fig. 8b: Gradient of the double-mass curve for the tidal range at the tidal gauge Schulau correlated to that at the gauge of Heligoland (sensivity for change:1,5 %).

with respect to that one at the gauge of Heligoland (fig. 8b). The higher tolerance for the data of the gauge Schulau is obviously necessary for getting proper results. The reason behind is that at this further upstream located gauge the impacts of freshwater discharge variations on tidal water levels are stronger than at Kollmar. The higher tolerance is explainable as a filtering technique for supressing these effects.

Determination of deepening effects

Estabilshed method

The local estuarine mean low and high water levels at each estuarine gauge (LWL_{EGi}, HWL_{EGi}) were approximated by use of multiple regression as a function of the corresponding parameters (LWL_{Hel}, HWL_{Hel}) and the mean tidal range(TR_{Hel}) at the offshore gauge Heligoland (fig. 1), the latter one as a measure for the offshore energy input, and additionally the inland fresh water discharge (Q_f). Effects of estuarine waterway deepening on tidal water levels at the island of Heligoland (fig. 1) do not occur; they could therefore be used as well as an independent boundary condition as the inland fresh water discharge. Empirical optimizations led to the following functional equations for estuarine mean low and mean high water levels:

$$LWL_{EGi} = a_{1,i} \cdot LWL_{Hel} + a_{2,i} \cdot TR_{Hel} + a_{3,i} \cdot Q_f^{b1,i} \quad (1)$$

$$HWL_{EGi} = a_{4,i} \cdot HWL_{Hel} + a_{5,i} \cdot TR_{Hel} + a_{6,i} \cdot Q_f^{b2,i} \quad (2)$$

Regression analysis was initially carried out for the period immediately before the waterway deepening on the basis of the time series of monthly means of the period from 1970 to 1974 in order to determine the coefficients. A comparison of computed and measured data made evident the reliability of the approximation (fig. 9 - 11). Afterwards these coefficients were used to determine the estuarine mean tidal peaks on the basis of the boundary conditions for the offshore tidal parameters and the freshwater discharge for the period after the waterway deepening. The differences between measured and computed data are regarded as the deepening effects D_L and D_H (fig. 9 - 11).

Changes of mean tidal peaks and range

The changes of mean tidal peaks and range are rather small at the estuarine mouth but increase upstream. Exemplary the changes of mean high and low tide at the gauges Cuxhaven, Kollmar, Schulau and Zollenspieker (fig. 1) are compared: There is no change for mean high tide at the gauge Cuxhaven and the change in mean low water is only 4,5 cm (fig. 12). Further upstream at the tidal gauge Kollmar the changes are more pronounced: 6,0 cm for mean high tide (fig. 9a) and 8,9 cm for mean low tide (fig. 9b). Again for this gauge also the scatter is much lesser for mean low tide than for mean high water levels. The effects of waterway deepening on mean tidal peaks at the gauge Schulau is higher than downstream: Mean high tide has risen for 12,8 cm (fig. 10a) and the mean low water level has been lowered for 25,1 cm (fig. 10b). The scatter of the monthly mean peaks is of an acceptable

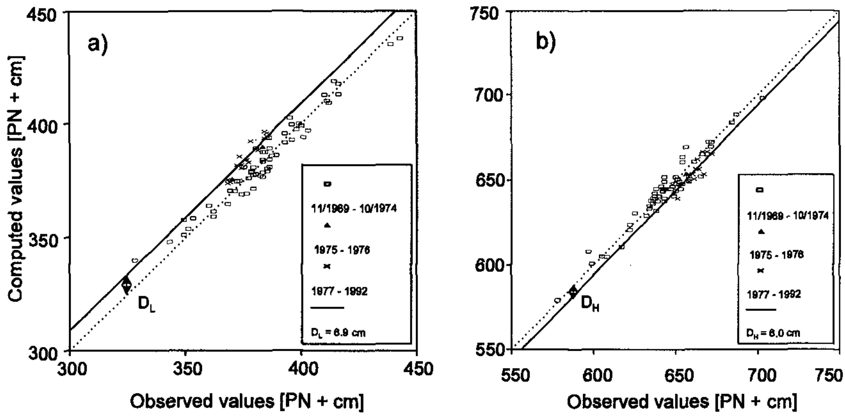

Fig. 9: Determination of mean low water level changes D_L (a) and mean high water level changes D_H (b) due to waterway deepening to C.D.-13,5 m (tidal gauge Kollmar)

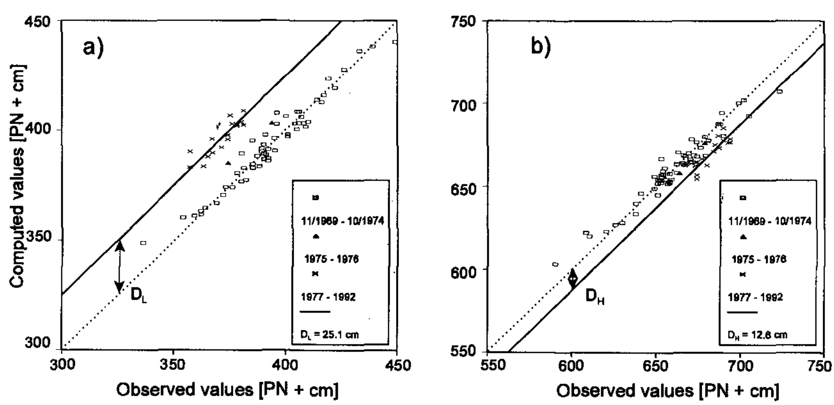

Fig. 10: Determination of mean low water level changes D_L (a) and mean high water level changes D_H (b) due to waterway deepening to C.D.-13,5 m (tidal gauge Schulau)

order of magnitude with respect to the objective of the analysis. The tidal gauge Zollenspieker is located upstream of the harbour of Hamburg; there has been no dregding in that part of the estuary. Nevertheless the deepening effects are also here significant: an increase of mean high tide of 17,3 cm (fig. 11a) and a lowering of the mean low water level of 18,3 cm (fig. 11b). Particularly for the mean low water levels the scattering of data is remarkably higher than for the time series of the gauges being located further downstream. This effect must be credited to the here stronger impact of the variations in freshwater discharges.

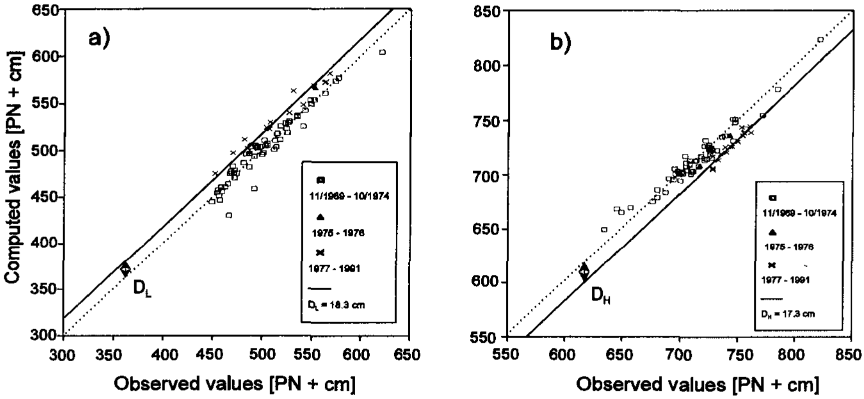

Fig. 11: Determination of mean low water level changes D_L (a) and mean high water level changes D_H (b) due to waterway deepening to C.D.-13,5 m (tidal gauge Zollenspieker)

The changes of the tidal peaks are mostly non-symmetrical with respect to that of the tidal range (fig. 12): In the estuarine stretch where the deepening has taken place the descendence of the LWL is larger than the rise of the HWL. Contradictory in the upstream area where no dredging has been carried out the changes in tidal range are symmetrically distrubuted on mean high and low tide. The deepening causes two superimposing effects: a

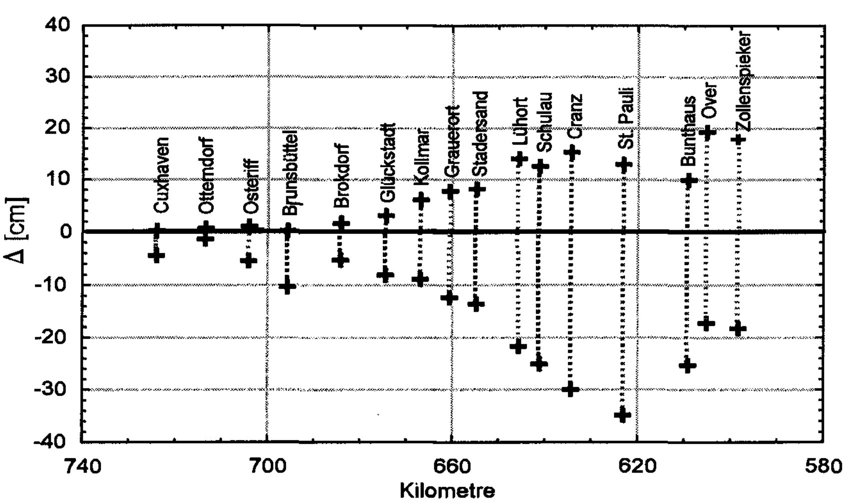

Fig.12: Changes of mean low an high water levels along the Elbe estuary due of waterway deepening to C.D.-13,5 m

lowering of mean sea level and an increase of tidal range resulting in a lower rise of high tide than fall of low tide. In the non-deepened stretches of the estuary the increase of tidal range due to the impact of higher tidal energy from the downstream deepened part of the estuary is dominant. Since there is no lowering of the mean water level the changes for high and low water peaks have a similar order of magnitude (fig. 12) which fits into the explanation of the deepening effects on tidal water levels given before (fig. 4 - 6).

Comparison with previous model tests

The effects of the Elbe waterway deepening have been investigated before execution by hydraulic model tests with both a movable and a non-movable bed [BAW 1974]. In comparison to the measured effects the forecasted changes are remarkably smaller (fig. 13). But the test results fit much better if compared with the changes occuring immediately after dredging in the transition period of the first two years (fig. 9 - 11) whereas the later changes of the mean peaks exceed the forecast significantly. This is due to a readaption of estuarine morphology to the changed tidal hydrodynamics occurring after deepening. This cross-sectional enlargement allows again an increase in tidal energy enforcing afterwards once more morphological changes. Generally the slopes of the estuarine navigation channel are

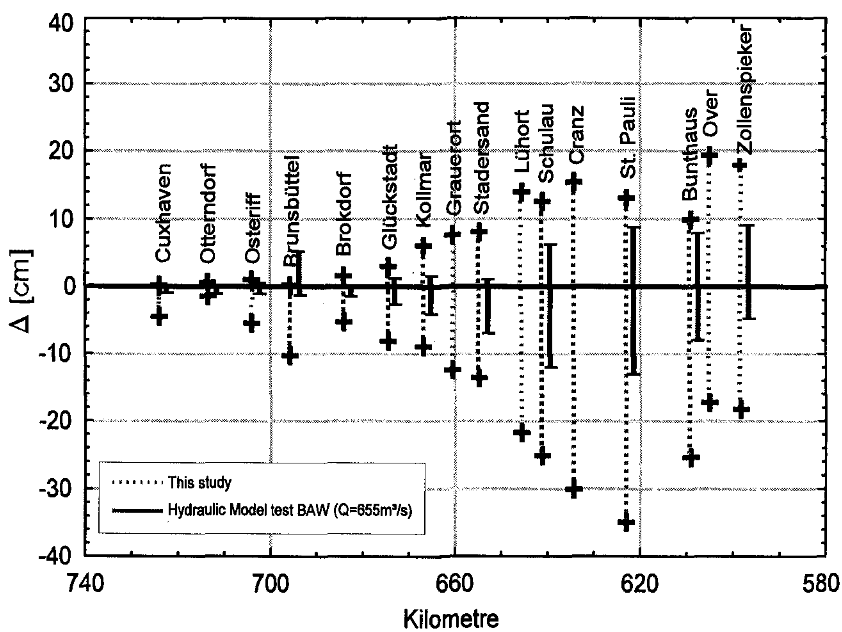

Fig. 13: Comparison of evaluated changes of mean tidal peaks and range with forecast by hydraulic model test

after deepening steeper than fitting to natural conditions. Furthermore both capital and maintainance dredging leads to lowering of the bottom beyond the required navigational depth. Consequently these effects in acting together with the increased tidal energy create a process of cross-sectional readaption continuing after capital dredging. until a new morphodynamical equilibrium is established (fig.14). This effect of a morphological phase-lag after estuarine deepenings has to be considered for forecasts in order to get proper and reliable results for the effects of anticipated estuarine deepenings with respect to tidal water levels.

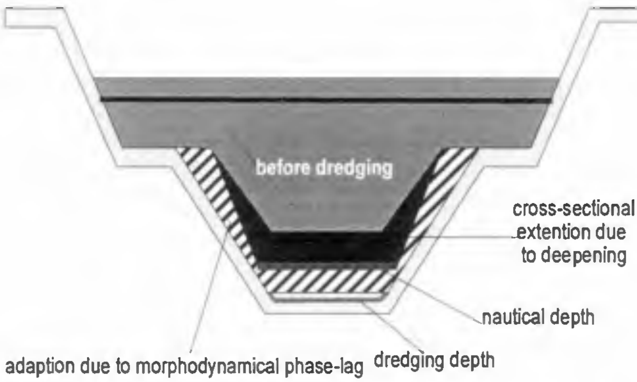

Fig. 14: Scheme of morphodynamical phase-lag after deepening of an estuarine navigation channel

Conclusions

Deepenings of estuarine waterways effect an increase in tidal range and a lowering of the mean water level. The superimposition of both leads to relatively larger lowering of the tidal low water peaks than heightening of the high water levels. Upstream of the dredged parts of the estuary only an increase of tidal range occures contributing evenly to the changes of the low and high water peaks.

It has been shown that even for successive deepenings of estuaries a separated quantification for singular measures is possible by combined application of double-mass and regression analysis. Double-mass analysis is a useful tool for the evaluation of coherent time series being suitable for event-related regression analysis. The implemantation of physically sound boundary conditions and parameters allows a proper quantification of deepening effects on tidal range and peaks.

The morphological phase-lag after the dredging itself allows a further significant change of tidal water levels afterwards. Its time scale is about years. Hydrodynamical modeling of deepening effects must take these effect into consideration for getting reliable results.

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