Analysis of Salinity Alterations due to Estuarine Waterway Deepening by Artificial Neural Networks

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Summary

Deepening of estuarine waterways effects primarily changes of tidal water levels and secondarily that of tidal volumes and salt intrusion. These effects are subject of Environmental Impact Assessments which are often checked by afterwards monitoring for preservation of evidence. After the deepening of the waterway in the Outer Weser estuary among others such measurements were carried out for salinity. Since the data indicated alterations of salt intrusion into the Weser estuary a reliable quantification of the changes by conventional procedures like e. g. nonlinear regression analysis failed. However test with Artificial Neural Networks (ANN) provided reliable results for the respective data sets gained before and after the waterway deepening. Whereas the application of the ANN which was trained with data before the deepening mismatched with the data gained after deepening. These differences provide a reliable measure for the increased salt intrusion into the Weser estuary due to the deepening of the Waterway.

Keywords

tide, salinity, artificial neural network (ANN), estuary, waterway deepening

Zusammenfassung

Fahrwasserausbauten in Ästuarien bewirken erstrangig Veränderungen des Tideregimes und nachfolgend auch die des Salzeintrags nach oberstrom. Diese potenziellen Auswirkungen werden in Umweltverträglichkeitsprüfungen untersucht, deren Ergebnisse hinsichtlich ihrer Verlässlichkeit durch Beweissicherung überprüft werden. Nachdem Ausbau des Fahrwassers in der Außenweser wurden entsprechend u. a. Messungen der Salzgehalte vorgenommen. Da die Daten Indizien für Änderungen des Salzgehalts aufzeigten und deren umfassende Quantifizierung mit Methoden wie nichtlinearer Regression fehlschlugen, wurden Analysen mit Hilfe Künstlicher Neuronaler Netzwerke (KNN) ausgeführt. Damit konnten die Salzgehalte jeweils vor und nach dem Ausbau mit hoher Qualität reproduziert werden. Es zeigte sich weiterhin, dass mit dem Künstlichen Neuronalen Netzwerk, das mit den Daten vor dem Ausbau trainiert worden war, für die nach dem Ausbau gewonnen Daten keine entsprechende Übereinstimmung erreichbar war. Die dabei offenbar werdenden Differenzen konnten zur Quantifizierung der ausbaubedingten Änderungen der Salzgehalte genutzt werden.

Schlagwörter

Tide, Salzgehalt, Ästuarien, Fahrwasserausbauten, Künstliche Neuronale Netzwerke (KNN)

Contents

1 Introduction

Major harbours are often located at tidal estuaries where as well large natural water depths as traffic links to the inland are available, in particular for inland navigation. The growth of container ships and their corresponding draft, the depth and sometimes also the width of the waterways in the estuaries had to be increased several times leading to changes in hydro- and morphodynamics. One of these effects is an increasing salt intrusion into the estuaries affecting on the one hand ecology and on the other the ability of the surrounding farms to use the water of the estuary or of connected channels for their animals or plants.

According to planning law important infrastructure measures have to be proven for an environmental assessment procedure. If these results provide only an uncertain foundation for a reliable and appropriate appraisal, the planning approval authority has the option to establish a conservation of evidence procedure.

This strategy was applied by the planning approval authority for the deepening of the waterway in the outer Weser estuary in 1997. In particular for hydro- and morphodynamics a detailed measuring programme and corresponding data analysis were constituted in the decision on the official planning approval. Part of the programme were among others measurements on salt content at distinct measuring station in the Weser estuary (Fig. 1) in order to detect any increase of salt intrusion into the estuary.

The first data analysis carried out by the project operator Federal Waterway Authority Bremerhaven showed no indications for a significant change of salt intrusion into the Weser estuary (WSA BREMERHAVEN 2010). In respect of the interests of the Federal State of Lower Saxony a reassessment nonlinear regression analyses were carried out by the Coastal Research Station. The results highlighted significant changes of salt intrusion into the estuary after the waterway deepening, but it was not possible to quantify these changes, particularly for low and high values of salinity. In order to overcome this deficit the data set was reanalysed by applying artificial neural networks, which allowed finally a reliable determination of increasing salt intrusion into the Weser estuary due to the waterway deepening of the outer Weser estuary.

2 Investigation Area and Data Set

The area of investigation extends from the Outer Weser estuary; where the channel deepening has almost no effect, up to Intschede upstream the tidal barrier in Bremen-Hemelingen. Between these locations the area of interest with the gauges Bremerhaven, Nordenham, Strohauser Plate and Brake is settled (Fig. 1).

For the calculation two datasets for salinity for each location are available (WSA BREMERHAVEN 2010). The first dataset contains the time series from 1997 to 1998. This is a time series which is not influenced by the deepening, because the salinity was measured before the dredging started. The second time series starts in 2006 and contains the data after the waterway deepening.

Figure 1: Investigation Area.

3 Methodology

Artificial neural networks (ANN) are computational models inspired from the thinking pattern of human brain. They can learn and generalize from experiences, and they can abstract essential information from data. The network is made of various single units -the neurons- which are connected to each other by simple arithmetical functions. For the quantification of the alteration in salinity a Multi-Layer-Feed-Forward-Network was chosen (BERKENBRINK and NIEMEYER 2011). This type of ANN connects the neurons to each other in just one direction. The neurons are arranged in several layers. The neurons in the input-layer get all information about the process governing parameters. The neurons in the output-layer represent the result. Between these layers the hidden-layers are settled (Fig. 2).

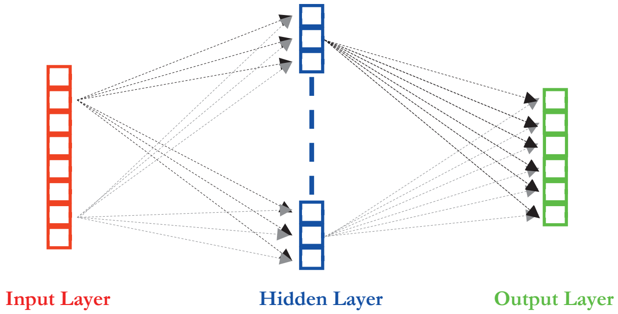

Figure 2: Illustration of the set-up.

These neurons change the values during the learning process till the output-layer get results with sufficient quality. For this kind of problem a supervised learning process was chosen. That means the output-layer is compared to measured data-sets and the neurons in the hidden-layer and the connection between all neurons are changed till the output-layer fits to the measured dataset. After this process the values for the hidden-neurons and the connection will be fixed and the ANN can calculate data of similar processes.

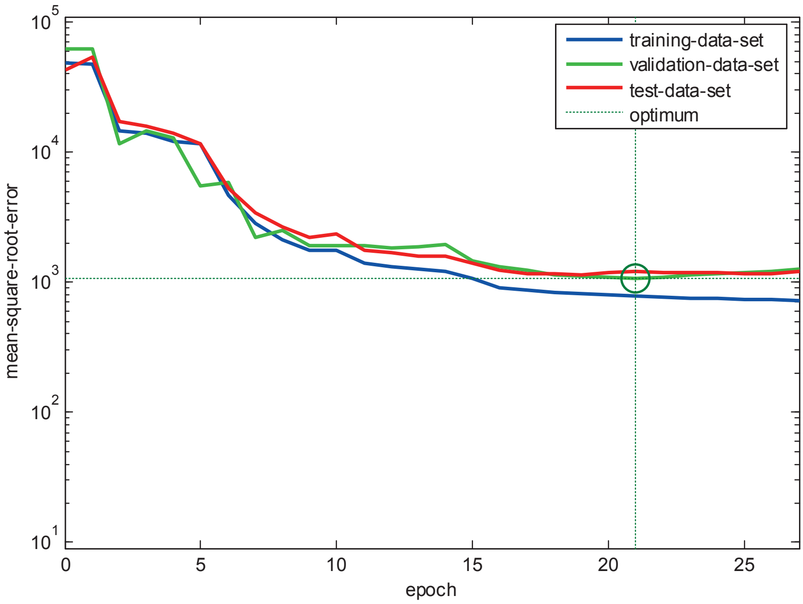

Figure 3: Training-process of the ANN.

To insure the generality the data set is split into three parts. 70 % of the data set is used for the training in order to fit the neurons and the connections of the ANN. Another 15 % of the data-set is used for validation. To be sure, that the ANN does not memorize the data, the learning process of the ANN is controlled by the validation data-set. During the training the mean-square-root-error between output and measured data is calculated for each training-epoch. The same procedure is carried out for the validation data-set.

While the mean-square-root-error for the training-data-sets getting smaller after each epoch, the validation- data-set reach the point, where this error gets bigger. This is the point, where the memorizing-process starts. Then the training-process has to be stopped and the ANN is fixed (Fig. 3).

The quality of the ANN is verified by regression-diagrams (Fig. 4). They show the functional correlation between calculated and measured data. There is a good agreement between calculated and measured data which is seen in the low distribution of the values around the regression line and this line is similar to the angle bisector, following called reference line, for which calculated and measured data are identical.

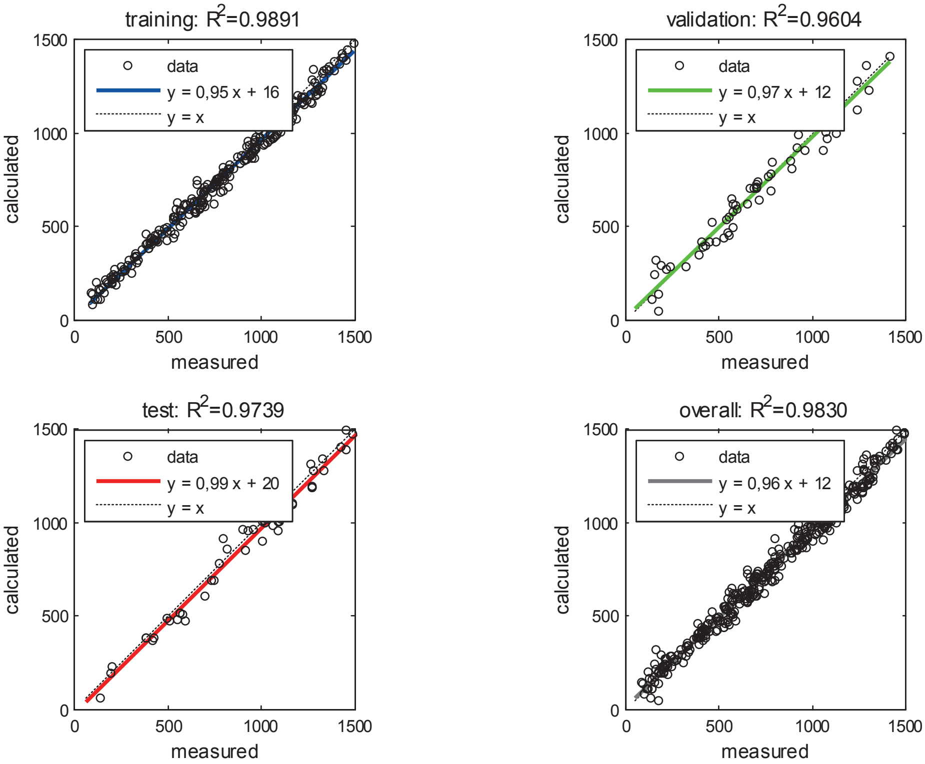

Figure 4: Results of a trained ANN [0,01 ‰] (example: Bremerhaven).

The ANN is now suitable for other data-sets for the same location under similar conditions. It will calculate like the test-data-set the salinity with the following boundary condition: different time steps for the salinity, tidal range and tidal high water level in the Outer Weser (Aussenweser) and the freshwater discharge in Intschede, which represent the most important governing factors for salinity in the estuary. Seasonal effects such as storm surges or dry summers are implicitly included. The topography is not considered in the ANN. If there is a significant variation between the Outer Weser and the point of interest it can be identified and quantified by the results of the ANN.

4 Calculation by an ANN

4.1 Bremerhaven

The data set of 1998 for Bremerhaven does not cover the whole year and therefore the analysis by ANN may miss seasonal effects. 70 % of the 401 available data sets were used for the training of the ANN, the rest for testing and validation. The agreement between measured and calculated data is very close (Fig. 5). The distribution is very low and the regression and reference line fit nearly exact.

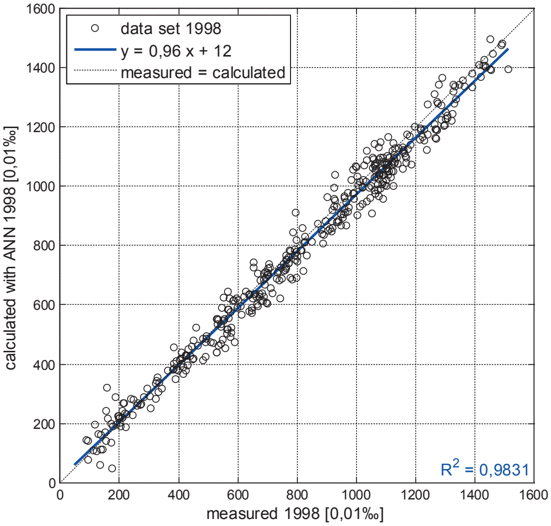

Figure 5: Scatter plot for calculated and measured salinities for gauge Bremerhaven: data set from 1998 before waterway deepening.

This ANN is afterwards used for calculating the salinity values after the waterway deepening and then compared with the measuring data being available for the years 2006-2008 after the deepening. The corresponding scatter plot highlights that the calculated salinity values underestimate the salt intrusion after the deepening the more the higher the values (Fig. 6). This indicates a significant change in the salt intrusion into the Weser estuary since the measurements in 1998, which data were used for the training process of the ANN. Obviously the deepening of the waterway has significantly changed the process of salt intrusion into the estuary. This is a physically absolutely plausible result for which no analysis by ANN is indispensably necessary, but it makes a reliable quantification possible.

The alterations are neither constant nor linear. Up to a value of about 4 ‰ the salinity remains nearly the same as before the deepening, though scattering gets stronger around the reference line (Fig. 6). Above that threshold the measured values are underestimated by the ANN which indicates an increase of the salinity after the deepening of the waterway which is represented by a nonlinear regression. The distance between both regression lines of the calculations with the data set from 1998 and the data set from 2006-2008 is the measure for the alteration in salinity caused by the waterway deepening (Fig. 7).

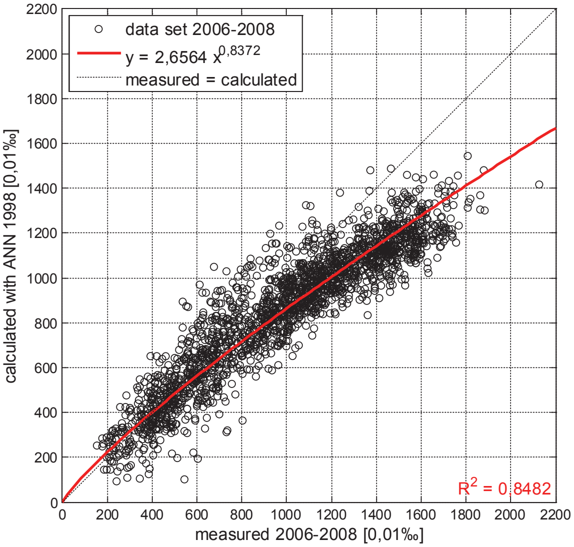

Figure 6: Scatter plot for calculated and measured salinities for gauge Bremerhaven: data set from 2006-2008 after waterway deepening.

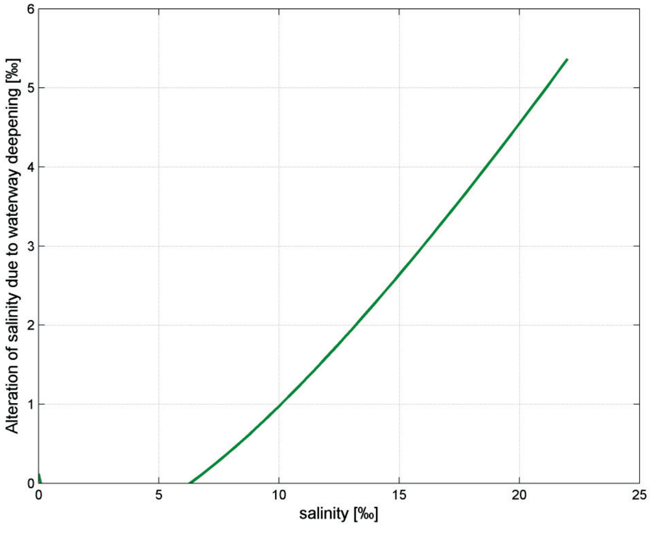

Figure 7: Alteration of salinity due to the waterway deepening at the location Bremerhaven.

For the complete time series this results in a difference of 1.1 ‰ increasing for salinities higher than 12 ‰ to values of 1.6 up to 4.2 ‰. The mean difference is determined by the difference between values calculated with the ANN established with data for the situation before the deepening of the waterway in comparison with the measured values after the deepening.

4.2 Nordenham

The longest time series with 701 values for the training are available for the gauge Nordenham which allows establishing an ANN with complete seasonal variations. The comparison of measured and calculated data shows a very good agreement (Fig. 8). There is only small scattering around the reference line.

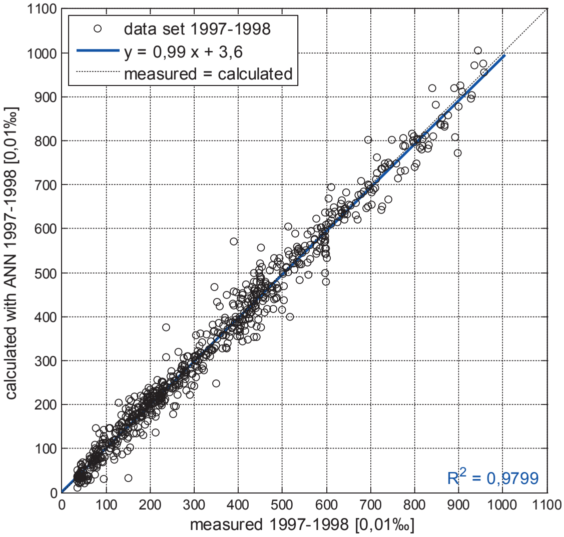

Figure 8: Scatter plot for calculated and measured salinities for the gauge Nordenham: data set from 1998 before waterway deepening.

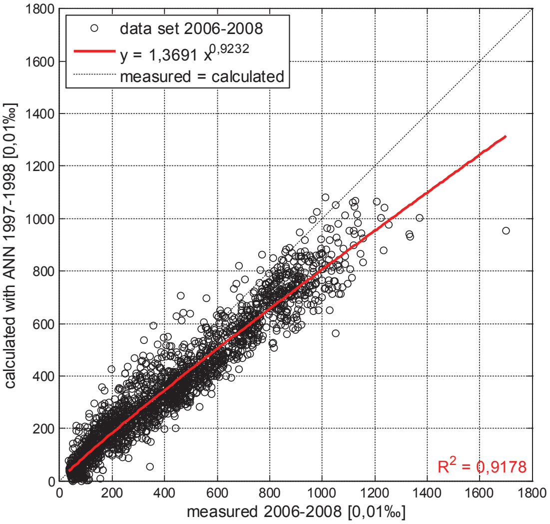

Figure 9: Scatter plot for calculated and measured salinities for gauge Nordenham: data set from 2006-2008 after waterway deepening.

Similar to the results for the location Bremerhaven the application of the ANN trained with the data set from 1998 for the data set of 2006-2008 results in an underestimation of the measured values. The impact of the waterway deepening is again represented by the differences between calculated and measured data for salinity. The effect of the waterway deepening is unknown to the ANN which therefore calculates lower salinity values than measured (Fig. 9). For the whole time series this results in a mean difference of 0.73 ‰ with maximum deviations from 1.8 ‰ up to 3.5 ‰ above a threshold of about 10 ‰ (Fig. 10).

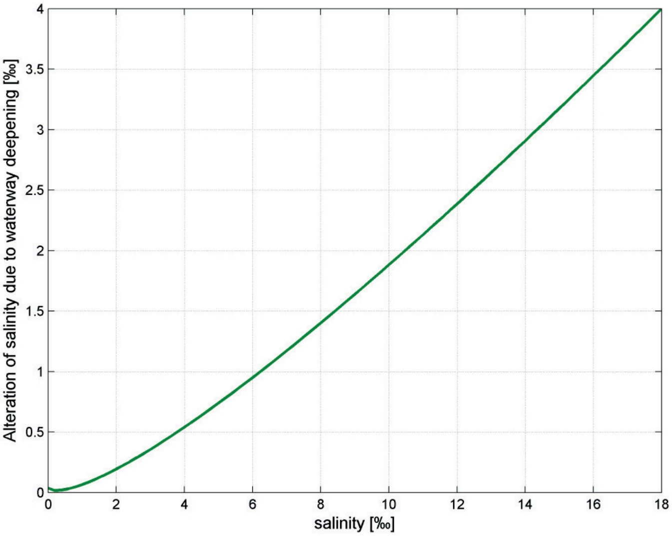

Figure 10: Alteration of salinity due to waterway deepening at the location Nordenham.

4.3 Strohauser Plate

The data set from the location Strohauser Plate is comparable to the data set of Bremerhaven. 70 % of the 484 measured values were used for the training of the ANN. Therefore it has to be taken into consideration that not all seasonal effects are implemented in the ANN. Anyway it shows similar reliable results like the ANN trained by the all-embracing data set of Nordenham. The correlation between measured and calculated data is nearly exact with a very small scatter (Fig. 11).

The application of the ANN trained for the data set from 1998 on the data set of 2006-2008 results here again in lower salinity values than measured (Fig. 12). In comparison to the results gained for the two locations further downstream the relative underestimation of the salinity values is higher and increases particularly for the higher ones. The mean value of the differences is 0.53 ‰ due to deepening of the waterway in the Outer Weser Estuary (Fig. 13).

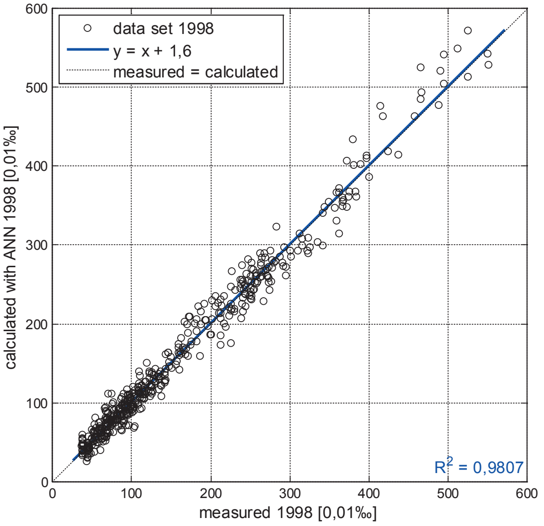

Figure 11: Scatter plot for calculated and measured salinities for gauge Strohauser Plate: data set from1998 before waterway deepening.

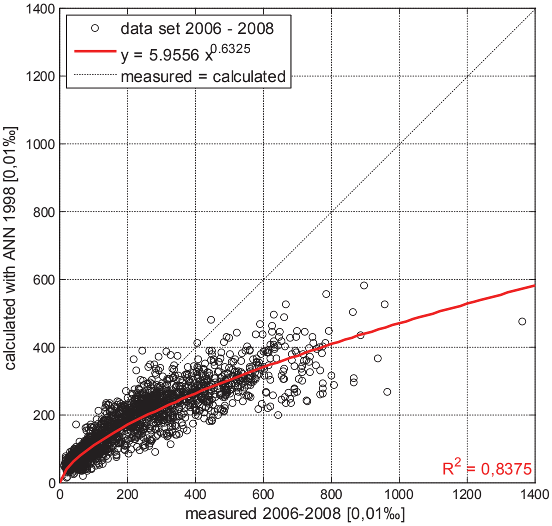

Figure 12: Scatter plot for calculated and measured salinities for gauge Strohauser Plate: data set from 2006-2008 after waterway deepening.

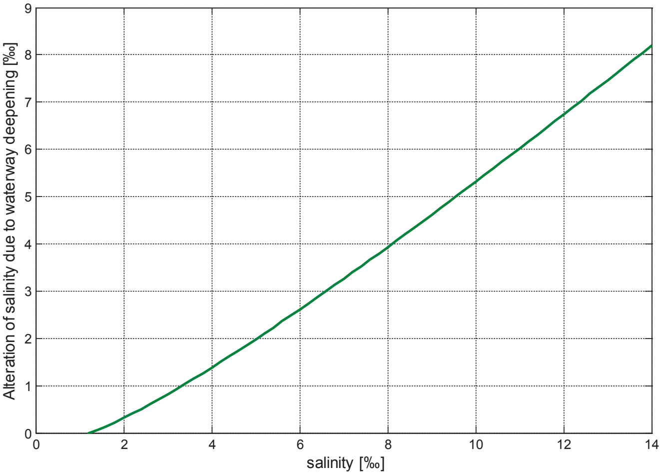

Figure 13: Alteration of salinity due to waterway deepening at the location Strohauser Plate.

4.4 Brake

For Brake a complete data set with 711 values covering all seasonal effects was available. There is a good agreement between the values calculated by the ANN and measured data (Fig. 14). The scatter is very low and the regression line fits nearly exactly with the reference line.

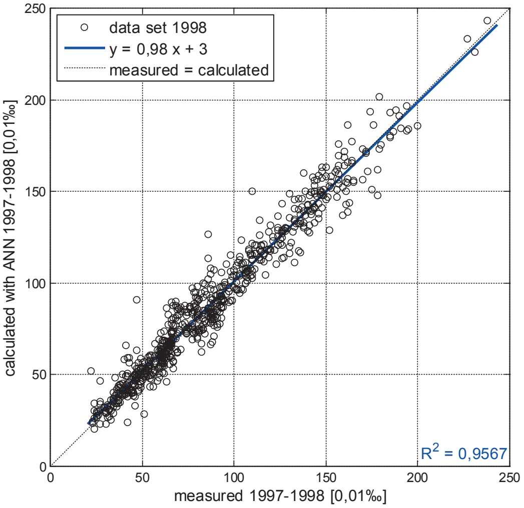

Figure 14: Scatter plot for calculated and measured salinities for gauge Brake: data set from 1998 before waterway deepening.

Applying the ANN to the data set from 2006-2008 the relative underestimation of the measured salinity values above a threshold of 1.5 ‰ is significant (Fig. 15). The intrusion of salt water from the North Sea ranges further upstream after the waterway deepening.

But this effect is only significant for the higher salinity values. The lower values scatter more which is an effect of the relatively small absolute values. Effects of the waterway deepening are at the location Brake are only significant for absolute values higher than 1.5 ‰ (Fig. 16).

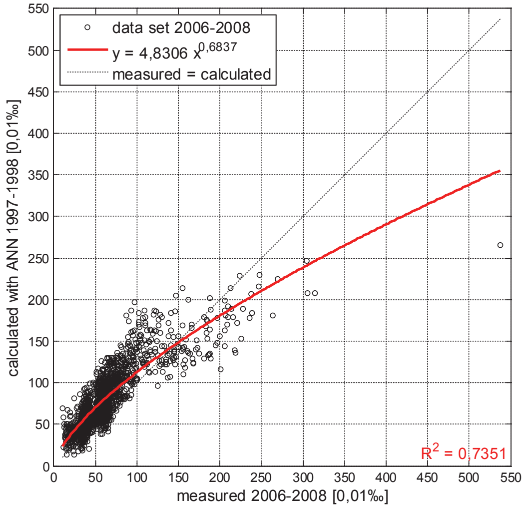

Figure 15: Scatter plot for calculated and measured salinities for gauge Brake: data set from 2006-2008 after waterway deepening.

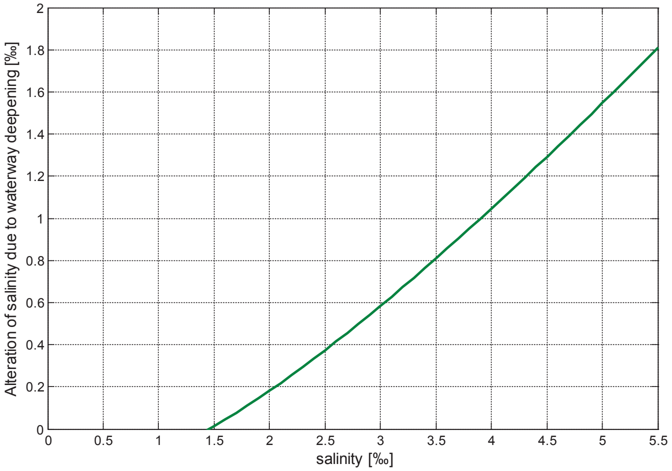

Figure 16: Alteration of salinity due to the waterway deepening at the location Brake.

5 Evaluation of the methodology

In order to prove suitability and reliability of ANNs control experiments were carried out with the data set from the location Nordenham -the one with the longest time series. Up to now the ANN were only trained with the data set from 1998 and then applied for the one from 2006-2008. The disagreement between measured and calculated values must be induced by effects which are not included in the learning process of the ANN which are obviously the effects of the changed topography due to the waterway deepening after 1998 and before 2006. In order to prove the reliability of the ANN its training is carried out again by using only half of the data set (test data set 1). Afterwards this ANN is adapted to the other half of the data set (test data set 2).

The ANN provides reliable results for test data set 2. The scatter of sporadic values is a little bit higher, but the mean value of the calculated salinity fits to the measured ones. Both data sets are from the same period without any significant change of the estuarine topography and the ANN reproduces the salinity values correctly and consistently (Fig. 17).

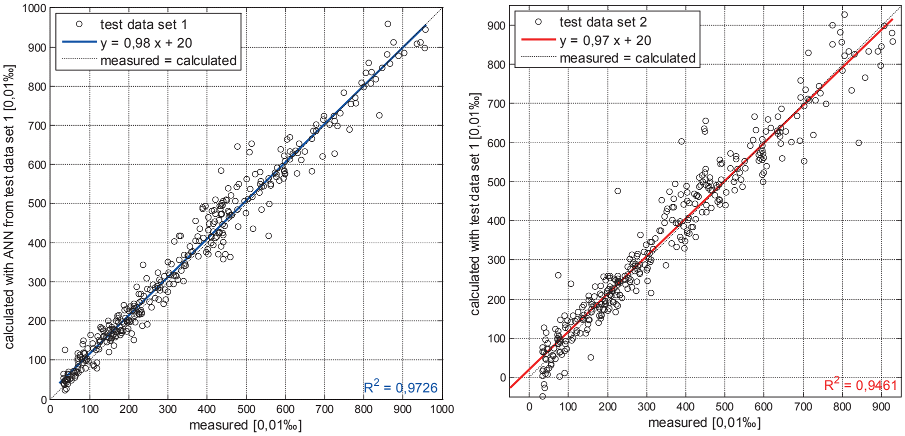

Figure 17: Training and application of the ANN for test data sets before waterway deepening.

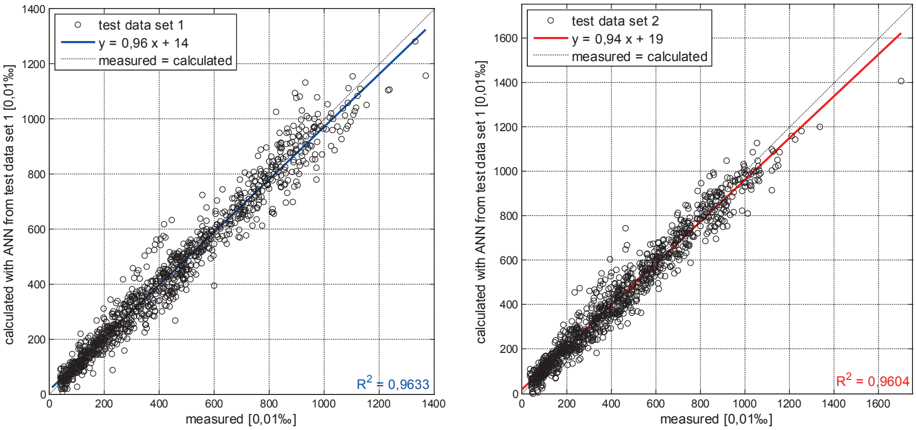

Figure 18: Training and application of the ANN for test data set after waterway deepening.

As an additional proof for the reliability of the methodology the same procedure was done with the data set of 2006-2008. Now the ANN learns the behavior of the salinity intrusion for the Weser Estuary after deepening of the waterway and provides results with a similar reliability as gained by the calculations with the data set of 1998. Training and application of the ANN show very good and reliable results. Calculated and measured values are of the same magnitude with a small scattering (Fig. 18).

The results of both analyses illustrate the capability and reliability of the methodology to reproduce salinity values by Artificial Neural Networks if there is no significant change in boundary conditions which are not considered for the training.

6 Summary and Conclusions

The quantification of changes in salt intrusion in the Weser Estuary after deepening of the waterway has been carried out by application of Artificial Neural Networks. The study highlights the reliability of that methodology for this purpose. It allows the identification of significant patterns in data sets and their reproductions by functional relationships.

With the data set of 1998 -measured before the waterway deepening started- an ANN was set up for each station in the Weser Estuary. This ANN was adapted to the data set of 2006-2008, which was gathered after the deepening of the waterway. After training with the corresponding input values tidal range, water level, freshwater discharge and salinity in the Outer Weser, ANNs can reproduce the salinity for each location further upstream. These parameters govern dominantly salt intrusion into an estuary if there are no further impacts like a significant change in the topography of the estuary. This was demonstrated by plausibility tests which highlighted suitability and reliability of the methodology by application of ANNs.

Based on the ANN output the alteration in salinity can be quantified. For every location an increase of salinity above a certain threshold was identified with growing the more the higher the absolute values are. Salt intrusion further upstream takes place since the waterway deepening leads to larger flood volumes.

7 References

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