

## CHAPTER 74

### Morphological Changes in a Fine Sand Tidal Estuary After Measures of River Improvement

by

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Artificial shipping channels in fine sand tidal estuaries are difficult to maintain. The attempt to stabilize the river beds and thus the fairway in the upper reaches of the Outer Weser by means of systems of river structures has been a success. The further deepening of the fairway necessitated the artificial narrowing of the river bed. The successes of improvement achieved over a prolonged period have up to now been satisfactory. Some explanations concerning the effects of the river structures on the morphology are given in the present report. In the improved river bed a continuous shifting of sediments is taking place, which is mainly due to the incessant action of the tidal currents. It is inevitable in this process that sand is drifted into the deep excavated channel. If one has a good knowledge of the natural shifting processes, it is possible nowadays, by using suitable Hopper suction dredgers, to employ to a certain extent methods of dynamic river engineering by means of the proper artificial shifting of the excavated soil within the cross sections of the river.

The capability of improvement of tidal rivers and their estuaries is of great importance for the sea ports that are situated on them. This is particularly true in a time when the dimensions of sea-going ships are still increasing and the countries are confronted with the problem of permanently having to improve the approaches to their sea ports, if they want to participate in overseas trade also in the future.

The reason why the improvement of fine sand tidal estuaries is so difficult and so expensive, depending on the local hydrographical and morphological conditions, is that the sediments are continually shifted on account of the tidal currents which are constantly changing in place and time and varying in their force as well as on account of the motion of the sea and the wash of the waves.

This renders the improvement, the maintenance, and the marking of artificial fairways for ocean shipping rather difficult.

The safe and easy operation of such ships in narrow waters necessitates therefore sufficiently deep and wide fairways in stable river beds. In order to achieve this, river structures (groynes, training walls) may be employed and/or dredging operations undertaken.

It is precisely in the field of dredging that completely new aspects have developed during the past years with respect to the improvement and the maintenance of fairways in tidal river beds, owing to the construction and the employment of very big Hopper suction dredgers. This raises the question whether the conventional and extremely cost-intensive river structures using mats made of shrubbery or plastic material and stones can perhaps be dispensed with in the future in the improvement of fairways in morphologically instable tidal estuaries.

This report deals with the successes achieved in the improvement of the Outer Weser, the approach to the ports on the Lower Weser Bremen, Brake, Nordenham, and Bremerhaven, by means of artificial river structures.

A few sentences only on the area where the investigation was made :

The Weser together with the Jade and the Elbe flow on a rather small stretch of coast into the south-eastern part of the North Sea. From there tidal waves penetrate periodically into the estuaries of these rivers and in places produce flood and ebb tide velocities of up to 2.50 m/sec in the deep river beds at mean tidal amplitudes of up to 3.50 m (Fig. 1).

Decisive for the size of the river bed cross sections is the quantity of the mean tidal waters.

At ebb tide 151 million cubic metres of water flow through the cross section of the Weser at km 65 (Bremerhaven), to which the Weser river contributes about 15 million cubic metres. Owing to the water coming from the adjacent tidal flats the volume of water at ebb tide increases rapidly towards the sea and amounts to as much as 855 million cubic metres 35 km below Bremerhaven (km 100).

The relation between cross section and quantity of flow in the Outer Weser is the following :

$$c = \frac{F_{em}}{T_{em}} = 14,200$$

From this formula a cross-section preserving mean velocity of flow at ebb tide of 0.61 m/sec can be derived. This relation is of great significance for the measures of improvement,

for it means that there is always a certain equilibrium between the river bed cross section and the hydrodynamic forces of the tidal currents. This equilibrium must be taken into consideration for improvement measures. If it is not possible to permanently increase the quantity of flow in a river bed, then the deepening of the fairway, which is necessary to enable shipping traffic, can only be carried out, if the enlargement of the cross section in the fairway is compensated by a reduction of the cross section of the same volume in the lateral areas of the river. What matters above all is that the hydraulic capacity of the river bed cross section is maintained.

In a bifurcation of a river conditions are different, because here it is as a rule possible to influence the respective quantities of flow in the individual river beds.

In the Outer Weser both cases exist in the section of improvement, namely the system of "one river bed" and that of "several river beds". From km 65 to km 78 there is nowadays only one single tidal river bed with adjacent tidal flats of different size. Then, further out towards the sea, a bifurcation follows. As a system with almost two parallel river beds, which comprises several big sandbanks, the Weser then flows into the sea.

The factor which determines the morphological changes in the section from km 65 to km 100 are the tidal currents. The ebb tide is, as a rule, stronger on the slopes on the right-hand side, seen in downstream direction. The flood tide predominates, on the other hand, on the opposite slopes and in the "lee-side" areas of the ebb behind the sands. Apart from local influences also the effect of the Coriolis forces manifests itself here. In all those areas where the ebb tide is clearly stronger, a resulting shift of sediments in the direction of the ebb tide must be reckoned with. A shift of sediments in the direction of the flood tide will result in all those places where the flood tide clearly predominates over the ebb tide.

The resulting conditions of current must always be taken into consideration in all measures of improvement and maintenance in tidal currents and must already be taken into account in the plannings; and what is more, they must be the very basis of sensible river engineering planning.

The estuary of the Outer Weser has considerably changed during the past centuries due to tidal currents and the motion of the sea. When in 1891 the first measures of river improvement had to be carried out in the upper reaches of the Outer Weser, because the big transatlantic passenger steamers which the Norddeutsche Lloyd had taken into service a couple of years earlier could reach Bremerhaven only with

difficulty and only at flood tide, the river bed between km 65 and km 78 still had a natural width between the edges of the tidal flats of between 1,300 m and 2,300 m (Fig. 2). The mean depths of the river bed were between 4 m and 6 m. The river bed was split in itself several times by middle grounds. Bars hindered the passage of the big passenger ships, so that they did not run according to schedule.

The first artificial measures of river improvement were therefore intended to provide a continuous fairway with a width of 200 m and a depth of 8 m below low water in the Outer Weser below Bremerhaven. Owing to the steady development of the sizes of ships a first attempt was made as early as 1906 to deepen the fairway to 10 m below low water. This aim could not be reached, however, on account of unfavourable morphological developments in the seaward bifurcation of the river. Neither river structures nor extensive dredging operations were able to check the silting up in the Wurster Arm, the eastern part of the river, which served as the main channel until 1922. This situation compelled the competent authorities in 1921 to abandon the fairway in the Wurster Arm and to create a completely new fairway in the western part of the river, the Fedderwarder Arm, which was in some way favoured by nature.

This relocation of the fairway took place on the basis of very extensive hydrographical investigations, from which the future trends of the morphological changes in the inner area of the Weser estuary could be deduced with sufficient precision.

In the realization that in a "one-river-bed" system an artificial deepening of the fairway necessitates an artificial lateral diminution of the river cross section and in the "two-river-bed" system which follows in seaward direction an immediate success of the river improvement measures can be expected only if the quantity of flow in the new channel can be considerably increased at the cost of the Wurster Arm, river structures and dredging operations for the first time carefully co-ordinated and harmonized in their effects were made use of on a large scale. The function of the river structures was to reduce the too wide river cross sections, to stabilize the river beds in their position, and in the area of the bifurcation also to influence the development of the quantities of flow in favour of the new channel. The dredging operations served in the first place to excavate a new fairway and subsequently to remove the sand that had been drifted again into this artificial fairway. The dredged soil was without exception used as "building material" in the reshaping of the river bed cross sections.

The measures undertaken between 1922 and 1928 were a complete success. After the damage in the fairway which was

mainly due to insufficient maintenance during World War II had been repaired, the fairway in the Outer Weser could be deepened without exception to 11.0 m below chart datum in 1965, after the system of river structures had been completed, and in 1972 without particular effort even to 12.0 m below chart datum.

This success in river improvement is mainly due to the

- profile changing
- profile stabilizing and
- current influencing effect

of the many training walls and groynes, which were built as the situation required and thus have gradually developed into an effective system in the course of the past eighty years (Fig. 3). Nowadays the river structures form the backbone of an estuary which is instable by nature. Their effect was above all that the shifting of sediments in the river bed which was due to the current could be reduced and largely be brought under control.

The effects of the structures can be demonstrated qualitatively and to a certain extent also quantitatively in various ways. Two examples have been chosen for this purpose :

The first river structures in the Outer Weser were two training walls opposite and below Bremerhaven. The function of these walls was to dam detrimental minor channels up against the main channel and to cause them to silt up. The quantities of flow of the minor channels that had been dammed up were to increase the scavenging effect of the tidal currents in the usable range of the main channel.

From the comparison of the maps (Fig. 4) we can recognize qualitatively that the silting up of the minor channels behind the walls developed as expected. The natural improvement of the depths which was expected in the usable range of the main channel could not take place, however, to the degree as desired, because the water displaced from the minor channels had an erosive effect outside the usable range of the main channel. This can be very well illustrated in the charts showing the changes of depths. They show the resulting shiftings of sediments due to the current in their full scope and intensity. It must be borne in mind here, however, that the positive development of the depths in the narrow usable range of the main channel after 1898 was mainly achieved by the employment of dredgers and that the dredged soil was discharged in the minor channel which still existed below the training wall on the left bank. This action accelerated the silting up of the minor channel.

It took as much as twenty years, namely until 1921, before the minor channel west of the training wall built opposite

Bremerhaven was completely silted up. The position of the sedimentation areas in the period from 1915 to 1921 shows the tendency to further alluvia on the western tidal flat - and what is particularly important - to sediments in the fairway before the bifurcation Wurster Arm/Fedderwarder Arm, as well as considerable hollows in the entrance to the Fedderwarder Arm. Here the natural tendency to deepen the Fedderwarder Arm becomes visible, which in 1921 made it necessary to abandon the fairway in the Wurster Arm and to develop a completely new fairway in the Fedderwarder Arm, which is obviously favoured by nature.

The river structures built in connexion with the relocation of the fairway between 1922 and 1928 with simultaneously deepening the fairway to a depth of 10 m below chart datum were above all groups of groynes on both sides of the river in the upper section of improvement and, in addition to that, training walls in the area of the bifurcation. The river improving functions of the structures were very different, depending on the local conditions.

The groynes of km 72 and km 76.4 left bank, for example, were intended to contribute in the first place to quickly and definitely silting up a minor channel which was already in the process of silting up, and secondly to further reduce the width of the remaining main channel cross section. Therefore the construction of the groyne km 72 left bank was made step by step in accordance with the morphological development. The function of all other groynes was primarily to fix the newly determined lines of groyne heads and to actively reshape the cross section of the river bed.

The dredged material obtained from the fairway was discharged in the first phase of improvement mainly before the entrance to the Wurster Arm, in order to artificially raise the bottom here and so to divert the water at ebb tide to the west into the new channel. The training wall which was gradually built out on the RSSt had in the first place the function of preventing the water from flowing into the wrong channel. It was to prevent that too large quantities of water at ebb tide were lost to the Wurster Arm.

The effects of these constructional measures become evident in the charts showing the changes of depths. The author would like to use another method here, however, in order to demonstrate the changing effect of river structures on the morphology of the river beds :

The changes in profile at km 72 (Fig. 5) :

This diagram shows the complete morphological development in the profile of km 72 over a period of 100 years. In 1921 the river bed in profile km 72 still had a width of 1,865 m, a cross section below chart datum of 10,300 sq. metres, and a

mean depth of 5.5 m. The gradual building out of the groyne at km 72 left bank by a total of 900 m (!) during the period 1922/1928, together with the development of a passive groyne on the other bank opposite to it, worked within a few years an amazing yet fully intended change in the profile. The western edge of the tidal flats could be very rapidly advanced, thus reducing the width of the cross section to less than 1,000 m and the cross section itself by about 2,000 sq. metres, yet increasing the mean depth to as much as 8.2 m. Owing to the deterioration of the cross-section stabilizing groynes during World War II, the profile widened again slightly after 1945, which immediately entailed a distinct reduction of the mean depths. The reconstruction work on the river structures after 1957 had at once a positive effect on the profile depths, because the widths of the river bed could be reduced again.

Without going so far as to explain all the details, the author will demonstrate in a combined comparison of map and depth changes (Fig. 6) as well as by a selected chart showing the changes in profile (km 81) (Fig. 7) the morphological changes in the bifurcation Wurster Arm/Fedderwarder Arm, which were influenced by river structures.

After 1900 the middle section of the Wurster Arm begins to deteriorate rapidly. The river bed shifts in westward direction towards the Robbenplate and in this process divides into two channels, in one of which the ebb tide predominates and in the other the flood tide. The explanation of this development lies in fundamental morphological changes in large areas in the Weser estuary, which cause a natural scavenging of the Fedderwarder Arm and ebb water is inevitably attracted by this channel. This development can be recognized very early in the charts showing the changes of depths, more clearly even than in the comparison of maps.

The attempt to stop the westward movement of the Wurster Arm by artificially stabilizing the eastern part of the Robbenplate is only of limited significance with respect to place and time. These river structures and the simultaneous dredging operations in the fairway cannot prevent the progressing splitting of the Wurster Arm.

The sole objective of the river improvement measures after 1921 is to develop a new fairway in the Fedderwarder Arm. Since the Fedderwarder Arm had at that time no sufficient total cross section, the improvement aim is in the first place to influence the morphological development with a few structures and to drive it in each development phase systematically into the desired direction :

- the training wall RSSt is to increase the quantity of flow at ebb tide in the Wurster Arm,

- the training wall LalüNSt is to prevent cross-currents and the drifting of sand from the estuary of the Fedderwarder Priel into the new channel,
- the training wall RNSt is to stop in this place the eastward movement of the Fedderwarder Arm.

In the course of the following years this wall is to become a fixed point in the whole system of river structures.

The further development in the new channel shows that the river structures in connexion with the dredging operations fully achieve their effects. It is above all clearly recognizable from the charts showing the changes of depths that now large masses of soil are shifted in the new channel due to the stronger tidal currents, which necessitates above all constant and extensive maintenance dredging operations in the fairway.

The chart showing the changes in profile of km 81 (Fig. 7) shows us the state of the Fedderwarder Arm when the relocation of the fairway was set about in 1922. Accelerated by the measures of river improvement, the widths and the cross sections in the Fedderwarder Arm increase rapidly, whereby the westward movement of the deep river bed is tolerated for some time, until the planned line of groyne heads along the western tidal flats has been reached in a natural way. This was the case in 1948. It was then begun to stop the further westward movement of the Fedderwarder Arm by the construction of passive groynes along the Langlütjen tidal flats. The river bed reacted as expected.

The purpose of the further raising of the training wall RSSt in 1952 to 1 m above chart datum and then in 1964 to 1.5 m above chart datum was to divert larger quantities of ebb water from the Wurster Arm to the Fedderwarder Arm. The result was not quite what one had imagined, however; the additional quantities of ebb water which had been gained for the Fedderwarder Arm do not work within the usable range of the latter, in its fairway that means, but outside of it, directly on the training wall RSSt, and lead here to the formation of a new minor channel and to an additional mobilization of large masses of soil which make extra dredging operations in the fairway necessary.

Which is now the realization to be gained from these maps and diagrams?

- The river beds in the area of improvement could be stabilized in their position by means of river structures, which made it possible to dredge durable and solid channels in the river beds, to maintain these at reasonable cost, and to mark them by fixed aids to navigation.



- The river bed cross sections could be transformed, by means of active river structures, so as to comply with the requirements of shipping. Originally very wide and flat river beds which were split in themselves, they could be provided with narrower but sufficiently deep cross sections. The limit of the capability of improvement of a river bed cross section is set by the volume of the tidal waters. This limit has not yet been gone beyond in the area of improvement in the Outer Weser.

This success in the stabilization and transformation would not have been achieved by dredging operations and the selected discharge of the dredged soil alone.

It was only through the effects of the system of river structures with their markedly

- profile stabilizing,
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that we succeeded in creating a fairway in the Outer Weser which is capable of further development. The fact that the dredged soil obtained from the improvement and maintenance work was re-used properly, from the river engineering point of view, contributed also to reaching the aim of improvement so quickly.

The principal objective of the improvement and maintenance should be to keep the drifting of sand from the lateral areas of a river bed into the artificial deep fairway as low as possible. Discharged soil from dredging operations must therefore by no means interfere with the desired morphological development of a river bed section or even influence it negatively; neither should this soil drift back into the deep fairway, or at least only as little of it as possible.

It is certainly wrong to remove the soil which is continually dredged from a river bed which is in equilibrium with the cross-section preserving forces of the current, from the cross section of that river bed. This would only cause an excessive widening of the cross section of the tidal river bed. The consequence would automatically be a new natural silting up of the cross section, which would in turn necessitate new dredging. It would be much better to leave the dredged soil as far as possible in the cross section, but to distribute it properly there.

This has become possible nowadays through the employment of modern Hopper suction dredgers, provided that their draught permits them to be employed in shallow water. If one has an exact knowledge of the mechanisms of the natural shifting of sediments in the tidal river beds which is due to the currents, these dredgers make it possible to employ methods of dynamic

river engineering, the aim of which should be to effectively further the desired change or stabilization of the tidal river beds by properly transferring the dredged soil.

First experiments have been made in this direction in the Outer Weser during the past years. The qualitative results hitherto obtained speak in favour of a continuation and improvement of the active re-use in river improvement operations of the dredged soil. The dredged soil may then become a material in river engineering and may by no means be in every case removed from the range of a tidal river bed cross section, that is to say from the inner sediment cycle of the river bed. The author thinks that the question of sediment cycles within tidal river beds must be given more attention in the future, in order to avoid unnecessary expenses for maintenance work in fine sand tidal river beds.

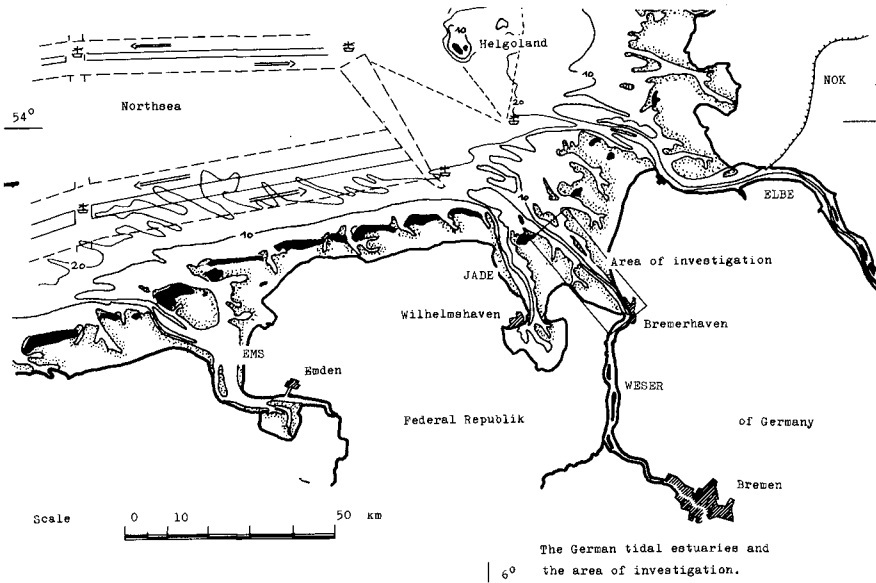


Fig. 1 The German tidal estuaries and the area of investigation

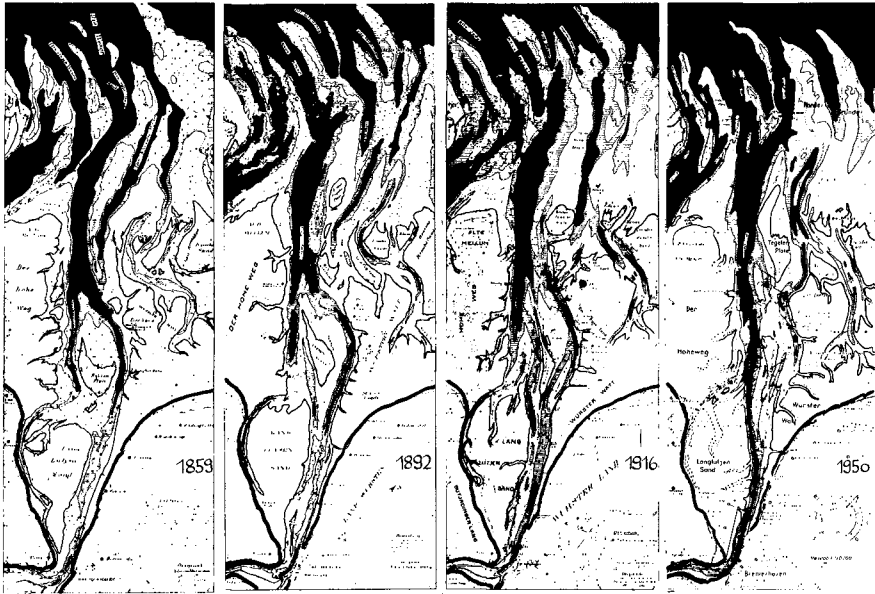


Fig. 2 The Outer Weser in 1859, 1892, 1916, 1950 - a rough comparison of maps

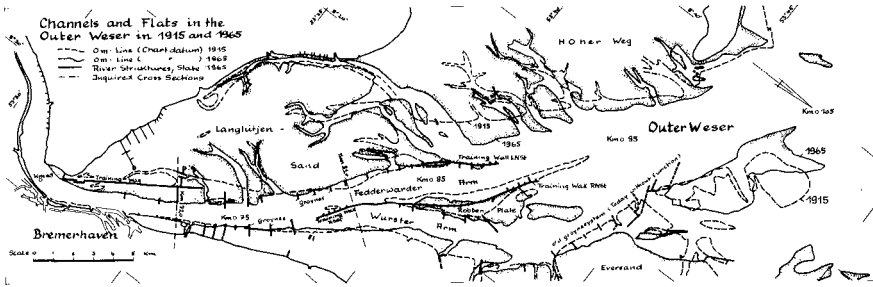


Fig. 3 River beds and tidal flats in the Outer Weser 1915 and 1965

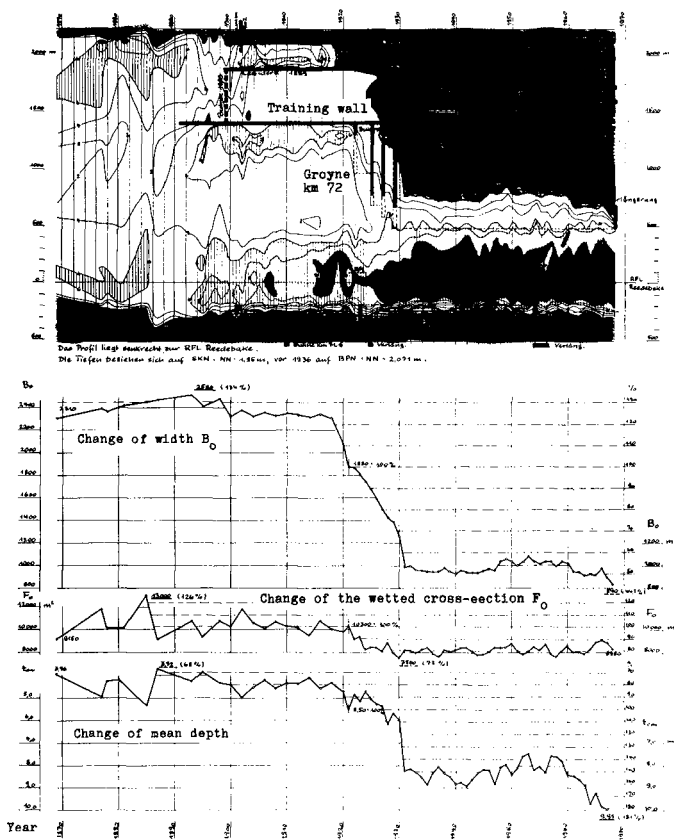


Fig. 5 Changes in the profile km 72, Outer Weser, 1869 - 1968

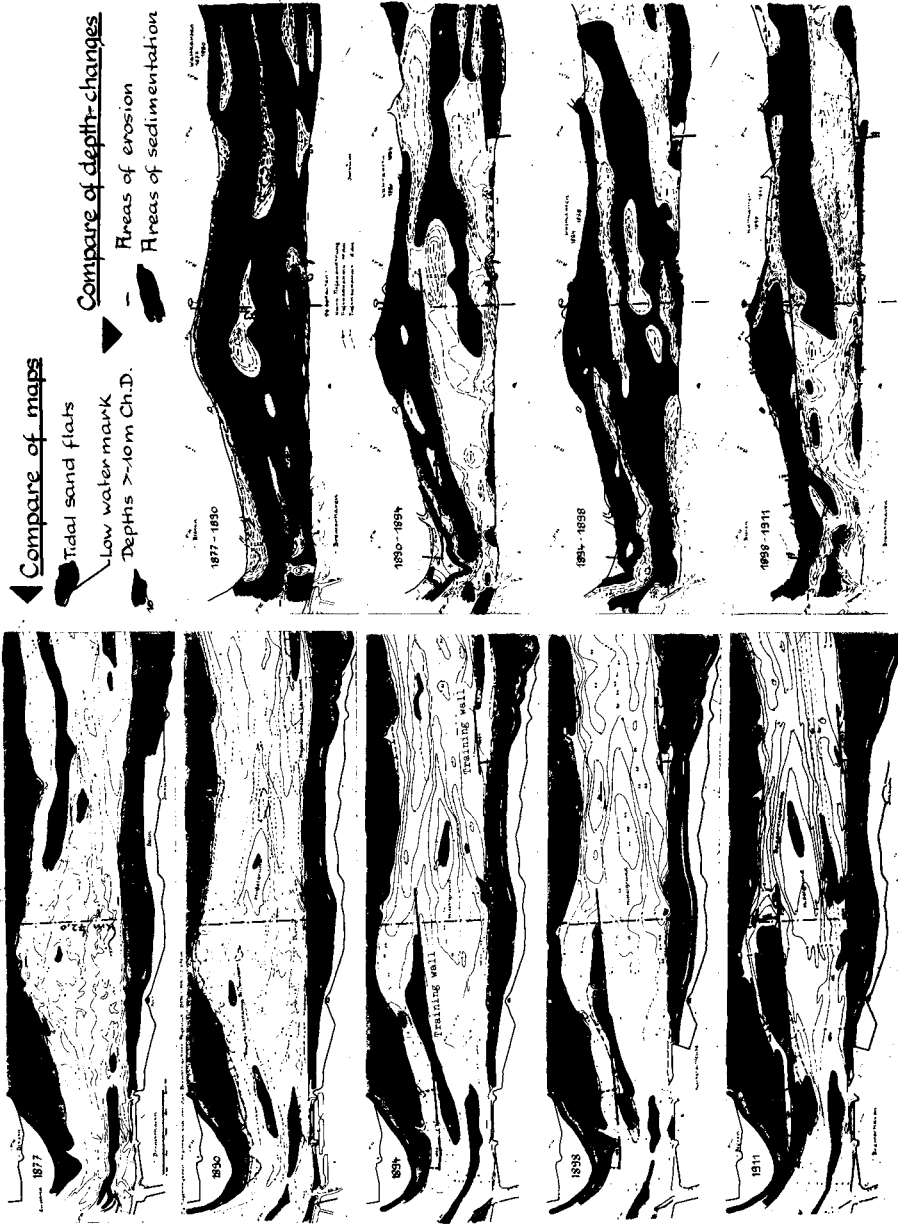


Fig. 4 Morphological changes after the construction of training walls in the section km 65 - 80

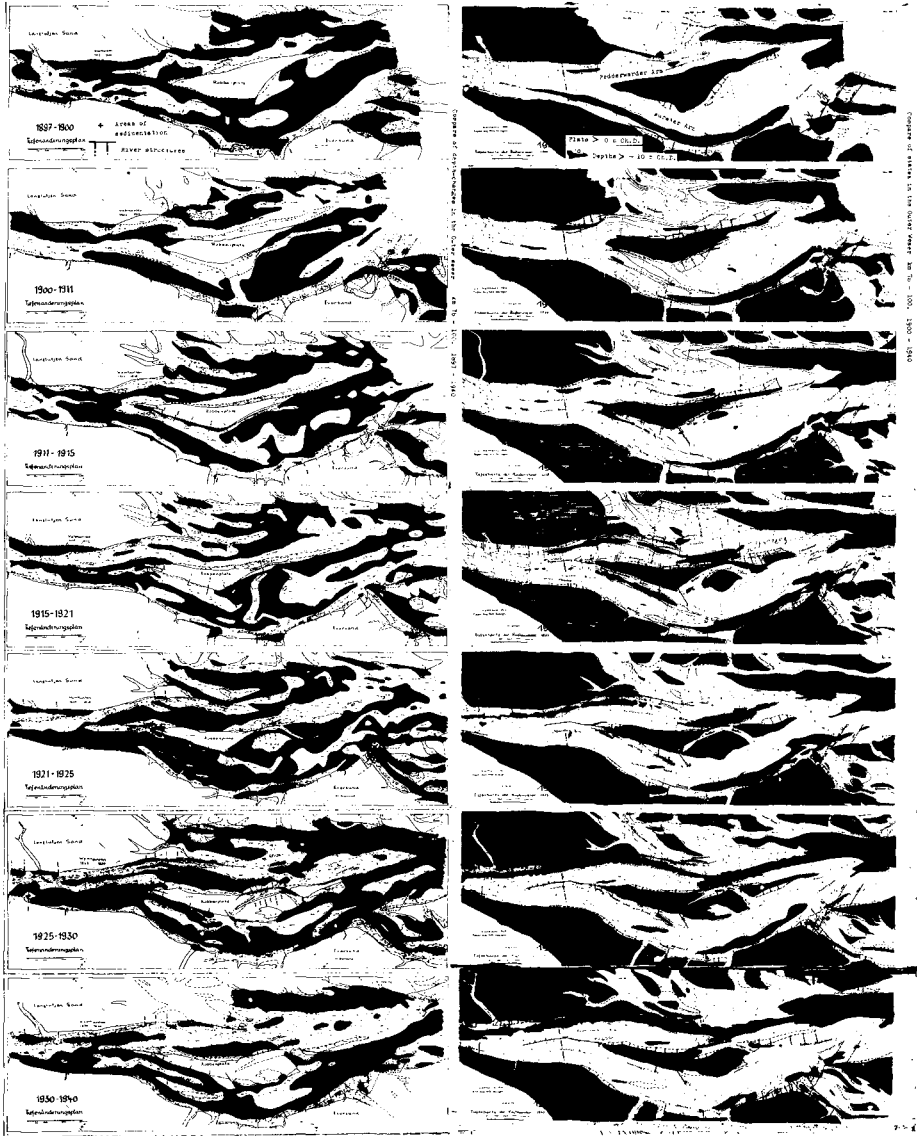


Fig. 6 Combined comparison of map and depth-changes, Outer Weser, km 78 - 100, 1900 - 1940

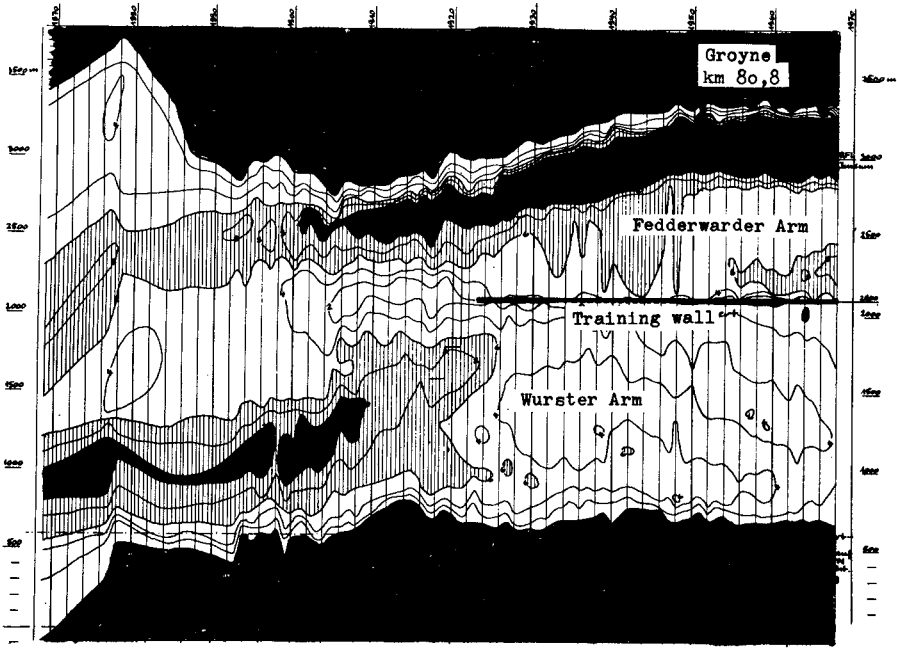


Fig. 7 Changes in the profile km 81, Outer Weser, 1869 - 1968