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The Eider Estuary

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1. Introduction

1.1 The Waters of the River Eider

The Eider rises “in the heart of Schleswig-Holstein” to the North-east of Neumünster; its former course to the North Sea covered about 190 kilometres (Fig. 1). As the Upper Eider, it first ran through the young-moraine region of Ostholstein in a northerly direction until it came close to the Baltic Sea near Kiel. Then it turned west and reached the town of Rendsburg half way across to the North Sea. Here, the river reached the lowlands, which it crossed as the Lower Eider in great meanders before the Eider estuary met the North Sea near Tönning. The corresponding catchment area was about 3,300 km² in size.

The condition of the Eider today is the result of extensive intervention measures which have drastically changed the river over the last 400 years and divided it repeatedly.

Today, after about 54 km, the Upper Eider merges with the Achterwehr shipping canal and then empties into the Kiel Canal after another three kilometres. Up to this point the catchment area amounts to around 300 km². Only rudimentary parts of the stretch towards Rendsburg have survived as the “Alte Eider” and as the “Obereidersee”, a secondary channel of the Kiel Canal with the harbour “Obereiderhafen” in Rendsburg.

The Lower Eider begins as a river without a source in Rendsburg’s harbour “Untereiderhafen”. The section to the interim reach at Lexfähr (km 23) and on to the tidal boundary at Nordfeld tidal gate (km 78) is referred to as the “Upper” and “Lower Inner Eider”. Further on, the “Tidal Eider” is separated from the subsequent channel of the “Outer Eider” by the Eider Barrier (km 110). In addition to the tidal volume, a freshwater discharge from a catchment area of around 2,100 km² flows through the mudflats into the North Sea at this point. The Eider estuary consists of the Tidal and the Outer Eider (Fig. 2):

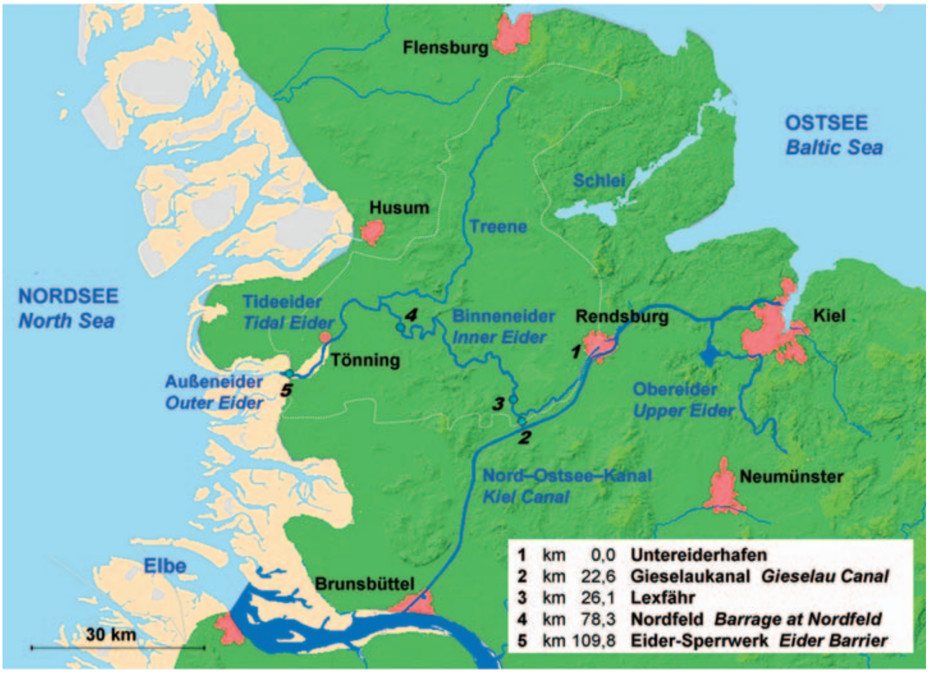

Fig. 1: Layout drawing of the Eider region

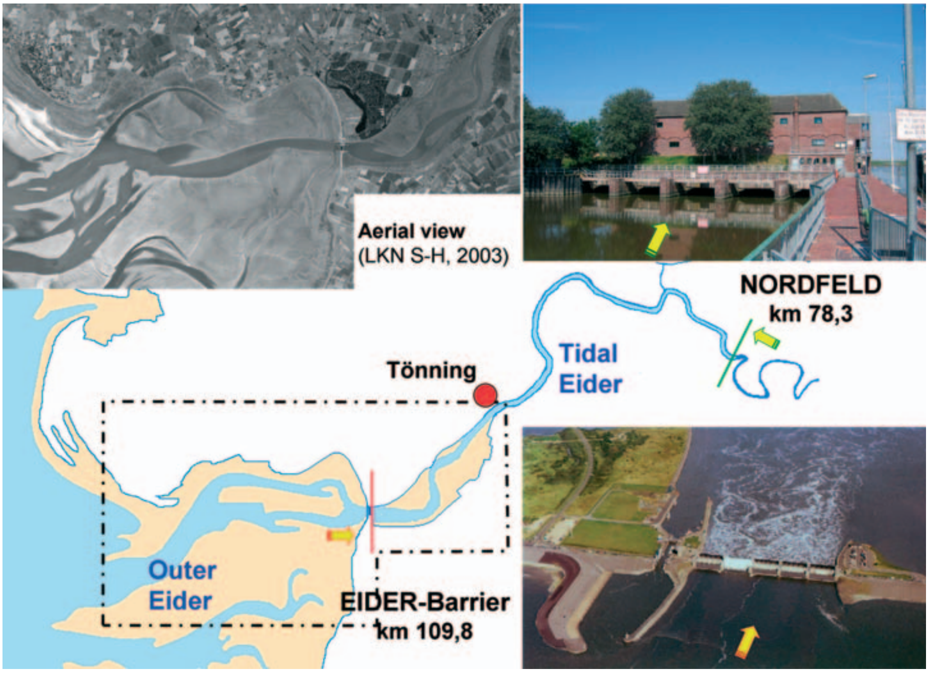

Fig. 2: Layout drawing photos of the Eider estuary (Tidal and Outer Eider)

1.2 Hydrological Characteristics of the Eider

Table 1: Hydrological characteristics of the Eider

Catchment area	2100	km^2	
Length of the tidal estuary	31	km	
Tidal range	0–3.5	m	Tide control
Tidal volume	25–30	mio m^3	
Current velocity	2	m/s	v_{max} Tönning
Current velocity	4	m/s	v_{max} Eider Barrier
Salinity	16–26	‰	Eider Barrier

1.3 Development of maritime traffic

The Eider already served the Vikings as a waterway from the North Sea to the Baltic region taking the route through the Eider–Treene lowlands to Haithabu on the Schlei. In those days, however, there was no through connection. The boats had to be pulled across land for several kilometres.

Under Danish rule, a continuous waterway between the North Sea and the Baltic was established with the construction of the Schleswig-Holstein Canal (Eider canal) between Kiel and Rendsburg in 1777–1784. It served also the trade between England, France, Holland and the Baltic states. Boats sailing on the Lower Eider could make use of the tidal flow, while those on the canal stretch sailed or were hauled. Compared to sailing around Skagen, the canal route only saved 1–3 days on average; but this was the safer route so that through-traffic accounted for about 45 % of shipping.

Traffic along the waterway brought economic prosperity; the Eider was theoretically affected by the Continental System (1807–1814), so that particularly intensive contraband traffic developed between Helgoland and Tönning, both occupied by Great Britain. Tönning

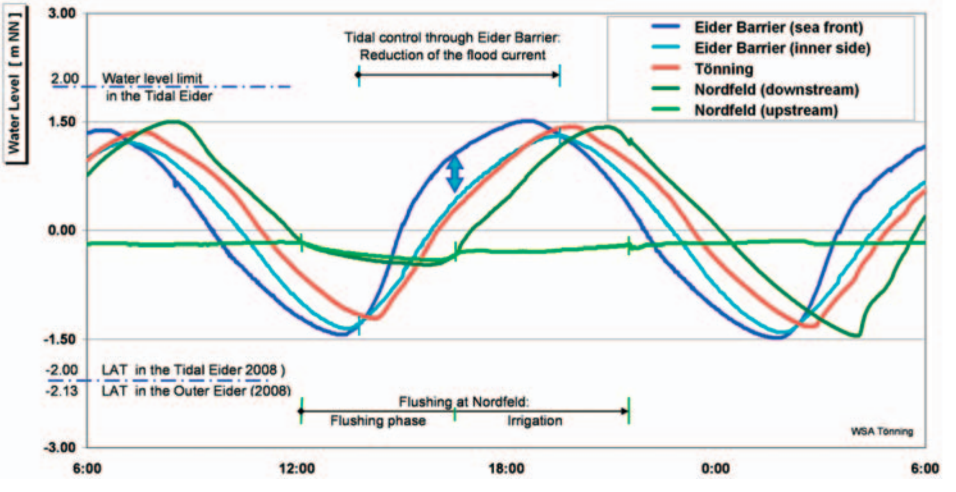

Fig. 3: Time series of tidal elevations in the Eider (August 7th and 8th, 2000)

Table 2 : Historical and current lock dimensions

Lock dimensions Eider			
	Historical Eider canal : Lock (canal dimensions)	**Gieselau lock, Lexfähre and Nordfeld**	**Eider Barrier**
Serviceable length	35.0 m* (28.7 m)	70.0 m	75.0 m
Inner width	7.80 m (7.45 m)	9.50 m	14.00 m
Sill depth	3.50 m (2.68 m) at MW	3.50 m at MW	4.00 m at MTlw
Tol. draught	–	2.,80 m	–
* Rendsburg from 1990: 70.0 m			

later became an export harbour for sheep and cattle to England. This trade abruptly succumbed to the outbreak of foot and mouth disease on the European continent in 1889.

In 1887–1895, the Eider canal was replaced by the Kaiser Wilhelm canal, today's Kiel Canal. By then, more than 284,000 ships had passed through the canal (STOLZ, 1984).

The connection between the North and the Baltic Sea along the Eider remains preserved to the present day, initially through the lock at Rendsburg between "Ober- and Untereiderhafen" which was rebuilt in 1887/95. Afterwards, from 1935/38, the waterway was substituted by the "Gieselau Canal" which is about 3 kilometres long and branches off the Lower Eider towards the Kiel Canal about 21 km downstream of Rendsburg. The route along the Eider could not compete with the Kiel Canal and rapidly lost its significance as an international trading route. Attempts around 1905 to revive ocean-going traffic in Tönning with regular services to England and Australia were short-lived.

As part of the Eider upgrade in 1935–38, dimensions for breakthroughs were defined: a maintained depth of the bottom at MW 3.30 m, the width of the bottom at 25.0 m and underwater slopes at 1:4 / 1:3.

Following the improvement of the network of highways and roads in the second half of the last century, the Eider also lost significance as a regional transport route. Hardly any commercial use can be seen today. The river has become popular for pleasure craft which sometimes take advantage of the tidal wave when passing shallow water reaches.

2. Geomorphology

2.1 History of Encroachments on the River System

In the face of recurrent storm surges, the construction of dykes along the Eider from the coast on upstream was furthered.

After damming the tributary Treene in 1570 and the Sorge in 1624, the tide progressed further inland, making more dyke construction necessary. Tidal influence was observed at the water-mill in Rendsburg for the first time in 1700. With the construction of the Eider canal at the end of the 18^{th} and the Kiel Canal at the end of the 19^{th} century (see section 1.3), the upper third of the discharge from the catchment area was partially and later on completely drained off into the Baltic Sea.

Following the construction of the Kiel Canal, measures for straightening of the Eider to approx. 20 km downstream of Rendsburg.

Between 1935 and 1938, extensive flood defence measures for 40,000 ha lowlands were carried out. This included the barrage with a drainage sluice at Nordfeld, the reach with a sluice at Lexfähr, the new construction of the Gieselau Canal and closure of the lock at Rendsburg, as well as the straightening of the Eider with a breakthrough at Tielenhemme.

Starting in 1950, attempts were made to solve the so-called "Eider problem", resulting from the tidal limit being pushed back to Nordfeld, by pumping stations installed along the lower Inner Eider and in the sluice at Lexfähr. The sluice at Nordfeld was used to flush the Tidal Eider, and from 1960 on approx. 100 groynes were built to reinforce the flushing effect on the section up to Tönning.

In the context of the Eider Barrier which was completed in 1973, the tidal volume of the Tidal Eider was considerably reduced by dyking the Katinger Watt. Further reductions arose by the restricted intake as normal business (lowering HW), by the introduction of the limit water level at MHW + 0.5 m and by the temporary inhibition of the flood current (only drainage) to support the drainage capacity. Normal operation also includes intermittent flushing in ebb direction to keep the tidal channel of the Outer Eider open.

In 1979, the north channel of the Outer Eider was blocked with a sandbank to support coastal protection at the peninsula of Eiderstedt.

2.2 Reaction of the System to the Encroachments

2.2.1 Construction of Dykes and Canals till 1936

With the completion of the Kiel Canal (1895) and no more freshwater discharge at Rendsburg, accumulations of silt increasingly interfered with the operation of the lock in Rendsburg. Moreover, as already observed before, the increase of the tidal range at the gauge at Rendsburg continued noticably, while the development of water levels at the gauge at Tönning close to the estuary mouth followed the trend as observed at the comparable tidal gauge at Husum. It was also ascertained that storm surges in relation to Tönning progressed further into the Eider estuary.

The main cause for this development was seen in on-going dyke construction along the Eider, while less significance was attributed to the reduced freshwater discharge and minor river improvement measures (MÜLLER and FISCHER, 1955).

2.2.2 Eider Barrage at Nordfeld (1936)

The barrage at Nordfeld moved the tidal boundary of the Eider around 80 km seawards. Already in the first planning stages in 1928, people were aware of possible difficulties arising from the barrage because of the expected deformation of the tidal wave and resulting silt deposition. A monthly accumulation of 2 cm of silt was expected on a section of 5 km below the dam (MÜLLER and FISCHER, 1955). The silt accumulation had been considerably underestimated. Thus, already within just a few years, the cross-sections along the 5 km stretch up to the mouth of the Treene near Friedrichstadt had sanded up and shrunk by up to 90 %. Investigations carried out after 1950 showed that the sediments came from the North Sea (WEINNOLD and BAHR, 1952). The deformation of the tidal wave with a steeper flood branch and flatter ebb branch resulted in an increase in the flood current velocity and decrease in the ebb current velocity to such an extent that sediment transported into the river by flood currents could no longer be eroded again and carried away during the ebb tide.

This aggradation considerably jeopardized the drainage of the Inner Eider as well as navigation on the Tidal Eider, because the inland water level of –1.0 m NN aimed at since 1938 could not be maintained.

After 1950, flushing operations through the sluice gate at Nordfeld, the groynes between Nordfeld and Tönning and sporadic initial dredging operations were no longer capable of reversing the aggradation. The Eider problem had not been solved satisfactorily.

2.2.3 Eider Barrier at Tönning (1973)

The weir structure, training walls and separating moles in connection with the lock were erected on an artificial island constructed in the protection of a ring dyke on the line "Hundeknöll-Vollerwiek" on the tidal flats.

Damming the main channel of the Eider ("Purrenstrom") initially meant that the Eider had to find a new bed around the barrage, resulting in increased aggradation in the tidal channel of the Outer Eider.

The enclosure of "Katinger Watt" by a dike and forcing the river through the barrage with a considerably reduced tidal volume completely changed the morphological processes in the Tidal Eider (Fig. 4). Already after a few years, a channel migration was established in the remaining tidal flat area which has been stable up to the present. There was a noticeable decrease in the intensity of aggradation of the Eider; in the meantime, the process seems to be limited to the relocation of sediment. This evaluation, however, does not apply to the area between +1 m NN and the limiting level of +2 m NN which has been hardly sur-

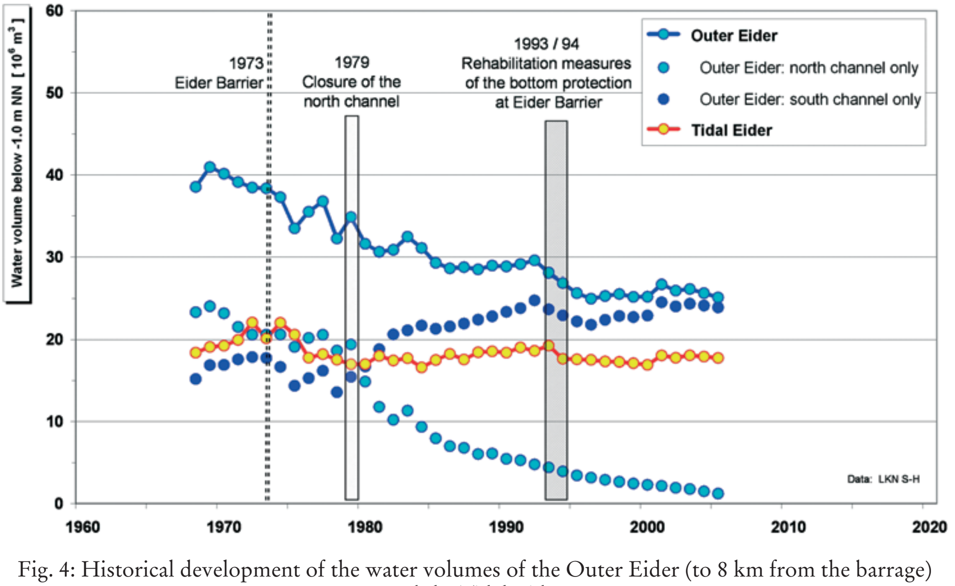

Fig. 4: Historical development of the water volumes of the Outer Eider (to 8 km from the barrage) and the Tidal Eider

veyed due to its vegetation. Given that the channel cross-sections are far narrower than in 1936 and with lowest water levels of only 0.5 to 1.0 m LAT (lowest astronomical tide), navigation is only possible depending on the tide or with tidal control through the Eider Barrier.

The migration of the channel in the Outer Eider did not take place as desired. Even after 1973, the "north channel" with a large cross-section still functioned as the main channel. By comparison, the "south channel" was only weakly developed in places. Neither initial dredging nor intensive flushing through the Eider Barrier brought any noticeable change. With the north channel moving northward towards Eiderstedt's seadike at a recent rate of about 80 m/a, it was decided in 1979 to block the channel by a sand dam which was not overtopped by HW. Since then, the north channel has been sanding up and the south channel has assumed an ebb-dominant shape over a 8–10 km long section starting from the barrage. Compared to former conditions, the channel cross-sections are far smaller, and water depths in the channel bends have been reduced. The outer banks region is located to the south of the tip of Eiderstedt. The morphologically instable region with its recurrent intensive changes from sand migration and repeated breakthroughs in the channel (delta problem) has posed a threat to navigation for more than 200 years. Correlations between the permanent transformation processes and construction measures in the Eider regime have not yet been proven.

3. Maintenance Measures in the Eider Estuary

3.1 Flushing Operations

Construction of the Eider Barrier in 1973 and damming of the "Eider North Channel" in 1979 were the last major encroachments on nature and landscape for the time being. In the interests of drainage capability and navigation, they were intended to contribute to the preservation or even improvement of the existing conditions of the Eider through special modes of operation of the flood gates in combination with flushing operations at Nordfeld. Neither did these measures result in the desirable optimum conditions of the system nor could the former status-quo be maintained.

The quality of the flushing operations can be judged as follows:

- the two systems "Tidal Eider" and "Outer Eider" have essentially reached an equilibrium with regard to volume constancy
- surveys for traffic safety reveal a trend for further growth of sandbars in the Tidal Eider
- increasing success of flushing operations can be verified in the "Outer Eider".

Up to now it has not been possible to quantitatively show an effect of tidal control on the morphodynamic processes of the Eider.

3.2 Dredging Needs and Technology

So far, no need for maintenance or upgrade measures for the improvement of the discharge capability could be substantiated. Neither does the above mentioned maritime traffic situation, based on the directives of the Federal Waterways Act (Bundeswasserstraßengesetz), require any action. No maintenance dredging is carried out in the fairway, although soil is relocated from "silt traps" such as outer harbours of locks or zones of minimal current action downstream of confluences.

Tidal and Outer Eider can only be travelled tide-dependent by vessels with a maximum draught of 2.0 m. Only shallow-draft special vessels are not affected by restrictions.

There is need for regular dredging in the outer harbours of the locks of the Eider Barrier where currents are small. After earlier deployment of hopper or suction dredgers, the water injection method has proved to be best for removing silty material. The water injection method is enhanced by the deep scour holes that have emerged on either side of the flood gates directly outside the harbour entrances. The centre of the inner scour hole is up to 10 m deeper than the maintained depth of the outer harbours while that of the outer scour hole is even extending to more than 25 m. Up to now, the outer harbours have been cleared once a year. Current observations indicate that the intervals will have to be shortened in the foreseeable future.

There is a need for annual dredging downstream of where the outer drains ("outer deeps") empty into the Tidal Eider, which have discharged their water on a natural gradient, so far. This also applies to Tönning harbour and a reach further upstream where, up to now, the deployment of an underwater "hydraulic plough" with air injection has proven practical for removing sediment depositions.

4. On-Going Monitoring and Analysis

As part of the 'preservation of evidence' (Beweissicherung) resulting from the construction of the Eider Barrier, the principal and owner of the structure, the federal state of Schleswig-Holstein, is among others responsible for a regular monitoring with

- measurements of water levels above and below the Eider Barrier
- measurements of salinity in the dammed Eider,
- surveys of the shorelines above the Eider dam and
- supplying evidence that the hydraulic storage capacity of the dammed-up Eider is sufficient.

The tasks performed by the responsible institutions are based on measurements made by the state of Schleswig-Holstein together with regular measurements by the Federal Administration of Waterways and Navigation (Wasser- und Schifffahrtsverwaltung – WSV) (water levels/surveys of the fairway). Airborne surveys complete the required surveying task of the state authority.

Within the framework of a regular monitoring of the water quality at selected locations is carried out. In parallel, the Federal Institute for Hydrology (Bundesanstalt für Gewässerkunde – BfG) has been monitoring the estuaries of the Ems, Jade/Weser, Elbe and the Tidal Eider for several years. The regional authority (Wasser- und Schifffahrtsamt – WSA) in Tönning processes water level measurements obtained from tidal gauges. Data are then analyzed with regard to their tidal parameters in the Federal Maritime Agency (Bundesamt für Seeschifffahrt und Hydrography – BSH).

5. Conclusions

The entire catchment area, including rivers Treene and Sorge, originally covered around 3,300 km². In a series of construction projects in the interest of coastal protection, drainage capability and navigation, one has interfered with the river regime in a substantial manner. These measures began with the construction of the dykes in the 15th century, including the reorganization of the drainage system and a repeated division of the river, completely separating the upper reaches. In 1973, measures were concluded with the construction of a storm surge barrage.

The experience gained on the Eider was of pioneering importance for other river damming measures in Germany. The concept of completely damming up tidal rivers with only a sluice structure (tidal gate) was renounced; storm surge barrages were erected instead. They prevented the penetration of only extremely high tides or were closed to protect against storm surges.

In 1964, an expert panel predicted that the solution found for the highly complex "Eider problem" would only be provisional. Meanwhile, this verdict has been corroborated by various observations. Nature always reacts to an encroachment on in the river regime. In the case of the Eider, the desired advantages were often gained at the cost of undesirable, strong side effects.

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