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Position paper: Effects of the Eastern Scheldt Storm Surge Barrier and tidal energy turbines on harbor porpoise (*Phocoena phocoena*) and harbor seal (*Phoca vitulina*) movements

SEAMARCO report 2019-01
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Authors:
Dr. ir. Ron Kastelein (SEAMARCO)
Dr Nancy Jennings (Dotmoth)

Commissioner to SEAMARCO:
Wageningen Marine Research
Contacts:
Michaela Scholl
Dr. Mardik Leopold

Funding agency:
The European Fund for Regional Development in relation to “OP-Zuid”

Contractor:
Dr. ir. R. A. Kastelein
Director & owner
SEAMARCO (Sea Mammal Research Company)
Applied research for marine conservation
Julianalaan 46
3843 CC Harderwijk
The Netherlands
Tel (Office): +31-(0)341-456252
Tel (Mobile): +31- (0)6-46-11-38-72
Fax: +31-(0)341-456732
E-mail: researchteam@zonnet.nl

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Abstract

The Eastern Scheldt Storm Surge Barrier, completed in 1986, was built to protect the Netherlands from flooding. The barrier has resulted in changes in the environment: specific fauna and flora are found around the concrete structures of the barrier; currents and tides have changed; sand and stone deposits have formed around the pillars; and changes in sand movements have resulted in the lowering of tidal flats.

The aim of this paper is to describe how the Eastern Scheldt Storm Surge Barrier and the existing and proposed tidal energy turbines within it affect harbor porpoises and harbor seals. Both species show individual differences in behavior and in responses to structures and sounds, and the conclusions drawn in this paper may not be valid for all animals in the population. In addition, sick animals may behave differently, or may be transported through the barrier by the currents. No consideration is given to effects on fish, the prey of porpoises and seals; any effect on fish may in turn affect their predators. Some of the information in this paper is applicable to nearby areas for which tidal energy turbines are being considered (Grevelingendam and Brouwersdam), but some is uniquely applicable to the biology and physics of the Eastern Scheldt Storm Surge Barrier.

The storm surge barrier restricts the movements of harbor porpoises, as they prefer not to enter narrow spaces such as the open gates. In addition, the strong turbulence caused by currents during the flood and ebb tides reduce the echolocation ability of porpoises to orient themselves and forage close to the barrier. The few harbor porpoises that cross the barrier probably do so at slack tides (most likely at high slack tide in the deeper central gates of the 3 sections of the barrier). At high slack tide, the turbines are turning very slowly or not at all, so healthy harbor porpoise are not expected to collide with the blades.

In the scenario of large-scale roll-out of turbines in multiple gates of the barrier, the turbines are expected to add to the barrier function, as they may partially block the gates. However, this added barrier function will affect a maximum of 30% of the total no. of gates of the barrier, if one array turbines is placed in every third gate (in 17 of the 62 gates). Lifting the turbines out of the water at slack tide will increase the likelihood of harbor porpoises crossing the barrier.

The storm surge barrier does not restrict the movements of harbor seals; they have been observed to cross the barrier even when the current is strong and turbulent. Turbines are unlikely to reduce the willingness of most harbor seals to cross the barrier. Harbor seals are not expected to collide with the blades, as they can use several sensory systems to detect the moving turbine blades, and have sufficient space below the turbines to cross the barrier.

Suggestions for research include tracking individual animals (either with tags, or via detectors in the gates), to see if, and under which conditions, the species cross the barrier. Underwater sound recordings of the active turbines will improve the prediction of their effect on the behavior of the seals and porpoises.

1 Introduction

The Eastern Scheldt and the storm surge barrier

The Eastern Scheldt Storm Surge Barrier is the largest of the Delta Works, a series of dams and barriers with gates that can be closed designed to protect the south-western part of the Netherlands from flooding. Instead of separating the Eastern Scheldt from the North Sea with a dam, a storm surge barrier was built that is only closed under extreme tide and storm surge conditions, so that the marine environment in the Eastern Scheldt is protected. The Eastern Scheldt, a former estuary, has always been a dynamic area with frequent changes in the shape and depth of waterbodies (**Fig. 1**). In and around the Eastern Scheldt there are ~140 species of water plants and algae, ~70 species of fish, ~350 species of other aquatic animals (https://www.clo.nl/indicatoren/nl1598-fauna-oosterschelde). The Eastern Scheldt is an important area for feeding, breeding, and overwintering birds; since 2002, it has been designated as a National Park, an EU Natura 2000, and a Ramsar Wetland site. The nearby Voordelta in the North Sea is also an EU Natura 2000 site and a Ramsar Wetland site. If the Eastern Scheldt had been closed with a dam, this rich saltwater environment would have been lost, together with the mussel and oyster culture, which would have had severe economic consequences for the regional fishing industry. The barrier was completed in 1986.

Fig. 1. The Rhine and Scheldt delta area in the south-west of the Netherlands. The Scheldt flows through Antwerp, Belgium, in the south; the Rhine delta from the north-east of this map. The Eastern Scheldt storm surge barrier (indicated by the red arrow) separates the Eastern Scheldt from the North Sea (Source: Google Earth).

The Eastern Scheldt Storm Surge Barrier has three sections with gates, from north to south: the ‘Hammen’ (675 m), the ‘Schaar’ (720 m) and the ‘Roompot’ (1440 m; **Fig. 2**), separated by two artificial islands. The barrier consists of 65 concrete pillars, between which 62 sliding steel doors are installed. Each gate is 39.5 wide, but they vary in height with the water depth: shallow at the sides and deeper towards the middle of each channel (varying from -4.5 to -10.5 m NAP). Open gates are held completely above the water level, and the passage height is normally determined by the water surface. Only in a combination of extreme high tide and set-up caused by strong winds, the water level reaches the concrete upper boundary of the gates (which is at + 1 m NAP). When all 62 gates are open, which is normally the case, three-quarters of the original tidal range is maintained.

2a

2b

Fig. 2. (a) Topview of the Eastern Scheldt Storm Surge Barrier, showing the two artificial islands and the three sections (Hammen, Schaar and Roompot), during flood tide (Source: Google Earth). (b) A diagonal view of the Roompot section of the surge barrier from the North Sea side during extreme high tide, showing the concrete pillars and the metal tube protections of the gates. The metal vertically sliding gates are down (Source: Rijkswaterstaat Beeldbank).

As the water passes through the open gates in the barrier, the flow first accelerates and then decelerates, producing strong turbulence either on the North Sea side of the barrier (during ebb tide) or on the Eastern Scheldt side of the barrier (during flood tide). In the tidal cycle, four periods per 12h 25 min can be distinguished:

1. Low slack tide (no current; **Fig. 3a**);
2. Flood tide (increasing, then decreasing current; turbulence on the Eastern Scheldt side (**Figs. 3b and c**);
3. High slack tide (no current);
4. Ebb tide (increasing, then decreasing current; turbulence on the North Sea side; **Figs. 3d and e**).

Fig 3. The Eastern Scheldt Storm Surge Barrier, showing water currents during the tidal cycle. The North Sea is to the left in all photos. (a) Slack tide (no current, no turbulence); (b) flood tide (weak current and turbulence on the Eastern Scheldt side); (c) flood tide (strong current and turbulence on the Eastern Scheldt side); (d) Ebb tide (weak current and turbulence on the North Sea side); and (e) ebb tide (strong current and turbulence on the North Sea side) (Source: Rijkswaterstaat Beeldbank).

Existing and proposed tidal energy turbines in the barrier

In 2008, Tocardo Tidal Power B.V., a global tidal energy company, started developing a tidal energy project and installed tidal energy turbines into the Eastern Scheldt Storm Surge Barrier in 2015. A 50 meter long structure with an array of five turbines attached to it was placed in gate Roompot 8, between two of the barrier's pillars.

The turbines are mounted on the Eastern Scheldt side of the surge barrier. Each turbine has two rotor blades, facing towards the North Sea. The underwater concrete threshold of the gate (sill beam) is at -9.5 NAP, the turbine axis at -4.8 m NAP, and the rotor diameter is 5.5 m. The distance between the blade plane and the protective stones on the bottom is ~5.5 m (**Fig. 4**). The distance between the concrete pillars and the rotor plane of the lateral turbines of the turbine array is 3.6 m, and the distance between the rotor planes of neighboring turbines is 1.2 m (de Fockert and Bijlsma, 2018).

The rotational speed of the rotor blades reaches a maximum of 44.5 revolutions per min (one revolution per 1.4 seconds, blade tip speed 12.5 m/s) at a water flow velocity of 4 m/s. At 4 m/s there is a cut-off: the turbine enters stall mode and decreases speed rapidly.

The daily turbine energy production depends on the water flow velocity. The tidal range is ~3.6 m. Under the current agreement, the turbines are lifted out of the water as a precaution above 60 cm head difference during ebb tide and 80 cm during flood tide. This requirement is expected to become less stringent, so that the turbines can operate up to 90/90 cm (de Fockert and Bijlsma, 2018).

It is difficult to conduct meaningful measurements of the underwater sound generated by the tidal energy turbines, because the storm surge barrier and the flowing water also generate sound. An attempt to standardize methods for such measurements is being made (Lawrence, 2018). However, at the moment no sound recordings are available for the turbines at the Eastern Scheldt Storm Surge Barrier.

The Dutch government has granted Tocardo permission to install one more array of turbines, in gate Roompot 10. This installation will be evaluated by the management of the storm surge barrier (with consideration for structural safety), the Dutch government (with a focus on environmental effects), and Tocardo (in terms of costs and energy production). Tocardo presently has the ambition to install turbines in up to 17 gates in the future.

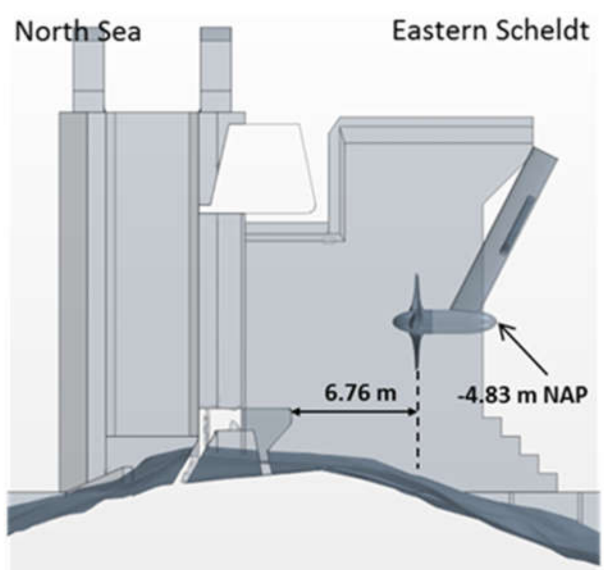

Fig. 4. Side view of the Tocardo turbine configuration at gate 8 of the Roompot section (Source: de Fockert and Bijlsma, 2018 © Deltares).

Current research and questions

Before the environmental permit for the installation of more turbines as intended by Tocardo, can be issued, an assessment of the effects of more turbines on the structure and safety of the storm surge barrier, currents, tidal range, natural sand movements, and marine mammals is required. However, the Eastern Scheldt Storm Surge Barrier is unique (size and shape), the turbines are unique (size, number of blades, revolutions per minute), and the location and tidal regime are unique, so information from other tidal energy turbines is of limited use for estimating the impacts of the proposed development. The studies that were commissioned to assess the effects of the existing five turbines in Roompot 8, meanwhile provide useful location-specific knowledge on the strength and pattern of the currents and the tidal regime within the gates and in the surrounding area, and the consequences for natural movements of sand (de Fockert and Bijlsma, 2018), but only for this limited scenario. The same applies to the research on movements of harbor seals (*Phoca vitulina*) and harbor porpoises (*Phocoena phocoena*) between the North Sea and the Eastern Scheldt (crossing the barrier), and local population dynamics of harbor porpoises and harbor seals (Leopold and Scholl, 2018; Leopold and Scholl, 2019).

This position paper was commissioned to predict the impact of the Eastern Scheldt Storm Surge Barrier on harbor porpoises and harbor seals when scaling-up and installing extra tidal energy turbines in more gates, based on the best available scientific knowledge and expert judgment. Suggestions for future research to improve the predictions are provided. No consideration is given to effects on fish species which porpoises and seals eat, but we note that any effect on fish may in turn affect their predators. Also no consideration is given to the effect of the barrier and turbines on the predators of harbor seals and harbor porpoises, such as grey seals.

In order to assess the effects of the barrier and the existing and proposed turbines on harbor porpoises and harbor seals, we answer the following specific questions:

1) Does the Eastern Scheldt Storm Surge Barrier itself prevent or reduce movements of harbor porpoises and harbor seals between the Eastern Scheldt and the North Sea?
2) What, if any, is the additional effect on porpoise and seal movements of the existing and proposed tidal energy turbines within the barrier?
3) What is the likelihood of porpoises and seals that do cross the barrier colliding with the turbine blades, and what are the potential effects of such collisions for the animals?

2 Effects of the barrier and turbines on harbor porpoises

Numbers of harbor porpoises in the Eastern Scheldt

The harbor porpoises in the Eastern Scheldt have been counted annually since 2009; the annual count varied between 15 and 61 animals; Rugvin Foundation; https://rugvin.nl/onderzoek/noordzee/). The numbers of animals counted per survey may have been influenced by many factors such as the weather conditions (especially in 2010), diving behavior of the porpoises, and training of observers. The numbers observed before and after turbine installation are similar (Leopold and Scholl, 2018). Both the number of live porpoises seen and the number of dead porpoises stranded in the Eastern Scheldt seem to be stable during the monitoring period (Leopold and Scholl, 2018). Photo identification studies show that some individual porpoises have been observed often, which suggests that once they are in the Eastern Scheldt, they tend not to leave (Leopold and Scholl, 2018), this was also concluded from prey analysis (Jansen et al., 2013). However, it is not known whether or not harbor porpoises swim in and out of the Eastern Scheldt by crossing the barrier more than once. Harbor porpoises occur all year round in the Eastern Scheldt also in the years that porpoises in the North sea tended to migrate Northward and left the coastal waters of the Netherlands. Approximately 16 dead porpoises are found annually in the Eastern Scheldt (Leopold and Scholl, 2018); most of them are young animals, like those found on beaches elsewhere in the Netherlands. It is not known if any of the dead porpoises found in the Eastern Scheldt were sick or dead animals moved there by the currents from the adjacent North Sea. So far none of the animals that have been photo-identified in the Eastern Scheldt, has been found dead in the Eastern Scheldt, suggesting that most animals found dead in the Eastern Scheldt have entered from the nearby North Sea, being already dead or still alive.

Why harbor porpoises enter the Eastern Scheldt

It is not clear whether or not harbor porpoises enter the Eastern Scheldt deliberately. The Eastern Scheldt does not appear to be particularly more or less suitable than the North Sea for harbor porpoises to forage, rest, find mates, reproduce and suckle their calves, though the background noise level in the Eastern Scheldt is probably lower than in much of the North Sea, due to the lower shipping density. Evidently, sufficient food is available in the Eastern Scheldt for a number of porpoises to survive, as evidenced by photo identification studies (Annemieke Podt and her photo identification team). Although a birth has never been observed, small recently-born calves have been observed every year since 2009 between April and August, suggesting that calves are born in the in the Eastern Scheldt (Rugvin Foundation; https://rugvin.nl/onderzoek/noordzee/).

Effect of the barrier on movements of harbor porpoises

Harbor porpoises are found in the Eastern Scheldt. The Storm Surge Barrier was completed in 1986, and harbor porpoise live on average 8-13 years, so they must be able to cross the barrier, at least in the direction of the Eastern Scheldt. However, so far no harbor porpoises have been observed crossing the storm surge barrier in either direction, and no radio telemetry studies have been conducted showing that individual harbor porpoises do cross the barrier.

The storm surge barrier is likely to restrict the movement of harbor porpoises, because eddies and turbulence within and around each gate form an acoustic barrier during flood and ebb tides, and because each open gate forms a relatively narrow physical passage.

Harbor porpoises use echolocation for orientation and foraging (Au, 1993). The dominant frequency of harbor porpoise echolocation clicks is around 125 kHz (Møhl and Andersen, 1973). Such high-frequency sound reflects easily from air bubbles, as likely encountered in eddies during ebb and flood tides in and near the gates of the storm surge barrier. The air bubbles (which occur mainly in the turbulence close to the barrier, as they rise and disappear) in the eddies are likely to be interpreted by the porpoises as a barrier, and could be termed an acoustic barrier. Toothed whales can be herded (and captured) with tubes on the bottom releasing air bubbles, causing a bubble curtain. A bubble wrap screen reduces propagation of high frequency sound above 250 Hz, and thus also harbor porpoise echolocation signals (Kastelein et al., in prep). Harbor porpoises may forage near eddies, as strong currents with eddies confuse fish and act as a barrier for them, which may increase the local fish density (Benjamins et al., 2015). However, harbor porpoises have not been seen foraging near the Eastern Scheldt Storm Surge Barrier.

Harbor porpoises, like other odontocetes, prefer not to enter passages that they perceive as narrow, even passages that seem large enough to allow several individuals to pass through. Kastelein et al. (1997) observed that a porpoise in a large floating pen preferred not to swim through a net with a stretched mesh size of 10 m (though a mesh size of 50 cm would be large enough to allow free passage). Beached, recently rehabilitated captive porpoises prefer not to swim through 2 x 2 m gates, and intensive training is required before they will do so (Kastelein personal observation of at least 20 stranded harbor porpoises which had to learn to swim through gates during their rehabilitation process). The porpoises probably detect the boundaries of a passage with their echolocation system and seem to perceive it as a plane and thus as a physical boundary.

Under normal conditions, each open gate forms a passage through the storm surge barrier that is bordered by the vertical pillars, the concrete threshold at the bottom (which vary in depth depending on the location of the gate), and the water surface. Therefore the tide determines the size of the passage through which an animal can swim, and harbor porpoises are expected to cross the barrier more readily at high slack tide than at low slack tide (~ 3.6 m difference). Apart from the tide, the position of each gate within the section of the barrier determines its surface area; in each section, central gates are deeper than lateral gates. Harbor porpoises are therefore more likely to cross the barrier through a central larger gates than through the lateral smaller gates. So, the most likely combination of tidal phase and location for healthy porpoises to cross the barrier is at high slack tide through a central gate. Porpoises are less likely to cross the barrier at low slack tide through a lateral gate.

Taking both the acoustic barrier function and the passage size into account, it seems most likely that harbor porpoises cross the barrier during high slack tides. Porpoise density is low on both sides of the barrier, and slack high tide periods are brief, so crossings are likely to be occasional events. Harbor porpoises can swim at speeds of ~7 km/h for at least 30 min (Kastelein et al., 2018), so they could, if desired, reach the barrier during high slack tide at short notice and cross the barrier deliberately. Alternatively, a porpoise may be chasing fish at high slack tide, the fish may move through the gates, and the porpoise may follow. This method is used to lure naïve captive harbor porpoises through a gate, by throwing a thawed fish just behind the gate opening. The urge to feed and the focus on the fish often makes the porpoise forget about the perceived boundary, and swim though the gate opening. Also a porpoise that is being chased by a predator (in this area that would be a grey seal; *Halichoerus grypus*) may also go through the gate. Four individual harbor porpoises, know from the photo-ID studies of Stichting Rugvin, in the Eastern Scheldt have healed bilateral tailstock lesions and additional body scarring likely induced by grey seals. These animals evidently (just) escaped this predator, either in the North Sea, or in the Eastern Scheldt, or (shortly) before passage through the barrier. (Podt & IJsseldijk 2017).

It seems unlikely that healthy harbor porpoises are carried into the Eastern Scheldt passively by the water current. The current near the gates is very strong at certain times of day, but it gradually increases when a porpoise approaches the gate. If the current starts to become uncomfortable, the porpoise can decide to swim to calmer waters. Starting from slack tide, the current and the turbulence slowly increase as the tide changes, allowing porpoises to get used to the change, or decide at some level to not cross the barrier and leave the area . Similarly, an animal approaching the barrier could choose to swim away from the increasing current and noise it is exposed to.

Harbor porpoises show individual variation in their behavior and responses to objects and sounds (Kastelein et al., 2000, 2001, 2005, 2008, 2018), depending on factors such as the individual's character, history, age and sex, and on the context, such as the location, tidal cycle (current, eddies/turbulence, water depth), whether the porpoise is alone or in a group, the weather conditions, season, etc. Thus it is possible that only very bold harbor porpoises are willing to cross the barrier, only in certain special conditions, while other conspecifics will never do so.

We believe that crossing the storm surge barrier from the North Sea to the Eastern Scheldt or from the Eastern Scheldt to the North Sea would be similar for a harbor porpoise. It could be that once they are in the Eastern Scheldt, some porpoises that adapt well to the local conditions and know where to find food at different periods of the day and tide, feel no urge to leave (photo identification has shown that some individual porpoises were in the Eastern Scheldt for more than 7 years; (Rugvin Foundation; https://rugvin.nl/onderzoek/noordzee/). The difference in porpoise density on each side of the barrier and migrating pattern in the North Sea (including the absolute number of harbor porpoises in North Sea) may determine whether there is a net inflow or outflow. As these conditions vary over the years, the net inflow and outflow will also vary.

Effect of existing turbines on harbor porpoises

The existing array of five turbines in gate Roompot 8 makes the passage through the open gate smaller, though ~5.5 m of water remains between the blade planes and the stony bottom protection below. When coming to an underwater barrier, harbor porpoises have a tendency to swim below it (Kastelein et al., 1995), so they would probably cross the storm surge barrier close to the concrete threshold, keeping away from the blades. However, due to the presence of the turbines, porpoises are expected to be less likely to cross the barrier through gate Roompot 8.

At the moment, only Roompot 8 gate of the 62 gates has an array of five tidal energy turbines, so that the effect of these existing turbines applies to only 1.6% (1/62) of the storm surge barrier (% based on the number of gates, disregarding the different gate sizes). A porpoise contemplating to cross the barrier can choose any of the other 61 gates. The increase in turbulence in and near the gate that is caused by the turbines (due to strong tidal streams which occur because the flow is constrained; de Fockert and Bijlsma, 2018) is unlikely to increase the barrier effect for porpoises, as most crossings are expected to occur at and around slack tides, when the currents are greatly reduced.

No underwater acoustic measurements have been carried out near the existing turbines in the Eastern Scheldt Storm Surge Barrier. Depending on their spectrum and source level, and on local propagation conditions, the sounds produced by the turning turbines may or may not have an effect on harbor porpoise behavior. However, porpoises are expected to cross the barrier only at and around slack tides, when the turbines are not moving and are thus not producing sound. If sound produced by the turning turbines is audible to the porpoises in the vicinity, it will either add an extra barrier effect, or help the porpoises to locate the turbines and thus avoid colliding with them.

Effect of extra turbines on harbor porpoises

If, as intended, more turbines are added to the barrier, this will be done in at least two stages: in the near future an array of turbines in gate Roompot 10, and later possibly one array of turbines in every third gate along the entire storm surge barrier. In both scenarios, the porpoises could still cross the barrier through gates with turbines at slack tides, but may prefer to avoid them.

Adding one extra array of turbines would increase the barrier function in 2 of the 62 (3.2%) gates of the storm surge barrier, leaving 60 gates (~97%) unaltered (note that the gates differ in size and the 97% signifies only the % of the total number of gates and not the available passage surface area). Adding an array of turbines in every third gate would increase the barrier function in 17 of the 62 gates (~27%) in the storm surge barrier, leaving 45 of the 62 gates (73%) unaltered. The number of crossings by harbor porpoises in both directions is probably very small (even without any turbines in the barrier), so the additional effect of the proposed turbines, even in 17 of the gates, is probably limited.

Likelihood of harbor porpoises colliding with turbines

It is unlikely that a healthy harbor porpoise crossing the storm surge barrier would collide with a turbine blade, as crossing is likely to occur during slack tides, when the blades are not moving. Even when the blades are moving, they turn relatively slowly (one revolution of each of the 2 blades per 1.4 seconds), so that they can easily be avoided by a healthy harbor porpoise. Apart from using echolocation to detect the blades, harbor porpoises can use vision. They have a *tapetum lucidum* and can thus see much better than humans during low light conditions in deep and or turbid water and in the shadow zone of objects and at night (Kastelein et al., 1990).

Since the installation of the array of five tidal energy turbines in the Eastern Scheldt Storm Surge Barrier in 2015, 34 dead porpoises found in the Eastern Scheldt were investigated, only two of which had blunt trauma consistent with collision (IJsseldijk, in Leopold and Scholl, 2018). However, collisions may have occurred in the North Sea, and the dead bodies may have entered the Eastern Scheldt with the currents, or the collisions may have been with boats, rather than with the tidal energy turbines. The number of speedboats in the Eastern Scheldt has increased during the last decade, and foraging porpoises have been observed almost colliding with the fast-moving boats (Ron Kastelein, six personal observations near Wemeldinge between 2015 and 2018).

Mitigation for harbor porpoises

Harbor porpoises are likely to cross the storm surge barrier only at slack tide, when the tidal energy turbines are not producing energy. Therefore, lifting the turbines out of the water at slack tide will increase the likelihood of harbor porpoises crossing the barrier (by making the gates less narrow in the perception of a porpoise).

The central gates in each section of the storm surge barrier are in deep water, and are therefore bigger than the lateral gates. The space under each array of turbines, where porpoises crossing the barrier through gates with turbines would swim, is therefore bigger in central gates than in lateral gates, assuming an identical positioning of the turbines in the storm surge barrier as the ones currently deployed in Roompot 8. For this reason, instead of placing the proposed turbines in every third gate, it seems advantageous (in regards to porpoise crossings) to place more turbines in lateral gates and fewer in central gates. On the other hand, if porpoises are not more likely to cross central larger gates than the lateral smaller gates, the addition of turbines reduces the remaining available space to cross relatively less in the larger gates than the smaller gates.

3 Effects of the barrier and turbines on harbor seals

Numbers of harbor seals in the Eastern Scheldt

Harbor seals occur in the Eastern Scheldt and the nearby North Sea (Voordelta). The number of harbor seals counted on the tidal flats of the Eastern Scheldt increased from a maximum of 13 animals in 1995 to 160 animals in 2016 (Leopold and Scholl, 2018). Similar numbers (around 150) of harbor seals were observed in the Eastern Scheldt before and after the array of Tocardo turbines was installed (Leopold and Scholl, 2019). In the North Sea (Voordelta) the number of harbor seals counted on the tidal flats increased from a maximum of 11 animals in 1995 to 478 animals in 2016.

Why harbor seals enter the Eastern Scheldt

Harbor seals visit the Eastern Scheldt both to forage for fish and (unlike harbor porpoises) to rest on tidal flats, where they are safe from most marine predators (worldwide those are sharks, killer whales, not occurring in the Eastern Scheldt, but harbor seals are possibly prey for male grey seals which do occur in the Eastern Scheldt) and terrestrial predators (humans, dogs, foxes) and speed boats and other shipping. It is possible that harbor seals mate in the Eastern Scheldt. In the Eastern Scheldt they give birth to their pups on tidal flats, and suckle the pups in the water for a period of 3-4 weeks until they wean. Diet varies individually, and with location, season and availability of the prey.

Effect of the barrier on movements of harbor seals

Radio telemetry on 32 harbor seals has shown that some individuals (4) crossed the storm surge barrier readily and frequently (due to the sample rate of the location determination, it is not clear during which periods of the tidal cycle the seals crossed the barrier), and probably forage on both sides of the barrier. Seals have been observed to cross all three channels of the Eastern Scheldt Storm Surge Barrier, and at times individuals have preferences for particular channels (Leopold and Scholl, 2018). The barrier does not seem to restrict the movement of some individuals at all, and large numbers of seals are present on both sides of the barrier. Harbor seals have even been observed several times, from the footpath of the storm surge barrier, swimming and maintaining their position in the eddies in strong currents on the North Sea side of gates in the Schaar and Hammen sections (Jaap van de Hiele personal observation). This suggests that harbor seals can swim fast enough to overcome the currents near the barrier during most or all tides. Unlike harbor porpoises, seals do not use echolocation, and are not afraid to swim through narrow areas in captivity (Ron Kastelein, personal observation 1983-2018). The eddies may confuse, and possibly damage fish and make them easier for harbor seals to capture, and the funnel action of the gates may concentrate fish. Gulls and terns have also been observed foraging for fish in the eddies (Ron Kastelein, personal observation, 1995-2018 & Mardik Leopold, personal observation). The area around the storm surge barrier is therefore likely to be attractive to harbor seals.

Harbor seals use three sensory modalities for foraging and orientation: vision, hearing and touch. Their underwater vison is better than that of humans due to their *tapetum lucidum* (Braekevelt, 1986). They can detect fish by listening to the low-frequency underwater sounds they produce (Kastelein et al., 2009), and by using their whiskers to feel water movements caused by the swimming fish (Dehnhardt et al., 2001). Harbor seals are coastal animals that have evolved in areas with surf, in which currents, noise and turbulences exist, and where the water is often relatively murky. When hauling out, seals may cross surf. Therefore, the Eastern Scheldt Storm Surge Barrier is unlikely to restrict the movements of harbor seals.

Effect of existing turbines on harbor seals

Under the existing array of five turbines in gate Roompot 8, ~5.5 m of water remains between the turbine blade planes and the stone bottom protection below. In contrast to harbor porpoises, harbor seals readily enter small spaces. At the SEAMARCO Research Institute, harbor seals often go behind a vertical board through a hole that is 50 cm in diameter, and rest in the space behind the board and the pool wall (this underwater space is 60 cm x 200 cm x 180 cm deep). A similar space in the porpoise pool has never been entered by any of the six porpoises that have lived there during 12 years. The reduction of the passage through gate Roompot 8 due to the existing turbines is not expected to restrict the movements of harbor seals in any way. Though telemetry data and experience with captive seals show that individual seals can behave very differently and react differently to stimuli (Kastelein et al., 2006 a,b; 2015; 2017; Leopold and Scholl, 2018), most seals are likely to cross the storm surge barrier with ease, regardless of the existing Tocardo turbines.

Joy et al. (2018) showed that harbor seals avoided the vicinity of a tidal SeaGen turbine on a monopole at sea, to a radius of ~ 200 m, thus reducing the likelihood of collision. The SeaGen turbine had two 8 m x 60 cm double-bladed rotors, connected to a monopile foundation by a wing-shaped crossbeam; each rotor produced up to 600 kW of power 18 to 20 h a day (https://en.wikipedia.org/wiki/SeaGen). It is unclear why the seals avoid that turbine, and which sensory modality was involved (hearing, vision and/or touch). Tidal energy turbines vary in terms of their location, size, sounds, type of blades, fixation, location relative to food sources, etc., and geographically seals vary in their level of familiarity with anthropogenic objects, and the seal density can play a role, so results cannot be extrapolated easily.

Effect of extra turbines on harbor seals

Increasing the numbers of tidal energy turbines within the Eastern Scheldt Storm Surge Barrier is expected to affect crossings of healthy harbor seals in such a small way, that is will be difficult, or impossible, to measure.

Likelihood of harbor seals colliding with turbines

No harbor seals have been found in the Eastern Scheldt with blunt trauma injuries since the array of five turbines was installed (IJsseldijk in Leopold and Scholl, 2019). Harbor seals are unlikely to collide with turbine blades, because seals can see, hear and/or feel (with their whiskers) the movements of the slow-turning blades, and can easily avoid them. Only a seal that is sick or distracted because it is actively foraging or fleeing from a predator is likely to come into contact with the blades. High level of predation does not occur in this area, but male grey seals do occasionally prey on young harbor seals, and the number carcasses with suspected grey seal attack markings seems to increase.

Mitigation for harbor seals
Mitigation measures are not discussed, as turbines are likely to have minimal effects on harbor seals.

4 Suggestions for research

This paper was commissioned because there are insufficient data to predict with certainty the effects of the existing and intended tidal energy turbines in the Eastern Scheldt Storm Surge Barrier on harbor porpoise and harbor seal crossings of the barrier, or to quantify the likelihood of healthy harbor porpoises and harbor seals colliding with the turbines. The following research could usefully be conducted in order to test our current predictions (we do not advocate this research, nor do we discuss the feasibility of the research ideas, as they depend on the need to conduct them, the technology developments, the available funding and the availability of sufficient animals for tagging):

1. Monitor the movements of harbor porpoises, to evaluate when they cross the barrier (only at slack tides?) and where they cross it (generally through the higher gates in the middle of each section?), by using radio-telemetry. However, radio-telemetry has rarely been conducted on harbor porpoises in the Netherlands. The method has limitations for this species, because the harbor porpoise is one of the smallest odontocetes in the world, and tags increase drag, thus increasing energy demands.
2. Monitor seal and porpoise movements through storm surge barrier gates with and without turbines. This could be done above water with cameras and below water with cameras and active sonar in the gates. The number of crossings is likely to be low (especially by porpoises), so sensors should be placed in as many gates as possible. Sensors in the gates may also be used to answer questions about harbor porpoise barrier crossings without the use of radio-telemetry.
3. Increase the photo ID effort by collecting photo’s more times per year and close to the barrier, and during different tidal phases, to get a better insight in the changes in the distribution of the porpoises within the Eaten Scheldt.
4. Monitor the effect of the turbines on fish crossings, aggregation, and behavior (confusion), etc., as the movements of the fish might explain the presence and movements of their predators (the seal and porpoises) in this area.
5. Professional sound recordings should be made near the tidal energy turbines in gate Roompot 8 and near a similar gate without turbines for comparison. The measurements should be made over at least 24 h (encompassing the entire tidal cycle), under various wind conditions, and at various distances from the barrier. The spectrum of the sound and the sound pressure level distribution in the area around a gate could help explain the movements of the porpoises near the gates and help to predict whether the turbines reduce porpoise crossings or not.

5 Acknowledgements

We thank Peter Scheijgrond (Dutch Marine Energy Centre) for providing information on the Tocardo turbines, Arnout Bijlsma (Deltares), Mardik Leopold (Wageningen Marine Research), Michaela Scholl (Wageningen Marine Research) and Frank Zanderink (Stichting Rugvin; Rugvin foundation) for their constructive comments on this paper. The project was commissioned to SEAMARCO B.V. by Wageningen Marine Research (PO number WUR1188208, contacts: Michaela Scholl and Mardik Leopold).

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