FLOOR HEINIS, CHRIST DE JONG, MICHAEL AINSLIE, WIL BORST AND TIEDO VELLINGA

Above: Following the Environmental Impact Assessment, the underwater sound related to all the different phases of the dredging cycle was monitored and compared with background sound and other sources of sound from shipping vessels and their potential effects on the marine fauna.

MONITORING PROGRAMME FOR THE MAASVLAKTE 2, PART III – THE EFFECTS OF UNDERWATER SOUND

ABSTRACT

The Port of Rotterdam is expanding to meet the growing demand to accommodate large cargo vessels. The construction of Maasvlakte 2 (MV2) started in September 2008. One of the licensing conditions is the monitoring of the underwater sound produced during its construction, with an emphasis on the establishment of acoustic source levels of the trailing suction hopper dredgers (TSHDs) during their various activities: dredging, transport and discharge of sediment.

TNO (Netherlands Organisation for Applied Scientific Research) Sonar and Acoustics carried out measurement and analysis activities for this monitoring. During an initial measurement campaign in September 2008, background measurements were performed in the absence of dredging. Source level and background sound measurements were made in the dredging area while MV2 dredging activities were underway in September 2009. In a final phase of the study, possible effects of underwater sound on marine fauna were considered for scenarios with and without dredgers. In this article, the principal results of the research are described and discussed in the context of the effects predicted in the Environmental Impact Assessment.

INTRODUCTION

Maasvlakte 2 is the Port of Rotterdam Authority's port extension project west of the existing Maasvlakte. The project area comprises approximately 2,000 hectares gross of which 1,000 hectares is the net infrastructure. The first phase of the project was finished April 2013.

To determine the effects of underwater sound generated by dredgers on fish and marine mammals, model calculations were made for the Environmental Impact Assessment (EIA) on the basis of the best knowledge available at the time. From these calculations it emerged that the sound level below the water in the vicinity of dredgers can exceed the hearing threshold of fish and marine mammals.

However, at a distance of more than a few hundred metres away from the vessel, it was thought that the threshold for avoidance would not be exceeded (Vertegaal *et al.*, 2007; Vellinga, 2007). On that basis, it was concluded in the EIA in 2007 that the area affected is negligible in size by comparison with the total space that is used by the animals as feeding grounds and migration areas.

This article focusses on the provision included in the Soil Removal Permit for the construction of Maasvlakte 2 on the monitoring of underwater sound related to the construction activities. The research conducted in the context of the aforementioned provision focussed on finding answers to the following questions:

- What is the source level of the underwater sound of the deployed dredgers during the various phases of the dredging cycle?
- How does the dredger sound relate to the background sound?
- To what extent are the effect contours (determined on the basis of the predicted received levels, weighted on the basis of the hearing sensitivity of the relevant species) related to the contours for a possible impact on marine organisms predicted in the EIA for a possible impact on marine organisms?

The Port of Rotterdam Authority does not have any extensive expertise in the field of the recording of underwater sound levels or processing measurement data and has therefore asked TNO (Netherlands Organisation for Applied Scientific Research) to elaborate a measuring strategy for the monitoring requirements stated in the permit.

The strategy has been included in full in the MV2 Construction Monitoring Plan. In this article, the principal results of the research will be described and discussed in the context of the effects predicted in the Environmental Impact Assessment.

MEASURING UNDERWATER SOUND

To comply with the permit conditions, the following measurements were executed:

- Registration of background sound at a fixed location in the Maasvlakte 2 area during one week in the year before the construction work;
- Registration of the background sound (at a fixed location) including the underwater sound as a result of the construction work over a period of one week in 2009;
- Recording of the sounds of various types of trailing suction hopper dredgers (TSHDs) during the various phases of the dredging cycle in the same week in 2009.

During the measuring week in 2009, the underwater sound related to all the different phases of the dredging cycle could be sufficiently monitored. It was therefore concluded, in consultation with the Dutch competent authority, that compliance with the Maasvlakte 2 Construction Monitoring Plan had been achieved (see Intermezzo “Representativeness of measurements”).

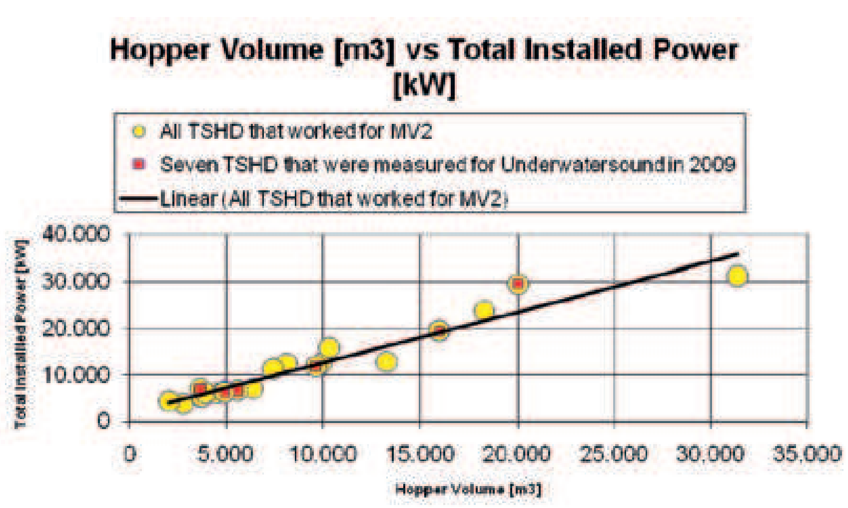
Another important component of the strategy established by TNO was the decision made in consultation with the Port of Rotterdam Authority and the Dutch competent authority to combine field measurements with acoustic propagation modelling. This made it possible to estimate underwater sound levels in an area that extends beyond the measurement location itself. The modelling works in two ways:

- *Inverse modelling:* calculating backwards to determine the acoustic source level of the dredgers during different parts of the dredging cycle from the recorded underwater sound of individual TSHDs;

INTERMEZZO: Representativeness of measurements in 2009

During the measurements conducted over a period of one week in October 2009, seven TSHDs were at work. Recordings were made of the underwater sounds produced by all seven vessels in various phases of the dredging cycle: dredging, transiting with a load, bottom discharging, rainbowing, pumping ashore and transiting without a load.

To provide an indication of the representativeness of the measurements, all 21 TSHDs deployed on the construction of Maasvlakte 2, including the 7 monitored vessels (marked with a red dot), are shown in the figure below. Two of them are virtually identical sister ships. The figure plots the total installed power (kW) and the load capacity of the ships (m^3). The figure shows that the seven vessels monitored are a representative selection of those working on Maasvlakte 2.



The Table below contains an overview of the phases of the dredging cycle that could be monitored. It can be seen that all phases of the cycle were recorded, so that an adequately representative picture has been established of the underwater sound during the entire range of work done. Because the sound levels for bottom discharging and pumping ashore, the phases in the dredging cycle for which relatively few data have been collected, appeared to be lower than these for the other activities, it was decided that sufficient data were gathered.

Weeks 39 and 40 in 2009	
Action	**number of events:**
Transit: fully loaded	**16**
Transit: empty	**16**
Dredging port side	**15**
Dredging starboard side	**10**
Rainbowing	**13**
Pumping ashore	**2**
Bottom discharge	**2**

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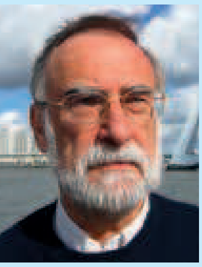
received a PhD in Natural Sciences in 1993 from the University of Amsterdam. She is a consultant specialised in freshwater, estuarine and marine ecology. From 1988-1999 she was at AquaSense Consultants. She was responsible for the marine ecological issues in the EIA for Maasvlakte 2 and now advises the Port of Rotterdam Authority on these issues.

CHRIST DE JONG

received a MSc (1986) and PhD (1994) in Technical Physics from the University of Eindhoven, the Netherlands. In 1986 he joined TNO (Netherlands Organisation for Applied Science), where he works in the field of underwater and ship acoustics. He is ship acoustic advisor for the Royal Netherlands Navy. Since 2007 he has studied the environmental impact of anthropogenic underwater sound.

MICHAEL AINSLIE

received a BSc in Physics from Imperial College, London, UK in 1981, MSc in Mathematics from the University of Cambridge, UK in 2011, and PhD in Ocean Acoustics from the Institute of Sound and Vibration Research (ISVR), University of Southampton, UK in 1992. He is Visiting Professor at ISVR's Centre for Ultrasonics and Underwater Acoustics and was awarded the 1998 A. B. Wood medal by the UK Institute of Acoustics.



WIL BORST

received a MSc, Civil Eng, at Delft University of Technology in 1974 and joined De Weger International, followed by Svasek BV. In 1987 he took over Netherlands Dredging Consultants. From 1991-2002 he lectured part-time at the Groningen State Polytechnic. He is a founding member of Blue Pelican Associates. In 2005 he joined the Maasvlakte 2 organisation to draft the EIA and is now responsible for monitoring the possible effects on the marine environment.

TIEDO VELLINGA

received a degree in Civil Engineering from Delft University of Technology in 1979. He then joined the Port of Rotterdam Authority working on infrastructure and water management. He is currently Professor, Ports and Waterways at Delft University of Technology, Director Environmental Monitoring at Maasvlakte 2, and project leader for the development of the Environmental Ship Index.

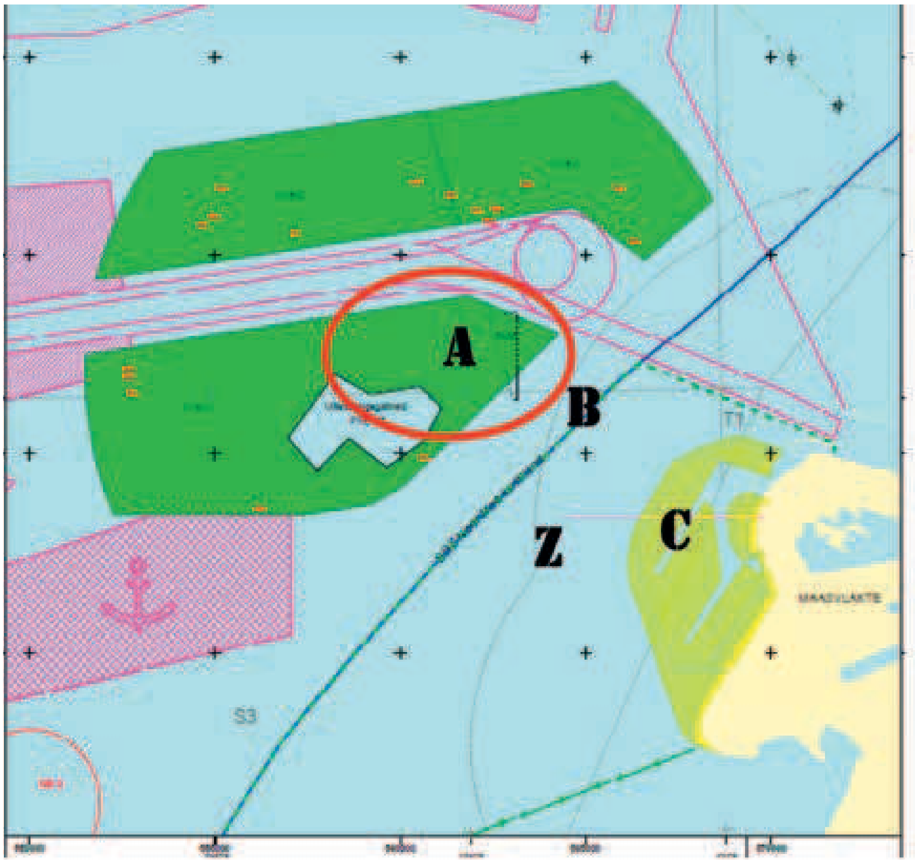


Figure 1. Map showing the future Maasvlakte 2 (C, lime green) and the approved sand dredging areas/borrow areas (green). The red oval shows where sand was actually dredged for the construction of Maasvlakte 2. The large letters show the sites where recordings of underwater sounds were made. Z: background sounds; A: sand dredging; B: transport of sand (transit); C: construction area (bottom discharge, rainbowing and pumping ashore).

this is the part of the research that focusses specifically on compliance with the requirements of the permit (determining source levels for TSHDs);

- *Forward modelling:* here, on the basis of one or more sources, sound levels are calculated for the entire three-dimensional space below the surface of the water; on the basis of these calculations, the predicted sound as received by marine animals, weighted according to the animal's hearing characteristics, can be drawn up in a map.

UNDERWATER AMBIENT SOUND MEASUREMENTS

There are no specific national or international standards for measuring underwater ambient sound. Therefore, TNO proposed a measurement plan, which was fixed in consultation with the Port of Rotterdam Authority and the Dutch competent authority.

Hydrophones

Measurements of the background sounds prior to the construction of Maasvlakte 2 (the baseline measurements) were conducted in the week of 8 -15 September 2008 at a fixed location (designated as Z in Figure 1) which was less than 5 km from the borrow area (the area where the sand was dredged) and the future Maasvlakte 2. The monitoring set-up used in 2008 is shown schematically in Figure 2.

Hydrophones were deployed from a small boat on which the recording system was operated. During this week, recordings were made over a period of 5.5 consecutive days 2 m above the seabed and over a period of more than 3 days in the same period at a height of about 7 m above the seabed (total water depth was approximately 20 m). A six-second sample was recorded every minute.

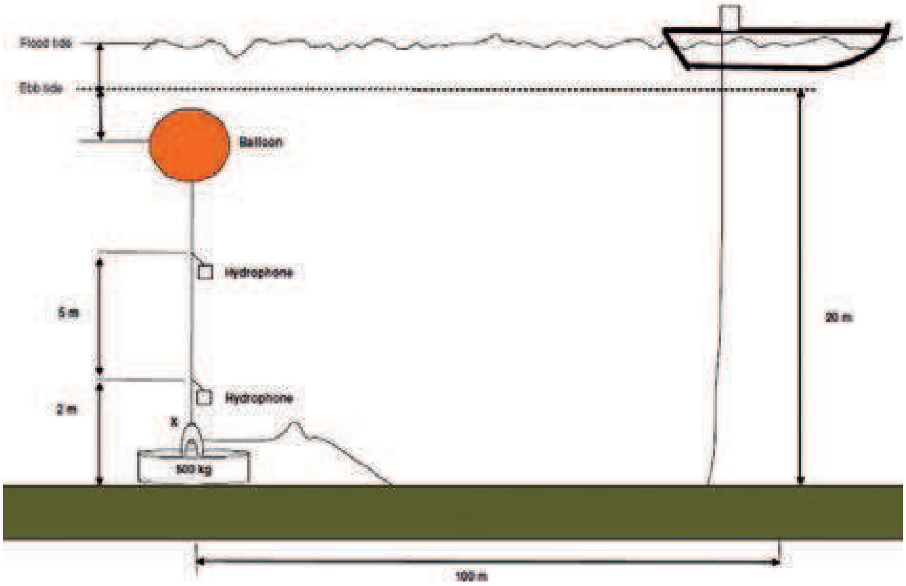


Figure 2. Schematic representation of the fixed monitoring set-up at location Z during the baseline measurements in 2008.

SESAME

To eliminate the practical problems associated with underwater sound recording from a boat during an extended time period, TNO developed the Shallow water Extendible Stand Alone Acoustic Measuring System *SESAME* (see Figure 3). *SESAME* was deployed during the Maasvlakte 2 construction in the period 25 September to 2 October 2009 at a position about 2 km east from the measurement location of the 2008 campaign. This position avoided the risk of damage by fishing vessels to the system, which was underwater and thus not visible at the water surface. The basic principles and further details for the ambient sound measurements in 2008 and 2009 can be found in Dreschler *et al.* (2009) and de Jong *et al.* (2010).

In both measurement campaigns, information on all shipping, including the active dredgers in the vicinity of the Maasvlakte 2 area, was logged by using an Automatic Identification System (AIS) receiver to investigate the correlation between shipping activity and ambient sound levels. The trajectories of all ships sailing in the Maasvlakte area during the 2009 measurement campaign are displayed in Figure 4. Weather conditions, such as wind speed and direction, were monitored by two meteo systems: One positioned at a fixed location in the Maasvlakte area and the other on board of the measurement ship for the mobile measurements.

The acoustic data collected using the hydrophones were converted into sound pressure levels (SPL) per one-third-octave band, with a frequency range of 20 Hz to 80 kHz (2008) and 12.5 Hz to 160 kHz (2009). The different calculation steps required to do this are described in section 4.2 of the first TNO report (Dreschler *et al.*, 2009).

The statistics of the one-third-octave band SPL (see Intermezzo "metrics for underwater sound") measured at the location Z (Figure 1) prior to 2008 and during the construction of Maasvlakte 2 (2009) are shown in Figure 5. The sound levels measured in 2009 were generally higher than those found in 2008.

There was a strong correlation with the distance to dredgers and it is likely that the dredgers in transit contributed most to the underwater sound found at the location. The dredgers sometimes sailed very close to the fixed *SESAME* monitoring station and the variations in the background sounds measured in 2009 were much higher than the variations measured in 2008.

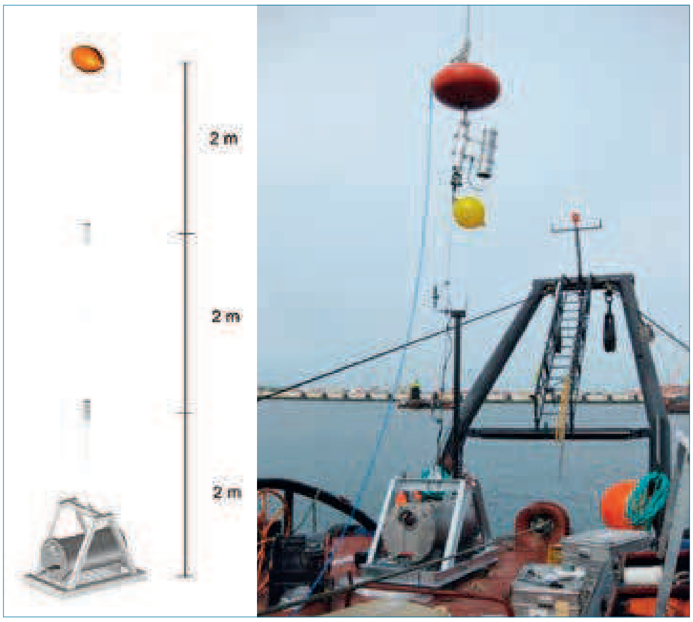


Figure 3. The *SESAME* stand-alone recording system (left: drawing, right: picture on board of measurement vessel *'Mon Desir'* prior to deployment). The buoy providing the upward force for the hydrophone cable remained underwater.

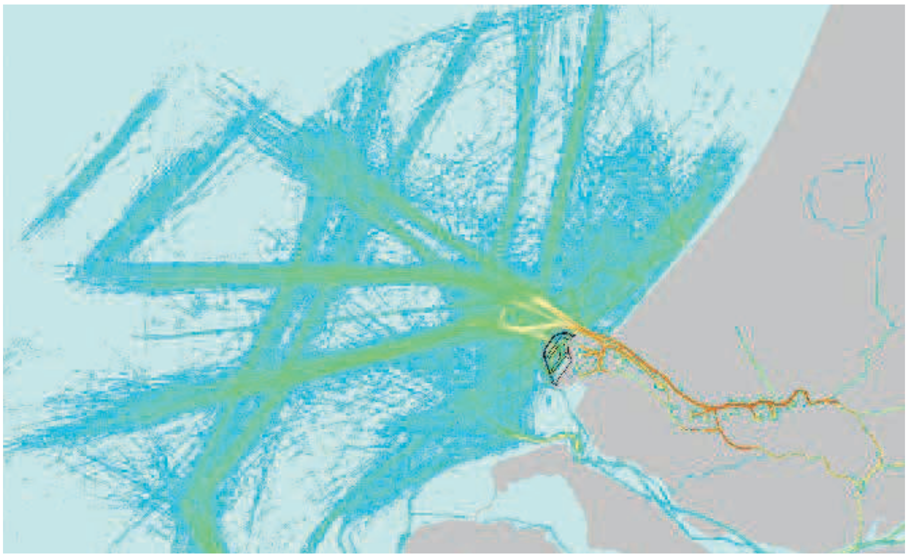


Figure 4. Trajectories of ships during the 2009 measurement campaign.

Shipping traffic

At frequencies up to 10 kHz, the measured sound pressure levels proved to be significantly affected by variations in shipping traffic. The effect was also perceptible at higher frequencies, but much less so. The effects associated with shipping started to decline from a frequency of approximately 5 kHz onwards.

Wind speed

The wind also affected the measured sound pressure levels. At higher frequencies, there was a strong positive correlation between wind speed and measured sound pressure levels: above approximately 10 kHz, sound caused by the wind, for example as a result of waves, was a significant component of background sound. In the frequency range between 100 Hz and 10 kHz, a negative correlation was found between wind speed and background sound, probably as result of an increase in propagation loss as waves get higher so that sound is scattered and absorbed at the water surface rather than reflected.

Dredger (TSHD) underwater sound measurements

There are no specific national or international standards for measuring the radiated sound of dredgers nor of other ships operating in shallow water. TNO proposed a new measurement procedure and analysis method for this study. The proposal was communicated with the National Physical Laboratory in the UK, which applied a similar approach in their study of underwater sound arising from marine aggregate dredging operations (Robinson *et al.*, 2011).

Figure 6 gives an example of the geometry of the radiated sound level measurements of the dredgers during their various activities. The measurements were carried out with two hydrophones at 6 and 12 m from the water surface, deployed from a small boat (Figure 7).

From 22 September to 5 October 2009 (inclusive), radiated sound recordings of individual TSHDs, linked to the various phases of the dredging cycle were made at a range of locations. The approximate locations of the monitoring stations are shown in Figure 1.

The dipole source levels corresponding to the various phases of the dredging cycle were determined using "inverse modelling". This means that the sound levels measured for each third-octave band at various distances from the dredger were back-calculated to the sound level at the source (in this case the dredger). A detailed description of how these

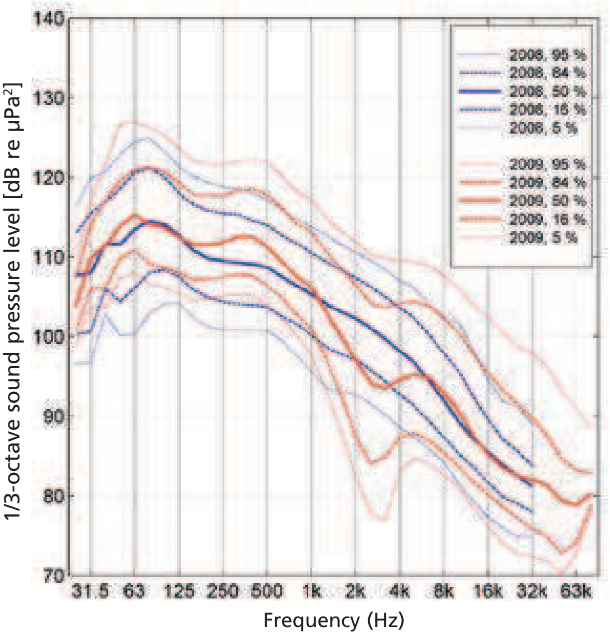


Figure 5. Statistic N percent exceedance levels of the measured sound pressure levels (SPL) per one-third-octave band at a fixed station in the area between the borrow area and the Maasvlakte 2 construction area in 2008 (blue lines) and 2009 (red lines). The dip in the 2009 curves at 3 kHz may be the result of the night-time presence of large numbers of small fish with a swim bladder (see de Jong *et al.* 2010).

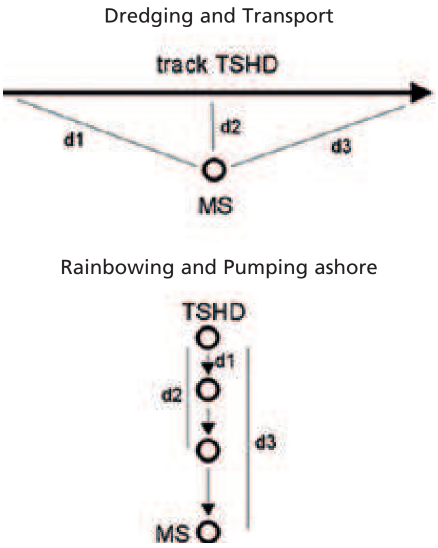


Figure 6. Above, procedures for measuring underwater radiated sound of dredgers during various operations (de Jong *et al.*, 2010). For a reliable estimation of the source level, measurements with one or more hydrophones are carried out at several distances (d1, d2, d3). MS = Measurement station.

calculations were made and the underlying assumptions are set out in Chapter 4 of the TNO report (De Jong *et al.*, 2010).

The maximum values for these source levels for the different activities are shown in Figure 8. The figure shows that dredgers produce the most sound as they move from the borrow areas to the discharge area and vice-versa.

During the sand dredging, comparable levels were produced although the levels in most third-octave bands were a few decibels lower. During pumping ashore and rainbowing, the maximum source level at frequencies between 500 Hz and 10 kHz was comparable with that of a vessel dredging sand but substantially lower than at frequencies outside this range.

The lowest source levels were measured during the bottom discharging of sand at frequencies above 1 kHz and at frequencies

INTERMEZZO: Metrics for underwater sound

The underwater sound recorded by hydrophones ('underwater microphones') is generally analysed and quantified in terms of "levels" and expressed in decibels. Note that there are different "levels" to describe different aspects of different types of sound and that underwater sound levels are not comparable to sound levels in air.

- The underwater sound measured by a hydrophone or received by a marine animal is here quantified in terms of a *Sound Pressure Level (SPL)*: ten times the logarithm to the base 10 of the quadratic sound pressure averaged over a specified time interval and in a specified frequency bandwidth; unit: dB re 1 μPa^2.
- For the total dose of sound received over a specified time interval a *Sound Exposure Level (SEL)* was used: ten times the logarithm to the base 10 of the quadratic sound pressure integrated over a specified time interval and in a specified frequency bandwidth; unit: dB re 1 $\mu Pa^2 s$.

The sound radiated by individual ships and dredgers is quantified in terms of a "source level". *The Monopole Source Level (MSL)* expresses the mean square sound pressure at a distance *r* in a certain direction in the far field of the source (where the sound pressure and particle velocity are in-phase and decrease inversely proportional to the distance from the source), scaled back to a reference distance r_{ref} = 1 m from the acoustic centre of the source. This definition is appropriate for a monopole in free space, i.e., a point source that radiates sound continuously and uniformly in all directions, in a homogeneous, isotropic medium, without absorption and free from boundaries.

In practice, the underwater environment in which sound is measured is complex, because of the effects of reflections at the water surface and seabed and of variations of the speed of sound across the water depth. Especially the reflections at the water surface often referred to as *Lloyd's Mirror effect*, have a large impact on the sound radiated by surface ships. When comparing published ship "source levels", one must be alert for the definition, the measurement conditions, experimental procedures and environmental parameters, as well as for inconsistencies in reference distances, units and bandwidths, which are all given in various ways in the literature.

In this study, the MSL of the dredgers is estimated using a point-to-point propagation loss model, assuming a source position at 4 m below the water surface. Because the actual depth of the acoustic centre will differ per ship, this monopole source level was converted to a Dipole Source Level (DSL), which includes the contribution of the surface image and is therefore independent of the assumed source depth. At high frequency, DSL exceeds MSL by about 3 dB. At low frequency, MSL exceeds DSL by an amount that increases with decreasing frequency. Source levels are here expressed in dB re 1 $\mu Pa^2 m^2$. (The levels are the same as the source levels in "dB re 1 μPa at 1 m" which one often encounters in literature, though the levels can never be measured "at 1 m").

The frequency content of sound is reported in standardised 'third-octave' bands (ISO 266: 1997). Single number broadband levels express the energetic sum of the levels in the individual frequency bands. Where appropriate, the reported levels are weighted for the sensitivity of marine animals to specific frequencies. The precautionary M-weighting function (Southall *et al.* 2007) was used for "high-frequency cetaceans" for the harbour porpoise *Phocoena phocoena* and the M-weighting function for "pinnipeds in water" for the harbour seal *Phoca vitulina*.

Figure 7. Measurement platform *'Mon Desir'* (Sleepvaart en Baggerbedrijf J.J. Saarloos, Dordrecht).

of 500 Hz and less during rainbowing. At a frequency of approximately 100 Hz, the source level for all phases of the dredging cycle is comparable, with the exception of rainbowing.

Dredgers pumping ashore are never anchored; for rainbowing they sail on to the shore and put the bow of the vessel on the underwater slope and start pumping. The propulsion keeps the dredger in place. When pumping ashore they are coupled to the floating pipeline and use dynamic positioning or their bow thrusters and propulsion to stay on the spot. In all probability, the production of underwater sound by dredgers is primarily caused by cavitation linked to the propellers and bow thrusters.

The total amount of sound generated by the TSHDs depended also on the way the dredge masters operated the vessel – some used the bow thruster all the time, some did it incidentally.

UNDERWATER SOUND MODELLING AND SOUND MAPS

In addition to the local information provided by the ambient sound measurements at a field position, acoustic modelling makes it possible to calculate underwater ambient sound levels in a wider area. TNO applied its in-house *AQUARIUS* sound propagation model, an advanced implementation of the theory described in (Weston 1971, Weston 1976), to produce sound maps.

To give an example, the maps in Figure 9 show a calculation result for the sound generated by the activities of dredgers in the Maasvlakte 2 area at two points in time on 29 September 2009. The main modelling parameters are summarised in Table I. The area measures 15 x 15 km. Background sounds caused by, for example, wind and waves or other shipping and harbour activities are not included in the calculations for these maps.

The yellow circles show the locations of the various dredgers. The spread of the sound is shown in circles because the vessels are effectively considered to be point sources. The resulting contours with the same sound level can be seen as the worst-case scenario

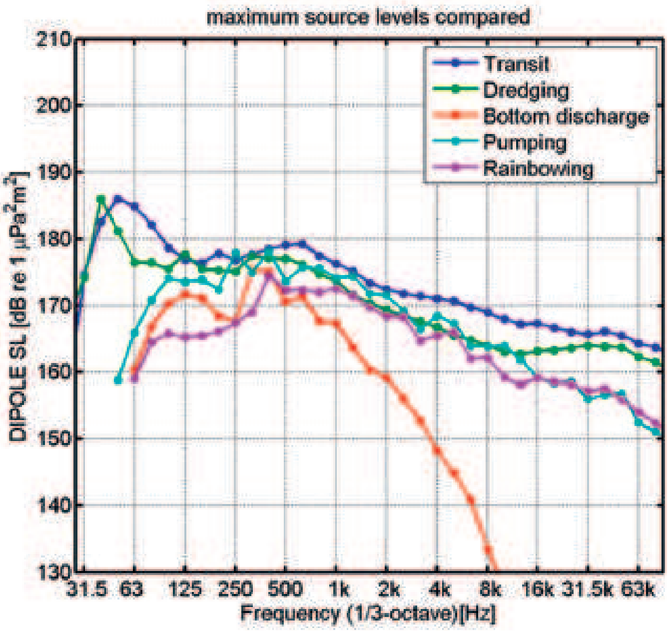


Figure 8. Maximum dipole source level spectra for the various activities of dredgers during the construction of Maasvlakte 2.

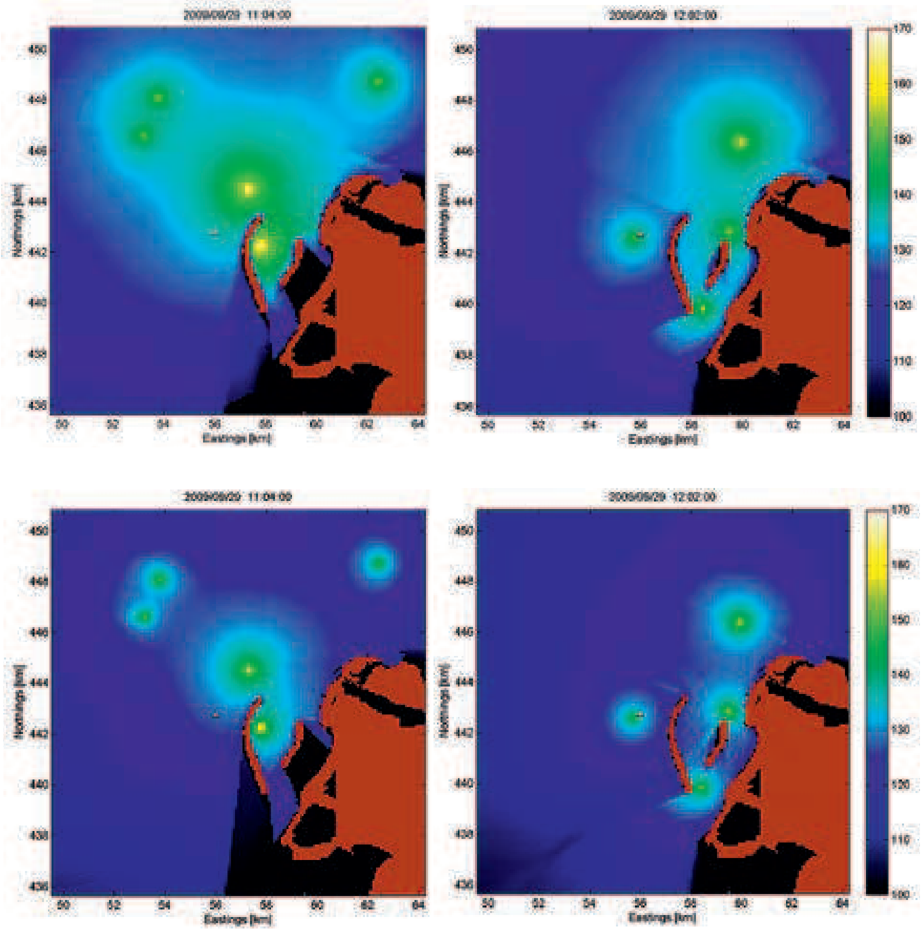


Figure 9. Sound maps for two points in time on 29 September 2009 1 m above the bed (top panels) and 1 m below the surface (bottom panels). The colours show the broadband sound pressure level (dB re 1 μPa²). The white triangle shows the location of *SESAME*.

Table I. Input data for calculations of sound maps

Parameter	Value
Sediment sound speed	1960 m/s*
Wind speed	0 m/s*
Source level	selected on the basis of the best match with activity and speed (data from Automatic Identification System)
Depth	1 m above the seabed, representative for animals located somewhere in the water column, with the exception of the upper metres (depending on the frequency) 1 m below the water surface, representative for animals that swim close to the surface
Time	29 September 2009 11.04 29 September 2009 12.02

** These parameters were selected in such a way that the sound was propagated relatively well, resulting in "worst case" effect distances. At wind speeds exceeding approx. 4 m/s and lower sediment speeds, dissipation and absorption prevent sound from travelling as far. The sediment sound speed of 1960 m/s is the velocity of the sound through the seabed, which is different from through water only. The seabed consist (mainly) of sand in the North Sea near the Maasvlakte (Ainslie, 2010).*

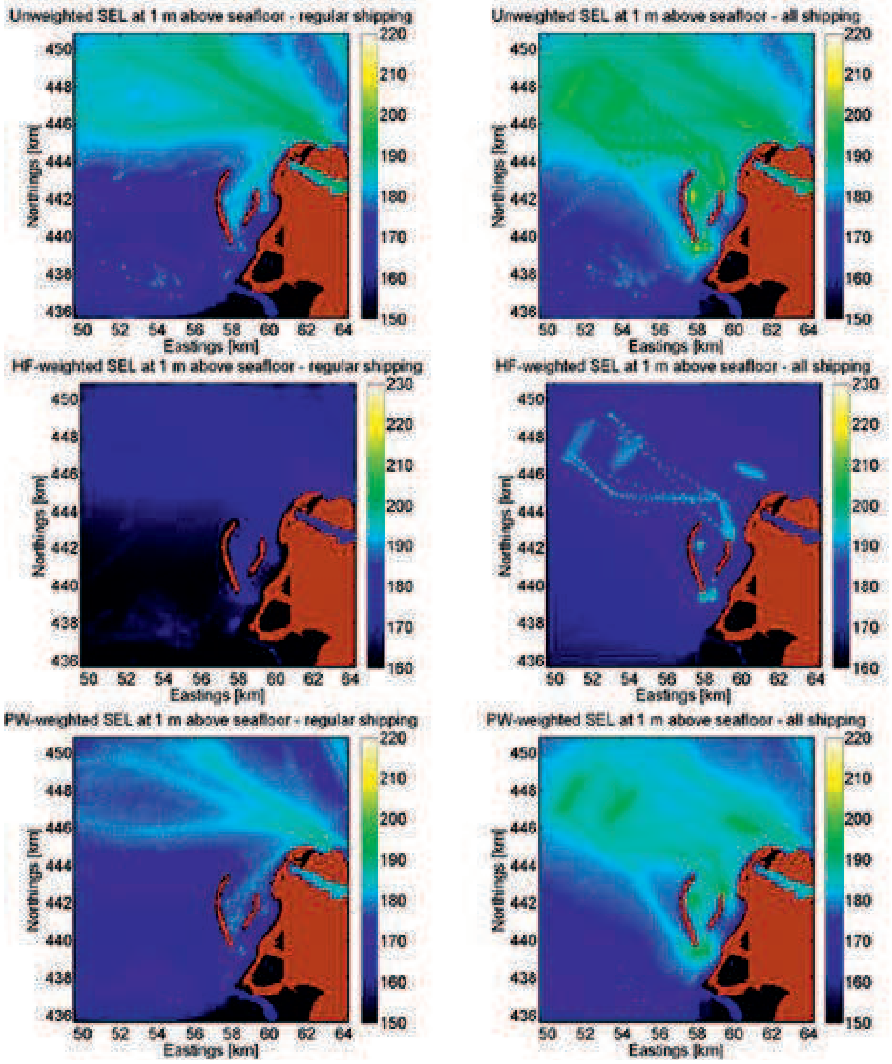


Figure 10. Sound maps generated by regular shipping (left) and regular shipping + dredgers (right) at a depth of 1 m above the seafloor. The figure shows the cumulative broadband sound exposure level (dB Re 1 μPa²s) for a period of 24 hours: non-weighted (top, representative for fish), M-weighted for "high frequency cetaceans" (centre, representative for harbour porpoise) and M-weighted for "pinnipeds in water" (bottom, representative for seals).

because the calculations are based on a wind speed of 0 m/s and a sediment sound speed that is appropriate for coarse sand.

The sound maps in Figure 9 are snapshots taken from movies showing the variations in the soundscape at the two depths in question on 29 September 2009 (0.00 to 24.00 hours). The movies can be found on the DVD accompanying the TNO report of Ainslie *et al.* (2012). The DVD also includes movies for scenarios in which other shipping traffic is included and in which no dredgers are active.

In combination with the information about the shipping traffic (from an AIS), the measured (maximum) source level of the TSHDs during the various activities (Figure 8) and a statistically averaged source level spectrum (Wales and Heitmeyer, 2002) for other ships in the area, the *AQUARIUS* model was applied to calculate maps of the Sound Exposure Level (SEL) accumulated over 24 hours.

SEL maps weighted in accordance with an animal's hearing sensitivity give an impression of the total amount of sound to which an animal is exposed when that animal is located at a particular place in the area studied for a period of 24 hours (in other words, if the animal is not swimming). The impact of the dredging and discharge activities on the soundscape as experienced by fish, harbour porpoises *Phocoena phocoena* and harbour seals *Phoca vitulina* if they were to remain in a single location for a period of 24 hours can be read off by comparing the three left-hand panels (regular shipping) with the three right-hand panels (regular shipping + dredgers) in Figure 10 and Figure 11. Figure 10 shows the situation 1 m above the seafloor and Figure 11 the situation at a depth of 1 m below the surface.

ASSESSMENT OF EFFECTS ON MARINE FAUNA

Underwater sounds can affect marine organisms in different ways depending on the sound pressure level and the frequency (see, for example, Richardson *et al.,* 1995; Kastelein *et al.,* 2008). The literature generally distinguishes between zones of responsiveness, ranging from a zone in which the sound is heard but where the animal does not respond, to a zone in which severe physical harm or even death can occur. In between, there are zones in which behaviour is affected, with the animal swimming away from the sound or being attracted to it, and a zone where the animal's hearing may be affected temporarily or permanently (temporary hearing threshold shift = TTS, and permanent hearing threshold shift = PTS respectively).

In addition, there can be masking effects in some animals. This is the situation in which the frequency range, and level, of the non-natural sound is comparable to the sounds produced by the animals or their prey. This can be a particular problem for animals that track their prey using echolocation, the harbour porpoise being one example. Since ship sounds are relatively low-frequency sounds, there is no overlap with the very high frequency of the vocalisations used by harbour porpoises (in the 120 kHz range) and so this does not play a role.

Effect criteria at Maasvlakte 2

In the study conducted by TNO for the Port of Rotterdam Authority, the main criterion adopted for affecting animals was the sound exposure level (SEL), with the possibility of a temporary rise in the hearing threshold (TTS). The values derived by Southall *et al.* (2007) for continuous sound, with the SEL being weighted for the specific hearing sensitivity of the animals, have been adopted for harbour porpoises and seals. 'M-weighting' (Southall *et al.,* 2007) was used here. Alongside TTS, the values thought to result in a permanent increase in the hearing threshold (PTS) have been taken into account for harbour porpoises and seals. There are no thresholds for fish relating to harm after exposure to continuous sound generated by, for example, shipping. The criteria proposed by the US Fish Hydroacoustic Working Group (FHWG) relate to pulse sounds generated by pile driving (Oestman *et al.* 2009). There is a distinction here between small fish (< 2 grams fresh weight) and larger fish (> 2 grams fresh weight). It is not clear to what extent these values can be applied to continuous sound. The threshold values for continuous sounds are often slightly higher than for pulse sounds and so the application of these criteria to continuous sound would produce a "worst case" description of the possible effects. An overview of the thresholds used can be found in Table II.

Stationary marine mammals and fish

Based on a comparison of the 24-hour SEL maps (Figures 10 and 11) with the thresholds shown in Table II at which fish, harbour porpoises and harbour seals may suffer TTS, an area can been calculated where these risk thresholds are exceeded. Without the contribution of dredgers, this area is, at 1 m above the seafloor (worst case), 68 km^2 for small fish and 23 km^2 for large fish (30% and 10% respectively of the area of 225 km^2 studied). When the dredgers are present, these areas are 97 km^2 and 72 km^2 respectively (43% and 32%). The areas for seals and harbour porpoises at 1 m above the seafloor are, respectively, 10 km^2 and 0.0 km^2 (4% and 0%) assuming regular shipping traffic only, and 72 km^2 (seal) and 0.5 km^2 (harbour porpoise) (32% and 0.2%) when the contribution of dredgers is

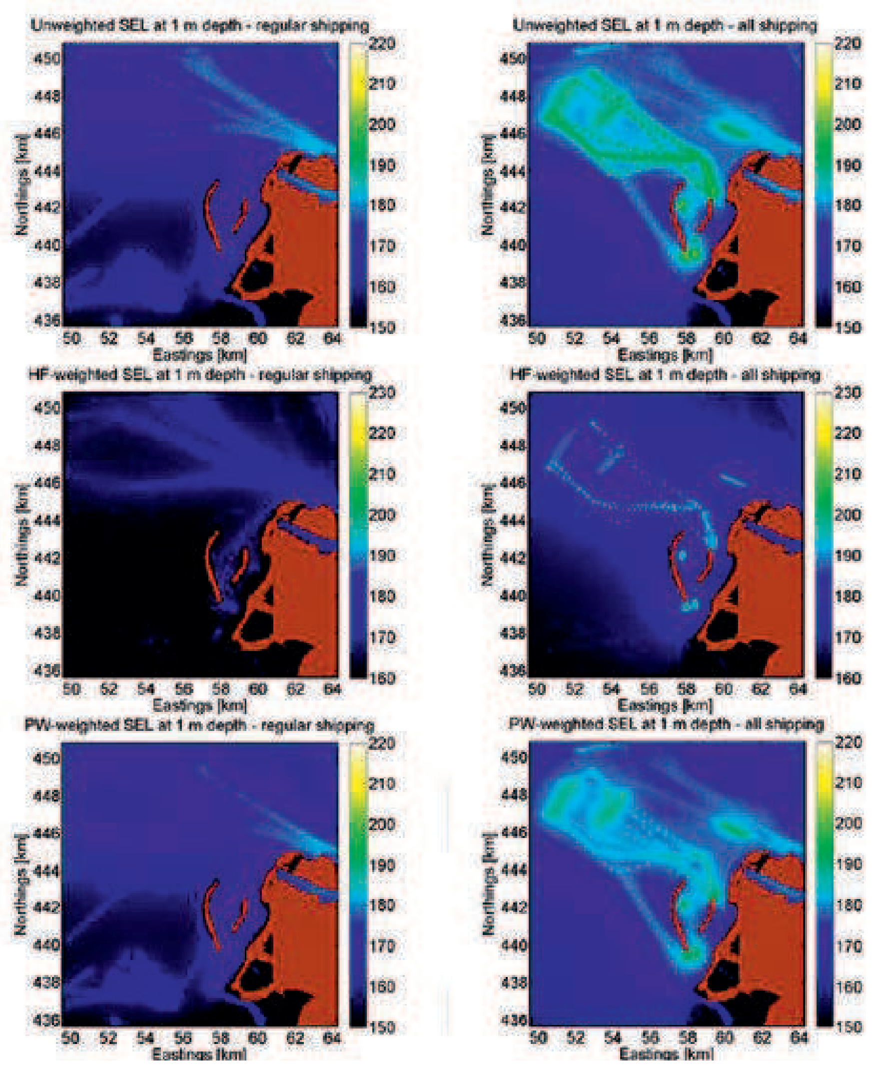


Figure 11. Sound maps generated by regular shipping (left) and regular shipping + dredgers (right) at a depth of 1 m below the surface. The figure shows the cumulative broadband sound exposure level (dB Re 1 μPa^{2}s) for a period of 24 hours: non-weighted (top, representative for fish), M-weighted for "high frequency cetaceans" (centre, representative for harbour porpoise) and M-weighted for "pinnipeds in water" (bottom, representative for seals).

Table II. SEL thresholds in dB re 1 μPa^{2}s for risk of PTS and TTS. Thresholds for harbour porpoise and harbour seal from Southall *et al.* (2007) and for fish from Oestman *et al.* (2009).

Species (or group)	PTS risk threshold	TTS risk threshold	Weighting
harbour porpoise	215	195	M_{hf}
harbour seal	203	183	M_{pw}
fish > 2 g	-	187	none
fish < 2 g	-	183	none

M_{hf} = M-weighting for "high frequency cetaceans" (including harbour porpoise)

M_{pw} = M-weighting for "pinnipeds in water" (seals).

Table III. Distance to dredgers at which the TTS threshold (see Table II) is exceeded for harbour porpoises, seals and fish at a depth of 16 m (worst case).

TTS threshold	Harbour porpoise 195 dB re 1 μPa^{2}s	Seal 183 dB re 1 μPa^{2}s	Fish > 2 g 187 dB re 1 μPa^{2}s	Fish < 2 g 183 dB re 1 μPa^{2}s
Distance to dredging vessel	n/a	90 m	100 m	400 m

In all cases, the animal is moving at a speed of 1 m/s with respect to the dredging vessel.

Total exposure duration of 24 hours.

taken into account. These areas are much smaller for animals located close to the surface.

Swimming fish and marine mammals

The *AQUARIUS* model was also used to calculate the levels of underwater sound to which individual fish, harbour porpoises and seals were exposed at various depths when swimming at a relative speed of 1 m/s in a straight line past a single TSHD engaged in dredging sand. The calculations adopted the following worst-case principles:

- A total exposure duration of 24 hours; in reality, the hearing of an animal will recover, at least in part, over the course of those 24 hours but it is not known at what level this will be the case;
- The highest source level found in the study was used – the level generated by the loudest dredging vessel sailing to and from the borrow area and the discharge area (dark blue line in Figure 8); it was assumed that this was also the maximum source level during sand dredging;
- Minimal propagation loss at higher frequencies (wind speed 0 m/s an sediment sound speed of 1960 m/s).

The results of the calculations are stated for depths of 1 m and 16 m in Figure 12 and Table III. For harbour porpoises, the TTS risk thresholds are not exceeded at any distance from the dredging vessel. TTS may occur in seals if they swim past the vessel at a depth of 16 m and a distance of 90 m or less. In the case of fish, the distances are 100 m or less for larger fish (> 2 g) and 400 m or less for small fish (< 2 g). The distances are shorter for animals swimming closer to the sea surface (Figure 5, top). They are 15 m for seals and 20 m for small fish. At this depth, the TTS risk thresholds are not exceeded for harbour porpoises and larger fish.

The 24-hour sound maps presented in Figures 10 and 11 provide an accurate and representative picture of the changes in the soundscape during the construction of Maasvlakte 2. However, on the basis of these maps, it is not possible to satisfactorily establish the cumulative dose of sound to which the animals are exposed when they are swimming through the area. The results of the calculations presented in Figure 12 and Table III do indeed give an impression of the distance from a TSHD at which animals may suffer TTS but it is not possible to determine on that basis the probability that this will indeed actually happen. Actual exposure depends not only on the position of the animal with respect to the source and the propagation conditions but also

Table IV. Calculated SEL values for south-north transits (swimming speed = 6 km/h).

Shipping	Weighting	Threshold from Table II SEL_{TTS}: dB re 1 μPa^{2}s	Average (single transit) SEL: dB re 1 μPa^{2}s	24 hour exposure (several transits) SEL + 9.8: dB re 1 μPa^{2}s
S	none	n/a	172.4	182.2
S + D	none	n/a	176.8	186.6
S	M_{hf} (harbour porpoise)	195	160.3	170.1
S + D	M_{hf} (harbour porpoise)	195	170.7	180.5
S	M_{pw} (seal)	183	166.2	176.0
S + D	M_{pw} (seal)	183	172.6	182.4

S = regular shipping; S + D = regular shipping + dredgers

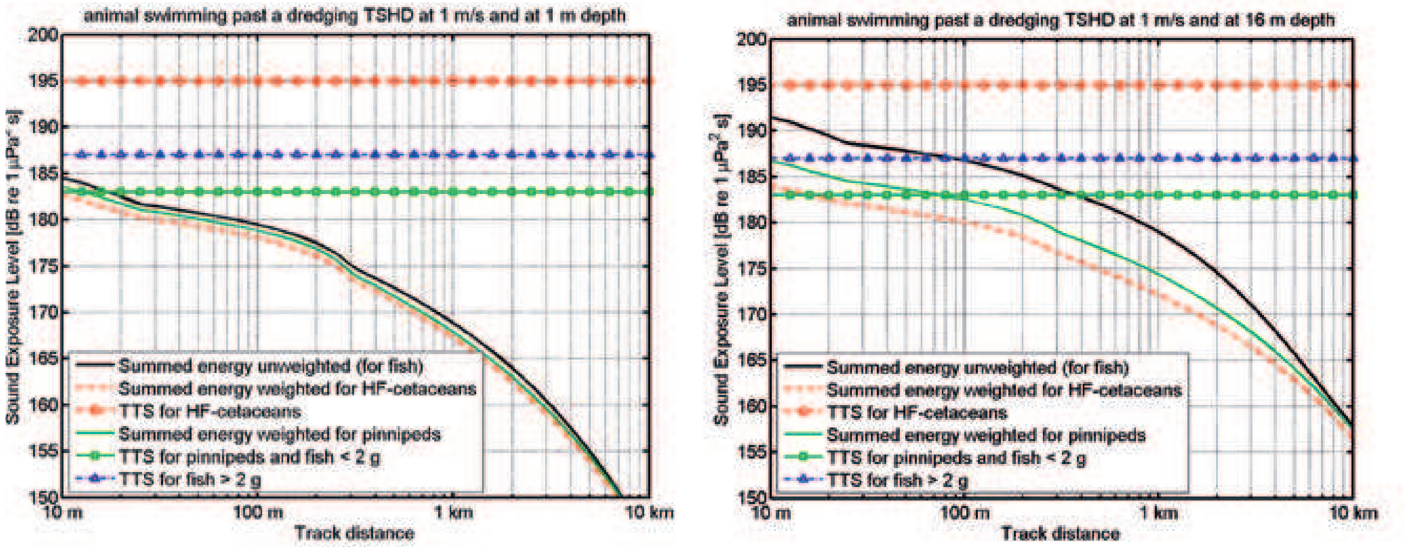


Figure 12. Relationship between distance to dredging vessel and sound exposure level (SEL) in dB re 1 μPa²s of a swimming animal with a relative speed with respect to the ship of 1 m/s at a depth of 1 m and 16 m.

on the animal's behaviour over time. Marine organisms are always on the move and so calculations were also made to determine the sound exposure level that harbour porpoises and seals receive when swimming along a straight north-south line through the area, i.e., the aforementioned dynamic sound maps.

These calculations were not made for fish. Fish generally swim more slowly than harbour porpoises and seals. When estimating the impact on fish, the worst-case approach can be adopted based on the results of the calculations for stationary animals (Figure 6 and Figure 7 and accompanying text). It is assumed here that animals start to swim at intervals of 15 minutes from 15 points situated at intervals of 500 m on a line on the southern edge of the area of 15 x 15 km between kilometre 50 and kilometre 57, proceeding northwards at a speed of 6 km/h. This means that a single transit through the area takes 2.5 hours. It was decided to adopt straight lines because all the animals then cover the same distance. The starting time for the first 15 animals was midnight on 28/29 September, after which a new group of 15 animals started out every 15 min until the end of the same day (midnight on 29/30 September 2009). The total sound exposure level was calculated for all 1440 (24×4×15) animal transits. The total sound exposure level for an animal making the south-north crossing of 15 km repeatedly without a break in a consecutive period of 24 hours is estimated to be 9.8 dB (=$10\log_{10}$(24 h / 2.5 h) higher than the exposure for single transits. Table IV contains an overview of the mean results of the exposure calculations. This shows that the TTS risk thresholds are not exceeded for swimming harbour porpoises and seals. In fact, fewer than 0.1% of the individual seals and even fewer of the harbour porpoises are exposed to a sound level that exceeds the TTS risk threshold.

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