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 (m³). 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.

<table>
<thead>
<tr>
<th>Weeks 39 and 40 in 2009</th>
<th>number of events:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transit: fully loaded</td>
<td>16</td>
</tr>
<tr>
<td>Transit: empty</td>
<td>16</td>
</tr>
<tr>
<td>Dredging port side</td>
<td>15</td>
</tr>
<tr>
<td>Dredging starboard side</td>
<td>10</td>
</tr>
<tr>
<td>Rainbowing</td>
<td>13</td>
</tr>
<tr>
<td>Pumping ashore</td>
<td>2</td>
</tr>
<tr>
<td>Bottom discharge</td>
<td>2</td>
</tr>
</tbody>
</table>
FLOOR HEINIS 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 Ultrasounds 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.

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.

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.


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.
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
calculated 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

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**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 μPa².
- 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 μPa² 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 μPa² m². (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*. 
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.
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.

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).

### Table I. Input data for calculations of sound maps

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sediment sound speed</td>
<td>1960 m/s*</td>
</tr>
<tr>
<td>Wind speed</td>
<td>0 m/s*</td>
</tr>
<tr>
<td>Source level</td>
<td>selected on the basis of the best match with activity and speed (data from Automatic Identification System)</td>
</tr>
<tr>
<td>Depth</td>
<td>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</td>
</tr>
</tbody>
</table>
| 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).
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 be calculated where these risk thresholds are exceeded. Without the contribution of dredgers, this area is, at 1 m above the seafloor (worst case), 68 km² for small fish and 23 km² for large fish (30% and 10% respectively of the area of 225 km² studied). When the dredgers are present, these areas are 97 km² and 72 km² respectively (43% and 32%). The areas for seals and harbour porpoises at 1 m above the seafloor are, respectively, 10 km² and 0.0 km² (4% and 0%) assuming regular shipping traffic only, and 72 km² (seal) and 0.5 km² (harbour porpoise) (32% and 0.2%) when the contribution of dredgers is
Table II. SEL thresholds in dB re 1 μPa²s 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).

<table>
<thead>
<tr>
<th>Species (or group)</th>
<th>PTS risk threshold</th>
<th>TTS risk threshold</th>
<th>Weighting</th>
</tr>
</thead>
<tbody>
<tr>
<td>harbour porpoise</td>
<td>215</td>
<td>195</td>
<td>Mhf</td>
</tr>
<tr>
<td>harbour seal</td>
<td>203</td>
<td>183</td>
<td>Mpw</td>
</tr>
<tr>
<td>fish &gt; 2 g</td>
<td>-</td>
<td>187</td>
<td>none</td>
</tr>
<tr>
<td>fish &lt; 2 g</td>
<td>-</td>
<td>183</td>
<td>none</td>
</tr>
</tbody>
</table>

\[ M_{hf} = M\text{-weighting for “high frequency cetaceans” (including harbour porpoise)} \]
\[ M_{pw} = M\text{-weighting for “pinnipeds in water” (seals).} \]

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).

<table>
<thead>
<tr>
<th>TTS threshold</th>
<th>Harbour porpoise</th>
<th>Seal 183 dB re 1 μPa²s</th>
<th>Fish &gt; 2 g 187 dB re 1 μPa²s</th>
<th>Fish &lt; 2 g 183 dB re 1 μPa²s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance to dredging vessel</td>
<td>n/a</td>
<td>90 m</td>
<td>100 m</td>
<td>400 m</td>
</tr>
</tbody>
</table>

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.

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 and 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 smaller 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).

<table>
<thead>
<tr>
<th>Shipping</th>
<th>Weighting</th>
<th>Threshold from Table II SEL TTS: dB re 1 μPa²s</th>
<th>Average (single transit) SEL: dB re 1 μPa²s</th>
<th>24 hour exposure (several transits) SEL + 9.8: dB re 1 μPa²s</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>none</td>
<td>n/a</td>
<td>172.4</td>
<td>182.2</td>
</tr>
<tr>
<td>S + D</td>
<td>none</td>
<td>n/a</td>
<td>176.8</td>
<td>186.6</td>
</tr>
<tr>
<td>S</td>
<td>Mhf (harbour porpoise)</td>
<td>195</td>
<td>160.3</td>
<td>170.1</td>
</tr>
<tr>
<td>S + D</td>
<td>Mhf (harbour porpoise)</td>
<td>195</td>
<td>170.7</td>
<td>180.5</td>
</tr>
<tr>
<td>S</td>
<td>Mpw (seal)</td>
<td>183</td>
<td>166.2</td>
<td>176.0</td>
</tr>
<tr>
<td>S + D</td>
<td>Mpw (seal)</td>
<td>183</td>
<td>172.6</td>
<td>182.4</td>
</tr>
</tbody>
</table>

S = regular shipping; S + D = regular shipping + dredgers
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 (24x4x15) 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 (=10log10 (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.

REFERENCES


Figure 12: relationship between distance to dredging vessel and sound exposure level (SEL) in dB re 1 μPa 2s 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.
CONCLUSIONS

Measurements 2008 and 2009
In 2008, the measured background sound was dominated by underwater sound from shipping in virtually the entire frequency range. Only in situations with little nearby shipping and at frequencies of more than 10 kHz, the wind was the main determining factor. Sound pressure levels for the background sound measured in 2009 were, in general, slightly higher than during the measurements in 2008 and were closely correlated with the distance from passing dredgers to the SESAME underwater sound monitoring station.

A new method has been developed for the analysis of the measured radiated sound associated with the various activities of the individual dredgers. TSHDs produced most sound when they were travelling to and from the borrow and discharge areas at relatively high speed. The next noisiest activity was sand dredging.

During pumping ashore and rainbowing, the source levels in the frequency range between 500 Hz and 10 kHz were comparable with the level of vessels dredging sand, but significantly lower at higher and lower frequencies. The lowest sound levels were produced during the bottom discharge of sand. It can be assumed that the underwater sound generated by the TSHDs in this area was mainly caused by cavitation from the propellers and bow thrusters.

Dredging sound and fish and marine mammals
The EIA (Vertegaal et al., 2007; Vellinga, 2007) concluded – on the basis of now outdated assumptions – that the behaviour of fish and marine mammals can be influenced up to a distance of a few hundred metres from a dredging vessel. TNO adopted different principles, criteria and calculation methods for the final underwater sound monitoring study. For the assessment of effects on animals, the criteria recommended by Southall et al. (2007) were adopted.

Because of the lack of relevant data to develop thresholds for effects of underwater sound on animal behaviour, it was decided to focus on the risk that animals experience a temporary hearing threshold shift (TTS). This risk is associated with the total underwater sound dose that animals are exposed to during 24 hours. TTS onset may occur when the cumulative weighted sound exposure level received by an animal exceeds a specified threshold level. It is likely that this is a safe choice, because there are indications that, at sound levels below the TTS threshold, there are no changes in behaviour in some marine mammal species, including the seal (Southall et al. 2007).

To establish a picture of the possible maximum effect distances, calculations were made to determine where, in the area of 15 x 15 km under study, thresholds for TTS onset would be exceeded by sound from ships in the area if an animal were to remain stationary there for a period of 24 hours. The worst case calculations for animals spending 24 hours at 1 m above the seabed – which is not realistic for marine mammals because they have to breathe – produced the following results:

• For fish, the size of the area affected increases from 23 km² to 72 km² as a result of dredging activities; the areas affected for smaller fish are 68 km² and 97 km² for regular shipping only and shipping including dredging, respectively.

• The area in which seals can suffer TTS is 10 km² in the scenario with regular shipping traffic only and 72 km² if there is also dredging activity.

• For harbour porpoises, these areas are 0.0 and 0.5 km² respectively.

The areas are much smaller for animals closer to the surface. The threshold value for a permanent hearing threshold shift (PTS) was not exceeded in any of the cases studied or in any of the species in question.

In order to obtain an impression of more realistic effect contours, calculations were made to determine the extent to which fish, seals and harbour porpoises swimming (once) past a vessel dredging sand at a relatively low relative speed of 1 m/s (3.6 km/h) may suffer TTS (or PTS). Seals swimming past a stationary vessel dredging sand will only suffer TTS if they are swimming 1 m above the seafloor at a distance of 90 m or less from a dredging TSHD; if they are swimming at 1 m below the surface, this distance will be approximately 11 m. Harbour porpoises will not suffer TTS in any of the scenarios studied.

The effect distances for fish are larger at 1 m above the seafloor: 100 m for fish weighing more than 2 g and 400 m for smaller fish.

In the case of fish swimming closer to the surface – at a depth of 1 m – the criterion is not exceeded for fish weighing more than 2 g and the distance will be 20 m for smaller fish. The threshold value for a permanent threshold shift (PTS) was not exceeded in any of the cases studied or in any of the species in question.

From this it can be concluded that the effect contours around a dredger calculated in this study are lower for harbour porpoises and seals than the “few hundred metres” mentioned in the EIA and that they are of the same order of magnitude for fish.

In reality, marine mammals never stay at the same location for a long time in natural conditions; they are constantly swimming in order to feed and to move from one place to another.

Calculations were therefore made for the situation in which seals and harbour porpoises swam for a period of 24 hours at a realistic speed of 6 km/h along north-south lines in the area measuring 15 x 15 km (9.6 transits in 24 hours).

To establish a worst-case scenario (the sound level is lower near the surface of the water) calculations were only conducted for animals swimming 1 m above the seafloor for a period of 24 hours. In this rather unrealistic scenario (marine mammals are unable to breathe underwater), less than 0.1 % of the harbour porpoises and seals are exposed to the risk of experiencing a temporary hearing threshold shift (TTS), even in the presence of dredging activities representative for the construction of Maasvlakte 2.