



# A Result of Accidental Noise Pollution: Acoustic Flowmeters Emit 28 kHz Pulses That May Affect Harbor Porpoise Hearing

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Large rivers like the Elbe or the Weser are periodically entered by harbor porpoises of the North Sea. They may even move 97 km upstream to the port of Hamburg, where their presence is highest in spring. This migration is believed to be related to important anadromous prey species travelling upstream for spawning. An acoustic flowmeter in the port of Hamburg emits signals in the hearing range of harbor porpoises. The pulses have a duration of 0.2 ms, a peak frequency of 28 kHz, a source level of 210 dB re 1  $\mu$ Pa and an inter-pulse interval of 4.2 s. The signals are continuously emitted from both sides of the river at a location where the river is 400 m wide. We evaluated the potential of these signals to induce temporary threshold shift (TTS) in harbor porpoise hearing. Hearing tests with a harbor porpoise in human care were conducted to determine TTS onset. We modelled the acoustic field based on underwater noise measurements. The acoustic flowmeters emit pulses in a highly directional beam with a source level high enough for inducing TTS in harbor porpoises by a single exposure up to a distance of approximately 72 m. The received cumulative sound exposure levels for harbor porpoises travelling along the flowmeters are mainly dependent on the timing and distance to the sound source. Accordingly, a close approach to the flowmeter at the time of transmission should be prevented. This could be the case, if vessels force harbor porpoises to displace closer to the flowmeters. We therefore suggest to decrease acoustic flowmeter source levels. This case study emphasizes the need for a mandatory authorization process prior to the use of underwater sound for any purpose with potential effects on aquatic life. Such an authorization process should carefully consider potential effects for target and non-target species.

**Keywords:** harbor porpoise *Phocoena phocoena*, noise pollution, temporary threshold shift (TTS), noise mitigation, hearing

## INTRODUCTION

Anthropogenic noise is omnipresent in almost all terrestrial and aquatic ecosystems and has been recognized as one of the most hazardous forms of pollution (Andrew et al., 2002; World Health Organization, 2017). Its environmental effects are considered as a key threat to biodiversity at an unpredictable scale (Kunc et al., 2016). The heavy reliance on acoustic perception across marine

mammal, bird and fish species results from adaptations to living in an environment where light propagation is poor but sound propagation is excellent. Numerous anthropogenic activities generate underwater noise, including industry, e.g. during the construction and operation of offshore wind farms (Dähne et al., 2013; Brandt et al., 2018; Graham et al., 2019), shipping (e.g. reviewed in Erbe et al., 2019) or the clearance of unexploded ordnance (von Benda-Beckmann et al., 2015; Siebert et al., 2022). Intense sound is also emitted during seismic explorations of the seafloor (e.g. Sarnoci&acute;ska et al., 2020), by military sonars (Filadelfo et al., 2009; Curé et al., 2016; Isojunno et al., 2016) or for the deterrence of animals (Brandt et al., 2013a; Brandt et al., 2013b; Götz and Janik, 2013).

Biological consequences of noise exposure are reflected on multiple scales, reaching from displacement (Brandt et al., 2018), physiological stress (Rolland et al., 2012), disturbances in communication (Erbe et al., 2016; Kragh et al., 2019) or foraging (Wisniewska et al., 2018) up to hearing impairment (Reichmuth et al., 2019; Schaffeld et al., 2019). Anthropogenic noise is widely recognized as a pervasive and significant threat to wildlife (Francis and Barber, 2013), which can be particularly detrimental for vulnerable animals with high metabolic rates (Hoekendijk et al., 2018; Rojano-Doñate et al., 2018), like the harbor porpoise (*Phocoena phocoena*). Short disturbances that affect foraging time (Wisniewska et al., 2018) may accumulate over repeated noise events and affect the long-term fitness of harbor porpoises, which forage nearly continuously to meet energy demands (Wisniewska et al., 2016).

For harbor porpoises, the key to successful hunting is a well-functioning hearing system, since they sense their environment acoustically by echolocation. Harbor porpoises are considered to be very sensitive to effects of noise and are therefore regarded as an indicator species in noise impact evaluations (Tougaard et al., 2015; Southall et al., 2019). Being critically dependent on sound perception for orientation, communication and foraging (Villadsgaard et al., 2007; Wisniewska et al., 2016; Sørensen et al., 2018) makes harbor porpoises vulnerable to noise disturbance.

In European waters, harbor porpoises are protected amongst others within the framework of the Habitats Directive (listed in annexes II and IV European Union, 1992) and Council Regulation 812/2004 (European Union, 2004) (Council Directive 92/43/EEC). Damage to hearing is to be regarded as injury within the meaning of Section §44 (1) of the Federal Nature Conservation Act. Its prevention therefore demonstrates the most important tool for the regulation of underwater noise in German waters. While a permanent threshold shift (PTS) is generally considered as an injury, Germany has the strictest definitions and considers even temporary threshold shifts (TTS) as injury [e.g. ASCOBANS Advisory Committee (2014)]. A TTS represents the limit where noise affects hearing and can be measured without damaging the individual being tested. TTS assessments are therefore a perfect tool for estimating effects on hearing. Affected hearing can potentially affect the survival of an individual (Mann et al., 2010; Morell et al., 2017; Morell et al.,

2021a; Morell et al., 2021b), decreasing fitness and possibly leading to long-term population consequences (King et al., 2015). Temporarily affected hearing thresholds have been found in harbor porpoises after the exposure to single noise exposures with high received levels (Lucke et al., 2009), but also after an exposure to multiple events with lower received levels (Kastelein et al., 2016).

Historic reports prove that harbor porpoises not only inhabited coastal waters (Gilles et al., 2016; Hammond et al., 2017), but also lower stretches of large rivers e.g. as shown by sightings or strandings in the Weser River south of Bremen (Häpke, 1880) or even up to Magdeburg, which is upstream the Elbe River at a distance of 400 km from the coast (Kölmel, 1998). The number of harbor porpoises in the southern North Sea strongly declined between 1950 and 1970 (Addink and Smeenk, 1999). Since the late 1990s harbor porpoise sightings increased again in estuaries and rivers running into the North Sea (Camphuysen, 2004; Wenger and Koschinski, 2012; Taupp, 2021). These ecosystems are highly threatened and modified by anthropogenic activities and disturbances (Kennish, 2002; Mahoney and Bishop, 2017). Moving upstream rivers despite the continuous presence of vessels and limited space to evade is believed to be prey driven (Wenger and Koschinski, 2012; Leopold, 2015). Spatial and temporal occurrence of harbor porpoises in this area correlates with the annual migration of anadromous fish species like smelt (*Osmerus eperlanus*) and twaite shad (*Allosa fallax*), which are known to spawn in this area (Wenger and Koschinski, 2012; Leopold, 2015; Thiel, 2015).

Although great effort is made in Germany to mitigate noise related to the construction of Offshore Windfarms ASCOBANS Advisory Committee (2014), some noise sources exist that have been overlooked. This study aims to estimate the potential to induce TTS by an acoustic flowmeter, which is regularly applied in rivers to measure the water flow velocity. This was achieved by making underwater noise measurements along the flowmeter and performing hearing tests with a harbor porpoise in human care, which was exposed to comparable acoustic signals. This study sheds light on gaps in noise regulation and raises attention for the naive application of acoustic devices.

## METHODS

### Study Area and Underwater Noise Measurements

An acoustic flowmeter exists 97 kilometers upstream the Elbe (Portal Tideelbe, accessed: 2022-05-12) in an area with regular harbor porpoise sightings (Wenger et al., 2016). The flowmeter (Quantum Hydromet, Germany) emits signals at 28 kHz (Frequency tolerance  $\pm 1.4$  kHz) with a peak source level of 218 dB re 1  $\mu$ Pa and a -6 dB beamwidth of 26°, according to the spec sheet. It is located in the Elbe River close to the port of Hamburg (Figure 1) and adjacent to the Natura 2000 conservation area “Neßsand”. The water depth at this site is an almost constant 18 m with a very steep slope in the area close to the riverbanks. The ultrasonic aqua flowmeter system consists of two pairs of hydroacoustic transducers and receivers, which

are located at the north and south riverbank, transmitting acoustic signals from both sides of the Elbe River to obtain the flow speed from the measured difference in travel time between upstream and downstream direction.

We recorded underwater sound at three depth levels (2, 5, 8 m below water surface) by a linear vertical hydrophone array, which was fixed with snap hooks to a steel guidance cable on board of a vessel. At each water depth, underwater noise was recorded by two hydrophones with different sensitivities, to cover a wide dynamic range a) TC4014, sensitivity = -180.3 and -185.5 dB re 1V  $\mu\text{Pa}^{-1}$ , Reson Teledyne, DK, b) TC4013, sensitivity = -210.7 to -212.8 dB re 1V  $\mu\text{Pa}^{-1}$ , Reson Teledyne, DK, and c) d/140/h, sensitivity = -169.0 dB re 1V  $\mu\text{Pa}^{-1}$ , Neptune Sonar Ltd., UK). Underwater noise was recorded using the Avisoft Sound Recording Software (Avisoft Bioacoustics, Germany). Signals were pre-amplified by 0-20 dB with an eight-channel power amplifier (B2008APC – SN1212000, ETEC, DK) with a passband from 1 to 300 kHz. Recordings were digitized with a data acquisition card (NI USB 6366, National Instruments, USA) sampling at 750 ksamples  $\text{s}^{-1}$  and saved as wav files with a 16-bit resolution.

Acoustic signals from the flowmeter on both sides of the Elbe River were recorded on transects along the river. Therefore the vessel was steered upstream of the flowmeter, where the engine was stopped. The vessel drifted on transects at different distances to the flowmeters downstream, while the hydrophone array was in the water. Additionally, underwater noise was recorded during one transect from one flowmeter to the other by diagonally crossing the Elbe River. During this transect the engine was running. A mobile GPS device (Garmin 72H, CH) on top of the hydrophone array recorded simultaneously GPS positions at a sample rate of 1 Hz.

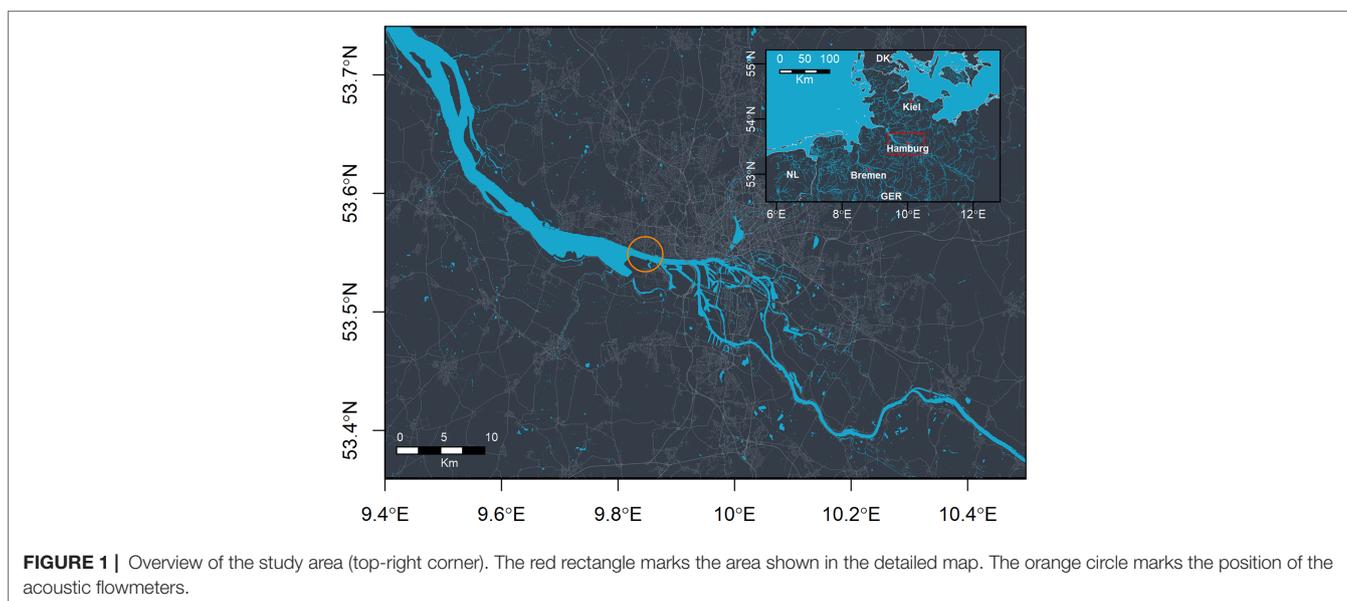
The underwater noise recordings, which were gathered on the different transects were analyzed with custom written manuscripts in MATLAB (MathWorks, USA). The sound

pressure level (SPL, RMS) and sound exposure level (SEL) were calculated for each detected signal and correlated to the corresponding GPS position on the track.

## Sound Propagation Model

The sound propagation was modelled based on the determined sound exposure levels for single acoustic signals and the corresponding recording locations. The aim of the sound propagation model was to generate a high-resolution spatial array with modelled SELs of single signals for the entire area of investigation. The sound transmission in the area is dependent on the propagation loss but also on the directivity of the sound source. Therefore, the propagation loss was estimated based on the recordings from the direct transect between the two flowmeters only, as this was assumed to be in the center of the beam. The source level was estimated from these results by the use of a logarithmic regression. Additional signals were used to determine the directional characteristic of the transmission beam.

Sound propagation was modelled for a three-dimensional area reaching 1000 m (x-axis) down- and upstream of the acoustic flowmeter, a width of 391 m between the two flowmeters (y-axis) and a depth of 18 m (z-axis). The received level was calculated with a resolution of  $1 \times 1 \times 0.1$  m (x × y × z). This calculation was based on a simplified ray tracing model and the passive sonar equation (Urick, 1983). The model assumes a spherical propagation loss of  $20 \times \log_{10}(\text{distance})$  and considers a three-way-propagation, taking the direct path and the first reflection from the surface and the bottom into account. The reflection coefficient is dependent on sediment type and angle of the ray. Based on a sample, the sediment was determined as muddy sand, which has a density of  $1,782 \text{ kg m}^{-3}$  and a sound velocity of  $1,599 \text{ m s}^{-1}$  (Urban, 2002). The loss by reflection was calculated for each indirect path considering the angle, the given speed of sound and density. The estimated source



level, propagation loss over distance and the directivity index were taken into account. The estimated SEL for each cube within the array corresponds to the sum of the direct path and the first reflection from the surface and the bottom. Absorption was not considered, as this was assumed negligible at 28 kHz in freshwater and over short distances.

## Effects on Hearing Thresholds

The effect of a comparable stimulus like the acoustic flow meter on harbor porpoise hearing was assessed by hearing tests with an animal in human care. The experiments were conducted in 2014 at the Fjord & Bælt Centre in Kerteminde (DK). The study animal was a healthy adult female harbor porpoise born in 1995. The animal and the experimental setup were the same as in Schaffeld et al. (2019). All trials were conducted adhering to the respective ethical principles as well as to the relevant international and national guidelines for animal experiments and under constant supervision of experienced biologists and animal trainers. Experienced animal trainers monitored animal condition and signs of stress of the animal throughout all experiments. In case of an observed stress response the experiments would have been stopped immediately. The harbor porpoise has been trained 2 times a day through standard operant conditioning and positive reinforcement techniques by a team of professional animal trainers.

Hearing thresholds were determined by measuring auditory evoked potentials (AEPs) of the brainstem, a commonly used non-invasive electrophysiological technique (Nachtigall et al., 2016; Ruser et al., 2016; Schaffeld et al., 2019). AEPs were recorded by silver plated electrodes, gently attached to the body surface by suction cups, while the animals hearing was stimulated. A rugged notebook (Panasonic Toughbook CF30) computer was used to digitally generate stimuli, which were converted to analogue by a USB multifunction data acquisition card (NI USB 6251, National Instruments, Austin, TX). The stimuli were updated at a 1MHz rate with a 16 bit resolution and bandpass filtered (100 Hz–250 kHz, 24 dB/octave, Krohn Hite, Brockton, MA) before emission by the transducer. The generated stimuli were emitted by a TC4033 transducer (Teledyne Reson, Denmark), placed at depth of 0.8m and a distance of 1m in front of the animal. Generated stimuli consisted of 1024 tone pips for each tested sound intensity. Each pip consisted of five cycles of the stimulus waveform with a cosine envelope, leading to a plateau of one cycle. The epoch length was 17 ms (Figure 2). Received sound pressure levels of test stimuli were calibrated by averaging 1024 stimuli prior to each trial with a TC4013 hydrophone (Teledyne Reson, DK).

Baseline hearing threshold at 28 kHz was determined and tested for temporary threshold shifts (TTS) after the exposure to a fatiguing stimulus. A tone at 28 kHz with a duration of 3.5 s was used for the exposure trials, which was emitted by a HS17 transducer (Neptune Sonar Limited, UK). The harbor porpoise was exposed once a day. Sound exposure levels were changed every day. All playbacks of hearing test stimuli and

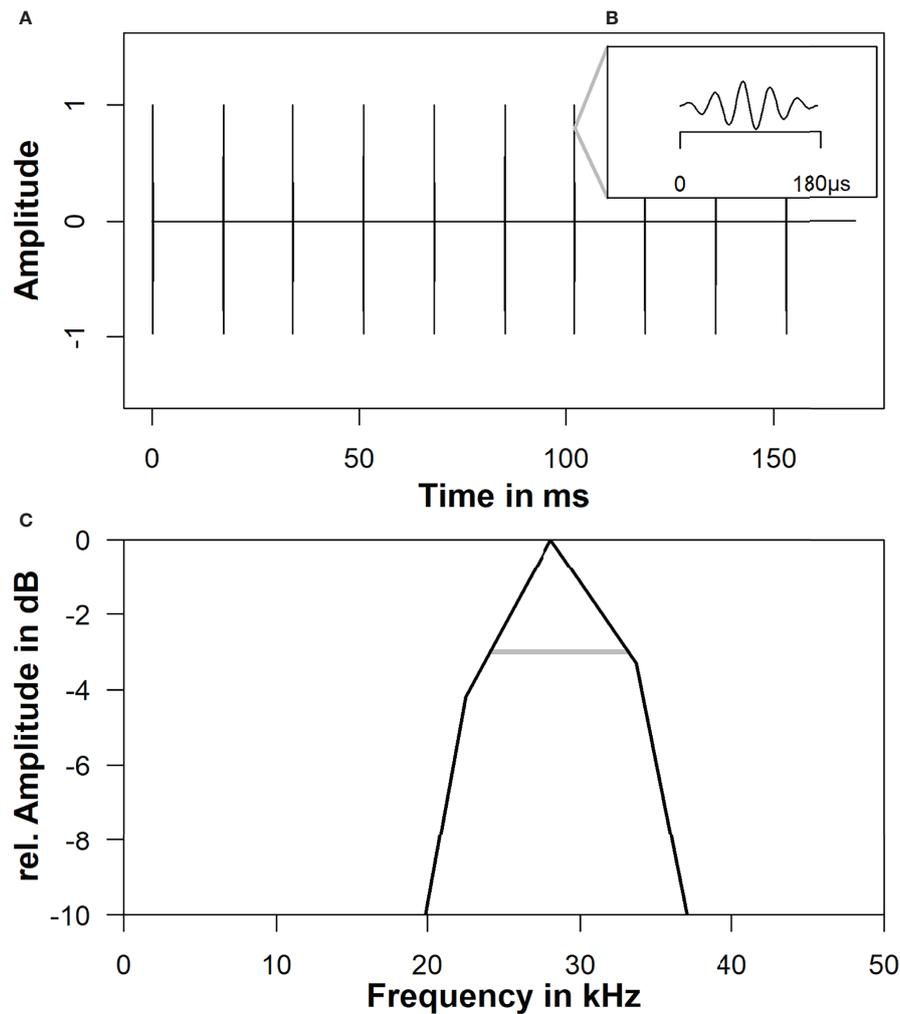
recordings of auditory evoked potentials were conducted with custom written software (Evoked Response Study Tool, EVREST, (Finneran et al., 2008; Finneran, 2009).

The sound exposure level (SEL; dB re 1  $\mu\text{Pa}^2\text{s}$ ) associated with the onset of TTS ( $\text{TTS}_{\text{onset}}$ ) was defined as a significant shift from baseline hearing. This  $\text{TTS}_{\text{onset}}$  was estimated by a linear regression of sound exposure levels and the determined hearing threshold shifts (in dB) relative to the baseline.

## Simulation of Received Levels of Travelling Harbor Porpoises Along Flow Meter

We simulated swimming tracks through the area to evaluate potential effects of the flow meter on the hearing. We defined transects in the direction of the river with a constant y-axis position, passing the flowmeters. We simulated such transects for each of the 391 possible y-axis positions over the complete width of the river. For each of these 391 simulated tracks along the x-axis, we calculated harbor porpoise positions at the time of the reception of the acoustic flowmeter signals. We calculated the positions of the harbor porpoise on each track from 1,000 m before up to the distance of 1,000 m behind the flowmeters. The first reception was assumed at the starting position at a distance of 1,000 m to the flowmeter. Each following reception was obtained from the *inter-pulse interval*  $\times$  *swim speed*. We applied swim speeds between 0.25 and 8  $\text{m s}^{-1}$ . This broad range was chosen to represent harbor porpoises at all life stages and to include slowly swimming individuals, like mother and calf pairs. Data on the swim speed of harbor porpoises are rare due to their inconspicuous lifestyle and poor accessibility. Maximum swim speed for animals in human care were determined at 2  $\text{m s}^{-1}$  (Kastelein et al., 2018), 4.3  $\text{m s}^{-1}$  (Otani et al., 2001), and in the wild at 4.3 and 6.1  $\text{m s}^{-1}$  (Gaskin et al., 1974; Otani et al., 2000). A mean swim speed of a free-ranging harbor porpoise was determined at 0.9  $\text{m s}^{-1}$  (Otani et al., 2000). Since the authors are not aware of any publication of swimming speed of harbor porpoises in river systems, the effect of flow velocity on swim speed was estimated as the sum of the maximum swim speed and assumed maximum flow velocity. A maximum swim speed of 7.7  $\text{m s}^{-1}$  was estimated, considering an estimated maximum flow velocity of 1.6  $\text{m s}^{-1}$  (pers. comm. Nino Ohle in 2017, HPA).

Large variations in received levels occur at close distances to the flowmeters as signals are emitted in a very narrow beam. This may result in uncertainties when estimating the cumulative received levels, since these are dependent on the timing when the harbor porpoise enters the main beam with regards to the inter-pulse interval. We addressed this time-related variability by shifting the start positions along the travelled distance for a given swim speed between two pulses. Therefore, we tested multiple starting positions corresponding to the distance a harbor porpoise can travel for the tested swim speed between two consecutive pulses. The received level for each position on the track was obtained from the modelled acoustic array. Since we do not know at which water depth a harbor porpoise would most likely migrate through the area around the acoustic flowmeters, we assumed a continuous diving depth of 5 m for practical reasons. However, the sound field does not show substantial



**FIGURE 2 |** Tone pips, used as hearing stimuli. **(A)** Section with ten tone pips out of a complete train consisting of 1024 repetitions. **(B)** Detail view of one pip (five cycles of 28 kHz carrier) within the pip train. **(C)** Frequency spectra of the 28 kHz tone pips with  $\pm 3$  dB bandwidth levels (gray horizontal lines).

differences in received sound exposure levels over depth. The estimated received levels from both acoustic flowmeters were accumulated for each simulated track and presented as the mean for all tested starting positions. We only considered received signals with single pulse SEL exceeding an effective quiet threshold. Single events below a certain single signal sound exposure level ( $SEL_{SS}$ ) have never been shown to induce a TTS or affect recovery and are therefore regarded as “effective quiet” (Ward et al., 1976; Finneran, 2015). In absence of an effective quiet threshold we regard the lowest  $SEL_{SS}$  capable of inducing a TTS by multiple exposure. This was determined at 145 dB re  $1 \mu Pa^2 s$  for pile-driving noise (Kastelein et al., 2016). The 145 dB re  $1 \mu Pa^2 s$  derives from exposures to pile-driving noise with a peak frequency between 500 and 800 Hz. Harbor porpoise hearing at 28 kHz is better than at 500 to 800 Hz. Differences between hearing thresholds account for approximately 40 dB (Kastelein et al., 2002; Ruser et al., 2016). In the absence of an empirically derived effective quiet

threshold, we defined instead a threshold which is “still higher than effective quiet threshold” (SHEQ) as a proxy. Accordingly, we adjusted the SHEQ to 105 dB re  $1 \mu Pa^2 s$  and considered received levels on the track only if this value was exceeded.

## Evaluation of Potential to Induce a TTS

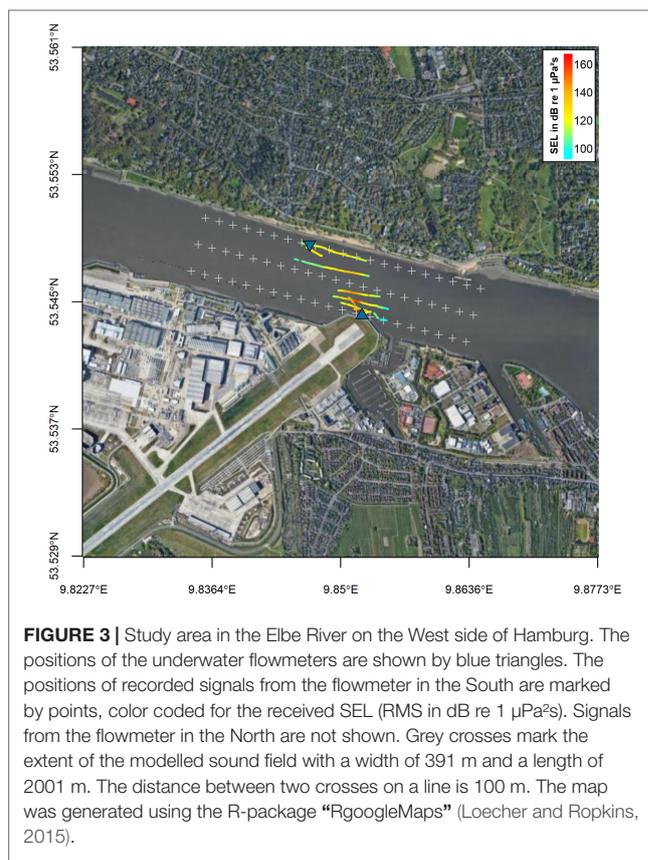
The potential to induce a TTS in harbor porpoises from exposure to signals of the flowmeter was evaluated by using the modelled acoustic field and simulated harbor porpoise travel. A TTS can be induced in three different scenarios. Single pulses (1) can induce a TTS. For this scenario, we used the  $SEL-TTS_{onset}$  which derives from the hearing tests with a harbor porpoise in human care exposed to a 28 kHz tone. A TTS can be induced also by multiple exposures (2). The single  $SEL-TTS_{onset}$  cannot be directly transferred to a multiple exposure, as the same SEL of exposure does not automatically induce the same shift, if the SEL is received over a longer duration. The assumption that an

equal cumulative SEL induces an equal hearing shift is only valid for continuous fatiguing noises or for exposures with similar duty cycles (e.g. Mooney et al., 2009; Finneran et al., 2010a; Finneran et al., 2010b; Kastelein et al., 2014b; Popov et al., 2014; Kastelein et al., 2015a). We followed instead the suggested noise exposure criteria of Southall et al. (2019, Table 6), who suggested a frequency weighted cumulative SEL-TTS<sub>onset</sub> of 153 dB re 1  $\mu\text{Pa}^2\text{s}$ . Since this SEL-TTS<sub>onset</sub> is frequency weighted, based on the audiogram of harbor porpoises (National Oceanic and Atmospheric Administration; National Marine Fisheries Service, 2016; Southall et al., 2019), this onset cannot be transferred directly to the single pulse exposure levels of the modelled sound field. According to the proposed frequency weighting, the amplitude of a 28 kHz signal is effectively decreased by 0.3 dB. This means, that the SEL-TTS<sub>onset</sub> for multiple pulses accounts for 153.3 dB re 1  $\mu\text{Pa}^2\text{s}$ . Flight transects were simulated in order to estimate the TTS potential for a multiple exposure. We tested, if the cumulative received SEL for the entire track along the x-axis and at a constant y-axis position exceeds the cumulative SEL-TTS<sub>onset</sub> suggested by Southall et al. (2019). This approach does not regard potential avoidance reactions of the animals, where animals identify the position of the flowmeter and stay out of the area with highest noise levels. Potential reactions of harbor porpoises are assumed to be highly variable. Therefore we chose a further approach to assess the TTS potential as a function of the location within the sound field. We evaluated the potential to induce a TTS for harbor porpoises, which do not show a flight response but rather stay in the area (3). Based on the sound field of the flowmeter and the determined inter-pulse interval, we calculated the time for each position, needed to exceed the cumulative SEL-TTS<sub>onset</sub> of 153 dB re 1  $\mu\text{Pa}^2\text{s}$  (frequency weighted).

## RESULTS

### Underwater Noise Recordings

We analyzed 839 recorded signals from the flowmeter in the North at distances between 3 and 763 m. Sound pressure levels (RMS) were determined between 98 and 164 dB re 1  $\mu\text{Pa}$ . Sound exposure levels ranged from 61 to 132 dB re 1  $\mu\text{Pa}^2\text{s}$ . 750 signals were analyzed from the flowmeter in the south at distances between 19 and 663 m. Sound pressure levels ranged from 94 to 164 dB re 1  $\mu\text{Pa}$ . The SEL were determined between 86 and 134 dB re 1  $\mu\text{Pa}^2\text{s}$  (Figure 3). The source levels of the flow meters were determined from the received levels in the main beam at distances up to 150 m. The best fit for the logarithmic regression was determined at  $20 \times \log_{10}(\text{distance})$ . The source level for both flowmeters was estimated at 210 dB re 1  $\mu\text{Pa}$  at 1 m with a peak frequency of 28 kHz (Figure 4A). The signal duration (T90, time interval with 90 % of energy) was determined as 0.2 ms. The signal consisted of five cycles with a rise and fall in amplitude (Figure 4B). Signals from both flowmeters were recorded with an inter-pulse interval of 4.2 s (Figure 4C). The emission of signals alternated between the north and south flowmeter, leading to an effective inter-pulse interval of 2 s. Sound exposure



**FIGURE 3** | Study area in the Elbe River on the West side of Hamburg. The positions of the underwater flowmeters are shown by blue triangles. The positions of recorded signals from the flowmeter in the South are marked by points, color coded for the received SEL (RMS in dB re 1  $\mu\text{Pa}^2\text{s}$ ). Signals from the flowmeter in the North are not shown. Grey crosses mark the extent of the modelled sound field with a width of 391 m and a length of 2001 m. The distance between two crosses on a line is 100 m. The map was generated using the R-package “RgoogleMaps” (Loecher and Ropkins, 2015).

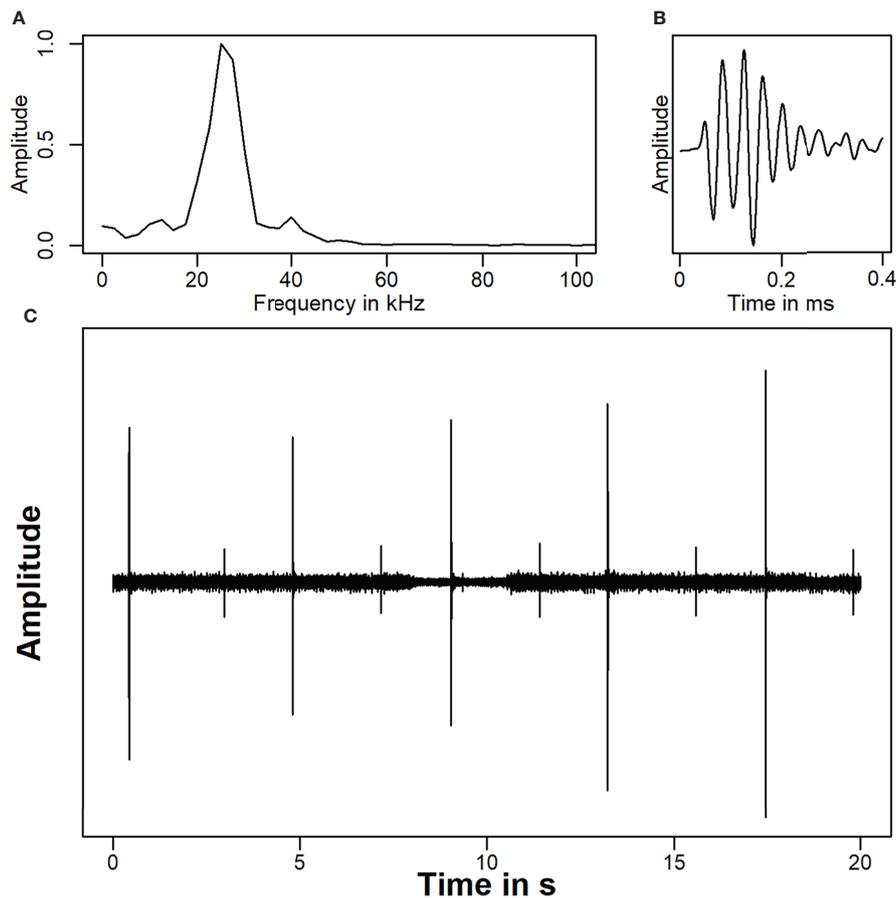
levels ranged from 77 to 164 dB re 1  $\mu\text{Pa}^2\text{s}$  for the flowmeter in the north and from 78 and 165 dB re 1  $\mu\text{Pa}^2\text{s}$  for the flowmeter in the south within the modelled sound field (2000×390×18 m, Figure 5). The variability of modelled sound exposure levels over depth was low (median standard deviation <0.1 dB). The single arrays of modelled sound fields for the two flowmeters were combined in a shared array (Figure 6), which was used in all further simulations.

### Baseline Hearing Thresholds

Baseline hearing at 28 kHz was measured over 14 trials resulting in a mean hearing threshold of 82.0 dB re 1  $\mu\text{Pa} \pm 2.4$  dB (range 78.2–88.1 dB re 1  $\mu\text{Pa}$ ). We obtained a critical value ( $p \leq 0.05$ ) of 85.7 dB re 1  $\mu\text{Pa}$  as the threshold for a significant hearing elevation. Accordingly, any hearing shift larger than 3.8 dB was regarded as a TTS.

### Post-Exposure Thresholds

Hearing thresholds after an exposure to a 3.5 s fatiguing tone at 28 kHz were conducted in eleven trials. The animal was exposed to SELs between 139.7 and 156.3 dB re 1  $\mu\text{Pa}^2\text{s}$ . Post-exposure hearing thresholds were between 86.7 and 97.6 dB re 1  $\mu\text{Pa}$ , accounting for elevated thresholds between 4.8 and 15.7 dB. Accordingly, all post-exposure thresholds exceeded the critical value of 3.8 dB. The TTS<sub>onset</sub> was estimated by a linear regression



**FIGURE 4** | Underwater noise recording at a water depth of 5 m during a vessel passage close to the flow meter in the north. **(A)** The spectrogram of the time wave was generated for one flow meter signal in a time window of 0.4 ms by the function “spec” from the package “seewave” (Sueur et al., 2008) **(B)**. The time representation of the signal show that the signal consists of five cycles **(C)**. The 20 s recording shows each five signals from the flow meter in the North and in the South. The signals from the North have a higher amplitude, as recordings were made closer to this flowmeter.

of threshold shifts versus sound exposure levels. According to the linear regression (intercept=-83.95, slope=0.64), the critical value of 3.8 dB was exceeded at an SEL of 137.4 dB re  $1 \mu\text{Pa}^2\text{s}$  (Figure 7). This  $\text{TTS}_{\text{onset}}$  was subsequently used to evaluate the TTS potential for single exposures to the flowmeter signals.

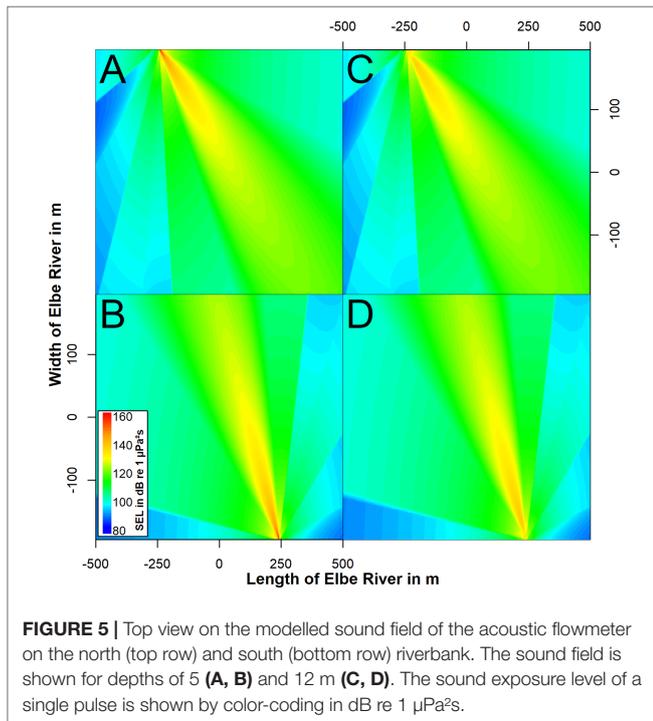
### Evaluation of TTS Potential After Exposure to Single Flowmeter Pulses

The SEL- $\text{TTS}_{\text{onset}}$  for a single exposure was determined at 137.4 dB re  $1 \mu\text{Pa}^2\text{s}$ . The underwater noise measurements and the following sound propagation model show that the source level of the underwater flowmeter exceeds this  $\text{TTS}_{\text{onset}}$ . Single pulses therefore contain sufficient SEL to induce a TTS in a harbor porpoise. The flowmeters are highly directional leading to a narrow beam, in which amplitudes are highest. Within the beam of highest amplitude, the modelled sound fields at a depth of 5 m show single SELs above the  $\text{TTS}_{\text{onset}}$  up to a distance of approximately 72 m from the flowmeter in the north and 74 m from the flowmeter in the south. Since the flowmeters are

not aligned in a  $90^\circ$  angle to the x-axis these distances in the beam do not correspond to the distance in the y-axis, meaning the position in the width of the river. Harbor porpoises which travel along a transect need to keep a distance of 40 m to the flowmeter in the north and 60 m to the flowmeter in the south in order to avoid TTS from a single exposure.

### Evaluation of TTS Potential for Harbor Porpoises, Which Stay Around the Flowmeters

Based on the constant inter-pulse intervals, we calculated the duration until the SEL- $\text{TTS}_{\text{onset}}$  was exceeded for every position in the modelled sound field. This was done to estimate the TTS potential for harbor porpoises, which do not show a flight response but rather stay within the area (Figure 8). The area of highest potential to induce TTS is between the two flowmeters. If a harbor porpoise stays within this area for 1 to 30 minutes, TTS can be induced. The risk for TTS strongly decreases, when leaving the narrow beam of highest amplitude.



## Received Levels on Simulated Flights

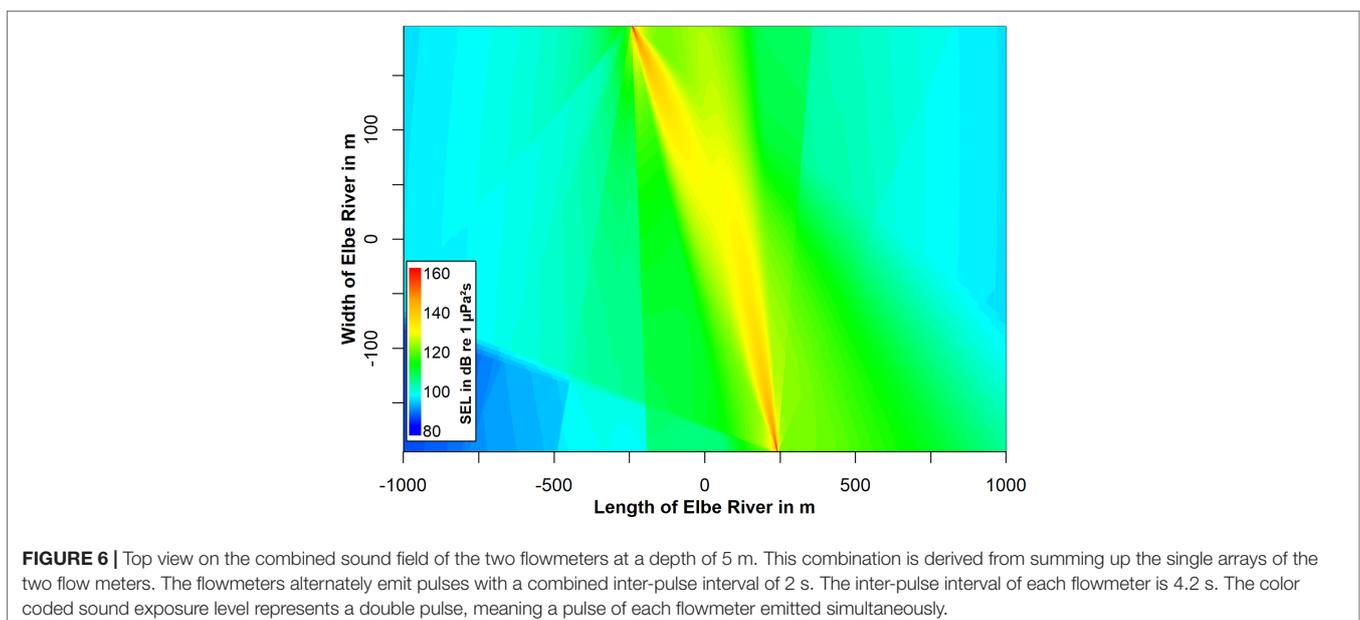
The received SEL for harbor porpoises travelling along the acoustic flow meters were simulated, assuming a swim speed between 0.25 and 8  $\text{m s}^{-1}$  (Figure 9). We accumulated the received sound exposure levels for each transect line. We simulated swimming path along the x-axis without any simulated zigzag courses. Travelling harbor porpoises with a swimming speed above 2  $\text{m s}^{-1}$  would not receive

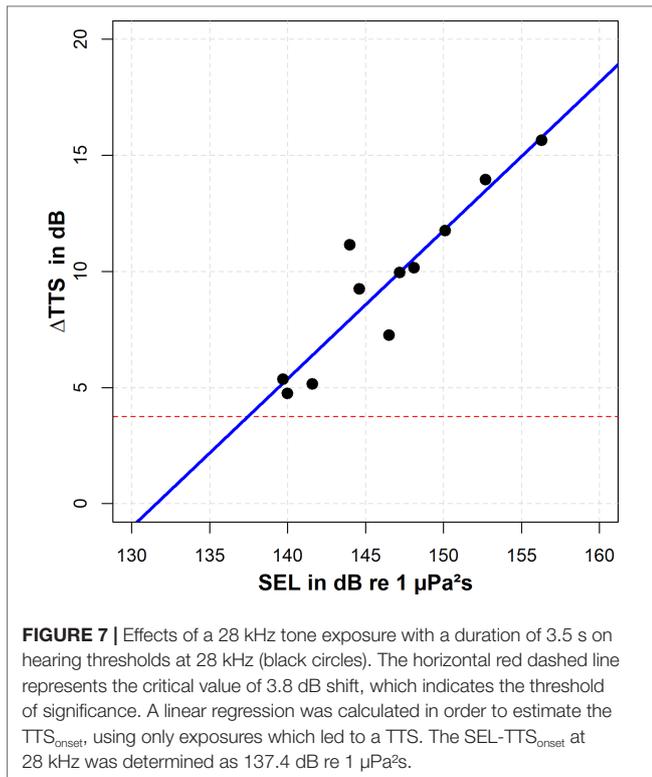
sufficient SEL from multiple pulses to induce TTS. The TTS-potential is comparably low. However, harbor porpoises swimming with a speed of 0.9  $\text{m s}^{-1}$  could receive cumulative sound exposure levels exceeding the  $\text{SEL-TTS}_{\text{onset}}$  up to distances of about 20 m. The received  $\text{SEL}_{\text{cum}}$  is strongly dependent on the timing of pulses. If the harbor porpoises is within the narrow beam of highest amplitude at the moment a pulse is emitted, the received cumulative SEL can be as high as 165 dB re 1  $\mu\text{Pa}^2\text{s}$  for all swimming speeds and a TTS would be likely.

## DISCUSSION

### Evaluation of Potential Effects of the Flowmeter on Harbor Porpoise Hearing

The acoustic flowmeter has the potential to temporarily affect harbor porpoise hearing. Sound exposure levels exceeding 137.4 dB re 1  $\mu\text{Pa}^2\text{s}$  can induce TTS at 28 kHz, as shown by the exposure experiments with animals under human care. A much higher  $\text{SEL-TTS}_{\text{onset}}$  of 166 dB re 1  $\mu\text{Pa}^2\text{s}$  was found for an exposure of harbor porpoises to 32 kHz band noise (Kastelein et al., 2019a). This difference of 29 dB in the  $\text{TTS}_{\text{onset}}$  could be explained by the much higher SPL and much shorter exposure duration in this study. The flow meters in the Elbe River are believed to induce TTS at close distances up to 74 m after the reception of a single pulse. Received cumulative SELs exceed the  $\text{TTS-onset}$  for travelling transect at close distances with less than 2  $\text{m s}^{-1}$  (Figure 9). Although harbor porpoises are capable of swimming faster, slower swim speed levels have been measured for mother calf pairs (Gaskin et al., 1974; Otani et al., 2000; Otani et al., 2001). It is reasonable to assume that a swim speed > 2  $\text{m s}^{-1}$  cannot be maintained if the health of animals is affected by diseases or animals have to swim against the current.





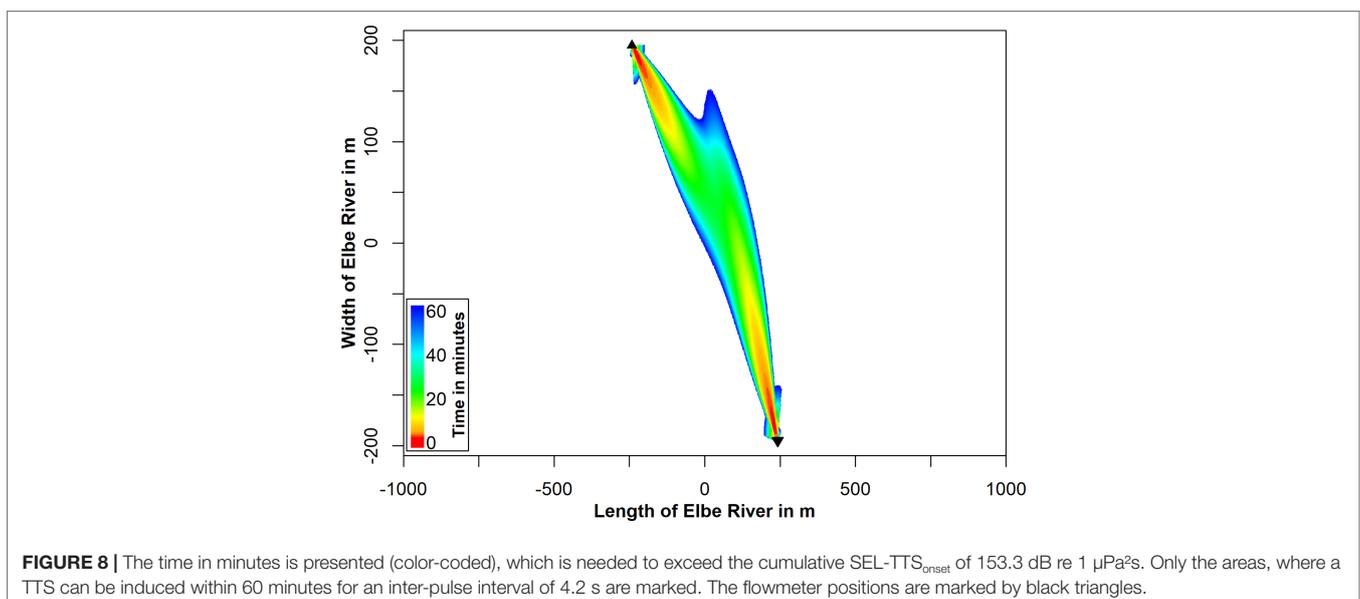
Following the recommend noise exposure criteria for marine mammals (Southall et al., 2019), a PTS is expected at a cumulative SEL of 173 dB re 1  $\mu Pa^2s$ . The highest SEL within the acoustic field was estimated at a SEL of 165 dB re 1  $\mu Pa^2s$ . To exceed the  $PTS-SEL_{onset}$  of 173 dB re 1  $\mu Pa^2s$ , seven pulses with a SEL of 165 dB 1  $\mu Pa^2s$  would be needed. Accordingly, a harbor porpoise would need to stay at close distance to the flowmeter for 28.7 s.

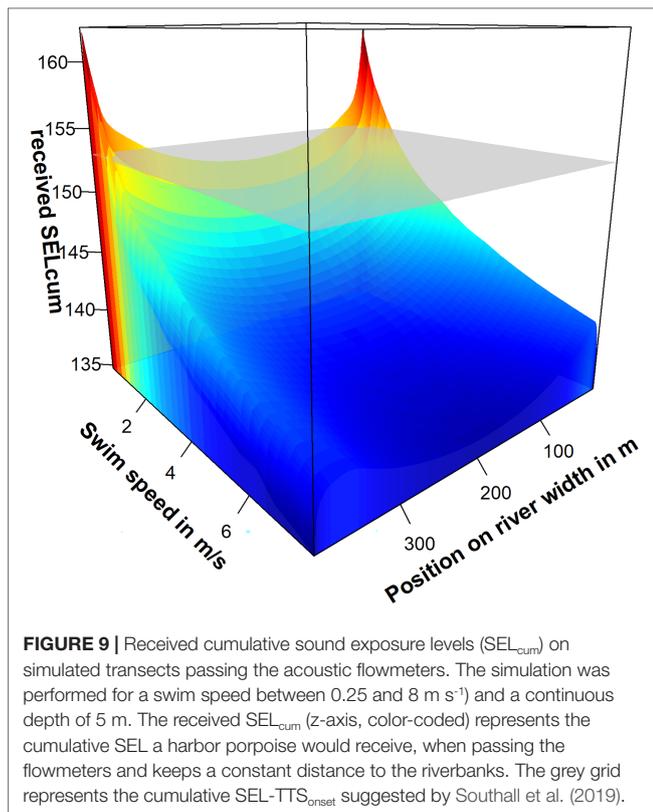
The presence of harbor porpoises in the port of Hamburg is believed to be driven by the migration of prey species (Wenger et al., 2016). Very limited fish species show good hearing abilities at frequencies as high as the 28 kHz flowmeter signals (Ladich and Fay, 2013). Effects on fish distribution are therefore believed to be negligible. If for some reason prey species aggregate close to the flowmeter, harbor porpoises could try to get access to this important food source despite high sound exposure levels. If the energetic benefit is high enough, harbor porpoises could tolerate the exposure to these signals. We found a period of less than 60 minutes being sufficient to induce a TTS along the entire width of the Elbe River as well as areas close to the flowmeter where a TTS can be induced in minutes.

### Effects on Behavior

Effects of anthropogenic noise are numerous and must not be restricted to injuries and death. The introduction of underwater noise within the hearing range of harbor porpoises can also elicit behavioral changes. An increased swim speed and breathing rate but also aversive behavior with jumping out of the water was shown for harbor porpoises in human care, when exposed to comparable pinger signals (Kastelein et al., 2014a; Kastelein et al., 2015c). Accordingly, it is likely that harbor porpoises are likewise disturbed by the flowmeters in the port of Hamburg and try to avoid close approaches to the flowmeters. Such disturbance effects may even result in decreased individual fitness and could lead to long-term population consequences (King et al., 2015).

It is reasonable to assume, that entering the sound field elicits discomfort or stress in the animals. In this case, the acoustic flowmeter could create a barrier effect and could lead to habitat loss. This could slow down or prevent the return of harbor porpoises. Future research should focus on such a





potential barrier effect and habitat exclusion. The Elbe River is highly exposed to ship traffic, which contributes significantly to the underwater soundscape. However, the Elbe River is most likely of high ecological importance for harbor porpoises with strong biological drivers, as harbor porpoises regularly occur in this noisy area. Future studies should investigate the habitat usage of harbor porpoises in this area to determine its ecological importance. Currently no systematic monitoring of harbor porpoises in large river systems exists, although sightings are regularly reported (Wenger and Koschinski, 2012; Wenger et al., 2016). Monitoring is needed for harbor porpoises, which are protected throughout their range, to better understand the driving factors for entering rivers. This possible barrier with a TTS potential should also be addressed for harbor seals, since these animals also occur in this area (Taupp, 2019) and are capable of hearing the acoustic flowmeter signal (Kastelein et al., 2009a; Kastelein et al., 2019b). Seals may also suffer from habitat exclusion by the acoustic signals of the flowmeter as acoustic signals with a 28 kHz component are even used for deterring seals (Kastelein et al., 2015b). Potential effects on seals should be considered in future research.

## Management Approach for Noise Mitigation

The understanding of effects of noise on marine life evolved over the last decades and is still scarce, since the field of research

regarding potential effects of anthropogenic underwater noise is relatively new. This could be the reason why underwater acoustic devices are still applied without considering potential biological effects. Likewise, acoustic deterrent devices are used around aquacultures in Scotland to prohibit depredation by seals causing economic loss. However, this happens unregulated to such an extent that up to 37 % of a Special Area of Conservation for harbor porpoises could exceed the threshold for TTS within a day (Findlay et al., 2021).

The simulation of harbor porpoises travelling along the acoustic flow meter could reveal a high variability in the received cumulative SEL. This large variability is due to the inter-pulse interval of 4.2 s, the narrow beam of the flowmeter and the swimming speed of harbor porpoises. Although more pulses could be received on the complete track for a slower swimming speed, the highest possible received levels do not differ significantly between different speeds. This clearly demonstrates that the timing and the distance to the sound source are the most important factors for the received cumulative SEL.

Our results demonstrate that the risk for TTS is highest in a comparably small area up to 74 m from the source. Due to the porpoises' good hearing abilities at 28 kHz (Kastelein et al., 2002; Ruser et al., 2016), the flowmeter signals might be heard from larger distances and could keep animals at a distance from the sound source. Travelling harbor porpoises could possibly choose to travel in the middle of the Elbe River when passing the flowmeter. The high ship traffic in the Elbe might affect harbor porpoise distribution, as well. Accordingly, harbor porpoises might have to choose between high vessel and flowmeter noise exposure. We believe that following approaches for noise mitigation could help to reduce such conflicts between anthropogenic activities and wildlife.

Switching off the flowmeter in the presence of vessels could be an option to mitigate potential effects on harbor porpoise hearing. Vessel presence could be derived in real-time from AIS data or background noise levels. We assume that the presence of vessels negatively affects the flow measurement. Switching off the flowmeter in such situations would therefore have only minor effects on the recorded data. Furthermore, there is no need for such a high temporal resolution of flow measurements. A much lower temporal resolution could still be sufficient to ascertain flow speed trends. Emissions could also start with a lower source level and increase gradually so that harbor porpoises are not surprised by high level signals at close range. The advantage of the currently used high source level and short inter-pulse interval is that travelling harbor porpoises can hear the signal at sufficient distances and are aware of them in time to react. In theory, this reduces the probability that harbor porpoises enter the area of highest received levels. A possible adjustment could be measuring the flow speed on an hourly basis. A measurement could start with signals with reduced source levels, which are gradually increased in steps of 3 dB, giving the harbor porpoise time to react. For instance, the SEL could start at 102 dB re 1  $\mu Pa^2 s$  and could be increased by 3 dB each 4.2 s. After the emission of 13 signals, corresponding to

50 s, the  $TTS_{onset}$  for a single exposure could be exceeded. This would give the harbor porpoise sufficient time to leave the area of highest intensity, until the actual flow velocity measurement starts. Such an adjustment represents an effective noise mitigation and should be considered, if technically feasible. The underwater measurements revealed that the acoustic flowmeters on the northern and southern bank of the Elbe River were misaligned. Accordingly, an adjustment of the orientation could allow for lower source levels, without any loss in quality of the results. A source level reduction of the flowmeter was already instructed by the HPA to improve the current situation.

Due to the lack of an established monitoring program of harbor porpoises in the Elbe River, we do not have any information on whether harbor porpoises regularly occur close to the acoustic flowmeters. Harbor porpoises frequently pass the sound field of the acoustic flowmeters as they are sighted up- and downstream (Wenger et al., 2016). An exposure to high received levels could be tolerated, if the expected benefit is high. We do not have detailed information on the overall application of these devices in large river systems. The HPA runs two more flowmeters upstream the Elbe River in addition to the flowmeter in the port of Hamburg (pers. comm. HPA). The presence of harbor porpoise in this area is assumed lower, but the current database is insufficient for reliable estimates. Additional flowmeters could be applied along the Elbe River or other river systems by different operators, as well. It is reasonable to assume that harbor porpoises have to pass other acoustic barriers during their annual upstream travel. A mandatory authorization process for acoustic devices should be carefully considered, if effects on the hearing of marine mammals can be expected.

## Conclusion

The distribution of harbor porpoises largely overlaps with areas where anthropogenic activities take place. A perfect management of these activities would prevent any negative impact on harbor porpoise health or behavior but simultaneously maintain anthropogenic activities. This case study casts a new light on the application of acoustic devices without considering biological consequences. The acoustic flowmeter has the potential to induce TTS in harbor porpoises. Decreasing the source level and increasing the inter-pulse intervals could help to mitigate potential effects on harbor porpoise hearing. Effects on spatial distribution of present harbor porpoises and seals are likely. The occurrence of harbor porpoise in this area suggests that good reasons for a 97 km upstream travel exists. Information on harbor porpoise presence and habitat usage is missing, which underscores the need for a monitoring program along the Elbe River. Unfortunately, further examples of incautious noise emission exist (Findlay et al., 2021). This emphasizes the need for a mandatory authorization process prior to the use of underwater sound for any purpose with potential effects on

aquatic life. Such an authorization process should carefully consider potential effects for target and non-target species.

## DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## ETHICS STATEMENT

The animal study was reviewed and approved by Danish Ministry of Food, Agriculture and Fisheries.

## AUTHOR CONTRIBUTIONS

AR, MS and US were involved in designing the project and applying for the project grant. AR and TS prepared the underwater noise measurements, which were conducted by AR, TS and MS. The underwater noise recordings were analysed by MS. Hearing tests with a harbour porpoise in human care were performed by AR. All analyses to evaluate the TTS potential for a harbour porpoise in the sound field of the acoustic flowmeters were performed by TS under supervision of AR, JS and US. All authors provided critical feedback and helped to shape the research and analysis. The manuscript was written by TS with supportive contributions to the final version of all authors. All authors contributed to the article and approved the submitted version.

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