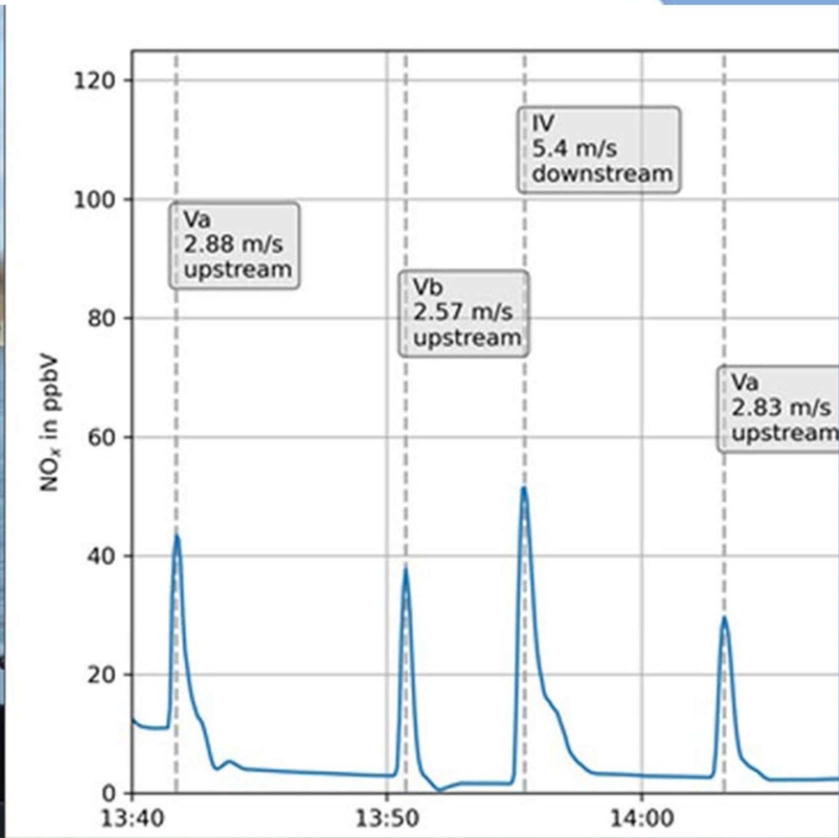
SUSTAINABLE WATERWAY TRANSPORT, CLEAN AIR

Action B 4: Modelling, evaluating and scenario building

Harbour monitoring Part E: Determination of NO_x emission rates of passing vessels from onshore measurements and application for emission calculation



CLEAN INLAND SHIPPING

WWW.CLINSH.EU

Project: CLINSH – Clean Inland Shipping

Goal: The objective of LIFE CLINSH is to improve air quality in urban areas situated close to ports and inland waterways, by accelerating IWT emission reductions.

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Contributors: **Landesamt für Natur, Umwelt und Verbraucherschutz Nordrhein-Westfalen (LANUV NRW)**

University of Bremen, Institute of Environmental Physics

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Authors:	**Kai Krause**	**(IUP, Universität Bremen)**
	Dr. Folkard Wittrock	**(IUP, Universität Bremen)**
	Dr. Dieter Busch	**(LANUV)**
	Anton Bergen	**(LANUV)**

Action B.4: Modelling, evaluating and scenario building

Harbour monitoring Part E:

Determination of NO_x emission rates of passing vessels from onshore measurements and application for emission calculation

Project management:	**Kai Krause & Dr. Folkard Wittrock**
	IUP, Universität Bremen
and	**Dr. Dieter Busch & Anton Bergen**
	Fachbereich 77
	Landesamt für Natur,
	Umwelt und Verbraucherschutz (LANUV)
	Nordrhein-Westfalen
	Leibnizstrasse 10
	45610 Recklinghausen
Cover pictures:	**Dieter Busch, LANUV**

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1. Introduction

In cities along busy waterways such as the Rhine, the diesel engines of inland vessels are a significant source of emissions. The total amount and effect of these emissions depends on the traffic density along those waterways and the emissions of the individual vessels.

In order to limit the effects of these emissions on air quality, the Central Commission for Navigation on the Rhine (CCNR) and the EU established various regulations for ship engines over the years, each of which, however, only applies to new engines (new ship construction or replacement of old engines). Engines on ships already in service are subject to grandfathering. The effect of these requirements is therefore limited, as ship engines have a very long service life. There is no provision for continuous monitoring of emissions from ships in service, as is the case with road vehicles, for example.

To determine the emissions of shipping traffic, there has been a lack of concrete input data, both on the actual shipping traffic and on the emission behavior of the various ship engines during real cruising operation. Therefore, a large number of assumptions had to be made in order to determine the emission means caused by the ships.

An attempt was made to develop a scenario for the associated shipping traffic using freight statistics. This was followed by an estimation of the composition of this traffic scenario from different vessel types and sizes.

In a further step, further assumptions had to be made about the engine equipment and the respective average cruising speed (upstream/downstream) in order to determine the emissions. These assumptions then formed the basis for estimating the power requirement and the associated diesel consumption from theoretical power curves of average ship engines.

This estimated diesel consumption in turn formed the basis for calculating the emission levels from shipping traffic. It is obvious that such a large number of assumptions also results in a considerable, potential for uncertainties in the resulting emissions.

It therefore seemed reasonable to develop more realistic methods for determining ship emissions. Direct measurement of ship emissions is possible with two methods that were used in the CLINSH project:

a) direct measurement using in-situ instruments on board the ships themselves

b) Measurement of emissions from passing ships with an automatic and continuous measuring shore station.

In both cases usually relative emission factors are derived e.g., the amount of emitted substances per amount of consumed fuel is determined. To evaluate the total amount of an emitted substance of the ship traffic, further information about the fuel consumption is needed, but often not available or rather uncertain.

Both methods were successfully applied in the CLINSH project. Direct measurement of NO_X emissions was carried out on more than 40 inland vessels that participated in the CLINSH project. In addition, two continuously measuring, automatic measuring stations were set up by the LANUV as part of CLINSH on the Rhine near Duisburg and in the port of Neuss, with which it was possible to record and evaluate around 19,000 emission peaks from passing ships in the years 2018-2020.

In addition, AIS receivers were set up at both measuring stations, with which it was possible to record the real ship traffic and to evaluate and classify it with regard to ship type, length class, direction of travel and speed (over ground).

Within the context of CLINSH a method to derive absolute nitrogen oxides (NOx) emission rates (in grams per second) out of high-resolution onshore measurements has been developed. In favorable wind conditions the plumes of passing ships are transported towards the measurement site located at the riverbank. At the measurement site the plume can be clearly identified as a short time enhancement (a peak) in the measured NOx concentration. These peaks can be attributed to specific source ships and the respective emission rate can be calculated out of the peak area. An example time series with attributed ships is shown in Figure 1.

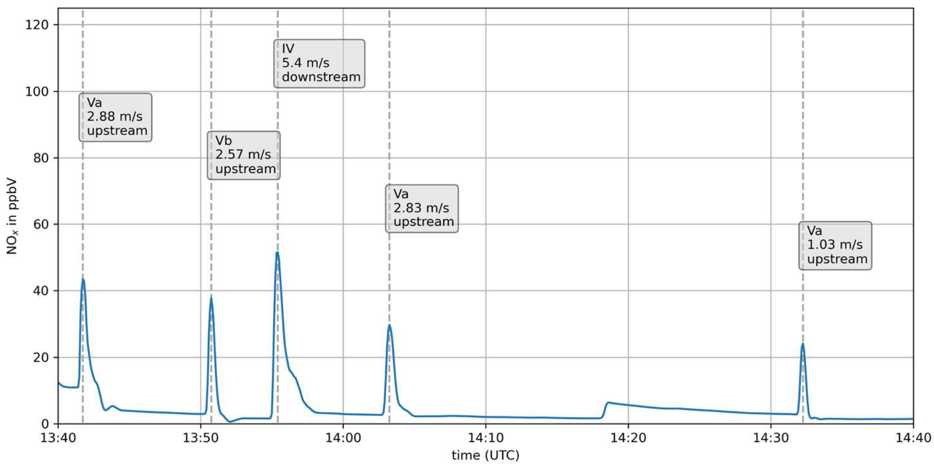

Figure 1: AIS signals from passing ships used for the assignment of NOx peaks to specific vessels.

From that information about the direction of travel, speed, and length classes of the passing vessels can be determined.

2. Measurement sites

The LANUV set up two continuous measurement stations in Duisburg and in Neuss, which measured NOx concentration and meteorological parameters such as atmospheric pressure, humidity, temperature, wind speed and wind direction close to the river Rhine. The temporal resolution of those measurements is five seconds. Additionally, those measurement stations also were supplemented with AIS (automatic identification system) receivers, which deliver information about the passing ships. In favourable wind conditions (meaning blowing ship plumes towards the in situ systems), both measurement stations show strong enhancements of NOx when a ship passes the measurement site, which can be clearly seen as a peak in the time series.

Duisburg Rhine Harbour (DURH)

In Duisburg the measurement site is located on the eastern riverbank of the Rhine and the predominant wind direction has a westerly component, which means emissions from ships are transported towards the measurement site most of the time and a high number of peaks can be identified within the measured NOx concentration time series. Generally, the measurement site is well located to derive emission rates, as it is close to the Rhine and the entrance to the Duisburg harbour basins. Therefore, the measured concentration peaks can be differentiated for ships that pass the measurement site in different driving conditions e.g., ships that drive upstream against the river current or downstream with the river current. This measurement site has been set up in October 2017 and is still active. For CLINSH the emission rates have been derived for the years 2018 to 2020.

Neuss Rhine Harbour (NERH)

In contrast the measurement site in Neuss is located within the harbour itself, which is located west of the Rhine. Buildings and vegetation block the direct line of sight from the measurement station to the Rhine. In combination with the predominant south-westerly wind direction, there are only a few plumes detected from ships that are steaming along the Rhine. Nevertheless, due to its location directly within the harbour, the measurement site is well suited to evaluate the emissions of slow ships within the harbour areas and without the influence of river currents. This measurement station was set up in September 2017 and dismantled at the end of 2019. Therefore, emission rates have been derived for the years 2018 to 2019.

Figure 2: Satellite image of the measurement site in Duisburg (DURH). (Map data ©2015 Google)

Figure 3: Automated measurement station in Duisburg as seen from the Rhine
(Photo: Dr. D. Busch, LANUV).

Figure 4: Satellite image of the measurement site in Neuss (NERH). (Map data ©2015 Google)

Figure 5: Automated measurement station in Neuss (Photo: Dr. D. Busch, LANUV).

3. Data processing

The combination of the different measurements and the received AIS signals allows to calculate ship emissions from passing ships using three different steps which will be described in the following.

Peak identification

The first step is to identify the peaks caused by passing ships. To identify these peaks, a low pass filtered time series is calculated out of the measured time series using a running median with a window length of 5 minutes. This low pass time series describes the changes in the background concentration caused by meteorological factors and other emission sources but excludes the short-term variation caused by passing ships. The low pass filtered time series is then subtracted from the measured time series, which results in a time series, which is close to zero on average, but still shows the sharp peaks caused by the passing ships. For those peaks it is then checked, if they exceed a defined threshold, to ensure they are actual enhancements and not only noise in the measurements. In this case the threshold was defined as 2 ppb_V. For each identified peak, the time of occurrence (t_{peak}), the peak width and the height of the maximum above the background concentration is determined.

Ship assignment

The second step is then to identify the respective source of the peak. For each peak it is checked whether there were ships in a 5 km radius around the measurement site up to 5 minutes before the peak maximum was measured. For each ship corresponding AIS signals within the given time frame are collected and interpolated to a one second time resolution. For each AIS signal position a trajectory is calculated to check if emissions caused at that specific ship position could have been transported to the measurement site by wind. The wind speed and direction used for these trajectories are the 30 min averages of wind speed in wind direction at the measurement site. Each trajectory is calculated for the time frame between the timestamp of the AIS signal (tAIS) and the time of the peak (tpeak) maximum. Afterwards, it is checked, if the trajectory ends within a 50 m radius of the measurement site. If only the trajectories of a single ship end close to the measurement site in the given time frame, the ship is assigned to the peak as the respective source.

The final assignment of the source position is then based on the distance to the measurement site. From all possible AIS positions, with trajectories ending close to the measurement site, the closest one is assigned as the source position. In case several ships are identified as a possible source of the peak, the peak is neglected for further analysis, as the unambiguous assignment of a single source is not possible.

After the responsible ship has been identified, all the information for that ship passage is assigned to the peak. The first assigned ship position is the position transmitted 180 seconds before tAIS and the last assigned position is the position 180 seconds after t_{peak}.

Calculation of emission rate

In the third step the NO_x emission rate for each peak with a valid source ship is calculated. As the stations only measure the concentration of NO_x at the measurement site and not at the stack of the ship, a model has to be applied to estimate the emission rate from the concentration enhancement found at the measurement site. A simple approach is to assume that the plume of the ships can be described by a Gaussian-Puff-Model:

$$C(x,y,z) = \sum^{n_{puff}} \frac{Q\,dt}{\sigma_x\,\sigma_y\,\sigma_z\,(2\,\pi)^{1.5}} \times exp\left(\frac{-(x-U\times(t-dt))^2}{2\,\sigma_x^2}\right) \times \exp\left(\frac{-y^2}{2\,\sigma_y^2}\right) \times \left[exp\left(\frac{-(z-H)^2}{2\sigma_z^2}\right) + \exp\left(\frac{-(z+H)^2}{2\,\sigma_z^2}\right)\right]$$

where concentration at a point (C (x, y, z)) can be described as a function of the emission rate (Q), the dispersion due to atmospheric stability (σx, σy, σz), the length of time of the emission (dt) at a certain source point (x=0, y=0), funnel height (H), the total transport time (t) and the wind speed (U). The wind direction is always along x. The model releases a puff of pollutants at the ship's position, which is then transported by the wind for an amount of time (t) and dispersed according to the current atmospheric stability. The amount of time (t) is different for each ship position and is always the time of occurrence of the peak maximum (tpeak) minus the time of the respective AIS signal (tAIS). The result is a concentration field caused by the emission of pollutants at the specific ship location for time dt.
This step is then repeated for all ship positions. The calculated concentration fields then describe how the plume developed during the ship passage.

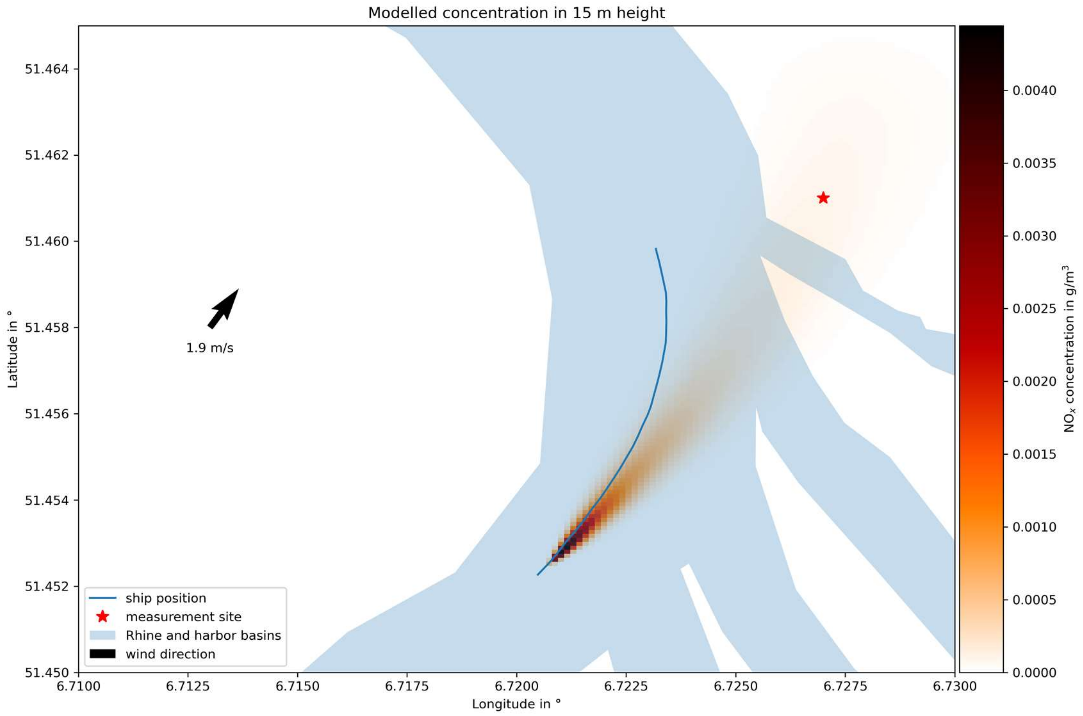

Figure 6: Modelled exhaust plume for a cargo ship of class Va (110 x 11.4 x 3.5 m, cargo capacity 2800 tons) steaming upstream and passing the measurement site in Duisburg at 29th of August 2018 around 10:46 am. Wind direction was southwest and windspeed about 1.9 m/s.

Table 1: Atmospheric stability classification scheme based on surface wind speed and solar insulation for daytime conditions and cloud cover during nighttime conditions (Pasquill 1968). Ranging from very unstable (A) to moderately stable (E).

Surface wind speed	Daytime solar radiation			Nighttime cloud cover	
(ms^{-1})	Strong	Moderate	Slight	>= 4/8 clouds	<= 3/8 clouds
< 2	A	A-B	B	-	-
2-3	A-B	B	C	E	F
3-4	B	B-C	C	D	E
4-6	C	C-D	D	D	D
> 6	C	D	D	D	D

Table 2: Atmospheric dispersion parameters σy, σx and σz for different stability classes in dependence of distance (x) from source in meter. For intermediate cases such as B-C the average of both values has been taken (Briggs 1973).

Stability Class	$\sigma_y(x)$ and $\sigma_x(x)$	$\sigma_z(x)$
A	$0.32x(1+0.0004x)^{-0.5}$	$0.24x(1+0.001)^{-0.5}$
B	$0.32x(1+0.0004x)^{-0.5}$	$0.24x(1+0.001)^{-0.5}$
C	$0.22x(1+0.0004x)^{-0.5}$	$0.2x$
D	$0.16x(1+0.0004x)^{-0.5}$	$0.14x(1+0.003)^{-0.5}$
E	$0.11x(1+0.0004x)^{-0.5}$	$0.08x(1+0.00015)^{-0.5}$
F	$0.11x(1+0.0004x)^{-0.5}$	$0.08x(1+0.00015)^{-0.5}$

As the emission rate is unknown the model is run with an arbitrary emission rate (Q_{model}). The height of the plume centre is approximated to be at the height of the funnel above water level, assuming that the plume quickly bends down due to wind and movement of the ship. It is also assumed that this height is always roughly the same for all ships. Dispersion parameters are chosen according to atmospheric stability, which has been determined using the wind speed at the measurement site and incoming global radiation (DWD Climate Data Center) and cloud coverage (DWD Climate Data Center) from a nearby weather station of the German Weather Service located at the Düsseldorf-Airport.

To derive the emission rate, the integrated measured concentration, i.e. the area under the peak (C_{meas}), which has been corrected for the fluctuating background, is then compared to the modelled concentration at the measurement site, i.e. the area under the modelled peak (C_{model}).

Assuming the model sufficiently describes the ships plume, the only difference between modelled concentration and measured concentration is caused by the different emission rate. Therefore, the real emission rate of the ship (Q_{meas}) can be estimated by the following equation:

$$Q_{meas} = \frac{C_{meas}}{C_{model}} Q_{model}$$

This approach assumes, that the emission rate is constant for the whole modelled time domain. An example case can be seen in Figure 7, where a ship passage on the 22nd August 2018 around 04:36 pm has been modelled and evaluated in the scheme described above.

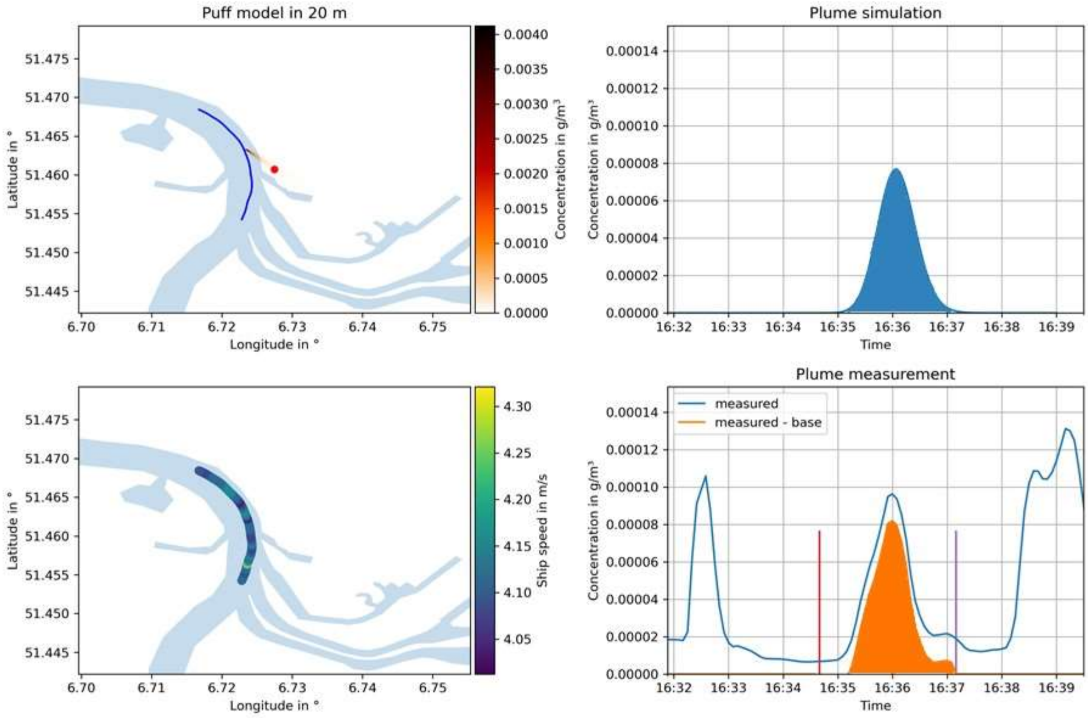

Figure 7: Example of a plume simulation in comparison to the respective measurement. Upper left panel shows the plume at the time when highest concentration has been measured. Upper right panel shows the respective modelled peak. Lower left shows the ship speed over ground for each time step. Lower right shows measured concentration over time, where the blue line represents the concentration, and the orange line shows the background corrected concentration of the peak. Red and purple lines indicate the limits of the peak. Modelled (blue, upper right plot) and measured peak (orange, lower right plot) area are the same.

Quality control

Not in all cases the assumptions made within the model truly reflect the conditions at the time of measurement. To assess the quality the derived emission rate, several criteria have been established. Most of those criteria are based on the uncertainty of the input parameters and how the influence the derived emission rates.

For each peak and thus each individual ship passage, Monte-Carlo-Simulations are performed, where the wind speed (U), wind direction (θ), atmospheric stability, and position of the ship in longitude, latitude and height are varied within their respective uncertainty range. For each of these parameters (j) this results in set of simulations and for each of those simulations the concentration at the measurement site is determined. For each parameter, the resulting concentrations of a set are then summarized by the mean value ($mean_{Cj}$), the standard deviation (σ_{Cj}) and the minimum (min_{Cj}) and maximum value (max_{Cj}). These values are then compared to the reference simulation of the unperturbed input parameters.

To be evaluated further within the context of CLINSH, the following five criteria must be met by the set of Monte-Carlo-Simulations for each input parameter:

1) $mean_{Cj}$ / C_{model} must be within between 0.5 and 1.5, to eliminate cases with a systematic deviation caused by the uncertainty of a single input.
2) σ_{Cj} / C_{model} must be lower or equal to 1, to eliminate cases with a high variability caused by the uncertainty of a single input.
3) The difference between min_{Cj} / C_{model} and max_{Cj} / C_{model} must be lower than 2, to eliminate cases with a large spread between minimum and maximum of the set due to the uncertainty of a single input.
4) the absolute error of the derived emission rate must be lower than 5 g/s, which eliminates cases, where the uncertainty is on a larger order of magnitude than the emission rate.
5) the relative error of the derived emission rate must be lower than 200%, which eliminates cases, where the uncertainty is much larger than the emission rate.

The uncertainty of the derived emission rate is given by:

$$\sigma_Q = \sqrt{\left(\frac{\partial Q_{meas}}{\partial C_{meas}} \times \sigma_{Cmea}\right)^2 + \left(\frac{\partial Q_{meas}}{\partial C_{model}} \times \sigma_{Cmodel}\right)^2}$$

where σ_{Cmeas} is the uncertainty of the measured trace gas concentration and σ_{Cmodel} is the uncertainty of the modelled trace gas concentration. The uncertainty of the model is defined as:

$$\sigma_{Cmodel} = \sqrt{\sigma_{CU}^2 + \sigma_{C\theta}^2 + \sigma_{Cstability}^2 + \sigma_{Clon}^2 + \sigma_{Clat}^2 + \sigma_{CH}^2}$$

where each σ_{Cj} is the standard deviation of the modelled trace gas concentrations of the Monte-Carlo-Simulations with respect to changes of an individual input parameter (j). In the Monte-Carlo-Simulations each parameter is changed individually, therefore possible interactions between changes of more than one parameter at a time are neglected.

Table 3: Uncertainties of the input parameters used in the Monte-Carlo-Simulations.

Abbreviation	Name	Calculation of value
σ_{lon}	Ship position in longitudinal direction	Uncertainty of the AIS signal, 10 m
σ_{lat}	Ship position in latitudinal direction	
σ_{H}	Plume height	$\sqrt{\sigma_{fh}^2 + \sigma_{wl}^2}$
σ_{fh}	Funnel height	Estimated, 5 m
σ_{wl}	Water level	Mean high water level – mean low water level
σ_{θ}	Wind direction	Estimated 10°
σ_{U}	Wind speed	Standard deviation of measured wind speed
$\sigma_{stability}$	Atmospheric stability	Atmospheric dispersion parameters of class with lower stability and higher stability than the assigned class
σ_{Cmeas}	Uncertainty of the measured concentration	$\sqrt{std(peak)^2 \times n}$, where n is the number of nodes used to calculate the peak area

4. Results

For Duisburg, a total of 22.625 ship peaks have been identified and could be assigned to a specific source ship and for 16.423 of those peaks it was possible to determine the emission rate and fulfil the criteria mentioned above.

In Neuss 5.200 peaks have been identified and the respective emission rate has been derived, in 3.238 cases those derived emission rates fulfil the quality criteria. These emission rates were than summarized in context of the respective CEMT ship class, the direction of travel (upstream or downstream) and their speed over ground. Figure 8 shows the ship classification scheme used in CLINSH.

Figure 8Figure 8: Overview over the ship classification system used in this report, analogous to the classification according to CEMT. Ship Graphics: Buerau Voorlichting Binnenvaart

The analysis of shipping traffic on the Rhine has shown that the main share of freight traffic on the Lower Rhine is handled by vessels of the size classes IV (85 m, 16% 23%), Va (110 m, 32%-42%) and Vb (135 m, 15%-21%) with a share of 70-80% (Figure 9). In addition, there are pushed and coupled units, which together account for about 7%-10% of the total traffic. The smaller cargo ships and tankers of classes I, II and III play only a minor role. (LANUV 2021b)

Due to the high number of ship passages of the three ship classes IV, Va and Vb (85-135m), the emission rates of the respective class can thus be well characterised under real sailing conditions (e.g. figures 10, 12, 14). For the ship classes with smaller shares in Rhine traffic, there are fewer observations overall, which leads to a higher uncertainty of the summarised emission rates for this class.

For the smaller ship classes (I-III), there is partly not enough data to classify the determined different emission rates in relation to direction of travel or speed with certainty. This can lead to larger error ranges for the determined emission classes.. However, these are relativized in the emission calculations for the individual sections of the Rhine due to the low traffic shares of these ship classes.

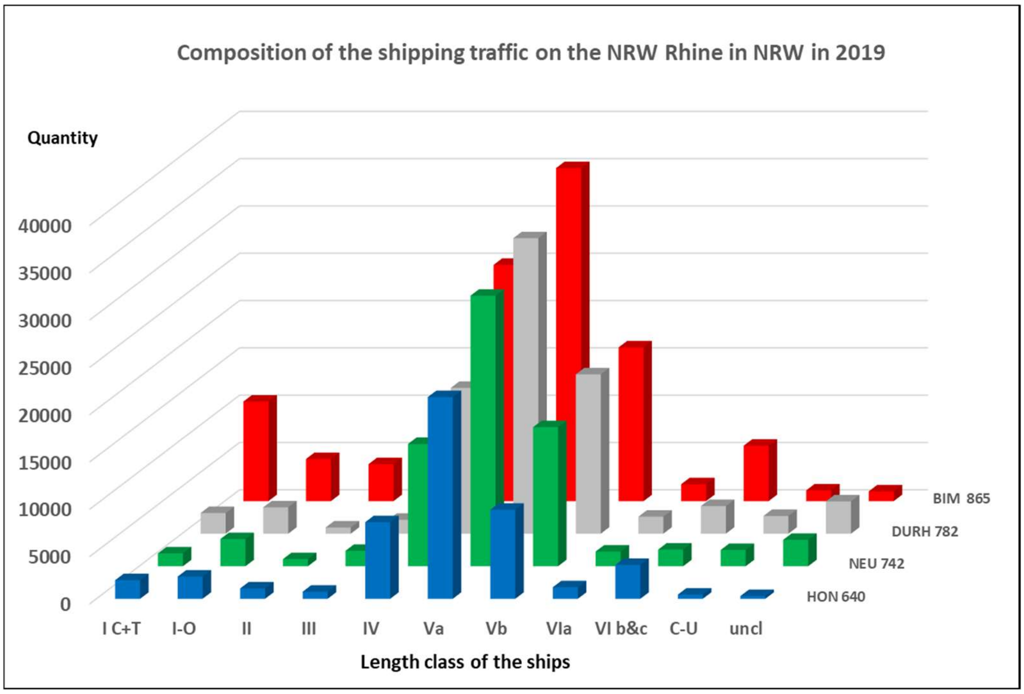

Figure 9: Ship traffic on the North Rhine-Westphalian section of the Rhine (Rhine-km 640-865) in 2019, composition according to the individual vessel size classes (For ship classes see Fig. 8; I C+T = cargo and tanker ships; I-O = other ships; VI = pushed convoy, VIa = 2 barges; VIb & c = 4-6 barges; C-U = coupled unit; uncl = ship not clearly classifiable via AIS signal.

In general, the emission rate correlates with the size of the ships, with larger ships generally having higher emission rates than smaller ships. Furthermore, speed over ground also correlates with emission rates, with higher speeds over ground leading to higher emission rates.

Furthermore, there is also a correlation with the direction of travel: ships travelling against the current, i.e. upstream, have a higher emission rate over ground in the respective speed class than ships travelling downstream at the same speed over ground.

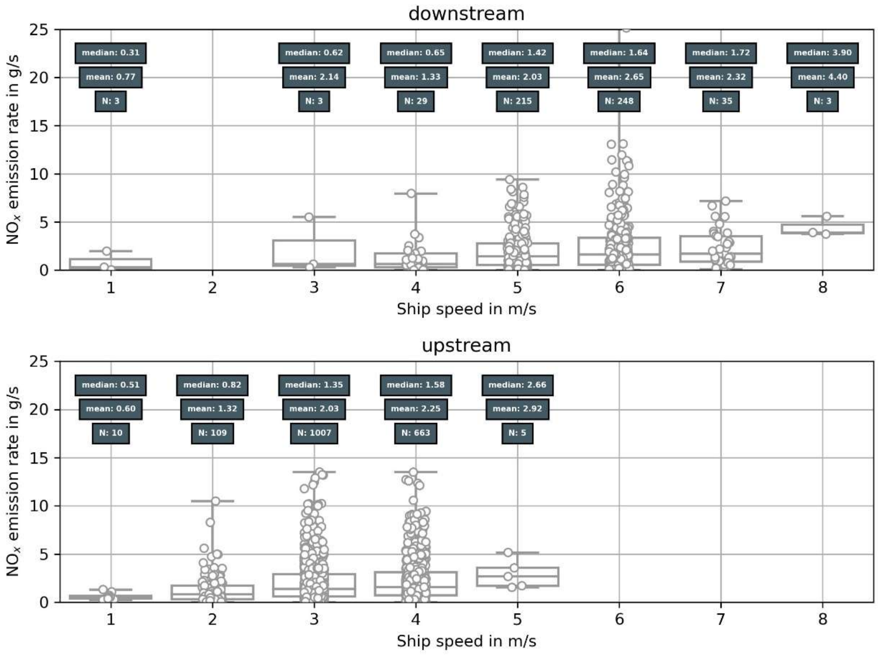

Figure 10: Emission rates for ship class IV (85 x 9.5 x 2.5 m, cargo capacity 1350 tons) in dependence of ship speed over ground and direction of travel. (Data measured at DURH)

Figure 11: MS Freya, an example for a 85 m tanker vessel (Photo: Arne Harms)

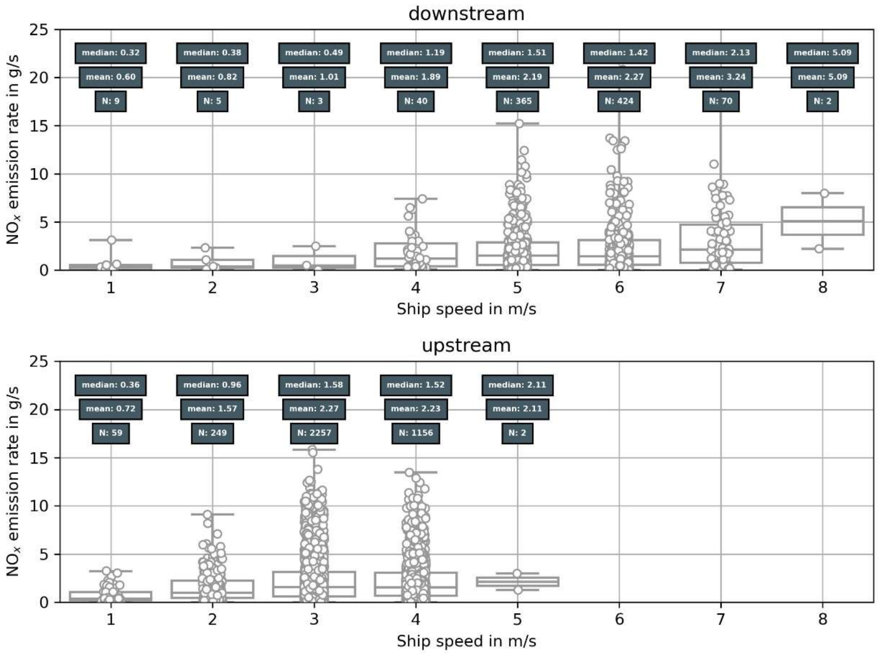

Figure 9: Emission rates for ship class Va (110 x 11.4 x 3.5 m, cargo capacity 2800 tons) in dependence of ship speed over ground and direction of travel (Data measured at DURH)

Figure 13: MS CURA DEI, an example for a 110 m cargo vessel (Photo: Dr. D. Busch)

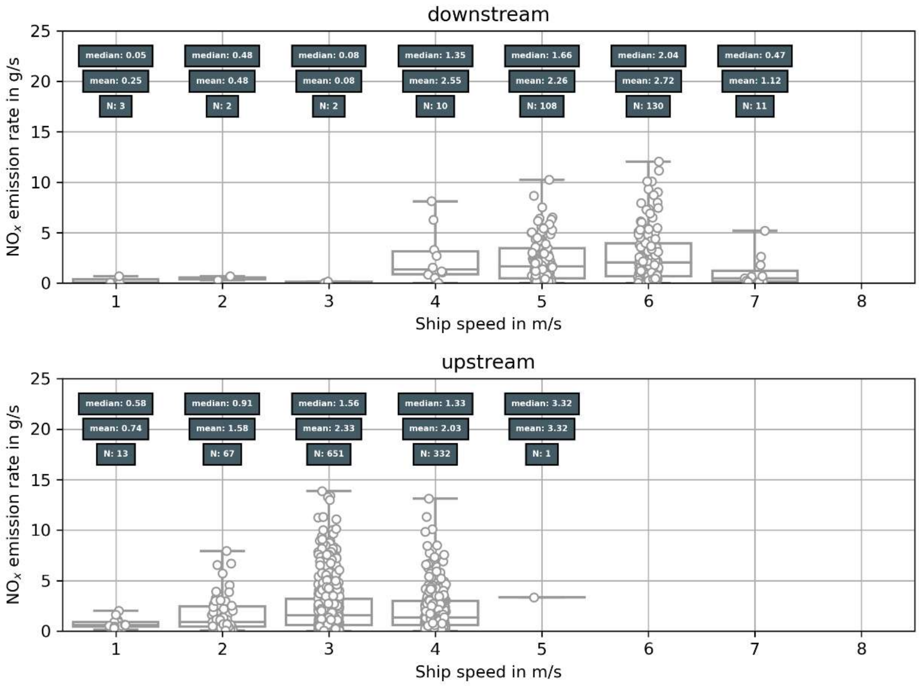

Figure 10: Emission rates for ship class Vb (135 x 11.4 x 3.5 m, cargo capacity 4000 tons) in dependence of ship speed over ground and direction of travel (Data measured at DURH)

Figure 15: MS ORIANA, an example for a 135 m cargo vessel (Photo: Dr. D. Busch)

5 Application of the Emission factors: Calculations of Emissions for the emission cadaster in North Rhine-Westphalia

The State Office for Nature, Environment and Consumer Protection (LANUV) maintains the emission register for inland waterway transport in North Rhine-Westphalia. This register has so far been based on ship data, which is determined from traffic reports and freight data. In addition, estimates have been required for other variables (e.g. motorisation, average speed of ships), which are included in the emission calculations. The theoretically required engine power is estimated from speed/power curves and the associated emissions are determined from power/emission curves via the diesel consumption of the ships. Hence, there are potential sources of uncertainty in the calculated emissions. Therefore, it makes sense to develop a method for determining emissions in which, as far as possible, all relevant variables are determined based on real measured data.

By using the automatic measuring stations for CLINSH, it was possible to quantify many emission peaks of the passing ships and to assign them to each individual ship via the AIS-Signals using the procedure already described in the previous chapters. By classifying the emission factors, it was possible to develop a new method for determining NO_X emissions from moving ships. This method has already been used in the LANUV modelling for the port areas of Duisburg and Neuss.

Emissions from moving vessels on the Rhine River

The emission calculation was carried out with the objective of representing the pollution situation caused by inland navigation vessels on the Rhine as accurately as possible and thereby to use real measured date. Therefore, both the ship movements and the emission factors were determined directly based on the actually operating ships.

For this purpose, the vessel movement data was derived from their AIS-Signals. This electronically transmitted identifier, which every commercial vessel sends at intervals of a few seconds to a few minutes, contains, among other data, information regarding the size and type of the vessel and its position and speed.

Classification of the data

The AIS data provide the possibility to classify passing vessels according to their size, direction of travel (upstream/downstream) and speed.

The size classification was carried out according to the scheme of the Dutch "Buerau Voorlichting Binnenvaart" (Figure 8), which is based on the CEMT (European Conference of

Ministers of Transport), French: "Conférence Européenne des Ministres des Transports (CEMT)".

For the speed classification, speed classes in the range of 0 to 9 m/s were defined in 1 m/s increments. Furthermore, an additional category was defined for the few vessels with speeds above 9 m/s. Each ship was assigned to one of the classes according to its speed. This classification was also used as a basis for determining the emission factors, which made it possible to determine different emission factors [g/s] for each combination of direction of travel, ship speed and ship size and to assign these to the corresponding ships.

Calculation of the emissions

Within the CLINSH project, this method was used to determine the emissions from moving ships for the Rhine kilometres 728 to 756 and 770 to 794 in NRW and for the port areas of Duisburg and Neuss for the year 2018. In the following, the procedure is explained in more detail.

The range of the AIS-signals depends on the strength of the transmitting system and the installation height of the transmitting antenna. Signals from large container ships that have their bridge raised while being fully unloaded thus have a greater range than the transmitting systems of smaller cargo ships.

The surrounding terrain geometry also has an influence on the range of the AIS-signals. In the winding and mountainous Middle Rhine Valley, for example, it is significantly shorter than on the flat Lower Rhine.

The evaluation of the incoming AIS-signals from the AIS-receivers used for CLINSH in Duisburg and Neuss showed reliable reception at a distance of about 10 km. With increasing distance, the number of detectable AIS-signals also decreased continuously.

Between the two CLINSH stations there was therefore a range of about 14 kilometres in which the number of AIS-signals received was significantly lower than expected. Since most of the ships that reach or leave the confident reception area in Neuss, presumably also reach the safe reception area in Duisburg, the number of ships for the unconfident sections were interpolated.

For each Rhine kilometre for which coverage with an AIS-receiver was available, the emission calculation was carried out separately. The speed of the ships can be used to calculate the time, which a ship needs to pass the distance on the Rhine, and thus the timespan in which it emits pollutants. The emission of each individual ship is calculated from the product of the time and the respective emission factor. The sum of the emissions of the individual ships finally gives the total amount of emissions of all ships sailing in the observed Rhine sections. Table 4 shows an excerpt from the calculation data, which demonstrates how the calculations were carried out for the individual Rhine kilometres. The calculated emissions for selected Rhine kilometres are shown in Table 5.

Table 4: Extract of the ship data used for the calculation of the NO_X-Emissions on the Rhine. *The total NO_X-Emission shown is computed for the Rhine-Kilometre 782 for the year 2018. The same computation has been carried out for each observed Rhine-Kilometre.*

Rhine-Kilometre	Ship class	Direction	Speed over ground [m/s]	Time per km [s]	Emission Factor NO_X [g/s]	Emission NO_X [g]
			v	(1/v)*1000=t	EF_{NOX}	$t*EF_{NOX}$
782	IV (85m)	upstream	4	250	2.25	563
782	Va (110m)	downstream	6	167	2.27	379
782	Va (110m)	downstream	5	200	2.19	438
782	IV (85m)	upstream	3	333	2.03	676
…	…	…	…	…	…	…
Total NO_X Emission per year at Rhine-Kilometre 782:						59 t

Table 5: Emissions of moving inland vessels on the Rhine at different Rhine-Kilometres.

	NO_X-Emissions of Inland Vessels per Rhine-kilometres [t/yr]		
Rhine-Kilometre	2018	2019	2020
730	36.3	35.8	no data
740 (Neuss harbour)	53.3	49.0	no data
750	47.2	42.9	no data
772	45.5	42.4	39.6
782 (Duisburg harbour)	85.7	50.1	50.0
792	57.7	48.4	47.1

The results of the calculations with the described new method show, that 3,743t NO_X (1,643t NO_X at Düsseldorf/Neuss and 2,100t NO_X at Duisburg) were emitted by moving inland vessels in the study area Neuss/Düsseldorf-Duisburg for the year 2018.

Emissions from moving vessels in the ports of Duisburg and Neuss

As with the calculations for the Rhine, the calculation of the emissions of the moving inland vessels in the ports of Neuss and Duisburg for the year 2018 was based on the AIS-signals of the vessels. They delivered information about the average speed, the individual ship classes, the number of ships handled in the examined year in the respective ports, separated by the ship class and the positions of the ships in the ports at which they had moored.

In addition, emission factors were determined for the individual ship size and speed classes, as described above. Furthermore, the official number of ships were requested from the port operators. These were not available separated by ship class, so the AIS-data were scaled using the official figures, so that the distribution of ship classes from the AIS-data could be used, but the number of ships still corresponded to the information received from the port operators.

As in the calculations for the Rhine, the times required to cover the distances in the ports were calculated from the speed of the ships. Table 6 shows the mean speed over ground and the emission factors for the distinct ship classes, which were used in the calculations of the emissions.

Table 6: Speed class and Emission factors used for the calculation of the emissions of the moving vessels in the ports of Duisburg and Neuss.

Harbour	Ship class	Speed class of vessels [m/s]	Emissions factor [g/s]
Duisburg	I Freighter and Tanker	2.5	0.31
	I other ships	2.5	0.56
	II	2.5	0.45
	III	1.5	0.55
	IV	1.5	0.5
	Jowi Class	1.5	0.55
	Coupled units	1.5	0.63
	Va	1.5	0.52
	Vb	1.5	0.57
	VIa	1.5	0.62
	VIb	1.5	0.37
	VIc	1.5	0.38
	not classified	1.5	0.63
	Unclassified large	1.5	0.63
Neuss	I Freighter and Tanker	0.5	0.42
	I other ships	1.5	0.27
	II	1.5	0.43
	III	1.5	0.55
	IV	1.5	0.5
	Jowi Class	0.5	0.39
	Coupled units	0.5	0.32
	Va	1.5	0.52
	Vb	0.5	0.36
	VIa	0.5	0.34
	VIb	0.5	0.14
	VIc	0.5	0.38
	not classified	1.5	0.63

With this information, it was possible to assign a speed class and an emission factor to each ship according to the ship size class. Emissions were then calculated separately for each ship by multiplying the time required to cover the distances in the port by the respective emission factor. The overall emissions were finally calculated from the sum of the partial emissions of all ships.

When calculating the emissions, it had to be taken into account that the ships are not evenly distributed in the port. Some ships, for example, sail through the entire harbour, right into the farthest basin, while others moor relatively close to the harbour entrance. This was addressed as described below.

Since the ships sail through different areas of the harbour, line sources were defined that describe the travel path in the harbour area (Figure 16, Figure 17).

Figure 11: Defined Emission line sources of moving vessels in the port of Duisburg.

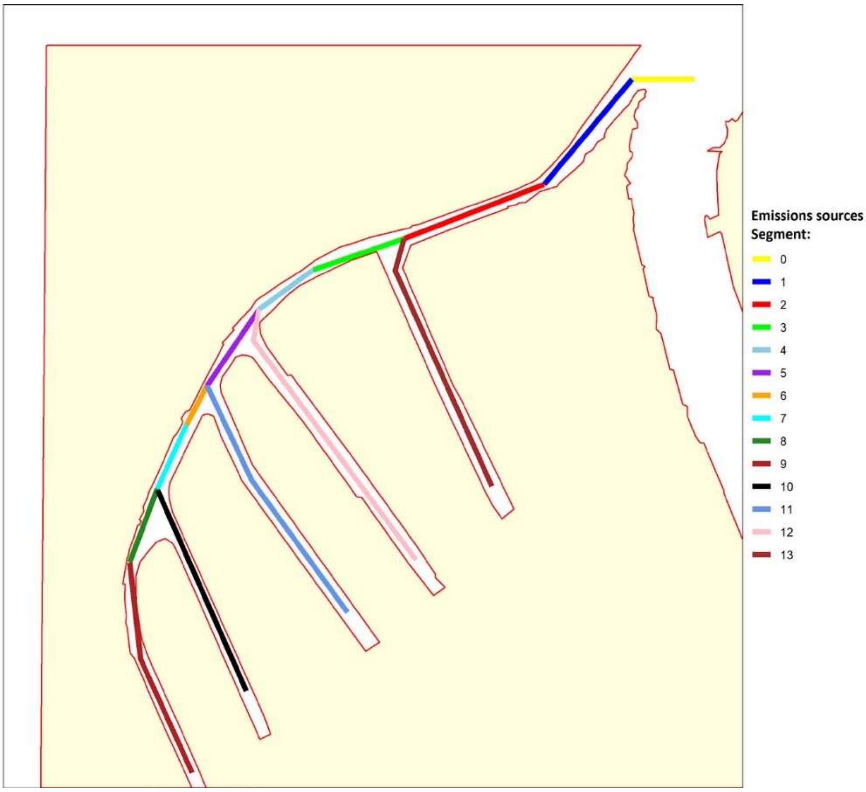

Figure 17: Defined Emission line sources of moving vessels in the port of Neuss

For the differently coloured segments in these graphs, the emission contributions of the individual ships were added up separately, taking into account that only some of the ships pass each individual segment. Thus, in the port of Neuss, all ships entering the port still pass-through segment 0, whereas segment 13 is only sailed through by ships that continue all the way to basin 1. Figure 18 and Figure 19 show which ships were considered in the respective line segment.

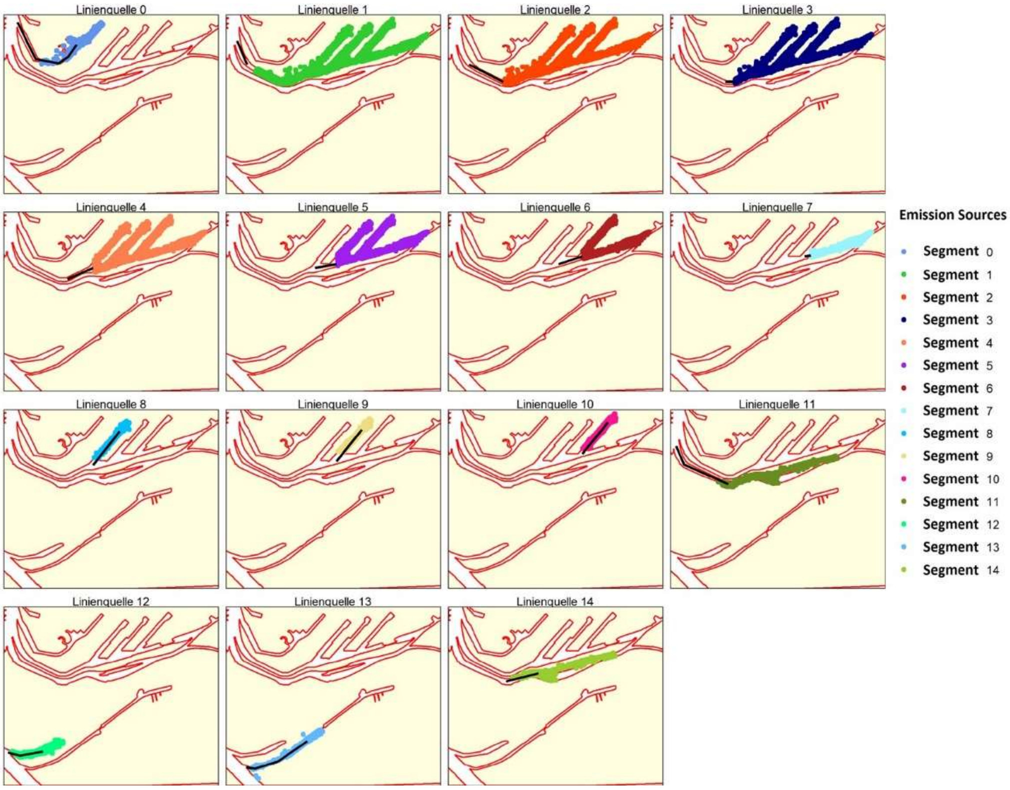

Figure 12: Assignment of ships to the line sources of the shipping routes in the port of Duisburg. The black lines show the individual emission sources and the coloured points show the ships which were considered in the calculation of the specific emission source.

For all, but the locked vessels, it was assumed that each vessel entering the port would leave by the same route, so the emissions for each line source segment were multiplied by a factor of two. Table 7 shows the calculated emissions.

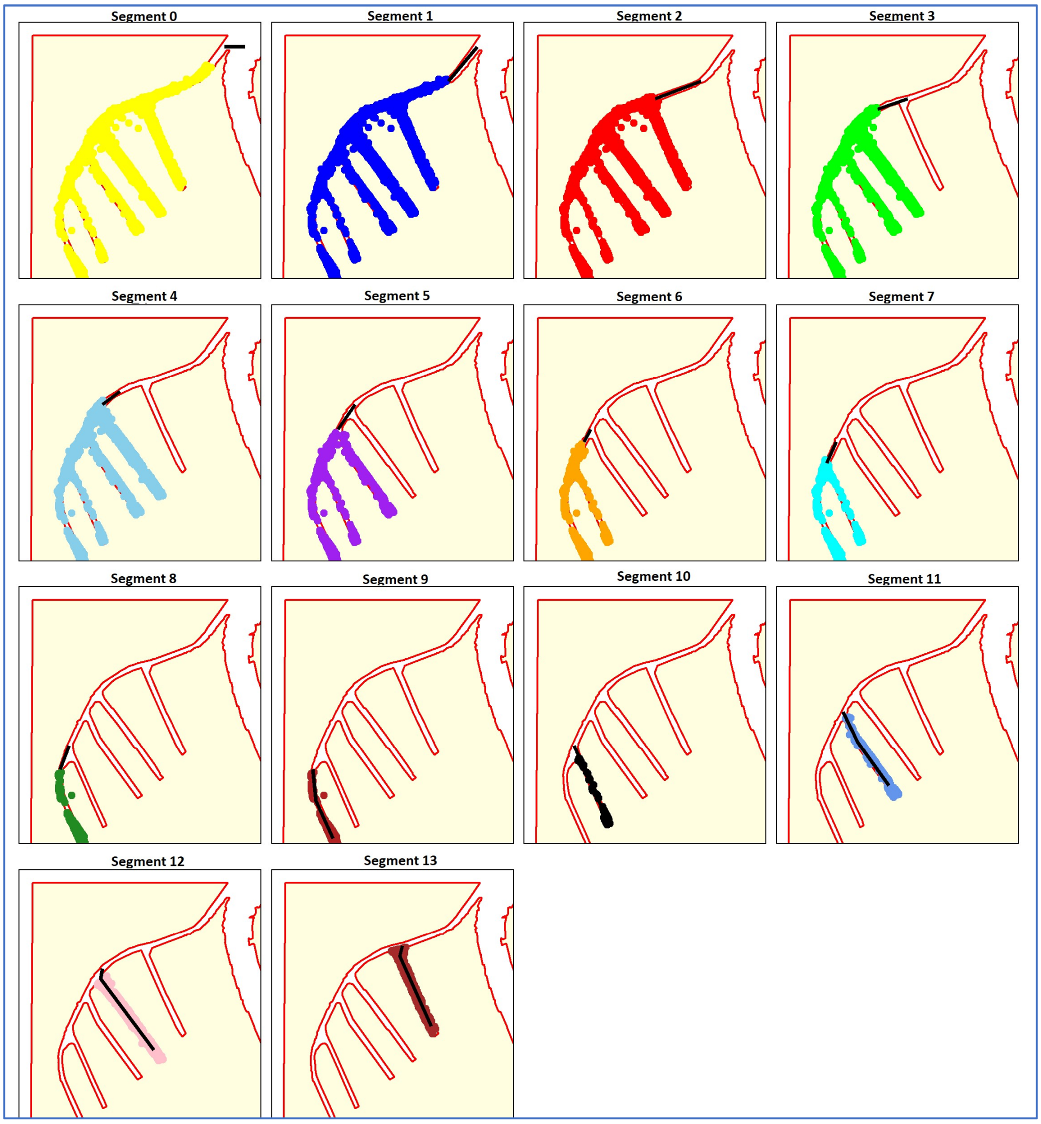

Figure 13: Assignment of ships to the line sources of the shipping routes in the port of Neuss. The black lines show the individual emission sources and the coloured points show the ships which were considered in the calculation of the specific emission source**.**

Table 7: Total NO_x emission caused by driving vessels in t/a for each segment (DURH and NERH)

Harbour	Emission Source	NO_x-Emission [t/a]
Duisburg	Segment 0	4.9
	Segment 1	4.9
	Segment 2	7.3
	Segment 3	1.7
	Segment 4	5.0
	Segment 5	2.7
	Segment 6	2.9
	Segment 7	0.7
	Segment 8	2.3
	Segment 9	0.4
	Segment 10	0.7
	Segment 11	2.1
	Segment 12	1.9
	Segment 13	3.3
	Segment 14	0.4
	total	41.2
Neuss	Segment 0	1.6
	Segment 1	3.5
	Segment 2	3.8
	Segment 3	1.6
	Segment 4	1.0
	Segment 5	0.6
	Segment 6	0.2
	Segment 7	0.4
	Segment 8	0.3
	Segment 9	0.9
	Segment 10	0.2
	Segment 11	0.4
	Segment 12	2.0
	Segment 13	2.1
	total	18.6

The results show that in 2018 around 41 t NO_x were emitted by moving ships in the port of Duisburg. For the port of Neuss, the results show an emission quantity of nearly 19 t NO_x for the same year (Table 7).

6. Conclusion

Within the CLINSH project, a new method for the calculation of inland vessel emissions was developed, which, by using AIS data and onshore emission factors, makes it possible to determine the calculations based on actual registered ship data. This new method offers the possibility to eliminate existing uncertainties that are present in the current emission register for inland vessels in NRW due to necessary estimations. The method could already be applied based on emission calculations for moving ships on the Rhine and in the ports of Duisburg and Neuss. It is planned to use this procedure for the future update of the inland waterway vessel emission register of the state of North Rhine-Westphalia for the determination of emissions.

7. Outlook

Previous estimates of emissions from inland navigation, required making a variety of assumptions about shipping traffic, motorisation, ship speed, fuel consumption and emission behaviour of the respective engines, as direct emission measurements of real traffic were not available.

Each of these assumptions naturally also has a certain margin of error. If a large number of assumptions are included in such estimates, large uncertainties can arise in the resulting emissions.

The newly developed method offers the possibility of estimating NO_X emissions from inland navigation more realistically on the basis of direct onshore measurements.

An important basis for this is the recording and classification of real ship traffic according to ship size class, speed over ground and uphill/downhill travel. Thus, for the first time, data of real shipping traffic are available for an estimation of emissions.

With the automatic measuring stations, it was possible to record the NO_X emission peaks of the passing ships for more than 19,000 ship passages in the years 2018-2020 with suitable wind direction and to identify the causing ships using AIS data. Using the Gaussian-Puff-Model, it was possible to calculate emission factors from these onshore measurements. Thus, about 19,000 onshore emission factors are available for classification according to ship size class, speed over ground and upstream/downstream travel, which can be used to determine emissions from all shipping traffic. Another advantage of these factors is that not only the emissions of the main engine, but also the emissions of auxiliary units such as bow thrusters, etc. are included.

The emission factors collected in 2018-2021 have already been applied by LANUV for the port areas of Duisburg and Neuss/Düsseldorf within the framework of CLINSH to calculate shipping-related emissions. The method and results are presented in this report in Chapter 3.

Further explanations are also compiled in the CLINSH report of the LANUV "Harbour monitoring Part C: Emission inventories of the Neuss and Duisburg port areas" and in the LANUV "Technical report 123: Harbour monitoring Part B: Emission inventories of the Neuss and Duisburg port areas".

In the meantime, the measuring results of the DURH measuring station in Duisburg on the Rhine for the year 2021 have also been evaluated. This results in about 8,000 additional emission factors for the passing ships.

When updating the emission factors with these new data, there are only minor changes in the first decimal place and more often only in the second decimal place. At the same time, the number of observations increases considerably, especially for the most common ship classes (IV (85 m); Va (110 m) and Vb (135 m)), which together account for more than 80 % of the shipping traffic on the Lower Rhine.

The continuous measuring station in Duisburg will remain in operation in the coming years. It is planned to continue evaluating the measurements in the manner described in this report in order to improve the quality of the derived emission rates.

The LANUV will carry out the upcoming update of its emission register "Inland vessels" both on the basis of recording real ship traffic via the evaluation of AIS signals and on the application of the ships' emission factors for NO_X measured onshore

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- *“Harbour Monitoring Part A: Air quality on the Rhine and in the inland ports of Duisburg and Neuss/Düsseldorf. Immission-side effect of emissions from shipping and port operations on nitrogen oxide pollution" (already published)*
- *"Harbour Monitoring Part B: Determination of NO_X and particulate matter emissions from inland vessels at berth" (already published)*
- "Harbour Monitoring Part C: Emission inventories for the ports of Duisburg and Neuss/Düsseldorf"
- "Harbour Monitoring Part D: Analysis of shipping traffic on the Rhine for the years 2018-2020”
- “Harbour Monitoring Part E: Determination of NO_X emission rates of passing vessels from onshore measurements, comparison to onboard observations and application for emission calculations”
- "Harbour Monitoring Part F: Root Cause Analyses for Air Quality Measurement Results in the Inland Ports of Neuss and Duisburg)”

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Visiting address
Provinciehuis Zuid-Holland
Zuid-Hollandplein 1
2596 AW The Hague
The Netherlands

Mailing address
Provincie Zuid-Holland
Postbus 90602
2509 LP The Hague
The Netherlands

Visiting address
Provinciehuis Zuid-Holland
Zuid-Hollandplein 1
2596 AW The Hague
The Netherlands

Mailing address
Provincie Zuid-Holland
Postbus 90602
2509 LP The Hague
The Netherlands