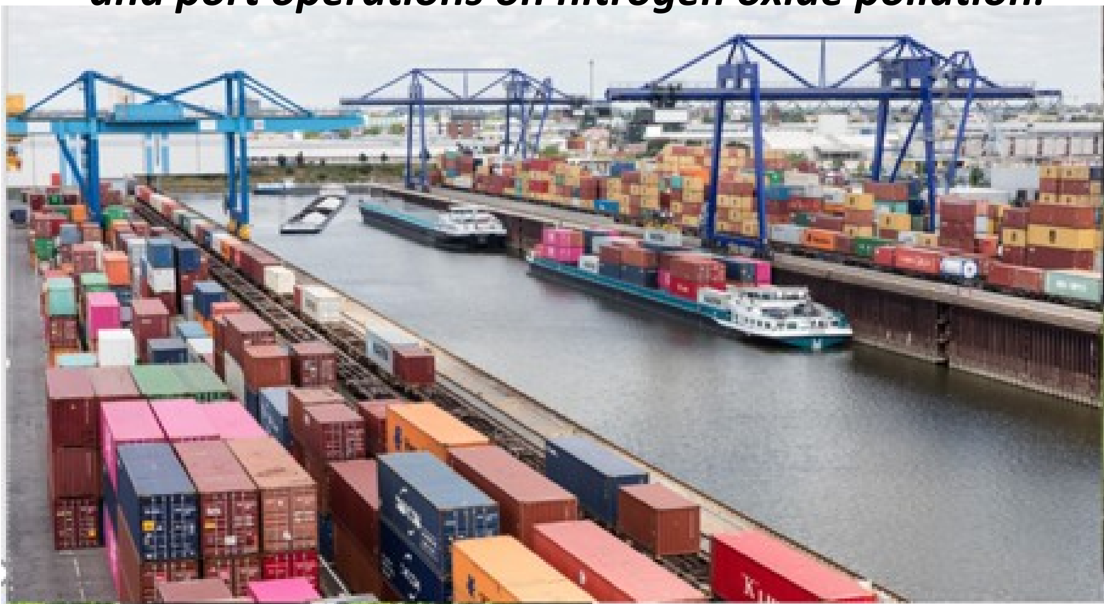
CLINSH

SUSTAINABLE WATERWAY TRANSPORT, CLEAN AIR

B 4: Modelling, evaluating and scenario building

Harbour monitoring: Air quality on the Rhine and in the inland ports of Duisburg and Neuss/Düsseldorf.

Part A: *Immission-side effect of emissions from shipping and port operations on nitrogen oxide pollution.*



CLEAN INLAND SHIPPING

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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.

Project reference: LIFE15 ENV/NL/000217

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B.4 Modelling, evaluating and scenario building

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

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CLINSH moves it forward !
(Push boat at Duisburg, Photo: D.Busch, LANUV)

1. Introduction

Ensuring good quality of the air we breathe is one of the essential foundations of human health. Therefore, in the "Directive on Ambient Air Quality and Cleaner Air for Europe" (2008/50/EC)[1], the EU established limit values for particulate matter (PM_{10}: annual mean 40 µg/m³, maximum exceedance of 50 µg/m³ on 35 days/a) and nitrogen dioxide (NO_2: annual mean 40 µg/m³, maximum exceedance of 200 µg/m³ on 18 hours in a calendar year) that are binding for all Member States. For Germany, the directive was made binding by the 39th BImSchV[2].

With 18 million inhabitants, the federal state of NRW has the highest population of all German federal states. Around ten million inhabitants live in the Rhine-Ruhr metropolitan region, making it one of the most densely populated regions in Europe. In such densely populated metropolitan areas, the air is polluted by a variety of pollution sources (such as industry, domestic heating, road traffic, planes, etc.). There are eleven major cities in NRW directly on the Rhine with about 3.3 million inhabitants. The six largest cities on the Rhine are Cologne (1.1 million), Düsseldorf (0.6 million), Duisburg (0.5 million), Bonn (0.3 million) Krefeld (0.2 million) and Neuss (0,16 million). In these cities, the limit values of the EU Air Quality Directive for NO_2 could not be met for many years due to the high road traffic pollution, so that air pollution control plans had to be drawn up and updated[3,4,5,6,7,8]. These plans also included root cause analyses and measures to reduce NO_2 pollution.

In these cities along the busy Rhine waterway, the diesel engines of inland navigation are also a significant source of emissions. The amount and effect of these emissions on air quality are also influenced by factors such as fleet composition and age of engines, traffic density, river morphology and location and equipment of berths.

In the discussion about suitable measures to reduce pollution, NO_X emissions from inland vessels have therefore also become the focus of public debate [9,10,11,12,13]. One of the theses was that inland vessels could be one of the main causes of the limit value exceedances for NO_2 occurring in the conurbations. At first glance, this thesis did not seem implausible, since calculations with the "older" version of the state's own "Emissions register for inland shipping in NRW" (Emissionskataster für den Schiffsverkehr in NRW)[14] showed high emission levels from inland vessels for the affected cities on the Rhine in the overall balance.

Even though the NO_2 pollution has decreased significantly in 2020 and the limit values were complied with for the first time at all official state measuring stations, the safe compliance with the annual mean value for NO_2 (40 µg/m³) is still a challenge in the urban agglomerations. For precautionary reasons, the pollution must be further reduced by suitable measures in order to ensure compliance with the limit values in the future. The question thus remains relevant.

The German inland waterway fleet has an average age of over 50 years, and the propulsion engines used are on average more than 30 years old[15]. In the past, emission regulations for ship propulsion systems were less stringent than for trucks. More recent regulations, such as in the EU's NRMM (Non Road Mobile Machines) Directive 2016/1628[16], only apply to new ships or when the old engine on an older ship is replaced by a new engine. The older engines are grandfathered for the remaining period of use and therefore only have to comply with the emission regulations applicable in their year of construction. For many ship propulsion systems, therefore, no binding emission requirements apply at all. Therefore, significant reductions in ship emissions through routine fleet renewal are not to be expected in the short term for inland navigation.

Similar to vehicles in road and rail transport, inland vessels are also inspected for safety and functionality at regular intervals. Ship owners are free to choose in which EU Member State they want their vessels to be inspected. Within the framework of administrative assistance, LANUV NRW queried the data available in the German ZBBD database (German Ship Inspection Commission) on the engines and generators of the ships inspected by the Commission(15). The data used was mainly from German ships, but about 100 Dutch and Belgian ships are also included. In total, data sets were available from 304 tanker vessels and 670 cargo motor vessels. For 291 tank motor ships and 622 cargo motor ships, information was available on the year of construction of the ship propulsion systems. The average age of the engines of the cargo ships was 37.5 years and for the tankers 22 years.

Unfortunately, the data from the Dutch and Belgian inspection commissions could not be made available to the LANUV for further evaluation within the framework of administrative assistance. The inclusion of additional Dutch and Belgian data would have led to an even more reliable result. Nevertheless, due to the relatively high number of vessels with regard to the age of the main engines and the associated emission regulations, the evaluation of the German ZBBD database provides a representative picture of the current engine stock of the fleet that can be used for the emission estimates. Tab. 1 shows the evaluated data of the ships, separated into cargo and tanker vessels.

More detailed evaluations of the age, performance and emission requirements of the propulsion engines and generators on the inland vessels of the different length classes can be found in the already available LANUV contribution to CLINSH **"Harbour monitoring Part B: Determination of NO_X and particulate matter emissions from inland vessels at berth"**(17). The above-mentioned contribution has already been published on the CLINSH homepage and the LANUV homepage and can be viewed there.

The official measurements for the EU Directive (2008/50/EC)(1) have so far mainly referred to the measurement of air pollution on busy multi-lane roads with multi-storey and narrow peripheral buildings, as it was known that "hotspots" of pollution, directly affecting the residents, must be assumed here. The contributions of shipping have not yet been the focus of detailed official measurements. Within the framework of "CLINSH", the opportunity arose to carry out an intensive measurement programme on air pollution caused by intensive shipping traffic in ports and on the busy section of the Rhine in North Rhine-Westphalia.

For this purpose, measuring stations were set up on the German-Dutch border and also on the border to Rhineland-Palatinate directly on the Rhine. With these measuring points, an impression of the air pollution caused by shipping traffic could be gained directly on the shore. The focus of the investigations for CLINSH was a special measuring programme on air quality in the largest inland port in Central Europe in Duisburg and in the second largest inland port in North Rhine-Westphalia in Neuss/Düsseldorf. The programme ran from December 2017 to May 2019.

Cargo vessels	Size Class of ships					
	< 40 m	41-67 m	58-67 m	68-86 m	86-110 m	> 110 m
Number of ships (Total)	14	29	69	361	185	12
Year of construction	1876-2002	1884-2017	1902-1965	1889-1996	1897-2017	1970-2007
Mean year of construction	1943	1948	1945	1950	1974	1989
Mean age (years)	77	72	75	70	46	31
Main engine						
Power range (kW)	65-353	121-780	147-616	276-1491	456-2700	993-2030
Average power (kW)	230	302	383	616	1066	1281
Year of construction	1957-2014	1937-2018	1950-2017	1949-2019	1959-2019	1972-2006
Mean year of construction	1985	1979	1969	1980	1997	1996
Mean age (years)	35	41	51	40	23	24
With Emission stage (%)	1 (7%)	5 (17%)	3 (4%)	79 (22%)	89 (48%)	3 (28%)

Tanker vessels	Size Class of ships				
	< 40 m	41-67 m	68-86 m	86-110 m	> 110 m
Number of ships (Total)	37	9	118	135	5
Year of construction	1886-2017	1937-2016	1954-2016	1956-2015	1990-2009
Mean year of construction	1955	1969	1993	1996	2003
Mean age (years)	65	51	27	24	17
Main engine					
Power range (kW)	71-447	221-632	315-1492	588-2236	1491-2290
Average power (kW)	224	389	778	1164	1681
Year of construction	1955-2018	1958-2016	1957-2018	1961-2016	2001-2008
Mean year of construction	1992	1985	2000	2001	2005
Mean age (years)	28	35	20	19	15
With Emission stage (%)	11 (30%)	3 (33%)	76 (64%)	82 (61%)	4 (80%)

Tab. 1: Data on inland vessels and their propulsion engines after evaluation of the data for CLINSH from the German ZBBD Database 2019 [15].

As the particulate matter concentrations measured in NRW as part of the state measuring network had already been regularly below the EU limit values for years, the CLINSH measuring programme concentrated on investigating air pollution with NO_2. In order to be able to differentiate the pollution in the ports more precisely, a very high density of measuring points was chosen in the special measuring programme for CLINSH.

2. Portrait of the ports

2.1 Duisburg: duisport - leading logistics hub in Central Europe(18)

Company name: Duisburger Hafen AG

Year of foundation:	**1926**
Size of workforce:	**approx. 1.500**
Annual turnover: (2019)	**292,6 Mio euros**
Annual throughput:	**123,7 Mio t**
Industry:	**Logistics**

duisport
excellence in logistics

The Duisburger Hafen AG is the ownership and management company of the Port of Duisburg, the world's largest inland port. With a total throughput of over 123.7 million tonnes and 4.0 million TEU (2019), the Port of Duisburg is the leading logistics hub for cargo handling in Central Europe. As a trimodal logistics hub, duisport combines an optimal geographical location, good site conditions and comprehensive logistics know-how.

We are the network - With a wide range of logistics services, the Port of Duisburg offers companies, operating at the location, the best conditions for handling goods. Eight multimodal container terminals, more than 400 weekly train connections to around 100 direct destinations in Europe and Asia as well as extensive warehouse and storage capacities are linked on site with market and customer-oriented services.

With this approach, the ***duisport* Group** covers a wide range of services and acts as a full-service provider. In addition to the handling of goods (including merchandise in containers, imported coal, iron/steel, mineral oil/chemicals), the offer includes settlement management, the development of integrated port and logistics concepts, intermodal transport services and specialized industrial goods packaging.

Together with partners, ***duisport*** is developing transcontinental train connections, for example along the "New Silk Road" trade route between Duisburg and China. Today, around 60 trains a week already run between the Port of Duisburg and almost two dozen destinations such as Shanghai, Wuhan or Chongqing. In the area of packaging logistics, logistics services are provided worldwide for mechanical and plant engineering - for example, with its own locations in Belgium, the Netherlands, France, China or India.

This makes the ***duisport* Group** both the national and the international connecting axis between producers and customers, it links markets and is a driver for regional and global flows of goods. The company sees itself as a partner of the logistics industry and makes decisive contributions to the optimization of transport chains. To this end, concepts and solutions, tailored to the most diverse customer requirements, are developed and implemented. This concept benefits in particular the more than 300 logistics-oriented companies located in the Port of Duisburg, which generate an annual value added of around 3 billion euros. In total nearly 50,000 jobs in the Rhine-Ruhr region depend on the Port of Duisburg - and the trend is rising. According to ***duisport***, around 9,855 tankers and cargo ships called at the inland port of Duisburg (including the Ruhr estuary, parallel port and outer port) for loading or unloading in 2018.

2.2 Neuss: RheinCargo – Young company with tradition [19]

Company name:	**RheinCargo GmbH**
Year of foundation:	**2003**
Size of workforce:	**approx. 650**
Annual throughput:	**(2019) 50 Mio. t**
Industry:	**Logistics**

The Rhine not only separates the neighbouring cities of Neuss and Düsseldorf, it also connects them. Both port cities have been shaped by the river since the beginning of their settlement. Both cities laid the foundation for their industrial port in the 19th century. Today, on both sides of the river, **RheinCargo GmbH & Co. KG** runs the operational port and rail business here.

Founded in 2012, **RheinCargo** is a joint venture between **Neuss-Düsseldorfer Häfen GmbH & Co. KG** and **Häfen und Güterverkehr Köln AG**. **RheinCargo** combines port logistics, rail freight transport and real estate leasing in six Rhine ports in Neuss, Düsseldorf and Cologne. On a port area of almost 700 hectares, the company handles around 50 million tonnes annually. More than 650 employees work for the company. **RheinCargo** offers its customers tailor-made trimodal logistics services and all port services from a single source. The environmentally friendly transport modes of ship and rail play a fundamental role in this.

The close connection of the state capital to shipping and fishing is also underlined by the anchor symbol in the city's coat of arms. On 9 November 1886, the city council decided to build an industrial harbour in the area of the so-called "Lausward", a sub-area of today's Hafen district. The harbour was ceremoniously opened on 30 May 1896.

On the opposite bank, the Neuss city administration commissioned the Berlin engineering firm Havestadt & Contag in 1894 to further develop the side arm of the Rhine that had been used as a harbour since 1835. The concept laid the foundation for the bifurcated Neuss harbour system, that exists today parallel to the harbour basin 1. Over 100 years, both harbours continued to develop. Neuss continuously expanded its harbour with four additional harbour basins. With the development and expansion of its media port, Düsseldorf has shown since the 1980s how modern urban development and industrially used areas can be combined.

The first merger plans for the two ports were already in place in the 1920s and 1940s. In 1994, Stadtwerke Düsseldorf AG, Städtische Hafenbetriebe Neuss and Deutsche Bahn AG commissioned an expert opinion on the consolidation of combined cargo transport in the Neuss-Düsseldorf area. Among other things, due to the above-average traffic potential and the operation of four transshipment terminals in a very confined space, the report recommended a consolidation of the two ports in partnership as "absolutely necessary". In view of the strong competition, this is the right strategy to jointly master the challenges of the future.

On 1 January 2003, the two port companies then merged to form Neuss-Düsseldorfer Häfen GmbH & Co. KG (NDH). The shareholders are Stadtwerke Neuss GmbH and Stadtwerke Düsseldorf AG.

According to the port operator, around 799 tankers and 5,986 cargo ships called at the Port of Neuss in 2018.

Fig. 1: Aerial view of Neuss-Düsseldorf port (Photo: Rheincargo)

3. Measuring methods and measuring points

To determine the pollution of the air with nitrogen oxides, the LANUV NRW uses two different methods in official air quality monitoring, which were also applied in the CLINSH measurement programme. In NRW, immission measurements of nitrogen dioxide are carried out both with the reference method specified by the **EU Directive 2008/50/EC "on ambient air quality and cleaner air for Europe"**(1) and with the so-called passive sampler method according to DIN EN 16339 **"Air quality method for the determination of the concentration of nitrogen dioxide by means of passive samplers"**(20,21,22). The passive sampler method according to DIN EN 16339 is recognized as equivalent for official measurements for the EU Directive.

3.1 Discontinuous measurements with passive samplers in the ports

In this procedure, two passive samplers (tubes) are always placed in a weatherproof box, hanging from existing poles (e.g. lampposts) at each measuring location and replaced after approx. four weeks. The mean value is calculated from the results of the double samples as the result of the sampling period.

The measurement results generated in this way per year are combined to form an annual mean value. The targeted exposure time of 28 days cannot always be met for logistical reasons. For this reason, the annual mean is calculated as a weighted annual mean proportional to the respective sampling period of the monthly individual results. The coordinates of the measuring points and the data of the individual runs can be found in the appendix (A_Tab_1a and 1b as well as A_Tab_2a and 2b).

Fig. 2: Passive collector: weatherproof box with two collection tubes inserted (Photo: LANUV NRW)

3.2 Continuous measuring stations

In addition to the passive samplers, the LANUV had the opportunity to deploy two additional stations measuring nitrogen oxides automatically at short intervals (every 5 seconds) after the start of the CLINSH project. At the end of 2017, a continuously measuring station was installed in the port area of Neuss as well as in Duisburg, which made high-resolution measurements of nitrogen oxides (NO and NO_2, sum NO_X), the recording of fine dust pollution and data on meteorology possible.

As a rule in NRW, air is sucked in at a height of 3.5 m above ground during continuous measurements and fed through sampling lines to the measuring stations at the individual measuring points. Data collection at the stations takes place at five-second intervals. Extensive information on the measuring stations of the LANUV and aggregated current measurement results of these two stations were or are continuously available on the internet on the homepage of the LANUV[(23,24)]. An annual mean value can also be calculated from these results.

The measurement results of these stations form a valuable basis for the temporal analyses of the load courses and also for the elucidation of the location of load sources and their quantitative shares in the measurement results.

The **Duisburg measuring station (Rhine port, DURH, Rhine km 782)** is located in Duisburg-Laar on the Rhine dike below the entrance to the port channel of the Port of Duisburg. It is located on the leeward bank (main wind direction) at a distance of about 150 m from the Rhine and is therefore particularly suitable for investigating emissions from ships sailing on the Rhine.

Fig. 3: Automatic measuring station on the Rhine in Duisburg (Photo: D. Busch, LANUV)

The **Neuss (Rheinhafen, NERH) measuring station** was located on the premises of the company UCT (Transshipment Container Terminal) in the Neuss port area, directly on the quay wall of the Rhine Canal, the access to the four Neuss port basins. This measuring station was therefore particularly well-suited for investigating the emissions of ships, travelling in the port traffic. It was dismantled again at the turn of the year 2019/2020.

Fig. 4: Interior view of a measuring container with measuring and recording devices (Photo: LANUV)

3.4 Procedure for determining background pollution in NRW

The officially applicable assessment standard for air pollution in Germany is set by the 39th BImSchV(2). The limit values of the ordinance apply to publicly accessible areas such as residential areas, where people spend all day. However, the 39th BImSchV also lists exceptions. The immission limits are not assessed *"at locations within areas to which the public has no access and where there is no permanent residential accommodation"*. Many of the measuring points in the port area are located on such company premises or commercial areas without public access, so that these values there do either not necessarily have to be complied with.

The air pollution at a measuring point is usually composed of both an already existing basic pollution of the air bodies carried by the wind (background pollution) and the emission sources acting locally on these air bodies (e.g. road traffic, domestic heating, etc.). These add up to the background pollution and then lead to the locally measurable air pollution.

As a rule, in all regions of the EU there is already a basic level of NO_2 and PM_{10} in the air, even without the influence of local or regional emission sources. This pollution originates both from the long-distance transport of emission quantities from other regions by wind and from the area-wide dispersion of emissions from supra-regional sources. Before evaluating the measurement results obtained, the so-called "background pollution" present everywhere in the study area (here: conurbations on the Lower Rhine) must first be determined.

Added to this is the so-called "urban" additional pollution. For example, emissions from road traffic in a large city not only have an effect directly at the roadside, but the emissions on all city streets, from house heating, construction machinery, etc. also increase air pollution in other places, e.g. in city parks or cemeteries. These rather large-scale burdens are also described as urban additional pollution. This pollution is naturally higher in densely populated regions such as the Rhineland than in small towns in sparsely populated regions such as the Eifel or the Rothaargebirge.

In order to be able to assess the effect of the various local emission sources within the framework of official air monitoring, the regional background pollution has to be known. Since it is not possible to set up suitable background measuring points for all measuring locations in NRW, the LANUV operates a few representative background measuring points with the lowest possible local emission effects.

For modelling purposes in the context of clean air planning, the LANUV determines the magnitude of the **background pollution for the Rhineland** from the mean value of six representative background-measuring stations, not directly dominated by road traffic in Datteln, Düsseldorf-Loerick, Hattingen, Hürth, Cologne-Chorweiler and Wesel. The concentrations of NO_2 and particulate matter (PM_{10}) measured here and the background pollution levels determined from it are compiled for the years 2018-2020 in Tab. 2.

This resulted in a calculated background pollution for the Lower Rhine (Duisburg, Neuss, Bad Honnef) of about 21 µg/m³ NO_2 for the year 2018. The decreasing trend is clearly visible at all measuring points and thus also at the "background load" in the following years. The regional background in the Rhineland for NO_2 fell in the annual mean from 21 µg/m³ in 2018 to 17 µg/m³ in 2020. A clearly decreasing trend in the annual mean from 18 to 14 µg/m³ can also be observed for particulate matter (PM_{10}) (Tab. 2).

Annual parameters for background pollution NO_2 in µg/m³				
Station	**Station identifier**	**Year**		
		2018	**2019**	**2020**
Datteln-Hagen	**DATT**	18	17	16
Düsseldorf Loerick	**LOER**	25	22	19
Hattingen-Blankenstein	**HATT**	17	16	14
Hürth	**HUE2**	21	20	16
Köln-Chorweiler	**CHOR**	24	23	20
Wesel-Feldmark	**WESE**	21	19	--
	Mean (µg/m³)	**21**	**20**	**17**

Annual parameters for background pollution fine dust (PM_{10}) in µg/m³				
Station	**Station identifier**	**Year**		
		2018	**2019**	**2020**
Datteln-Hagen	**DATT**	21	19	18
Düsseldorf Loerick	**LOER**	17	14	13
Hattingen-Blankenstein	**HATT**	15	13	13
Hürth	**HUE2**	19	17	15
Köln-Chorweiler	**CHOR**	18	16	15
Wesel-Feldmark	**WESE**	20	16	--
	Mean (µg/m³)	**18**	**16**	**15**

Tab. 2: Development of background pollution and derivation of the average background pollution for NO_2 and particulate matter in the Rhineland for the years 2018-2020 as calculated by the LANUV.

4. Implementation and results of the measurement projects

4.1 Influence of inland vessels on air quality directly on the banks of the Rhine

The aim of the study was to record the NO_2 pollution of the air directly on the banks of the Rhine by means of passive samplers. Two sections of the Rhine at the borders of North Rhine-Westphalia were suitable for this investigation.

The place with the highest traffic density of inland vessels in NRW is the German-Dutch border in the area of Bimmen/Lobith. Here, usually more than 100,000 ship movements per year are registered (Tab. 3). It is therefore to be expected that in NRW the effect of ship emissions on air quality in the riparian zone is highest in this area.

Also at the border of NRW to Rhineland-Palatinate, the influence of ship traffic to and from NRW as the section with the lowest traffic density of inland vessels on the Rhine in NRW was also investigated.

On both stretches of the Rhine, the LANUV maintains a permanently staffed water laboratory for the continuous monitoring of the Rhine to ensure the drinking water supply, so that passive samplers for CLINSH could be installed in part directly on the sampling rafts or close to the Rhine. The supervision of the measuring points and the sampling could also be ensured by specialized personnel on site.

4.1.2 Measurement programme in Bimmen/Lobith

4.1.2.1 Monitoring sites

In the area of the German-Dutch border (Bimmen/Lobith-Tolkamer), the LANUV has been operating the German-Dutch water monitoring station (IMBL= International Monitoring Station Bimmen-Lobith) together with the Dutch RIJKSWATERSTAAT for many years. In order to be able to continuously check the quality of the Rhine water here, sampling rafts have been installed on the left (Rhine km 865) and right (Rhine km 863.3) bank of the Rhine. The Rhine is about 400 m wide at Bimmen/Lobith.

These sampling rafts were an ideal location to also install air sampling points (passive samplers) on the Rhine on the left, windward bank (Bi_raft) and the right, leeward bank (Lob_raft). The sampling height was about 2 m above the water level. With these measuring sites, the effect of ship emissions on NO_2 concentrations in the air can be recorded well without direct influence of road traffic (Fig.5).

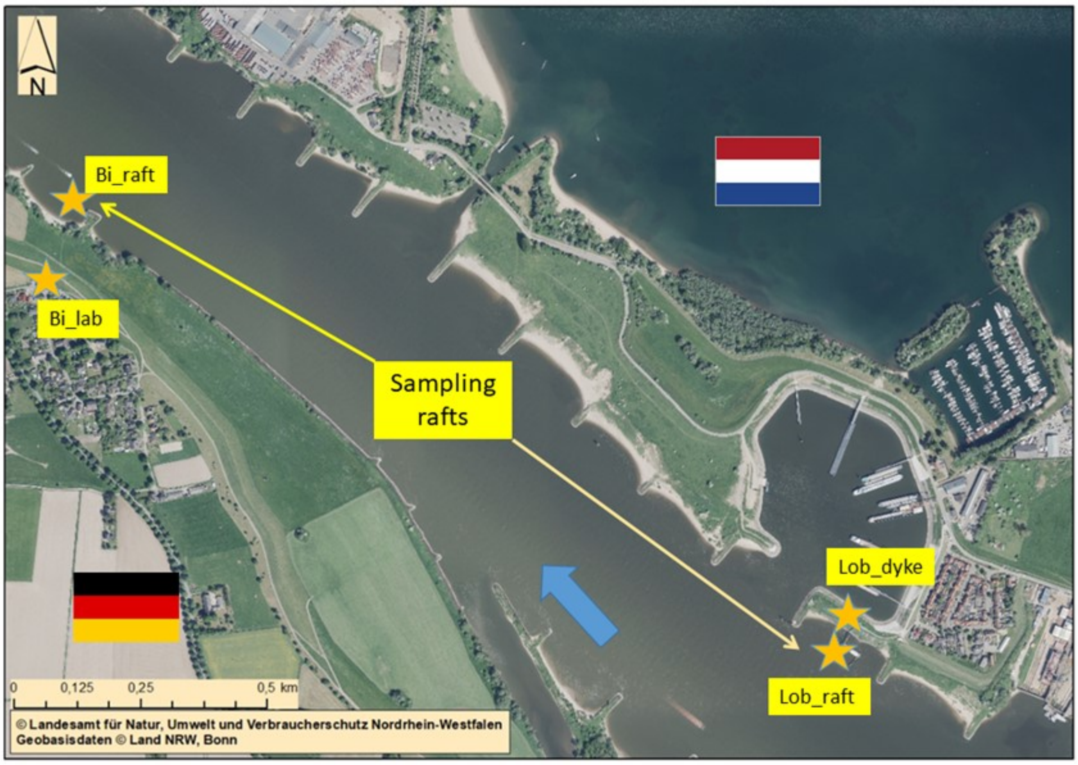


Fig. 5: Measurement sites on the German-Dutch border

Bimmen is a small, rural village on the left (German, western) bank of the Rhine with little road traffic and no major ground-level emitters. The wind here, comes predominantly from westerly directions. Winds from western directions are not yet polluted with ship exhaust. For this reason, another measuring point was installed, approx. 130 m from the Rhine, directly on the left dike crest at the laboratory building as a reference for recording the background NO_2 pollution present in Bimmen. Therefore, it was not necessary to resort to the mathematical determination of the background load (see Chapter 3.4), which is otherwise customary in the context of official air monitoring.

In the course of the investigations, in 2019 a further measuring point was added on the leeward dike crest on the right bank about 10 m above the water level at Lobith, in order to be able to better assess the height distribution of the NO_2 concentrations and thus the influence of ship exhaust on the air quality in the hinterland of the right bank.

4.1.2.2 Results in Bimmen/Lobith

The measurement programme in Bimmen-Lobith has started in April 2016 and run until 31.12.2020. In June 2021, measurements were resumed as part of a cooperation between LANUV, the University of Bremen and the Federal Institute of Hydrology (BFG). Due to the high water situation of the Rhine, there were temporary failures in the measurement results, as the sampling rafts were not accessible. The annual mean values to be used for the assessment of air quality within the meaning of the EU Directive could be formed at the Bimmen and Lobith sites for the data sets from 2017 to 2020 (Tab. 3).

The estimation of the rural background pollution present here was carried out by means of the passive sampler on the windward side of the dike crest. The annual mean NO_2 value measured here was 17-18 µg/m³ in 2017 and 2018. In 2019, the value dropped to about 16 µg and in 2020 further to 13.5 µg/m³. This background pollution in the Bimmen area already includes a share of large-scale distributed inland waterway vessel emissions in the Lower Rhine region in the order of approx. 0.5-1 µg/m³.

A modelling of the ubiquitous NO_2 pollution in the Duisburg metropolitan area in 2016 by means of the EURAD model by the Rheinisches Institut für Umweltforschung (University of Cologne)[(25)] resulted in a value of 15.6 µg/m³. This value corresponds well with the values measured in Bimmen in 2017-2019 and shows that no significant local pollution sources are effective in Bimmen with the prevailing westerly wind directions.

If the calculated procedure, described in Chapter 3.4, for determining background pollution in the Rhineland was applied in the area of the German-Dutch border, a background pollution of 21 µg/m³ would have resulted here for the year 2018. This value is 4 µg above the air pollution with NO_2 actually measurable in 2018 on the dike crest.

There are no land-based emission sources of NO_X between the passive collector on the dike crest and the Rhine. In order to estimate the influence of inland navigation on air quality, it was assumed in the evaluations that the background pollution at the respective sections of the Rhine is the same upwind and downwind and that the measured differences in the measurement results are mainly influenced by navigation. The more distant the measurements in windward and leeward sections of the Rhine are from each other and the more additional local sources are present, the less accurate this estimation is.

The measuring points in Bimmen and Lobith are about 1.7 Rhine km apart. The left bank of the Rhine is clearly agricultural both in Bimmen and opposite Lobith-Tolkamer, the only western emission source (agricultural plant, 6.6 t NO_X/a) is about 3 km away from both measuring points and is likely to have a minor impact on both measuring points to the same extent. Further major ground-level emission sources of nitrogen oxides are not known in the area of the left bank of the Rhine (windward side). For this reason, it can be assumed that the background pollution in Lobith-Tolkamer with NO_2 is of a comparable magnitude as in Bimmen (Fig. 6).

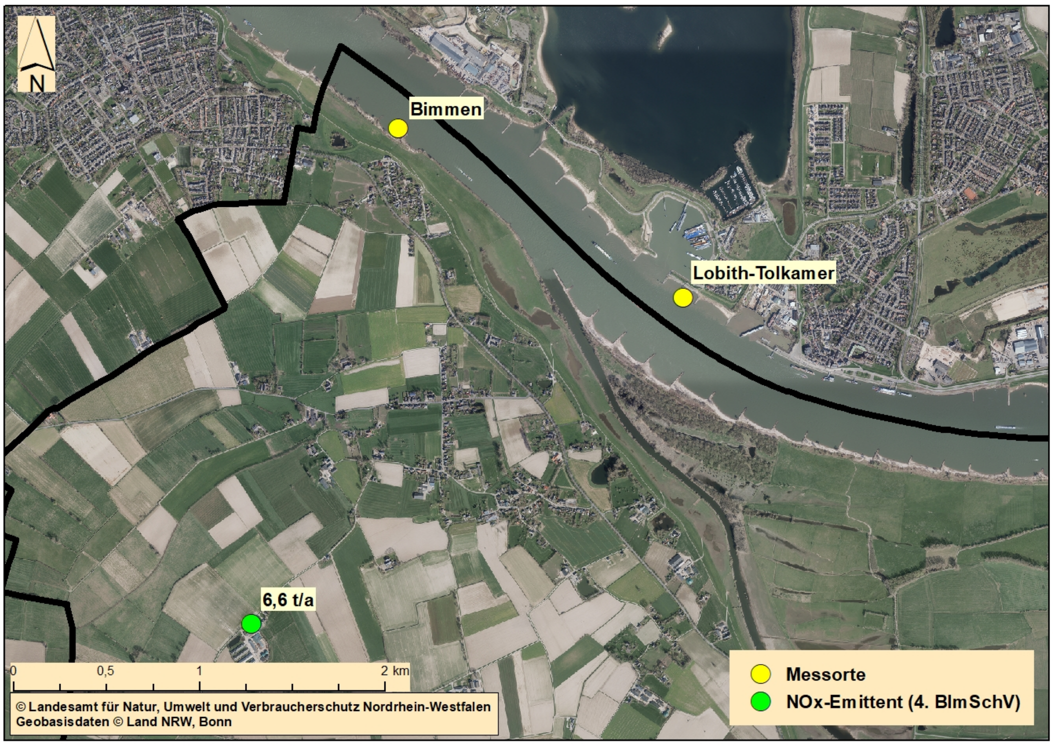


Fig. 6: Location of the monitoring sites on the Lower Rhine at Bimmen (km 865) and Lobith (km 863.3)

Main wind direction West wind ⇨	NO_2 concentrations (µg/m³) annual mean			
	Left bank (windward)		Right bank (leeward)	
Year	Bi_lab	Bi_raft	Lob_raft	Lob_dike
2017 Δ to Bi -lab	18,0	19,8 1,8	21,0 3,0	--
2018 Δ to Bi -lab	17,5	19,4 1,9	21,1 3,6	--
2019 Δ to Bi -lab	15,8	16,8 1,0	20,6 4,8	20,1 4,3
2020 Δ to Bi -lab	13,5	14,1 0,6	18,1 4,6	17,8 4,3

Tab. 3: Weighted annual mean values of NO_2 air pollution at the Rhine near Bimmen/Lobith

At the measuring point on the measuring raft on the left bank, a weighted annual mean NO_2 value of 19.8 and 19.4 g/m³ was obtained (windward side) in 2017 and 2018. Compared to the concentrations at the top of the dike (Bi_lab), the concentration here was about 2 µg/m³ higher in both years. It can be assumed that this increase was caused solely by inland shipping. In 2019 (16.8 µg/m³) and 2020 (14.1 µg/m³), the concentrations on the left, windward sampling raft also decreased. The difference in the increase in concentration caused by shipping (conc. Bi_raft - conc. Bi_lab), which decreases progressively over the years, is striking here. In 2019, the difference was 1.0 µg/m³ and fell further to 0.6 µg/m³ in 2020 (Fig. 7).

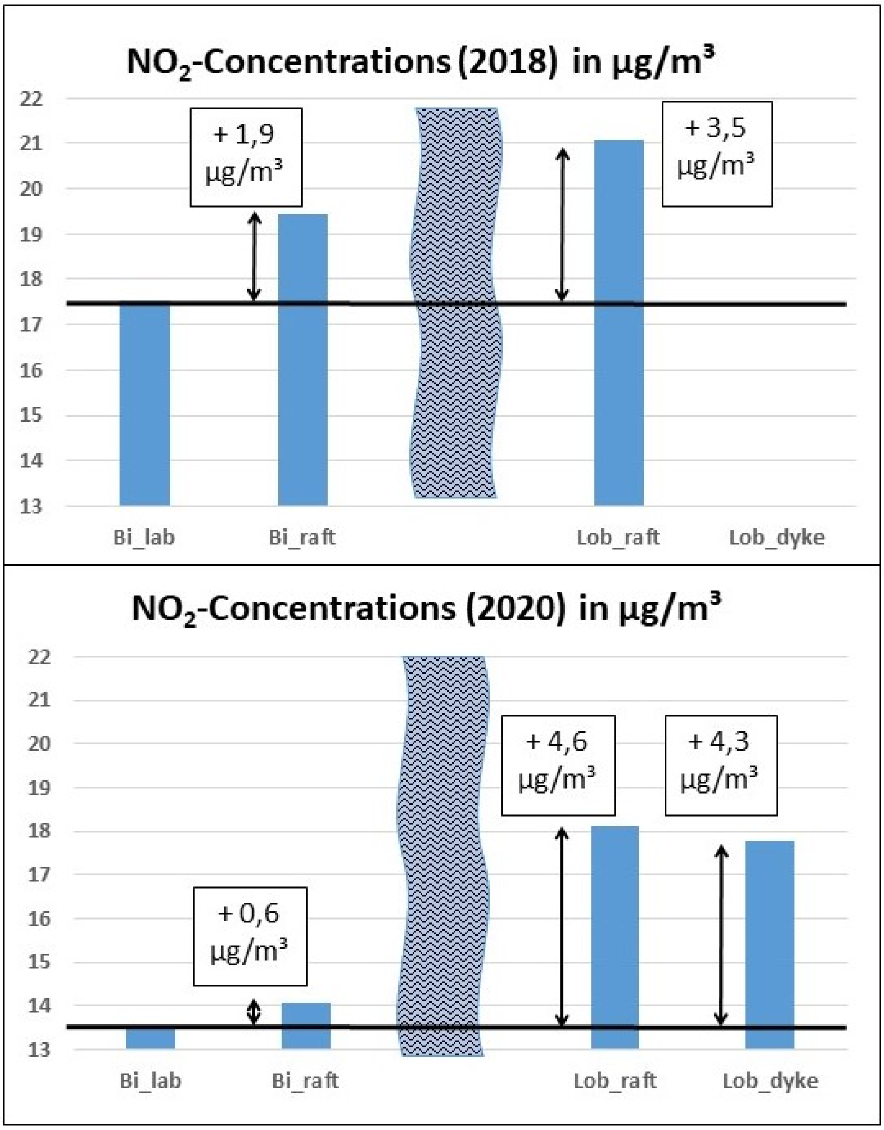


Fig. 7: Development of NO_2 concentrations at the Rhine near Bimmen/Lobith

Since the wind on the German-Dutch border comes predominantly from westerly directions, it is to be expected that the ship exhaust gases have an effect predominantly on the right, eastern bank of the Rhine. The measurement results on the sampling raft (Lob_raft) on the right bank (leeward side) in the Lobith-Tolkamer area confirm this thesis. In 2017 and 2018, the annual mean NO_2 value here was 21 µg/m³. In 2019 (20.6 µg/m³) and 2020 (18.1 µg/m³), the annual mean values also decreased on the Lobith sampling raft, but not as significantly as on the left bank.

The concentration increases for NO_2 detected on the right-hand sampling raft show a clear increase over the course of the study years compared to the results on the left-hand embankment ("background pollution", Bi_lab). The concentration increases compared to the Bi_lab monitoring site were in the range of +3 µg/m³ to +3.6 µg/m³ in 2017/2018. In 2019, this difference increased to +4.8 µg/m³ and was +4.6 µg/m³ in 2020. Under the assumptions described above, these differences are also attributable to the emissions of the passing inland vessels.

The measurements on the right-hand dike, which have been ongoing since 2018, show that the ship emissions, which were emitted about 2-3 m above the water level, are still detectable in similar concentrations on the dike crest at about 12 m above the water level.

4.1.2.3 Discussion of the results in Bimmen/Lobith

In general, a decreasing trend of absolute detectable concentration values was shown in Bimmen/Lobith for all monitoring sites in the years 2017-2020. However, the development of the concentration increases caused by the barges on the sampling rafts (Bi_raft, Lob_raft) varied.

The section of the Rhine at the German-Dutch border is passed by about 100,000 to 110,000 inland vessels per year. A comparison of the evaluation of **AIS** signals (**A**utomatic **I**dentification **S**ystem, mandatory automatic identification system to be used by commercial vessels) carried out for CLINSH and the reports of the Federal Waterways and Shipping Administration (WSV) yielded the following results:

Ship passages on the German-Dutch border		
Year	**AIS-Signals, km 865**	**WSV-Reports[26]**
2018	**58.200** (2nd half-year) *****	**111.352**
2019	**108.800**	**106.499**
2020	**109.500**	**103.624**

Tab. 4: Ship passages at Bimmen
(* due to availability of AIS data)

Based on the measurements carried out on the Rhine in Bimmen/Lobith, the influence of ship emissions can be estimated quite well. According to the Water and Shipping Authority Duisburg, the shipping channel in the study area is rather on the left side of the Rhine. When the water level is sufficient, however, it can be observed that ships travelling upstream also use the right side of the Rhine, as here the current conditions are presumably more favourable for upstream navigation.

The emissions are mainly carried by the wind to the leeward side (eastern, right bank) and are effective there. The windward measurement result at the IMBL laboratory building was chosen as the reference value ("regional background").

Compared to the "regional background" on the left bank, shipping traffic on the right bank leads to significant increases in NO_2-concentrations. In 2017/2018, these were +3.0 to +3.6 µg/m³ on an annual average and even rose to +4.8 µg/m³ in 2019.

The concentration increases on the measuring rafts caused by the ships and the "regional background load" of Bi_lab show an opposite development of the ship influences over the years. The uneven development of the differences could have two causes:

a. Shifting of upstream ship traffic to the right side of the river, possibly caused by low water levels on the left side of the Rhine in combination with decreasing flow velocities on the right side.

b. Stronger share of westerly wind directions in 2019 and 2020.

Unfortunately, a more detailed analysis of the causes of effects was not possible within the CLINSH project. Local wind roses to assess the distribution of wind directions in the study years were not available. The wind roses of more distant locations (Wesel, Borken, Duisburg, Neuss) showed no significant changes in the main wind directions.

In 2019 and 2020, a supplementary NO_2 measurement was carried out on the lee-side dike crest. The results show that the emissions generated at a low height above the water level are also detectable at a height of about 12 m above the water level and can have an effect beyond the dike crest in the hinterland. Thus, increases in concentrations due to ship emissions can also occur in the leeward near-shore parts of the communities. However, it has to be taken into account that these effects decrease with increasing distance from the banks of the Rhine. Such experiences are also made with the inner-city effects of emissions from road traffic.

Even with decreasing traffic density, the effects of emissions from inland navigation can be expected to decrease. The picture for 2018 is as follows: Taking the number of ships passing at Bimmen as a reference (100%), in 2018 the number of ships at Duisburg (km 782) was still approx. 79%, below Neuss (km 744) approx. 61% and just before the border with Rhineland-Palatinate (Bad Honnef, km 640) approx. 44%. Thus, it can be expected that upstream, due to the lower number of moving ships, both the emission amounts and the ship-related shares of air pollution in the riparian zones of the cities along the Rhine will decrease.

4.1.3 Measurement programme in Bad Honnef/Bad Godesberg

4.1.3.1 Measuring points in Bad Honnef/Bad Godesberg

The installation of water and air measuring points directly on the Middle Rhine and without influence of road traffic is much more difficult than in Bimmen due to the topographical situation and the ownership of the riparian properties. Since the supervision of the passive samplers could only be realized by the staff of the water laboratory in Bad Honnef, the measuring points were also set up here at the sampling points for the continuous water abstractions. Since the bank opposite the measuring station in Bad Honnef already belongs to Rhineland-Palatinate, the air measuring station had to be set up on the left bank about 8 km downstream (Fig. 8).

In the area of Bad Honnef, a direct measurement on the bank of the Rhine is more difficult. The left bank of the Rhine is significantly higher than the laboratory site on the right bank. Although westerly winds prevail here as well, the dynamics of the wind event are difficult to assess due to the topography of the Rhine valley (hill formations near the shore on the left, western bank). Unfortunately, a suitable wind rose showing the distribution of wind directions in 2018/2019 was not available.

The Rhine is about 300 m wide in the area of Bad Honnef/Bad Godesberg. The sampling raft at Bad Honnef on the right (eastern, leeward) bank of the Rhine is not permanently accessible, so the measuring point was placed directly at the fence of the laboratory property at a distance of about 25 m from the Rhine. The water level of the Rhine is on average about 7 m lower here. A second measuring point was installed about 60 m from the Rhine at a height of about 5 m above ground on the roof of the laboratory building (about 12 m above mean water level) (Fig. 9). A directly opposite windward measuring point in Oberwinter without traffic influence could not be set up in Bad Honnef due to the topography, residential development and also the lack of territorial responsibilities (Federal State of Rhineland-Palatinate).

The measuring point on the left, windward bank of the Rhine is located about 8 km downstream of Bad Honnef near Bad Godesberg. The Rhine is about 330 m wide here. Here, analogous to the procedure in Bimmen/Lobith, a passive sampler could be installed directly on the sampling raft on the Rhine (Fig. 10). Due to the topography of the left bank and the directly adjacent residential buildings, it was unfortunately not possible to install a second measuring point to estimate the background here, as in Bimmen.

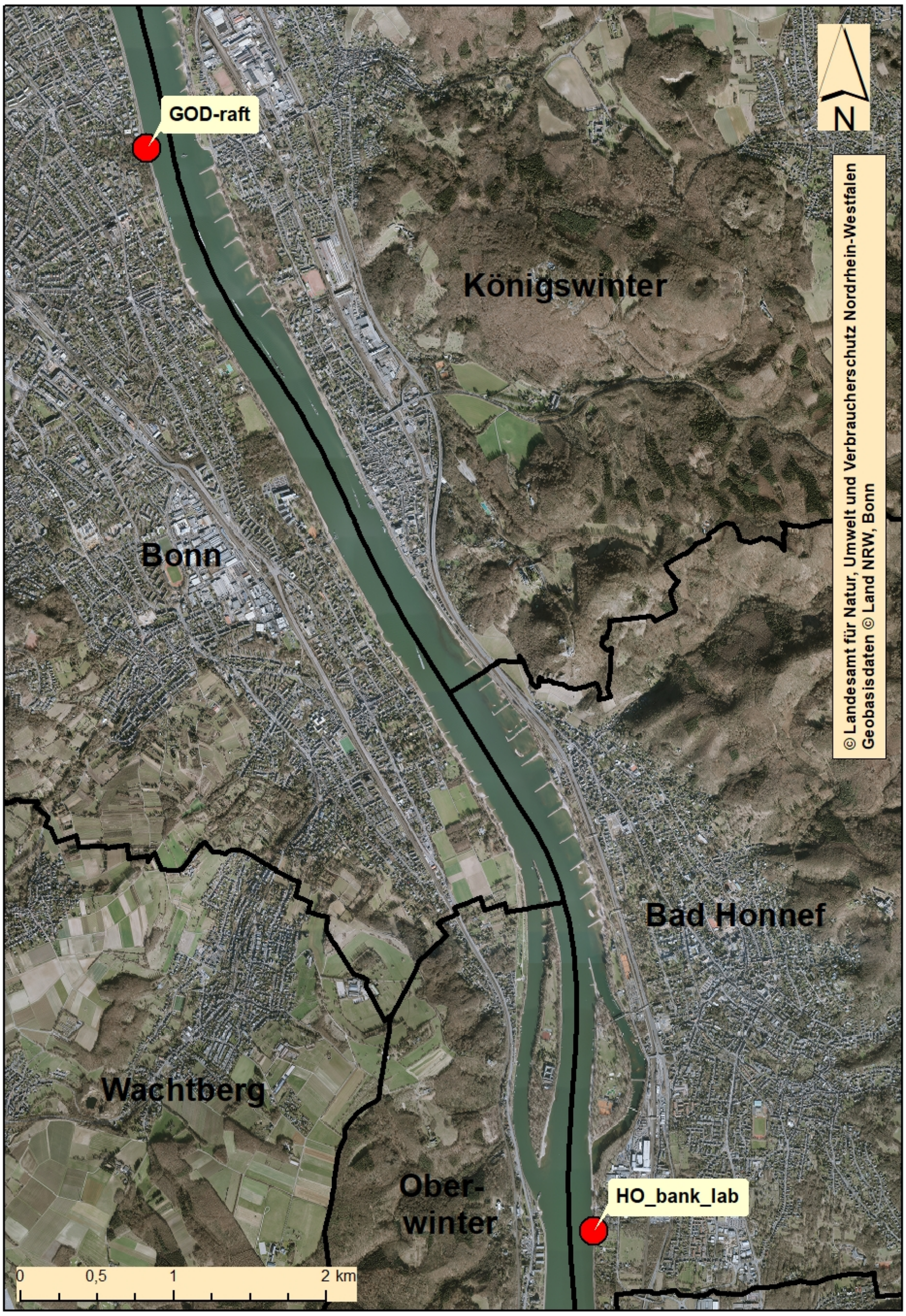


Fig. 8: Location of the monitoring sites on the Middle Rhine at Bad Honnef (Rhine km 640) and Bad Godesberg (Rhine km 647.9)

Fig. 9: Passive collectors in Bad Honnef (HO_bank and HO_lab)

Fig. 10: Passive collector in Bad Godesberg (GOD_raft)

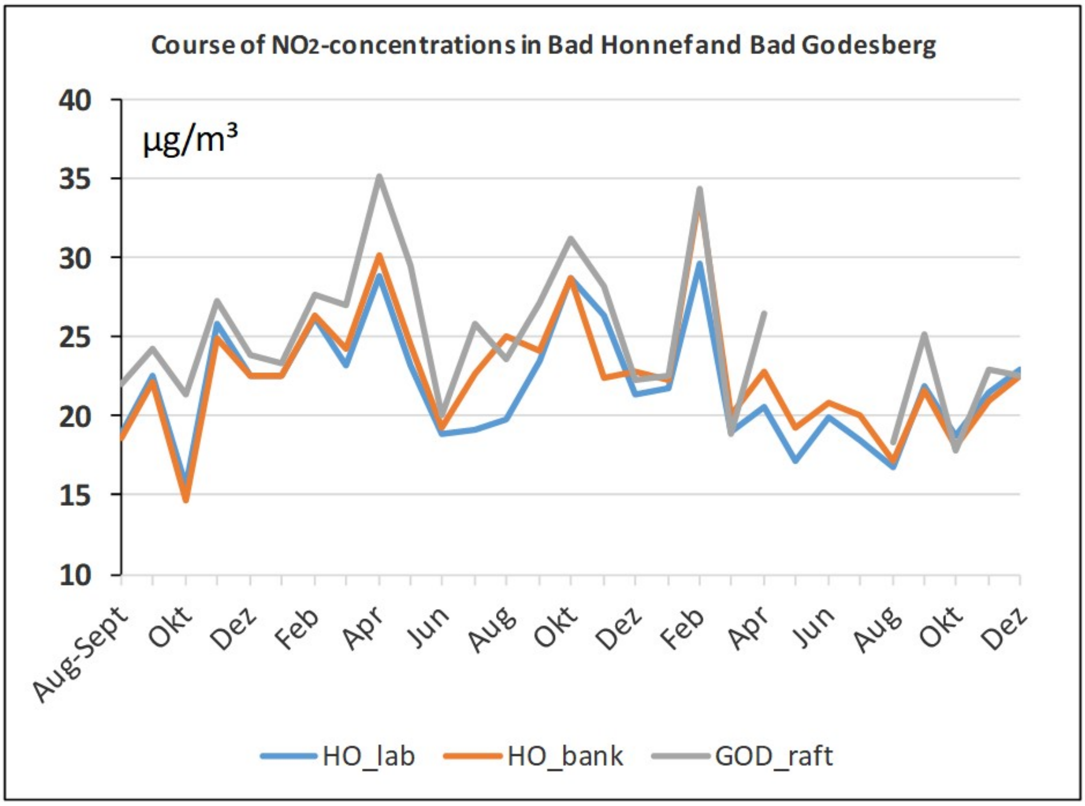


Fig. 11: Course of NO_2 concentrations in Bad Honnef and Bad Godesberg

An evaluation of ships' AIS signals showed that in 2019, about 50,500 inland vessels passed this section of the Rhine. In 2020, the number was around 48,000 vessels. For 2018, unfortunately, AIS data are only available for the 2nd half of the year, in which approx. 22,400 ship passages were detected.

The course of the concentrations measured at the measuring points is shown in Fig. 11. Without a measuring point to estimate the existing background, the order of magnitude of the background pollution was estimated mathematically, as is usual for modelling within the framework of the air pollution control planning of the LANUV (see Chap. 3.4). This was 21 µg/m³ for NO_2 in 2018 and 20 µg/m³ in 2019. The annual mean values for NO_2 concentrations determined in both study years are summarized in Tab. 5 and Fig. 12.

All parameters are far below the binding EU limit value of 40 µg/m³. As at the German-Dutch border, there is a trend towards decreasing concentrations for the weighted annual mean values from 2018 to 2019 at the monitoring sites in Bad Honnef and Bad Godesberg. These parameters were 2.5 µg/m³ (Bad Honnef) and 3.6 µg/m³ (Bad Godesberg) lower in 2019 than in 2018.

NO_2 annual mean values for Bad Honnef / Bad Godesberg			
Year	HO_bank	HO_lab	GOD_raft
2018	24,3	23,4	26,7
Δ to reHG	3,4	2,4	5,7
Δ HO_ bank – HO_lab	1,1	0,9	
2019	21,8	20,9	23,1
Δ to reHG	1,8	0,9	3,1

Tab. 5: Annual mean values for NO_2 at the measuring points in Bad Honnef and Bad Godesberg and respective difference (Δ) to the calculated background (reHG)

The measuring point (HO_bank) located directly on the shore and at a lower level produced an annual mean value that was about 1 µg/m³ higher than the measuring point on the roof of the laboratory building about 50 m from the shore in both study years (Fig. 12). This difference in pollution was present in both years of investigation.

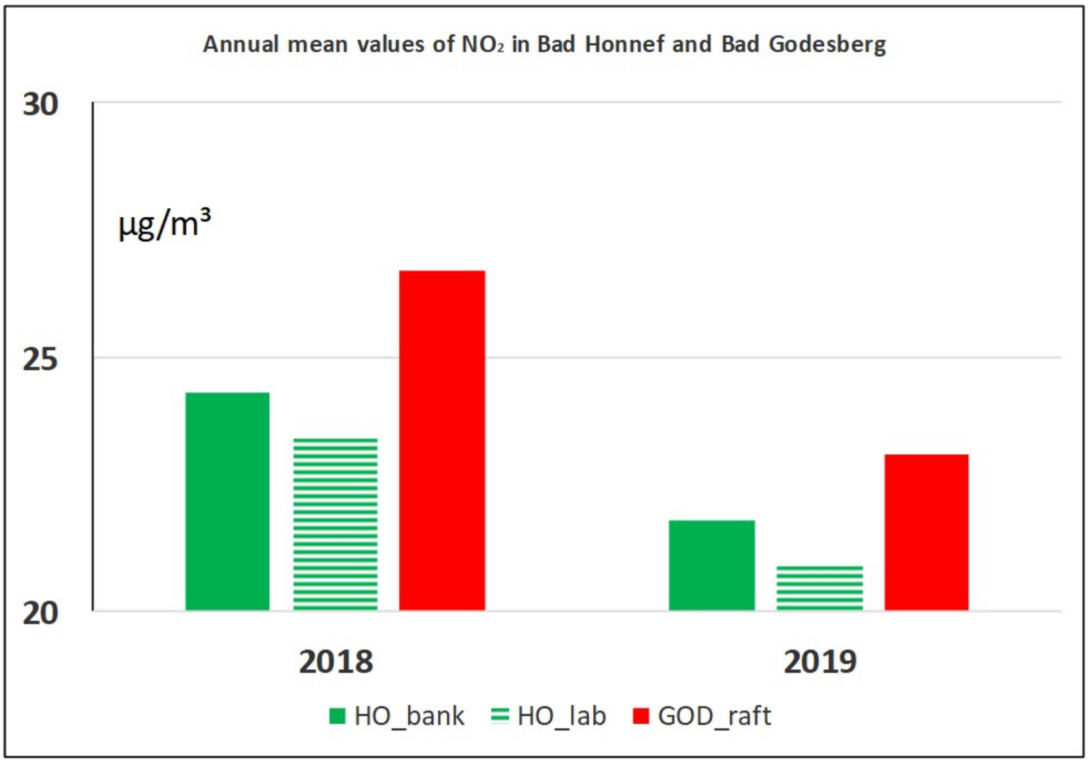


Fig. 12: Comparison of the annual mean NO_2 values of the stations in Bad Honnef and Bad Godesberg

The increased concentrations on the bank are presumably caused by the effects of ship exhaust gases emitted in the trough-shaped Rhine bed, which led to the somewhat higher concentrations there (Tab. 5).

In comparison with the calculated background, the measuring point directly on the bank showed a concentration increase for NO_2 of 3.4 µg/m³ for 2018. On the laboratory roof, the increase was still 2.4 µg/m³. In the following year, these differences were significantly lower and amounted to 1.8 µg/m³ on the banks of the Rhine.

Here, too, the increases compared to the calculated background (Rhineland) are due to local emission sources in the study area. However, the exact share of ship emissions cannot be quantified more precisely. The concentration differences occurring between the measurement results of **HO_bank** and **HO_lab** are an indication that these ship shares could be in the range around 1 µg/m³.

For the passive sampler in Bad Godesberg, which was positioned directly on the Rhine close to the passing ships, a mean value of 26.7 µg/m² was obtained for 2018 and thus an increase of about 5.7 µg/m³ compared to the background pollution (see Chapter 3.4). This rather high difference compared to the results from Bimmen/Lobith can certainly be attributed to a large extent to shipping traffic. A conceivable cause could be an accumulation of ship exhaust gases in the air above the water level in the case of poor ventilation in the trough-shaped Rhine bed. In 2019, a lower annual mean value of 23.1 µg/m³ and a lower increase compared to the calculated background value of 3.1 µg/m³ resulted.

The NO_2 concentration measurements in Bad Honnef and Bad Godesberg do not give such a clear picture in the evaluation as in Bimmen/Lobith. In addition, local road traffic in the rather urban study area certainly contributes to the concentration increases.

Unfortunately, no wind roses (distribution of wind directions over time) were available for evaluation in the study area. Due to the lack of further meteorological accompanying parameters, the unfavourable topographical conditions and the widely separated measuring points on the left and right banks of the Rhine, a more detailed analysis of the measurement results as for Bimmen/Lobith was not possible. Therefore, the measurements were discontinued at the end of 2019.

4.2 Monitoring in the port areas of Duisburg and Neuss/Düsseldorf

A second focus of the investigations was on air quality pollution from ships and port operations in the ports of Neuss and Duisburg. In both study areas, very extensive measurement networks were set up by the LANUV for the "CLINSH Special Measurement Programme" to record air pollution with nitrogen dioxide (NO_2). The fine dust concentrations (PM_{10}) could only be recorded in the two continuously measuring stations due to the high measurement effort.

The measuring stations in both harbour areas were selected according to various criteria. One objective was to be able to represent the spatial pollution situation in the port area using scientific criteria. In doing so, any existing pollution hotspots should also be reliably identified. The location of the measuring points was chosen in such a way that, in addition to the emissions caused by shipping, other sources in the port area such as port railways and lorry traffic could also be assessed and modelled within the framework of polluter analyses. An important goal was to obtain sufficient data on air quality in order to subsequently be able to better quantify the results of the planned causal analyses using real measurement data.

For this reason, a much denser measurement network was established in both study areas than is normally the case for the purposes of official air monitoring, which is intended to verify compliance with the EU limit values for the protection of human health. Verifying compliance with the limit values of the EU Directive was not the primary objective of the CLINSH measurement programme.

4.2.1 Monitoring in the port area of Duisburg

4.2.1.1 Monitoring locations and periods in the port area of Duisburg

In the port area of Duisburg, a total of 27 measuring stations with passive collectors as well as one measuring station **(DURH)**, measuring automatically in close time sequence, were set up. In addition, two traffic measuring stations of the state measuring network (**DUFW, DUMB)** were included in the evaluation, which were located in the approximately 6*5 km study area.

The location of the measuring stations is shown in Fig. 13. The measurements of the continuous station will be continued in 2021. The coordinates of the measuring points and the data of the study periods can be found in the Appendix, Part A: Tab A_1 b and Tab A_2b.

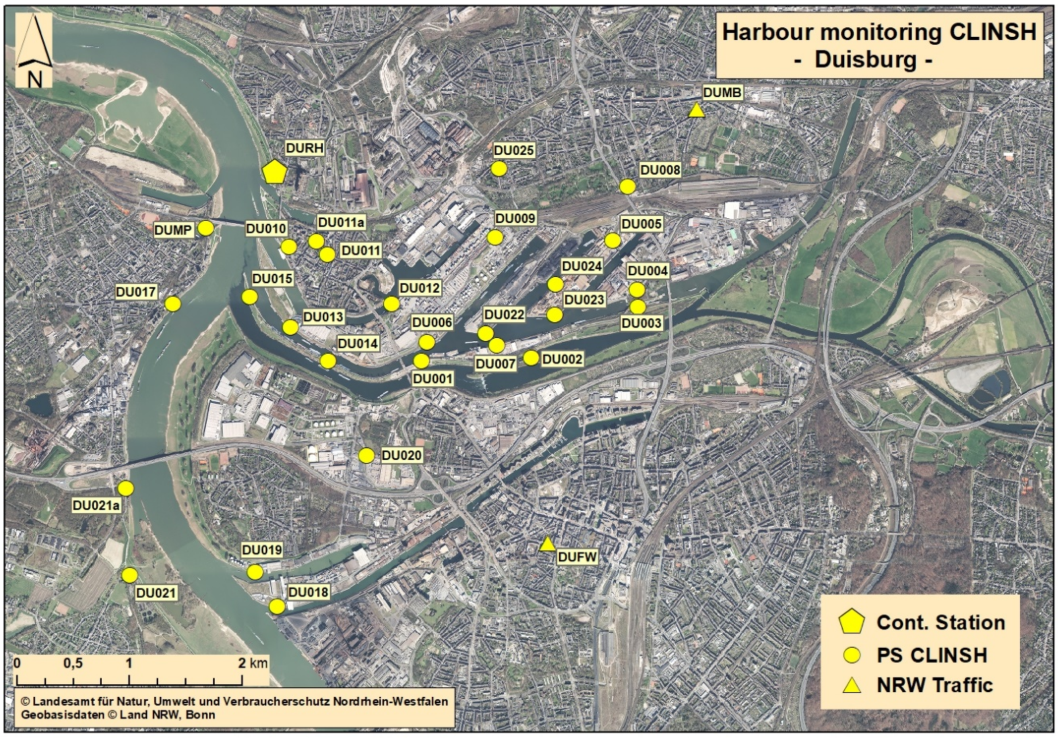


Fig. 13: Location of the measuring points in the port area of Duisburg
PS CLINSH: Passive collector CLINSH project
NRW traffic: Passive sampler of the state measuring network, traffic

4.2.1.2 Measurement results in the port area of Duisburg

Before evaluating the results, the so-called "background pollution" with NO_2 everywhere in the conurbations along the Rhine have to be determined at first (see chapter 3.4). For the year 2018, the calculated background pollution for the Rhineland was 21 µg/m³ for NO_2. The difference of the measured NO_2 concentrations exceeding this value is attributed to the regionally effective emissions within the framework of the clean air planning.

The NO_2 pollution measurable in the air is subject to a variety of influencing factors. Some of the known emission sources are subject to seasonal fluctuations. These include, for example, domestic heating and energy supply. In addition, various meteorological factors (wind direction, wind strength, humidity, ozone formation potential, etc.) also influence the specific formation and decomposition processes of NO_2 in the air chemistry. Fig. 14 shows the seasonal course of NO_2 concentrations in the Duisburg port area based on the mean value of all Duisburg measuring points.

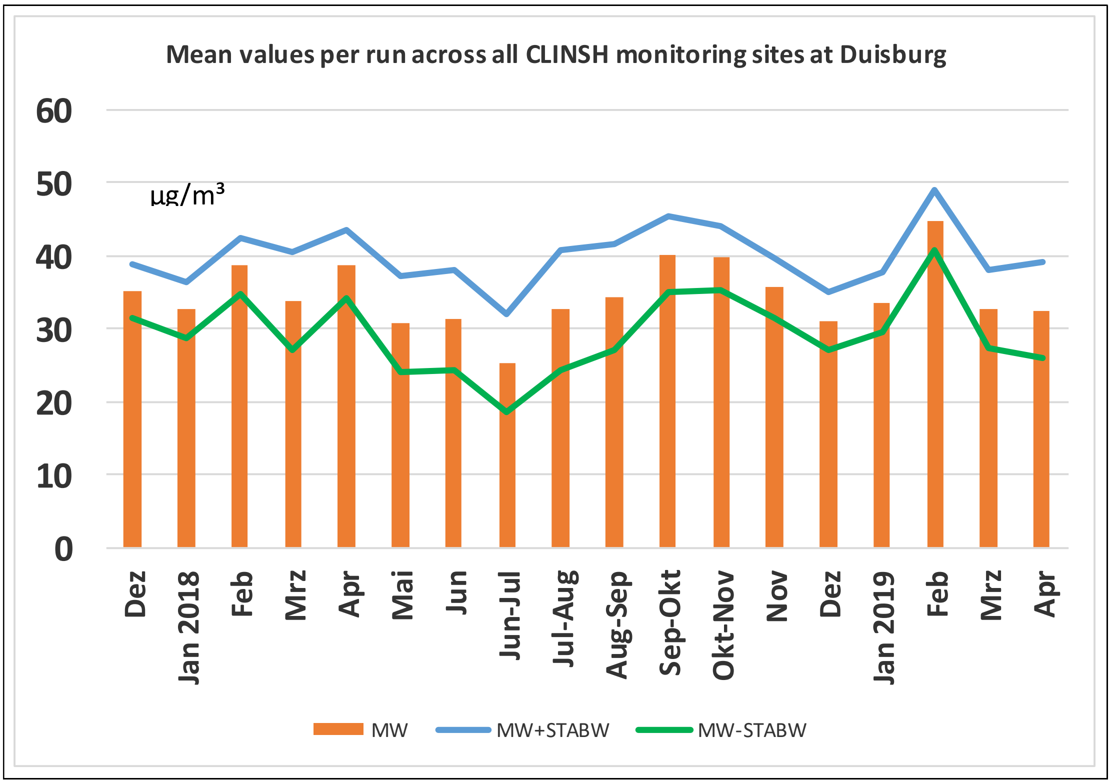


Fig. 14: Seasonal fluctuations in NO_2 pollution (µg/m³) in the port of Duisburg, shown as mean values (MW) over all CLINSH monitoring sites with standard deviation (STABW).

Some of the measuring points in Duisburg show quite different pollution values. Fig. 15 shows the pollution of the port area in the form of a classified pollution map. The annual mean values for the individual measuring points can be taken from Tab. 6. A compilation of the individual measurement results from Duisburg are listed in the Appendix, Tab. A_3 a.

At the measuring points located directly on the Rhine in the Duisburg area, annual mean values of 26 µg/m³ to 30 µg/m³ were measured on the windward side of the left bank and 27 µg/m³ to 32 µg/m³ on the leeward side of the right bank. Compared to the background pollution, site-specific increases in NO_2 pollution in the range of 6 µg/m³ to 11 µg/m³ were recorded for the measuring sites located directly on the Rhine in Duisburg in 2018. However, the concentration increases detectable here are not only attributable to the influence of ship exhaust from the Rhine. The air quality of these locations is additionally influenced by other urban (road traffic, domestic heating, etc.) as well as industrial emission sources. A more detailed evaluation of the pollution proportions is planned and will probably be available after the cause analyses have been carried out in late summer 2021 (report part F).

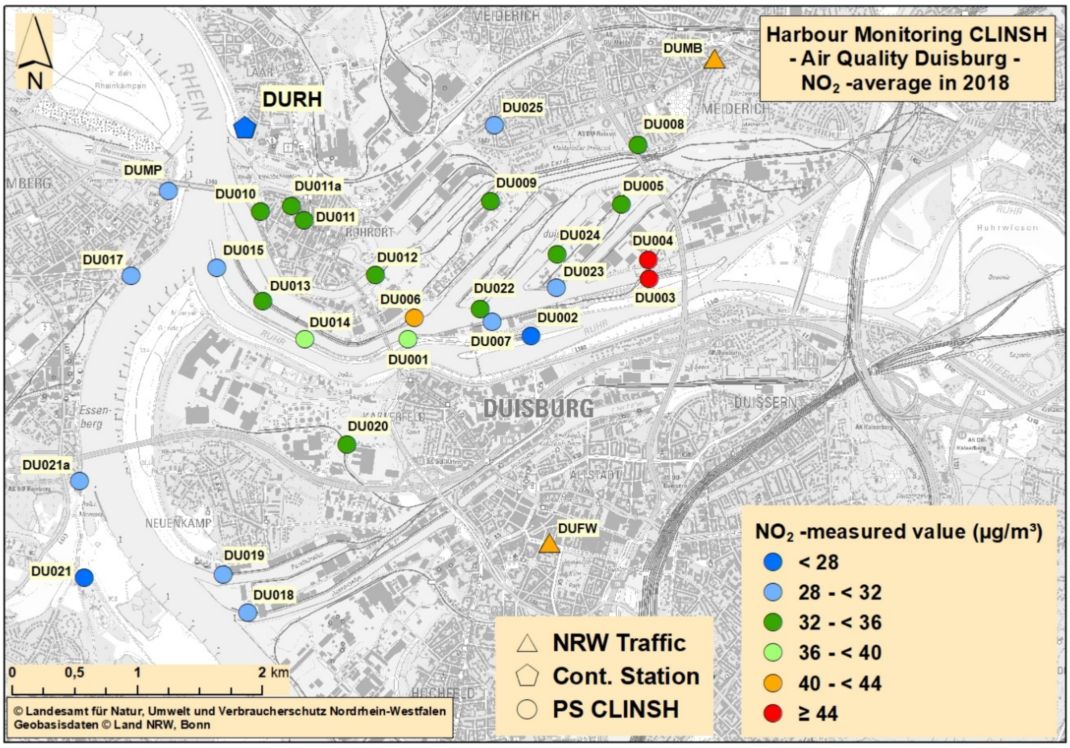


Fig. 15: Air pollution with NO_2 in Duisburg harbour - Classified annual mean values 2018

Between the harbour basins and at the harbour canal, the NO_2 concentrations at 11 measuring points are between 31 and 37 µg/m³. The twelfth measuring point (**DU006**) at the harbour canal shows a higher load of 43 µg/m³, the cause of which could not be conclusively clarified. It could, for example, have been caused by construction work in the vicinity of the measuring point. The measuring points **DU020** and **DU025**, located on industrial sites, show annual NO_2 values in the concentration range 30-32 µg/m³.

At the three measuring points located in the residential area between the port and the Rhine, the annual mean NO_2 concentrations were between 33 and 36 µg/m³. In Duisburg, too, the traffic measuring points of the state measuring network (**DUFW** 41 µg/m³; **DUMB** 42 µg/m³) generally showed higher NO_2 concentrations than in the port areas.

Measuring point	Valid values n	Annual weighted average 2018 µg/m³	Remarks	Measuring point	Valid values n	Annual weighted average 2018 µg/m³	Remarks
DU001	13	36,4		DU015	13	31,6	
DU002	7	27,1	EM	DU017	10	30,4	EM
DU003	13	47,4		DU018	13	31,9	
DU004	13	47,3		DU019	13	30,5	
DU005	13	32,9		DU020	13	32	
DU006	12	43,2		DU021	12	25,7	
DU007	13	31,3		DU021a	8	29,5	EM
DU008	13	32		DU022	13	33,1	
DU009	13	35,2		DU023	13	31,5	
DU010	13	35,7		DU024	13	33,1	
DU011	13	35,1		DU025	12	30,3	
DU011a	8	32,9	EM	DUMP	6	30,5	EM
DU012	13	33,5		DURH		27	CMS
DU013	11	34,9		DUMB		42	NRW traffic
DU014	13	36,6		DUFW		41	NRW traffic

Tab. 6: Weighted annual mean values of the NO_X results in the Duisburg study area for 2018.
EM= simple mean value as n < 11; CMS = continuous monitoring station
NRW traffic = official traffic measuring station of the State of NRW

4.2.1.3 Air pollution at the Duisburg locks

The two CLINSH monitoring sites at the lock basin of the Meiderich lock (**DU003, DU004**) showed the highest values of the special monitoring programme with annual mean NO_2 concentrations of 47.3 and 47.4 µg/m³.

The locks in the Duisburg port area connect the Rhine with the Rhine-Herne Canal (RHK). The RHK has its special significance in the development of the industrial area in its catchment area, which is characterized by a high density of public ports and factory ports with correspondingly strong destination and source traffic. 2/3 of the volume of goods, transported on the RHK, can be attributed to this traffic (Fig. 16).

The exact data on the locks carried out in 2018 were obtained from the responsible WSV office in Duisburg (**WSA** (Wasser- und Schifffahrtsamt) **Westdeutsche Kanäle**). The Meiderich lock is the actual main lock from the Rhine to the Rhine-Herne Canal. In 2018, a total of 12,846 commercial vessels and 1,684 recreational boats passed through this lock (Tab. 7).

According to information from the WSA Westdeutsche Kanäle, the Meiderich lock has not been in operation from the beginning of October until December 2018 due to construction work. During this time, there has been an increased volume of traffic at the Ruhr lock. In the same year, 2,050 commercial vessels and 76 recreational boats passed through the Ruhr lock. Construction work was also carried out in the lock area at the Ruhr lock from July 2018. The measuring point here was therefore partially inaccessible, so that from 20 June 2018 until the end of the year there have been total failures in the measurement results or invalid results due to excessively long exposure times.

Fig. 16: Meiderich lock, aerial view

The actual figures on lock movements given by the **WSA Westdeutsche Kanäle** (Waterways and Shipping Office) as lock operator are lower than those, given in the Federal Transport Report 2018(26). The report mentions a number of 17,134 vessels for commercial navigation in 2018. The causes of the differences could not be clarified. This report assumes for the evaluation that the data of the WSA reflect the real operating figures of the lock.

Type of ship	Name of lock: Schleuse Meiderich												
	Lockings in 2018												
	Jan	Feb	Mrz	Apr	Mai	Jun	Jul	Aug	Sep	Okt	Nov	Dez	**Total**
Freight vessel	**524**	**636**	**799**	**694**	**633**	**596**	**818**	**925**	**878**	**99**	**--**	**--**	**6589**
Freight vessel couple unit	**58**	**55**	**96**	**91**	**105**	**70**	**87**	**87**	**65**	**9**	**--**	**--**	**723**
Tanker vessel	**573**	**593**	**616**	**555**	**526**	**507**	**620**	**732**	**641**	**65**	**--**	**--**	**5482**
Tanker vessel vouple unit	**2**	**4**	**5**	**4**	**2**	**10**	**10**	**14**	**1**	**--**	**--**	**--**	**52**
Professional navigation													**12846**
Sport boats													**1684**
Type of ship	**Name of lock: Ruhrschleuse**												
	Lockings in 2018												
	Jan	Feb	Mrz	Apr	Mai	Jun	Jul	Aug	Sep	Okt	Nov	Dez	**Total**
Freight vessel	**141**	**215**	**244**	**217**	**202**	**171**	**40**	**0**	**0**	**15**	**143**	**98**	**1486**
Freight vessel couple unit	**2**	**11**	**20**	**12**	**14**	**23**	**2**				**1**		**89**
Tanker vessel	**47**	**50**	**56**	**68**	**82**	**84**	**17**			**2**	**44**	**26**	**475**
Tanker vessel vouple unit	**--**	**--**	**--**	**--**	**--**	**--**	**--**	**--**	**--**	**--**	**--**	**--**	**--**
Professional navigation													**2050**
Sport boats													**76**

Tab. 7: Vehicles towed in 2018 according to data from the WSA West German Canals

Fig. 17: Meiderich lock, upstream lockage, view downstream (Photo: D. Busch, LANUV)

Fig. 18: Meiderich lock, exit of a 110 m vessel after upstream lockage. (Photo: D. Busch, LANUV)

In order to be able to assess the influence of the lock activities at the two locks, passive collectors were also installed on the premises of the Meiderich lock to the right and left of the lock chamber. The annual mean NO_2 concentrations for both collectors in 2018 were 47 µg/m³. The values can be explained by the lock operations (with the ships' main engines running). The warm ship exhaust gases either rise directly from the lock chamber or collect in the lock chamber during the valley lock and are then pressed out of the lock chamber in concentrated form by the rising water during the subsequent upstream lock. In both cases, the air bodies charged with ship exhaust directly influence the passive collectors installed at the lock chamber (Fig. 18).

The estimation of the NO_X quantities generated during the locking processes was carried out with the test version of the newly revised programme **LuWas** (Luftschadstoffbelastung an Wasserstraßen) of the BFG. The calculations resulted in a NO_X quantity of 5.76 tonnes (Tab. 8) for the NO_X emissions generated by the lock processes in the lock chamber in 2018, which were emitted directly next to the passive collectors in the lock chamber (Fig. 19).

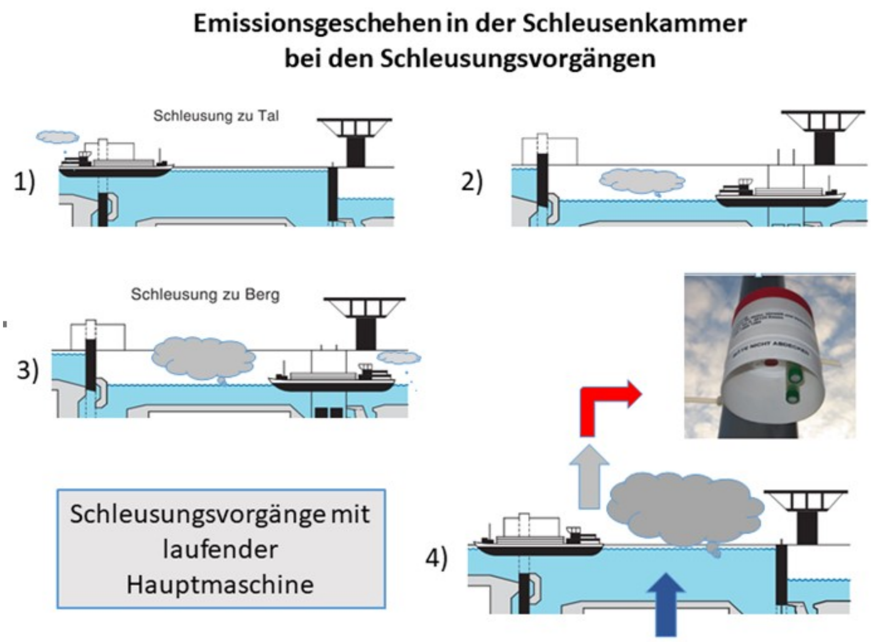


Fig. 19: Emission events in the lock chamber during lock operations. Locking operations with the main drive running (Source: The figure was created by using graphics from the WSV)

Fig. 20 shows the annual trends in NO_2 concentrations at the two measuring points at the Meiderich lock and the Ruhr lock. The effects of the construction measures from October onwards can be seen in the significantly lower NO_2 concentrations in Meiderich. The annual mean value of these measuring points would probably have been even higher without these construction measures. The total failure of the measured values at the Ruhr lock was also caused by construction work and the associated lack of accessibility of the passive collectors from June 2018.

Schleuse Duisburg Meiderich		NO_X (t/a)		
		2015	2018	2020
	Länge	calculated	interpoliert	calculated
Upper water	600 m	5,73	5,46	5,29
Lock basin	211 m	6,04	5,76	5,57
Lower water	600 m	7,96	7,60	7,35
		PM_{10} (kg/a)		
Upper water	600 m	151	141	134
Lock basin	211 m	158	147	139
Lower water	600 m	207	192	183

Tab. 8: Emissions at the Meiderich lock

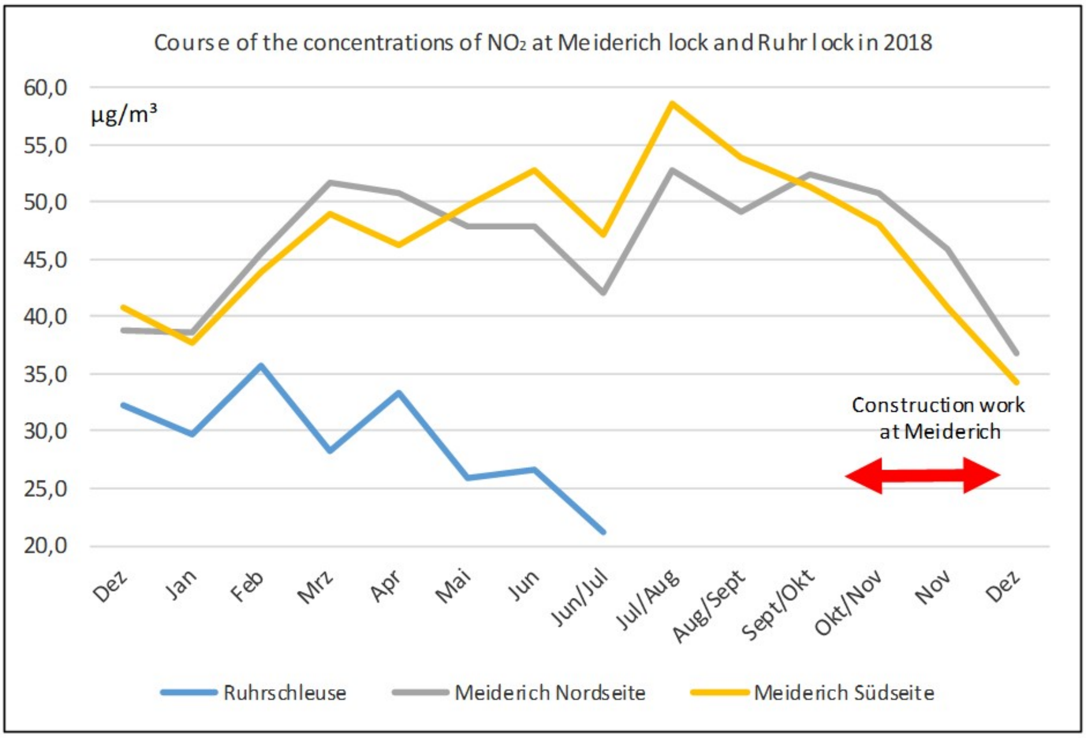
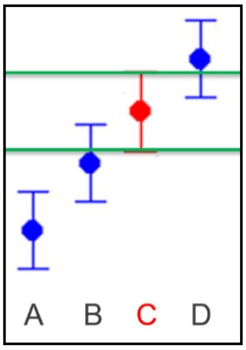


Fig. 20: Course of NO_2 concentrations at the lock monitoring sites in 2018

4.2.1.4 Statistical evaluations of the measurement results at Duisburg port area

The NO_2 measurement results of the Duisburg study area from 2018 were subjected to an intensive statistical evaluation. In Fig. 22, the annual mean values per measuring points are presented with their 95% confidence interval in ascending order. From the figure, conclusions about significant differences in NO_2 pollution can be drawn by visually comparing the confidence intervals. At the same time, different exposure groups can be identified.



The loads on measuring points differ significantly from each other if their confidence ranges do not overlap. The visual derivation is exemplified in Fig. 21. The following can be derived: The load on measuring point C differs significantly from the load on measuring point A, but not from the load on measuring points B and D. The load on measuring point D differs significantly from the load on measuring point A and B, but not from that on measuring point C. Measuring point B only shows a significantly different load to D. The load on measurement point A, in turn, differs significantly from measurement points C and D.

Fig. 21: Schematic of the evaluation possibilities of Fig. 22

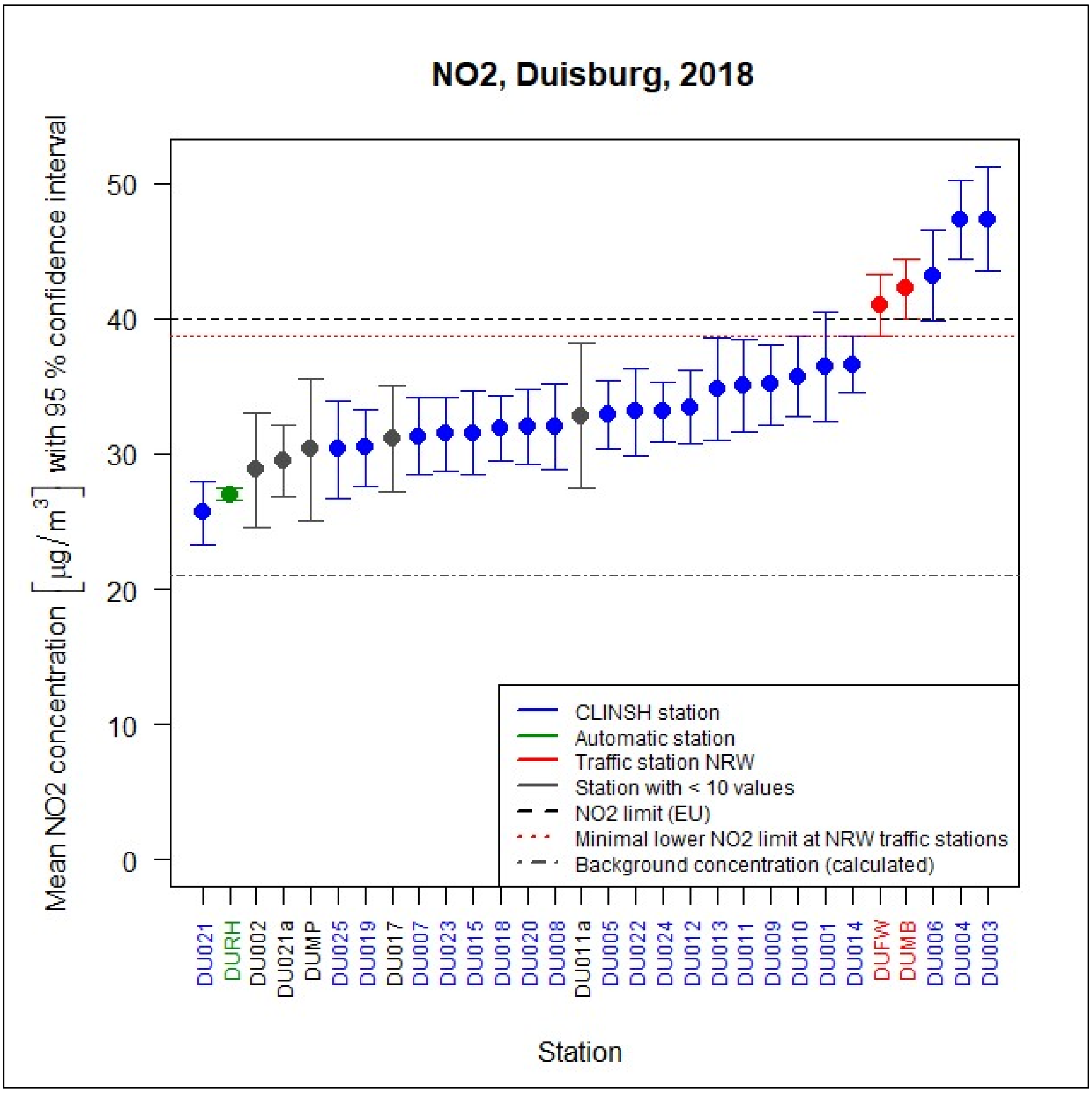


Fig. 22: Mean values and 95 % confidence interval of the annual mean NO_2 values 2018 in the Duisburg study area.

Fig. 22 shows a comparison of pollution levels found at the individual measuring points in 2018 and their confidence intervals (95%). It is striking that most of the monitoring sites near the Rhine show the lowest annual mean values. This applies to all measuring points on the left, windward bank of the Rhine (**DU021, DU021a, DU017, DUMP**) as well as to the result at the automatic measuring station **DURH** and to another, leeward measuring point (**DU019**).

In comparison with the annual means of the two traffic monitoring stations located in the study area (**DUFW, DUMB)**, which were still just above the EU limit value in 2018 with 41 and 42 µg/m³ respectively, almost all CLINSH monitoring stations at Duisburg show lower annual mean values. For 21 CLINSH monitoring sites, there is even a statistically significant lower pollution level.

The statistical analysis of the mean concentrations of NO_2 at the CLINSH monitoring points compared to those of the Duisburg traffic stations shows a significant difference between these two groups (analysis of variance of logarithmized concentrations, $p = 1.36 \cdot 10^{-7}$). The mean concentration at the traffic stations is 23% higher than the mean value of the CLINSH stations.

Only the results at the measuring points at the lock chambers (**DU003, DU004**) and the harbour canal (**DU006**) below harbour basin A reached higher annual mean values than the traffic measuring points, but the cause of it could be clearly clarified for the two measuring points located at the lock basin Meiderich (cf. chapter 4.2.1.3).

For the two Duisburg traffic measuring points, where the EU limit value for NO_2 (annual mean 40 µg/m³) was also exceeded, concentration increases of 20-21 µg/m³ were significantly higher compared to the regional background than the CLINSH measuring points located directly on the Rhine (**DU017, 019, 021, 021a, DUMP**), which in the annual mean only showed increases in the range of 5-9.5 µg/m³. Thus, it becomes clear that the ship emissions are not high enough, even on the busy section of the Rhine in Duisburg to explain the high measured values at the traffic measuring points.

4.2.2 Monitoring in the Neuss/Düsseldorf port area

4.2.2.1 Measurement locations and measurement periods at Neuss/Düsseldorf

In the port area of Neuss, a total of 20 measuring stations with passive collectors as well as one measuring station (**NERH**), measuring automatically in close time sequence, were set up for CLINSH. In addition, six traffic measuring stations of the state measuring network (**DDBG**, **NEKS, VNEB, VNEM2, VDSR, DBIL**), which were located in the approximately 6*5 km study area, were included in the evaluation. The location of the measuring stations is shown in Fig. 20. The measurements of the continuous station were discontinued at the end of 2019. The coordinates of the measuring points and the dates of the study periods can be found in the Appendix, Tab A_1a and Tab A_2a.

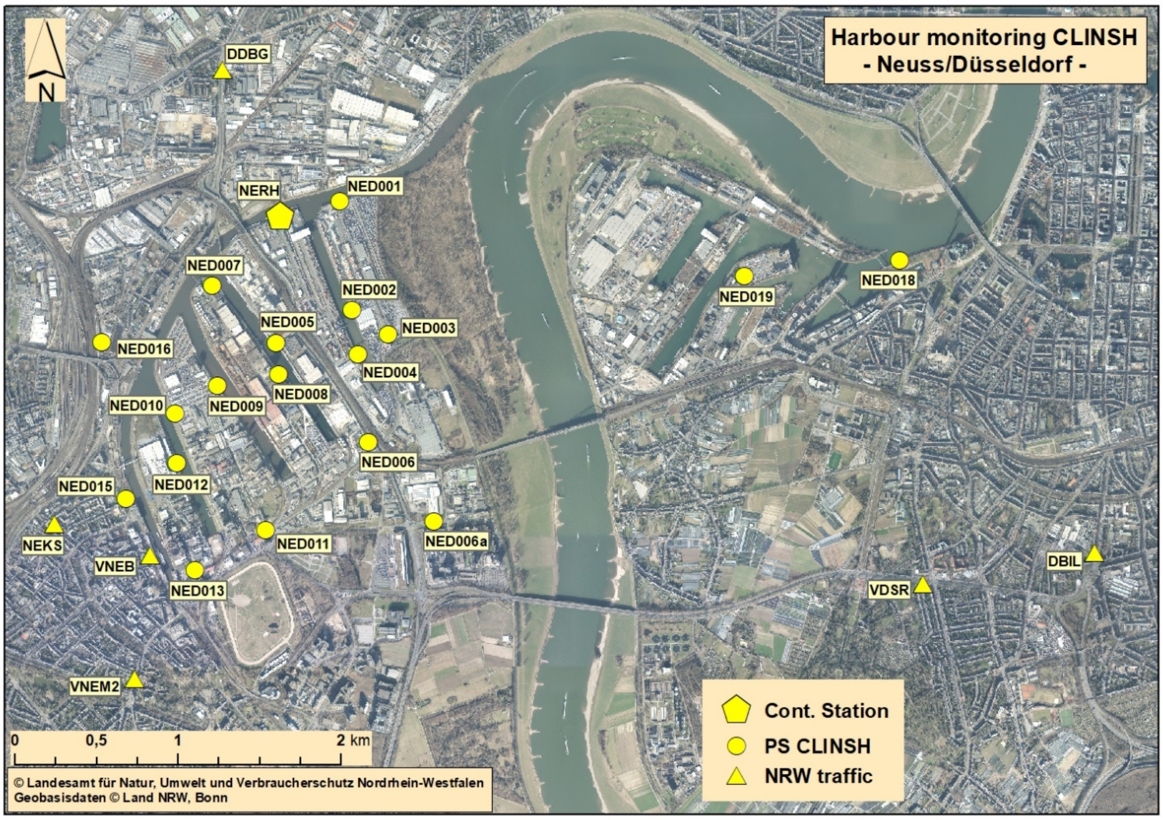


Fig. 23: Location of the measuring points in the Neuss/Düsseldorf port area
PS CLINSH : Passive collectors CLINSH project
NRW traffic: official passive collectors of the state measurement network, traffic

4.2.2.2 Measurement results in the port area of Neuss

The background load for the Rhineland calculated for the year 2021 was 21 µg/m³ for NO_2. The difference of the measured NO_2 concentrations exceeding this value is attributed to the pollution resulting from local or regional emissions within the framework of clean air planning.

The NO_2 pollution, measurable in the air, is also subject to the various influencing factors already described in more detail for Duisburg (see chapter 4.2.1.2). Fig. 24 shows the seasonal course of NO_2 concentrations in the Neuss port area based on the mean value of all measuring points of Neuss.

The measuring points in the port area of Neuss/Düsseldorf also show quite different pollution values in some cases. Fig. 25 shows the pollution of the port area in the form of a classified pollution map. The annual mean values for the individual measuring points can be found in Tab. 6. A compilation of the individual measurement results from Neuss can be found in the Appendix, Tab. A_3b.

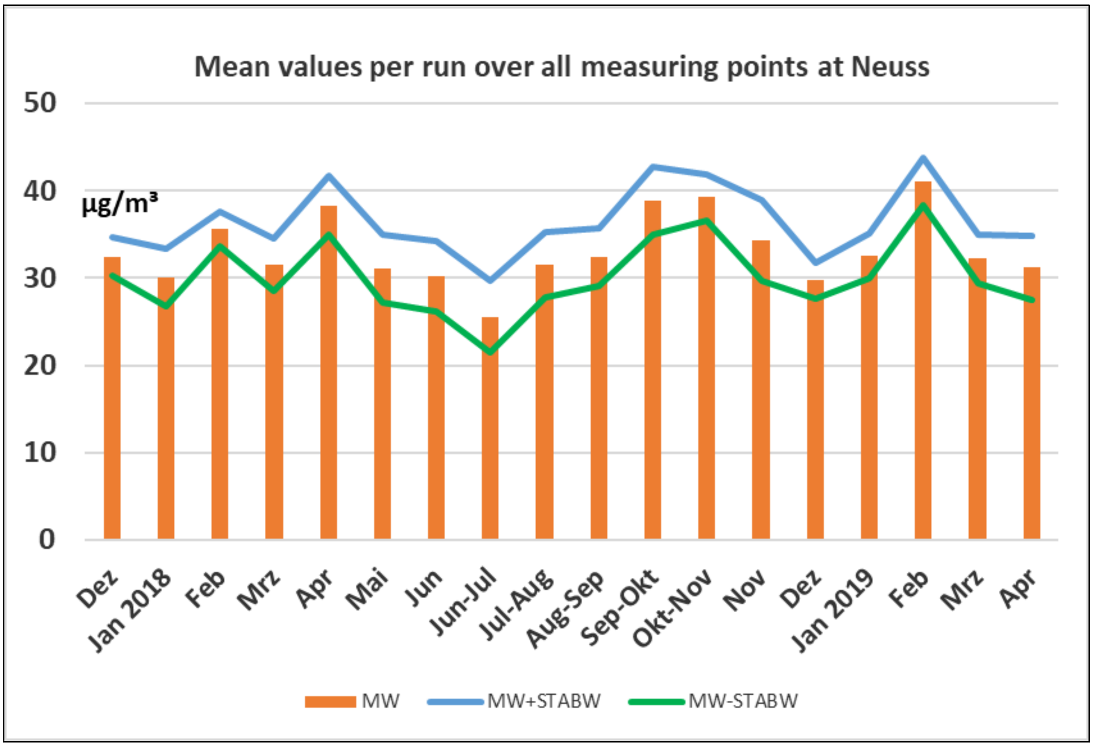


Fig. 24: Seasonal fluctuations in NO_2 pollution (µg/m³) in the port of Neuss, shown as mean values (MW) across all CLINSH monitoring sites with standard deviation (STABW)

For the measuring points in the port of Neuss, annual mean NO_2 values between 29 µg/m³ and 39 µg/m³ were recorded in 2018. This results in concentration increases in the range of 8 to 18 µg/m³ for the annual characteristic values of the NO_2 concentrations in the port of Neuss in comparison with the calculated background value for the Rhineland. The measuring points at port basins 2 and 3 (**NED009, NED010, NED012**) had the lowest values in the port area of Neuss in 2018 with mean annual concentrations of 29-30 µg/m³. The two measuring points in the port area of Düsseldorf (**NED018, NED019**) also show rather low annual mean values of 21 and 32 µg/m³.

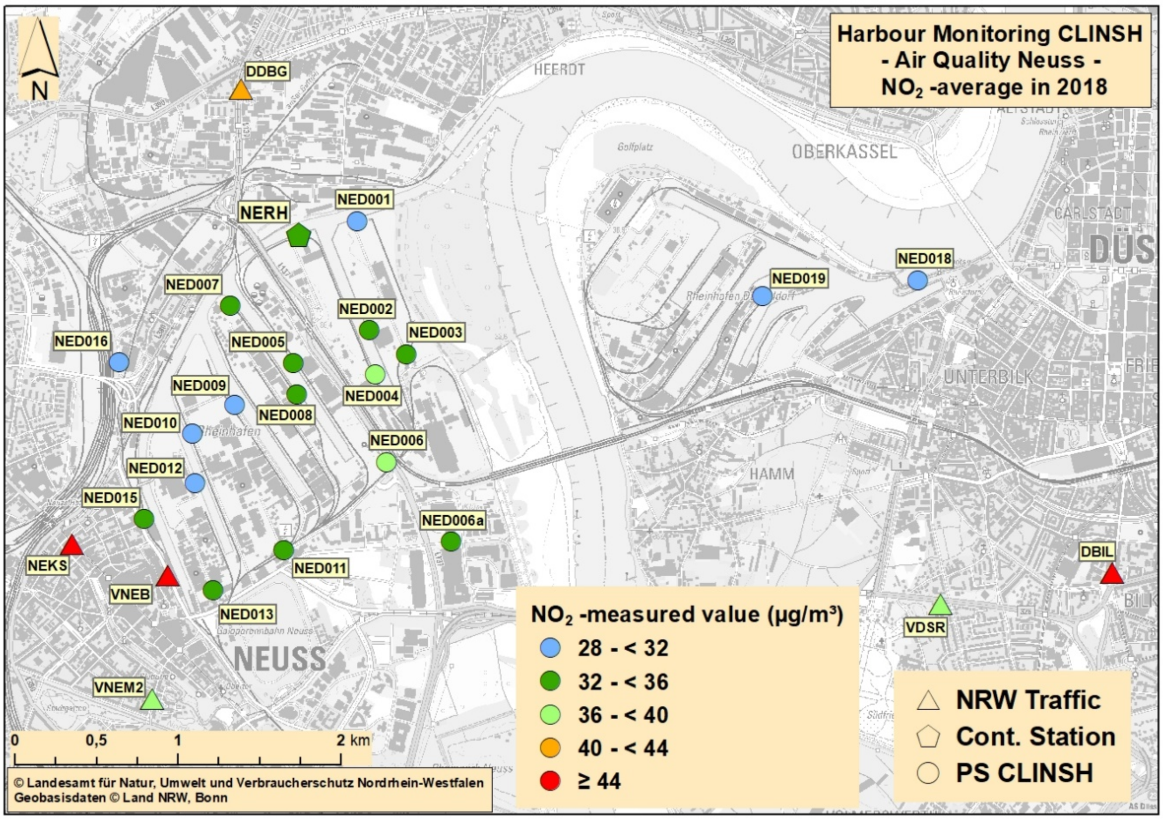


Fig. 25: Neuss harbour - annual mean values 2018 for NO_2

The highest annual mean value of 39 µg/m³ was determined at the measuring point **NED006** (Königsberger Straße/Floßhafenstraße), which is clearly influenced by other traffic (road and rail). In the case of some of the measuring points in the port area of Neuss with higher pollution levels in an internal comparison, it can be assumed that, in addition to the emissions caused by ships and port operations, influences from road traffic on busy (through) roads in the immediate vicinity are also effective. At five of the six traffic measuring points of the state measuring network located in the study area, significantly higher concentration values were determined as an annual mean in 2018 (**VNEM2** 40 µg/m³; **DDBG** 43 µg/m³; **NEKS** 44 µg/m³; **VNEB** 45 µg/m³; **DBIL** 54 µg/m³). In 2020, the EU limit value of 40 µg/m³ NO_2, applicable here, was complied with also at these traffic-monitoring systems on an annual mean.

The effects of road traffic emissions become particularly clear when comparing the annual characteristic values of the monitoring station **VNEB** (45 µg/m³) with those of the CLINSH monitoring stations **NED013** (33.4 µg/m³) and **NED015** (35 µg/m³). The busy “Batterie Straße” runs directly parallel to the Harbour Basin 1. The **VNEB** monitoring station, located directly on the road, has significantly higher annual mean NO_2 concentrations in 2018 than the two nearby harbour monitoring stations **NED013** and **NED 015**. The difference between the annual means is 11 and 10 µg/m³, respectively.

Measuring point	Valid values n	Annual weighted average 2018 µg/m³	Measuring point	Valid values n	Annual weighted average 2018 µg/m³	Remarks
NED001	13	31,5	NED013	13	33,4	
NED002	13	33,8	NED015	13	35	
NED003	13	34,4	NED016	13	31,1	
NED004	13	38	NED018	13	30,8	
NED005	13	35,7	NED019	13	31,8	
NED006	13	39,2				
NED006a	13	35,7	NERH	continuous	33	CMS
NED007	13	31,9	DDBG	12	43	NRW traffic
NED008	13	32,3	DBIL	12	54	NRW traffic
NED009	13	30,2	VDSR	12	39	NRW traffic
NED010	13	28,8	NEKS	12	44	NRW traffic
NED011	13	32,8	VNEB	12	45	NRW traffic
NED012	13	29,3	VNEM2	12	40	NRW traffic

Tab. 9: Weighted annual mean values of the NO_X results in the study area Neuss/Düsseldorf in 2018.

CMS = Continuous monitoring station
NRW traffic = Official traffic monitoring station of the State of NRW

4.2.2.4 Statistical evaluations of the measurement results in the Neuss port area

The NO_2 measurement results of the Neuss/Düsseldorf study area from 2018 were subjected to an intensive statistical evaluation. In Fig. 26, the annual mean values of the measuring points were presented with their 95% confidence interval in ascending order. Conclusions about significant differences in exposure can be drawn from the figure. At the same time, different exposure groups can be identified. A description of the procedure can be found in chapter 4.2.1.4 and in Fig. 21.

In the statistical comparison of the Neuss/Düsseldorf annual mean values, all CLINSH monitoring sites in the port area show lower annual mean values in 2018 than five of the six traffic monitoring sites located in the study area.

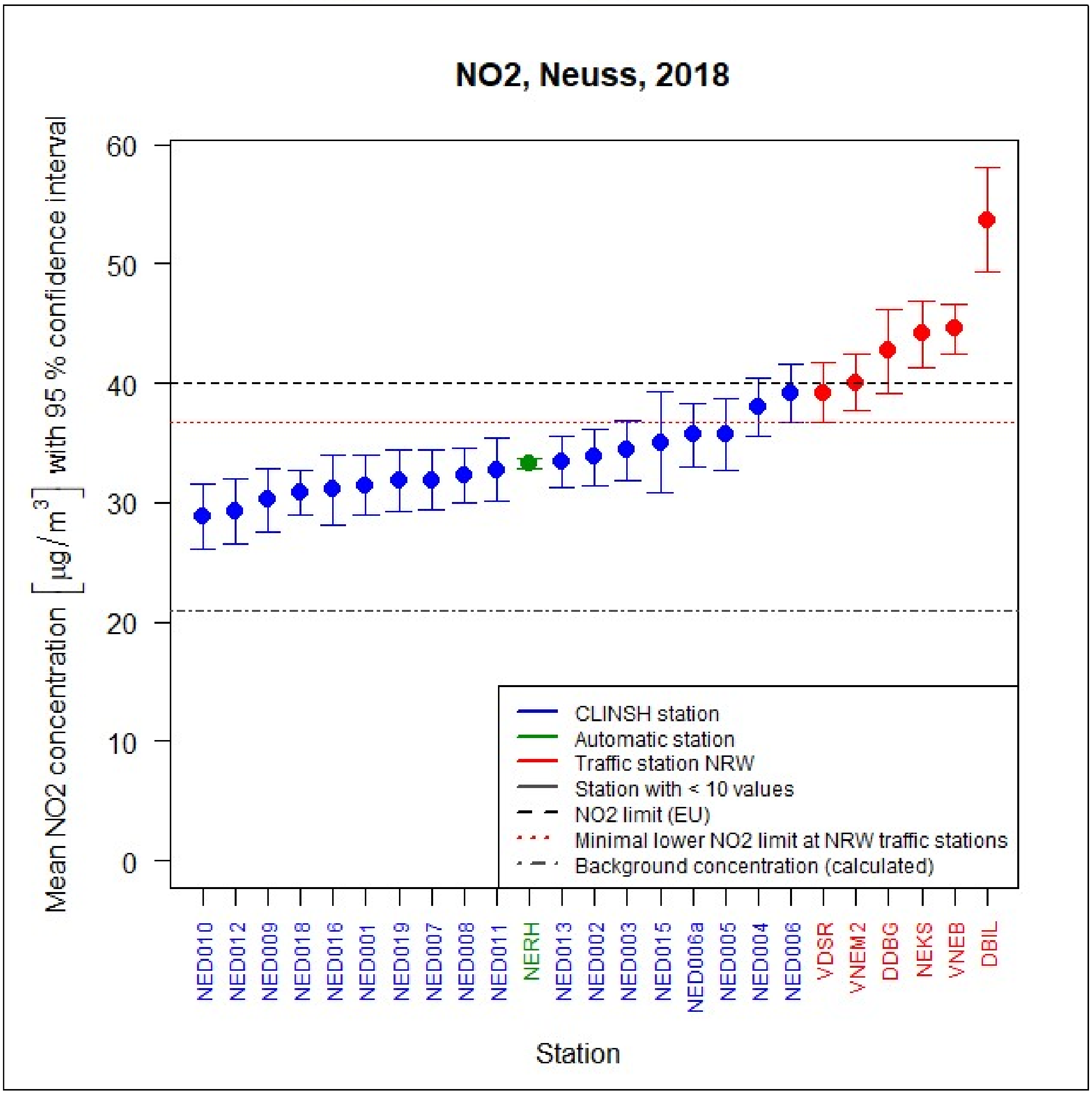


Fig. 26: Mean values and 95 % confidence interval of the 2018 annual mean NO_2 values in the Neuss/Düsseldorf research area.

Thirteen of the 19 Clinsh monitoring sites are significantly lower polluted than the traffic monitoring site with the lowest annual mean value (**VDSR**, 39 µg/m³). In comparison with the more heavily polluted traffic monitoring stations **NEKS, VNEB** and **DBIL**, even 17 of the 19 investigated monitoring stations show a significantly lower pollution level for NO_2. The measuring point **NED018**, located directly on the Rhine on the right-hand, leeward bank of Düsseldorf, has an annual mean value of 30.8 µg/m³, which is one of the lowest annual mean values in the study area.

A comparison of mean concentrations at CLINSH measuring points and at traffic measuring points in Neuss shows a significant difference between these groups. (analysis of variance for log concentrations, $p < 2.2 \cdot 10^{-16}$). The mean concentration at traffic measuring points is 33% higher than at CLINSH-stations.

Also the two traffic measuring points *NEKS* (44 µg/m³) and **VNEB** (45 µg/m³), located directly at the port area of Neuss, reach significantly higher concentration increases of 23-24 µg/m³ compared to the regional NO_2 background load (21 µg/m³) than the CLINSH measuring points **NED013** (33.4 µg/m³) and **NED015** (35 µg/m³), located in the immediate vicinity in the port area. Thus, also in Neuss it becomes clear, that the NO_X emissions from shipping and port operations are not high enough to explain the high measured values at the traffic measuring points.

4.3 Measurement results from the monitoring stations in Duisburg and Neuss

The measurement results of these continuously measuring stations form a valuable supplement for the temporal analyses of the load courses and also for the clarification of the location of load sources and their quantitative shares in the measurement results.

Due to the rapid succession of continuous measurements of nitrogen oxides (every 5 seconds), the CLINSH team was able to record the exhaust gas clouds (plume) of passing ships when the wind directions were suitable. This made it possible to make an important additional contribution to the CLINSH project by determining emission factors for over 8,500 ships on land. With these results it was possible to model the emission quantities of the moving ships on the Rhine and in the ports with a new method based on real measurements.

The **Duisburg measuring station (Rheinhafen, DURH, Rhine km 782)** is located in Duisburg-Laar on the leeward side of the Rhine dike (main wind direction) below the entrance to the harbour canal in the port of Duisburg and is approx. 150 m away from the shore. It is therefore particularly suitable for investigating emissions from ships sailing on the Rhine.

Fig. 27: Measuring station on the Rhine at Duisburg (Photo: D. Busch, LANUV)

The **Neuss (Rheinhafen, NERH) measuring station** was located on the premises of the company UCT (Umschlag Container Terminal) in the port area of Neuss, directly on the quay wall of the Rhine Canal, the access to the four Neuss port basins. This measuring station is therefore particularly suitable for investigating the emissions of ships travelling in the port traffic.

Fig. 28: Measuring station on the Rhine canal at Neuss harbour (Photo: D. Busch, LANUV)

4.3.1 General development of the pollution situation

At both measuring stations (DURH; NERH) a similar decreasing concentration development was observed over the years for the annual parameters for NO_2 as well as for PM_{10}, as already described for the NO_2 concentrations at the German-Dutch border. At both measuring stations, which are directly influenced by shipping and port operations, the annual mean values are well below the limit values of the EU Directive (Tab. 10).

Station	Year	NO_2 Annual average µg/m³	PM_{10} Annual average µg/m³	PM_{10} Daily mean with exceedances of 50 µg/m³
DURH	2018	27	23	10
	2019	26	19	2
	2020	21	22	1
NERH	2018	33	22	6
	2019	30	19	3

Tab. 10: Annual parameters for NO_2 and PM_{10} at the two continuous monitoring stations in Neuss (NERH) and Duisburg (DURH)

4.3.2 Results of the continuous measuring station in Duisburg (DURH)

On the one hand, the continuous measurements allow a better assessment of the temporal concentration trends of the investigated pollutants and, on the other hand, a relation of the evaluations to the respective meteorology at the location of the measurements. The prevailing wind directions at certain concentration levels play an important role in clarifying the causes of pollution.

Fig. 29 shows the percentage distribution of wind directions at the DURH measuring station during the year under investigation. In 2018, the south-westerly and south-easterly wind directions accounted for the largest share of the distribution. In particular, wind directions with a westerly component, blowing over the Rhine, carry ship emissions towards the measuring station. For north-easterly wind directions, which also have a larger share in the distribution, no ship emissions are to be expected at the station. The small share of the eastern wind directions (90°) in the distribution is remarkable.

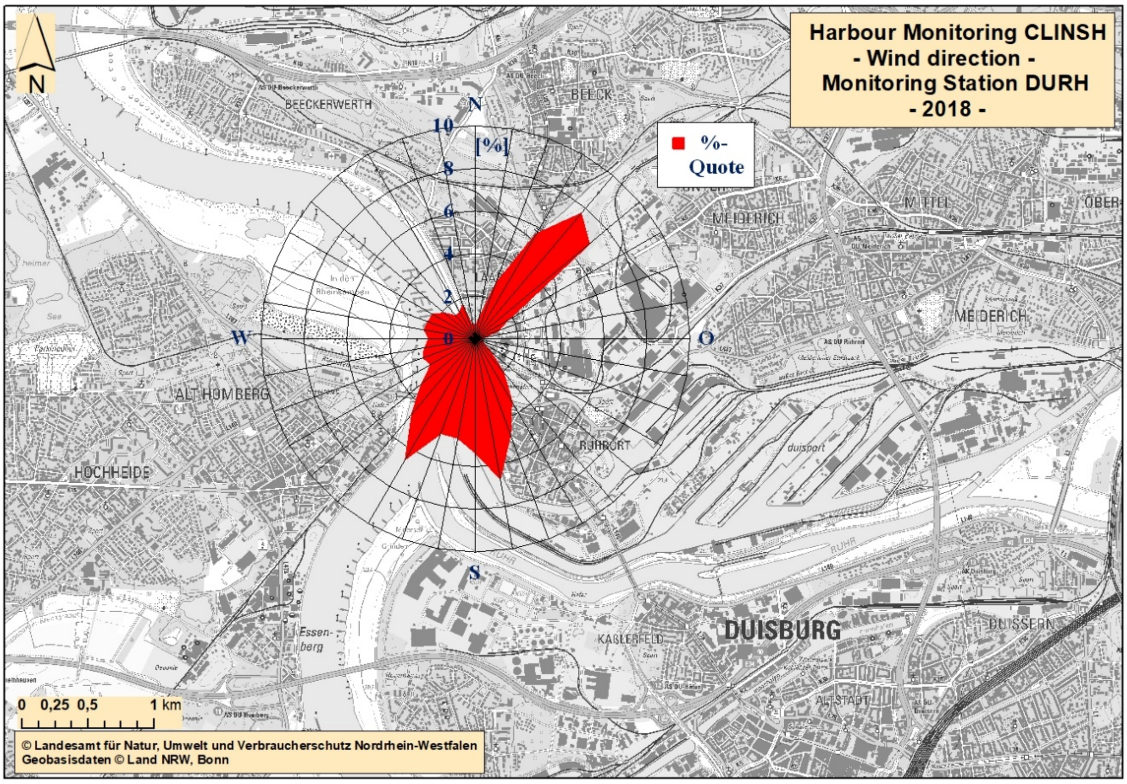


Fig. 29: Percentage distribution of wind directions occurring in 2018 at the DURH station in Duisburg

Figs. 30 and 32 show the mean values of the occurring NO_X and PM_{10} concentrations in the respective wind directions. The diagrams thus show the spatial distribution of the concentration occurrence. Fig. 30 clearly shows that rather low NO_X concentrations were measured in westerly wind directions sweeping the Rhine and thus including ship emissions. The highest concentrations occur with southerly (180°) and easterly wind directions (90°). Especially the very rarely occurring easterly wind directions (Fig. 23) contain higher NO_X

concentrations, which in all probability do not come from the ships but from other sources in the industrial and urban area.

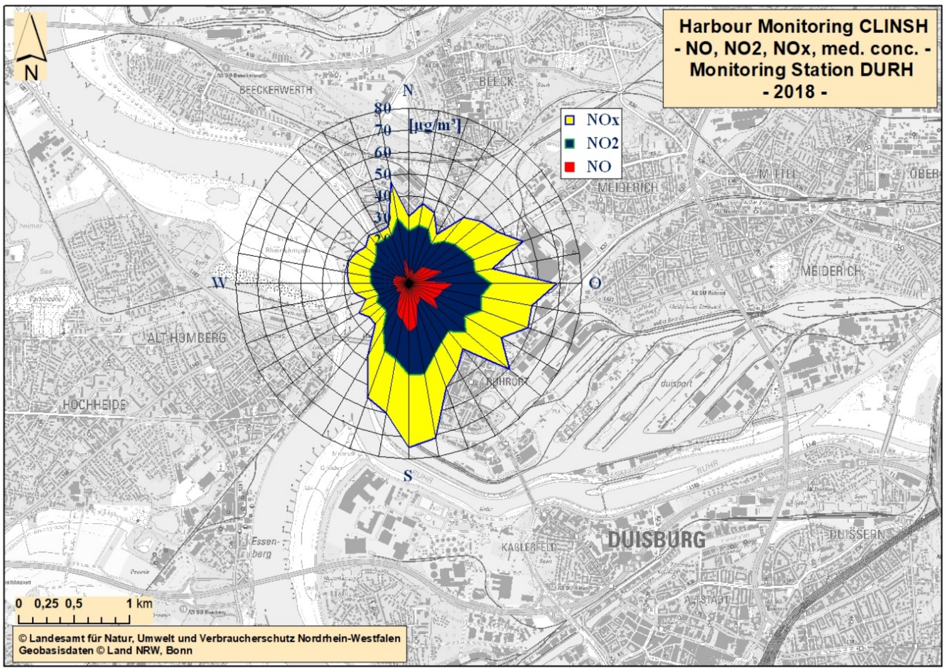
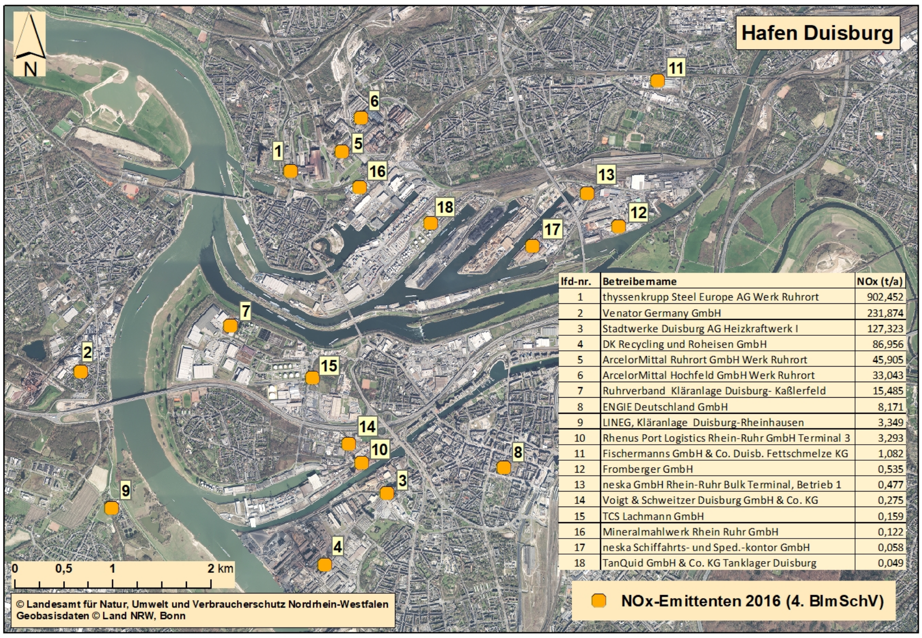


Fig. 30: Measured mean NO, NO_2 and NO_X concentrations with different wind directions at the station Duisburg-Rheinhafen (DURH)



lfd-nr.	Betreibername	NOx (t/a)
1	thyssenkrupp Steel Europe AG Werk Ruhrort	902,452
2	Venator Germany GmbH	231,874
3	Stadtwerke Duisburg AG Heizkraftwerk I	127,323
4	DK Recycling und Roheisen GmbH	86,956
5	ArcelorMittal Ruhrort GmbH Werk Ruhrort	45,905
6	ArcelorMittal Hochfeld GmbH Werk Ruhrort	33,043
7	Ruhrverband Kläranlage Duisburg- Kaßlerfeld	15,485
8	ENGIE Deutschland GmbH	8,171
9	LINEG, Kläranlage Duisburg-Rheinhausen	3,349
10	Rhenus Port Logistics Rhein-Ruhr GmbH Terminal 3	3,293
11	Fischermanns GmbH & Co. Duisb. Fettschmelze KG	1,082
12	Fromberger GmbH	0,535
13	neska GmbH Rhein-Ruhr Bulk Terminal, Betrieb 1	0,477
14	Voigt & Schweitzer Duisburg GmbH & Co. KG	0,275
15	TCS Lachmann GmbH	0,159
16	Mineralmahlwerk Rhein Ruhr GmbH	0,122
17	neska Schiffahrts- und Sped.-kontor GmbH	0,058
18	TanQuid GmbH & Co. KG Tanklager Duisburg	0,049

Fig. 31: Location of reportable NO_X emitters in the port area of Duisburg
(according to 11th BImSchV [32]).

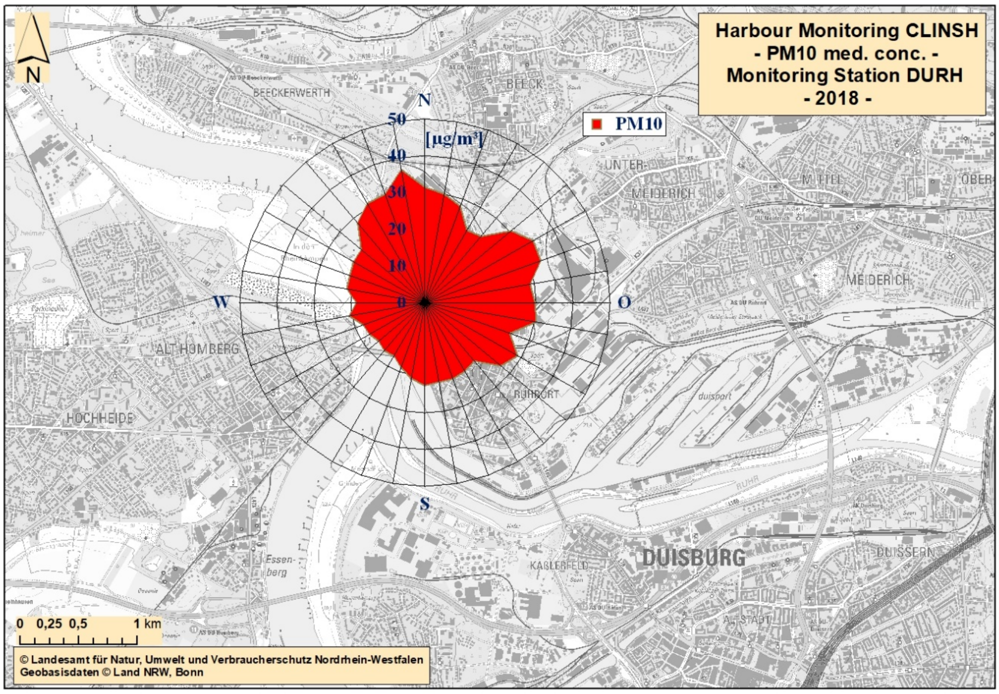


Fig. 32: Measured mean PM_{10} concentrations at different wind directions at the station Duisburg-Rheinhafen (DURH)

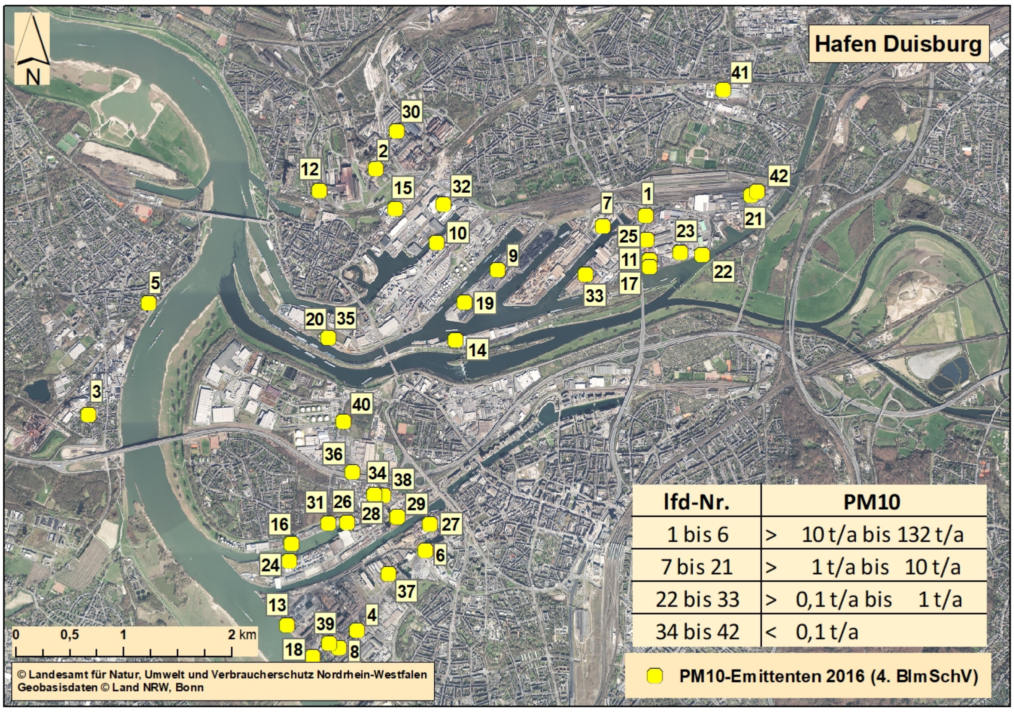


Fig. 33: Location of reportable PM_{10} emitters in the port area of Duisburg
(according to the 11th BImSchV [32])

The location of the installations known to be NO_X emitters in the Duisburg port area that are subject to reporting under the 11th BImSchV(32) and licensing under the 4th BImSchV(31) is shown in Fig. 31. Whether the emission levels of an installation can have an impact on the air quality in its direct vicinity, depends essentially on its emission level. Only ground-level emission sources such as road traffic already have an effect in their direct vicinity.

The higher the emitting chimney of the plant, the smaller the effect on the air quality of the breathing air near the ground in its immediate vicinity. For example, the emission levels of power plants with chimney heights of 50-100 m only take effect at a distance of many kilometers and essentially increase the background pollution there. The effects of the emission sources shown in Fig. 31 as examples for Duisburg are included in the planned modelling of the causes of air pollution in the port areas with the corresponding data.

The distribution of PM_{10} is similar to that of NO_X. Here, too, increased PM_{10} concentrations occur with easterly wind directions compared to westerly winds, which are also likely to originate from the industrial and urban area. The location of the installations in the port area of Duisburg, known as PM emitters, which are subject to reporting under the 11th BImSchV and licensing under the 4th BImSchV, is shown in Fig. 33.

When evaluating the measurement results, the question arises whether the conditions in the study area of the measurement year 2018 can also be representative for other years. In the meantime, the results of three measurement years are available for the DURH measurement station. A comparison of the results for the distribution of the wind directions and the mean concentrations, occurring at the respective wind directions, is compiled in Figures 34-36.

The comparison of the wind roses over the years 2018, 2019 and 2020 shows that the distributions of wind directions and wind direction-dependent pollutant concentrations, present in 2018. also occurred in a similar configuration in the following years. The results for 2018 can therefore be considered as representative. In none of the three years there are indications that significantly increased NO_X concentrations occur at the station during westerly winds that sweep the Rhine and thus carry the emissions of the inland vessels.

Shipping traffic on the Rhine near Duisburg

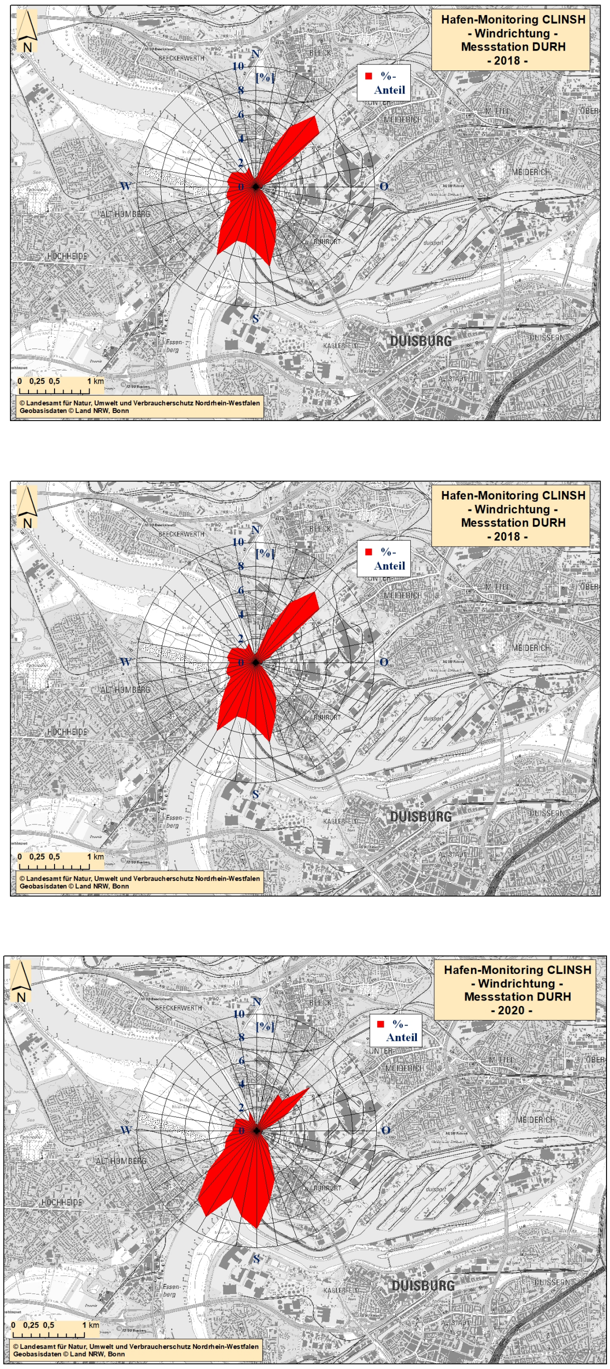


Fig. 34: Percentage distribution of the different wind directions at the DURH station in 2018, 2019 and 2020.

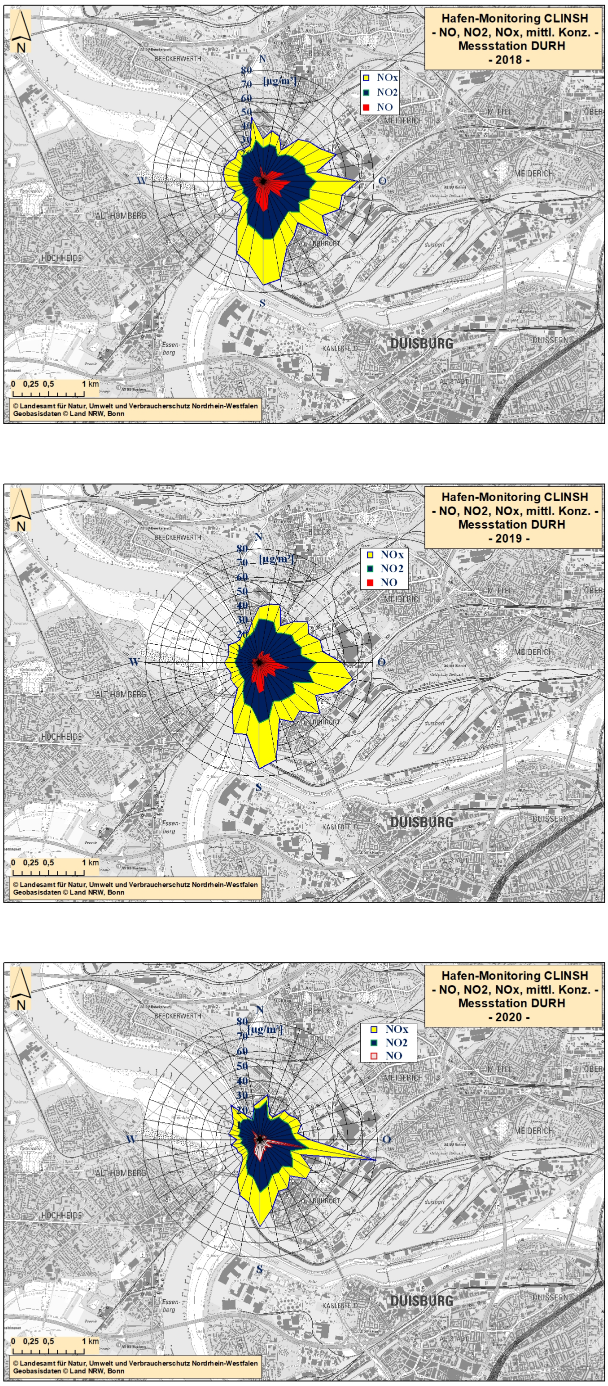
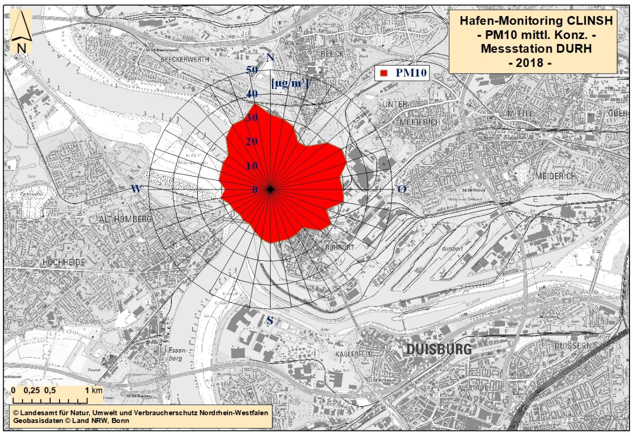
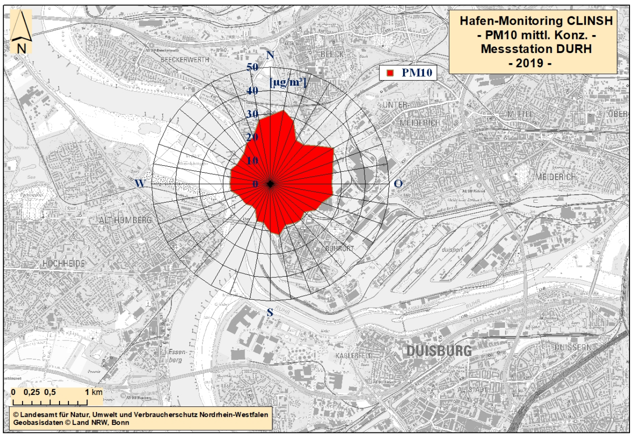


Fig. 35: Comparison of measured mean NO, NO_2 and NO_X concentrations at different wind directions at the DURH station in 2018, 2019 and 2020.





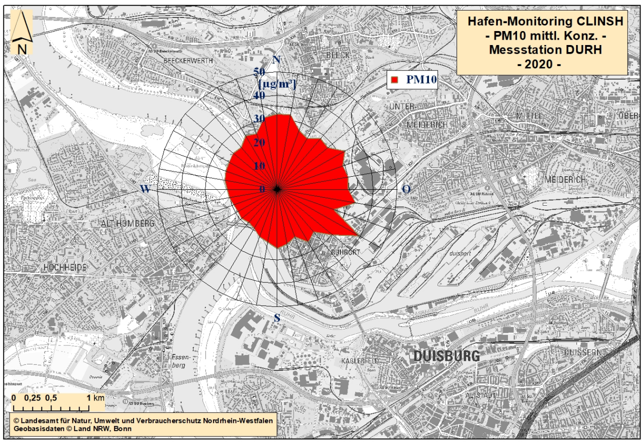


Fig. 36: Comparison of the measured mean PM_{10} concentrations at different wind directions at the DURH station in the years 2018, 2019 and 2020

4.3.3 Continuous measuring station Neuss

Fig. 37 and 38 show the percentage distribution of wind directions at the continuous measuring station NERH during the year under investigation. It is striking that the predominant wind directions occurred in a rather cross-shaped appearance with main directions NE, SE, SW and NW components. Channeling effects due to the tall buildings in the harbour area and the effect of the harbour basins as "air corridors" certainly play a role in this distribution. In 2018, the southeasterly wind directions had the largest share in the distribution at the NERH station.

Fig. 39 and Fig. 41 show the mean values of the occurring NO_X and PM_{10} concentrations in the respective wind directions in 2018. The diagrams thus represent the spatial distribution of the concentration occurrence. It can be clearly seen that in Neuss, too, lower NO_X concentrations were measured in westerly wind directions than in winds with easterly components. The highest concentrations occur with east-south-east (100^o) and south-east wind directions (150^o).

The distribution of PM_{10} is similar to that of NO_X. Here, too, easterly (100^o) and southerly (180$^{o)}$ wind directions result in increased PM_{10} concentrations compared to westerly winds.

The comparison of the wind roses over the years 2018 and 2019 shows that the distributions of wind directions and wind direction-dependent pollutant concentrations, present in 2018, also occurred in a similar configuration in the following year. However, the proportion of north-easterly wind components was slightly lower in 2019 than in 2018, but the results for 2018 can also be considered as representative.

A comparison of the distribution of the measured mean NO_X concentrations (Figs. 39, 40) also shows a comparable pollution pattern in 2019 as in 2018. However, here in 2019 the mean load decreased from approx. 90 to 70 µg/m³ for wind directions around 100^o.

For particulate matter PM_{10} (Fig. 41, Fig. 42), the picture is similar; here, too, the mean load for wind directions from 100^o decreased from approx. 30 to 20 µg/m³. For southerly wind directions, there was an increase in the mean fine particulate pollution from approx. 30 to 40 µg/m³ in 2019.

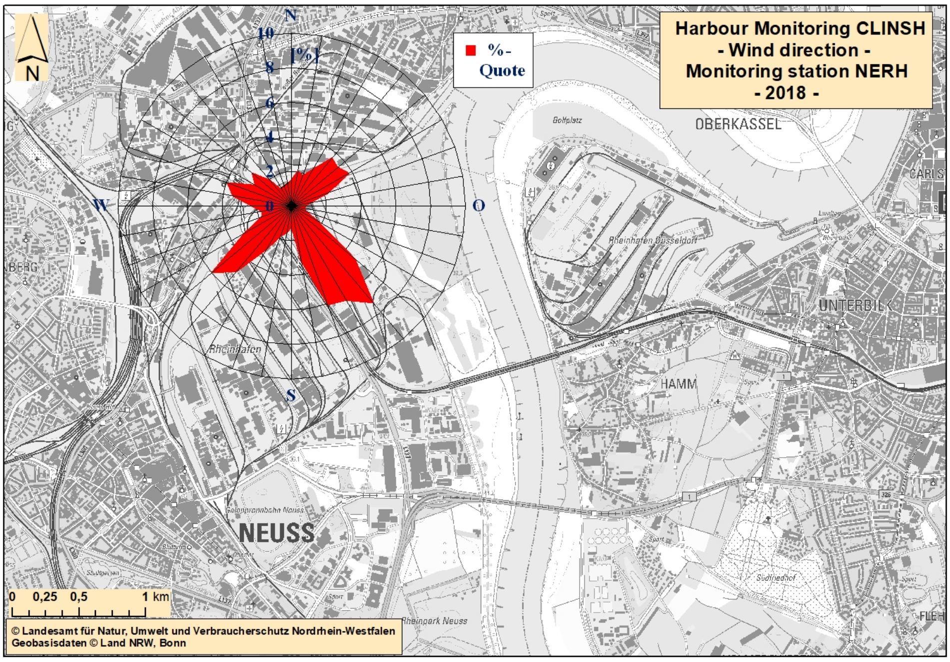


Fig. 37: Percentage distribution of wind directions at the NERH station in 2018

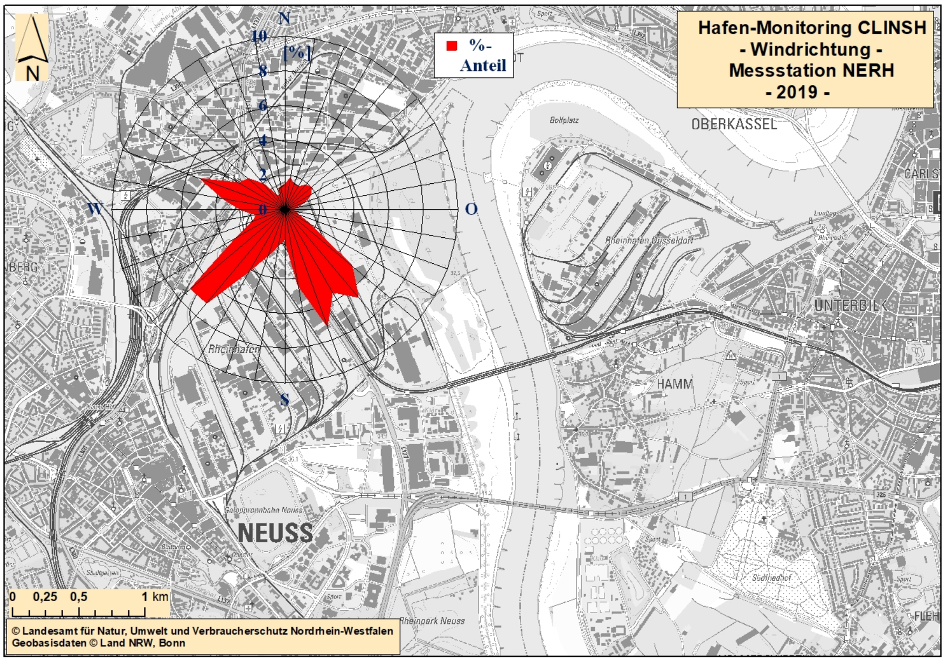


Fig. 38: Percentage distribution of wind directions at the NERH station in 2019

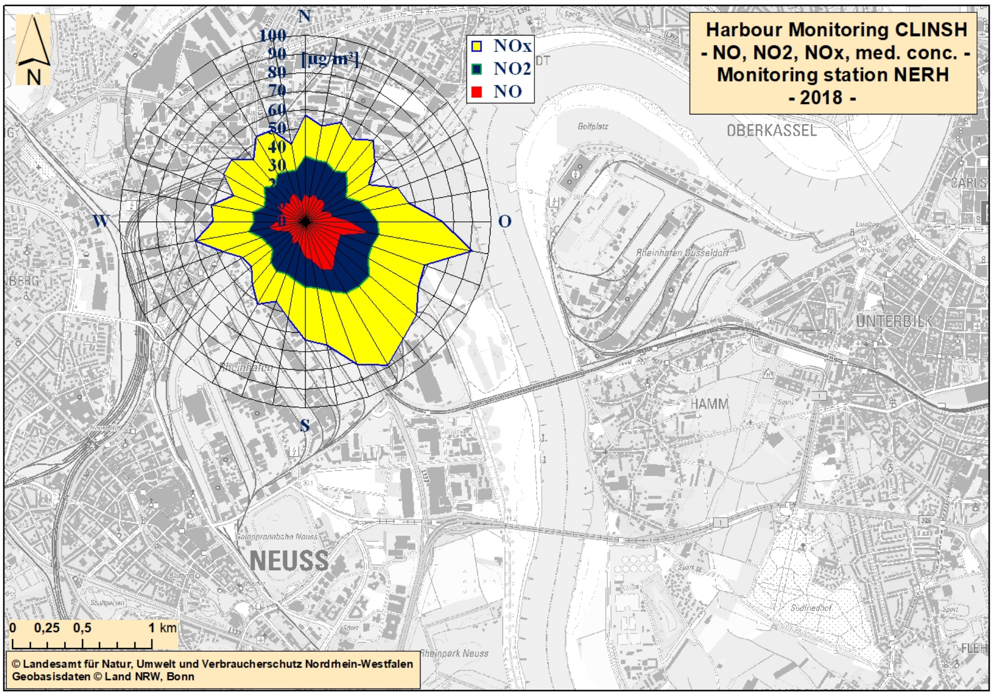


Fig. 39: Mean NO, NO₂ and NOx concentrations at different wind directions at the station Neuss-Rheinhafen (NERH) in 2018

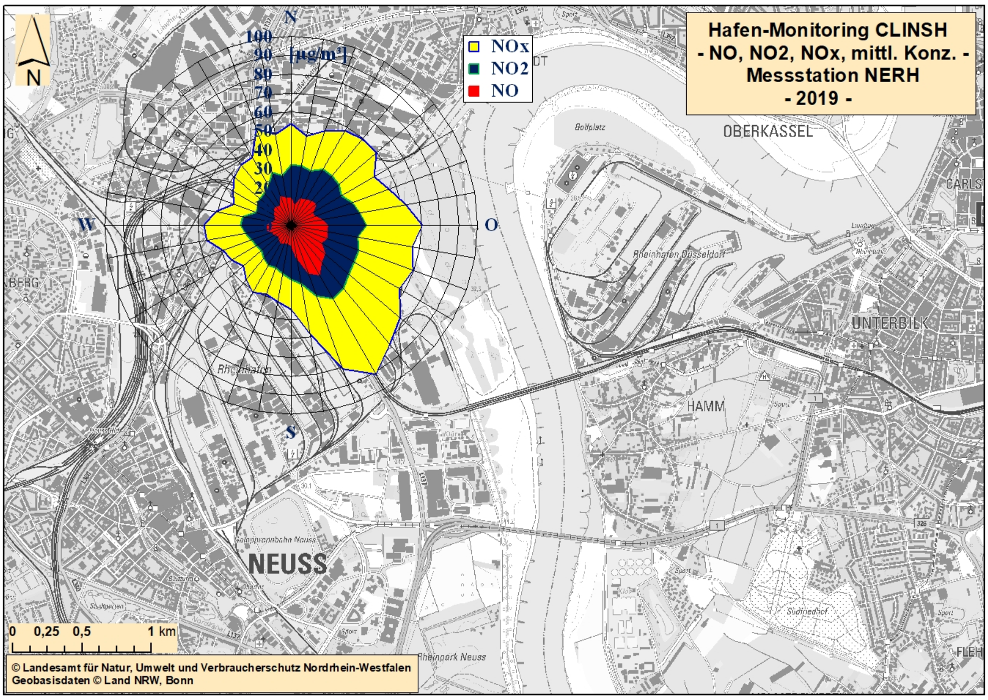


Fig. 40: Mean NO, NO_2 and NO_X concentrations at different wind directions at the station Neuss-Rheinhafen (NERH) in 2019

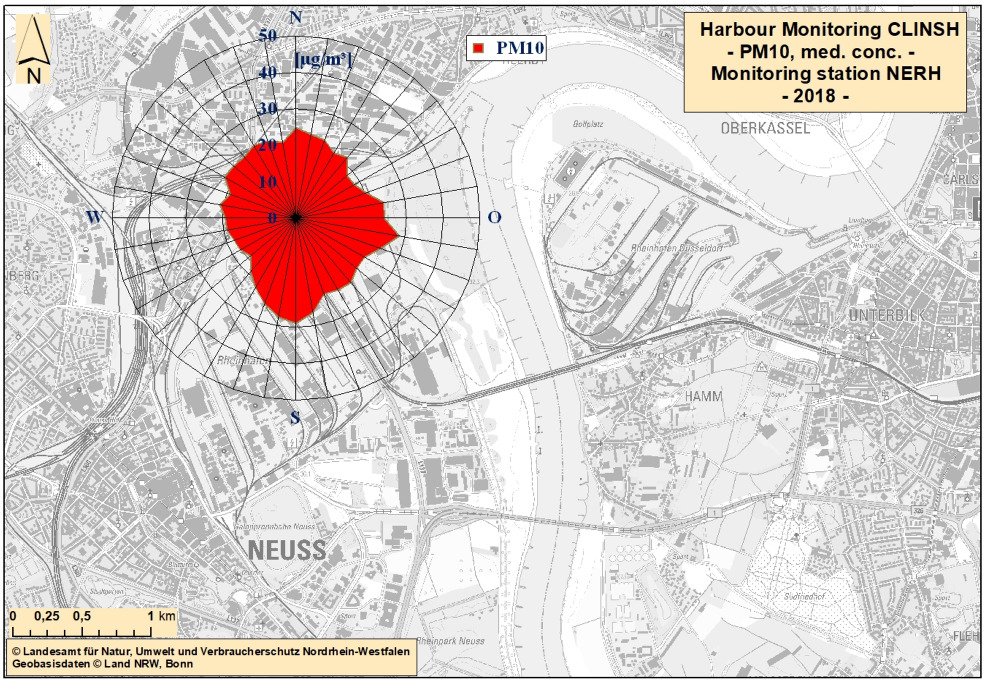


Fig. 41: Mean PM10 concentrations at different wind directions at the station Neuss-Rheinhafen (NERH) in 2018

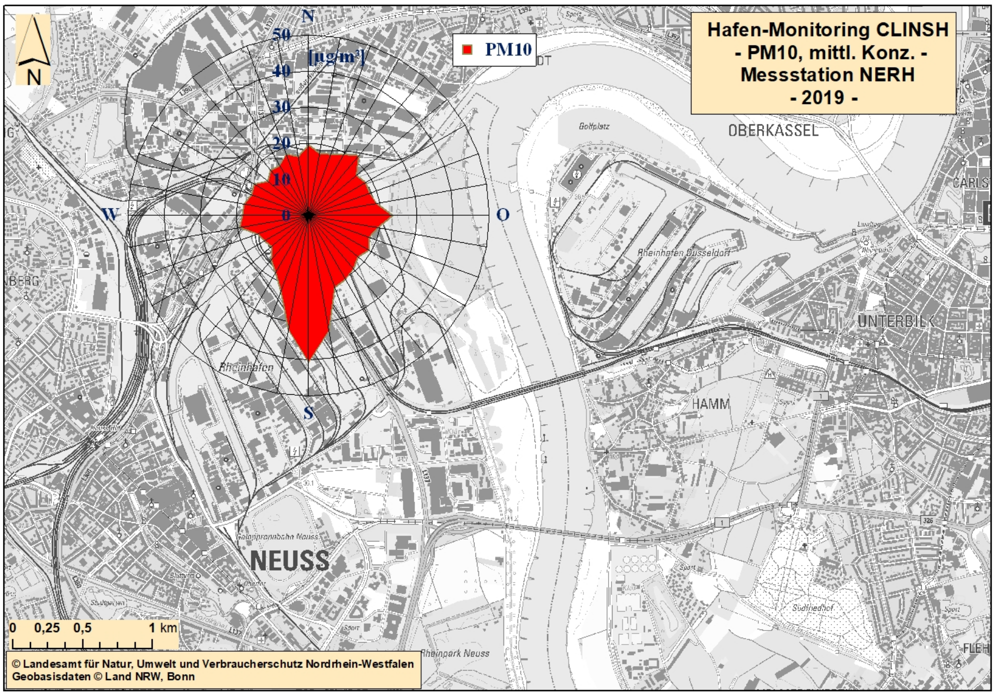


Fig. 42: Mean PM10 concentrations at different wind directions at the station Neuss-Rheinhafen (NERH) in 2019

4.3.4 Statistical evaluation of the results at the automatic measuring stations

4.3.4.1 Occurring concentration fluctuations at the stations DURH and NERH

The temporal courses of the concentrations of NO, NO_2, NO_X and PM_{10} are characterized by high variability. Figures 43-46 show examples of the courses of NO_2 and PM_{10} at the measuring stations **DURH** and **NERH**.

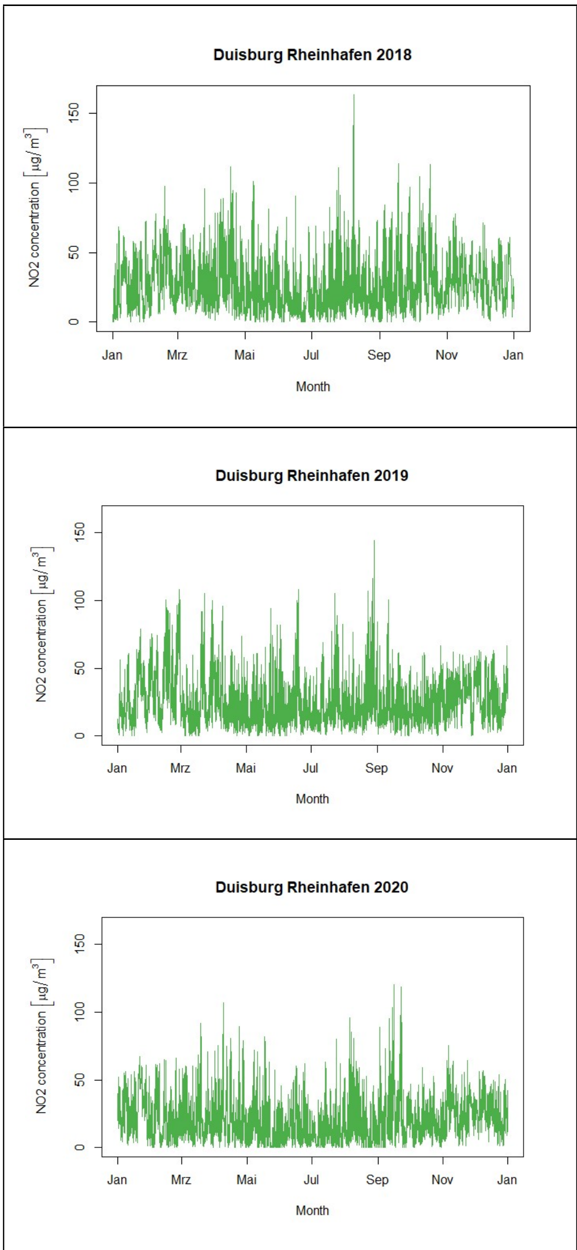


Fig. 43 a-c: NO_2, hourly mean concentration values, DURH 2018-2020

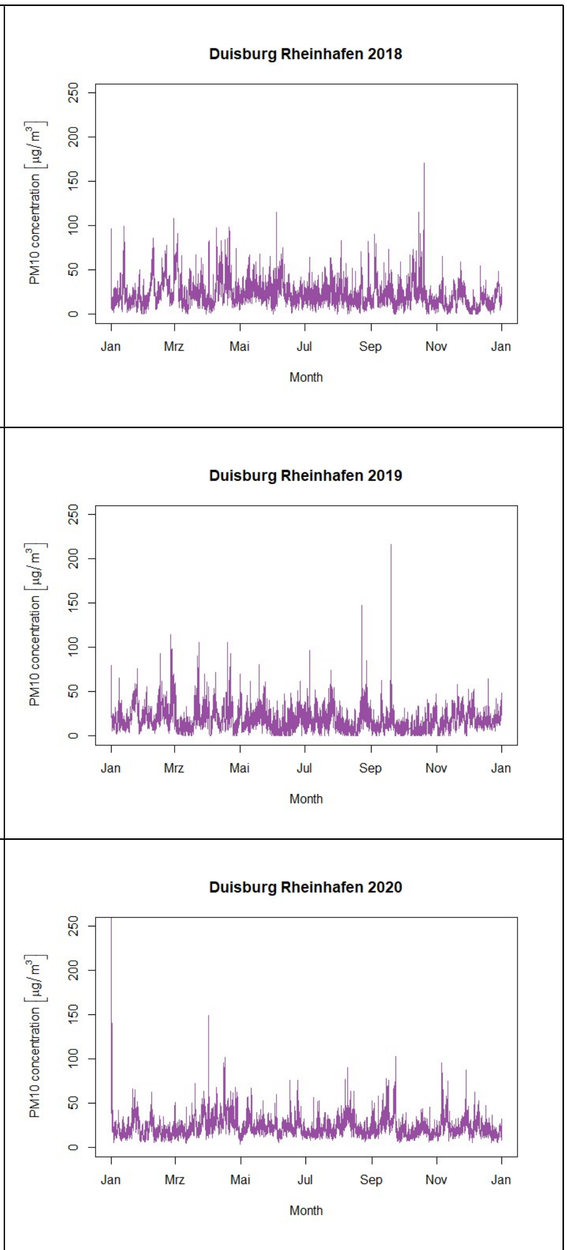


Fig. 44 a-c: PM_{10}, hourly mean concentration values, DURH 2018-2020

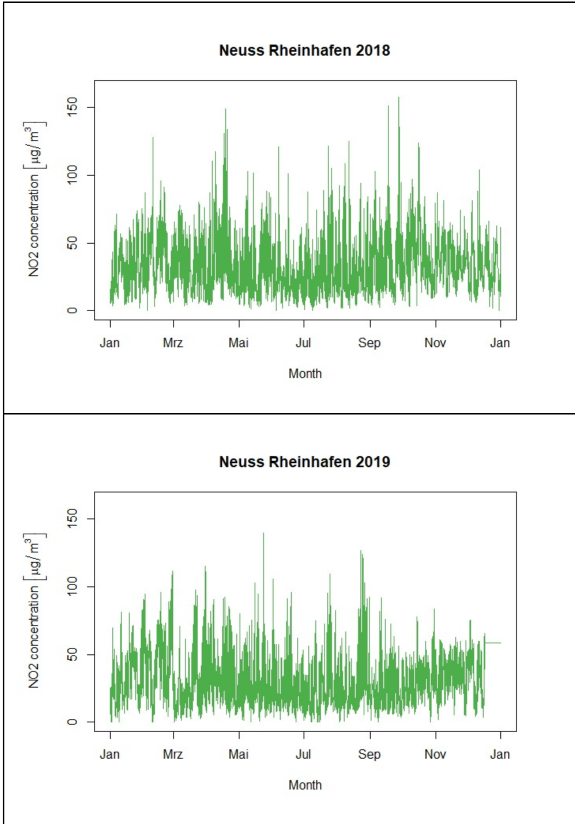


Fig. 45 a,b: NO_X, hourly mean concentration values, NERH 2018-2019

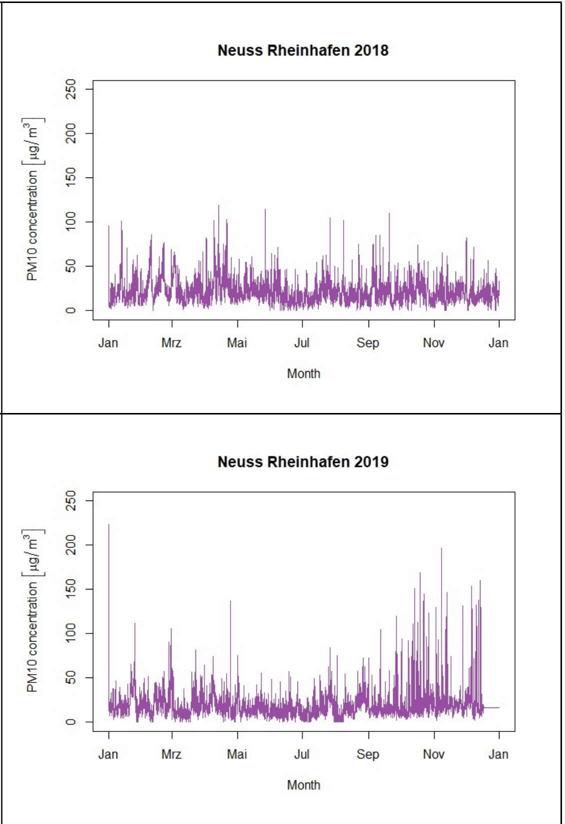


Fig. 46 a,b: PM_{10}, hourly mean concentration values, NERH 2018-2019

At both stations it can be seen that the peak concentrations for NO_2 as well as the peak concentrations for PM_{10} occur throughout the year. Seasons with a particular accumulation of peak concentrations cannot be identified. Remarkable is the particularly high PM_{10} peak of over 500 µg/m² in Duisburg on New Year's Day 2020 (in Fig.44c: clipped at 250 µg/m³), which can be classified as an effect of the New Year's Eve fireworks in the city of Duisburg.

4.3.4.2 Maxima of the NO_2 hourly mean values

In addition to the annual mean value (40 µg/m³), the EU has also defined limit values for the hourly mean value for NO_2. It was bindingly stipulated that an hourly mean value of 200 µg/m³ may only be exceeded 18 times a year. The evaluation of the measurement results of the CLINSH monitoring showed that no hourly mean exceedances of this limit value occurred at either port station. The maxima of the hourly means in Duisburg were 163 µg/m³ and in Neuss 158 µg/m³ in 2018 (Tab. 11). The limit value for the hourly means is thus safely adhered to at both stations.

Maximum hourly mean values (HMV) for NO_2						
Year	Duisburg - DURH			Neuss - NERH		
	Date	Max. HMV µg/m³	HMV > 100 µg/m³	Date	Max. HMV µg/m³	HMV > 100 µg/m³
2018	07.08.2018	163	16	27.09.2018	158	49
2019	28.02.2019	145	11	23.05.2019	139	15
2020	15.09.2020	120	12	--	--	--

Tab. 11: Maximum hourly mean values (HMV) of NO_2 at the measuring stations in Duisburg and Neuss and number of hourly mean values above 100 µg/m³.

4.3.4.3 Statistical analysis of concentrations over the course of the year

The temporal courses of the concentrations and thus the chronic stresses become more clearly visible when concentrations are summed over time. Individual peaks that visually stand out in Figs. 43-46, but only represent short-term situations, are relativized in such a cumulative representation in such a way that peak values usually do not influence the cumulated courses as significantly as it may initially appear after considering the measured concentration courses.

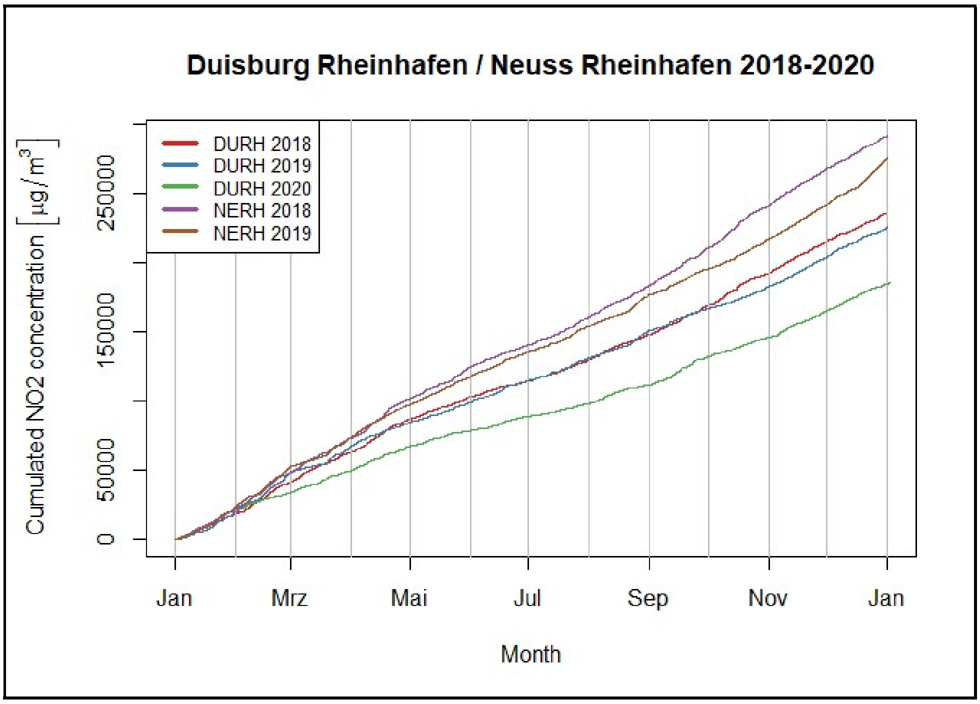


Fig. 47: Hourly mean NO_2 concentrations summed over one year at the stations Duisburg Rheinhafen (DURH) and Neuss Rheinhafen (NERH)

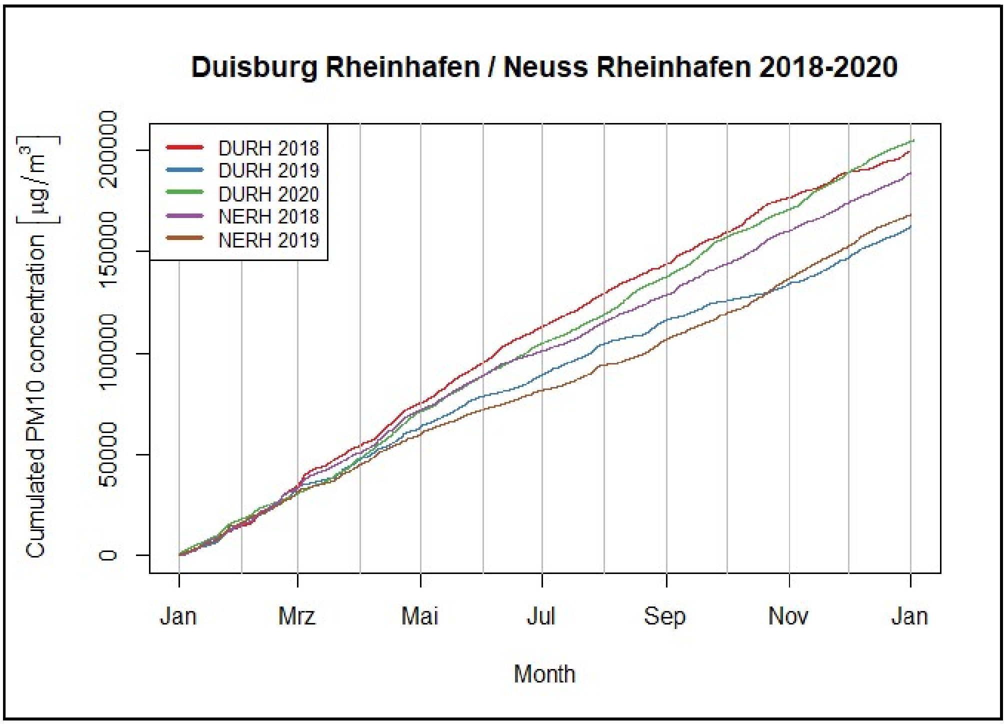


Fig. 48: Hourly mean PM_{10} concentrations summed over one year at the stations Duisburg Rheinhafen (DURH) and Neuss Rheinhafen (NERH)

Fig. 47 shows that in 2018 and 2019 the concentration totals of NO_X in Neuss increase faster than in Duisburg. No comparison is possible for 2020 due to the lack of measurement data in Neuss. In the course of the year, all courses between May and September show a somewhat flatter increase than in the other months. The courses of PM_{10} (Fig. 48) hardly show such a seasonal dependency, the increase is almost linear with slightly varying steepness of the increase.

PM_{10} does not show the clear separation between the stations that can be seen for NO_2. If the annual concentration totals are arranged in ascending order, the order for NO_2 is DURH 2020, DURH 2019, DURH 2018, NERH 2019, NERH 2018, i.e. a separation of stations by location, while for PM_{10} there is a mixing of station order: DURH 2019, NERH 2019, NERH 2018, DURH 2018, DURH 2020. When comparing the progressions for NO and NO_X, a similar picture emerges as for NO_2.

For a comparison of the concentration trends at the **DURH** and **NERH** stations in 2018-2020, it is useful to average the measured values (for NO_2 and PM_{10}, see Figures 45-46) in small time intervals in order to compensate the effect of short-acting scatter. One hour was chosen as time interval. However, it is still necessary to relate concentration changes over time or location to structural factors like month, weekday or daytime and to separate these from effects that are due to the particular conditions of a year or a location.

Additionally, random changes must be separated from structural changes. To this end, measured concentration courses were described by a statistical model, which uses the factors mentioned to describe measured data. Doing this it becomes obvious to which extent factors contribute to the modelling and whether contributions of a factor depend on other factors.

The investigation of the logarithmic concentrations of NO, NO_2, NO_X, PM_{10} per location and year showed that the factors station, year, month, day of the week, time of day (in hours) had a significant influence on the measured values (method: analysis of variance). The logarithmic values were used, because their distribution approximates the normal distribution required by the analysis of variance, while this does not apply to the original values, which can only assume non-negative (≥zero) values.

However, as expected, the individual factors do not act independently of each other. Rather, it is necessary to consider the combination effect (interaction) of several factors. The test of whether the addition of another variable provides a significantly better description of the data yielded a positive result for all four concentrations and all members of the model sequence, so that always the most complicated of all the descriptions considered is to be used for the discussion of the processes. As an example, the considered model sequence for NO_2 is shown in Table 12. Thus, it became clear that model 9, including the possible interactions (Station:Year) and Station:Month:Year), guarantees the best results (Tab. 13)

Considered models

Model 1: ln(NO2) ~ 1

Model 2: ln(NO2) ~ Station

Model 3: ln(NO2) ~ Station + Year

Model 4: ln(NO2) ~ Station + Year + Month

Model 5: ln(NO2) ~ Station + Year + Month + WDay

Model 6: ln(NO2) ~ Station + Year + Month + WDay + Hour

Model 7: ln(NO2) ~ Station + Year + Month + WDay + Hour + Station: Year

Model 8: ln(NO2) ~ Station + Year + Month + WDay + Hour + Station: Year + StatMon

Model 9: ln(NO2) ~ Station + Year + Month + WDay + Hour + Station: Year + Station: Month:Year

Tab. 12: Modelling for the significance of the factors station, year, month, day of the week, time of day on the measured NO_2 concentration.

It follows from the analysis in Tab. 13 that the triple interaction of station, month and year must also be taken into account when comparing temporal series. Thus, it is not possible to make simple statements such like *"In year „XXXX", the concentrations at location YY were always "ZZ"% higher"*. Rather, differences follow a complicated pattern. This does not mean, however, that the concentration course at one location in one year differs over the whole year from the course of another year or another location.

Models tested	Residual degrees of freedom	Residual sum of squares	Degrees of freedom	Sum of squares	F value	P value
1	43818	43645				
2 vs 1	43817	41682	1	1962.98	2638.12	< 0.0001
3 vs 2	43815	40641	2	1040.59	699.24	< 0.0001
4 vs 3	43804	38244	11	2396.96	292.85	< 0.0001
5 vs 4	43798	36652	6	1592.71	356.75	< 0.0001
6 vs 5	43775	34193	23	2458.54	143.66	< 0.0001
7 vs 6	43774	34190	1	3.41	4.58	0.0324
8 vs 7	43763	33919	11	271.06	33.12	< 0.0001
9 vs 8	43730	32539	33	1380.02	56.20	< 0.0001

Tab. 13: Testing the models against each other.
A p value $p < 0.05$ indicates an improvement against the preceding model.

Fig. 49 shows the courses of the mean monthly NO_2 concentrations and Fig. 50 the courses of the mean monthly PM_{10} concentrations with their respective 95% confidence intervals within the different years of investigation. The values have already been adjusted for the effects of weekday and time.

There are certainly months in which two locations or two years had indistinguishable mean concentrations. For a discussion of these patterns, Figures 49 and Fig. 50 show the mean concentrations for NO_2 and PM_{10} after adjustment for weekday and time-of-day effects. The adjustment is necessary because not all weekdays and times of day occur equally in all months. The concentrations shown apply to Wednesday, 12:00 p.m. Other weekdays or times of day would cause a vertical shift of all curves while retaining their shape.

The comparison of two progression curves is done by comparing the confidence intervals for each month. If they overlap, the means are considered as indistinguishable, otherwise they are significantly different. For such a comparison, the possible number of overlaps is between 0 (complete non-agreement, significantly different overall trends) and 12 (complete non-distinguishability. The more overlaps, the more the two courses match.

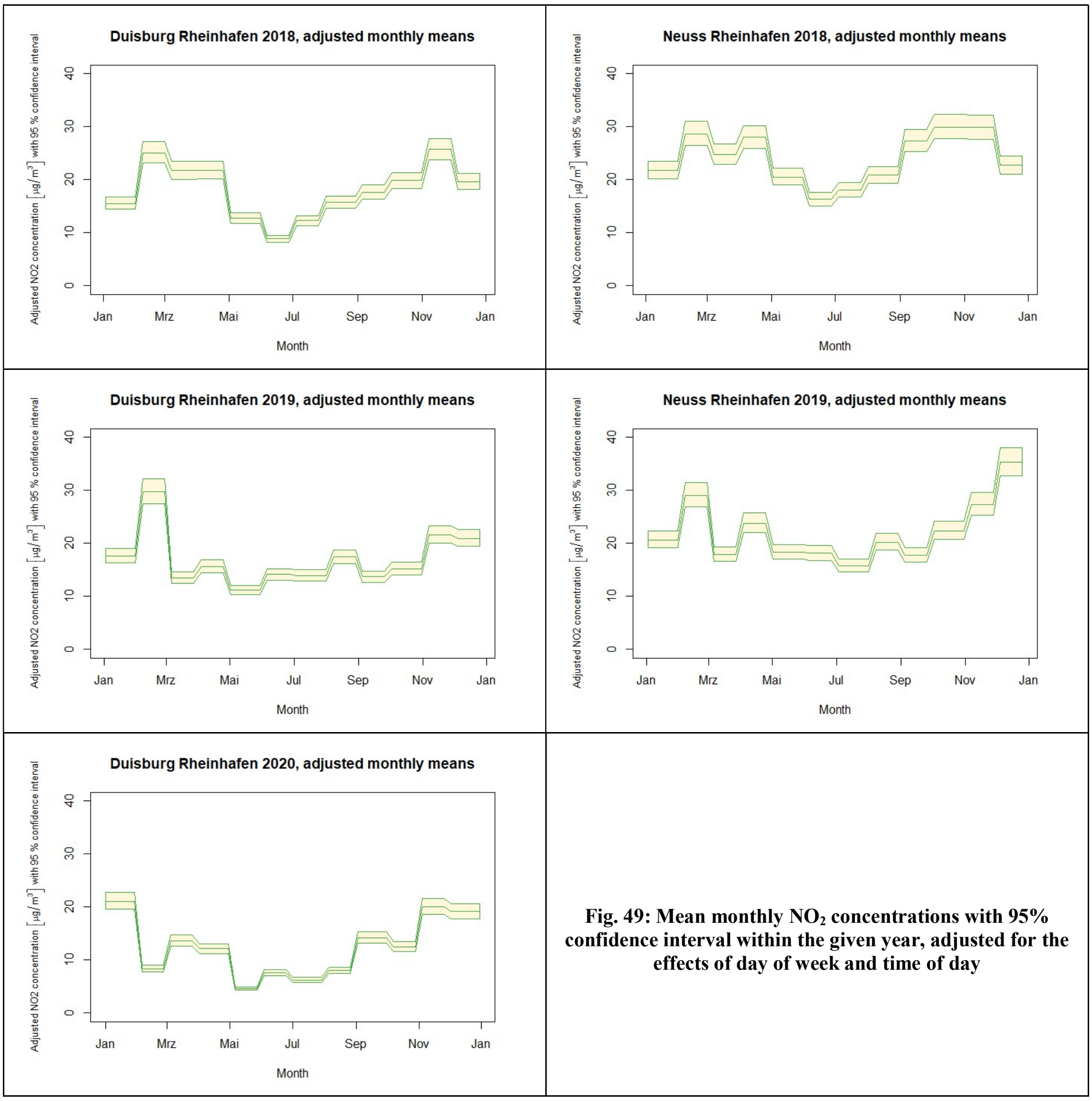


Fig. 49: Mean monthly NO_2 concentrations with 95% confidence interval within the given year, adjusted for the effects of day of week and time of day

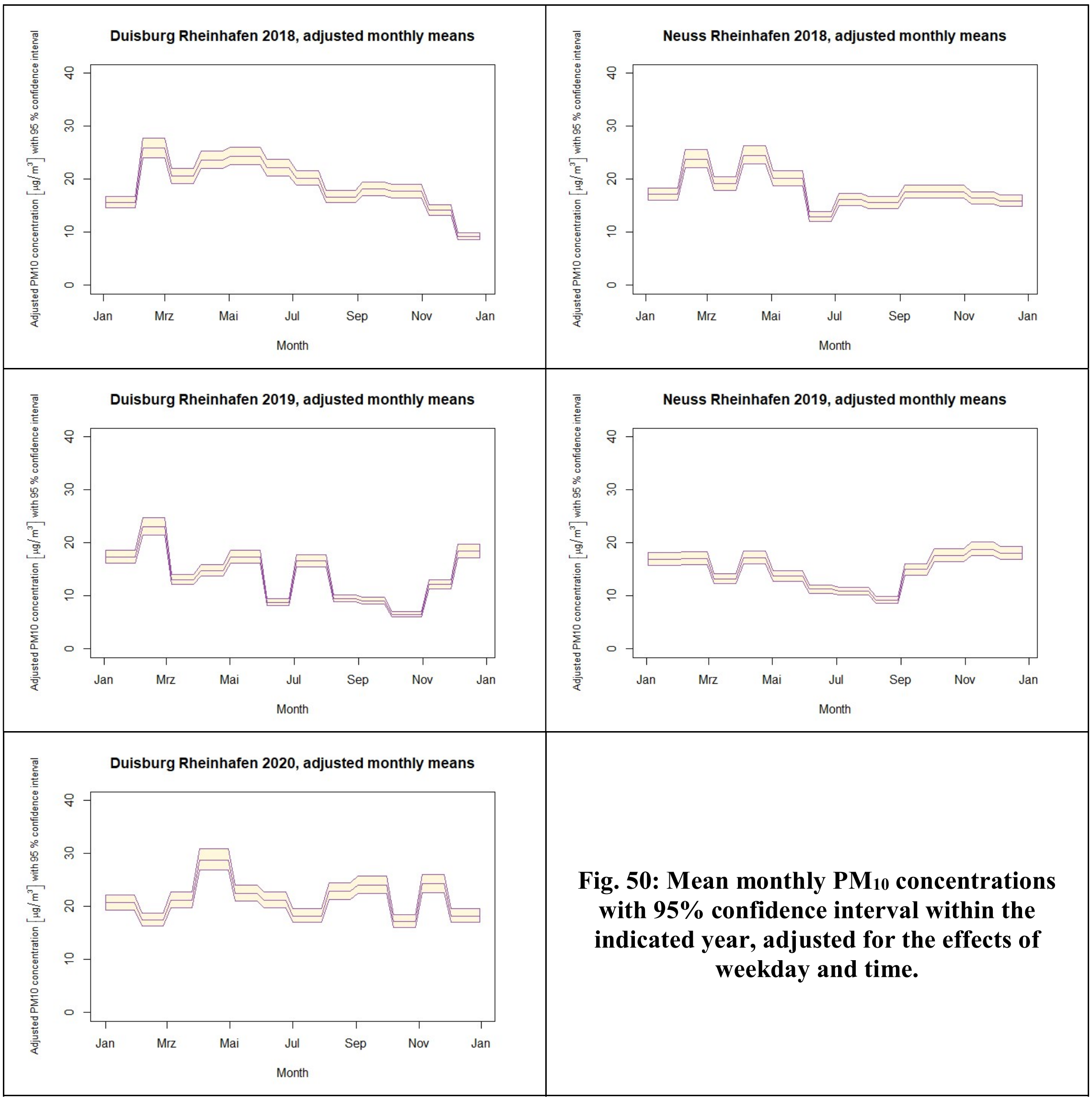


Fig. 50: Mean monthly PM_{10} concentrations with 95% confidence interval within the indicated year, adjusted for the effects of weekday and time.

Tables 14 and 15 show that the temporal courses of the concentrations of NO_2 and PM_{10} differ broadly in shape and level. For the DURH station it is true that temporally close courses are not necessarily more similar than temporally more distant courses. No statement can be made about this for the NERH station, as only two years were investigated.

To illustrate the differences between courses, Figs. 51 and 52 show the monthly differences between the courses of the NO_2 concentration of different years and different locations.

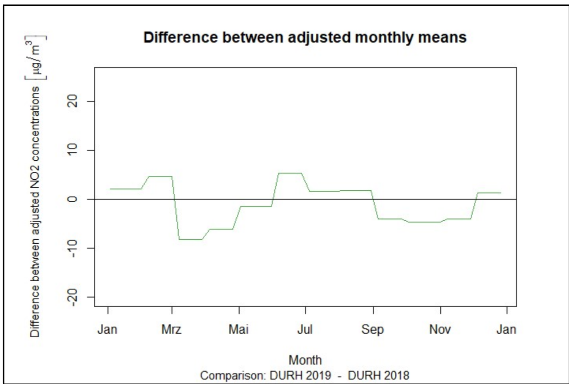
The differences between the monthly trends of NO_2 between years (Figs. 51, 52) show that there are differences here that do not take the form of a simple shift. Uniform seasonal figures are not discernible, but this was not to be expected according to the results of the variance analysis.

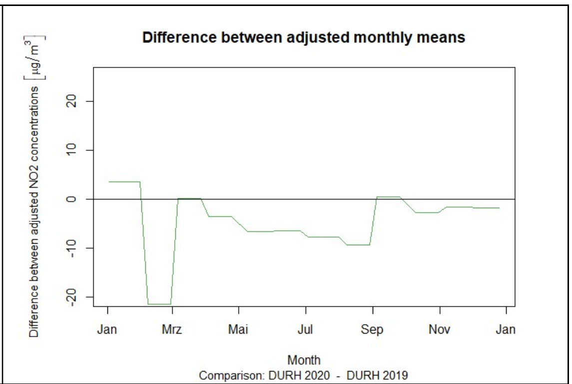
NO_2	DURH18	DURH19	DURH20	NERH18
DURH18				
DURH19	5			
DURH20	2	4		
NERH18	4	3	1	
NERH19	5	3	1	7

Tab. 14: Number of months where the monthly mean values of two courses of NO_2 concentration [µg/m3] were statistically indistinguishable.

PM_{10}	DURH18	DURH19	DURH20	NERH18
DURH18				
DURH19	2			
DURH20	5	2		
NERH18	7	3	5	
NERH19	2	4	3	5

Tab. 15: Number of months where the monthly mean values of two courses of PM_{10} concentration [µg/m^3] were statistically indistinguishable.





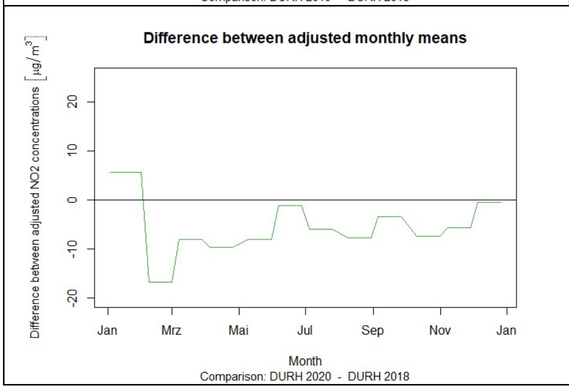


Fig. 51: Differences between mean monthly NO_2 concentrations in different years at DURH, adjusted for the effects of day of weekday and time.

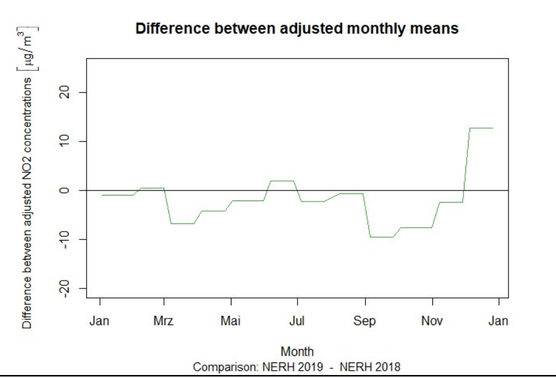


Fig. 52: Differences between mean monthly NO₂ concentrations in different years at NERH, adjusted for the effects of day of weekday and time.

The differences between the monthly trends of NO_2 between years (Figs. 51, 52) do not take the form of a simple shift. Uniform seasonal figures are not discernible, but this was not to be expected according to the results of the variance analysis.

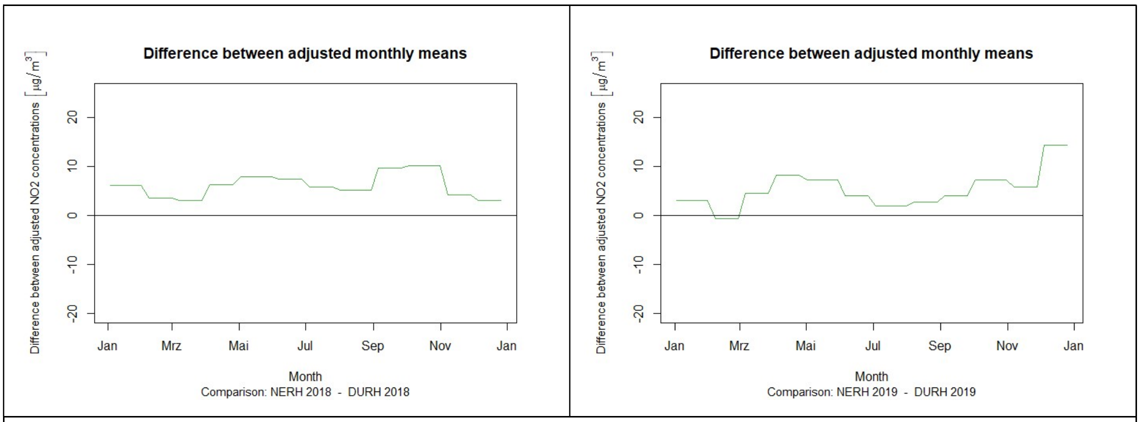
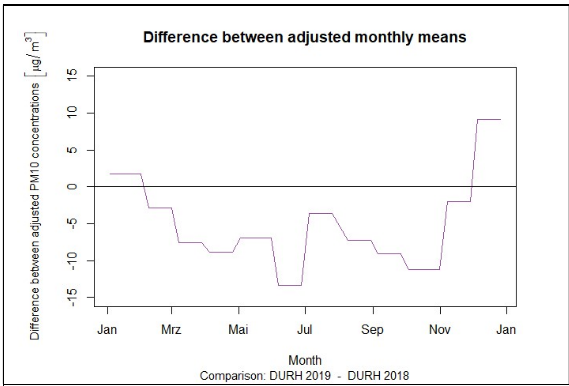
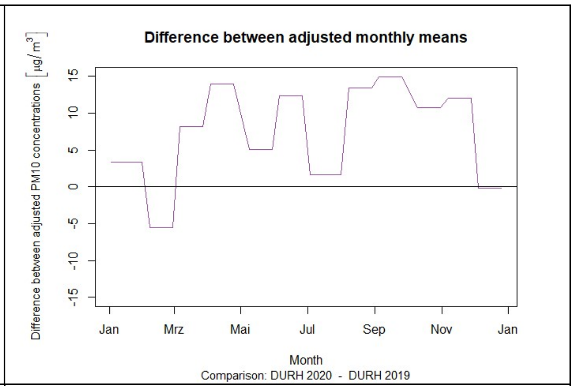


Fig. 53: Differences between mean monthly NO₂ concentrations in the same year at DURH and NERH, adjusted for the effects of weekday and time.

The differences between the monthly courses of NO_2 in comparison to **DURH** and **NERH** for one year each (Fig. 53) show that indeed also here no seasonal pattern is discernible, but the differences tend to have a constant character, especially in 2018, when the mean concentration in **NERH** was more or less consistently higher than in **DURH**. In 2019, the differences are more pronounced.





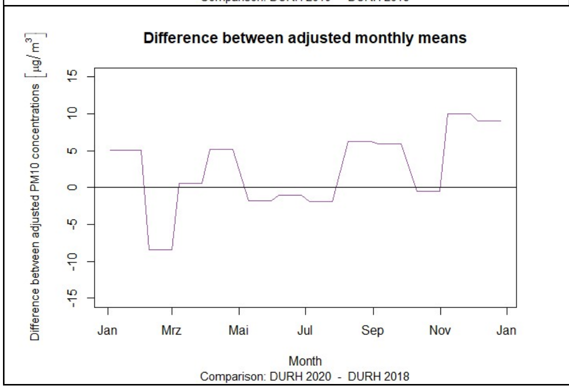


Fig. 54: Differences between mean monthly PM_{10} -concentrations in different years at DURH, adjusted for the effects of weekday and time.

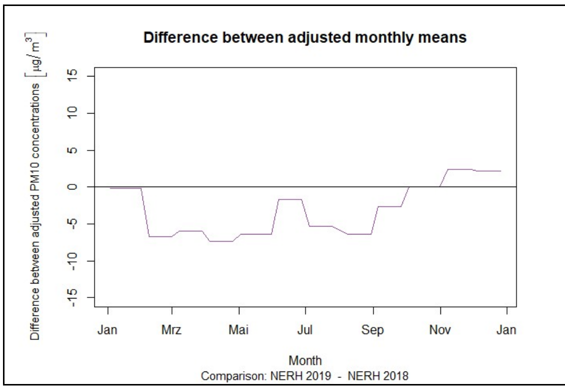
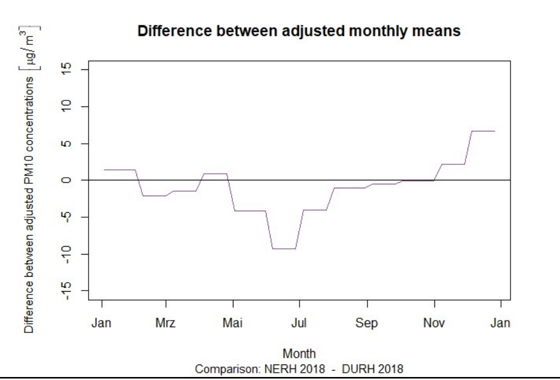


Fig. 55: Differences between mean monthly PM_{10} -concentrations in different years at NERH, adjusted for the effects of day of weekday and time.

For the differences between the monthly courses of PM_{10} between years (Figs. 51, 52) it is effective the similar as for the corresponding differences for NO_2: differences are not simple shifts, a uniform seasonal figure cannot be discerned. The variation of differences is numerically larger for PM_{10} than for NO_2, but this is related to the overall larger range of PM_{10} values.

The difference between PM_{10} courses of the same year in **DURH** and **NERH** (Fig. 56) shows clearly more variation than the same comparison for NO_2.



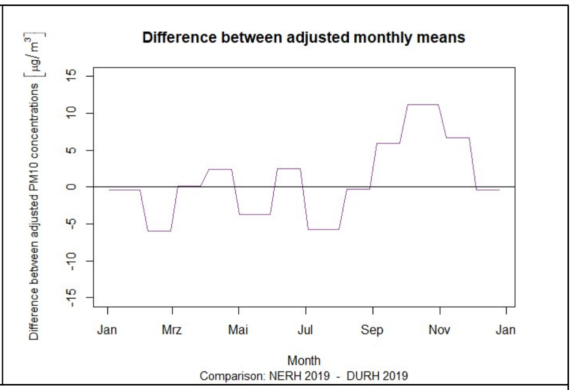


Fig. 56: Differences between mean monthly PM_{10} concentrations in the same year at DURH and NERH, adjusted for the effects of weekday and time.

In summary, the temporal courses of NO_2 and PM_{10} at the stations **DURH** and **NERH** show the same structural dependencies on basic factors. The statistical analysis shows the presence of daytime and weekday - rhythms for both sites, albeit of slightly different intensity. It also shows that concentrations differ between years and within a year over the months. The changes over months do not occur every year in the same way. However, this occurs in different ways at both sites and over the years. For the assessment of a site and for future measurements, it is therefore true that conclusions from one site to another are of questionable quality and that the measurement strategy must always cover the entire year.

Ships passage on the Rhine at Düsseldorf/Neuss (Photo: H.Eckhoff, LANUV)

5. Recording the emissions of individual ships

5.1 Emission peaks and identification of associated ships

Nitrogen oxide emissions from diesel engines essentially consist of a mixture of nitrogen monoxide (NO) and nitrogen dioxide (NO_2). The sum of both substances is called NO_X. Directly at the exhaust, the proportion of NO initially predominates. A part of it is converted into NO_2 by the air chemistry within a short time after discharge.

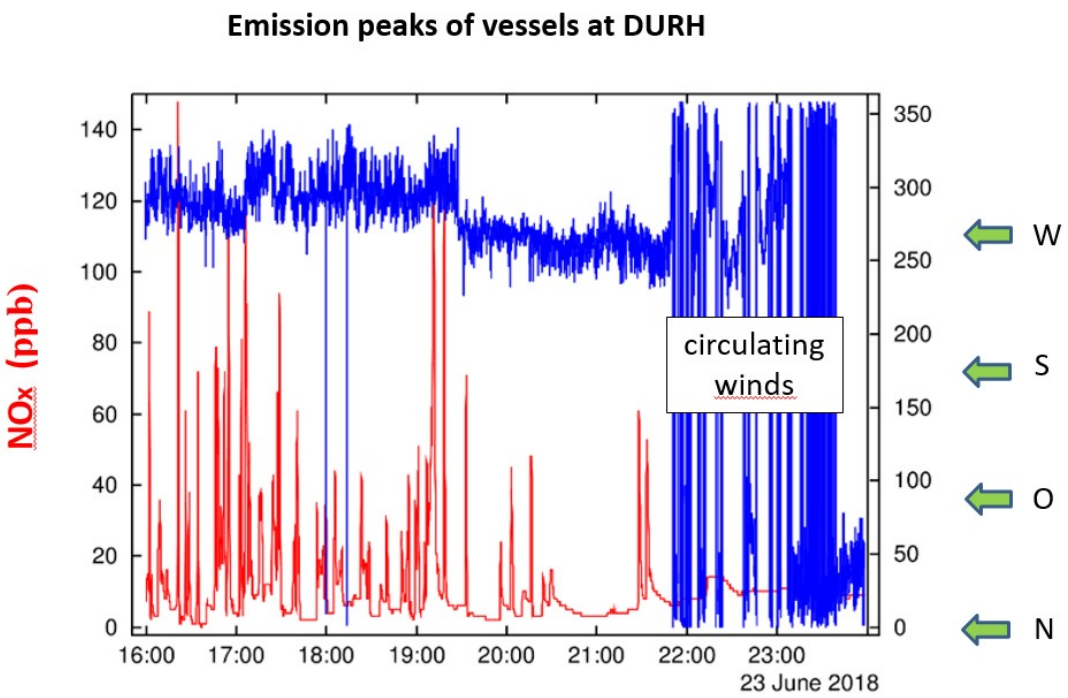


Fig. 57: Clearly visible emission peaks of passing barges at the DURH station with northwesterly wind directions, shown by the NOx concentrations

In case of suitable wind directions with westerly components, the ship emissions are carried to the measuring station as an exhaust gas cloud (plume). With the automatic measuring station in Duisburg, the rapid succession of measurements (every 5 seconds) made it possible to directly record the pollution peaks of passing ships.

Fig. 57 shows very nicely such a situation on 23.06.2018. In the period from 16:00 h to approx. 21:45 h, the peaks of the passing ships are visible with constant northwesterly wind directions. Afterwards a situation with circulating winds occurred, where no more ship peaks were visible.

With the help of the **AIS** signals (**A**utomatic **I**dentification **S**ystem, mandatory automatic identification system for merchant ships), emitted by the ships, these peaks can in many cases be assigned to the size class, direction of travel and speed of the passing ship. (Fig. 58). Reliable identification is always possible, when individual ship peaks can be distinguished from each other. If several ships pass the station at the same time, the peaks overlap. A clear assignment of the peak to a ship is not possible then.

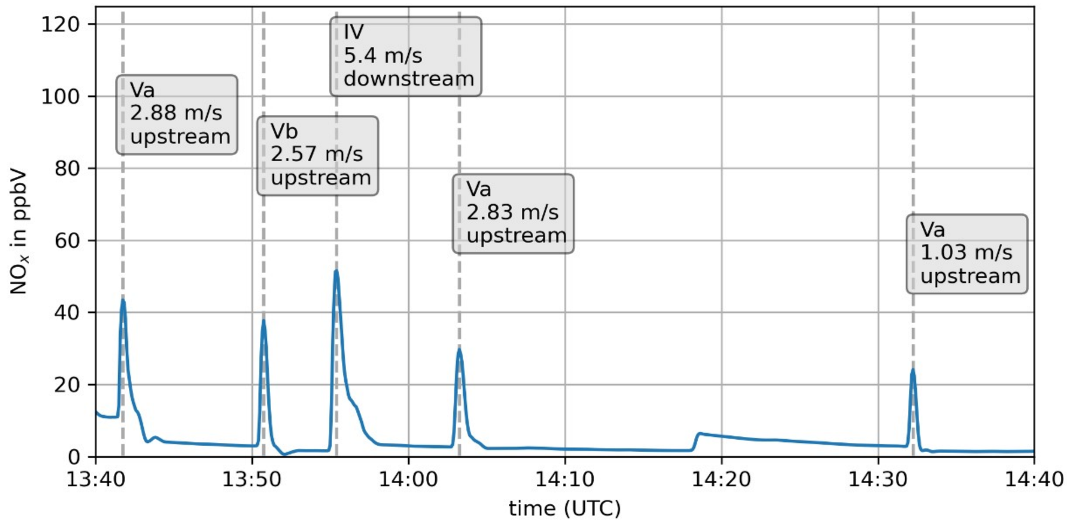


Abb. 58: Assignment of NOx peaks to the direction of travel, speed and length classes of the passing vessels by means of AIS signals

IV : Europe vessel (Rhine-Herne Canal vessel): 85 × 9.50 × 2.5 m, cargo capacity 1,350 t
Va : Large Rhine vessel: 110 × 11.4 × 3.5 m, cargo capacity 2,800 t
Vb : Large Rhine vessel: 135 × 11,4 × 3,5 m. cargo capacity 4,000 t

Fig. 59 shows a situation with an initial southeasterly to southerly wind direction. The course of the red concentration line shows a relatively high and rather indifferent NO_X load. The concentration course shows that the higher nitrogen oxide concentrations visible at the left side of Fig. 59 do not originate predominantly from ships, but from other sources. From about 07:00 onwards, the wind shifts to a southwesterly direction over the south and sweeps across the Rhine. The indifferent load drops significantly to about 1/3 of the previous concentrations, at the same time the peaks of the ships passing on the Rhine become visible.

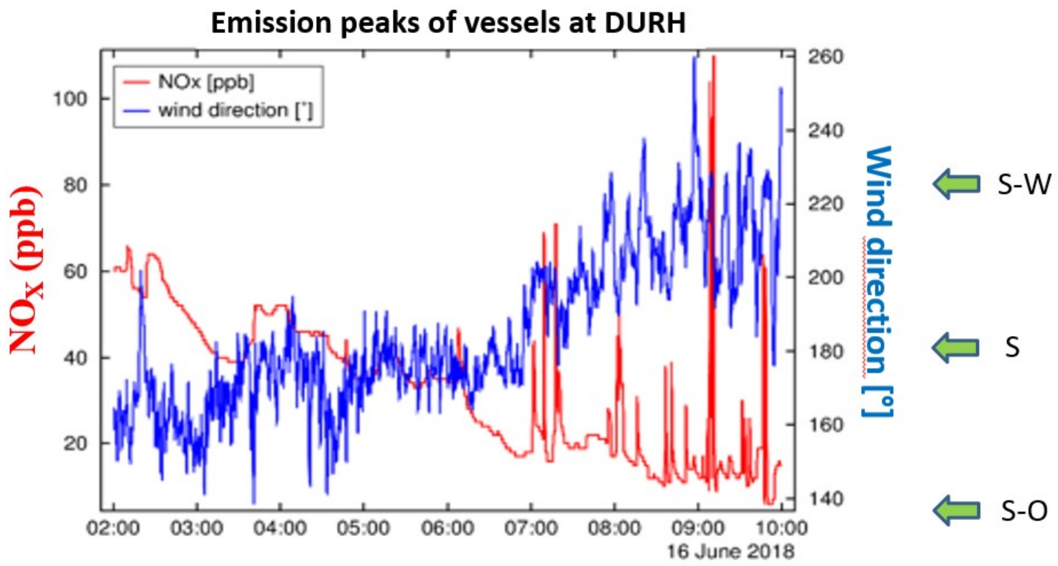


Fig. 59: Effects of changing wind directions on the nitrogen oxide (NO_X) concentrations measurable at the DURH station.

High indifferent NO_X load with wind from SE and S.

Low basic NO_X load with clearly visible ship peaks with wind from SW across the Rhine.

5.2 Derivation of emission factors and a method for realistic calculation of ship emissions on the Rhine

When evaluating load peaks, the area of the peak can also be used to estimate the emission quantity. If the causing ship can be clearly identified via the AIS signals, an attempt can then be made to derive emission factors for the respective ship class via the onshore measurements. With the automatic measuring station Duisburg (**DURH**), positioned directly on the Rhine below the harbour entrance, 17,711 ship peaks could be assigned to the ships passing on the Rhine. Of these, 7,808 observations also met the strict quality criteria (previously defined for the study) for deriving emission factors from the available onshore measurements.

These emission factors derived from the onshore measurements were classified according to ship class, direction of travel (upstream or downstream) and speed. The emission factors of passing ships obtained by onshore measurements form an important new data basis for a more realistic determination of the NO_X quantities, emitted by ships sailing on the Rhine. The report section **"Harbour Monitoring Part E: Onshore Measurements: Identification of passing inland vessels based on AIS signals and determination of the corresponding emission factors for NO_X based on onshore measurements"** contains detailed information on the method of derivation of the onshore factors and the results obtained.

Based on the evaluation of the AIS data, it was possible for the first time to map the real composition of shipping traffic on the Rhine with regard to the length class of the ships (Fig. 60) and the real speeds. The classification of the ships was carried out according to the scheme of the Dutch "Buerau Voorlichting Binnenvaart" oriented at the CEMT (European Conference of Ministers of Transport, French: Conférence Européenne des Ministres des Transports **(CEMT)**). Information on the method of traffic analysis and the resulting outcomes can be found in the report section **"Harbour Monitoring Part D: Analysis of shipping traffic on the Rhine for the years 2018-2020".**

Size Class	Type of ship
I	 **Spitz, Peniche** **Length** 38,5 m - **width** 5,05 m, **draught** 2,2 m - **cargo capacity** 350 t
II	 **Campine vessel** **Length** 55 m - **width** 6,6 m, **draught** 2,50 - **cargo capacity** 655 t
III	 **Dortmund-Ems-canal vessel** **Length** 67 m - **width** 8,2 m, **draught** 2,50 - **cargo capacity** 1000 t
IV	 **Rhein-Herne-canal vessel** **Length** 85 m - **width** 9,5 m, **draught** 2,50 - **cargo capacity** 1350 t
Va	 **Large Rhine vessel** **Length** 110 m - **width** 11,4 m, **draught** 3,0 m - **cargo capacity** 2750 t
Vb	 **Large Rhine vessel** **Length** 135 m - **width** 11,4 m, **draught** 3,5 m - **cargo capacity** 4000 t

Fig. 60: Size classes of cargo and tanker vessels in this report, analogous to the classification according to CEMT.[4]
Ship Graphics: Buerau Voorlichting Binnenvaart

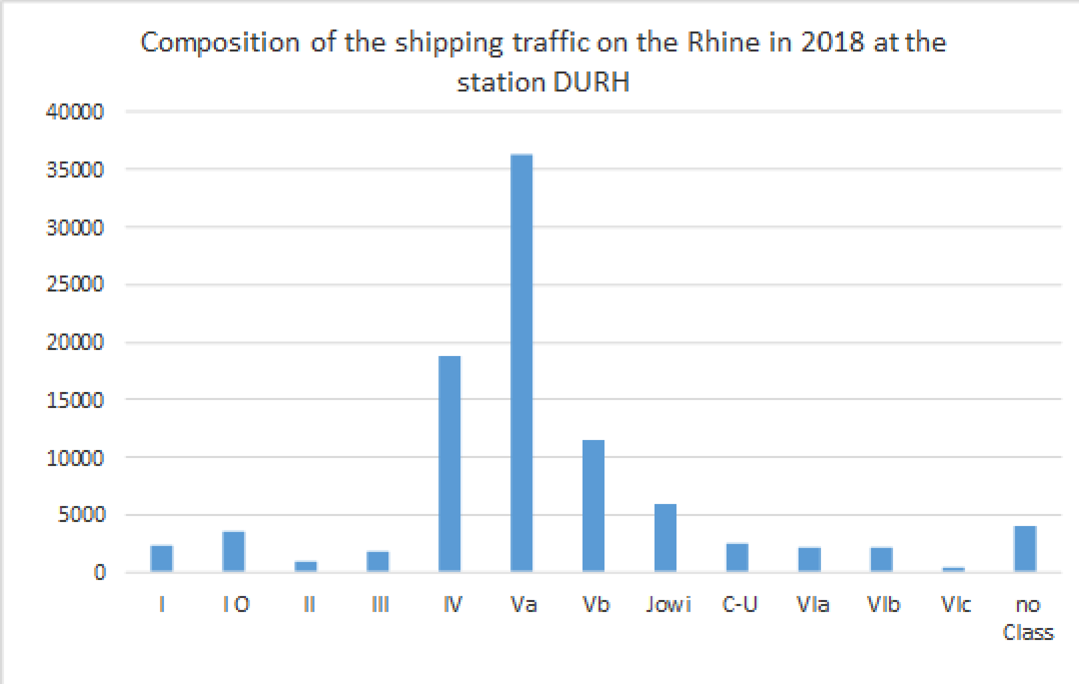


Fig. 61 Composition of shipping traffic at the measuring station DURH (Rhine km 782) in 2018
JOWI = Jowi Class (extra wide 135 m ship) C-U = Coupling unit

Based on the evaluation of the AIS signals collected at the **DURH** measuring station, it was possible to determine the passage of a total of 92,225 inland vessels at Rhine-km 782 for 2018, which were classified according to their length. The assignment of the length classes can be seen in Fig. 60.

All ships with a length of less than 40 m that were not recorded as tankers, cargo or passenger ships (e.g. official vehicles, firefighting and police vehicles, laboratory ships, private vessels etc.) were grouped as class "I O". Due to faulty or incomplete AIS signals, a total of 4,010 ships (no class) could not be classified.

By means of the combination of both data bases, it was for the first time possible within the framework of CLINSH to develop a new method for a more realistic calculation of the NO_X emission quantities, actually expected from shipping traffic, based on emission factors of ships, derived from real onshore measurement data and the mapping of real shipping traffic.

Within the framework of CLINSH, LANUV NRW developed and applied this new method for the years 2018-2020 for the Rhine sections of the study areas Duisburg and Neuss/Düsseldorf. In this method, the amount of the respective ship emissions was determined as a line source per Rhine kilometer and year.

Using this method, the LANUV determined an emission quantity of NO_X of 2,439 t for the year 2018 for the 38.3 km long section of the Rhine belonging to the urban area of Duisburg. For the individual river km 782 (location of the measuring station **DURH**), an emission quantity of 69.5 t NO_X resulted for the year 2018. The determined emission quantities on the Rhine were georeferenced as a line source and are included in the modelling for the cause analyses.

A more detailed description of the methods used and the emission quantities determined for the years 2018-2020 can be found in the report section **"Harbour Monitoring Part C: Emission Inventories for the Ports of Duisburg and Neuss/Düsseldorf"**(27).

For the evaluation possibility of the data from the automatic **measuring station Neuss (NERH)**, a different but also advantageous situation arises:

Since the measuring station is located on the western bank, ship emissions from ships, sailing on the Rhine in Neuss, can only be carried towards the measuring station by winds with easterly components. With these wind directions, caused among other things by the many high building structures in the harbour, a clear assignment of pollution peaks to the ships passing on the Rhine is very rarely possible.

However, the continuous measuring station in the port of Neuss was well suited to derive emission factors from the measurement results (see Fig. 62) of the ships travelling at low speeds and without current influence in the port. With the measuring station positioned directly on the Rhine Canal in Neuss, approx. 5,200 ship peaks could be assigned to the ships sailing in the harbour. Of these, 890 observations met the strict quality criteria for deriving emission factors for ships navigating in the harbour.

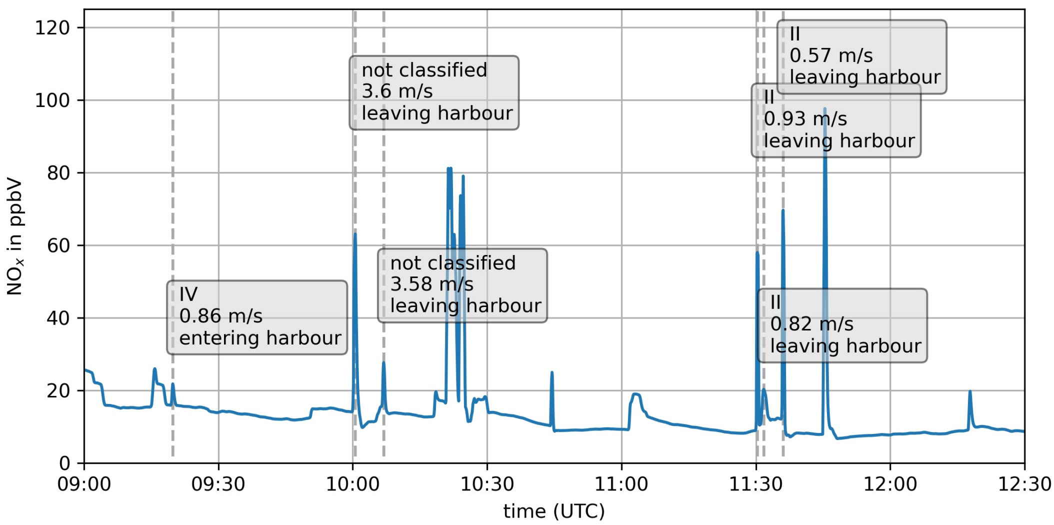


Fig. 62: Assignment of NO_X peaks to the direction of travel, speed and length classes of the vessels manoevering in Neuss harbour II, IV, V: Shipclasses, see Fig. 60

The classified data of the emission factors obtained in the port of Neuss were used by the LANUV, in combination with the evaluation of the AIS data from the port areas, to estimate the emission quantities arising from shipping traffic in the port. For the year 2018, a total emission quantity of 109.3 t NO_X resulted for shipping traffic in the port of Duisburg. Of this, 62.6 t were attributable to port-related traffic and 46.7 t to shipping traffic in the so-called "Hafenkanal" (port canal) from and to the Meiderich lock.

For shipping traffic in the port of Neuss, an emission quantity of 63.5 t NO_X was calculated. For both ports the calculated emission quantities were georeferenced in the form of line sources and shape files were generated for the modelling by the LANUV for CLINSH (cause analyses for the air pollution measured at the ports in 2018).

For the calculation of emissions from the tanker and cargo vessels moored at the port quays, the LANUV carried out an analysis of the generators actually on board. In addition, a method was developed to realistically estimate the actual emissions of the moored ships. Details on the data analysis and methodology are described in the report part **"Harbour monitoring, Part B: Determination of NO_X and particulate matter emissions of ships at berth"** (17), which is already available.

For the year 2018, an amount of about 9,46 t NO_X and 0.59 t PM was emitted by moored tankers and cargo ships in the port of Neuss. For the port of Duisburg, a total quantity in the order of 15.48 t NO_X and 0,76 t PM was emitted by the ships at berth. These emission quantities were also georeferenced as point or line sources and are included in the modelling planned for CLINSH (cause analyses for the air pollution measured at the port measuring points in 2018).

6. Conclusions from of the measurement programmes

6.1 Impact of ship emissions directly on the bank

Based on the measurements carried out on the Rhine in Bimmen/Lobith, the impact of ship emissions (approx. 110,000 ship passages per year) can be estimated quite well. The terrain in the study area is relatively flat, there are dikes to the right and left of the Rhine, so that the mean water level is about 8-10 m below the top of the dike.

The study hypothesis was that with the predominantly westerly wind directions on the Lower Rhine, the ship exhaust gases escaping at 1-3 m above the water level spread out above the water surface and are drifted in the center of gravity by the wind to the right side of the Rhine. The measuring point at the laboratory on the left dike should therefore show the lowest measured values in the order of magnitude of the regional background.

The results of the investigations confirm this hypothesis. As expected, during the three years of investigation, higher concentrations have been found on both rafts of the IMBL, located directly on the Rhine, than on the windward dike. The only locally effective emission source here is the inland waterway traffic on the Rhine. On the windward, left bank of the Rhine, increases in the NO_2 concentrations (annual mean), detectable in the air, in the range of 1-2µg/m³ were traceable. On the leeward bank, concentration increases in the order of 3 to 5 µg/m³ could be detected.

It can be assumed that the concentration increases (annual mean), detectable on the two measuring rafts on the left and right bank of the Rhine, are the direct effects of the approximately 110,000 annual inland waterway vessel passages.

The additional measurements, carried out on the leeward dike crest on the right bank from 2018 onwards, show that the emissions generated just above the water level are also detectable at a height of 8 to 10 m above the water level and can have an effect beyond the dike crest in the hinterland. Results from Bad Honnef showed that the annual mean values of the two measuring stations (25 and 50 m distance from the Rhine, respectively) already decrease by approx. 1 µg/m³ at 50 m distance from the Rhine and in 5 m above the ground. Experience with inner-city emission dispersion from road traffic also suggests that the direct effects of ship emissions decrease relatively quickly with increasing distance from the banks of the Rhine.

However, these emissions also have an effect as an additional concentration increase in the background pollution. EURAD modelling by the University of Cologne (24) for the Duisburg conurbation for the year 2016 estimated this share of inland waterway vessels in the ground-level background NO_2 concentrations (expected large-scale background pollution for NO_2 modelled with EURAD: 15.6 µg/m³) at about 0.5 µg/m³.

Upstream of Bimmen, the traffic density and thus also the effect of emissions decreases continuously. The traffic density of inland vessels in the Rhine section of NRW for the year 2018 was as follows: The Rhine section with the most ship passages for NRW is located at the German-Dutch border in the Bimmen-Lobith area (Rhine km 865). Upstream, the number of passing ships steadily decreases. Compared to Bimmen, the number of ships below the port of Duisburg (km 782) is still about 70%, below Neuss (km 744) about 57% and shortly before the border to Rhineland-Palatinate (Bad Honnef, km 640) about 45%. It is therefore to be expected that upstream, due to the decreasing number of moving ships, the ship-related shares of air pollution in the cities along the Rhine will decrease.

6.2 Pollution situation in the port areas

The measurement results from the study areas in Neuss/Düsseldorf and Duisburg show that the NO_2 concentrations detectable directly on the Rhine and also in the port areas were lower than expected. At the measuring points of the special measuring programme in Neuss, all annual mean values were below 40 µg/m³.

The situation was similar in the port area of Duisburg. Here, too, almost all annual mean values were below 40 µg/m³ in 2018. Only three measuring points showed values above 40 µg/m³. All of these measuring points were located in areas not accessible to the public, so that the EU Directive cannot be applied here. For the Meiderich lock, the high annual mean values could be plausibly explained by the concentrated ship exhaust gases escaping from the lock chamber. The third measuring point with an annual mean value above 40 µg/m³ was probably influenced by construction activities.

Based on the facts presented and known at the beginning regarding the age of the engines of the active inland navigation fleet and the resulting emission quantities on the Rhine (and the West German canal network), a relatively high influence on the air quality in the cities located on waterways has also been assumed up to now. However, metrological proof of this assumption of a high share of air pollution by inland vessels has been completely lacking so far.

The measurement results of the CLINSH project in the ports of Neuss and Duisburg show that despite the spatial proximity of the sources "port" and "inland waterway vessel", the contribution to urban air pollution by shipping traffic cannot be of the magnitude assumed at the time. All measuring points of the special measuring programme, which were located in or close to residential areas in Duisburg showed annual mean values for NO_2 concentrations in a range of 33 and 36 µg/m³ for 2018.

The annual mean values at the monitoring sites located directly on the Rhine near Duisburg also ranged from 26 µg/m³ to 30 µg/m³ for the windward (left) bank and from 27 µg/m³ to 32 µg/m³ for the leeward (right) bank. All NO_2 annual mean values positioned in the immediate vicinity of the emission source "shipping traffic on the Rhine" were thus clearly below the EU limit value of 40 µg/m³.

In contrast, six of the eight "traffic stations" of the state monitoring network also located in the study area on busy roads showed annual mean NO_2 concentrations between 41 and 54 µg/m³ in 2018. These significantly higher pollution levels compared to the CLINSH monitoring stations were predominantly caused by the additional contribution of emissions from road traffic. The measurement results collected as part of CLINSH clearly show that NO_X emissions from shipping and port operations are not high enough to explain the high measured data at the traffic measuring points.

This becomes particularly clear when comparing the two traffic measuring points **NEKS (44 µg/m³)** and **VNEB (45 µg/m³)** located directly at the Neuss port area with the two CLINSH measuring points **NED013 (33.4 µg/m³)** and **NED015 (35 µg/m³**), which are located in the immediate vicinity and have significantly lower pollution levels. For all four monitoring sites, the regional background NO_2 concentration in 2018 was 21 µg/m³. The NO_2 concentration increases at the two CLINSH monitoring sites, caused by a variety of factors, were in the range of 12-14 µg/m³, while the two traffic monitoring sites showed significantly higher concentration increases of 23-24 µg/m³.

6.3 Outlook

The measurement programmes, method developments and modelling carried out within the framework of CLINSH made it possible to obtain a very detailed clarification of the contribution of emissions from shipping traffic to air quality on the banks of the Lower Rhine and the settlement areas near the river, which has not been available before in this current level of detail.

In cooperation with the University of Bremen, it was possible to determine the corresponding NO_X emission factor in addition to ship size, direction of travel and speed on the basis of the continuous measurement of the DURH station for more than 7,800 ship passages. These emission factors and other data obtained within the framework of CLINSH form an important basis for a more realistic recording of the actual effects of ship emissions and thus also for the future updating of NRW's "Shipping" emission register(14).

The report part **"Harbour monitoring Part B: Determination of NO_X and particulate matter emissions from inland vessels at berth",** belonging to the project, was completed in April 2021 and is already available on the "CLINSH" homepage. The procedure described there forms an important basis for the calculation of emissions caused by ships at berth in the port and was used for the emission calculations in the NRW ports.

The report parts **"Port Monitoring Part C: Emission Inventories for the Ports of Duisburg and Neuss/Düsseldorf", "Port Monitoring Part D: Analysis of shipping traffic on the Rhine for the years 2018-2020"** (28), as well as "**Port monitoring Part E: Onshore measurements: Identification of passing inland vessels based on AIS signals and determination of the associated emission factors for NO_X based on onshore measurements"**(29) (Lead: University of Bremen) are expected to be available in August 2021.

The final evaluations (e.g. modelling and detailed analyses of the load shares of various emission sources for the individual measuring points) are currently being prepared and require extensive computing time. The associated report **("Port Monitoring Part F, Cause Analyses on the respective shares of different emission sources in the air pollution measured in Neuss/Düsseldorf and Duisburg)(30)** on the EU Life project "CLINSH" is expected to be completed in September 2021.

A new LNG-fuelled tanker vessel on the Rhine at Duisburg

(Photo: D. Busch, LANUV)

7. Acknowledgement

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Thank you for the good cooperation for the CLINSH project
(White water rafting at Neuss, Photo: D.Busch, LANUV)

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Even a port can show beautiful views (Photo: T.Zang, LANUV)

9. List of Tables

10. List of figures

Large Coupling unit at Duisburg (Photo: D.Busch, LANUV)

11. Annex

Bezeichnung	Koordinate Ost/West UTM	Koordinate Nord/Süd UTM	Typ
NED001	340027	5676830	PS
NED002	340102	5676169	PS
NED003	340326	5676022	PS
NED004	340138	5675900	PS
NED005	339637	5675967	PS
NED006	340204	5675368	PS
NED006a	340603	5674886	PS
NED007	339247	5676318	PS
NED008	339654	5675780	PS
NED009	339276	5675712	PS
NED010	339017	5675540	PS
NED011	339575	5674833	PS
NED012	339031	5675237	PS
NED013	339142	5674587	PS
NED015	338718	5675024	PS
NED016	338567	5675976	PS
NED017	339666	5676747	PS
NED018	343464	5676470	PS
NED019	342511	5676375	PS
NERH	**339666**	**5676747**	**CMS**
NEKS	338276	5674870	NRW traffic
VNEB	338863	5674680	NRW traffic
VNEM2	338769	5673926	NRW traffic
DBIL	344657	5674693	NRW traffic
VDSR	343604	5674505	NRW traffic

A_Tab. 1a: Coordinates of the measuring points in the Neuss research area

Bezeichnung	Koordinate Ost/West UTM	Koordinate Nord/Süd UTM	Typ
DU001	343440	5701815	PS
DU002	344421	5701842	PS
DU003	345367	5702305	PS
DU004	345360	5702355	PS
DU005	345146	5702892	PS
DU006	343488	5701984	PS
DU007	344111	5701957	PS
DU008	345277	5703369	PS
DU009	344096	5702921	PS
DU010	342258	5702836	PS
DU011	342605	5702765	PS
DU011a	342505	5702880	PS
DU012	343176	5702328	PS
DU013	342278	5702118	PS
DU014	342613	5701814	PS
DU015	341909	5702388	PS
DU017	341226	5702323	PS
DU018	342158	5699623	PS
DU019	341963	5699933	PS
DU020	342953	5700973	PS
DU021	340847	5699902	PS
DU021a	340853	5700622	PS
DU022	344015	5702059	PS
DU023	344625	5702229	PS
DU024	344633	5702496	PS
DU025	344134	5703530	PS
DUMP	341520	5703004	PS
DURH	**342132**	**5703510**	**CMS**
DUFW	344566	5700187	NRW traffic
DUMB	345892	5704064	NRW traffic

A_Tab. 1b: Coordinates of the measuring points in the Duisburg research area

Neuss			
Lauf	von	bis	Tage
1	28.11.2017	27.12.2017	29
2	27.12.2017	24.01.2018	23
3	24.01.2018	22.02.2018	29
4	22.02.2018	22.03.2018	28
5	22.03.2018	25.04.2018	34
6	25.04.2018	24.05.2018	29
7	24.05.2018	20.06.2018	27
8	20.06.2018	18.07.2018	28
9	18.07.2018	15.08.2018	28
10	15.08.2018	13.09.2018	29
11	13.09.2018	11.10.2018	28
12	11.10.2018	09.11.2018	29
13	09.11.2018	07.12.2018	28
14	07.12.2018	04.01.2019	25
15	04.01.2019	01.02.2019	28
16	01.02.2019	04.03.2019	31
17	04.03.2019	02.04.2019	29
18	02.04.2019	01.05.2019	29

A_Tab_2a: Sampling cycles for the passive samplers in the Neuss port area

Duisburg			
Lauf	von	bis	Tage
1	29.11.2017	27.12.2017	28
2	27.12.2017	24.01.2018	23
3	24.01.2018	21.02.2018	28
4	21.02.2018	21.03.2018	28
5	21.03.2018	25.04.2018	35
6	25.04.2018	23.05.2018	28
7	23.05.2018	20.06.2018	28
8	20.06.2018	18.07.2018	28
9	18.07.2018	15.08.2018	28
10	15.08.2018	12.09.2018	28
11	12.09.2018	10.10.2018	28
12	10.10.2018	07.11.2018	28
13	07.11.2018	05.12.2018	28
14	05.12.2018	02.01.2019	27
15	02.01.2019	30.01.2019	28
16	31.01.2019	01.03.2019	29
17	01.03.2019	01.04.2019	31
18	01.04.2019	02.05.2019	31

A_Tab_2b: Sampling cycles for the passive samplers in the Duisburg port area

M Ort	Lauf																	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
DU001	34,6	34,3	41,6	44,6	43,2	34,5	35,5	29,1	34,4	19,5	41,1	42,1	39,2	32,3	33,8	47,8	34,6	35,4
DU002	32,3	29,7	35,8	28,3	33,4	25,9	26,6	21,2	k. Zugang	k. Zugang	zu lang	k. Zugang	zu lang	k. Zugang	k. Zugang	41,1	29,2	26,1
DU003	40,8	37,7	43,9	49,0	46,2	49,7	52,9	47,2	58,7	53,9	51,4	48,0	40,8	34,3	40,6	48,4	40,5	47,1
DU004	38,9	38,6	45,5	51,7	50,9	47,9	47,9	42,1	52,8	49,2	52,4	50,9	45,9	36,9	36,4	51,6	40,1	51,1
DU005	35,8	32,1	38,3	30,5	36,4	28,4	31,9	23,9	30,1	35,1	38,9	37,2	33,9	30,5	34,3	44,3	34,9	29,5
DU006	41,4	40,2	48,0	45,0	49,3	40,8	39,5	30,7	40,7	45,8	49,2	47,7	gestohlen	39,4	40,4	50,5	41,1	43,1
DU007	36,6	32,6	37,2	28,5	36,2	27,0	28,0	21,4	28,2	30,9	38,4	36,2	31,4	29,7	32,1	41,0	29,1	26,4
DU008	31,9	33,6	38,8	30,1	36,2	26,2	27,5	21,4	28,0	33,5	39,4	37,7	33,8	29,6	32,4	42,8	30,3	26,6
DU009	40,0	37,3	42,2	33,5	38,6	32,8	34,9	23,6	29,4	36,0	41,5	38,9	35,9	31,8	36,2	47,0	41,3	31,7
DU010	39,3	35,1	39,8	32,7	40,9	29,4	32,7	24,5	34,8	37,9	42,7	40,1	38,2	34,0	36,7	48,3	35,5	32,9
DU011	39,3	34,5	40,1	30,6	38,9	28,6	31,4	24,1	29,8	33,8	41,6	39,5	43,2	39,2	41,9	53,5	40,5	36,5
DU011a	nicht beprobt						26,7	21,7	28,1	31,3	40,3	38,8	38,8	37,1	37,3	48,9	38,1	30,4
DU012	35,2	31,6	38,4	33,1	38,1	30,0	29,9	24,0	32,5	33,9	40,0	39,0	33,4	29,6	32,9	44,7	31,5	30,7
DU013	32,7	31,8	38,9	29,7	39,7	27,7	26,9	gestohlen	gestohlen	33,1	41,4	43,7	38,4	30,2	30,8	45,3	31,8	29,3
DU014	33,6	35,0	40,0	35,7	38,6	32,9	35,7	30,7	40,5	37,1	41,3	40,3	36,6	30,5	36,0	42,6	34,3	38,7
DU015	30,6	29,4	34,3	32,2	36,5	28,7	26,3	21,1	29,0	31,6	38,3	39,3	34,9	27,0	29,4	40,6	27,7	31,1
DU017	34,1	31,1	37,1	31,2	gestohlen	29,3	27,0	19,6	28,9	gestohlen	37,5	38,7	gestohlen	30,9	32,5	48,5	30,8	37,4
DU018	31,4	27,9	33,7	36,0	36,6	28,5	31,6	24,7	28,6	29,7	36,4	37,8	32,0	28,6	28,2	41,8	27,1	33,7
DU019	33,2	28,3	34,8	29,7	33,7	25,9	27,6	20,5	28,5	32,4	38,0	37,2	31,5	26,9	29,1	41,5	25,9	27,4
DU020	36,2	31,5	38,6	30,0	36,7	27,0	28,8	22,6	28,6	31,6	37,8	36,5	34,0	31,5	36,4	45,6	31,5	28,5
DU021	27,5	24,0	31,8	26,8	gestohlen	22,6	22,7	18,8	23,8	24,7	28,3	30,7	29,6	23,8	25,0	37,7	21,3	25,0
DU021a	nicht beprobt						27,7	25,3	29,0	28,6	34,3	34,0	31,0	26,0	30,4	38,7	26,9	30,0
DU022	38,7	34,9	39,4	32,3	36,9	30,8	26,8	20,8	28,8	34,4	38,2	39,9	36,6	30,2	32,8	44,4	30,5	29,1
DU023	30,5	28,3	40,4	29,4	34,3	27,3	28,8	23,2	29,8	32,2	37,0	36,6	32,1	28,2	31,6	42,1	29,5	29,2
DU024	36,3	33,9	33,9	31,5	37,1	28,1	32,8	26,4	31,2	36,3	38,2	38,1	33,3	29,0	33,3	42,6	34,4	30,4
DU025	31,1	28,5	35,1	28,8	35,8	25,5	25,1	20,5	26,7	30,9	Ausfall	42,5	34,0	29,0	30,2	44,8	31,6	27,4

A_Tab. 3a: Compilation of all NO_2 measurement results (µg/m³) from the port of Duisburg

M Ort	Lauf																	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
NED001	32,3	28,8	35,3	28,5	36,7	30,6	29,7	23,8	28,7	31,1	38,5	36,9	31,0	27,1	34,9	39,7	30,3	29,7
NED002	34,3	34,3	35,9	32,9	33,6	31,5	34,9	27,0	29,2	32,8	40,6	41,5	34,8	30,6	34,8	42,9	33,7	31,1
NED003	32,4	30,1	37,6	33,0	40,4	33,4	31,6	26,1	34,3	33,6	39,3	40,0	34,8	30,2	33,1	42,3	34,6	31,9
NED004	35,0	37,2	37,3	37,4	44,2	38,1	33,5	32,5	37,4	39,6	43,9	42,8	36,5	30,5	37,1	45,5	35,9	34,4
NED005	32,1	29,5	32,7	34,8	40,5	35,1	30,5	31,9	36,4	33,2	47,1	43,3	35,9	30,7	33,2	41,1	32,9	31,8
NED006	35,5	31,9	40,5	38,1	45,1	39,1	41,5	34,5	41,4	38,1	44,0	42,7	37,3	31,5	36,6	46,3	37,6	42,5
NED006a	36,3	33,6	35,7	31,1	42,3	35,5	35,0	30,2	29,8	37,1	43,8	41,0	33,7	32,6	34,9	42,9	36,4	34,3
NED007	30,5	26,8	35,3	31,3	37,2	29,6	29,4	24,3	32,7	30,4	36,1	38,6	32,9	27,4	30,6	39,2	28,7	31,3
NED008	30,4	28,0	34,5	31,2	35,6	29,1	29,2	25,5	33,2	33,1	38,6	38,2	31,9	29,2	32,3	38,2	30,7	31,4
NED009	29,8	25,4	34,3	29,1	34,4	27,4	26,7	22,4	27,1	28,9	35,7	38,5	32,2	28,5	30,2	39,5	30,6	27,7
NED010	28,6	24,6	33,4	26,0	33,9	26,2	24,2	20,7	26,8	27,6	33,8	36,2	31,4	27,7	30,1	36,8	30,3	26,7
NED011	32,7	28,8	36,5	32,6	38,5	32,3	30,0	23,4	31,0	31,2	38,2	38,0	33,9	29,0	30,4	40,5	31,3	32,0
NED012	30,0	25,9	34,3	29,4	34,5	25,2	24,8	20,5	27,1	27,4	33,7	36,1	32,0	27,4	28,2	37,4	27,7	26,5
NED013	31,9	29,3	34,9	31,1	38,7	34,2	31,7	26,1	32,3	31,7	36,7	39,9	33,4	32,1	32,8	40,9	34,0	33,1
NED015	33,7	32,3	38,1	33,2	39,4	30,3	28,7	22,8	31,2	31,4	38,7	42,4	52,0	33,0	33,1	44,9	33,2	31,7
NED016	31,4	29,1	36,1	30,6	37,1	27,4	25,5	20,8	29,4	29,9	34,9	38,7	33,5	28,8	30,7	40,1	31,7	28,8
NED017	35,6	34,0	37,7	31,2	41,3	29,2	30,5	23,0	31,7	35,8	42,1	40,7	32,4	33,3	33,3	42,4	Ausfall	31,9
NED018	30,3	31,3	32,5	27,7	36,8	28,6	28,2	26,3	30,2	30,5	34,4	34,7	30,5	27,2	28,3	38,0	28,5	27,6
NED019	34,0	30,8	35,5	30,1	38,2	28,4	28,5	23,7	29,4	32,6	38,6	35,4	32,0	28,5	33,1	41,8	31,7	28,1

A_Tab. 3b: Compilation of all NO_2 measurement results (µg/m³) from the port of Neuss

12. CLINSH Partner

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