# Time trends of heavy metals and PAHs in blue mussels *(Mytilus edulis)* and contamination of sediments in the Kristiansandfjord, Southern Norway

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# Abstract

The Kristiansandfjord in Southern Norway has been contaminated for several decades (Green et al., 1985; Berge et al., 2007; Øxnevad et al., 2021). In this study, contaminant concentration data from blue mussel and sediments have been collected, mainly from 2010-2022. The selected contaminants were heavy metals As, Cd, Cr, Cu, Pb, Hg, Ni, as well as PAHs including benzo(a)pyrene. The aims of this study were to describe time trends for concentrations of contaminants in blue mussels and compare contaminant levels at different locations in the fjord. Additional aims were to determine environmental conditions and chemical status of locations in the fjord, and to perform a pollution assessment. The results of this study were discussed considering local industry discharges, as well as other sources of contamination from urban areas. This study found that concentrations of contaminants in blue mussels have with some exceptions remained the same, despite reduced industrial discharges and implemented sediment remediation actions. These measures may however still have contributed to the reduction of contaminant concentrations in the fjord. Contaminant concentrations were the highest at stations near discharge sources in both blue mussel and sediment. All sediment stations had contaminant concentrations leading to «very poor» environmental condition, similarly, all sediment stations had «not good» chemical status and most blue mussel stations had «not good» chemical status. The Kristiansandfjord is polluted with cadmium, copper, mercury, lead, nickel, zinc, and PAHs including benzo(a)pyrene, however, their effects on the ecosystem in the fjord are uncertain yet cause for concern. It may take a substantial amount of time and effort to reduce contaminant concentrations, and further monitoring is necessary. These findings may apply to other fjords and other types of marine ecosystems as well.

# Sammendrag

Kristiansandsfjorden har vært forurenset i flere tiår (Green et al., 1985; Berge et al., 2007; Øxnevad et al., 2021). I denne studien har det blitt samlet data for konsentrasjoner av miljøgifter i blåskjell og sediment, hovedsakelig fra 2010-2022. De utvalgte miljøgiftene var tungmetallene As, Cd, Cr, Cu, Pb, Hg, Ni, i tillegg til PAH-forbindelser inkludert benzo(a)pyren. Målene til denne studien var å beskrive tidstrender for konsentrasjoner av miljøgifter i blåskjell, og sammenligne konsentrasjoner på forskjellige steder i fjorden. Flere mål var å bestemme miljøtilstand og kjemisk status på forskjellige lokasjoner, samt vurdere forurensing. Resultatene av denne studien ble diskutert i lys av lokale industriutslipp, samt andre forurensingskilder fra byområdet. Denne studien fant at konsentrasjoner av miljøgifter i blåskjell har holdt seg lik med noen unntak, til tross for reduserte utslipp fra industri og tiltak iverksatt for å rydde opp forurenset sjøbunn. Disse tiltakene kan likevel ha vært med på å redusere konsentrasjoner av miljøgifter i fjorden. Konsentrasjoner av miljøgifter var høyest ved lokasjoner nærmest utslippskilder for både blåskjell og sediment. Alle sedimentstasjonene hadde konsentrasjoner som førte til «svært dårlig» miljøtilstand og «ikke god» kjemisk status, og nesten alle blåskjellstasjoner fikk «ikke god» kjemisk status. Kristiansandsfjorden er forurenset av kadmium, kobber, kvikksølv, bly, nikkel, sink og PAH-forbindelser inkludert benzo(a)pyren. Imidlertid er effektene på økosystemet i fjorden usikre, men gir likevel grunn til bekymring. Betydelig tid og innsats kan være nødvendig for å redusere konsentrasjonen av miljøgifter, og videre overvåking er nødvendig. Disse funnene kan også gjelde for andre fjorder og andre typer marine økosystemer.

# Contents

# Preface

I have always been passionate about the planet, and it is through my coastal ecology studies that I learned just how essential the marine environment is. My master's study is completed with this thesis; a description on contamination in the Kristiansandfjord. It has been exciting learning about the fjord in my city, and I am left with greater joy and engagement to the city and the fjord adjacent to it.

The thesis work started when Hilde Cecilie Trannum suggested a topic to my interest. I give a huge thank you to her and Sigurd Øxnevad for being my supervisors. Both have spent hours discussing and commenting on the thesis and given writing suggestions. They have given extensive and quick responses to my questions and doubts, and their expertise on contamination methods has been essential for the creation of this thesis. Thank you for inviting me on a field trip in the Kristiansandfjord, where I proudly collected three small blue mussels even though my large belly made it difficult to reach them.

During the process of writing this thesis, I was gifted with a beautiful baby boy. I thank my husband for supporting me in combining work with studying, and I thank my baby for being able to play by himself for a couple of hours each day.

Thank you, Emilie Johnsen, for tips on how to use statistics program R, which has been crucial for the creation of graphs.

Lastly, I thank God, for leading me through my studies and ultimately letting me receive a master's degree in coastal ecology.

Kristiansand, 20.04.23

Camilla Jantina Skjeggestad

# 1. Introduction

Large amounts of contaminants are introduced into the marine environment by urban and industrial activities, causing disturbances in marine ecosystems (Akcali & Kucuksezgin, 2011). This phenomenon is especially significant in coastal areas, since these are the main sinks of almost all anthropogenic contaminants (Akcali & Kucuksezgin, 2011). Coastal and estuarine areas are important for human inhabitants, and they often receive anthropogenic contaminants (Pan & Wang, 2012). Some key entry pathways for contaminants into marine systems are direct discharges from industry (Frid & Caswell, 2017). Industrial discharges may in some cases lead to a very depleted fauna, both few species and few individuals (Oug et al., 2013). Toxic contaminants such as heavy metals have caused increasing pressures on coastal ecosystems over the past decades because of human activities in coastal areas (Pan & Wang, 2012).

Heavy metals occur naturally in the environment (Akcali & Kucuksezgin, 2011; Pan & Wang, 2012), and while most of heavy metals are essential for life at low concentrations (Singh et al., 2011), many are toxic at high concentrations (Fu & Wang, 2011). Non-essential heavy metals such as mercury, cadmium, and lead cause toxicity at low concentrations (Andersen et al., 1996; Azeh Engwa et al., 2019). If heavy metals are remobilized, they can be a cause of future toxicity (Frid & Caswell, 2017). Further, resuspended contaminated sediments may hinder restoration, remediation, and management of contaminants in areas with historical contamination (Friedman et al., 2009). Heavy metals accumulate in sediments, as a sink, and can also be released from sediments (Pan & Wang, 2012). They bioaccumulate easily in the aquatic environment and are non-degradable (Shaheen et al., 2019; Pan & Wang, 2012; Wang et al., 2015). They are also taken up by marine organisms, entering the food chain and transferred to upper trophic levels, eventually leading to adverse effects on humans due to seafood consumption (Bryan & Darracott, 1979; Wang, 2002). Due to this biomagnification in food chains, heavy metals can have significant environmental consequences (Mishra et al., 2019). These consequences can be substantial and long lasting in spite of restauration efforts (Pan & Wang, 2012). Heavy metal contamination in marine ecosystems is a growing global environmental concern (Sharma et al., 2020), and because of their ecological impacts and concern for seafood safety, the levels of heavy metals in marine ecosystems deserve attention (Wang et al., 2005).

Mercury is generally regarded as the most toxic metal in marine ecosystems, followed by cadmium, copper, zinc, nickel, lead and chromium (ATSDR, 2013; Frid & Caswell, 2017). Mercury is used in thermometers, light bulbs, batteries, and several industrial processes (Frid & Caswell, 2017). The organic form of mercury, methylmercury, is highly toxic and bioaccumulates (Frid & Caswell, 2017). It is shown that exposure to mercury in marine fish can affect liver function, behavior, reproduction, gill function and lead to mortality (Huang et al., 2011; O'Bryhim et al., 2017). Another highly toxic contaminant is cadmium (ATSDR, 2013, Frid & Caswell, 2017), however, molluscs are often able to accumulate cadmium with no obvious adverse effects (Frid & Caswell, 2017). Cadmium is released from fuel combustion and the smelting of zinc and copper, and a main input to the marine environment is through road run-off (car tires and brake pads) (Frid & Caswell, 2017). A contaminant whose toxicity was previously used to discourage growth of barnacles and other fouling organisms on ships, is copper (Frid & Caswell, 2017). Copper enters the marine environment from industrial effluents and forms part of urban wastewater (Frid & Caswell, 2017). Copper is toxic to aquatic organisms (Clarke, 1997; Grosell et al., 2007), it can cause membrane damage, inactivation of enzymes and cell death (Hegedus et al., 2001; Nagarani et al., 2012). It has been shown that copper significantly reduces or alters benthic colonization (Olsgard, 1999; Trannum et al., 2004). Growth inhibition and mortality in marine organisms is caused by excess zinc (Yung et al., 2014). Zinc is used in plastics, inks and pharmaceuticals and reaches marine environments via urban wastewater and industrial discharges (Frid & Caswell, 2017). Zinc is essential for animals (Martelli et al., 2006), and plants (Sturikova et al., 2018), as is nickel (Frid & Caswell, 2017). Nickel enters the marine ecosystem through urban runoff and industrial point source effluence (Wang et al., 2020). Elevated levels in marine organisms may lead to toxic effects (Binet et al., 2018; Gissi et al., 2016), which has been documented for echinoderms, molluscs and crustaceans (DeForest and Schlekat, 2013; Gissi et al., 2016; Wang et al., 2014). Often associated with toxicity in benthic organisms (Ringenary et al., 2007), is lead. Lead was added to gasoline until the 1990s to improve combustion, and large volumes of lead were emitted to the atmosphere, which is the main route in which lead enters the marine environment (Frid & Caswell, 2017). Another significant source of lead in marine ecosystems is smelting works (Øxnevad et al., 2021). Further, chromium is a toxic compound which contaminates sediments throughout the world (Burgess et al., 2007). It enters aquatic systems through industry effluents (Bakshi & Panigrahi, 2018), possibly affecting photosynthesis in marine macroalgae (Baumann et al., 2009). Lastly, causing acute and chronic toxicity to marine organisms (Mamindy-Pajany et al., 2013), is inorganic arsenic. Arsenic enters the natural environment from coal burning and smelting processes (Szubska, 2018), creating risks for fish consumers through the food web (Szubska, 2018).

PAHs (polycyclic aromatic hydrocarbons) are environmental contaminants with a wide range of biological toxicity, therefore, remediation of PAHs from the environment is a global concern (Patel et al., 2020). Sixteen of the hundreds of known PAHs, have been designated High Priority Pollutants, and because of their potential toxicity, the 16 PAHs are of environmental concern (Hussar et al., 2012). They are highly toxic, carcinogenic and strongly affect organism health (Patel et al., 2020). Benzo(a)pyrene (B(a)P), one of the PAHs, is considered one of the most carcinogenic PAHs and is used as a marker for risk assessment (Patel et al., 2020). Sources of PAHs are fossil fuel burning, coal production and oil manufacturing (Hussar et al., 2012).

The toxicity of contaminants is affected by a number of factors, such as water temperature, salinity, oxygen and organic content (Frid & Caswell, 2017). According to several studies (Erickson et al., 1996; Meador, 1991; Pagenkopf GK, 1983; Welsh et al., 2000), water chemistry affects both toxicity and bioavailability of metals to aquatic organisms. Low temperature and high organic content affect the bioaccumulation of heavy metals in shellfish (Boening, 1999). Most importantly, toxicity depends on dosage (Tchounwhou et al., 2012). In addition, concentrations of contaminants in sediments have been reported to increase with decreasing particle size (Characklis and Wiesner, 1997; Evans et al., 1990; Lee et al., 2005; Sansalone and Buchberger, 1997). While several studies focus on effects of single compounds (Yang, 1994), organisms in a polluted environment are generally exposed to a mixture of compounds (De Zwart, & Posthuma, 2005). Toxicants may have different impacts when in mixtures, and cocktail effects and synergetic interactions are an area of great concern (Cedergreen, 2014). Further, toxicity depends on several biological factors such as age, gender, and genetics of individuals (Tchounwhou et al., 2012). Behavioral attributes, for instance, such as filter-feeding threatened the health of such organisms exposed to contaminants (Weltens et al., 2000). Lastly, the toxicity of contaminants is affected by the degree of exposure to contaminants (Frid & Caswell, 2017). After a chronic exposure of contaminants, some organisms may have obtained tolerance to contaminants, for instance in taxa with short generation times such as microalgae (Frid & Caswell, 2017).

Sediments have been used extensively to identify sources of contamination (DelValls et al., 1998). Contaminant concentration in sediment helps indicate contamination degree and potential threat of pollutants (Tavakoly Sany et al., 2014). Because contaminants are often particle bound, they sink to the sediment (Roberts, 2012), therefore, surface samples of sediments reflect contamination conditions (Bakke et al., 2007).

Molluscs are among the organisms most used as bioindicators for trace metal pollution (Rainbow, 1995). Bivalves closely reflect the extent of environmental pollution (Ragi et al., 2017), are well-known bioindicators of water quality (Angelo et al. 2007; Jović et al. 2011) and appear in monitoring programs globally. A biomonitoring program, called National Mussel Watch Program, was started in the United States in 1986, using naturally occurring populations of mussels and oysters (Beliaeff et al., 1997). Many contaminants were monitored, such as arsenic, cadmium, copper, mercury, nickel, zinc and PAHs (Beliaeff et al., 1997). Similar programs were used in the United Kingdom, The Netherlands, France, Canada, Australia, Japan, India, South Africa, and Russia (Frid & Caswell, 2017). Blue mussels *(Mytilus edulis, Linnaeus 1758)* are commonly used in such programs (Sheehan & Power, 1999). Along the whole Norwegian coast, contaminants in blue mussels have been monitored since 1981 (Schøyen et al., 2022). Blue mussels are filter-feeding, may be exposed to large amounts of contaminants, have a wide geographical distribution, are stationary and often the dominant species in their habitat, thus making them suitable species for biomonitoring (Sheehan & Power, 1999). Because they are filter-feeders and sedentary, they are sensitive to minor changes in their environment (Anagha et al., 2022). This filtration behavior makes them accumulate contaminants from the seawater, providing a measure of the concentration of seawater contaminants *in situ* (Beyer et al., 2017). Furthermore, they are often abundant in estuaries which have anthropogenic impacts, and they can withstand baseline levels of pollution (Sheehan & Power, 1999).

A typical Norwegian marine ecosystem is fjords. They have a complex topography including narrow passages, basins, sills, islands, and archipelagos and this complexity makes it possible for one fjord to contain distinct habitats and even ecosystems (Salvanes et al., 2018). Fjords have an overall high biodiversity and can be home to isolated populations of species (Salvanes et al., 2018). Because of rivers with outlets into fjords, fjords have typically been subject to industry in Norway (Ramirez-Llodra et al., 2022). The Kristiansandfjord is adjacent to Kristiansand, a city in southern Norway. The river Otra has its outlet into the fjord, which is connected to Skagerrak, the ocean area between Norway and Denmark. At the inner, urban part of the fjord there is a small basin with depths up to around 40 meters. Moving outwards, a narrow passage is found between the islands Odderøya and Dybingen. The island Bragdøya and surrounding archipelagos form a barrier between the inner basin and open waters, containing some sills. Østergapet is a narrow passage connecting the Kristiansandfjord with Skagerrak with depths of around 260 meters. The Kristiansandfjord contains many islands and archipelagos and stretches about 10 kilometers (Norgeskart, 2023). The fjord has been and still is strongly contaminated (Øxnevad et al., 2021). The inner part of the fjord is assessed to be in «moderate» ecological condition and chemical condition is classified as «not good» (Vann-nett, 2023a). The area is known to be moderately to severely polluted by heavy metals (especially nickel, copper and cobalt) and PAHs (Schøyen et al., 2017). Therefore, it is not recommended to eat blue mussels from the area (Norwegian Environment Agency, 2023a).

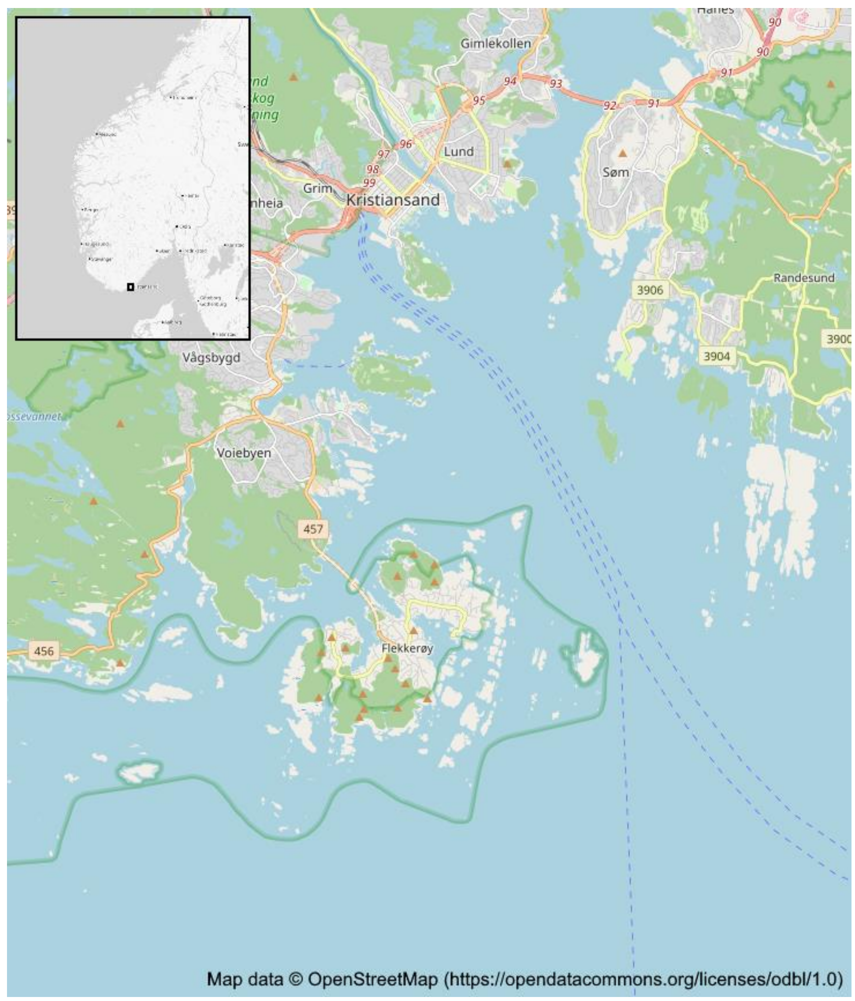



**Figure 1: The Kristiansandfjord**

Monitoring of contaminants in the Kristiansandfjord has been conducted for several decades. The monitoring has been done on behalf of the Norwegian Environment Agency, the Country Governor, Kristiansand Municipality, and the local industrial companies. The concentrations of heavy metals, PAHs and dioxins have been measured in blue mussels and sediment, as well as in fish, water and sediment biota, sampled at several stations in the Kristiansandfjord. The measured concentrations, pollution assessments and chemical status have been published in plenty of reports, which have provided valuable information about the environmental state of the Kristiansandfjord. In a report from 1985, there were found strong and obvious pollution effects such as poor biodiversity, which were believed to be due to industrial discharges. The pollution effects were strongest at the innermost part of the fjord, near industry (Green et al., 1985). In 2007, it was found that sediments in the Kristiansandfjord were polluted (Berge et al., 2007). In a report from 2021, it was concluded that the concentrations of PAHs had been in decline since 2010, and there were found significant downwards trends for concentrations of several heavy metals. In blue mussels, there were found significant downwards trends for arsenic, cadmium, chromium, copper, lead, nickel, and zinc at four out of five stations (Øxnevad et al., 2021).

The aims of the present study are
a) describing time trends for concentrations of contaminants in blue mussels from several stations in the Kristiansandfjord,
b) comparing levels of contaminants at different locations in the fjord,
c) determining environmental condition and chemical status of locations in the fjord and
d) assessing the pollution in the fjord, by collecting contaminant concentrations in blue mussels and sediment using data from published reports. The results will be discussed in light of discharges from local industry, as well as other sources of contamination such as runoff from urban areas, port activity, contaminated soil, local wastewater treatment plants, road traffic and measurements taken for the improvement of the environment in the fjord. Possible causes for concentration levels and time trends will be discussed. There has not previously been published an overall picture of contamination in the Kristiansandfjord on such a large scale as in this thesis, therefore, the results from this study may provide increased knowledge on how discharges of environmental contaminants from urban areas with industry affect coastal ecosystems.

# 2. Methods

Data was collected from monitoring reports from NIVA and the Norwegian Environment Agency to study contamination in the Kristiansandfjord. The master student participated in field work on September 30$^{th}$ 2022.

## 2.1 Data selection

Available data from the monitoring of contaminants in the Kristiansandfjord was utilized in this thesis, which looks at contaminants in blue mussel and sediment. Blue mussels were selected because they are bioindicators of water quality (Angelo et al. 2007; Jović et al. 2011), as previously mentioned, and because of their suitable biological attributes. Sediment was selected because they reflect contamination conditions (Bakke et al., 2007). The location of the Kristiansandfjord was selected because of the large urban area surrounding the fjord. It is the location of industrial companies discharging contaminants into the fjord over a long period of time, further, the location was selected because of the available data. Stations were selected based on the amount of available data, and they were selected with a variety of distance from contaminant sources. Contaminants that influence a marine ecosystem were selected, including heavy metals arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), mercury (Hg) and nickel (Ni), as well as PAHs (Polycyclic aromatic hydrocarbons); the sum of sixteen High Priority Pollutants, including own data for the PAH compound benzo(a)pyrene. To obtain the most data, published reports dating back to 2006 were selected, containing the oldest data from 1995. Before that, there was no sufficient feasible data, and the newest data is from 2022. Most of the data is from 2010-2022 (see Appendix A for details). Contaminant data was mostly selected from fall months September, October, and November since blue mussel spawning then has happened, however, a small amount of data was selected from spring months where this was the only data available (stations Fiskåtangen, Lumber and Timlingen in the years 2011 and 2013, and stations Fiskåtangen, Flekkerøygapet, Lumber, Svensholmen and Timlingen in the year 2019 only for PAHs and benzo(a)pyrene). For blue mussels, contaminant concentration was selected based on wet weight (w.w.) and for sediment contamination dry weight (d.w.) was selected. Only data from native blue mussels were selected, not from caged blue mussels.

## 2.2 Data collection

### 2.21 Concentration of contaminants in blue mussel and sediment

Data on concentrations of contaminants in blue mussel and sediment were collected from published reports by NIVA from 2006 to 2020 (see Table 1). Unpublished documents from NIVA and available data from the Norwegian Environment Agency online pages (Vannmiljø, 2022) were added to the data collection.

**Table 1: Reports selected for data on contaminants in blue mussel and sediment**

| Year | Source | Report number | Blue mussel | Sediment |
|---|---|---|---|---|
| 2006 | Berge et al., 2007 | 5506 | x | |
| 2010 | Næs et al., 2011 | 6145 | x | x |
| 2011 | Schøyen et al., 2012 | 6364 | x | |
| 2011 | Næs et al., 2012 | 6373 | x | |
| 2011 | Næs & Håvardstun, 2012 | 6377 | x | |
| 2012 | Schøyen et al., 2013 | 6540 | x | x |
| 2012 | Næs & Håvardstun, 2013 | 6547 | x | x |
| 2012 | Næs et al., 2013 | 6548 | x | x |
| 2013 | Næs et al., 2014 | 6664 | x | |
| 2013 | Schøyen et al., 2014 | 6695 | x | |
| 2014 | Håvardstun et al., 2015 | 6862 | x | |
| 2015 | Schøyen & Håvardstun, 2016 | 6977 | x | x |
| 2015 | Håvardstun & Næs, 2016 | 7006 | x | |
| 2016 | Næs et al., 2017 | 7123 | x | x |
| 2016 | Schøyen & Håvardstun, 2017 | 7146 | x | |
| 2018 | Næs & Håvardstun, 2019 | 7348 | x | |
| 2018 | Schøyen et al., 2019 | 7353 | x | |
| 2020 | Schøyen et al., 2021 | 7596 | x | x |
| 2020 | Øxnevad et al., 2021 | 7646 | x | x |

### 2.22 Statistics

Bar graphs showing the concentration of contaminants in blue mussel were created with data from the five past measurements, with the goal of comparing the stations. The same was done for sediment data, except all the available data found was selected. Scatterplots with a confidence interval of 95% were created, F-tests were conducted, and p-values were found to determine whether the changes in concentrations of contaminants in blue mussel were significant.

### 2.23 Environmental condition sediment

The sediments were classified for environmental condition according to (M-608, 2016). The five classes in the classification system show an expected increase in toxic environmental effects.

Colored lines showing condition classes were added to the bar graphs showing sediment concentrations.

**Table 2: Condition classes for sediment**

| | Unit | Class I | Class II | Class III | Class IV | Class V |
|---|---|---|---|---|---|---|
| | | Background | Good | Moderate | Poor | Very poor |
| Metals | | Background level | No toxic effects | Chronic effects from long-term exposure | Acute toxic effects from short-term exposure | Comprehensive toxic effects |
| Arsenic | mg/kg w.w. | 0-15 | 15-18 | 18-71 | 71-580 | >580 |
| Lead | mg/kg w.w. | 0-25 | 25-150 | 150-1480 | 1480-2000 | 2000-2500 |
| Cadmium | mg/kg w.w. | 0-0,2 | 0,2-2,5 | 2,5-16 | 16-157 | >157 |
| Copper | mg/kg w.w. | 0-20 | 20-84 | | 84-147 | >147 |
| Chromium | mg/kg w.w. | 0-60 | 60-620 | 620-6000 | 6000-15500 | 15500-25000 |
| Mercury | mg/kg w.w. | 0-0.05 | 0,05-0,52 | 0,52-0,75 | 0,75-1,45 | >1,45 |
| Nickel | mg/kg w.w. | 0-30 | 30-42 | 42-271 | 271-533 | >533 |
| Zinc | mg/kg w.w. | 0-90 | 90-139 | 139-750 | 750-6690 | >6690 |
| PAHs | | | | | | |
| Benzo(a)pyrene | µg/kg d.w. | 0-6 | 6-183 | 183-230 | 230-13100 | >13100 |
| PAH-16 | µg/kg d.w. | 0-300 | 300-2000 | 2000-6000 | 6000-20000 | >20000 |

## 2.24 Chemical status

For sediment, the chemical status was determined using EQS (Environmental Quality Standards) in coastal waters according to (Direktoratsgruppen vanndirektivet, 2018). EQS are calculated standards for contaminants for the protection of aquatic biological material. When concentrations of contaminants do not exceed EQS, there should be no effects on aquatic organisms. Determining chemical status was done by determining whether contaminant concentrations exceeded EQS or not, from a selection of contaminants, so-called priority substances. The two condition classes for chemical status are «good», meaning contaminant concentrations near background levels of naturally occurring substances, and «not good». Chemical status was considered «not good» if at least one of the contaminants had an exceeding concentration. When contaminants lie below EQS, it means the organisms have little to no deviation to the natural state. When contaminants exceed EQS, it means the organisms have moderate to very large deviation to the natural state. Another selection of contaminants, so-called river basin specific pollutants, is a contributing factor for the determination of ecological status. (Direktoratsgruppen vanndirektivet, 2018).

For blue mussels, EQS were used to determine the chemical status of blue mussels according to (Direktoratsgruppen vanndirektivet, 2018). Chemical status was considered «not good» if at least one of the contaminants had an exceeding concentration. Blue mussels with «not good» chemical status may contribute to deleterious effects in higher trophic organisms (Direktoratsgruppen vanndirektivet, 2018).

## 2.25 Pollution assessment

A pollution assessment of blue mussels was done based on PROREF (Norwegian provisional high reference contaminant concentration) according to (Schøyen et al., 2022). The PROREF value can be interpreted as the upper range of contaminant concentrations in reference/background stations – i.e., stations far from contaminant discharge sources (Schøyen et al., 2022). Stations with contaminants exceeding PROREF may be considered polluted, however, several factors and selections lie behind these values.

### 2.26 Discharges from companies

Industrial companies around the Kristiansandfjord were found using a map from the Norwegian Environment Agency (Vann-nett, 2023). The main companies around the fjord are Elkem Carbon, Glencore Nikkelverk and REC Solar. Elkem Carbon produces electrode paste and other carbon products to the silicon, aluminum, and ferroalloys industries (Elkem, 2023a). Elkem Carbon is a dominating source of PAHs (Hindar, 2018), and the seabed outside Elkem Carbon is contaminated, mainly linked to PAH (Olsen et al., 2018). The discharges have been reduced considerably in recent years, however, they remain too high, and the sediment contains concentrations too high for an acceptable environmental condition (Olsen et al., 2018). According to (Olsen et al., 2018) these following measures are recommended: i) Before implementing sediment measures, mapping of active inputs with subsequent discharge limiting measures, ii) Covering the area outside the company to prevent erosion and the spreading of contaminated sediment, iii) Monitoring of natural recovery in a nearby bay to follow the effect of reduced emissions linked to PAHs (Olsen et al., 2018). In 2021, NIVA published an updated report describing recommended actions. As part of a covering layer on the sediment, an erosion protection has been designed to avoid contamination spreading as a result of ship upheaval. Further measures are being taken to reduce PAHs and it is recommended that this be prioritized (Næs et al., 2021). Elkem Carbon has permission to pollution, first given in 1987 with the newest update from February 2023 (The Norwegian PRTR, 2023a). Elkem is committed to develop in accordance with the UN Sustainable Development Goals (Elkem, 2023b). Another company, Glencore Nikkelverk, produces nickel, copper and cobalt that is exported to the world (Nikkelverk, 2023). The sediment outside the company has high concentrations of heavy metals (Schøyen et al., 2021), and the company is a dominating source of copper and nickel discharges into the fjord (Hindar, 2018 from 7596). There has not been found recommended measures to obtain concentrations of an acceptable environmental condition. Glencore Nikkelverk has permission to pollution, first given in 1974 with the newest update from December 2022 (The Norwegian PRTR, 2023b). They are required by the Norwegian Environment Agency to reduce pollution as far as possible (The Norwegian PRTR, 2023b). Glencore's goal is to work for sustainable development and they have pollution goals lower than given in the pollution permission (Nikkelverk, 2023). Lastly, REC Solar produces solar panels for homes, businesses and power plants (Recgroup, 2023a). The company lies at the same bay as Elkem Carbon, meaning the same challenges for the environmental condition in the seabed as well as recommended measures for an acceptable environmental condition may be applied to REC Solar as Elkem Carbon. The company has permission to pollution, first given in 2007 with the newest update from January 2022 (The Norwegian PRTR, 2023c). According to REC Solar, the company has a commitment to sustainability, acknowledged by awards and accreditations, and their production is sustainable (Recgroup, 2023b).

Discharge data was found from The Norwegian PRTR from the companies Elkem Carbon, Glencore Nikkelverk and REC Solar. Tables showing discharges into water and into air from 2012-2021 were created. Data from 2012 and upwards was selected because it would give a suitable amount of data to compare with data from contaminant concentrations.

**Table 3: Discharges (kg/year) of contaminants from Elkem Carbon to water and air from 2012-2021**

| | As | | Cd | | Cu | | Pb | | Hg | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Water | Air | Water | Air | Water | Air | Water | Air | Water | Air |
| 2012 | | 105 | | 1 | | 103 | | 160 | | 10,2 |
| 2013 | | 169 | | 0,9 | | 30 | | 186 | | 9,8 |
| 2014 | | 95 | | 1,2 | | 72 | | 196 | | 8 |
| 2015 | | 443 | | 1 | | 207 | | 240 | | 9,5 |
| 2016 | | 311 | | 1,6 | | 243 | | 248 | | 9,7 |
| 2017 | | 365 | | 1,1 | | 148 | | 237 | | 8,5 |
| 2018 | | 428 | | 3,2 | | 523 | | 352 | 0 | 2 |
| 2019 | | 345 | | 1,6 | 0,01 | 321 | 0,03 | 263 | 0 | 2 |
| 2020 | | 114 | | 0,7 | 0,01 | | 0,84 | 17 | 0 | 5 |
| 2021 | | 170 | | 1,3 | 0,01 | | 0,86 | 25 | 0 | 7,6 |

| | Ni | | Zn | | B(a)p | | PAH-16 | |
|---|---|---|---|---|---|---|---|---|
| | Water | Air | Water | Air | Water | Air | Water | Air |
| 2012 | | 179 | | 978 | | | 3,3 | |
| 2013 | | 30,6 | | 452 | | | 11,3 | |
| 2014 | | 382 | | 574 | | | 8,6 | |
| 2015 | | 75 | | 756 | | | 6,9 | 833 |
| 2016 | | 74 | | 603 | 0,194 | 0,37 | 1,79 | 2948,74 |
| 2017 | | 0 | | 324 | 0,448 | 0,101 | 4,43 | 3881,73 |
| 2018 | 0,64 | 98 | | 782 | 0,51 | 0 | 5,38 | 260,18 |
| 2019 | 0,65 | 9 | 0,4 | 431 | 0,321 | 0,214 | 3,19 | 270,01 |
| 2020 | 1,11 | 1,4 | 5,15 | | 0,58 | 0,066 | 5,62 | 132,06 |
| 2021 | 1,03 | 2,8 | 8,85 | | 0,59 | 0,0664 | 5,73 | 53,39 |

Discharge data of contaminants from Elkem Carbon are available to air. Data of discharges to water is available only from the latest years, except from benzo(a)pyrene and PAHs where there is slightly more data to water (The Norwegian PRTR, 2023a). Most contaminants have had a decrease in discharge in recent years, except from mercury and benzo(a)pyrene.

**Table 4: Discharges (kg/year) of contaminants from Glencore Nikkelverk to water and air from 2012-2021**

| | As | | Cd | | Cr | | Cu | | Pb | | Hg | | Ni | | Zn | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Water | Air | Water | Air | Water | Air | Water | Air | Water | Air | Water | Air | Water | Air | Water | Air |
| 2012 | 141 | | 2,6 | | | | 1281,1 | 2849 | 10,9 | | | | 2094,8 | 1634 | 170,2 | |
| 2013 | 113,2 | | 2,5 | | | | 905 | 1658 | 10,2 | | | | 1689,5 | 1184 | 132,1 | |
| 2014 | 112,8 | | 2,4 | | | | 729,3 | 1145 | 9,9 | | | | 1275,6 | 912 | 107,4 | |
| 2015 | 113,7 | | 2,5 | | | | 656,7 | 1542 | 10,4 | | | | 1214 | 1149 | 117 | |
| 2016 | 296 | | 2,4 | | | | 689 | 1225 | 10,6 | | | | 1341 | 992 | 154 | |
| 2017 | 339 | | 0 | | | | 510 | 891 | 0 | | | | 984 | 776 | 102 | |
| 2018 | 174 | | 0 | | | | 468 | 852 | 1,9 | | 0,05 | | 949 | 537 | 60 | |
| 2019 | 113,6 | | 0 | | 9,3 | | 564,8 | 708 | 2,4 | | 0,3 | | 1097,6 | 510 | 54,3 | |
| 2020 | 78,8 | | 0 | | 19,8 | | 369 | 570 | 2,2 | | | | 1025 | 486 | 32,3 | |
| 2021 | 121,8 | | 0 | | | | 374,5 | 632 | 1,9 | | | | 1163,6 | 540 | 49,4 | |

Discharge data of contaminants from Elkem Carbon are available to water, except for contaminants chromium and mercury, where little data is available. Data of discharges to air is available only for copper and nickel. Most contaminants seem to have had a decrease in discharge in recent years, and cadmium discharges have been reduced to 0 mg/kg since 2017 (The Norwegian PRTR, 2023b)

**Table 5: Discharges (kg/year) of contaminants from REC Solar to water and air from 2012-2021**

| | As | | Cd | | Cr | | Cu | | Pb | | Hg | | Ni | | Zn | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Water | Air | Water | Air | Water | Air | Water | Air | Water | Air | Water | Air | Water | Air | Water | Air |
| 2012 | 1,1 | 1,54 | | 0,03 | 0,5 | 0,02 | 4 | 0,9 | | 0,5 | | 0,19 | 4,4 | 0,54 | 0,7 | 1,96 |
| 2013 | 0,2 | 1,52 | | 0,02 | 0,1 | 0,02 | 1,4 | 0,94 | | 0,79 | | 0,25 | 0,1 | 0,75 | 0,04 | 3,11 |
| 2014 | 3,2 | 2,12 | | 0,02 | 1,6 | 0,04 | 19,5 | 1,4 | | 1,3 | | 0,38 | 28,8 | 1,27 | 4 | 4,81 |
| 2015 | 2,7 | 4,06 | | 0,13 | 1,5 | 0,07 | 10,5 | 3,07 | | 1,5 | | 0,19 | 24,1 | 1,72 | 5 | 16,06 |
| 2016 | 3,6 | 4,92 | | 0,18 | 1,5 | 0,33 | 11,9 | 4,57 | | 0,87 | | 0,21 | 31,8 | 2,2 | 13 | 21,06 |
| 2017 | 3,2 | 4,85 | | 0,18 | 1,8 | 0,47 | 10,3 | 4,57 | | 0,57 | | 0,19 | 35,6 | 2,21 | 8 | 20,14 |
| 2018 | 3,4 | 0,12 | | 0,02 | 1,7 | 0,11 | 11,3 | 2,7 | | 0,19 | | 0,1 | 39,6 | 3,07 | 9,6 | 2,62 |
| 2019 | 0,6 | 0,15 | | 0 | 0,5 | 0,16 | 11,9 | 1,14 | | 0,13 | | 0,41 | 15,4 | 3,04 | 6,7 | 2,41 |
| 2020 | 0,5 | 0,1 | | 0 | 0,6 | 0,5 | 7 | 2,33 | | 0,26 | | 0,1 | 9,8 | 1,83 | 13 | 1,89 |
| 2021 | 0,3 | 0,43 | | 0,04 | 0,24 | 0,11 | 2,21 | 4,05 | | 0,3 | | 0,1 | 84 | 2,59 | 16,62 | 2,39 |

Data of contaminant discharges from REC Solar is available, but only to air for mercury, lead, and cadmium. Most contaminants seem to have had a decrease in discharge in recent years, except for nickel which had a relatively high amount discharged in 2021, as well as increased zinc discharges to water (The Norwegian PRTR, 2023c).

There have been implemented several measures to improve the environmental conditions in the Kristiansandfjord (see Table 6). The implemented measures apply to locations only at the innermost part of the fjord (Vann-nett, 2023a; Vann-nett, 2023b). Sedimentary remediation was implemented in 2003-2010 (Norwegian Environment Agency, 2023b), several action plans are finished and measures to improve knowledge about the marine environment have been started (Vann-nett, 2023a; Vann-nett, 2023b).

**Table 6: Measures taken for the improvement of environmental conditions in the Kristiansandfjord, with types of measures and the number of suggested, started, and finished measures**

| Measure type | Suggested | Started | Finished |
|---|---|---|---|
| Improvement of knowledge | 2 | 7 | |
| Sedimentary remediation | 3 | | 5 |
| Developing an action plan for contaminated seabed | 1 | | 3 |
| Reduction of discharges from industry | 1 | | 1 |
| Improvement of competence and information | | 1 | |
| Risk assessment and investigation of contaminated seabed | | 1 | 1 |
| Monitoring after sedimentary remediation | | 1 | |
| Supervision and follow-up | | 1 | |
| Permits and guidance | | 1 | |

### 2.27 Other sources of contamination

Maps from the Norwegian Environment Agency (Vann-nett, 2023a; Vann-nett, 2023b) were utilized to find other sources of contamination. Companies with runoff into the Kristiansandfjord that do not publish their discharges on The Norwegian PRTR are Hansa Borg Bryggerier, Christiansands bryggeri, Hennig-Olsen Is, Skagerakfisk SA Kristiansand and TINE Meieriet Sør. Additionally, the Kristiansandfjord is highly affected by runoff from urban areas and riverine imputs from Otra (see Table 7), contaminated soil (see Figure 2), local wastewater treatment plants (see Tables 8 and 9), port activity (see Table 10) and road traffic (highway 39 and other roads) (Vann-nett, 2023a, Vann-nett, 2023b).

**Table 7: Riverine loads in tonnes from Otra into the Kristiansandfjord in 2018 and 2020**

| | As | Cd | Cu | Cr | Hg | Ni | Pb | Zn |
|---|---|---|---|---|---|---|---|---|
| 2018 | 0,49 | 0,06 | 1,67 | 0,32 | 0 | 1,99 | 0,89 | 10,55 |
| 2020 | 0,92 | 0,11 | 2,98 | 0,69 | 0,0035 | 2,39 | 2,17 | 19,02 |

The river Otra is a source of heavy metal discharges into the Kristiansandfjord. All heavy metal amounts, except for copper, are higher in 2020 compared to 2018. Data collected from (Gundersen et al., 2019; Kaste et al., 2020).

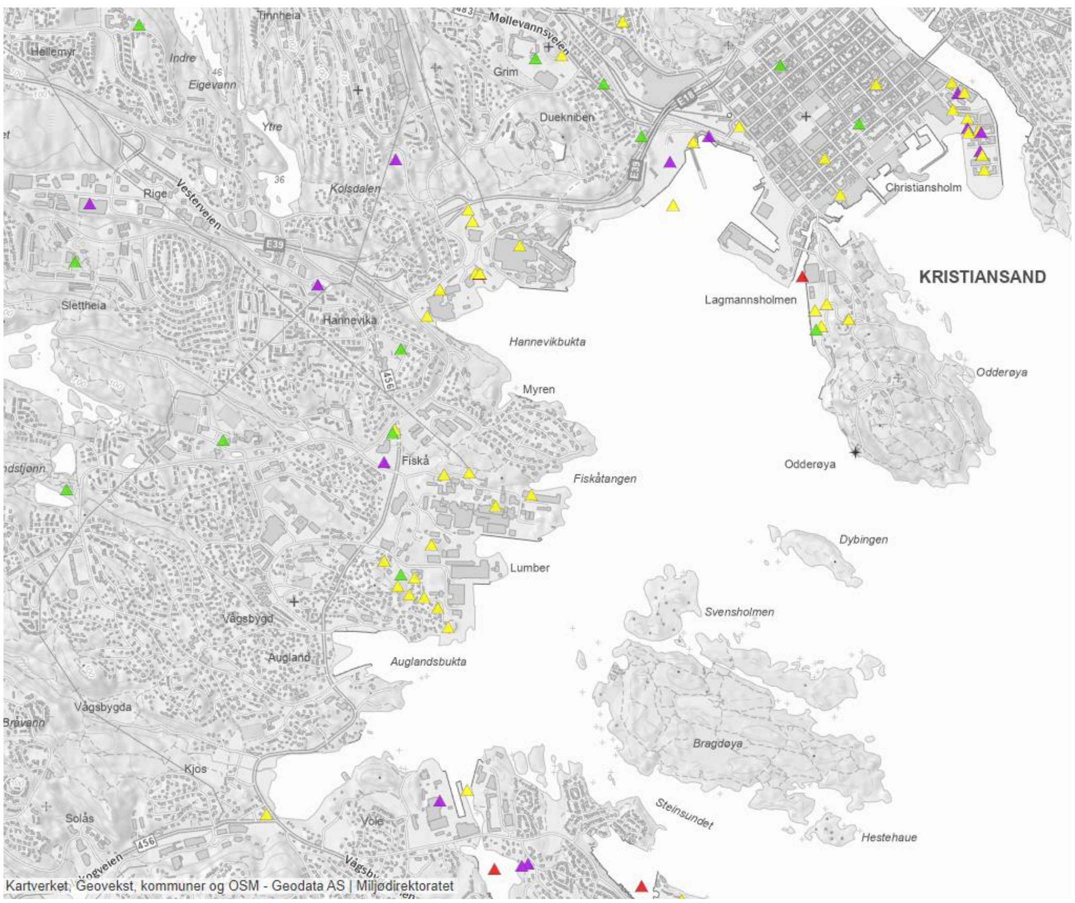



**Figure 2: Contaminated soil around the Kristiansandfjord, condition classes (green = «good», yellow = «moderate», red = «very poor», purple = «considered hazardous waste»). Figure from Vann-nett, 2023a**

The soil around the Kristiansandfjord is contaminated, locations classify from «good» condition to «considered hazardous waste».

**Table 8: Discharges (kg/year) of contaminants from Bredalsholmen wastewater treatment plant to water**

| | As | | Cd | | Cu | | Pb | | Hg | | Ni | | Zn | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Water | Air | Water | Air | Water | Air | Water | Air | Water | Air | Water | Air | Water | Air |
| 2012 | 10,46 | | | | 12,31 | | 2,21 | | 1,12 | | 46,73 | | 122,21 | |
| 2013 | 9,02 | | | | 16,18 | | 0,012 | | 1,532 | | 41,6 | | 127 | |
| 2014 | 3,4 | | 0,23 | | 18,34 | | 2,29 | | 1,54 | | 49,85 | | 136,48 | |
| 2015 | 6,01 | | 0,24 | | 19,6 | | 2,4 | | 1,24 | | 47,8 | | 141,3 | |
| 2016 | 1,1 | | 0,18 | | 11,69 | | 1,86 | | 0,79 | | 42,69 | | 123,15 | |
| 2017 | 7,491 | | 0,367 | | 17,797 | | 1,451 | | 0,01 | | 54,679 | | 122,734 | |
| 2018 | 6,295 | | 0,309 | | 14,87 | | 4,655 | | 0,001 | | 46,812 | | 121,537 | |
| 2019 | 6,142 | | 0,495 | | 16,082 | | 2,55 | | 0 | | 46,807 | | 223,825 | |
| 2020 | 6,192 | | 0,115 | | 13,234 | | 0,745 | | 0 | | 65,37 | | 134,012 | |
| 2021 | | | 1,612 | | 18,444 | | 4,116 | | 0 | | 129,146 | | 5185,604 | |

There are discharges of metal contaminants from Bredalsholmen wastewater treatment plant. Discharges of cadmium, nickel and zinc seem to have increased over the years, while mercury discharges have declined to 0 kg/year. Other contaminants generally seem to have had the same discharge amounts since 2012. Discharge data from the wastewater treatment plant was found from the Norwegian Environment Agency (The Norwegian PRTR, 2023d).

**Table 9: Discharges (kg/year) of contaminants from Odderøya wastewater treatment plant to water**

| | As | | Cd | | Cu | | Pb | | Hg | | Ni | | Zn | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Water | Air | Water | Air | Water | Air | Water | Air | Water | Air | Water | Air | Water | Air |
| 2012 | 10,46 | | 0,64 | | 63,28 | | 13,09 | | 4,64 | | 49,77 | | 275,54 | |
| 2013 | 9,02 | | 0,47 | | 33,2 | | 1,01 | | 3,24 | | 38 | | 221 | |
| 2014 | 3,4 | | 0,2 | | 26,8 | | 2,4 | | 3 | | 48,7 | | 213,4 | |
| 2015 | 6,01 | | 0,42 | | 26,64 | | 4,24 | | 1,41 | | 43,01 | | 176,99 | |
| 2016 | 1,1 | | 0 | | 2,8 | | 0,3 | | 0,2 | | 4,8 | | 16,8 | |
| 2017 | 7,491 | | 0,53 | | 46,482 | | 4,164 | | 0,045 | | 41,211 | | 272,461 | |
| 2018 | 6,295 | | 0,47 | | 25,855 | | 3,459 | | 0,002 | | 40,307 | | 224,563 | |
| 2019 | 6,142 | | 0,485 | | 39,21 | | 3,003 | | 0,03 | | 82,736 | | 258,929 | |
| 2020 | 6,192 | | 0,139 | | 42,881 | | 2,533 | | 0 | | 42,716 | | 238,414 | |
| 2021 | | | | | | | | | | | | | | |

There are discharges of metal contaminants from Odderøya wastewater treatment plant. Discharges generally seem to have remained the same over the years, except for a decline in lead, and the discharges of mercury have declined to almost 0 kg/year. Odderøya wastewater treatment plant has a considerable contribution of zinc and PAHs into the fjord (Schøyen et al., 2021). Discharge data from the wastewater treatment plant was found from the Norwegian Environment Agency (The Norwegian PRTR, 2023e).

**Table 10: Facts on the Port of Kristiansand**

| | Calls | Cruise calls | Containers | Passengers | Tonnes of goods |
|---|---|---|---|---|---|
| 2021 | 4475 | 18 | 50.894 | 394.125 | 3.504.500 |
| 2022 | 4888 | 128 | 49,500 | 1.603.480 | 3.345.400 |

The Kristiansandfjord has a large port activity. There has been a considerable increase of cruise calls and passengers arriving the Port of Kristiansand since 2021 (Port of Kristiansand, 2023a; Port of Kristiansand, 2023b).

## 2.3 Blue mussel sampling

Sampling was done by NIVA from 2006 to 2022 and had a general approach. Blue mussels were collected by snorkeling and wading and only individuals from native populations in good condition were collected. Ideally, at least 25 individuals measuring 3-6 cm were collected at each station. Blue mussel samples were marked with station number, name of collector, project number and date. The blue mussels were transported coolly and damp in clean, non-airtight, plastic bags of polyethylene. The collection of blue mussels was done in a way to prevent contamination. Whole blue mussels were stored at a temperature of -20 °C. The blue mussels were analyzed as soon as practically possible. The blue mussels were thawed, then the shells were cleaned with a knife or a scalpel, using gloves. The shells were opened carefully with a scalpel and put in water to allow liquids to escape. The offal was removed using a scalpel and collected in a clean and marked sample glass. To prevent cross contamination, different scalpel blades were used for every station. The total mass was measured. The samples were stored in a way that prevented decomposition and ensured good quality. Sample collection followed a standard set of guidelines, the latest in Standard Norge, 2017. Chemical analysis was done by Eurofins, ALS and NIVA.

Collecting blue mussels at Timlingen

Blue mussels found at Svensholmen

A boat was utilized for transportation between the stations. The island Odderøya can be seen in the background.

Wading at Svensholmen

**Figure 3: Collecting blue mussel samples, September 30th, 2022. Pictures by Camilla Jantina Skjeggestad**

**Table 11: Blue mussel stations**

| Station | Latitude | Longitude |
|---|---|---|
| Fiskåtangen | 58.12924 | 7.97750 |
| Flekkerøygapet | 58.08101 | 7.95909 |
| Lumber | 58.12444 | 7.97375 |
| Myrodden | 58.13284 | 7.97203 |
| Odderøya | 58.13166 | 8.00156 |
| Svensholmen | 58.12476 | 7.98703 |
| Timlingen | 58.12060 | 7.98165 |

The different locations and distances to the discharge sources reflect the spreading of contaminants and provide an overall picture of the Kristiansandfjord. Stations Fiskåtangen and Lumber are nearest to the discharge sources from two companies and station Odderøya lies close to Odderøya wastewater treatment plant. Station Odderøya should not be influenced by the companies' discharges (Schøyen & Håvardstun, 2017). Stations near the contaminant sources are considered to show the impact of the contaminants (Schøyen & Håvardstun, 2017). Stations Fiskåtangen, Timlingen and Svensholmen are monitoring stations, and it is assumed that these stations will cover the area of influence from the companies (Schøyen & Håvardstun, 2017). Myrodden is located at a distance from the contaminant sources (Schøyen & Håvardstun, 2017). The outermost station Flekkerøygapet lies outside of the assumed influence area of the companies and is considered a reference station (Øxnevad et al., 2021).

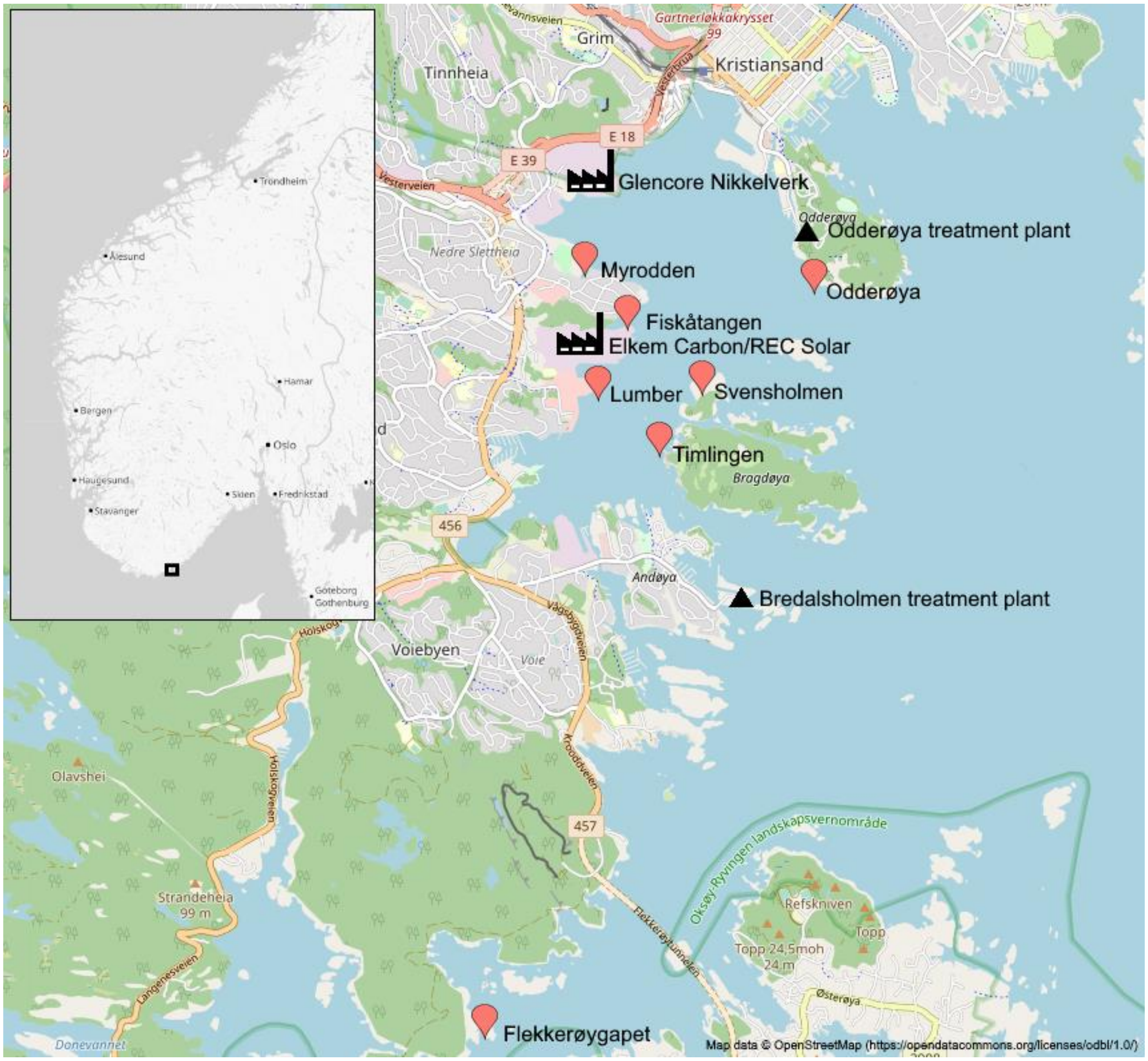



**Figure 4: Map of blue mussel sampling stations in the Kristiansandfjord, industry, and wastewater treatment plants**

## 2.4 Sediment sampling

Sampling was done by NIVA from 2006-2020 and the procedure had a general approach. A 0,1 $m^2$ van-Veen grab was used to collect sediment samples, except in 2012 where a Gemini Twin-Port sampler was used. The upper 0-2 cm of the surface was sampled to collect the most recently deposited material. The number of samples taken at each station varied. Where multiple samples were collected, they were merged into a mixed sample. The samples were stored at a temperature of -20 $^{o}$C. Sample collection followed a standard set of guidelines, the latest from Standard Norge, 2004. Chemical analysis was done by Eurofins, ALS and NIVA.

**Table 12: Sediment stations**

| Station | Latitude | Longitude |
|---|---|---|
| ES1 | 58.12751 | 7.97897 |
| ES2 | 58.12672 | 7.97863 |
| K17 | 58.12557 | 7.98241 |
| K18 | 58.12970 | 7.98748 |
| KH03 | 58.11944 | 7.97823 |
| X12 | 58.13473 | 7.97023 |

Stations K18 and X12 lie at a considerable distance from the discharge sources and are therefore thought to reflect the ecological status and give a representative picture of the state of the Kristiansandfjord (Schøyen et al., 2021). Station X12 can be used to explore changes in copper and nickel (Schøyen & Håvardstun, 2016). ES1, ES2, K17 and KH03 are considered monitoring stations, where KH03 has the longest distance from discharge sources (Øxnevad et al., 2021). K17 is the station furthest away from land and is the deepest station (Øxnevad et al., 2021). It is assumed that it lies outside of the influence area of the companies and is considered to reflect the impact of contaminants (Øxnevad et al., 2021).

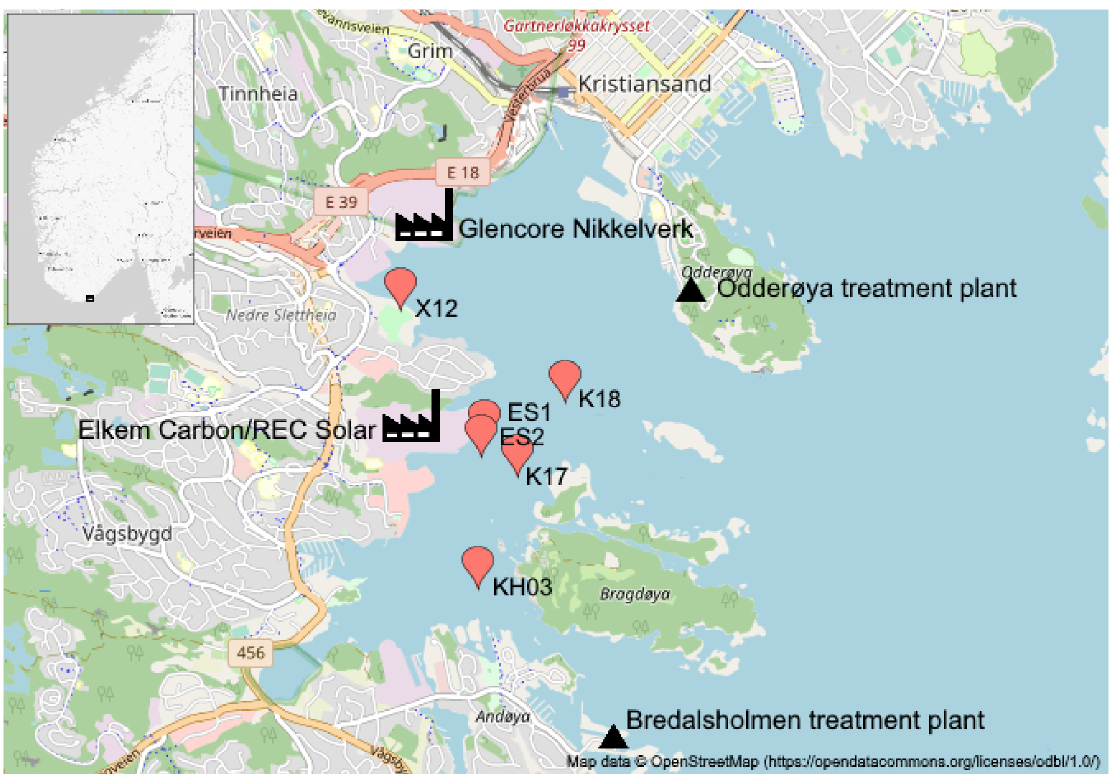


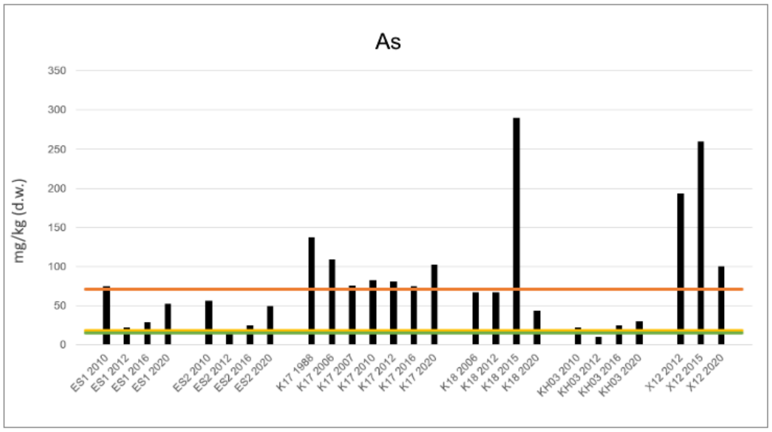

**Figure 5: Map of sediment sampling stations in the Kristiansandfjord, industry and wastewater treatment plants**

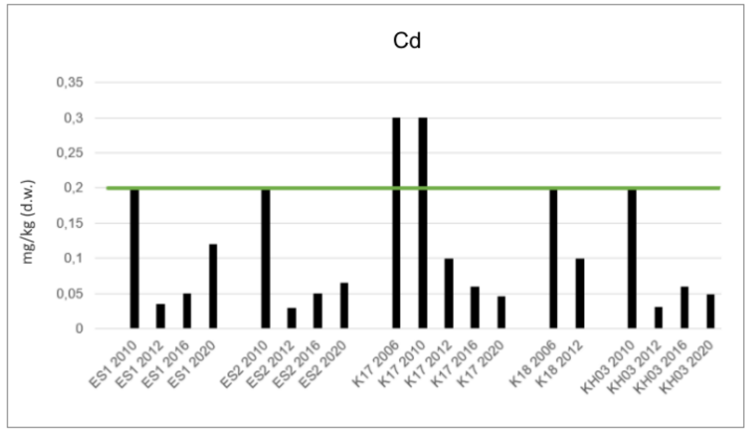
# 3. Results

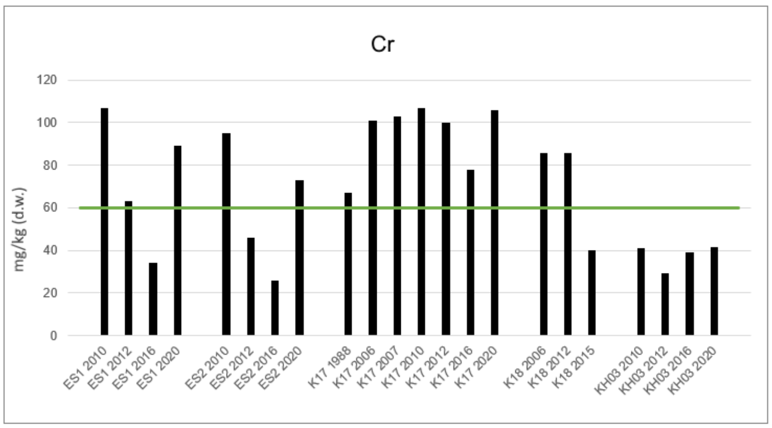
## 3.1 Contaminants in blue mussels per station

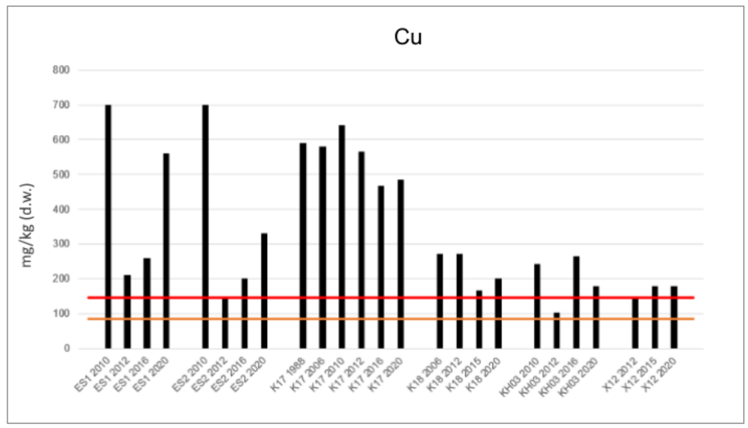
The chromium concentration was relatively high at station Odderøya in the year 2019 compared to the other stations (see Appendix B). Odderøya had the highest concentration of lead. Lumber was the station with the highest measured amounts of benzo(a)pyrene and PAHs. Cadmium had a slightly higher concentration at station Odderøya, the copper concentration was slightly higher at stations Myrodden and Fiskåtangen, and Myrodden and Odderøya had a slightly higher concentration of nickel. The concentration of arsenic, mercury, zinc was generally the same at each station. Blue mussels found at Flekkerøygapet had a much lower concentration of benzo(a)pyrene and PAHs compared to other stations.

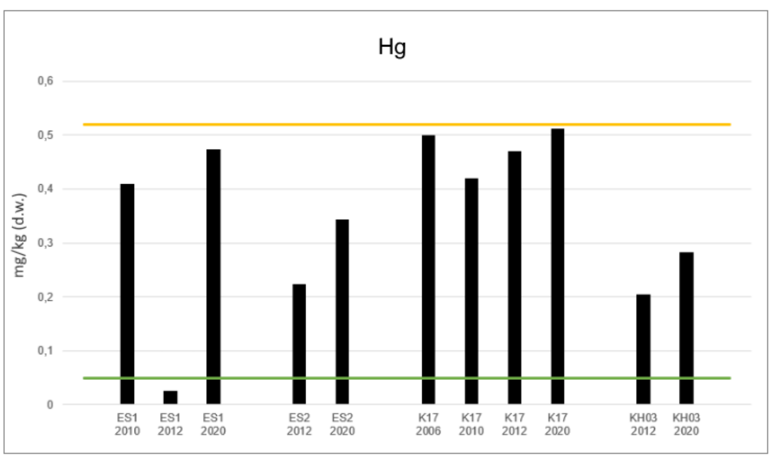
## 3.2 Environmental condition of sediment

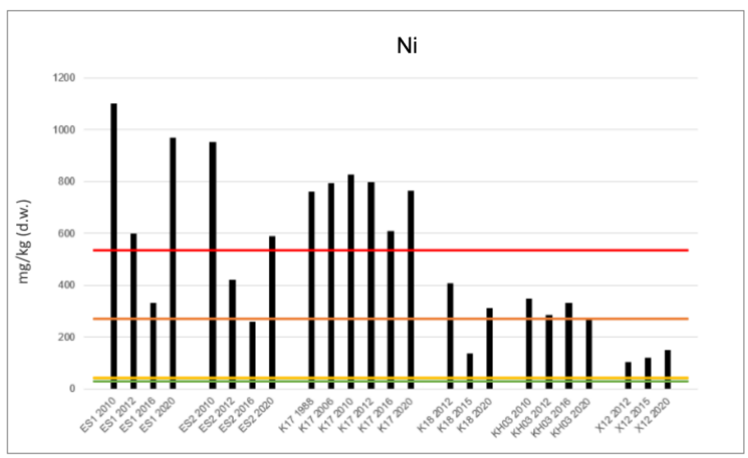


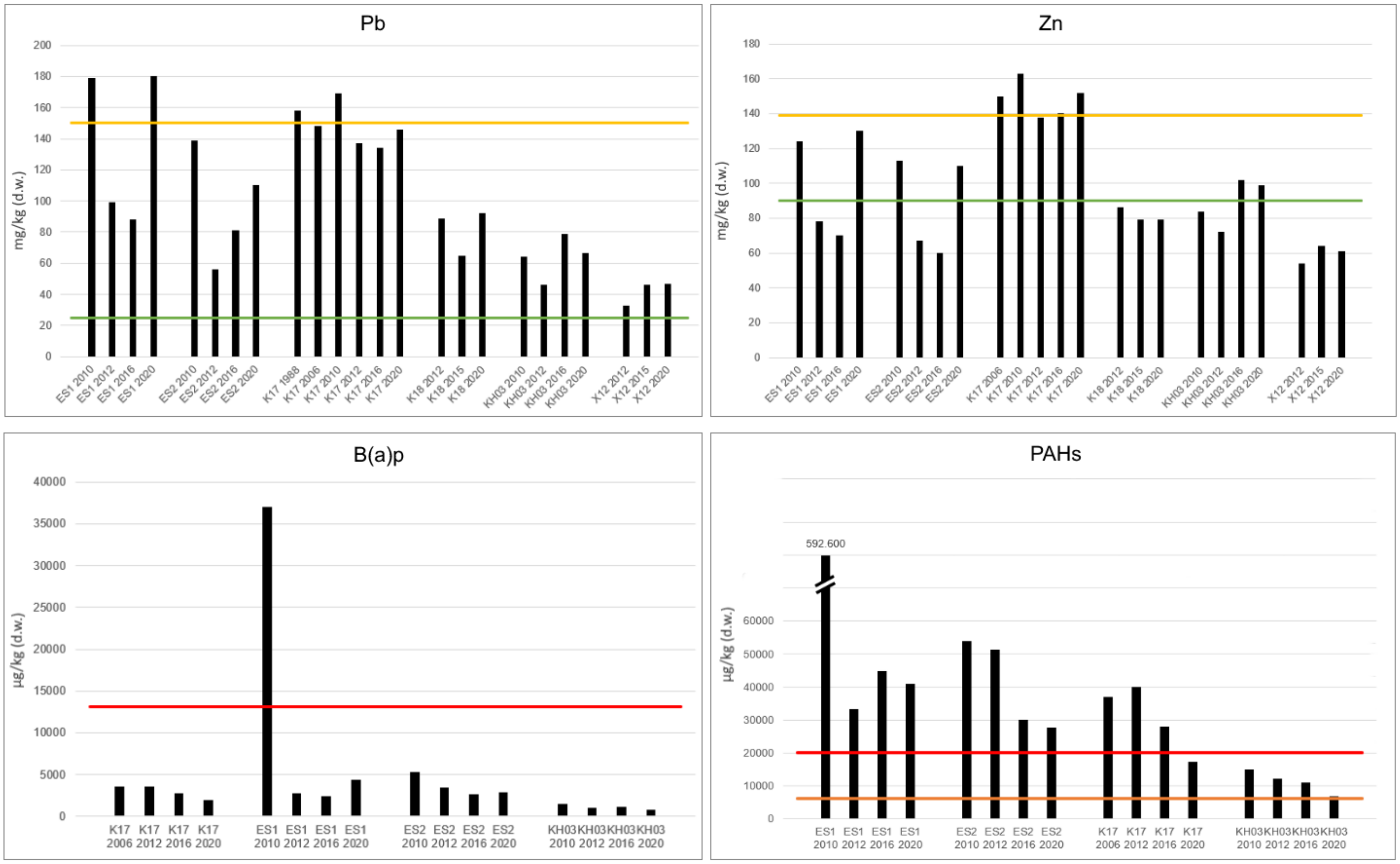



**Figure 6: Concentration of contaminants in sediment at the stations. Colored lines show limits of condition classes (blue = «background», green = «good», yellow = «moderate», orange = «poor», red = «very poor»).**

The measured concentrations of cadmium and chromium in sediments fall within the limits of condition classes «background» and «good» at all stations (see Figure 6). The concentations of mercury fall within the limits of «good» condition class. For zinc, the consentrations show «background» to «good» conditions at all stations, except K17 which classifies as having «moderate» condition. For arsenic, the concentrations fall within the limits of «moderate» condition class, except for stations K17, K18 and X12 which fall under condition class «poor». The measured concentrations of lead show «good» condition for all stations, except ES1 classifying as having «moderate» condition. K17 has historically had high lead concentrations. For nickel, the sediments are classified as having «moderate» and «poor» conditions, stations ES1, ES2 and K17 are classified as «very poor». For copper, almost all stations are classified as «very poor», where stations ES1, ES2 and K17 have had the highest concentrations. For benzo(a)pyrene and PAHs, all stations are classified as «very poor», except for PAHs concentrations from station KH03 which is classified as «poor». There were exceptionally high concentrations of benzo(a)pyrene and PAHs at ES1 in 2010, and stations ES1 and ES2 had PAH concentrations above the «very poor» condition limit in 2020. To summarize, metals cadmium, chromium and mercury were measured to classify the stations as «background» and «good». The concentrations of arsenic, nickel, lead and zinc were high, classifing the stations as «good», «moderate», «poor» or «very poor». The measurements of contaminants copper, benzo(a)pyrene and PAHs were very high, classifying the stations as having mostly «very poor» conditions. The stations K17, ES1 and ES2 seem to have had the highest concentrations of contaminants, and all stations have contaminants exceeding the limits for «very poor» environmental condition.

## 3.3 Chemical status

**Table 13: Chemical status sediment – priority substances. Concentration of contaminants in sediment (mg/kg d.w.) from 2020. Blue shows «good» chemical status, red shows «not good» chemical status, depending on lower or higher than EQS value.**

| Metal | EQS mg/kg d.w. | ES1 | ES2 | K17 | K18 | KH03 | X12 |
|---|---|---|---|---|---|---|---|
| Cadmium (Cd) | 2,5 | 0,12 | 0,065 | 0,045 | - | 0,0484 | - |
| Mercury (Hg) | 0,52 | 0,473 | 0,344 | 0,51 | - | 0,28 | - |
| Lead (Pb) | 150 | 180 | 110 | 146 | 92 | 66,6 | 47 |
| Nickel (Ni) | 42 | 970 | 590 | 764 | 310 | 266 | 150 |
| PAHs | EQS µg/kg d.w | | | | | | |
| Benzo(a)pyrene | 180 | 4350 | 2900 | 1948 | - | 779 | - |
| Chemical status | | Not good | Not good | Not good | Not good | Not good | Not good |

All stations have contaminants exceeding the limits of EQS and therefore classify as having «not good» chemical status. Nickel and benzo(a)pyrene concentrations exceed EQS at all stations.

Cadmium and mercury concentrations lie below EQS at all stations, and the lead concentration exceeded EQS at one station only.

**Table 14: Concentrations of river basin specific pollutants. Concentration of contaminants in sediment (mg/kg d.w.) from 2020. Grey numbers exceed EQS value.**

| Metal | EQS mg/kg d.w. | ES1 | ES2 | K17 | K18 | KH03 | X12 |
|---|---|---|---|---|---|---|---|
| Arsenic (As) | 18 | 53 | 50 | 102,6 | 44 | 29,8 | 100 |
| Chromium (Cr) | 620 | 89 | 73 | 106 | - | 41,4 | - |
| Copper (Cu) | 84 | 560 | 330 | 484 | 200 | 180 | 180 |
| Zinc (Zn) | 139 | 130 | 110 | 152 | 79 | 98,8 | 61 |

All stations have contaminants exceeding the limits of EQS. Arsenic and copper concentrations exceed EQS at all stations and chromium concentrations lie well below EQS at all stations.

**Table 15: Chemical status of blue mussels. Concentration of contaminants in blue mussel soft body (mg/kg w.w.) from 2022 (Odderøya and Myrodden from 2020). Blue shows «good» chemical status, red shows «not good» chemical status, depending on lower or higher than EQS value.**

| | EQS | Fiskåtangen | Flekkerøygapet | Lumber | Myrodden | Odderøya | Svensholmen | Timlingen |
|---|---|---|---|---|---|---|---|---|
| Mercury (Hg) | 0,02 mg/kg w.w. | 0,012 | 0,015 | 0,016 | - | 19,7 | 0,013 | 0,007 |
| Benzo(a) pyrene | 5 µg/kg w.w. | 10,9 | 0,397 | 96 | - | - | 11,4 | 7,99 |
| Chemical status | | Not good | Good | Not good | Not good | Not good | Not good | Not good |

All stations except Flekkerøygapet have exceeding limits of EQS and classify as having «not good» chemical status». The mercury concentrations lie below EQS at all stations except Odderøya, and the benzo(a)pyrene concentrations lie well above EQS at all stations except Flekkerøygapet.

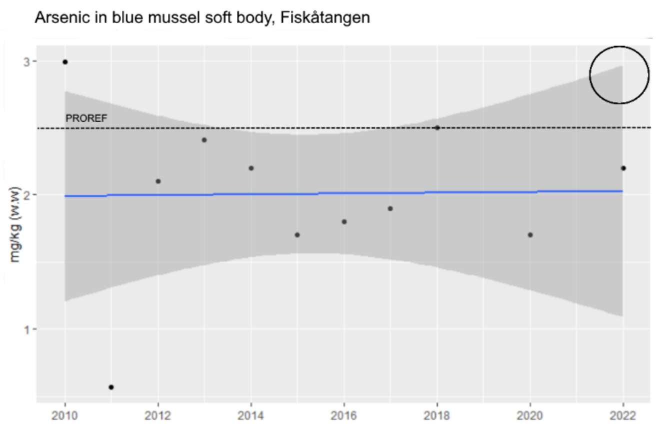
## 3.4 Pollution assessment

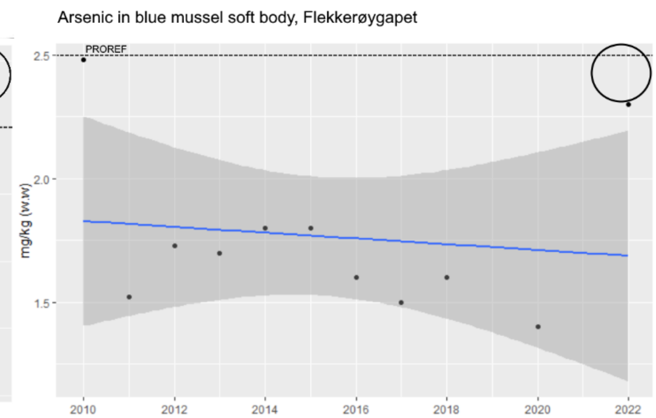
**Table 16: Pollution assessment of blue mussels based on PROREF (Norwegian provisional high reference contaminant concentration). Concentration of contaminants in blue mussel soft body (mg/kg w.w.) from 2022 (Odderøya and Myrodden from 2020). Grey numbers exceed PROREF.**

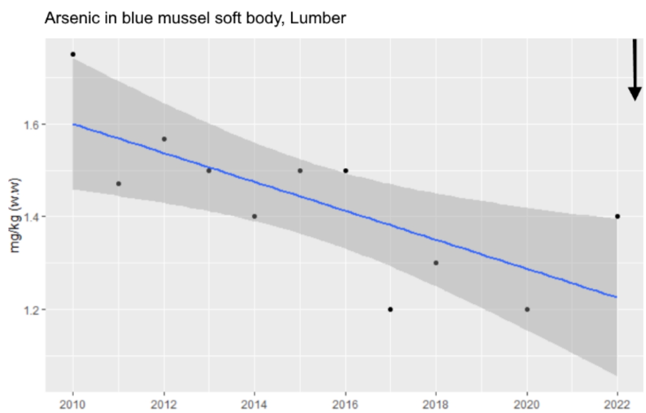
| Element | PROREF (mg/kg w.w.) | Fiskåtangen | Flekkerøygapet | Lumber | Myrodden | Odderøya | Svensholmen | Timlingen |
|---|---|---|---|---|---|---|---|---|
| Arsenic (As) | 2,503 | 2,3 | 2,2 | 1,4 | 1,9 | 1,47 | 2,2 | 1,9 |
| Cadmium (Cd) | 0,18 | 0,12 | 0,12 | 0,16 | - | 0,22 | 0,12 | 0,1 |
| Chromium (Cr) | 0,361 | 0,23 | 0,23 | 0,21 | - | 0,34 | 0,16 | 0,08 |
| Copper (Cu) | 1,4 | 2 | 0,6 | 1 | 2 | 1,53 | 1,2 | 1,4 |
| Mercury (Hg) | 0,012 | 0,012 | 0,015 | 0,016 | - | 0,0197 | 0,013 | 0,007 |
| Lead (Pb) | 0,2 | 1,1 | 0,78 | 0,4 | 0,54 | 3,87 | 0,46 | 0,24 |
| Nickel (Ni) | 0,29 | 1 | 0,4 | 0,7 | 0,7 | 0,74 | 0,7 | 0,4 |
| Zinc (Zn) | 17,66 | 17 | 13 | 16 | 16 | 21 | 14 | 16 |
| Priority substance | PROREF (µg/kg) | | | | | | | |
| Benzo(a)pyrene | 1.2 | 10,9 | 0,397 | 96 | - | - | 11,4 | 7,99 |
| PAH-16 | 30 | 128 | 9,02 | 949 | - | - | 109 | 144 |

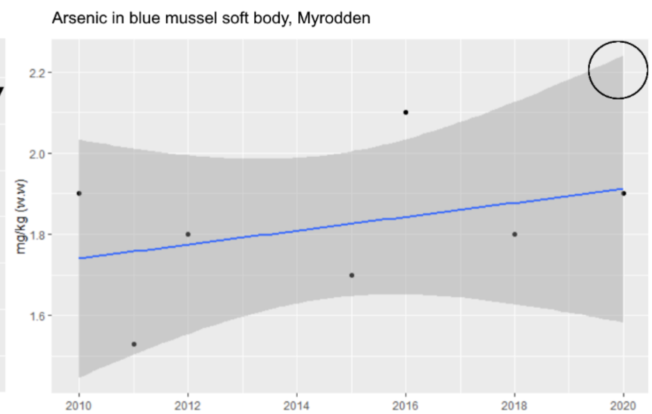
All stations have contaminants exceeding PROREF. Lead and nickel exceed PROREF at all measured stations. Cadmium and zinc exceeded PROREF at station Odderøya only. Copper exceeded PROREF at Fiskåtangen, Myrodden and Odderøya. Mercury exceeded PROREF at Flekkerøygapet, Lumber, Odderøya and Svensholmen. Arsenic and chromium had concentrations below PROREF at all stations. Of the measured stations, PAHs including benzo(a)pyrene exceeded PROREF at Fiskåtangen, Lumber, Odderøya and Svensholmen.

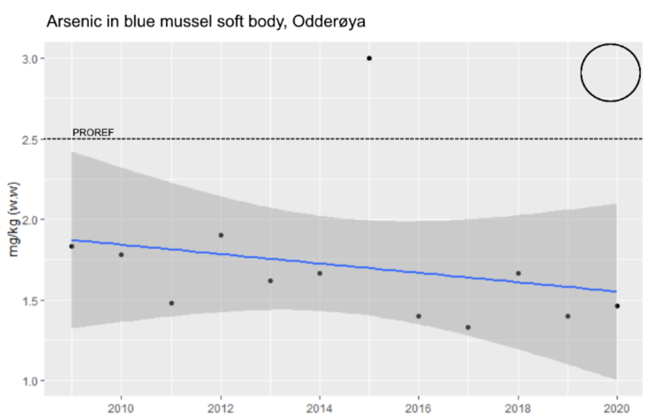
## 3.5 Time trends contaminants blue mussels

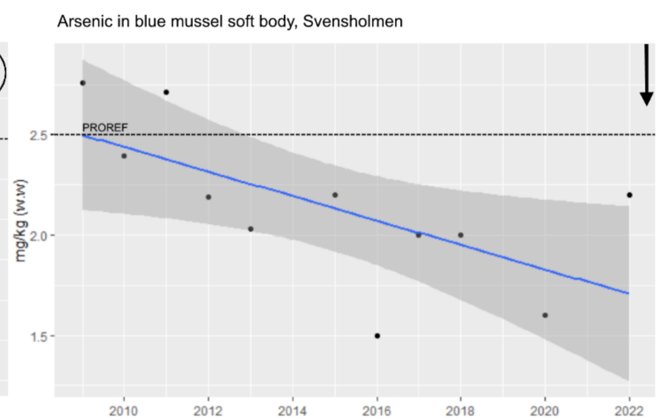


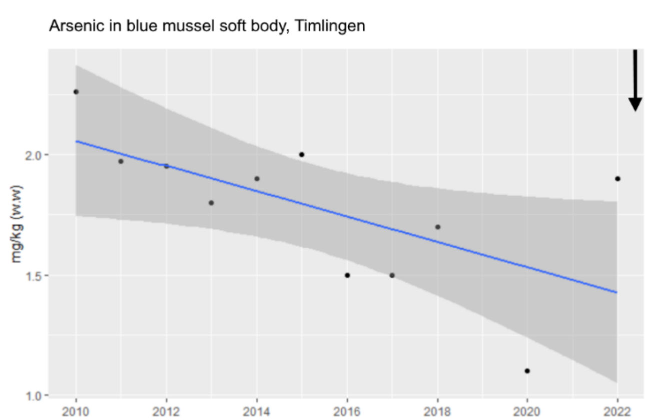



**Figure 7: Time trends for arsenic in blue mussel soft body at different stations with PROREF (Norwegian provisional high reference contaminant concentration). Concentrations are plotted with dots, a 95% confidence interval in grey and a trend line in blue. Arrows (↓ or ↑) show significant trend, circle (○) shows no significant trend.**

There has been a significant decline at stations Lumber, Svensholmen and Timlingen, there has been no significant change at the other stations. Most of the measurements lie below PROREF.

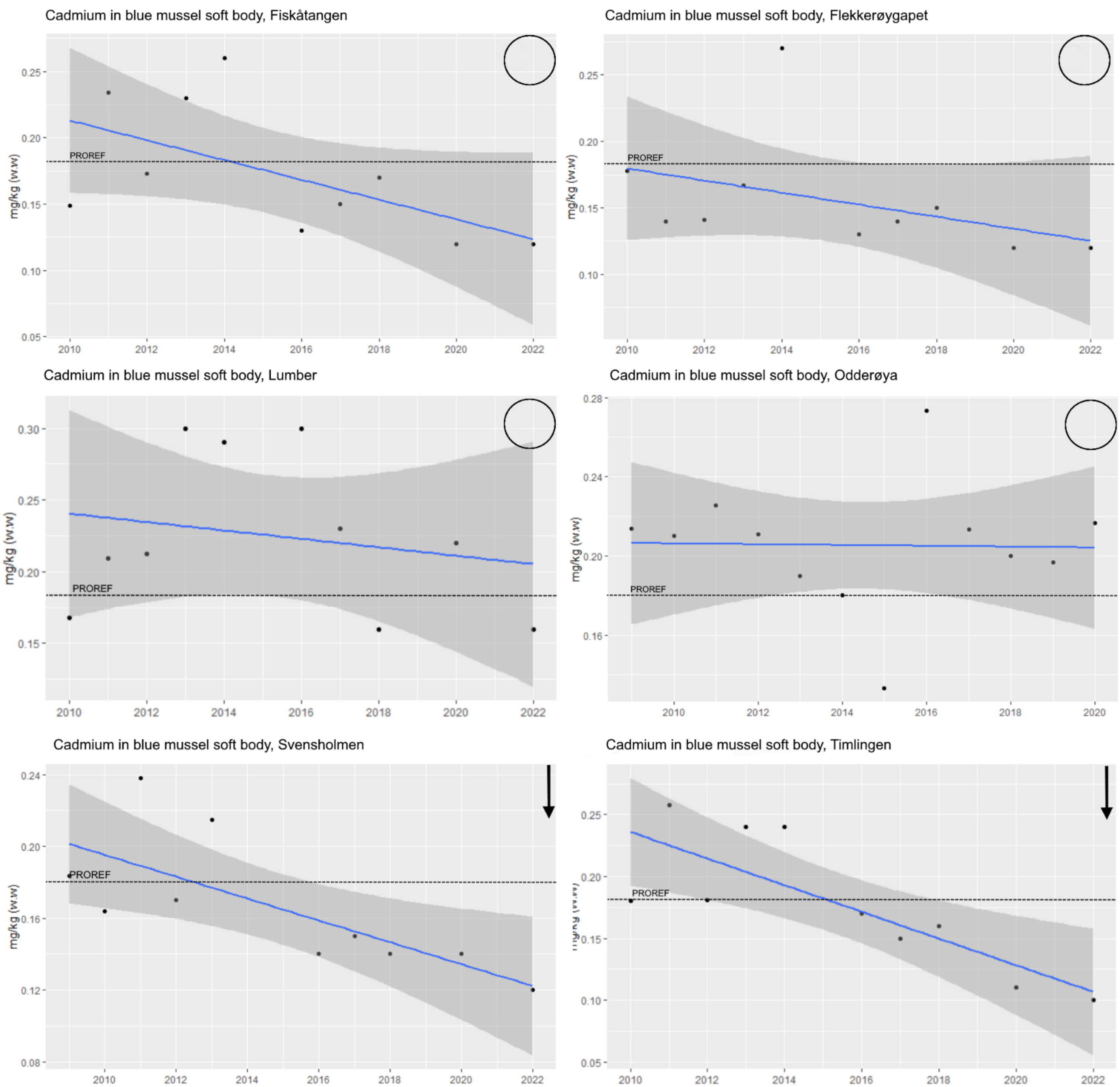
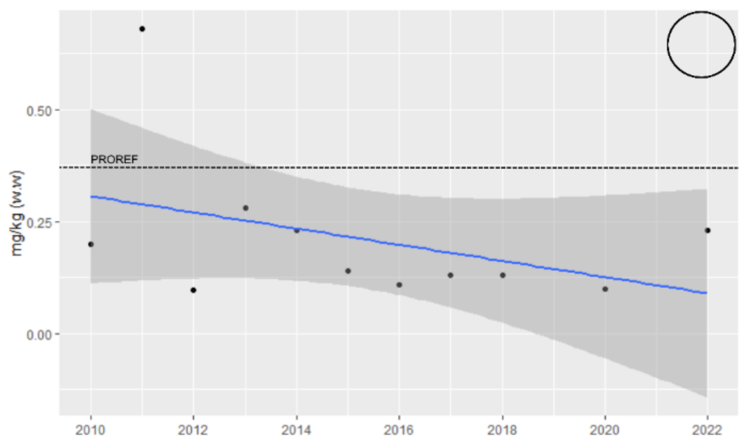


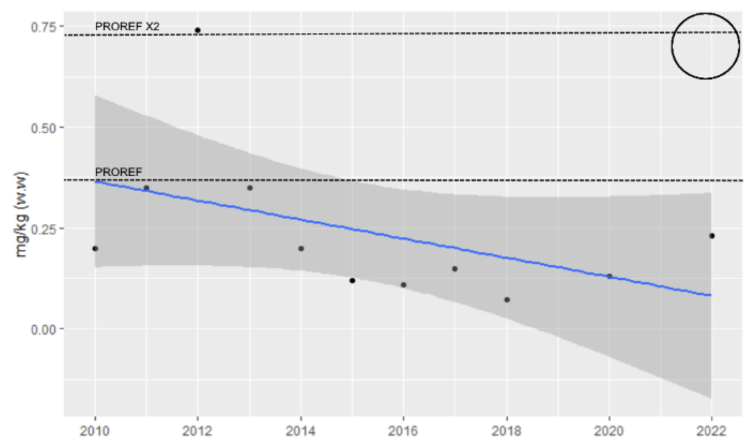
**Figure 8: Time trends for cadmium in blue mussel soft body at different stations with PROREF (Norwegian provisional high reference contaminant concentration). Concentrations are plotted with dots, a 95% confidence interval in grey and a trend line in blue. Arrows (↓ or ↑) show significant trend, circle (○) shows no significant trend.**

There has been a significant decline at stations Svensholmen and Timlingen, there has been no significant change at the other stations. All the latest measurements lie below PROREF except for at station Odderøya, and the Lumber station has previously had high measurements as well. Stations Fiskåtangen, Svensholmen and Timlingen have seen a change from measurements above to below PROREF.

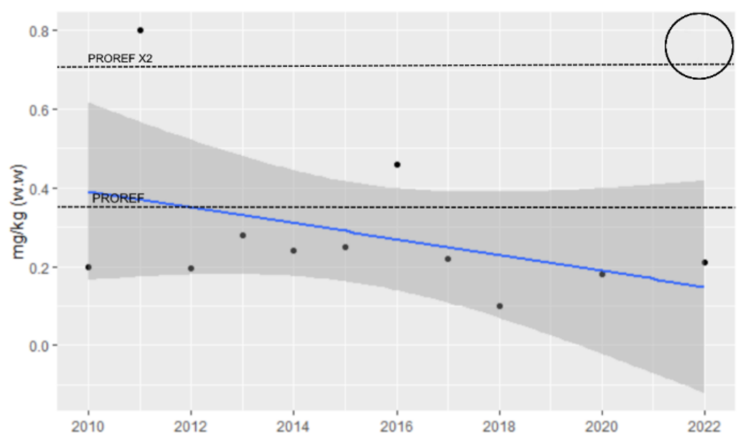
Chromium in blue mussel soft body, Fiskåtangen



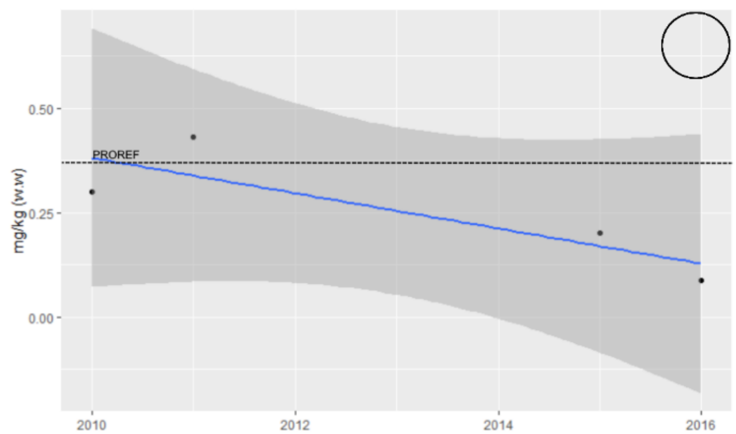

Chromium in blue mussel soft body, Flekkerøygapet



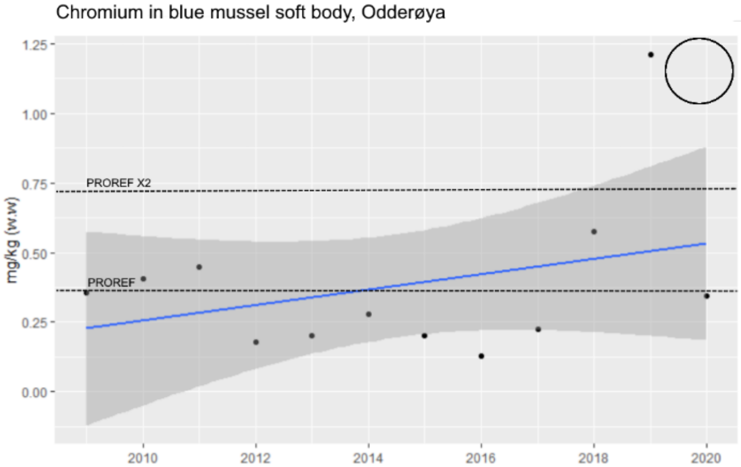

Chromium in blue mussel soft body, Lumber



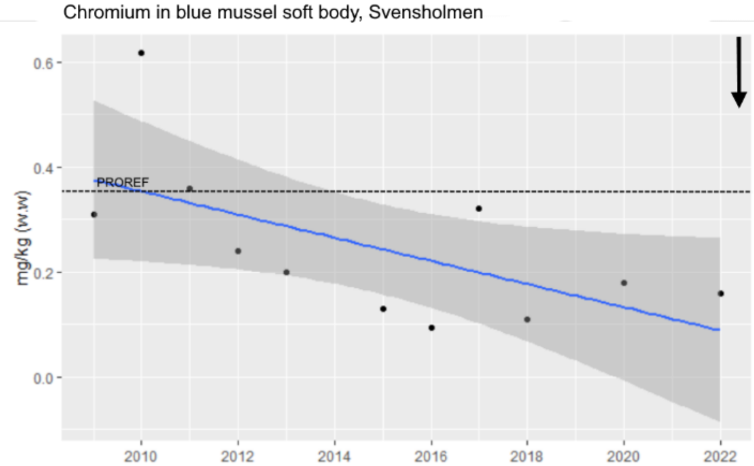

Chromium in blue mussel soft body, Myrodden




Chromium in blue mussel soft body, Odderøya




Chromium in blue mussel soft body, Svensholmen




Chromium in blue mussel soft body, Timlingen

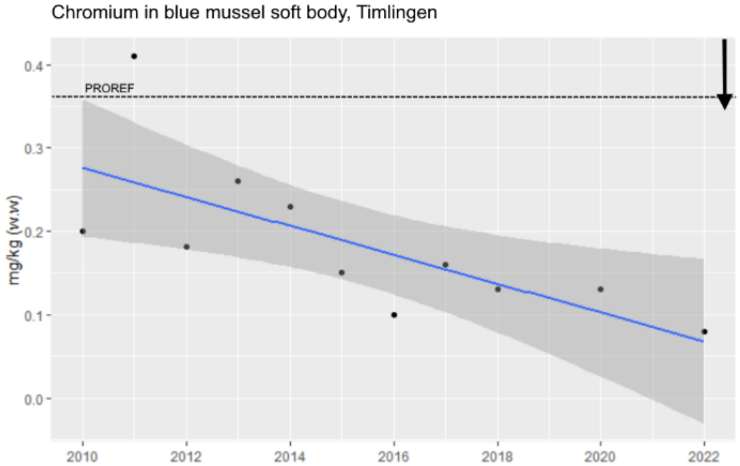
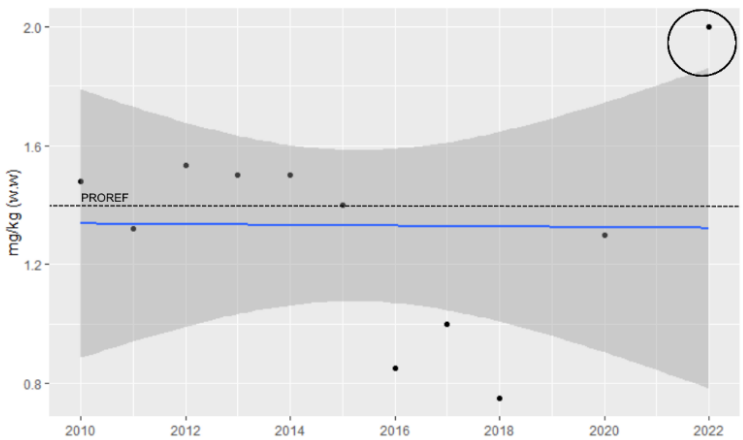


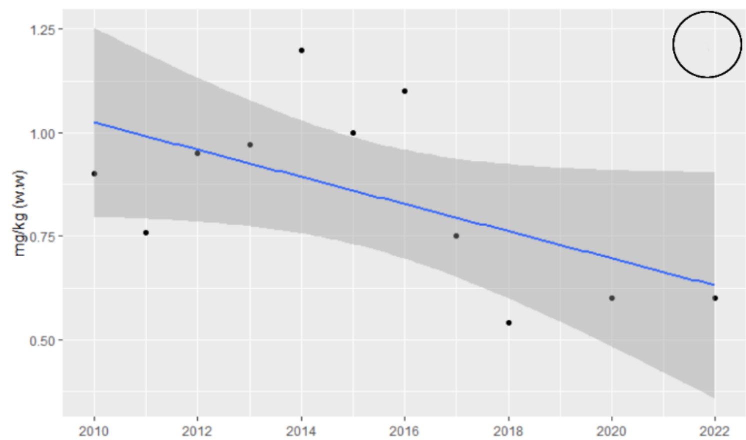
**Figure 9: Time trends for chromium in blue mussel soft body at different stations with PROREF (Norwegian provisional high reference contaminant concentration). Concentrations are plotted with dots, a 95% confidence interval in grey and a trend line in blue. Arrows (↓ or ↑) show significant trend, circle (○) shows no significant trend.**

There has been a significant decline at stations Svensholmen and Timlingen, there has been no significant change at the other stations. All the latest measurements lie below PROREF except for at station Odderøya with a high concentration in 2019.

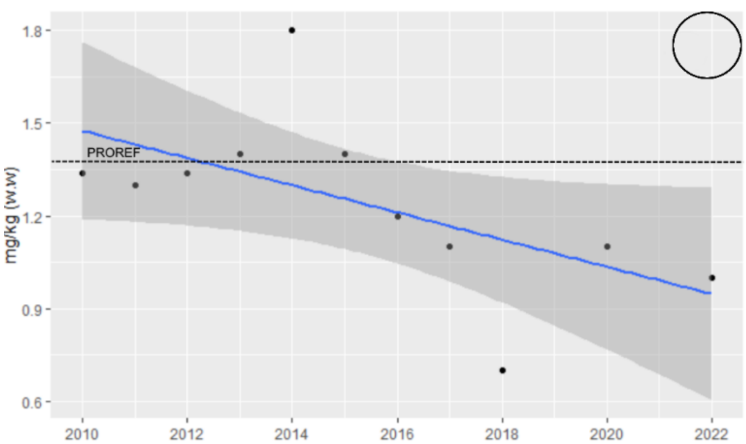
Copper in blue mussel soft body, Fiskåtangen



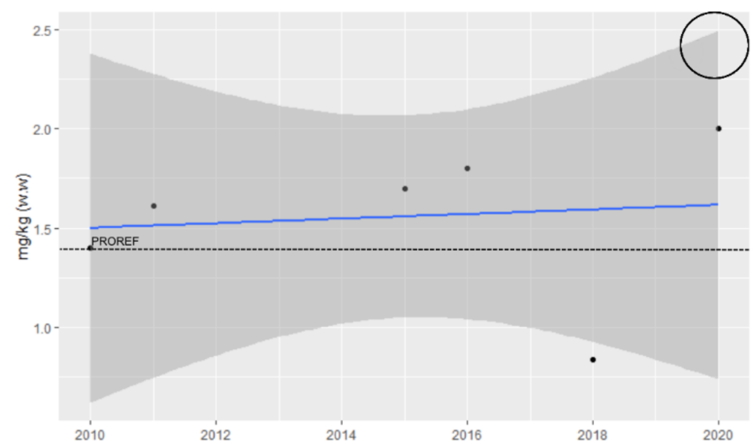

Copper in blue mussel soft body, Flekkerøygapet



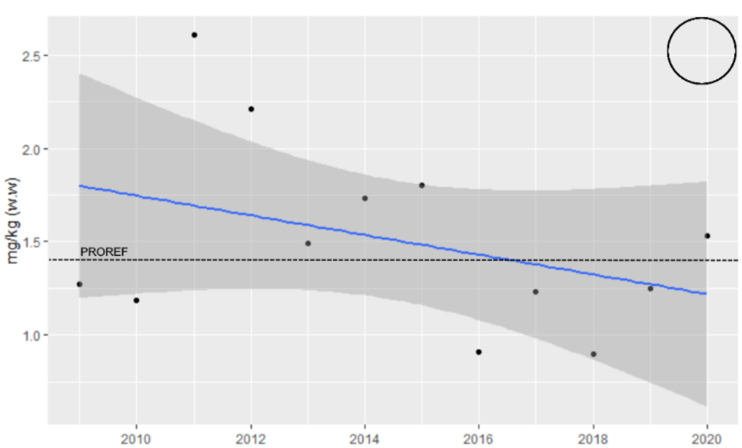

Copper in blue mussel soft body, Lumber



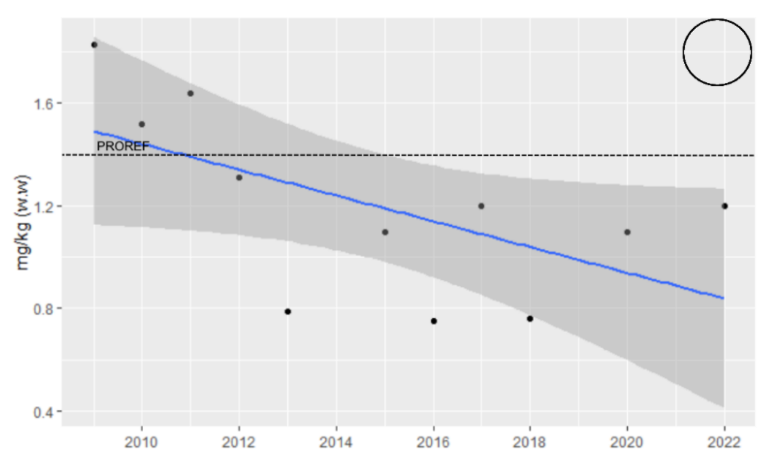

Copper in blue mussel soft body, Myrodden




Copper in blue mussel soft body, Odderøya




Copper in blue mussel soft body, Svensholmen




Copper in blue mussel soft body, Timlingen

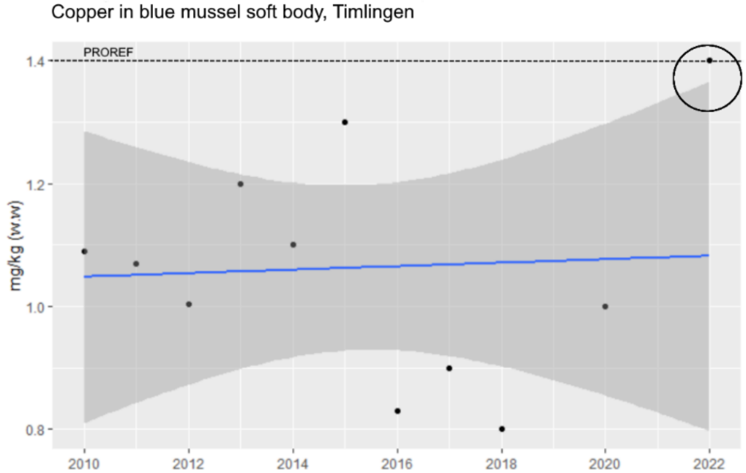
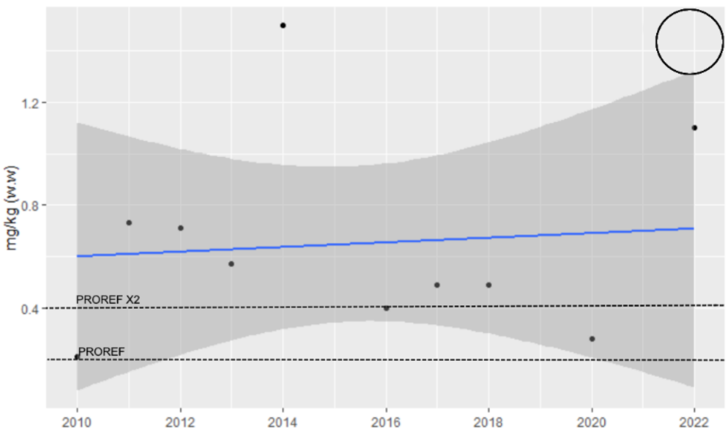


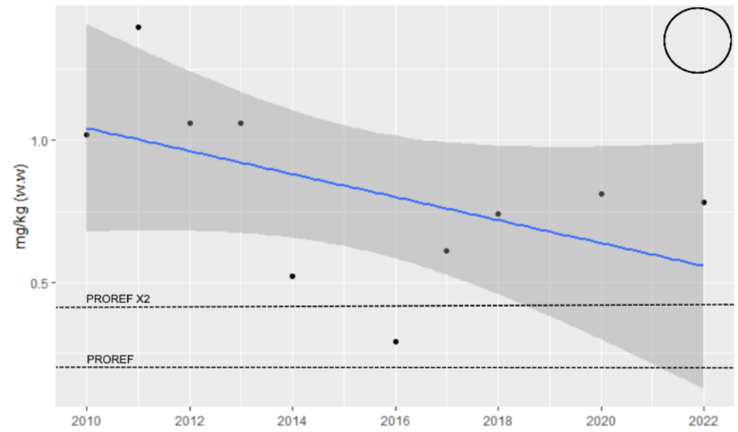
**Figure 10: Time trends for copper in blue mussel soft body at different stations with PROREF (Norwegian provisional high reference contaminant concentration). Concentrations are plotted with dots, a 95% confidence interval in grey and a trend line in blue. Arrows (↓ or ↑) show significant trend, circle (○) shows no significant trend.**

There have been no significant changes at either of the stations. Most of the stations had concentrations below PROREF recently. However, Myrodden had concentrations exceeding PROREF, Odderøya had a concentration exceeding PROREF in 2020 and Timlingen had a concentration near PROREF in 2022.

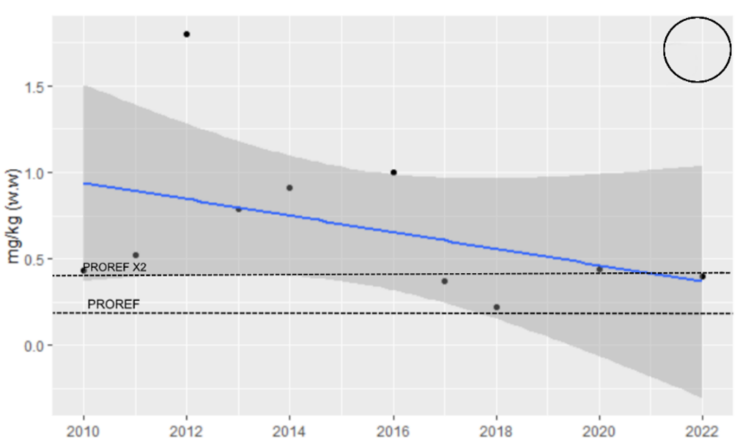
Lead in blue mussel soft body, Fiskåtangen



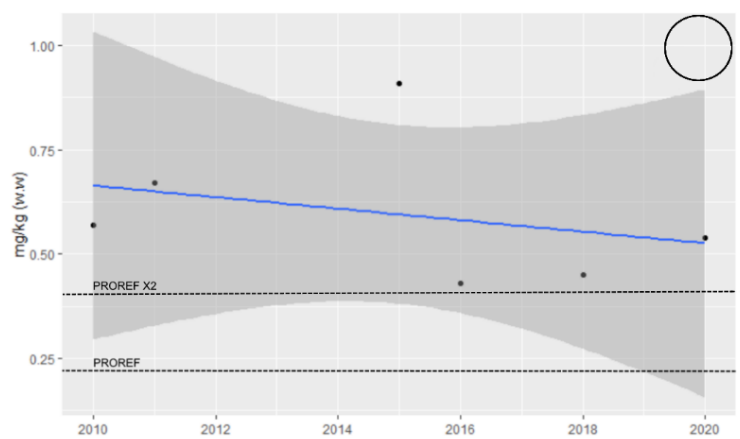

Lead in blue mussel soft body, Flekkerøygapet



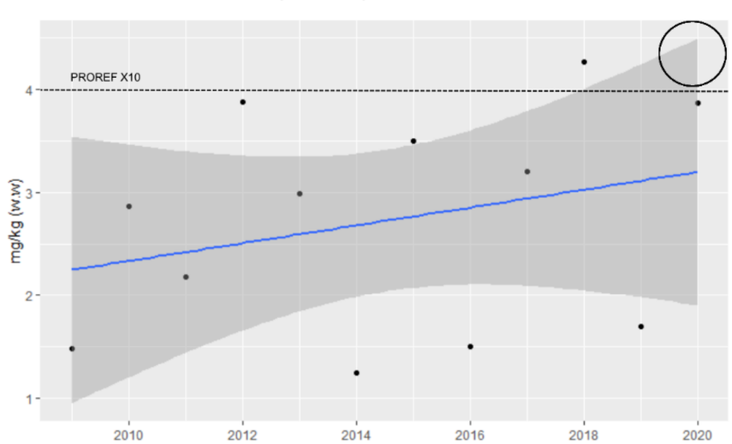

Lead in blue mussel soft body, Lumber



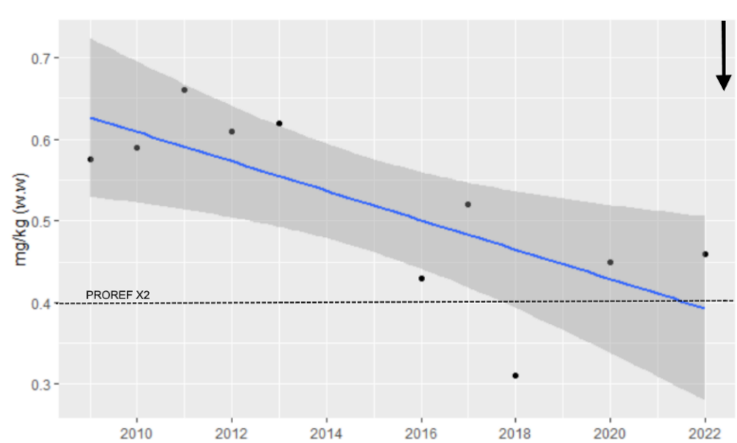

Lead in blue mussel soft body, Myrodden




Lead in blue mussel soft body, Odderøya




Lead in blue mussel soft body, Svensholmen




Lead in blue mussel soft body, Timlingen

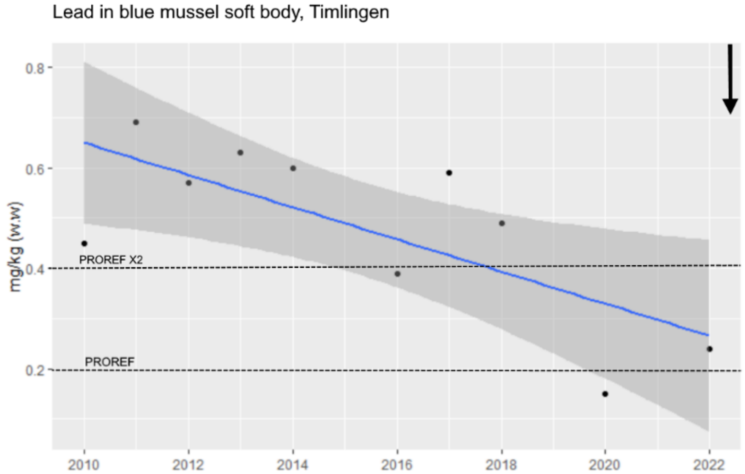


**Figure 11: Time trends for lead in blue mussel soft body at different stations with PROREF (Norwegian provisional high reference contaminant concentration). Concentrations are plotted with dots, a 95% confidence interval in grey and a trend line in blue. Arrows (↓ or ↑) show significant trend, circle (○) shows no significant trend.**

There has been a significant decline at stations Svensholmen and Timlingen, there has been no significant change at the other stations. The concentration of lead has recently exceeded PROREF x2 at all stations, with Timlingen as an exception where the concentration in 2022 was close to PROREF. The recent measurements at Odderøya have been close to PROREF x10.

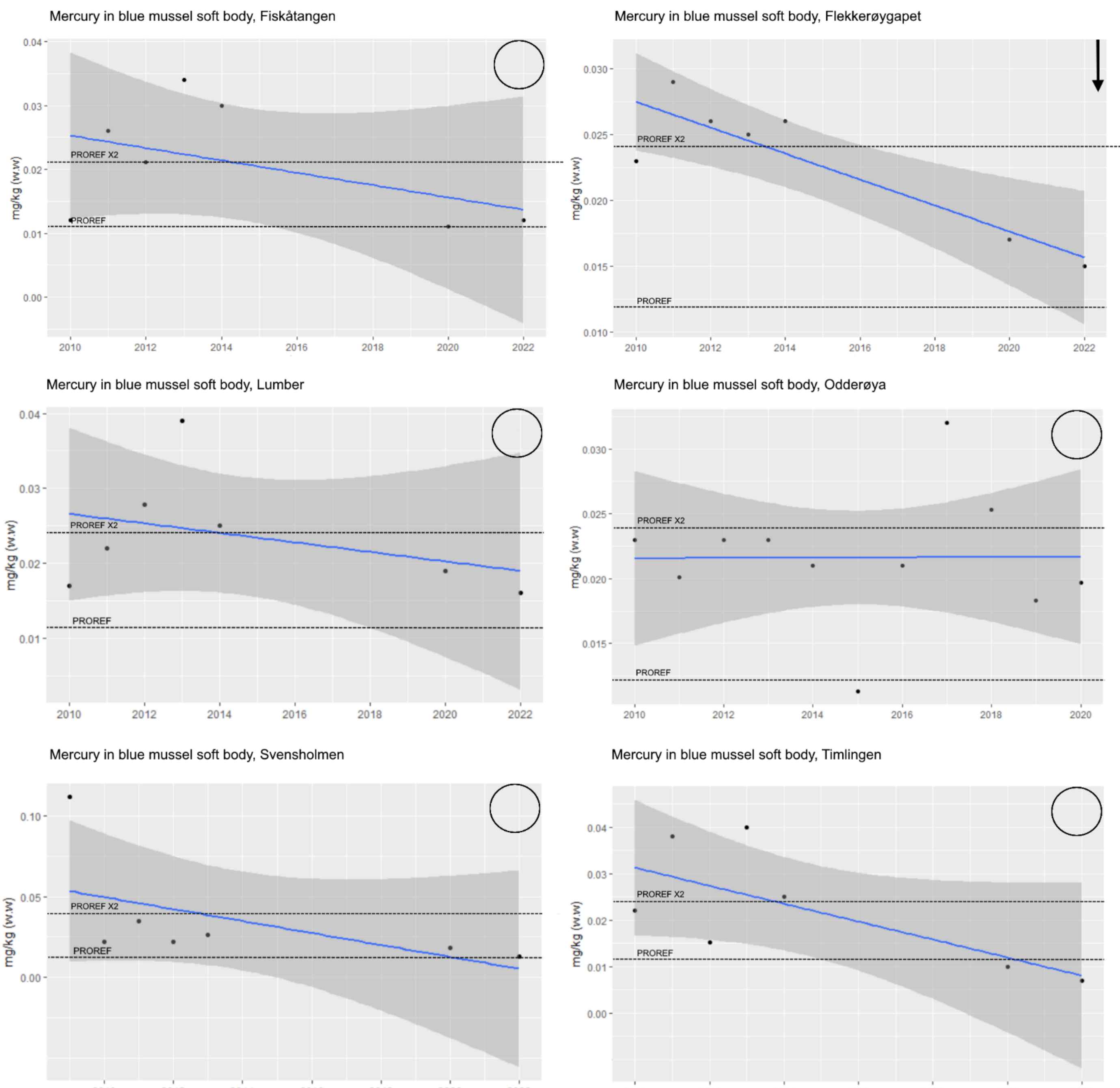
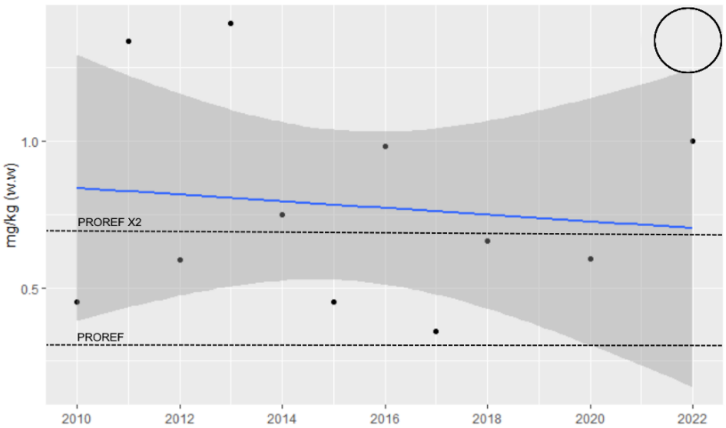


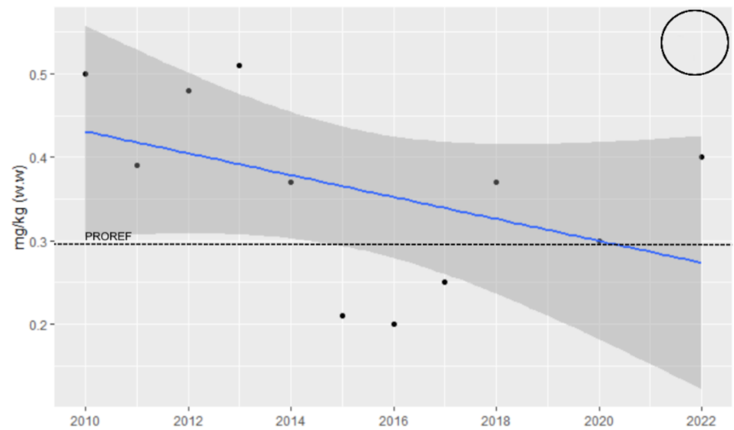
**Figure 12: Time trends for mercury in blue mussel soft body at different stations with PROREF (Norwegian provisional high reference contaminant concentration). Concentrations are plotted with dots, a 95% confidence interval in grey and a trend line in blue. Arrows (↓ or ↑) show significant trend, circle (○) shows no significant trend.**

There has been a significant decline at station Flekkerøygapet, there has been no significant change at the other stations. The measurements have all been between PROREF and PROREF x2, except for Timlingen where concentrations were below PROREF.

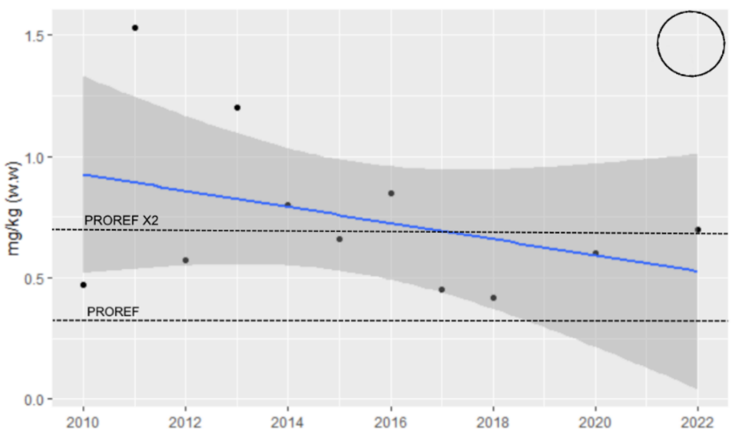
Nickel in blue mussel soft body, Fiskåtangen



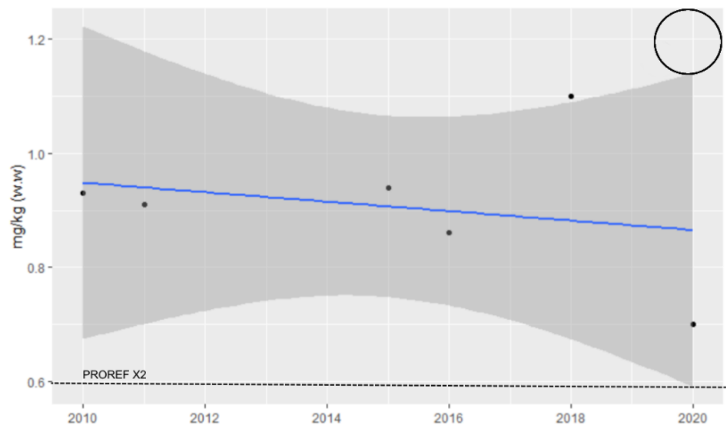

Nickel in blue mussel soft body, Flekkerøygapet



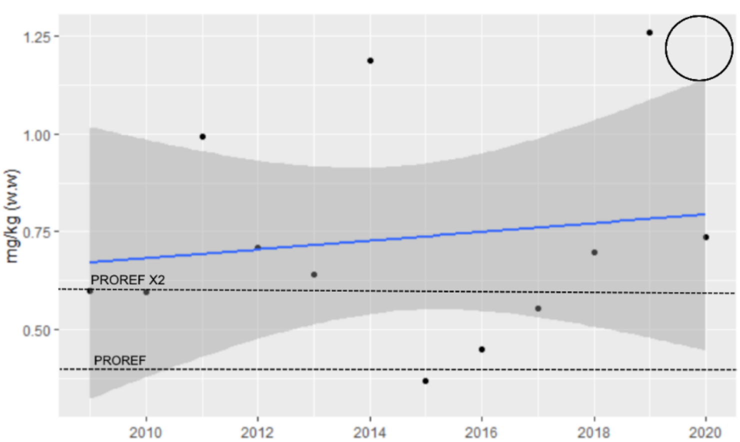

Nickel in blue mussel soft body, Lumber



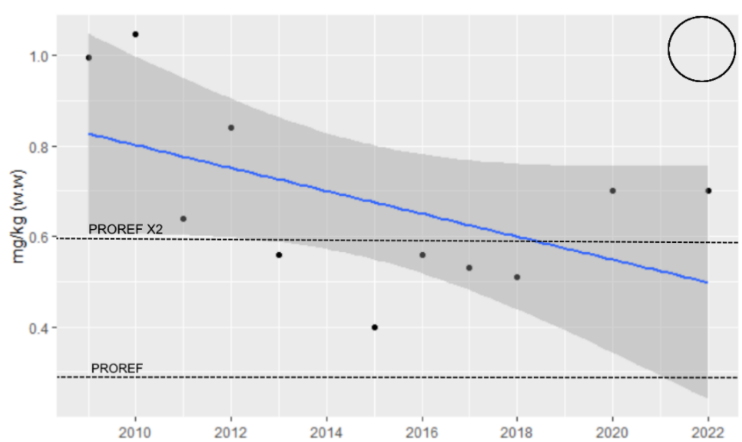

Nickel in blue mussel soft body, Myrodden




Nickel in blue mussel soft body, Odderøya




Nickel in blue mussel soft body, Svensholmen




Nickel in blue mussel soft body, Timlingen

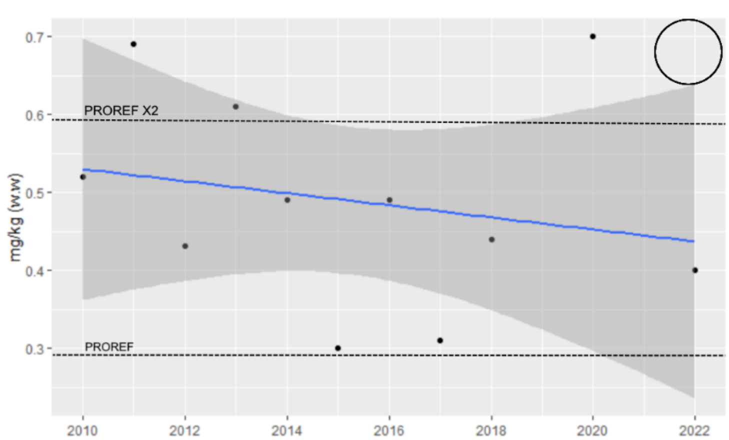
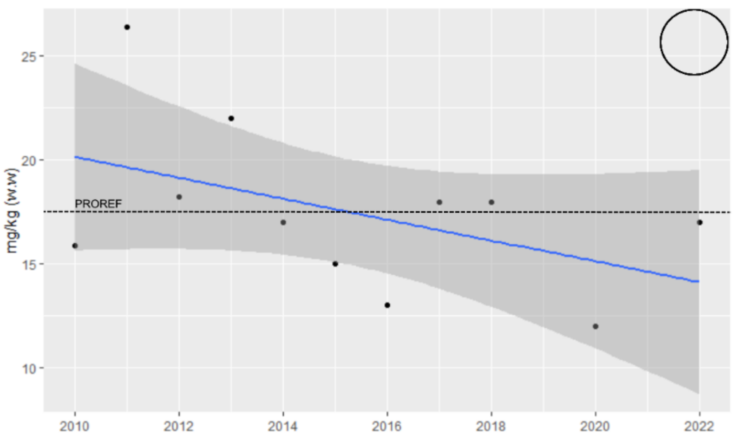


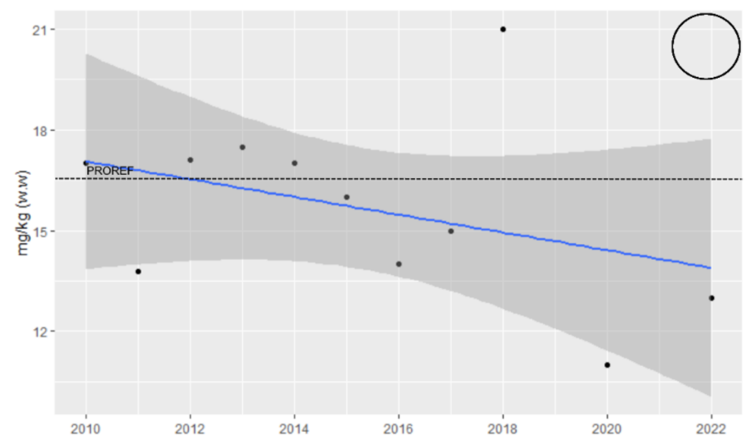
**Figure 13: Time trends for nickel in blue mussel soft body at different stations with PROREF (Norwegian provisional high reference contaminant concentration). Concentrations are plotted with dots, a 95% confidence interval in grey and a trend line in blue. Arrows (↓ or ↑) show significant trend, circle (○) shows no significant trend.**

There have been no significant changes at either of the stations. All stations had recent measurements exceeding PROREF x2, except for Flekkerøygapet and Timlingen where measurements exceeded PROREF.

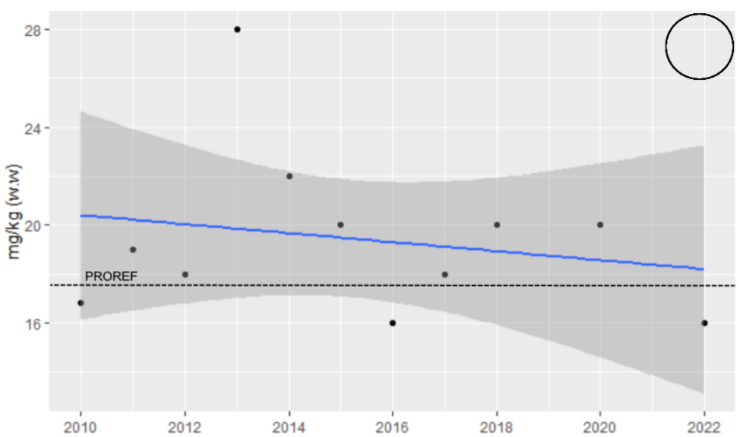
Zinc in blue mussel soft body, Fiskåtangen



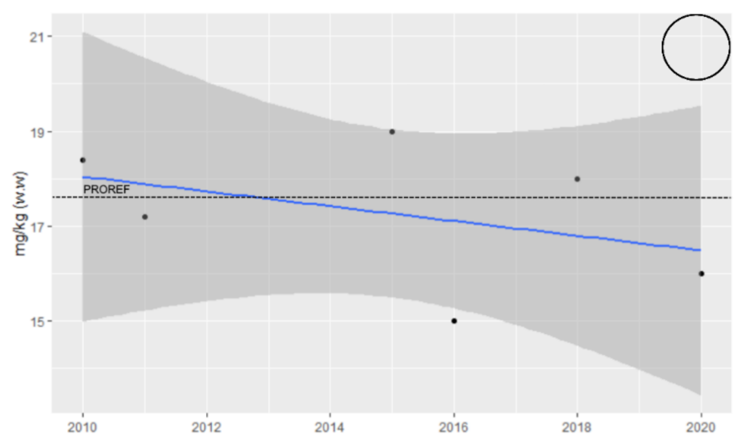

Zinc in blue mussel soft body, Flekkerøygapet



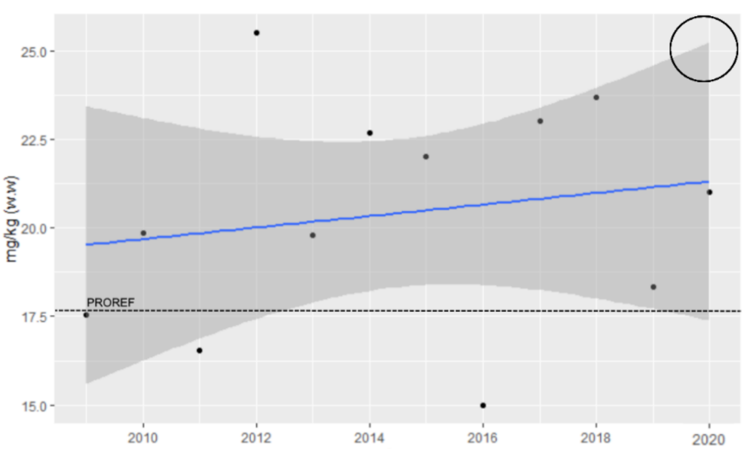

Zinc in blue mussel soft body, Lumber



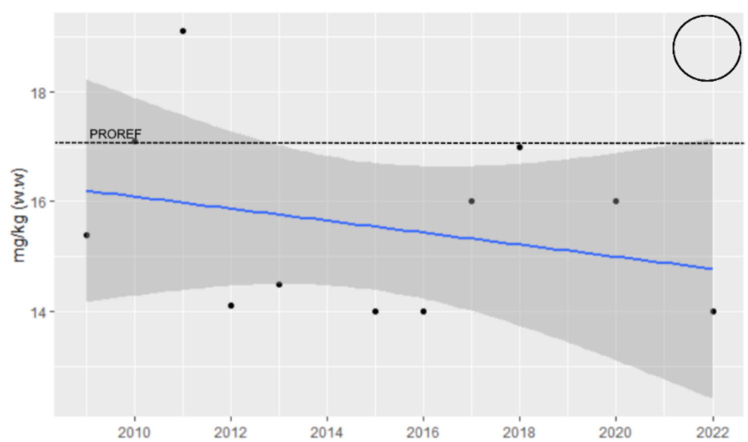

Zinc in blue mussel soft body, Myrodden




Zinc in blue mussel soft body, Odderøya




Zinc in blue mussel soft body, Svensholmen




Zinc in blue mussel soft body, Timlingen

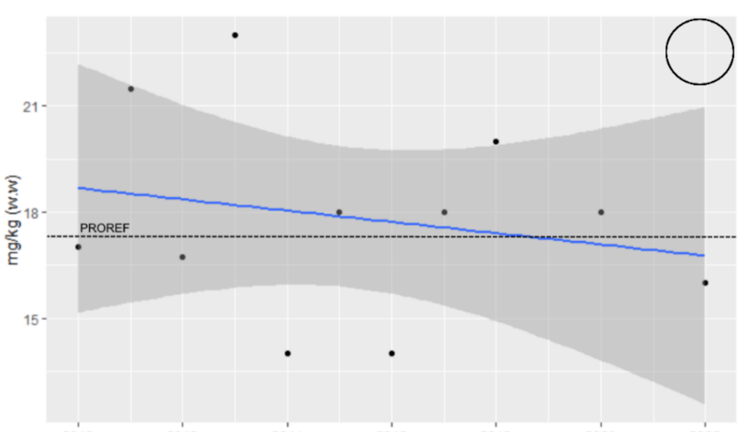


**Figure 14: Time trends for zinc in blue mussel soft body at different stations with PROREF (Norwegian provisional high reference contaminant concentration). Concentrations are plotted with dots, a 95% confidence interval in grey and a trend line in blue. Arrows (↓ or ↑) show significant trend, circle (○) shows no significant trend.**

There have been no significant changes at either of the stations. All the stations had the most recent measurements below PROREF except for Odderøya where all measurements were above PROREF.

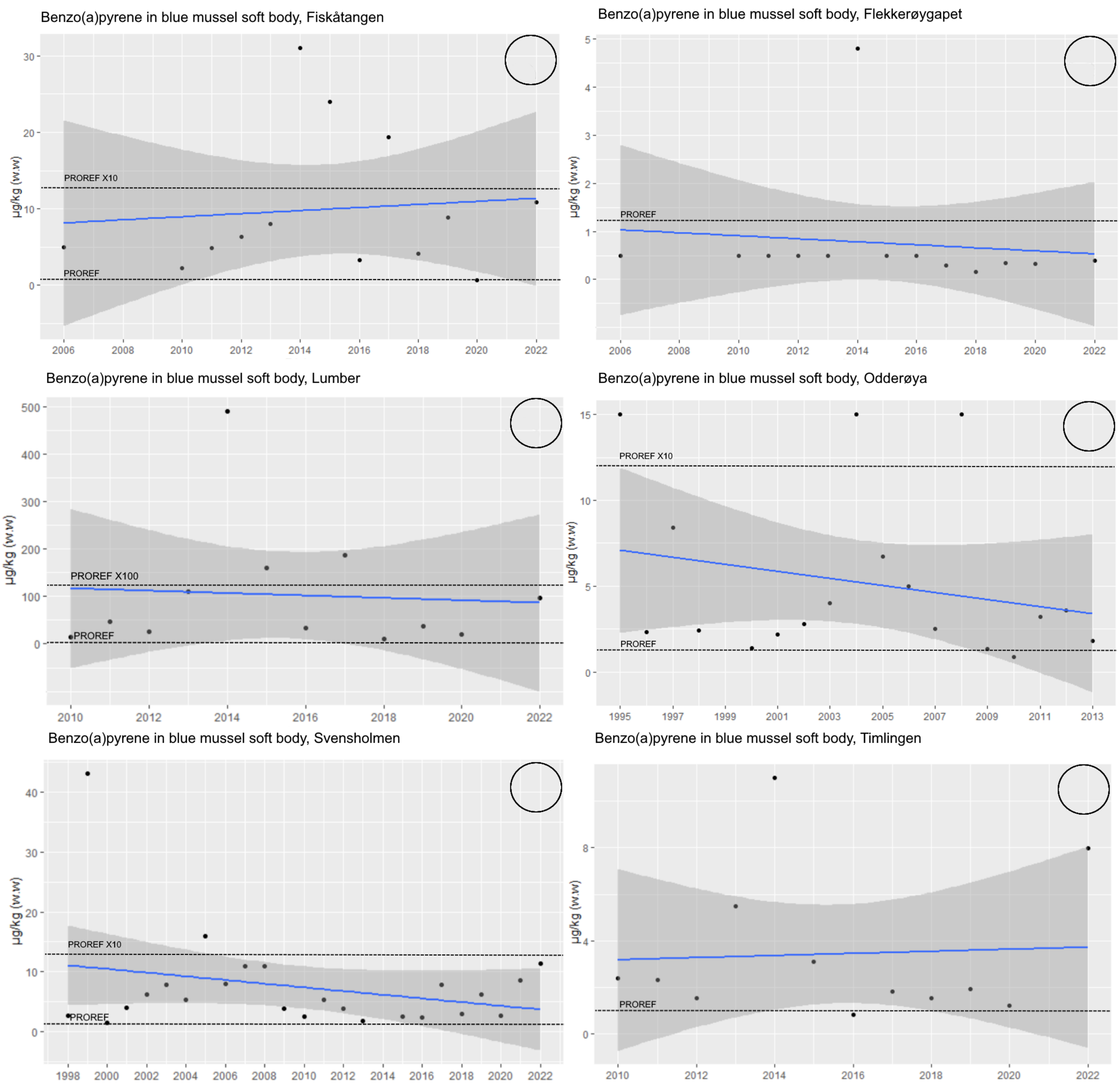


**Figure 15: Time trends for benzo(a)pyrene in blue mussel soft body at different stations with PROREF (Norwegian provisional high reference contaminant concentration). Concentrations are plotted with dots, a 95% confidence interval in grey and a trend line in blue. Arrows (↓ or ↑) show significant trend, circle (○) shows no significant trend.**

There have been no significant changes at either of the stations. All stations had high values of benzo(a)pyrene, all above PROREF. Fiskåtangen, Odderøya and Svensholmen had values between PROREF and PROREF x10, Lumber had values between PROREF and PROREF x100. Timlingen was the only station where measurements were close to, yet exceeding PROREF.

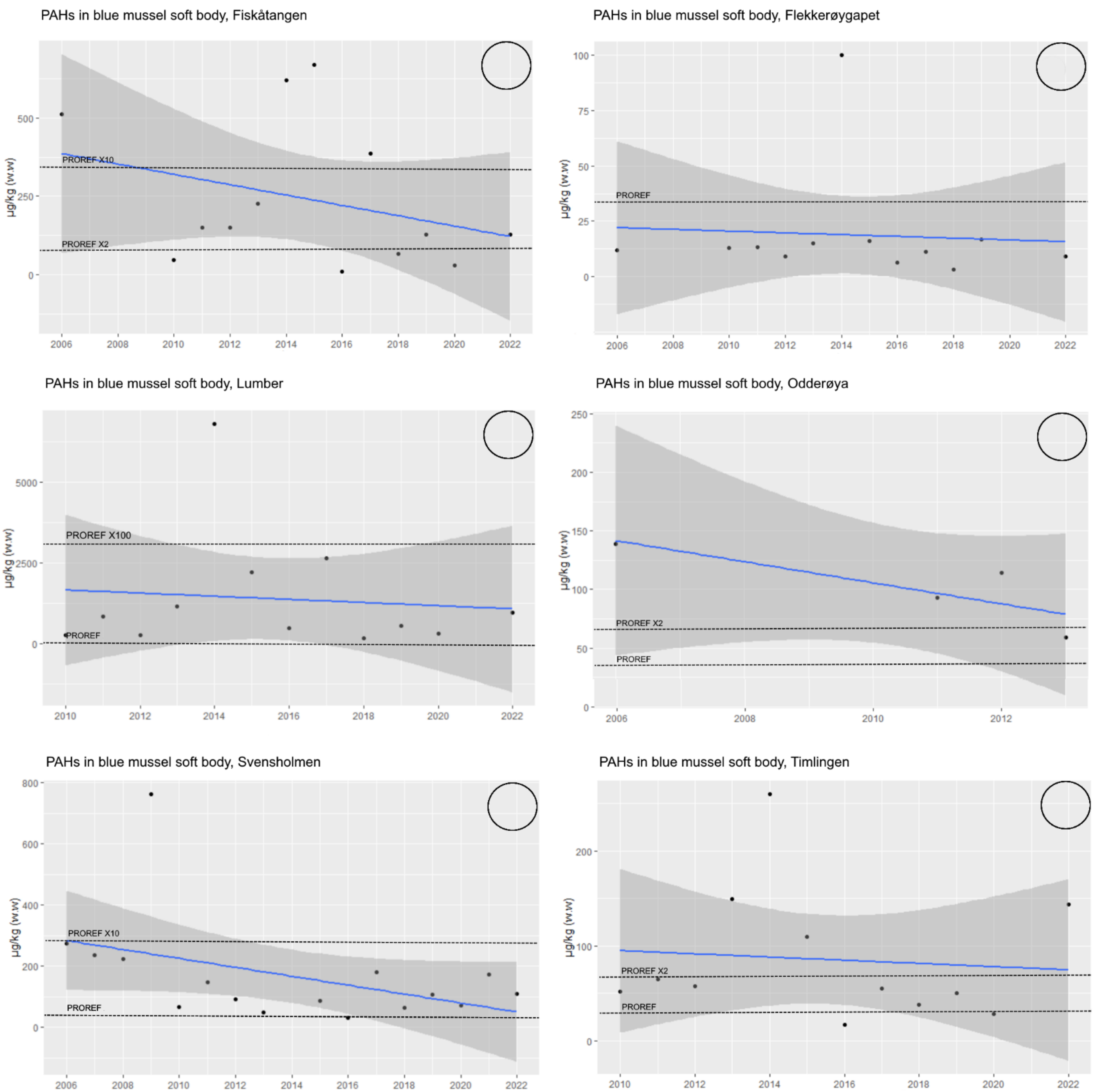


**Figure 16: Time trends for PAH-16 in blue mussel soft body at different stations with PROREF (Norwegian provisional high reference contaminant concentration). Concentrations are plotted with dots, a 95% confidence interval in grey and a trend line in blue. Arrows (↓ or ↑) show significant trend, circle (○) shows no significant trend.**

There have been no significant changes at either of the stations. All the stations had measurements well above PROREF, except for Flekkerøygapet which had values below PROREF.

To summarize, there have been significant declines at Lumber (arsenic), Svensholmen (arsenic, cadmium, chromium and lead), Timlingen (arsenic, cadmium, chromium and lead) and Flekkerøygapet (mercury). Otherwise, there have not been any significant changes, or increases in concentrations in blue mussels. Most of the measurements lay below PROREF for heavy metals arsenic, cadmium and chromium, however, station Odderøya had concentrations exceeding PROREF for these contaminants. Recently, most of the stations had concentrations of copper and zinc below PROREF. For copper, Myrodden and Odderøya had exceeding PROREF levels however, and for zinc, Odderøya had measurements above PROREF. Heavy metals lead, mercury and nickel exceeded PROREF at most stations. Lead concentrations exceeded PROREF x2 at all stations and approaching PROREF x10 at Odderøya. All stations had nickel concentrations exceeding PROREFx2. All stations exceeded PROREF for benzo(a)pyrene, where Fiskåtangen, Odderøya and Svensholmen had values between PROREF and PROREF x10 and Lumber had values between PROREF and PROREF x100. For PAHs, all the stations had measurements well above PROREF, except for Flekkerøygapet which had values below PROREF.

# 4. Discussion

The Kristiansandfjord has been contaminated for several decades. In 1985, it was documented that the fjord was polluted, supposedly due to industrial discharges (Green et al., 1985), and the fjord was still polluted in 2007 according to Berge et al., 2007. The aims of this study were to describe time trends for concentrations of contaminants in blue mussels in several stations in the Kristiansandfjord, as well as comparing these stations. Additional aims were to determine the environmental condition and chemical status at locations in the fjord, and to assess the degree of pollution. This will be done by discussing several discharge sources, such as local industry companies. Data on contaminant discharges from industrial companies Elkem Carbon, Glencore Nikkelverk and REC Solar were available, however, it was somewhat deficient (see Tables 3-5). Tables 3-5 show that most contaminants seem to have had a decrease in discharges in recent years from all three companies. The concentrations of contaminants in blue mussels have mainly remained the same throughout the investigated years (mainly 2010-2022), even though industrial discharges were reduced, and sediment remediation actions were implemented. Therefore, further monitoring is necessary.

## 4.1 Development of contaminant concentrations in blue mussel

There have been only a few significant changes in concentrations of contaminants in blue mussels at stations in the Kristiansandfjord (see Figures 7-16). Nevertheless, some significant declines of contamination in blue mussels were found. There were significant declines at Lumber (arsenic), Svensholmen (arsenic, cadmium, chromium, and lead), Timlingen (arsenic, cadmium, chromium, and lead) and Flekkerøygapet (mercury). The monitoring stations Timlingen and Svensholmen, which assumingly cover the influence area from Elkem Carbon and REC Solar (Øxnevad et al., 2021), both showed significant declines of several heavy metals in blue mussels. This may be explained by the reduced discharges by the companies (see Tables 3-5). On the other hand, such significant declines were not observed at Fiskåtangen, also a monitoring station, and it is unsure why. Blue mussels at the outermost station Flekkerøygapet showed a significant decline in mercury. Because this is a reference station, it is not expected to find any changes in concentrations, yet it did. A possible explanation for this can be related to Bredalsholmen wastewater treatment plant. There was namely a decline in mercury discharges from

Bredalsholmen wastewater treatment plant (see Table 8). Further, several contaminants had a downwards tendency even though they did not have a significant trend. This may indicate that reduced industrial discharges have contributed to significant declines in contaminant concentrations in the Kristiansandfjord, and further declines in contaminant levels may happen in the future.

Several measures have been implemented to improve the environmental conditions in the Kristiansandfjord (see Table 6). Among others, sediment remediation actions have been implemented and completed at five different locations in 2003-2010 (Norwegian Environment Agency, 2023b). Whether this has contributed to improved environmental conditions in the fjord, and to what degree, is not entirely clear. On the one hand, it can be argued that these measures have not or only to a small degree contributed to improved conditions in the fjord. It cannot be excluded that the sediment remediation actions implemented in 2003-2010 unintentionally could have caused contamination of sediments. When there is no control of the contents in the capping sediment, recontamination may happen. In addition, dredging has been carried out (Norwegian Environment Agency, 2023b) which may have caused contamination of sediments. This may have been the case at Hannevika in the innermost part of the Kristiansandfjord in 2012, where contaminated sludge covering the capping sediment was found after dredging (Laugesen et al., 2016). If heavy metals are resuspended, the restoration, remediation, and management of contaminants in the area may be hindered (Friedman et al., 2009), because the Kristiansandfjord has historical contamination (Green et al., 1985). Contaminated sediment can be a cause of future toxicity (Frid & Caswell, 2017), possibly also in blue mussel. In addition, heavy metals can have significant environmental consequences because of biomagnification (Mishra et al., 2019), and despite restauration efforts, consequences can be substantial and long lasting (Pan & Wang, 2012). On the other hand, it may be argued that the implemented measures may have contributed to an improved environmental condition in the fjord, because there were some significant reductions, however, results are yet to be identified. Because of biomagnification and bioaccumulation of contaminants, it may take a substantial amount of time until results can be detected. The sediment remediation actions in 2003-2010 were implemented in a few small areas only (Norwegian Environment Agency, 2023b), thus much work remains.

Contaminant concentrations in blue mussel have mostly remained the same. This may be explained by the fact that environmental consequences from biomagnification (Mishra et al. 2019), can be substantial and long lasting (Pan & Wang, 2012). Another consideration is that old blue mussels with old contamination may have been sampled, thus resulting in blue mussels containing more or less the same concentration of contaminants. Other sources of contamination (see section 2.27) are additional factors. While there is available data from industrial discharges and discharges from wastewater treatment plants, data for other sources of contamination (such as contaminated soil, urban runoff, erosion of sediment from ship propellers, and unintentional recontamination) are deficient. For this reason, it is very complex to assess where the contamination comes from. Although, data from increased port activity (see Table 10), may help explain higher contaminant concentrations in the fjord in 2022, because ship propellers from large ships may cause erosion of sediment. Additionally, increased riverine inputs from Otra (see Table 7) could be considered to affect recent contaminant concentrations. Increased runoff of contaminated sediments from land because of climate change is another consideration (McGovern et al., 2022). Discharges from other industries, contaminated soil around the Kristiansandfjord (see Figure 2), and road traffic may be additional contributing factors to few significant declines in contaminant concentrations, however, these are merely speculations as data from these sources are deficient.

In the report from 2021 (Øxnevad et al., 2021), there were found significant downwards trends for arsenic, cadmium, chromium, copper, lead, nickel, and zinc at four out of five locations (Fiskåtangen, Flekkerøygapet, Lumber and Timlingen). However, the present study found that this report used incorrect values in their data collection. Before 2015, values for blue mussel contaminant concentrations were from dry weight, and from 2015 values were from wet weight. Values of contaminant concentrations in dry weight are significantly higher than those in wet weight and cannot be compared in the same time series. That is why the conclusions regarding significant downwards trends for the heavy metals in blue mussels from that report can be discarded.

## 4.2 Comparing different locations in the Kristiansandfjord

### Blue mussel

The concentration of arsenic, mercury and zinc in blue mussels was generally the same at each station (see Appendix B). Odderøya had high concentrations of contaminants. This station had the highest concentration of lead, a high chromium concentration in the year 2019, and a slightly higher cadmium and nickel concentration compared to the other stations. Lumber also had elevated contaminant concentrations and had the highest measured amounts of benzo(a)pyrene and PAHs. Because Lumber lies near to Elkem Carbon, it is expected to find high concentrations of PAHs there, since Elkem Carbon is a dominating discharge source of PAHs (Hindar, 2018), also, the seabed outside Elkem Carbon is contaminated, mainly linked to PAH (Olsen et al., 2018). Myrodden also had higher concentrations of copper and nickel compared to other stations. This is expected, as Myrodden is the nearest station to Glencore Nikkelverk, which is a dominating source of copper and nickel discharges into the fjord (Hindar, 2018). High nickel concentrations may also be connected to excessive nickel discharges from REC Solar in 2022. After an inspection by the Norwegian Environment Agency, the company received a notice with a payment (The Norwegian PRTR, 2023e). Similarly, Fiskåtangen had a high concentration of copper. Hence, it can be argued that blue mussels at Odderøya were the most polluted, followed by Lumber, Myrodden and Fiskåtangen. This is expected, as they all are near discharge sources. Station Odderøya should not be influenced by the companies' discharges (Schøyen & Håvardstun, 2017), however, it is located near Odderøya wastewater treatment plant, whose contaminant concentrations generally seemed to have remained the same (see Table 9). This may be the cause of the high contaminant concentrations, as well as the lacking significant declines in contaminants in blue mussels. It may be argued that contamination at Odderøya will increase in the future, because of construction. Due to the future shutdown of Bredalsholmen wastewater treatment plant, the wastewater will be transferred to Odderøya wastewater treatment plant through a pipe, and will be discharged there (Kristiansand municipality, 2023). In addition, a new neighborhood, Kanalbyen, is under construction and will be located on the seaside at Odderøya (Kanalbyen, 2023). Because Flekkerøygapet is a reference station at a distance from discharge sources, it may be expected that blue mussels there had the lowest concentrations of contaminants. The benzo(a)pyrene and PAHs concentrations were much lower compared to other stations, however, the heavy metal concentrations were not notably lower. It is not clear why, but it may partly be explained by discharges from Bredalsholmen wastewater treatment plant. Measuring contaminants in the sediment at Flekkerøygapet would provide more information on where the heavy metals could come from; i.e. local vs. long-range transport.

### Sediment

The stations K17, ES1 and ES2 had the highest concentrations of contaminants (see Figure 6). K17 had the highest zinc concentration, ES1 and K17 were the highest in lead, and they all had the highest arsenic and copper concentrations. Additionally, there were exceptionally high concentrations of benzo(a)pyrene and PAHs at ES1 in 2010, and similarly, ES2 and K17 had high concentrations of PAHs. These three stations are the stations that are the nearest to Elkem Carbon and REC Solar. It may therefore be argued that these companies have had a strong impact on contaminants in the sediment at those locations, besides, K17 is considered to reflect the impact of contaminants (Øxnevad et al., 2021). Also, it is expected to find high concentrations of PAHs at stations close to Elkem Carbon, as earlier mentioned. The contaminant concentrations at stations K18, KH03 and X12 seemed to be lower compared to other stations. This is reasonable, since stations K18 and X12 lie at a considerable distance from the discharge sources (Schøyen et al., 2021), and the station KH03 has the longest distance from discharge sources (Øxnevad et al., 2021). It might have been expected to find higher concentrations of copper and nickel at station X12 since this is the station nearest to Glencore Nikkelverk, a dominating source of these heavy metals (Hindar, 2018).

## 4.3 Environmental condition and chemical status

### Environmental condition in sediment

The cadmium, chromium and mercury concentrations were low enough to result in «background» and «good» environmental class, therefore, it might be expected that the sediment, its biota and the ecoystem as a whole might be protected from the adverse effects these heavy metals have. Mercury and cadmium are two of the most toxic metals in marine ecosystems (ATSDR, 2013, Frid & Caswell, 2017), so it might be crucial these heavy metals had low concentrations. Most sediments had lead and zinc concentrations leading to «good» environmental condition, as a result, it might be argued that the ecosystems are protected from their toxicity. The arsenic concentrations, in contrast, resulted in «moderate», and «poor» environmental conditions. This means the ecosystem may have chronic effects from long-term exposure, and acute toxic effects from short-term exposure of arsenic, if it is inorganic arsenic. Also, the nickel concentrations were high, resulting in «moderate», to «very poor» environmental conditions. For that reason, the environment at the stations with the highest concentrations may have comprehensive toxic effects of nickel, since elevated levels of nickel in marine ecosystems may lead to toxic effects to organisms (Binet et al., 2018; Gissi et al., 2016). Further, the contaminants copper, benzo(a)pyrene and PAHs classified mostly all stations as having «very poor» conditions. This means that the ecosystems might have comprehensive toxic effects of these contaminants. This is concerning, because copper is toxic to aquatic organisms (Clarke, 1997; Grosell et al., 2007), causing membrane damage, inactivation of enzymes and cell death (Hegedus et al., 2001; Nagarani et al., 2012). In addition, benthic colonization might be significantly reduced or altered because of high copper concentrations (Olsgard, 1999; Trannum et al., 2004). Further, organism health might be strongly affected because of benzo(a)pyrene and other PAHs (Patel et al., 2020). PAHs are carcinogenic (Patel et al., 2020), therefore, the high concentrations in sediments in the fjord are cause for concern.

### Chemical status sediment

Of the priority substances, cadmium and mercury concentrations lay below EQS at all stations in 2020 (see Table 13), and the lead concentration exceeded EQS at one station only. By contrast, nickel and benzo(a)pyrene concentrations were above EQS at all stations, resulting in all stations having contaminants beyond the limits of EQS and classified as having «not good» chemical status. This means that contaminant concentrations might not be near background levels of naturally occurring substances in sediments in the Kristiansandfjord. Yet, the chemical status of stations K18 and X12 is based on two contaminants only, where nickel is the one contaminant to exceed EQS. Of the river basin specific pollutants, chromium concentrations lay well below EQS at all stations in 2020 (see Table 14), however, arsenic and copper concentrations were above EQS at all stations, resulting in all stations exceeding EQS limits. As a result, the ecological status at all stations might be affected.

### Chemical status blue mussel

All stations except Flekkerøygapet had concentrations above EQS limits (see Table 15) and therefore classified as having «not good» chemical status. Because Flekkerøygapet is a reference station at a considerable distance from industry discharges, this could be expected. The benzo(a)pyrene concentrations lay well above EQS at all stations except Flekkerøygapet. Because benzo(a)pyrene is carcinogenic (Patel et al., 2020), high concentrations in blue mussels are cause for concern. The mercury concentrations in blue mussels were below EQS at all stations except Odderøya. This is good, since mercury generally is thought to be the most toxic metal in marine ecosystems (ATSDR, 2013; Frid & Caswell, 2017). However, the mercury concentration in blue mussels at Odderøya in 2020 was remarkably high. This might cause concern for fish at that location, since mercury exposure can affect liver function, behavior, reproduction, gill function and lead to mortality (Huang et al. 2011; O'Bryhim et al. 2017), and it is possible this is the case for cod in the Kristiansandfjord. For instance, in a study from 2022, mercury concentrations in cod filet samples showed significant short term and long term upward trends (Schøyen et al., 2022). The exceeding limits of EQS in blue mussels are concerning, because they may contribute to deleterious effects in higher trophic organisms feeding on blue mussels (Direktoratsgruppen vanndirektivet, 2018).

To summarize, all sediment stations had contaminant concentrations leading to «very poor» environmental condition, all sediment stations had contaminants exceeding EQS limits, all sediment stations had «not good» chemical status, and most blue mussel stations had «not good» chemical status. Nevertheless, there is no good correlation between chemical status and ecological status (Oug et al., 2013). This was found in a study where contamination at sites in industrial fjords, including the Kristiansandfjord, were investigated (Oug et al., 2013). While chemical status is determined from the risk of contaminants on effects on organisms, ecological status is assessed by changes in the composition of bottom fauna (Oug et al., 2013). In other words, the bottom fauna state may be good despite poor chemical status. In fact, the bottom fauna state was classified as good in Fiskåtangen in 2012 despite having «not good» chemical status (Schøyen et al. 2012).

## 4.4 Pollution assessment

The pollution assessment is based on PROREF (Norwegian provisional high reference contaminant concentration) according to Schøyen et al., 2022. All blue mussel stations had contaminants exceeding PROREF (see Table 16), and all stations may therefore be considered polluted.

Arsenic and chromium had concentrations below PROREF at all stations, suggesting the Kristiansandfjord may not be polluted with these contaminants. Similarly, cadmium and zinc did not exceed PROREF at either of the stations, except for Odderøya, where the excess was slight. This suggests that the Kristiansandfjord might be polluted with cadmium and zinc to some degree. Cadmium pollution may not be especially problematic, and e.g. molluscs can accumulate cadmium with no obvious adverse effects (Frid & Caswell, 2017), and it is shown that cadmium has little effect on benthic colonization (Trannum et al., 2004). On the other hand, cadmium causes toxicity at low concentrations (Andersen et al., 1996; Azeh Engwa et al., 2019). So, the exceeding PROREF level at Odderøya may be a cause for concern. Zinc pollution may also be challenging, because excess zinc oxide can cause growth inhibition and mortality in marine organisms (Yung et al., 2014), though it is essential for plants (Sturikova et al., 2018), and animals (Martelli et al., 2006). Since the exceeding PROREF level of zinc is minor, the ecosystem at station Odderøya might not be affected by zinc. Copper, on the other hand, went beyond PROREF at Fiskåtangen, Myrodden and Odderøya, and concentrations were between PROREF and PROREFx2, so the Kristiansandfjord may be polluted with copper. Mercury also went beyond PROREF at several stations, namely Lumber, Odderøya, Svensholmen and reference station Flekkerøygapet. The fjord may therefore be considered polluted with mercury. This is a concern, since mercury can affect liver function, behavior, reproduction, gill function and lead to mortality (Huang et al., 2011; O'Bryhim et al., 2017). Mercury concentrations were high both near and far from discharge sources, because Flekkerøygapet and Svensholmen both lie at a considerable distance from industry discharges. Furthermore, PAHs including benzo(a)pyrene exceeded PROREF at Fiskåtangen, Lumber, Odderøya and Svensholmen, suggesting the fjord may be polluted with these contaminants. Benzo(a)pyrene concentrations were near PROREFx100 at Lumber and PROREFx10 at Svensholmen (see Figure 14). PAHs were notably higher than PROREF at Fiskåtangen, Lumber, Svensholmen and Timlingen (see Figure 15). The towering levels of PAHs are especially concerning because of their toxicity, as mentioned earlier. Lastly, lead and nickel exceeded PROREF at all measured stations, so the fjord may be considered polluted with these heavy metals. This is also problematic, as lead is often associated with toxicity in benthic organisms (Ringenary et al., 2007), and elevated levels of nickel in marine ecosystems may lead to toxic effects to organisms (Binet et al., 2018; Gissi et al., 2016). To summarize, the Kristiansandfjord is polluted with the contaminants cadmium, copper, mercury, lead, nickel, zinc and PAHs including benzo(a)pyrene, while toxic effects from arsenic and chromium are not likely. It is therefore reasonable that it is advised against eating blue mussels from the fjord (Norwegian Environment Agency, 2023a).

Although the Kristiansandfjord is polluted with several contaminants, their toxicity depends on several factors such as water temperature, salinity, oxygen, grain size and organic content (Frid & Caswell, 2017; Trannum et al., 2023). In sediments, the toxicity of contaminants depends on in which form they occur. Many contaminants, for instance PAHs, are often particle bound, making them less bioavailable (Ruus et al., 2015). Because toxicity is affected by water temperature (Frid & Caswell, 2017), climate change is an additional stressor. Toxicity also depends on biological factors such as age, gender and genetics of individuals (Tchounwhou et al., 2012). In addition, toxicants may have different impacts when in mixtures (Cedergreen, 2014), and the fjord might be subject to cocktail effects and synergetic interactions between contaminants. Furthermore, some organisms may have obtained tolerance to contaminants after chronic exposures (Frid & Caswell, 2017). For this reason, the actual toxicity the contaminants have and their effects on the ecosystem in the fjord is uncertain. It may be argued that contamination does not directly translate to less life in the fjord. As previously mentioned, there is no good correlation between chemical status and ecological status, and the responses of contaminants on bottom fauna are very complex (Oug et al., 2013).

## 4.5 How the findings in this study can be related to other marine ecosystems

The fact that there were only a few significant downward trends in contaminants in blue mussels in the Kristiansandfjord, may be transferred to other fjords, in Norway or other countries. When a fjord has received contaminant discharges from industry or other sources, and has for several decades, it may take a substantial amount of time to reduce contaminant concentrations in that fjord. Regarding this, further research is necessary. Still, this may apply to other types of coastal ecosystems as well, such as estuaries, mangroves, coral reefs, and open ocean. Many of the planet’s cities are coastal, and since urban areas contribute to discharges of contaminants into the sea (Angrill et al., 2017), it may be argued that the ecosystems outside coastal cities may have perpetual contamination. In the Kristiansandfjord, the stations nearest to industrial discharges had the highest contamination concentrations, and this may apply to other urban areas as well. This should be a consideration in urban planning, as it may be crucial to marine ecosystems. One may discuss whether new industries should be placed at locations which are already contaminated, to prevent other locations from being contaminated. One may consider whether new industry should be placed along marine ecosystems at all.

Since the Kristiansandfjord is polluted with various contaminants, several risks from the contaminants to living organisms apply. Even though the actual toxicity is uncertain, and there is no correlation between chemical status and ecological status (Oug et al., 2013), risks from contaminants may occur in other coastal ecosystems as well.

The findings from this study suggest that one cannot simply discharge contaminants on a long-term basis into marine ecosystems and expect contaminant concentrations to reduce when discharges are reduced. High contaminant concentrations may be irreversible in the short term. To reduce contaminant concentrations in marine ecosystems, it may be crucial to reduce discharges, and in time, one will hopefully see improvements in contaminant concentrations. This knowledge is important for urban planning, placement of new industry, for those who work for the improvement of environmental conditions in fjords, and ultimately for marine ecosystems, and for life on the planet as a whole.

## 4.6 Sources of error

The amount of blue mussel contaminant data selected from spring months as opposed to fall months, may have had a slight influence on the results. In addition, data plotting errors may have occurred.

## 4.7 Limitations and suggestions for further studies

This present study utilized one type of statistic test only. For further studies, other statistical analysis could provide increased understanding of the development of contaminants in the Kristiansandfjord. Multivariate statistics could have been used to study similarities between stations and discharges to get more insight about discharge sources. Further, a larger data set of concentrations of contaminants in blue mussels, including older data, could provide other significant trends. Therefore, future studies should include blue mussel contaminant concentrations in the following years. This study did not discuss which contaminant concentrations organisms tolerate, or what can be expected in terms of biodiversity and fitness in the fjord in the future if the current state does not improve. These can be interesting topics for further studies.

# 5. Conclusion

This thesis has collected available data on contaminant concentrations in blue mussels and sediments and described time trends for concentrations of contaminants in blue mussels at several stations in the Kristiansandfjord. Blue mussel and sediment stations located at different distances from contaminant discharge sources were compared. The environmental condition and chemical status at locations in the fjord were determined, and a pollution assessment was applied. This has been discussed in light of discharges from local industry, as well as other sources of contamination, and sediment remediation actions. Possible causes for concentration levels and time trends have been discussed.

The Kristiansandfjord has had high concentrations of contaminants for several decades (Green et al., 1985; Berge et al., 2007; Øxnevad et al., 2021). In this fjord, concentrations of contaminants in blue mussels have with some exceptions remained the same throughout the investigated years (mainly 2010-2022). This implies that contaminant concentrations in the Kristiansandfjord have mainly remained the same, despite reduced industrial discharges and implemented sediment remediation actions. Nevertheless, these measures may have contributed to the reduction of contaminant concentrations in the fjord. Still, it may take a substantial amount of time and effort to reduce contaminant concentrations. The reason why contaminant concentrations in blue mussels have generally remained the same, is not entirely clear, although continued contaminant discharges into the fjord from several sources may help explain this. Contaminant concentrations were the highest at stations near discharge sources in both blue mussel and sediment, still, all sediment stations had contaminant concentrations leading to «very poor» environmental condition. Similarly, all sediment stations had contaminants exceeding EQS limits and had «not good» chemical status. Additionally, most blue mussel stations had «not good» chemical status. The Kristiansandfjord is polluted with cadmium, copper, mercury, lead, nickel, zinc, and PAHs including benzo(a)pyrene, yet their effects on the ecosystem in the fjord are uncertain. Still, the high concentrations of these contaminants are concerning.

These findings may apply to other fjords and other types of marine ecosystems as well. Coastal ecosystems near cities may, like the Kristiansandfjord, have perpetual contamination. It is recommended this should be a consideration during urban planning, also monitoring of contaminants should be continued. The findings from this study are important for those working in urban planning and for the improvement of environmental conditions in fjords and other marine ecosystems, and ultimately for life on the planet overall.

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# 7. Figure and table list

# 8. Appendix A

**Data set of concentrations of contaminants in blue mussels and sediment**

Blue mussels

| Station: Fiskåtangen | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | As | Cd | Cr | Cu | Hg | Ni | Pb | Zn | PAH-16 | B(a)p |
| 2006 | | | | | | | | | 512 | 5 |
| 2010 | 2,48 | 0,149 | 0,2 | 1,48 | 0,012 | 0,45 | 0,21 | 15,9 | 46 | 2,2 |
| 2011 | 1,52 | 0,234 | 0,68 | 1,32 | 0,026 | 1,34 | 0,73 | 26,4 | 150 | 4,9 |
| 2012 | 1,7271 | 0,17271 | 0,09595 | 1,5352 | 0,021109 | 0,59489 | 0,71003 | 18,2305 | 150,574 | 6,35 |
| 2013 | 1,7 | 0,23 | 0,28 | 1,5 | 0,034 | 1,4 | 0,57 | 22 | 227 | 8 |
| 2014 | 1,8 | 0,26 | 0,23 | 1,5 | 0,03 | 0,75 | 1,5 | 17 | 620 | 31 |
| 2015 | 1,8 | | 0,14 | 1,4 | | 0,45 | | 15 | 670 | 24 |
| 2016 | 1,6 | 0,13 | 0,11 | 0,85 | | 0,98 | 0,4 | 13 | 72 | 3,3 |
| 2017 | 1,5 | 0,15 | 0,13 | 1 | | 0,35 | 0,49 | 18 | 386 | 19,4 |
| 2018 | 1,6 | 0,17 | 0,13 | 0,75 | | 0,66 | 0,49 | 18 | 66,3 | 4,18 |
| 2019 | | | | | | | | | 127 | 8,91 |
| 2020 | 1,4 | 0,12 | 0,1 | 1,3 | 0,011 | 0,6 | 0,28 | 12 | 28,7 | 0,67 |
| 2022 | 2,3 | 0,12 | 0,23 | 2 | 0,012 | 1 | 1,1 | 17 | 128 | 10,9 |

| Station: Flekkerøygapet | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | As | Cd | Cr | Cu | Hg | Ni | Pb | Zn | PAH-16 | B(a)p |
| 2006 | | | | | | | | | 12 | <0,5 |
| 2010 | 2,99 | 0,178 | 0,2 | 0,9 | 0,023 | 0,5 | 1,02 | 17 | <13 | <0,5 |
| 2011 | 0,57 | 0,14 | 0,35 | 0,76 | 0,029 | 0,39 | 1,4 | 13,8 | 13,13 | 0,5 |
| 2012 | 2,1 | 0,141 | 0,74 | 0,95 | 0,026 | 0,48 | 1,06 | 17,1 | 9 | <0,5 |
| 2013 | 2,41 | 0,167 | 0,35 | 0,97 | 0,025 | 0,51 | 1,06 | 17,5 | <15 | <0,5 |
| 2014 | 2,2 | 0,27 | 0,2 | 1,2 | 0,026 | 0,37 | 0,52 | 17 | 100 | 4,8 |
| 2015 | 1,7 | | 0,12 | 1 | | 0,21 | | 16 | 16 | <0,5 |
| 2016 | 1,8 | 0,13 | 0,11 | 1,1 | | 0,2 | 0,29 | 14 | 6,2 | <0,5 |
| 2017 | 1,9 | 0,14 | 0,15 | 0,75 | | 0,25 | 0,61 | 15 | 11,1 | 0,297 |
| 2018 | 2,5 | 0,15 | 0,071 | 0,54 | | 0,37 | 0,74 | 21 | 3,16 | 0,154 |
| 2019 | | | | | | | | | 16,7 | 0,335 |
| 2020 | 1,7 | 0,12 | 0,13 | 0,6 | 0,017 | 0,3 | 0,81 | 11 | | <0,323 |
| 2022 | 2,2 | 0,12 | 0,23 | 0,6 | 0,015 | 0,4 | 0,78 | 13 | 9,02 | 0,397 |

| Station: Lumber | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | As | Cd | Cr | Cu | Hg | Ni | Pb | Zn | PAH-16 | B(a)p |
| 2010 | 1,75 | 0,168 | 0,2 | 1,34 | 0,017 | 0,47 | 0,43 | 16,8 | 261 | 14 |
| 2011 | 1,47 | 0,209 | 0,8 | 1,3 | 0,022 | 1,53 | 0,52 | 19 | 835 | 46 |
| 2012 | 1,568 | 0,212 | 0,196 | 1,339 | 0,028 | 0,572 | 1,796 | 17,963 | 260,51 | 26,3 |
| 2013 | 1,5 | 0,3 | 0,28 | 1,4 | 0,039 | 1,2 | 0,79 | 28 | 1148,16 | 110 |
| 2014 | 1,4 | 0,29 | 0,24 | 1,8 | 0,025 | 0,8 | 0,91 | 22 | 6800 | 490 |
| 2015 | 1,5 | | 0,25 | 1,4 | | 0,66 | | 20 | 2200 | 160 |
| 2016 | 1,5 | 0,3 | 0,46 | 1,2 | | 0,85 | 1 | 16 | 470 | 33 |
| 2017 | 1,2 | 0,23 | 0,22 | 1,1 | | 0,45 | 0,37 | 18 | 2640 | 188 |
| 2018 | 1,3 | 0,16 | 0,1 | 0,7 | | 0,42 | 0,22 | 20 | 162 | 10,6 |
| 2019 | | | | | | | | | 542 | 38,1 |
| 2020 | 1,2 | 0,22 | 0,18 | 1,1 | 0,019 | 0,6 | 0,44 | 20 | 314 | 20,9 |
| 2022 | 1,4 | 0,16 | 0,21 | 1 | 0,016 | 0,7 | 0,4 | 16 | 949 | 96 |

| Station: Myrodden | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | As | Cd | Cr | Cu | Hg | Ni | Pb | Zn | PAH-16 | B(a)p |
| 2010 | 1,9 | 0,212 | 0,3 | 1,4 | 0,019 | 0,93 | 0,57 | 18,4 | | |
| 2011 | 1,53 | 0,243 | 0,43 | 1,61 | 0,028 | 0,91 | 0,67 | 17,2 | | |
| 2012 | 1,8 | | | | | | | | | |
| 2015 | 1,7 | | 0,2 | 1,7 | | 0,94 | 0,91 | 19 | | |
| 2016 | 2,1 | | 0,088 | 1,8 | | 0,86 | 0,43 | 15 | | |
| 2018 | 1,8 | | | 0,84 | | 1,1 | 0,45 | 18 | | |
| 2020 | 1,9 | | | 2 | | 0,7 | 0,54 | 16 | | |

| Station: Odderøya | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | As | Cd | Cr | Cu | Hg | Ni | Pb | Zn | PAH-16 | B(a)p |
| 1995 | | | | | | | | | | 15 |
| 1996 | | | | | | | | | | 2,3 |
| 1997 | | | | | | | | | | 8,4 |
| 1998 | | | | | | | | | | 2,4 |
| 2000 | | | | | | | | | | 1,4 |
| 2001 | | | | | | | | | | 2,2 |
| 2002 | | | | | | | | | | 2,8 |
| 2003 | | | | | | | | | | 4 |
| 2004 | | | | | | | | | | 15 |
| 2005 | | | | | | | | | | 6,7 |
| 2006 | | | | | | | | | 139 | 5 |
| 2007 | | | | | | | | | | 2,5 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 2008 | | | | | | | | | | 15 |
| 2009 | 1,835 | 0,214 | 0,355 | 1,27 | | 0,6 | 1,48 | 17,55 | | 1,333 |
| 2010 | 1,78 | 0,210 | 0,4067 | 1,1867 | 0,023 | 0,5967 | 2,863 | 19,87 | | 0,88 |
| 2011 | 1,48 | 0,226 | 0,45 | 2,6067 | 0,0201 | 0,9933 | 2,18 | 16,53 | 93,07 | 3,2 |
| 2012 | 1,9 | 0,211 | 0,18 | 2,21 | 0,023 | 0,71 | 3,88 | 25,5 | <113,92 | 3,6 |
| 2013 | 1,62 | 0,19 | 0,2 | 1,49 | 0,023 | 0,64 | 2,99 | 19,8 | 58,95 | 1,8 |
| 2014 | 1,667 | 0,18 | 0,28 | 1,733 | 0,021 | 1,1867 | 1,243 | 22,667 | | |
| 2015 | 3 | 0,133 | 0,2 | 1,8 | 0,0113 | 0,37 | 3,5 | 22 | | |
| 2016 | 1,4 | 0,273 | 0,13 | 0,91 | 0,021 | 0,45 | 1,5 | 15 | | |
| 2017 | 1,333 | 0,213 | 0,2267 | 1,233 | 0,032 | 0,5533 | 3,2 | 23 | | |
| 2018 | 1,667 | 0,2 | 0,5767 | 0,897 | 0,0253 | 0,6967 | 4,267 | 23,667 | | |
| 2019 | 1,4 | 0,197 | 1,21 | 1,25 | 0,0183 | 1,2567 | 1,7 | 18,333 | | |
| 2020 | 1,467 | 0,217 | 0,3433 | 1,533 | 0,0197 | 0,7367 | 3,867 | 21 | | |

| Station: Svensholmen | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | As | Cd | Cr | Cu | Hg | Ni | Pb | Zn | PAH-16 | B(a)p |
| 1998 | | | | | | | | | 249,7 | 2,7 |
| 1999 | | | | | | | | | 1100,62 | 43 |
| 2000 | | | | | | | | | 221,08 | 1,5 |
| 2001 | | | | | | | | | 157,28 | 4 |
| 2002 | | | | | | | | | 274,44 | 6,3 |
| 2003 | | | | | | | | | 232,32 | 7,8 |
| 2004 | | | | | | | | | 138,31 | 5,4 |
| 2005 | | | | | | | | | 339,44 | 16 |
| 2006 | | | | | | | | | 273 | 8 |
| 2007 | | | | | | | | | 237,37 | 11 |
| 2008 | | | | | | | | | 222,79 | 11 |
| 2009 | 2,76 | 0,184 | 0,31 | 1,83 | 0,112 | 0,995 | 0,575 | 15,4 | 762,16 | 3,8 |
| 2010 | 2,40 | 0,164 | 0,617 | 1,52 | 0,022 | 1,047 | 0,59 | 17,1 | <67,92 | 2,6 |
| 2011 | 2,71 | 0,238 | 0,36 | 1,64 | 0,035 | 0,64 | 0,66 | 19,1 | 148,8 | 5,3 |
| 2012 | 2,19 | 0,17 | 0,24 | 1,31 | 0,022 | 0,84 | 0,61 | 14,1 | <92,12 | 3,9 |
| 2013 | 2,03 | 0,215 | 0,2 | 0,79 | 0,026 | 0,56 | 0,62 | 14,5 | <49,7 | 1,8 |
| 2015 | 2,2 | | 0,13 | 1,1 | | 0,4 | | 14 | 87 | 2,6 |
| 2016 | 1,5 | 0,14 | 0,095 | 0,75 | | 0,56 | 0,43 | 14 | 32 | 2,4 |
| 2017 | 2 | 0,15 | 0,32 | 1,2 | | 0,53 | 0,52 | 16 | 181 | 7,91 |
| 2018 | 2 | 0,14 | 0,11 | 0,76 | | 0,51 | 0,31 | 17 | 63,3 | 2,97 |
| 2019 | | | | | | | | | 107 | 6,23 |
| 2020 | 1,6 | 0,14 | 0,18 | 1,1 | 0,018 | 0,7 | 0,45 | 16 | 72,6 | 2,73 |
| 2021 | | | | | | | | | 172 | 8,62 |
| 2022 | 2,2 | 0,12 | 0,16 | 1,2 | 0,013 | 0,7 | 0,46 | 14 | 109 | 11,4 |

| Station: Timlingen | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | As | Cd | Cr | Cu | Hg | Ni | Pb | Zn | PAH-16 | B(a)p |
| 1998 | | | | | | | | | 249,7 | 2,7 |
| 1999 | | | | | | | | | 1100,62 | 43 |
| 2000 | | | | | | | | | 221,08 | 1,5 |
| 2001 | | | | | | | | | 157,28 | 4 |
| 2002 | | | | | | | | | 274,44 | 6,3 |
| 2003 | | | | | | | | | 232,32 | 7,8 |
| 2004 | | | | | | | | | 138,31 | 5,4 |
| 2005 | | | | | | | | | 339,44 | 16 |
| 2006 | | | | | | | | | 273 | 8 |
| 2007 | | | | | | | | | 237,37 | 11 |
| 2008 | | | | | | | | | 222,79 | 11 |
| 2009 | 2,76 | 0,184 | 0,31 | 1,83 | 0,112 | 0,995 | 0,575 | 15,4 | 762,16 | 3,8 |
| 2010 | 2,40 | 0,164 | 0,617 | 1,52 | 0,022 | 1,047 | 0,59 | 17,1 | <67,92 | 2,6 |
| 2011 | 2,71 | 0,238 | 0,36 | 1,64 | 0,035 | 0,64 | 0,66 | 19,1 | 148,8 | 5,3 |
| 2012 | 2,19 | 0,17 | 0,24 | 1,31 | 0,022 | 0,84 | 0,61 | 14,1 | <92,12 | 3,9 |
| 2013 | 2,03 | 0,215 | 0,2 | 0,79 | 0,026 | 0,56 | 0,62 | 14,5 | <49,7 | 1,8 |
| 2015 | 2,2 | | 0,13 | 1,1 | | 0,4 | | 14 | 87 | 2,6 |
| 2016 | 1,5 | 0,14 | 0,095 | 0,75 | | 0,56 | 0,43 | 14 | 32 | 2,4 |
| 2017 | 2 | 0,15 | 0,32 | 1,2 | | 0,53 | 0,52 | 16 | 181 | 7,91 |
| 2018 | 2 | 0,14 | 0,11 | 0,76 | | 0,51 | 0,31 | 17 | 63,3 | 2,97 |
| 2019 | | | | | | | | | 107 | 6,23 |
| 2020 | 1,6 | 0,14 | 0,18 | 1,1 | 0,018 | 0,7 | 0,45 | 16 | 72,6 | 2,73 |
| 2021 | | | | | | | | | 172 | 8,62 |
| 2022 | 2,2 | 0,12 | 0,16 | 1,2 | 0,013 | 0,7 | 0,46 | 14 | 109 | 11,4 |

Values are specified in **mg/kg** for heavy metals As, Cd, Cr, Cu, Hg, Ni, Pb, Zn, and in **µg/kg** for PAHs.

Sediment

| Station: ES1 | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Year | As | Cd | Cr | Cu | Hg | Ni | Pb | Zn | PAH - 16 | B(a)p |
| 2010 | 75 | <0,2 | 107 | 699 | 0,41 | 1100 | 179 | 124 | 592600 | 37000 |
| 2012 | 22 | 0,035 | 63 | 210 | 0,026 | 600 | 99 | 78 | 33357 | 2800 |
| 2016 | 29 | 0,05 | 34 | 260 | | 330 | 88 | 70 | 45000 | 2400 |
| 2020 | 53 | 0,12 | 89 | 560 | 0,473 | 970 | 180 | 130 | 40900 | 4340 |

| Station: ES2 | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Year | As | Cd | Cr | Cu | Hg | Ni | Pb | Zn | PAH - 16 | B(a)p |
| 2010 | 56 | <0,2 | 95 | 699 | | 952 | 139 | 113 | 53875 | 5300 |
| 2012 | 19 | 0,029 | 46 | 150 | 0,224 | 420 | 56 | 67 | 51423 | 3500 |
| 2016 | 25 | 0,05 | 26 | 200 | | 260 | 81 | 60 | 30 | 2600 |
| 2020 | 50 | 0,065 | 73 | 330 | 0,344 | 590 | 110 | 110 | 27800 | 2900 |

| Station: K17 | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Year | As | Cd | Cr | Cu | Hg | Ni | Pb | Zn | PAH-16 | B(a)p |
| 1988 | 138 | | 67 | 590 | | 760 | 158 | | | |
| 2006 | 109 | <0,3 | 101 | 580 | 0,5 | 794 | 148 | 150 | 37021 | 3600 |
| 2007 | 76,14895 | | 102,6635 | | | | | | | |
| 2010 | 83 | <0,3 | 107 | 641 | 0,42 | 828 | 169 | 163 | | |
| 2012 | 81 | 0,1 | 99,98 | 566,4 | 0,4694 | 796,6 | 137 | 137,8 | 39904,2 | 3620 |
| 2016 | 75 | 0,06 | 78 | 468 | | 610 | 134 | 140 | 28000 | 2800 |
| 2020 | 102,6 | 0,0454 | 106 | 484 | 0,5124 | 764 | 146 | 152 | 17320 | 1948 |

| Station: K18 | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Year | As | Cd | Cr | Cu | Hg | Ni | Pb | Zn | PAH - 16 | B(a)p |
| 2006 | 67,56 | 0,2 | 85,88 | 699 | | | | | | 1302,5 |
| 2012 | 67,56 | 0,1 | 85,88 | 150 | 0,2726 | 406,8 | 88,8 | 86,32 | 15552 | 1282 |
| 2015 | 290 | | 40 | 200 | | 136 | 65 | 79 | | |
| 2020 | 44 | | | 330 | | 310 | 92 | 79 | | |

| Station: KH03 | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Year | As | Cd | Cr | Cu | Hg | Ni | Pb | Zn | PAH - 16 | B(a)p |
| 2010 | 22 | <0,2 | 41 | 242 | 0,24 | 347 | 64 | 84 | 15007 | 1480 |
| 2012 | 10,4 | 0,031 | 29,2 | 102,4 | 0,204 | 284 | 46 | 72 | 12101 | 1076 |
| 2016 | 25 | 0,06 | 39 | 264 | | 330 | 79 | 102 | 11000 | 1200 |
| 2020 | 29,8 | 0,0484 | 41,4 | 180 | 0,2822 | 266 | 66,6 | 98,8 | 6830 | 779 |

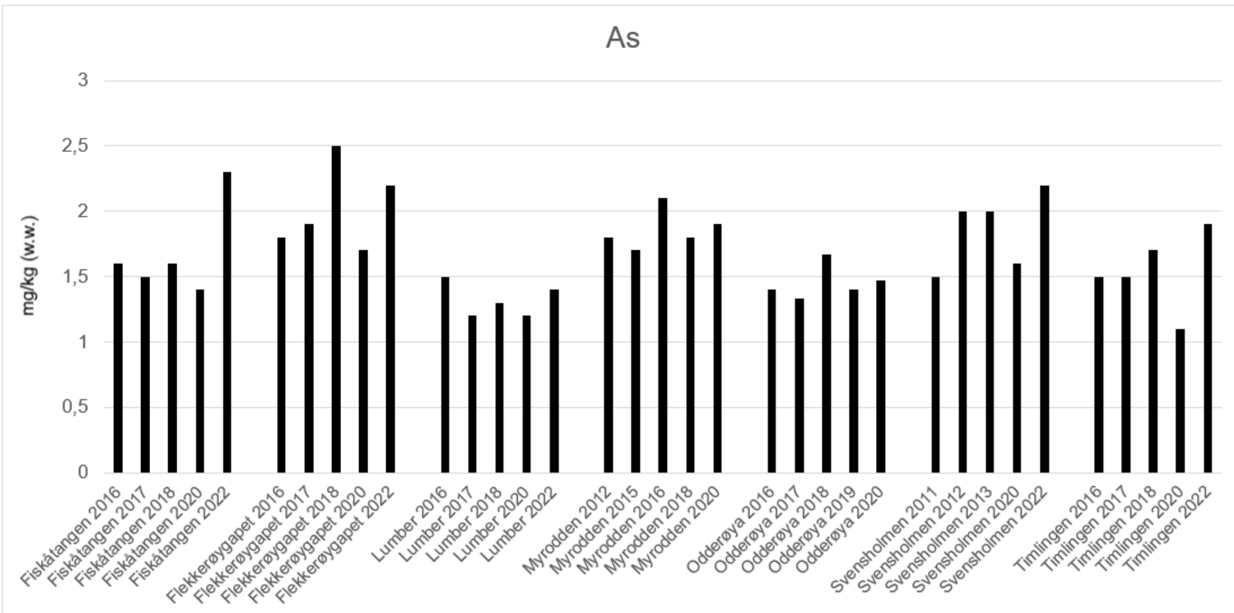
| Station: X12 | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Year | As | Cd | Cr | Cu | Hg | Ni | Pb | Zn | PAH - 16 | B(a)p |
| 2012 | 193 | 0,028 | | 147 | | 102 | 33 | 54 | | |
| 2015 | 260 | | 27 | 180 | | 120 | 46 | 64 | | |
| 2020 | 100 | | | 180 | | 150 | 47 | 61 | | |

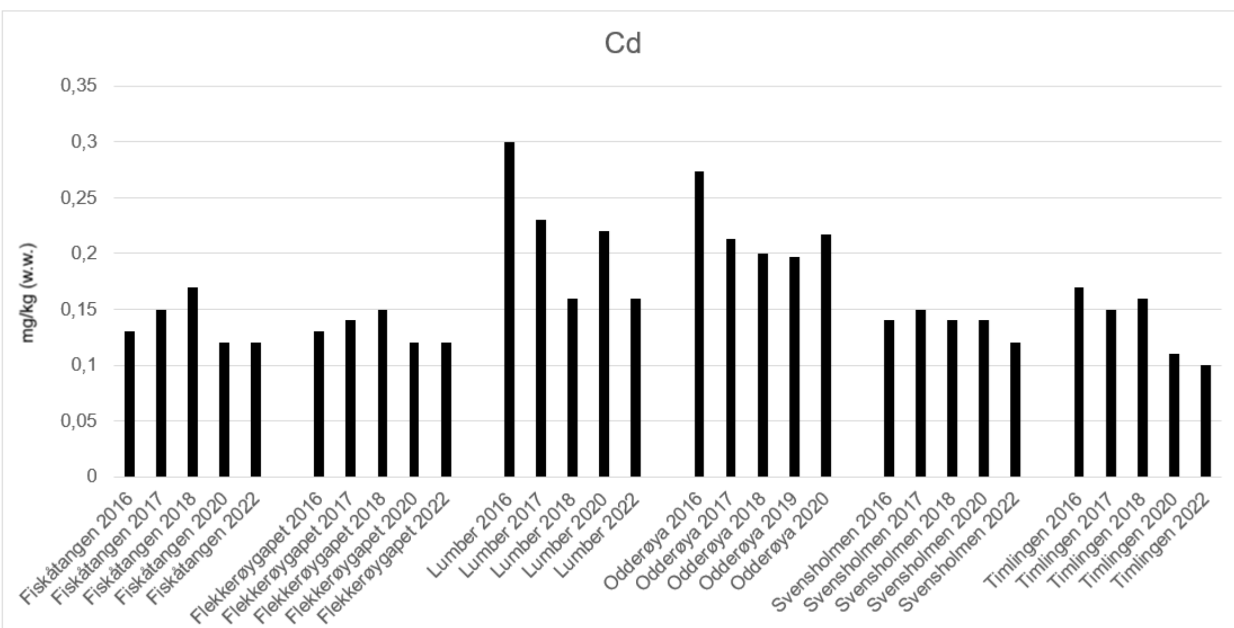
Values are specified in **mg/kg** for heavy metals As, Cd, Cr, Cu, Hg, Ni, Pb, Zn, and in **µg/kg** for PAHs.

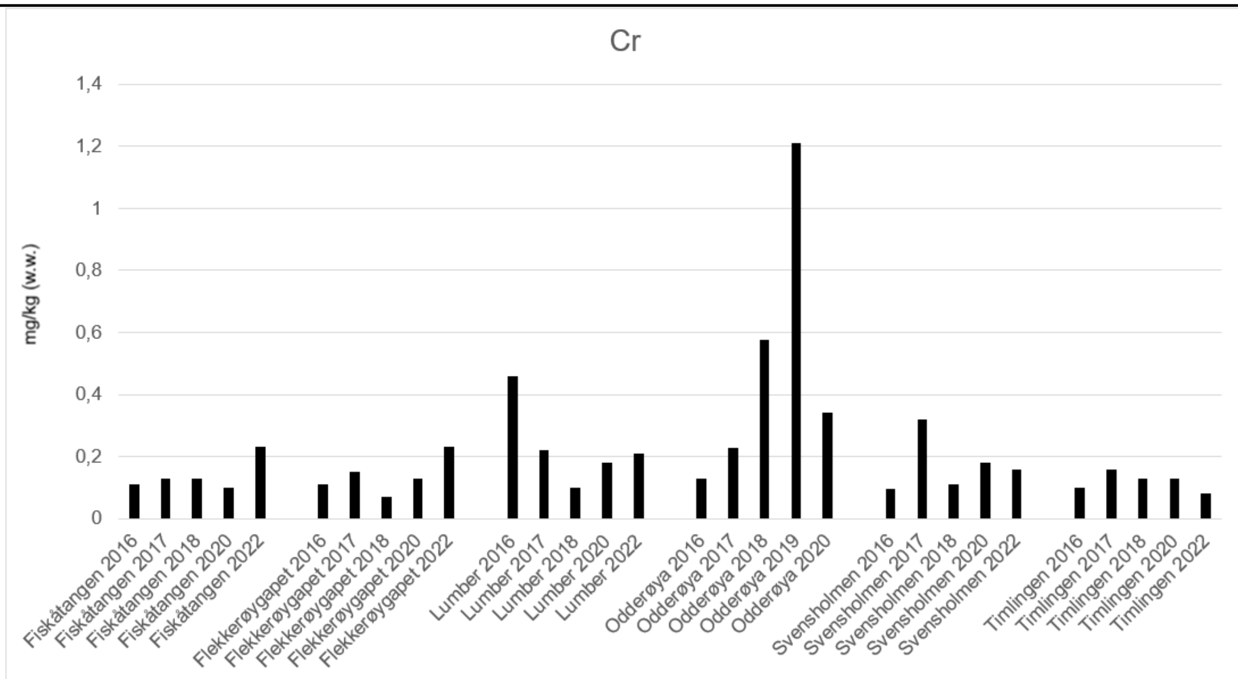
# 9. Appendix B

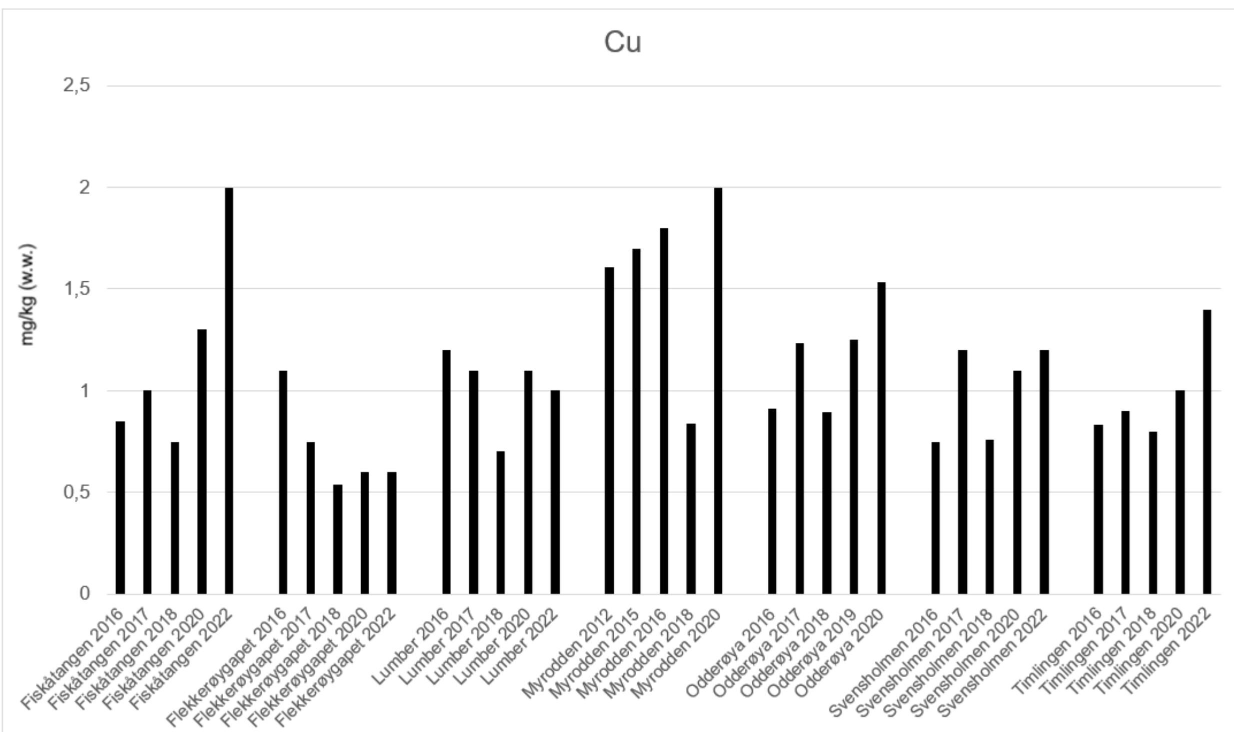
**Contaminants in blue mussels per station**

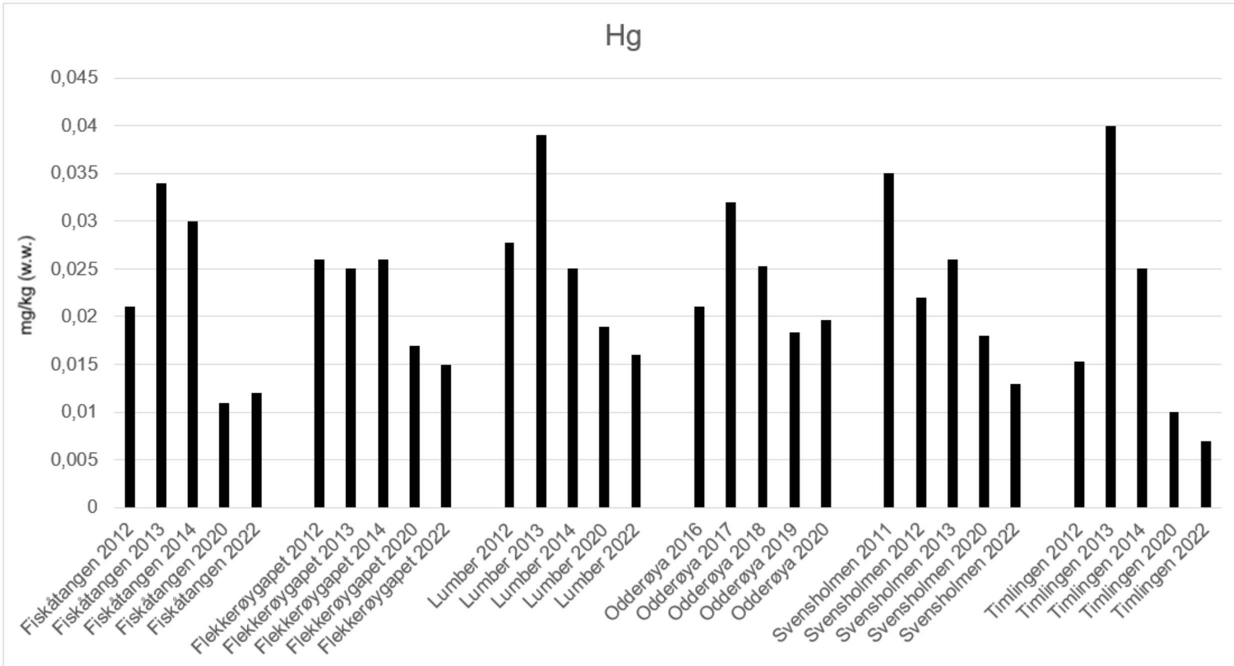
**Concentration of contaminants in blue mussel soft body at the stations, showing data from the past five measurements at each station.**

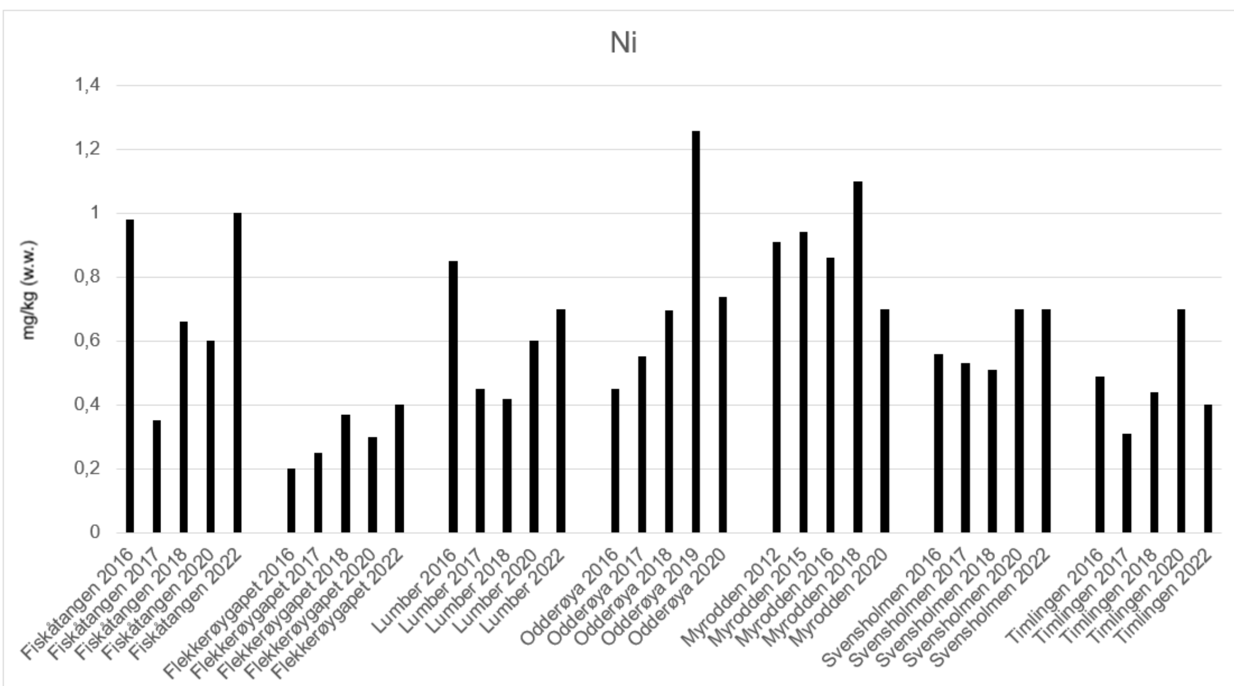


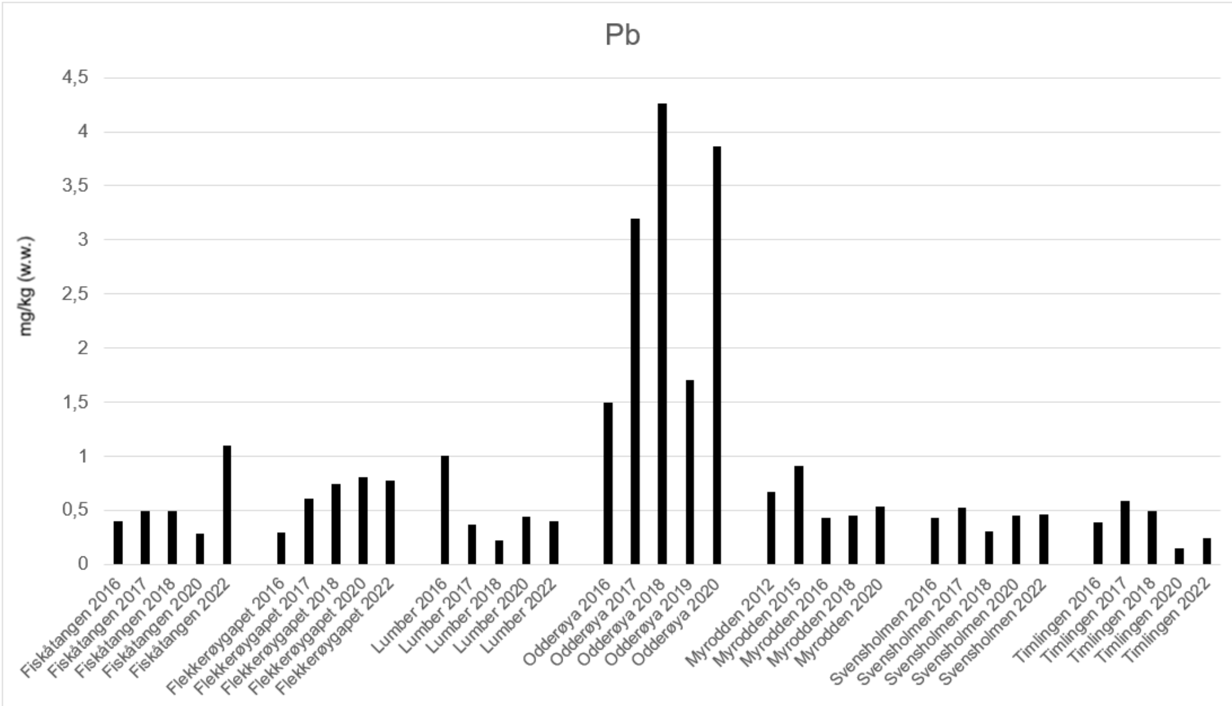



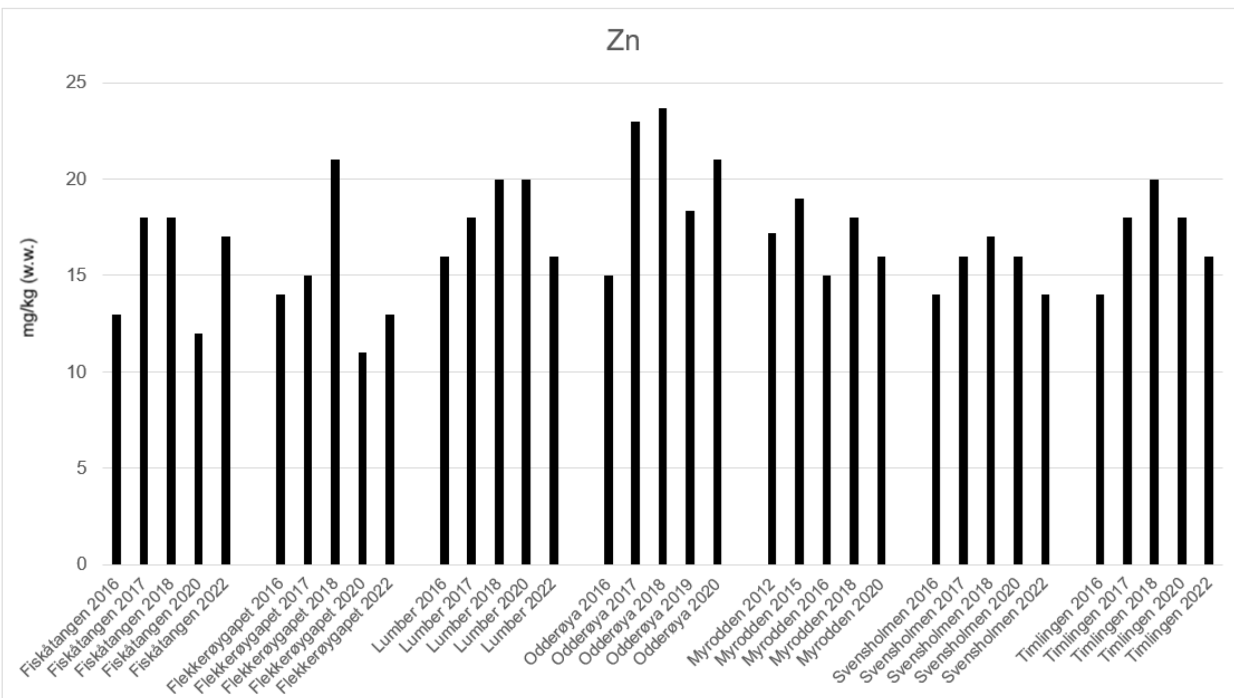

Cr
mg/kg (w.w.)
1,4
1,2
1
0,8
0,6
0,4
0,2
0
Fiskåtangen 2016
Fiskåtangen 2017
Fiskåtangen 2018
Fiskåtangen 2020
Fiskåtangen 2022
Flekkerøygapet 2016
Flekkerøygapet 2017
Flekkerøygapet 2018
Flekkerøygapet 2020
Flekkerøygapet 2022
Lumber 2016
Lumber 2017
Lumber 2018
Lumber 2020
Lumber 2022
Odderøya 2016
Odderøya 2017
Odderøya 2018
Odderøya 2019
Odderøya 2020
Svensholmen 2016
Svensholmen 2017
Svensholmen 2018
Svensholmen 2020
Svensholmen 2022
Timlingen 2016
Timlingen 2017
Timlingen 2018
Timlingen 2020
Timlingen 2022

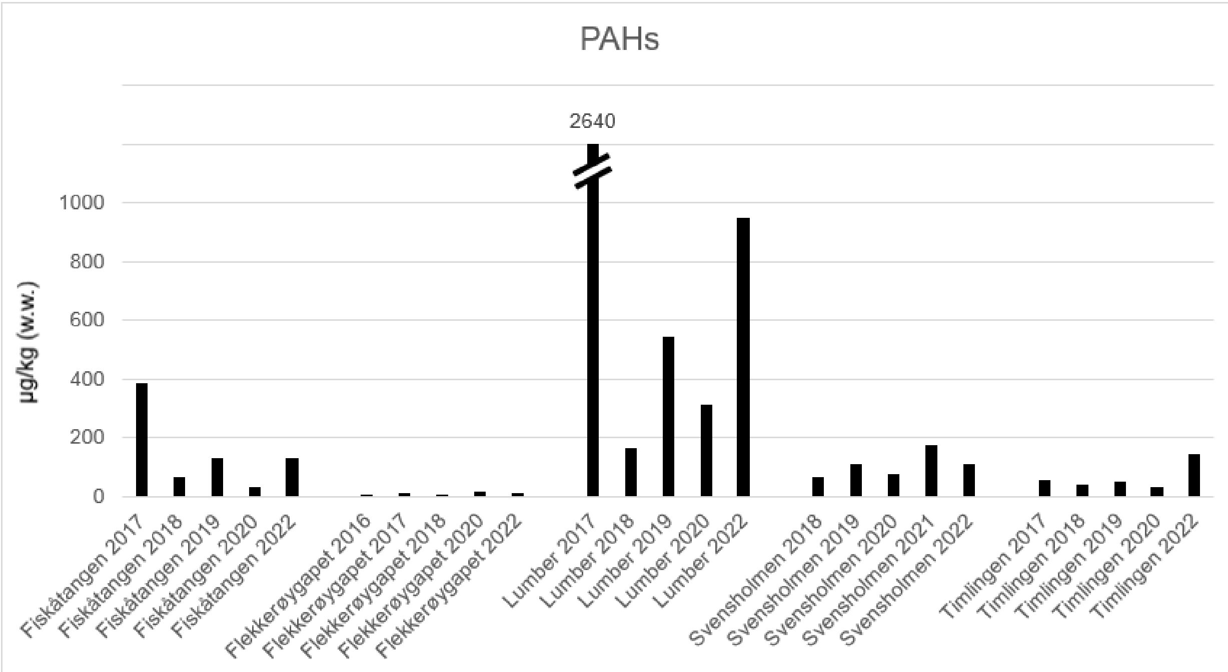

Cu
mg/kg (w.w.)
2,5
2
1,5
1
0,5
0
Fiskåtangen 2016
Fiskåtangen 2017
Fiskåtangen 2018
Fiskåtangen 2020
Fiskåtangen 2022
Flekkerøygapet 2016
Flekkerøygapet 2017
Flekkerøygapet 2018
Flekkerøygapet 2020
Flekkerøygapet 2022
Lumber 2016
Lumber 2017
Lumber 2018
Lumber 2020
Lumber 2022
Myrodden 2012
Myrodden 2015
Myrodden 2016
Myrodden 2018
Myrodden 2020
Odderøya 2016
Odderøya 2017
Odderøya 2018
Odderøya 2019
Odderøya 2020
Svensholmen 2016
Svensholmen 2017
Svensholmen 2018
Svensholmen 2020
Svensholmen 2022
Timlingen 2016
Timlingen 2017
Timlingen 2018
Timlingen 2020
Timlingen 2022

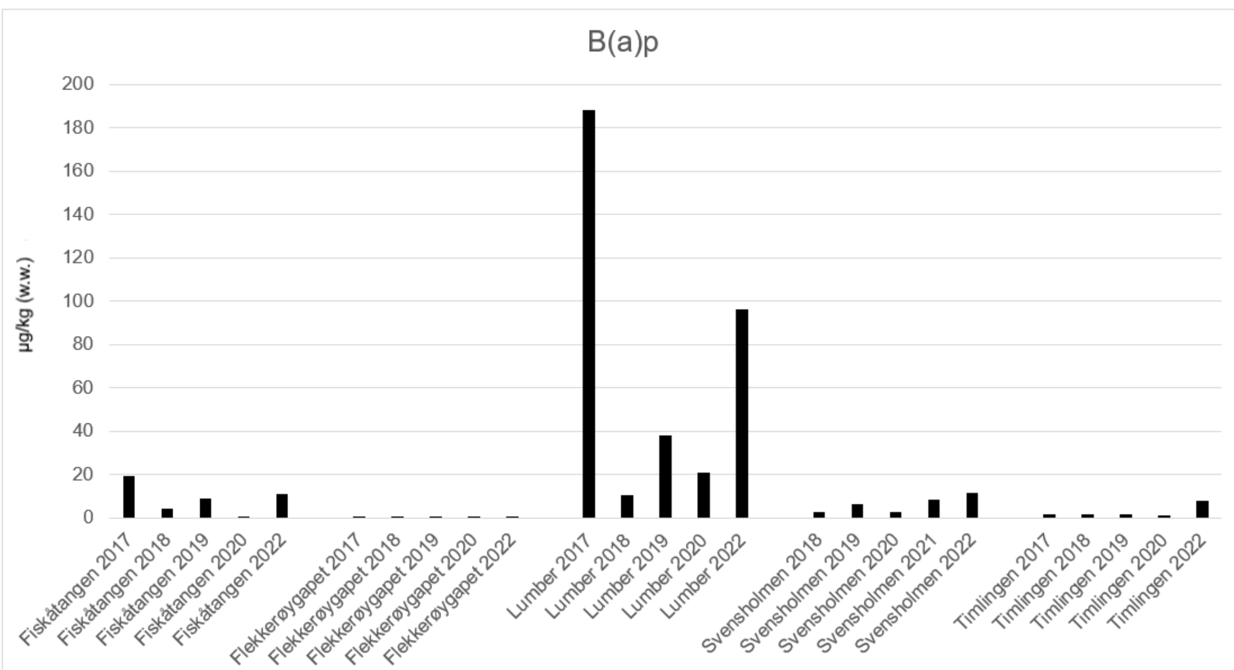

Hg
0,045
0,04
0,035
0,03
0,025
0,02
0,015
0,01
0,005
0
mg/kg (w.w.)
Fiskåtangen 2012
Fiskåtangen 2013
Fiskåtangen 2014
Fiskåtangen 2020
Fiskåtangen 2022
Flekkerøygapet 2012
Flekkerøygapet 2013
Flekkerøygapet 2014
Flekkerøygapet 2020
Flekkerøygapet 2022
Lumber 2012
Lumber 2013
Lumber 2014
Lumber 2020
Lumber 2022
Odderøya 2016
Odderøya 2017
Odderøya 2018
Odderøya 2019
Odderøya 2020
Svensholmen 2011
Svensholmen 2012
Svensholmen 2013
Svensholmen 2020
Svensholmen 2022
Timlingen 2012
Timlingen 2013
Timlingen 2014
Timlingen 2020
Timlingen 2022


Ni
1,4
1,2
1
0,8
0,6
0,4
0,2
0
mg/kg (w.w.)
Fiskåtangen 2016
Fiskåtangen 2017
Fiskåtangen 2018
Fiskåtangen 2020
Fiskåtangen 2022
Flekkerøygapet 2016
Flekkerøygapet 2017
Flekkerøygapet 2018
Flekkerøygapet 2020
Flekkerøygapet 2022
Lumber 2016
Lumber 2017
Lumber 2018
Lumber 2020
Lumber 2022
Odderøya 2016
Odderøya 2017
Odderøya 2018
Odderøya 2019
Odderøya 2020
Myrodden 2012
Myrodden 2015
Myrodden 2016
Myrodden 2018
Myrodden 2020
Svensholmen 2016
Svensholmen 2017
Svensholmen 2018
Svensholmen 2020
Svensholmen 2022
Timlingen 2016
Timlingen 2017
Timlingen 2018
Timlingen 2020
Timlingen 2022


Pb
mg/kg (w.w.)
4,5
4
3,5
3
2,5
2
1,5
1
0,5
0
Fiskåtangen 2016
Fiskåtangen 2017
Fiskåtangen 2018
Fiskåtangen 2020
Fiskåtangen 2022
Flekkerøygapet 2016
Flekkerøygapet 2017
Flekkerøygapet 2018
Flekkerøygapet 2020
Flekkerøygapet 2022
Lumber 2016
Lumber 2017
Lumber 2018
Lumber 2020
Lumber 2022
Odderøya 2016
Odderøya 2017
Odderøya 2018
Odderøya 2019
Odderøya 2020
Myrodden 2012
Myrodden 2015
Myrodden 2016
Myrodden 2018
Myrodden 2020
Svensholmen 2016
Svensholmen 2017
Svensholmen 2018
Svensholmen 2020
Svensholmen 2022
Timlingen 2016
Timlingen 2017
Timlingen 2018
Timlingen 2020
Timlingen 2022


Zn
mg/kg (w.w.)
25
20
15
10
5
0
Fiskåtangen 2016
Fiskåtangen 2017
Fiskåtangen 2018
Fiskåtangen 2020
Fiskåtangen 2022
Flekkerøygapet 2016
Flekkerøygapet 2017
Flekkerøygapet 2018
Flekkerøygapet 2020
Flekkerøygapet 2022
Lumber 2016
Lumber 2017
Lumber 2018
Lumber 2020
Lumber 2022
Odderøya 2016
Odderøya 2017
Odderøya 2018
Odderøya 2019
Odderøya 2020
Myrodden 2012
Myrodden 2015
Myrodden 2016
Myrodden 2018
Myrodden 2020
Svensholmen 2016
Svensholmen 2017
Svensholmen 2018
Svensholmen 2020
Svensholmen 2022
Timlingen 2016
Timlingen 2017
Timlingen 2018
Timlingen 2020
Timlingen 2022


PAHs
2640
μg/kg (w.w.)
0
200
400
600
800
1000
Fiskåtangen 2017
Fiskåtangen 2018
Fiskåtangen 2019
Fiskåtangen 2020
Fiskåtangen 2022
Flekkerøygapet 2016
Flekkerøygapet 2017
Flekkerøygapet 2018
Flekkerøygapet 2020
Flekkerøygapet 2022
Lumber 2017
Lumber 2018
Lumber 2019
Lumber 2020
Lumber 2022
Svensholmen 2018
Svensholmen 2019
Svensholmen 2020
Svensholmen 2021
Svensholmen 2022
Timlingen 2017
Timlingen 2018
Timlingen 2019
Timlingen 2020
Timlingen 2022


B(a)p
μg/kg (w.w.)
0
20
40
60
80
100
120
140
160
180
200
Fiskåtangen 2017
Fiskåtangen 2018
Fiskåtangen 2019
Fiskåtangen 2020
Fiskåtangen 2022
Flekkerøygapet 2017
Flekkerøygapet 2018
Flekkerøygapet 2019
Flekkerøygapet 2020
Flekkerøygapet 2022
Lumber 2017
Lumber 2018
Lumber 2019
Lumber 2020
Lumber 2022
Svensholmen 2018
Svensholmen 2019
Svensholmen 2020
Svensholmen 2021
Svensholmen 2022
Timlingen 2017
Timlingen 2018
Timlingen 2019
Timlingen 2020
Timlingen 2022