

# 1 First evaluation of wastewater discharge influence 2 on marine water contamination in the vicinity of 3 Arctowski Station (Maritime Antarctica)

4 Małgorzata Szopińska<sup>1\*</sup>, Aneta Luczkiewicz<sup>1</sup>, Katarzyna Jankowska<sup>1</sup>, Sylwia Fudala-  
5 Książek<sup>2</sup>, Joanna Potapowicz<sup>3</sup>, Agnieszka Kalinowska<sup>1</sup>, Robert Józef Bialik<sup>4</sup>, Stanisław  
6 Chmiel<sup>5</sup>, Żaneta Polkowska<sup>3</sup>

7 *1. Gdansk University of Technology, Faculty of Civil and Environmental Engineering, Department of*  
8 *Water and Waste Water Technology, 11/12 Narutowicza St., Gdansk 80-233, Poland;*  
9 *malszopi@pg.edu.pl;*

10 *2. Gdansk University of Technology, Faculty of Civil and Environmental Engineering, Department of*  
11 *Sanitary Engineering, 11/12 Narutowicza St., Gdansk 80-233, Poland;*

12 *3. Gdansk University of Technology, Faculty of Chemistry, Analytical Chemistry Department; 11/12*  
13 *Narutowicza St., Gdansk 80-233, Poland;*

14 *4. Institute of Biochemistry and Biophysics, Polish Academy of Science, Pawińskiego 5a, 02-106*  
15 *Warsaw, Poland;*

16 *5. Maria Curie-Skłodowska University, Faculty of Earth Sciences and Spatial Management,*  
17 *Department of Hydrology and Climatology, 2 cd Kraśnicka Ave., 20-718 Lublin, Poland*

18 \* corresponding authors (malszopi@pg.edu.pl, zanpolko@pg.edu.pl)

19 **KEYWORDS** Antarctica; wastewater management, surfactants, trace metals,

## 20 **ABSTRACT**

21 In Antarctica, waste is generated mainly during scientific research programmes and related  
22 logistics. In this study, the impact of wastewater on the western shore of Admiralty Bay was  
23 investigated during austral summer in 2017 and 2019. A range of physicochemical parameters  
24 and the presence of selected trace metals, formaldehyde and different groups of surfactants were  
25 determined in wastewater coming from Arctowski Station and in nearby coastal waters. The  
26 presence of selected trace metals (e.g., Cr: 2.7-4.4 µg/L; Zn: 15.2-37.3 µg/L; and Ni: 0.9 - 23.3  
27 µg/L) and the sums of cationic (0.3-1.5 mg/L), anionic (3.1-1.7 mg/L), and non-ionic (0.6-2.4

28 mg/L) surfactants in wastewater indicated the potential influence of anthropogenic factors on  
29 sea water. The determined surfactants are found in many hygiene products that end up in the  
30 waste water tank after human use and, if untreated, can be released into surface waters with  
31 discharge. In addition, the levels of some trace metals indicate that they cannot come only from  
32 natural sources, but are the result of human activity. The reported data show disturbances in the  
33 marine environment caused by non-treated wastewater discharge, *e.g.* by comparing the  
34 obtained results from the values of the no observed effect concentrations (NOECs) on selected  
35 Antarctic bioindicators, and provide information for the implementation of proper wastewater  
36 treatment at any Antarctic station in the future.

37

### 38 GRAPHICAL ABSTRACT



39

40

41

## 42 **1. Introduction**

43 Antarctica has unique value, as it is an international territory designated for peaceful and  
44 scientific purposes (The Antarctic Treaty, 1959). However, signs of anthropogenic activity in  
45 Antarctica have been visible since the 1960s (Sladen et al., 1966). The environmental  
46 consequences of human activities (both scientific and touristic) have been documented by  
47 several authors (Bargagli, 2008; Benninghoff and Bonner, 1985; Corsolini, 2009; Szopińska et  
48 al., 2017, Potapowicz et al., 2019), indicating different sources of pollution, such as atmospheric  
49 deposition and diesel fuel combustion; however, recently, waste and wastewater management  
50 have gained increasing concern (Connor, 2008, KumarBharti et al., 2016). Improper wastewater  
51 discharge in pristine Antarctic marine water may introduce not only persistent organic  
52 pollutants and other emerging organic and inorganic contaminants but also non-indigenous  
53 microorganisms, including human-associated pathogens and viruses (Tort et al., 2017).

54 To date, no continent-wide wastewater quality discharge guidelines have been developed and  
55 accepted by the countries operating bases and claiming territory in Antarctica. Annex III (Waste  
56 Disposal and Waste Management) of the Protocol on Environmental Protection to the Antarctic  
57 Treaty (hereafter, the Protocol) requires countries to preserve the environment for future  
58 generations (The Protocol on Environmental Protection to the Antarctic Treaty). It is therefore  
59 necessary to develop proper waste management plans. Annex III requires that all wastes  
60 produced or disposed of in the Antarctic Treaty area have limited negative impact on the  
61 environment. All liquid wastes, including domestic wastewater, need to be removed from the  
62 Antarctic Treaty area to the maximum practicable extent (Article 2, Annex III of the Protocol).  
63 Only if proper dilution and rapid dispersion are ensured can wastewater be discharged directly  
64 into marine waters (Article 5, Annex III), but this requirement is rather vague because no  
65 definitions were given for key terms, such as “assimilative capacity”, “initial dilution” or “rapid  
66 dispersal”. Investigation of the impact of continuous wastewater disposal into Antarctic marine

67 water ecosystems has been relatively limited. A few stations, such as McMurdo (Conlan et al.,  
68 2004; Lenihan and Oliver, 1995) and Davis (Stark et al., 2016, 2015) stations, have focused  
69 directly on this topic. The wastewater influence on the marine water quality of Admiralty Bay  
70 has been studied since 1997, e.g., research conducted at the Martel Inlet (Martins et al., 2005,  
71 2002; Montone et al., 2010) and also shows the favoured dispersion of wastewater at the  
72 discharge points, which is caused by local hydrodynamic conditions, especially tides (Montone  
73 et al., 2010). However, at the same time, some chemical indicators (such as sterols and linear  
74 alkylbenzenes) have been found in marine sediments (Martins et al., 2005, 2002), indicating  
75 contamination by continuous wastewater discharge. Combined evidence of environmental  
76 impacts caused by wastewater discharge from the Davis Station, East Antarctica (non-native  
77 microbiota and antibiotic resistance determinants in sediments, water in marine benthic  
78 communities, and histopathological abnormalities in local fish species), was also presented by  
79 Stark and co-authors (Stark et al., 2016).

80 In the area of current interest, Admiralty Bay, wastewater influence on ecosystems has been  
81 reported only in terms of microbiological pollution (faecal bacteria), presence of sterols and  
82 linear alkylbenzenes (Martins et al., 2005, 2002), while wastewater discharge from the  
83 Arctowski Polish Antarctic Station (western shore of Admiralty Bay) has not been investigated.  
84 Previous studies have confirmed that sewage discharges in the Antarctic area can cause  
85 environmental impacts on the local marine ecosystem and pose a risk of environmental  
86 degradation (Martins et al., 2005, 2002; Stark et al., 2016, 2015). Thus in this study, the  
87 dispersal and distribution of wastewater after discharge into the receiving environment  
88 (Admiralty Bay) was examined in 2017 and 2019 using measurements of nutrients, organic  
89 matter, trace metals (Pb, Fe, Cd, Zn, Cu, Ni, Co, and Cr), different groups of surfactants (non-  
90 ionic-SNI, cationic-SC and anionic-SA), and formaldehyde concentrations. Principal  
91 component analysis (PCA) was performed to observe potential correlations which provide



92 valuable information on the environmental fate of the chemical pollutants under study. In our  
93 work we described in detail chemical disturbances in Admiralty Bay after wastewater  
94 discharge. The main purpose of this study was an initial risk assessment given that the data  
95 obtained can be used for this purpose. Risk assessment has been evaluated by comparing the  
96 obtained results from the values of the no observed effect concentrations (NOECs) on selected  
97 Antarctic bioindicators. This type of research and data evaluation has been conducted for the  
98 first time in the vicinity of Arctowski Station, and the results may thus constitute baseline  
99 conditions for any future anthropogenic impact assessment. Moreover, our research confirms  
100 that the proposed set of contaminants, which can be determined by simple analytical procedures  
101 (including spectrophotometric methods), may be considered suitable for routine analysis in  
102 Antarctica to monitor compliance with environmental regulations. .

## 103 **2. Material and methods**

### 104 **2.1 Arctowski Station wastewater system and sampling design**

105 The study area is located on the western shore of Admiralty Bay (King George Island, South  
106 Shetland Islands, Fig. 1A) in a small ice-free area on the north-eastern tip of the Warsaw  
107 Icefield. Arctowski Station (62°09'34"S, 58°28'15"W; Fig. 1B), which was built in 1977,  
108 consists of a facility with fifteen separate buildings. The maximum population during the peak  
109 season (summer) at the station may reach 37 persons (Supplementary Material, Table S1).  
110 These people conduct scientific research and other activities connected with maintenance of the  
111 station. During the winter season, there are only 8 persons on the staff who are responsible for  
112 station maintenance and the long-term monitoring programmes (i.e., programmes in ecology,  
113 hydrology, oceanography, chemistry, and glaciology). Due to the freezing of surface waters,  
114 supplying the station with drinking and hygiene water (freezing of the lake from which the  
115 water is pumped) and wastewater disposal (freezing of the bay - place of discharge) are

116 especially challenging during the winter season. Daily water consumption at Arctowski Station  
117 during the period 2016-2019 was relatively low (149 L per person per day, Supplementary  
118 Material, Table S1). Nevertheless, access to drinking and household water is limited due to the  
119 sustainable usage of natural resources and the need to stay below the daily limit of 230 L per  
120 person per day (Supplementary Material, Table S1, Fig. S1).

121 Water (glacial and snow melt water) is obtained from the lake located near the station, which  
122 is supplied by Petrified Forest Creek (see Fig. 1B and Fig. 1C). There is no wastewater  
123 treatment plant at the Arctowski Station. Wastewater (grey and black water) is collected and  
124 directed to four buried septic tanks. The first tank (A) is connected to the main building and  
125 laboratory; the second (B) covers technical facilities, including toilets, showers and laundry  
126 facilities; the third (C) is connected to summer houses; and the fourth (D) is connected to the  
127 building known as the meteorological station (Fig. 1C). The facility at the main building is  
128 limited primarily to treating non-solid waste (maceration). In the other buildings, no wastewater  
129 treatment is applied. There is no information regarding the total volume of each septic tank;  
130 however, the amount of produced wastewater is estimated to be in the range of 31.4 – 80.7 m<sup>3</sup>  
131 per year (Supplementary Material Table S1; Fig. 2). Water consumption in relation to the  
132 number of people present at Arctowski Station is presented in Fig. S2 (Supplementary  
133 Material).

134 The liquid residues of septic tanks are discharged to Admiralty Bay. The wastewater  
135 discharge point is at Point Thomas (62°10'S 58°30'W) on the south side of the entrance to  
136 Ezcurra Inlet in Admiralty Bay (Fig. 1 B, sampling point no. 1). This location and the depth of  
137 the bay, which is more than 550 m (Rakusa-Suszczewski, 1993), are expected to provide proper  
138 conditions for the “initial dilution” and “rapid dispersal” of discharged wastewater.  
139 Nonetheless, to date, no research concerning the possible contamination of local marine  
140 ecosystems has been conducted.





141

142 **Figure 1.** Location of the study area: A) location of King George Island in relation to  
 143 Antarctica; B) location of Arctowski Station and sampling points; and C) location of Arctowski  
 144 Station facilities and septic tanks (Figs. A and B are adapted from Szopińska et al., (2018))

145 In this study, wastewater and marine water samples were collected during two sampling  
 146 campaigns conducted on 18-20 January 2017 and 1-5 April 2019. Wastewater was collected  
 147 from septic tank A, which is connected to the main building and laboratory (see Fig. 1C). To  
 148 analyse the dilution and dispersion of wastewater in the marine environment, the sampling  
 149 points were placed in the discharge area (point no. 1) and near the lighthouse (point no. 2),  
 150 approximately 1 km away from the discharge point. The samples were collected at regular time



151 intervals after discharge: after 0.5 h, 1 h, 2 h, 24 h, 48 h and 96 h. Sampling at point no. 2 was  
152 not possible during 2019.

## 153 **2.2 Sample analysis**

154 After collection, all samples were transported to the Arctowski Station laboratory. Redox  
155 potential, pH and conductivity were measured using a HQ40d portable multimeter in the field.  
156 For other physical and chemical analysis, samples were stored frozen at  $-20^{\circ}\text{C}$  and transported  
157 under unchanged temperature conditions to Poland. Before analysis all samples were allowed  
158 to thaw slowly overnight. Analysis included the determination of chemical oxygen demand  
159 (COD), inorganic nitrogen compounds ( $\text{N-NH}_4^+$ ,  $\text{N-NO}_3^-$ , and  $\text{N-NO}_2^-$ ), total nitrogen (TN),  
160 orthophosphate ( $\text{P-PO}_4^{3-}$ ) and total phosphorus (TP) using spectrophotometric methods (*XION*  
161 *500 spectrophotometer, Dr. Lange, GmbH, Germany*). To exclude chloride influence on COD  
162 analysis, the sample was diluted 10-fold. According to EN ISO 5667-3, samples for ammonium  
163 determination can be stored in plastic bottles up to one month in a freezer at below  $-18^{\circ}\text{C}$ .  
164 Specific chemical analysis included trace metal (Pb, Fe, Cd, Zn, Cu, Ni, Co, and Cr)  
165 determination using inductively coupled plasma mass spectrometry (*Thermo XSERIES 2 ICP-*  
166 *MS*). Acidified samples were analysed without filtration – total concentration of each metal was  
167 recorded under the following conditions: collision gas (Ar) flow:  $13\text{ L min}^{-1}$ ; aux. gas flow:  $0.7$   
168  $\text{L min}^{-1}$ ; nebulizer gas flow:  $0.9\text{ L min}^{-1}$ ; collision cell technology - CCT gas (8% Hydrogen in  
169 Helium) flow  $5.5\text{ mL min}^{-1}$ , CCT mode +3 Kinetic Energy Discrimination. A multi-element  
170 ICP-MS standards mix  $10\text{ mgL}^{-1}$  from Inorganic Ventures (Christiansburg, VA, USA) was used  
171 for calibration. Different groups of surfactants (SNI, SC and SA) and formaldehyde were  
172 determined using cuvette tests and a UV-VIS spectrophotometer (*Spectroquant Pharo 300*  
173 *Merck, Germany*). Biological oxygen demand in wastewater samples (5-day test,  $\text{BOD}_5$ ) was  
174 measured using WTW OxiTop, OC 100.



175 All analyses were carried out according to the Good Laboratory Practice (GLP) requirements.  
176 The basic validation parameters of the methods used are presented in Supplementary  
177 Information, Table S4. LCK Cuvette Tests quality assurance is provided in certificates based  
178 on Analytical Quality Assurance (AQA) System in accordance with the American Public  
179 Health Association (American Public Health Association et al., 2005).

## 180 **2.3 Statistical analysis**

181 Applying the results from two sampling campaigns, a multivariate dataset was created, and  
182 Principal Component Analysis (PCA) was employed to reveal correlations in the data using  
183 MATLAB Version: R2020a with Statistics and Machine Learning Toolbox Version 11.7.

## 184 **3. Results**

### 185 **3.1 General chemical characteristics**

186 To assess the environmental impact related to wastewater deposition, wastewater generated  
187 at both Arctowski Station and the seawater collected near the discharge point (receiving  
188 environment) (Fig. 1B, no. 1) and the second sampling point (Fig. 1B, no. 2), were analysed.  
189 The properties of the collected samples are presented in Table S2, Supplementary Information  
190 and summarised in Table 1. According to physicochemical analysis, wastewater presented  
191 values similar to those produced in countries with low populations and cold climates (Table S2,  
192 Supplementary Material), such as Norway (Pons et al., 2004). The BOD<sub>5</sub> values tested only in  
193 wastewater were 1099 mgO<sub>2</sub>/L in 2017 and 806 mgO<sub>2</sub>/L in 2019, with a BOD<sub>5</sub>/COD ratio of  
194 0.46-0.58, indicating that half of the organic matter is amenable to biodegradation. In seawater  
195 samples collected immediately after wastewater discharge, the COD value equalled 58.6  
196 mgO<sub>2</sub>/L in 2017 and 75.4 mgO<sub>2</sub>/L in 2019. After 24 h, the COD decreased back to the values  
197 measured before discharge (Table S2, Supplementary Material). In the case of pH, conductivity  
198 and redox value, their minor fluctuations can be the result of sea currents rather than wastewater



199 disposal. In terms of nutrient dispersion, the concentration levels of phosphorus and nitrogen  
200 compounds reverted in sea water to the values before discharge within two hours. Additionally,  
201 no significant changes in phosphorus and nitrogen compound concentrations at point no. 2 were  
202 observed (Table S2, Supplementary Material).

### 203 **3.2 Selected micropollutants analysis**

204 The presence of trace metals (Table S3, Supplementary Material) and selected organic  
205 micropollutants, such as formaldehyde and the sums of cationic (SC), anionic (SA), and non-  
206 ionic (SNI) surfactants (Fig. S2, Supplementary Material), were also analysed in wastewater  
207 and receiving waters. An increase in Zn concentration in seawater samples after wastewater  
208 discharge was noticeable in 2017 at both the second (up to 8.42 µg/L) and first (up to 3.04 µg/L)  
209 sampling points (see Table S3, Supplementary Material). In 2019, an increase in Zn  
210 concentration after wastewater discharge was also observed (increase from 0.19 µg/L before  
211 discharge to 0.98 µg/L after discharge). Nevertheless, the Zn concentration in wastewater in  
212 2017 was approximately two times lower than that in 2019. However, an increase in Fe  
213 concentration in seawater directly after discharge was also observed (from 0.54 to 2.01 µg/L in  
214 2017 and from 3.31 to 24.42 µg/L in 2019), and it decreased within the sampling time to 0.39  
215 in 2017 and 0.24 µg/L in 2019. Pb was present in wastewater at concentrations of 0.48 µg/L in  
216 2017 and 0.14 µg/L in 2019; however, it was below the detection limit (< 0.01 µg/L) in  
217 seawater, even directly after wastewater discharge. A similar phenomenon was observed for Cd  
218 and Co during both sampling campaigns. In wastewater samples in 2017 and 2019,  
219 concentrations ranged between 0.03-0.45 µg/L (Cd) and 1.68-2.13 µg/L (Co), while in the  
220 seawater samples after 24 h, Cd and Co concentrations were up to 0.02 µg/L. Regarding Ni,  
221 lower concentrations during the 2019 sampling campaign were observed in both wastewater  
222 and marine water (Table S3, Supplementary Material). For Cu an increase in concentration in  
223 wastewater and its receiver in sampling area no. 1 was observed between 2017 and 2019.

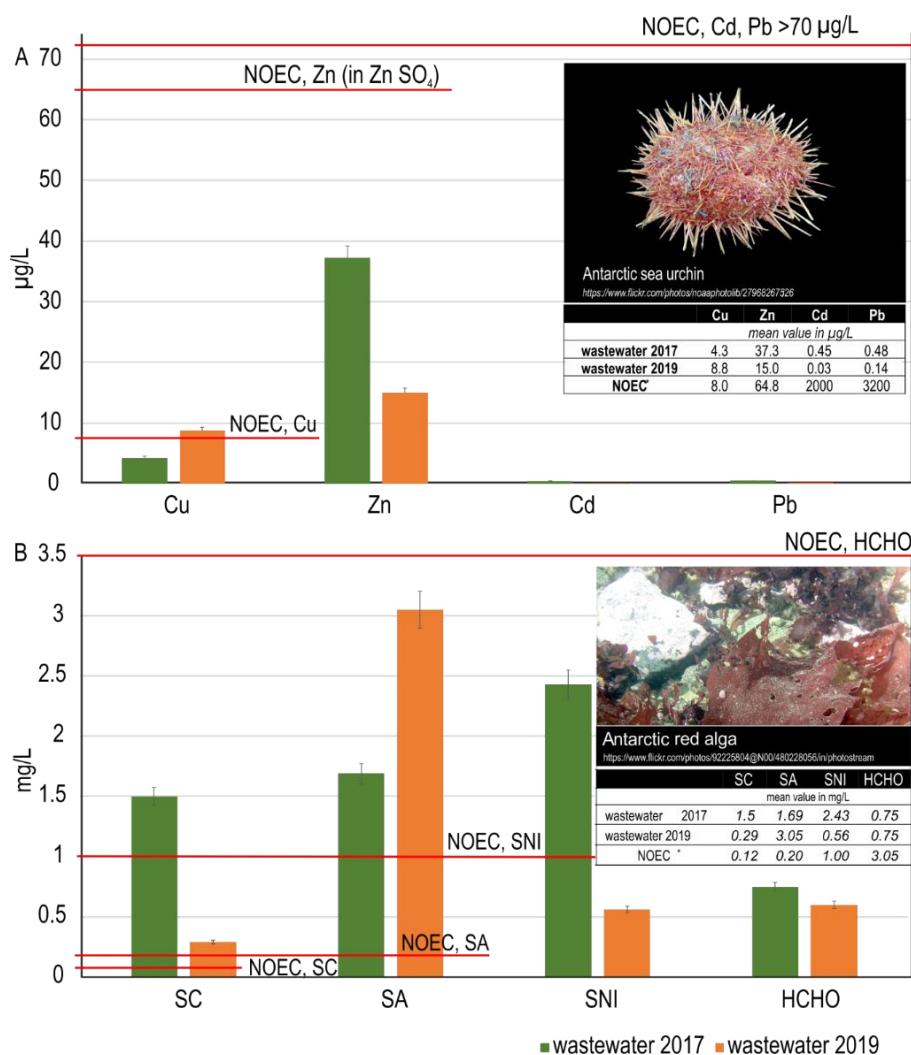
224 However, no visible trend (e.g., decrease in concentration in time after discharge) was observed  
225 during the 2019 sampling campaign.

226 Considering the toxicological properties of the analysed parameters (Kowalik, 2011;  
227 Olkowska et al., 2011; Thornton et al., 2001), the results have been assessed in relation to the  
228 available literature on the predicted no-effect concentration (PNEC) values. The analysis  
229 results alongside relevant PNECs are presented (Fig.2). Considering the wastewater micro-  
230 pollution characteristics, the concentrations of SC, SA, SNI, and heavy metals such as Cu  
231 exceed the NOEC parameter (Fig. 2A and B) for native species (Antarctic red alga and Antarctic  
232 sea urchin). It should be noted that this observation does not include the dilution factor after  
233 discharge.

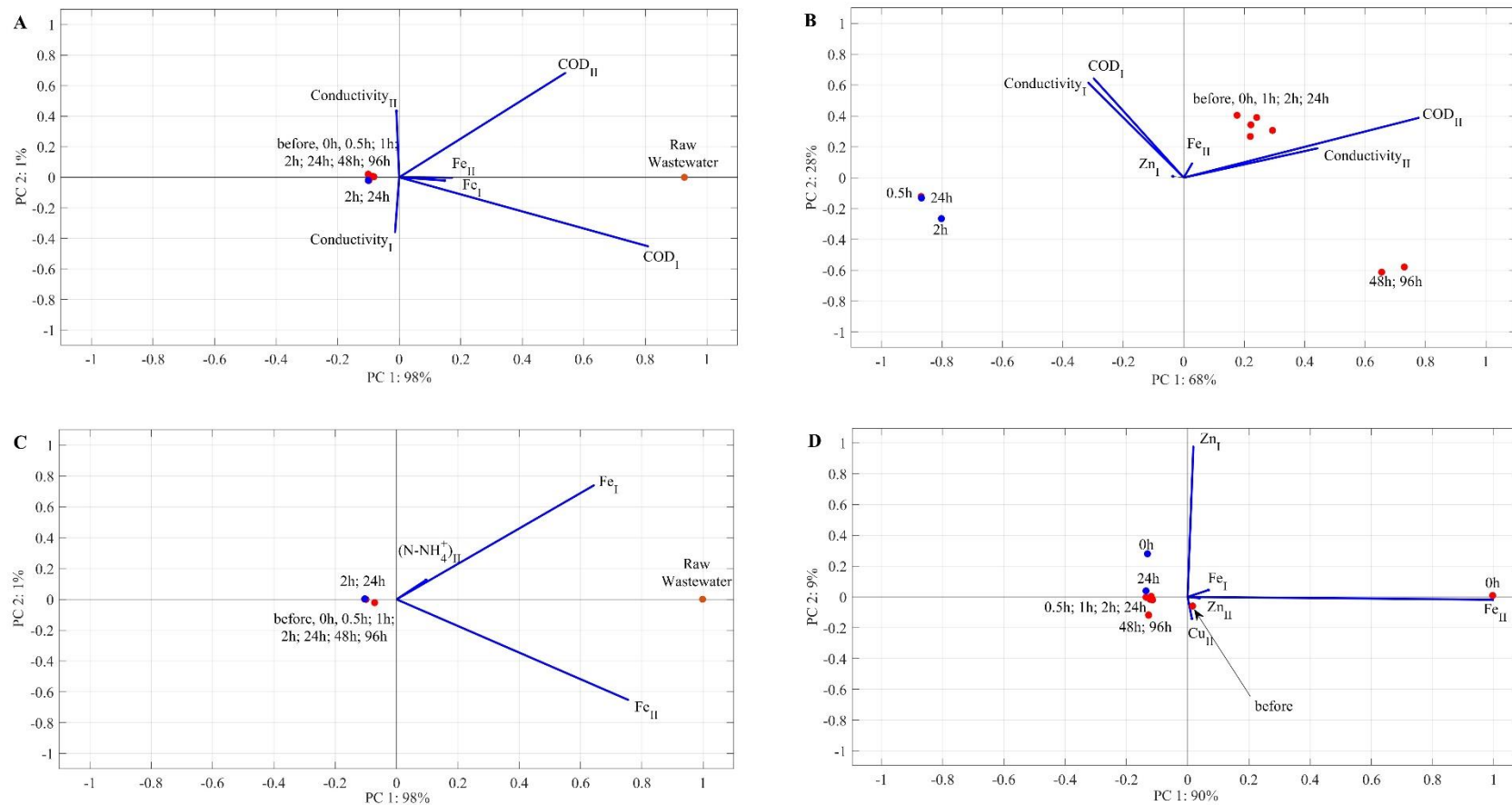
234 For multivariate parameter analysis, physico-chemical data were divided into two series, i.e.  
235 with raw wastewater results included (Fig. 3 A,C) and without (Fig. 3 B,D). For this analysis  
236 the redox parameter has been excluded. In addition, in the case of data without raw wastewater  
237 (Fig. 3 B,D), in order to characterise the most important parameter among components with  
238 low concentrations (micropollution) the following variables were also removed: COD,  
239 conductivity, pH, TP, TN. For all four series of data, two principal components were identified  
240 that represent 99% (Fig.3 A), 96% (Fig. 3 B), 99% (Fig. 3 C) and 99% (Fig. 3 D) of the variance,  
241 respectively. For the first case (Fig. 3 A), PC1 and PC2 were found to have a strong correlation  
242 with COD, but correlations with Fe and conductivity for both years were also significant. On  
243 the other hand, when the COD was excluded, (Fig. 3 C) PC1 and PC2 were strongly positively  
244 correlated with Fe for both years of data. In addition, there is positive correlation with  $\text{N-NH}_4^+$   
245 for the data obtained in 2019 (II). The PCA analysis performed for the series without raw  
246 wastewater characteristic (Fig. 3 B) confirmed a positive correlation with COD and  
247 conductivity, but it is noteworthy that there is a noticeable correlation with Zn for the first year  
248 data and Fe for the second year data. Moreover, participation of the second components (PC2)



249 in the representation of the entire variance increases significantly, up to 28%. These results are  
 250 confirmed in the fourth case (Fig. 3 D), in which some of the variables were omitted.



251  
 252 **Figure 2.** Selected micro-pollution concentrations in wastewater: A) heavy metals in  
 253 wastewater in relation to the literature values of the no observed effect concentrations (NOECs)  
 254 on Antarctic sea urchins (King and Riddle, 2001); B) organic micro-pollution concentrations in  
 255 wastewater in relation to the literature values of the NOECs on Antarctic red algae (Gheorghe et  
 256 al., 2013; Steber, 2007) Abbreviations: *SC* – sum of cationic surfactants; *SA* – sum of anionic  
 257 surfactants; *SNI* – sum of non-ionic surfactants; *HCHO* – formaldehyde



258

259 **Figure 3.** PCA biplots for various data sets. Projection of environmental variables and cases (sampling points) on the plane of two principal  
 260 components: A. Entire data set for recipient water and raw wastewater analysis (excluding redox parameter); B. Entire data set for recipient water  
 261 C. Reduced data set for recipient water and raw wastewater analysis (excluding redox parameter); D. Reduced data set for recipient water. Blue  
 262 dots refer to the sampling campaign in 2017, red dots to 2019; I and II in subscript means results obtained during sampling campaign in 2017 and  
 263 in 2019, respectively

## 264 4. Discussion

265 Wastewater generated at polar research stations is mainly derived from domestic (e.g., kitchens,  
 266 toilets, laundry rooms, and bathrooms) and from some technological (laboratories, repair  
 267 workshops, etc.) sources. This type of wastewater has properties typical of municipal wastewater  
 268 (for details, see Table 1). Different stations, however, may generate different kinds of wastewater  
 269 depending, e.g., on the specific research conducted there. In wastewater originating from Antarctic  
 270 stations, organic compounds of limited biodegradability (Wild et al., 2015), including  
 271 microplastics (Gheorghe et al., 2013), hydrocarbons, surface active agents and endocrine  
 272 disrupting compounds (Smith and Riddle, 2009), as well as pharmaceuticals (González-Alonso et  
 273 al., 2017), were noted.

274 **Table 1.** Wastewater physico-chemical parameters from Arctowski and other Antarctic stations

STATION NAME (ownership)	YEAR	TSS	COD <sub>total</sub> (COD <sub>dissolved</sub> )	BOD <sub>5</sub>	TP	N-NH <sub>4</sub> <sup>+</sup>	N-NO <sub>3</sub> <sup>-</sup>	N-NO <sub>2</sub> <sup>-</sup>	TN	Ref.
		[mg/L]	[mgO <sub>2</sub> /L]	[mgO <sub>2</sub> /L]	[mg/L]	[mg/L]	[mg/L]	[mg/L]	[mg/L]	
Arctowski Station (Poland)	2017	-	2390 (406)	1386	3.21	11.2	1.33	0.095	42.0	(present study)
	2019	-	1618 (1019)	806	3.44	63.9	0.863	0.035	98.2	
Davis Station (Australia)	2010	668 - 1896	1444 - 4823	90 - 3167	36-158	-	-	-	214- 704	(Stark et al., 2015)
McMurdo Station (USA)	1989- 1992	33-540	113-1000	26- 1600	1.6- 250	2.1-60	<0.04- 0.66	<0.003- 0.04	9.3- 130	(Crockett, 1997)
	1992- 1993	85- 1000	360-4100	170-1300	2.9-13	3.5-39	<0.04- 0.36	<0.01- 0.45	18-100	
Wasa Station (Sweden)	no data	1100	5800	3800	-	2.3	-	-	-	(Tarasenko , 2008)
Dome station (China)	A no data	40-60	80-120	30-50	-	5	-	-	-	(Tarasenko , 2008)



275 Nevertheless, the development and implementation of proper treatment methods may  
276 significantly mitigate this anthropogenic impact despite the lack of appropriate legal regulations  
277 for wastewater discharge in the requirements of the Environmental Protocol to the Antarctic Treaty  
278 (the Madrid Protocol).

#### 279 **4.1 Macro- and micro-pollution assessment in the western shore of Admiralty Bay**

280 Presented experimental design lends itself to answer questions about the initial dilution and  
281 dispersion of wastewater. In this study, according to basic parameters such as COD, pH, redox and  
282 nutrients (Table S2, Supplementary Material), receiver quality returned to the same state as before  
283 wastewater discharge, in general, after 24 h. Based on this indication, it could be assumed that  
284 Arctowski Station wastewater management achieved the Protocol requirements (Annex III, Article  
285 5) and that the receiving marine environment provided assimilative capacity, suitable dilution and  
286 rapid dispersal conditions. Nutrients are not suspected to have a significant effect on fauna and  
287 flora in the vicinity of the wastewater discharge. This is due to their rapid dilution in the waters of  
288 the Admiralty Bay, which has been demonstrated in this research. There is no eutrophication  
289 phenomenon in the vicinity of the Arctowski station, as in the case of urbanized areas. Nonetheless,  
290 natural biogeochemical cycles are potentially influenced by the continuous discharge of easily  
291 biodegradable wastewater ( $BOD_5/COD \geq 0.5$ ). This is of special concern and should be monitored,  
292 since the yearly volume of wastewater generated by the station can reach  $80.7 \text{ m}^3$ . Considering the  
293 mean values of daily water consumption (Table S1, Supplementary Material) and measured  
294 nutrient concentrations (Table S2, Supplementary Material), based on the product of these values,  
295 the total load of nitrogen is estimated to reach 2.28 - 5.34 kg/year (0.61 - 3.48 kg/year in ammonia  
296 form), phosphorus is estimated to reach 0.18 - 0.19 kg/year (0.06-0.11 kg/year in phosphate form),  
297 and organic matter expressed as COD is estimated to reach 88.0 - 129.9 kg/year. Especially in





298 nutrient-limited environments, any wastewater discharge entering the food web may upset the  
299 balance of the environment. High levels of organic material in wastewater may consume oxygen  
300 in water, causing reduced dissolved oxygen zone formation (Smith and Riddle, 2009). Hence,  
301 bottom water zones together with benthic invertebrates may be particularly at risk.

302 In our research, as important chemical markers of wastewater dissemination in the receiving  
303 environment, trace metals, surfactants and formaldehydes were chosen (Fig. S2, Table S3,  
304 Supplementary Material). Among the trace metals, potentially toxic heavy metals(Thornton et al.,  
305 2001), such as Cd, Cr, Cu, Ni, Pb and Zn, have been analysed. Moreover, taking into account  
306 ongoing discussion regarding the increase in filterable Fe concentration caused by the inflow of  
307 surface runoff into Antarctic costal seawater (Hodson et al., 2017), this element has also been  
308 analysed, considering wastewater as an additional source of Fe. Heavy metals were present in the  
309 Arctowski Station wastewater, with Zn, Pb, Fe and Ni at the highest concentrations (Table S3,  
310 Supplementary Material), and Zn and Fe of high significance (Fig. 3 C, D). Sources of Cd, Zn, Cu  
311 and Ni in domestic wastewater include personal care products, pharmaceuticals, cleaning products  
312 and liquid wastes (El Khatib et al., 2012; Eriksson and Donner, 2009; Tjandraatmadjia et al., 2006).  
313 These products used by people staying at the station go directly to the sewage tank or indirectly  
314 along with the waste. Part of the Zn and Cd load may also originate from transport emissions (El  
315 Khatib et al., 2012). Additionally, plumbing might be a source of Cu and Pb (Drozdova et al.,  
316 2019; El Khatib et al., 2012). In this case, the gradual replacement of Pb water pipes and fittings  
317 is recommended, especially during building renewal and renovation programmes (Thornton et al.,  
318 2001). Iron in wastewater may also originate from household products such as floor cleaners,  
319 laundry soakers or aerosol deodorants (Tjandraatmadjia et al., 2006). However, in the case of iron,  
320 its concentration in wastewater is also influenced by natural factors (Szopińska et al., 2018). Fresh



321 water in periglacial environments in this area contains easily soluble Al and Fe because the  
322 environment of King George Island is rich in pyrite (Paulo and Rubinowski, 1987). Considering  
323 the noticeable increase in Zn and Fe concentrations in seawater after wastewater discharge (Table  
324 S2, Supplementary Material, Fig. 3C and D), their accumulation in the impacted sediments is  
325 expected (Goldberg et al., 1975). Future studies are needed to analyse the responses of marine  
326 biota and benthic communities to the presence of heavy metals since their toxic effects have  
327 already been indicated (Bryan and Langston, 1992; King and Riddle, 2001; Lenihan et al., 2003;  
328 Sfiligoj, 2013).

329 Another special group of micropollutants analysed in this study are surfactants. Currently,  
330 surfactants are common components of the reagents used in industries and households (washing,  
331 wetting, emulsifying, and dispersing) due to their specific properties. As a result, different types  
332 of surfactants are added *inter alia* to personal care products, laundry and cleaning detergents  
333 (Olkowska et al., 2012). Thus, these compounds ultimately end up in wastewater. The  
334 classification of surfactants is usually made based on the chemical characteristics of hydrophobic  
335 groups: (1) ionic: cationic (e.g., benzyl ammonium chloride and dialkyl dimethyl ammonium  
336 chloride) and anionic (e.g., linear alkylbenzenesulfonates, secondary alkyl sulfates,  
337 perfluorooctanoic acid, and perfluorooctane sulfonates); (2) non-ionic: (e.g., octylphenol, nonyl  
338 phenol ethoxylates, and octylphenol ethoxylate) (Olkowska et al., 2012). In this study, the  
339 concentrations of cationic, anionic and non-ionic surfactants were analysed by spectrophotometry.  
340 This method is very useful for regular monitoring of this group of compounds and could be applied  
341 to Arctowski Station due to its reliability, availability and ease of use, which are important in the  
342 case of a lack of qualified staff (analytical chemists), especially during winter. The obtained results  
343 show the highest concentrations of anionic and non-ionic surfactants in both wastewater and



344 seawater (Fig. S2, Supplementary Material). This finding is consistent with the more frequent use  
345 of anionic and non-ionic surfactants than cationic surfactants (Olkowska et al., 2015).

346 We also checked the formaldehyde concentration level, which was detectable in wastewater and  
347 in seawater only directly after discharge (0.04-0.08 mg/L). Due to its high reactivity, colourless  
348 nature, stability and low cost, formaldehyde has been applied as a resinification agent, curing  
349 agent, synthetic agent, disinfectant, fungicide, and preservative (Lotfy and Rashed, 2002).  
350 Considering its minor concentration in the studied wastewater samples (0.60 - 0.75 mg/L),  
351 formaldehyde may originate from agents and disinfectants used during everyday activities at the  
352 station. Nevertheless, this aldehyde is highly toxic to living organisms – it may inhibit the  
353 physiological activity of cells by creating permanent connections with amino groups of proteins.  
354 Due to the ability to damage DNA and cause mutations in microorganisms, it also creates  
355 a carcinogenic risk. Hence, any wastewater containing formaldehyde might be toxic to  
356 microorganisms (Kowalik, 2011). Note that in niches exposed to formaldehyde or surfactants and  
357 other biocides (which permeabilize cell membranes and act as disinfectants), bacteria have evolved  
358 detoxification systems, e.g., the *frmRA(B)* operon (Denby et al., 2016) or *qacE* efflux pump genes  
359 (Pal et al., 2015).

360 Considering the available water consumption data (Table S1, Supplementary Material), the total  
361 annual loads of surfactants (SC, SA, SNI) and formaldehyde are estimated to be 0.016 - 0.082;  
362 0.092 - 0.165; 0.030 - 0.132 and 0.032 - 0.041 kg/year, respectively. Because wastewater is  
363 constantly disposed into Admiralty Bay, it may influence indigenous species. Potential  
364 environmental impacts, expressed as NOEC (the highest concentration/dose of a given substance  
365 in the test organism that does not cause severe effects or a significant increase), are presented in  
366 relation to micro-pollution detected in wastewater. The data summarised in Fig. 2 do not take into



367 account the dilution factor that occurs in seawater after discharge. Therefore, it is merely  
368 illustrative to present the potential risks of raw sewage emissions to the environment. The SC, SA,  
369 SNI, and Cu concentrations exceed the NOEC parameter, which suggests that these substances  
370 may cause damage in the tested species (*Antarctic red alga* and *Antarctic sea urchin*). Moreover,  
371 metal toxicity is also known for other species, e.g. two Antarctic marine microalgae – *Phaeocystis*  
372 *antarctica* (Gissi et al., 2015) and *Cryothecomonas armigera* (Koppel et al., 2017). However, data  
373 are presented via different toxicity assays to NOEC. These two species represent a very sensitive  
374 and a more tolerant species to metal contaminants, respectively. Based on 10% inhibition of  
375 population growth rate (IC10) values, *Phaeocystis antarctica* was most sensitive to copper (3.3  
376 mg/L), followed by cadmium (135 mg/L), lead (260 mg/L), and zinc (450 mg/L) (Gissi et al.,  
377 2015). On the other hand, for marine microalga *Cryothecomonas armigera*, the concentrations that  
378 reduced population growth rate by 10% (EC10) after 24-day for Cu, Pb, Zn, Cd and Ni were 21.6,  
379 152, 366, 454, and 1220 mg/L<sup>-1</sup>, respectively. Moreover, recently the data for the sea urchin used  
380 in Fig. 2 was reanalysed in (Koppel et al., 2020) to give EC values. The investigation showed  
381 EC10 and EC50 values, respectively, of Cu: 0.9 and 1.4 µg/L<sup>-1</sup>, and Zn: 56 ± 31 and 195 ± 44  
382 µg/L<sup>-1</sup> for 23 day larval development inhibition. Hence based on data presented by Koppel and co-  
383 authors (Koppel et al., 2020) processed considering the risk of contaminant mixtures using a toxic-  
384 units approach, the combination of Cu and Zn concentrations in the 2017 wastewater (Fig. 2) may  
385 be considered harmful *inter alia* to the sea urchin (e.g. *S. neumayeri*). Additionally, preliminary  
386 studies for microalgae have shown that *P. antarctica* and *C. armigera* are capable of accumulating  
387 potentially toxic concentrations of metals like copper and zinc (Koppel et al., 2020).

388 Moreover, as previously mentioned, trace metals have an affinity for particulate organic matter  
389 and thus may accumulate in the bottom zone (Licínio et al., 2008). Hence, a detailed study of



390 micro-pollution concentration levels in sediments and their environmental (ecotoxicological)  
391 impact needs to be addressed as a next step in research on wastewater disposal influence on wildlife  
392 health in Admiralty Bay.

### 393 **4.3 Wastewater technology innovations for sustainable impacts of Arctowski Station**

394 The treatment of domestic wastewater is a multistep process that includes physical, biological  
395 and chemical treatment steps (USEPA, 2012). Recently, advanced treatment methods such as  
396 advanced oxidation processes e.g. ozonation, or sorption-based processes e.g. activated carbon  
397 technologies (Kosek et al., 2020) have been applied consecutively in the context of  
398 pharmaceutical and other organic micro-pollution removal. According to the obtained results, there  
399 is no doubt that proper wastewater treatment is required to limit the adverse impact on receiving  
400 water and to comply with environmental safety requirements. However, the choice of proper  
401 wastewater treatment method/s is a complex engineering and economic problem that depends on  
402 the properties and volumes of generated wastewater, expected discharge requirements, potential  
403 sludge management and local conditions.

404 In the case of wastewater treatment plant construction in Antarctica, it is necessary to consider  
405 at least (1) operations at low temperatures (even  $-60^{\circ}\text{C}$ ); (2) large fluctuations in station population  
406 between the summer and winter seasons, causing significant variations in the generated wastewater  
407 volume; and (3) different effluent characteristics within the stations. Operations at low  
408 temperatures require heating or insulation of the wastewater lines, holding tanks, pumps and other  
409 treatment facilities (Stark et al., 2015). Moreover, the majority of wastewater treatment technology  
410 requires adequate pipe heating systems to prevent freezing and needs to be placed in enclosed  
411 buildings to limit the possibility of contact with wildlife. Additionally, the differences in  
412 wastewater characteristics are noticeable between various bases (Table 1).

413 As an example, we may consider BOD values in the non-treated wastewater, which in Antarctica  
414 are relatively high (up to 3167 mg/L at Davis Station (Stark et al., 2015)) and associated with high  
415 calorific value food input that is rich in fat within the standard diet (Connor, 2008). In addition to  
416 organic matter, conventional wastewater treatment plants are designed to remove nutrients and  
417 suspended solids. Nitrogen can be removed from wastewater mainly during biological processes,  
418 while phosphorus is removed mostly by biological treatment or by chemical precipitation (with  
419 iron or aluminium salts). However, in polar regions, treatment effectiveness due to extreme  
420 temperature conditions may vary significantly. Thus, the implementation of advanced wastewater  
421 treatment is needed, especially in terms of micro-pollution contamination. According to the  
422 available survey, in the majority of Antarctic stations, there is a lack of wastewater treatment.  
423 Gröndahl and co-authors (Gröndahl et al., 2009) reported that 37% of permanent stations and 69%  
424 of summer Antarctic stations lack any form of treatment facility. However, apart from biological  
425 and secondary treatment, even the presence of septic tanks or maceration is considered wastewater  
426 treatment (Gröndahl et al., 2009). Nevertheless, in recent years, ozonation,  
427 micro/ultra/nanofiltration, biologically activated carbon filtration, reverse osmosis, ultraviolet  
428 disinfection and chlorination were tested to obtain potable water and nontoxic brine concentrate in  
429 Antarctica (Allinson et al., 2018), especially for the separated 'grey' wastewater (liquid waste  
430 without input from toilets). This shows the efforts being made to minimise the environmental  
431 impact caused by wastewater effluent disposal. Considering the high expectation for protecting the  
432 Antarctic environment, novel approaches should also be considered, including the zero discharge  
433 of contaminants or introduced microorganisms, as well as the potential reuse of treated water,  
434 which is an important aspect of circular economy (Stark et al., 2015). The choice of technology  
435 should consider efficient energy consumption and reduction of carbon footprint (Zaborowska et

436 al., 2019). There are some innovative technologies based on advanced oxidation processes that  
437 may also be considered for implementation in polar regions or in small remote communities.  
438 Currently, electrolysis is a promising technology for small and variable flow wastewater treatment  
439 installations where simplicity of use, with high efficiency of removal of micropollutants and  
440 reduction in by-products, is important (Gomez-Ruiz et al., 2017). Electrochemical experiments  
441 were conducted with anodes consisting of boron-doped diamond (BDD) during landfill leachate  
442 treatment, which is very hard to treat. It was found that in BDD, organic substances were  
443 preferentially oxidised via a fast reaction with hydroxyl radicals, leading to very high removal  
444 rates, including micropollutants like bisphenol A (BPA), perfluoroalkyl and polyfluoroalkyl  
445 substances (PFASs) etc. (Fudala-Ksiazek et al., 2018; Gomez-Ruiz et al., 2017, Pierpaoli et al.,  
446 2021). BDD-based electrochemical oxidation could also be integrated with biochemical treatment  
447 processes to obtain synergistic effects in pollutant degradation. Zhao and co-authors (Zhao et al.,  
448 2010) used a synergistic combination of biochemical treatment and electrochemical oxidation for  
449 the selection treatment of landfill leachate on the electrode. Therefore, technology that combines  
450 BDD with a biological membrane reactor enables the effective removal of ammonium nitrogen  
451 and organic matter (together with micropollutants and microorganisms), and the treatment  
452 efficiency is rather stable and high, despite the high flow variability of wastewater. An additional  
453 advantage is the limited production of excess sludge (Fudala-Ksiazek et al., 2018). Thus, such a  
454 module system seems to be the optimal solution for wastewater treatment in the Antarctic region.

## 455 **5. Conclusions**

456 Specific properties of wastewater generated at polar research stations may have direct  
457 consequences on the Antarctic ecosystem. This study shows that Arctowski Station wastewater  
458 contains contamination such as trace metals, different groups of surfactants and formaldehydes.





459 Parameters such as the SC, SA and SNI surfactants may be selected as markers of human activity  
460 in Antarctica and can be considered as parameters for routine wastewater quality control before its  
461 disposal into the environment. Moreover, our results also indicate that wastewater contamination  
462 cannot be measured in seawater after one day of natural processes, except for the presence of  
463 anionic surfactants and Zn. Nevertheless, these results indicate that Arctowski Station wastewater  
464 management achieved the Protocol requirements (Annex III, Article 5) and that the receiving  
465 marine environment provided assimilative capacity, suitable dilution and rapid dispersal  
466 conditions. However, the Protocol does not include microbiological parameters and emerging  
467 pollutants such as BPA and PFAS. Detailed examination of the wide range of micropollution  
468 determination (including pharmaceuticals, poly- and per-fluorinated compounds, pesticides etc.)  
469 is needed to fully assess wastewater pollution and its impact on Antarctic ecosystems. Such  
470 detailed knowledge will help to focus appropriate research in the future and to target proper  
471 prevention and mitigation actions, especially in the development of suitable wastewater treatment  
472 systems in Antarctica to reduce its negative impact. In this process, in addition to scientific stations,  
473 the potential impact of increasing commercial tourism must also be considered. .

## 474 **6. Acknowledgements**

475 This research was supported by the National Science Centre Poland project task  
476 (MINIATURA2) entitled '*Recognition and selection of pollution markers introduced into*  
477 *Admiralty Bay via wastewater discharge: An example from Arctowski Polish Antarctic Station.*  
478 *King George Island. Maritime Antarctica*', agreement no. 2018/02/X/ST10/01539. The authors  
479 would like to thank Prof. Danuta Szumińska and the staff of Arctowski Station for their invaluable help  
480 during the field campaign.

## 481 **7. CRediT author statement**

482 **Małgorzata Szopińska:** Conceptualization, Methodology, Investigation, Visualization, Writing -  
483 Original Draft, Review & Editing, Project administration, Funding acquisition. **Aneta**  
484 **Łuczkiwicz:** Conceptualization, Writing - Review & Editing. **Katarzyna Jankowska:**  
485 Conceptualization, Investigation, **Sylwia Fudala-Książek:** Visualization, Writing - Review &  
486 Editing. **Joanna Potapowicz:** Validation, Writing - Review & Editing. **Agnieszka Kalinowska:**  
487 Writing - Review & Editing. **Robert Józef Bialik:** Visualization, Formal analysis, **Stanisław**  
488 **Chmiel:** Investigation. **Żaneta Polkowska:** Supervision

## 489 **8. Supplementary Material**

490 Supplementary Material consists of: S1. Additional information regarding the influence of  
491 wastewater discharge in Admiralty Bay, and S2. Detailed information regarding the applied  
492 chemical methods.

## 493 **9. References**

- 494 Allinson, M., Kadokami, K., Shiraishi, F., Nakajima, D., Zhang, J., Knight, A., Gray, S.R., Scales,  
495 P.J., Allinson, G., 2018. Wastewater recycling in Antarctica: Performance assessment of an  
496 advanced water treatment plant in removing trace organic chemicals. *J. Environ. Manage.*  
497 224, 122–129. <https://doi.org/10.1016/j.jenvman.2018.07.020>
- 498 American Public Health Association, American Water Works Association, Water Environment  
499 Federation, American Public Health Association (APHA), A.W.W.A. (AWWA) \& W.E.F.  
500 (WEF), 2005. *Standard Methods for the Examination of Water and Wastewater* 21st Edition,  
501 Standard Methods.
- 502 Bargagli, R., 2008. Environmental contamination in Antarctic ecosystems. *Sci. Total Environ.* 400,  
503 212–226. <https://doi.org/10.1016/j.scitotenv.2008.06.062>

- 504 Benninghoff, W.S., Bonner, W.N., 1985. Man's Impact on the Antarctic Environment, Scientific  
505 Committee on Antarctic Research, Scott Polar Research Institute. Cambridge, England.
- 506 Bryan, G.W., Langston, W.J., 1992. Bioavailability, accumulation and effects of heavy metals in  
507 sediments with special reference to United Kingdom estuaries: a review. *Environ. Pollut.* 76,  
508 89–131. [https://doi.org/10.1016/0269-7491\(92\)90099-V](https://doi.org/10.1016/0269-7491(92)90099-V)
- 509 Conlan, K.E., Kim, S.L., Lenihan, H.S., Oliver, J.S., 2004. Benthic changes during 10 years of  
510 organic enrichment by McMurdo Station, Antarctica. *Mar. Pollut. Bull.* 49, 43–60.  
511 <https://doi.org/10.1016/j.marpolbul.2004.01.007>
- 512 Connor, M.A., 2008. Wastewater treatment in Antarctica. *Polar Rec.* 44, 165–171.  
513 <https://doi.org/10.1017/S003224740700719X>
- 514 Corsolini, S., 2009. Industrial contaminants in Antarctic biota. *J. Chromatogr. A* 1216, 598–612.  
515 <https://doi.org/10.1016/j.chroma.2008.08.012>
- 516 Crockett, A.B., 1997. Water and wastewater quality monitoring, McMurdo Station, Antarctica.  
517 *Environ. Monit. Assess.* 47, 39–57. <https://doi.org/10.1023/A:1005786218570>
- 518 Denby, K.J., Iwig, J., Bisson, C., Westwood, J., Rolfe, M.D., Sedelnikova, S.E., Higgins, K.,  
519 Maroney, M.J., Baker, P.J., Chivers, P.T., Green, J., 2016. The mechanism of a  
520 formaldehyde-sensing transcriptional regulator. *Sci. Rep.* 6, 38879.  
521 <https://doi.org/10.1038/srep38879>
- 522 Drozdova, J., Raclavska, H., Raclavsky, K., Skrobankova, H., 2019. Heavy metals in domestic  
523 wastewater with respect to urban population in Ostrava, Czech Republic. *Water Environ. J.*  
524 33, 77–85. <https://doi.org/10.1111/wej.12371>

- 525 El Khatib, R., Lartiges, B.S., El Samrani, A., Faure, P., Houhou, J., Ghanbaja, J., 2012. Speciation  
526 of Organic Matter and Heavy Metals in Urban Wastewaters from an Emerging Country.  
527 Water, Air, & Soil Pollut. 223, 4695–4708. <https://doi.org/10.1007/s11270-012-1226-1>
- 528 Eriksson, E., Donner, E., 2009. Metals in greywater: Sources, presence and removal efficiencies.  
529 Desalination 248, 271–278. <https://doi.org/10.1016/j.desal.2008.05.065>
- 530 Fudala-Ksiazek, S., Sobaszek, M., Luczkiewicz, A., Pieczynska, A., Ofiarska, A., Fiszka-  
531 Borzyszkowska, A., Sawczak, M., Ficek, M., Bogdanowicz, R., Siedlecka, E.M., 2018.  
532 Influence of the boron doping level on the electrochemical oxidation of raw landfill leachates:  
533 Advanced pre-treatment prior to the biological nitrogen removal. Chem. Eng. J. 334, 1074–  
534 1084. <https://doi.org/10.1016/j.cej.2017.09.196>
- 535 Gheorghe, S., Lucaciu, I., Paun, I., Stoica, C., Stanescu, E., 2013. Ecotoxicological Behavior of  
536 some Cationic and Amphoteric Surfactants (Biodegradation, Toxicity and Risk Assessment),  
537 in: Biodegradation - Life of Science. InTech. <https://doi.org/10.5772/56199>
- 538 Gissi, F., Adams, M.S., King, C.K., Jolley, D.F., 2015. A robust bioassay to assess the toxicity of  
539 metals to the Antarctic marine microalga *Phaeocystis antarctica*. Environ. Toxicol. Chem. 34,  
540 1578–1587. <https://doi.org/10.1002/etc.2949>
- 541 Goldberg, E.D., Beynon, K.I., de Groot, A.J., Duinker, J.C., Elster, H.-J., Halstead, R.L.,  
542 Heurteaux, P., Kloke, A., La Riviere, J.W.M., Miller, D.R., Price, I., Yule, A.N., Duce, T.,  
543 1975. Entry, Distribution, and Fate of Heavy Metals and Organohalogens in the Physical  
544 Environment, in: McIntyre, A.D., Mills, C.F. (Eds.), Ecological Toxicology Research. New  
545 York, pp. 233–256. [https://doi.org/10.1007/978-1-4615-8945-7\\_14](https://doi.org/10.1007/978-1-4615-8945-7_14)

- 546 Gomez-Ruiz, B., Gómez-Lavín, S., Diban, N., Boiteux, V., Colin, A., Dauchy, X., Urriaga, A.,  
547 2017. Efficient electrochemical degradation of poly- and perfluoroalkyl substances (PFASs)  
548 from the effluents of an industrial wastewater treatment plant. *Chem. Eng. J.* 322, 196–204.  
549 <https://doi.org/10.1016/j.cej.2017.04.040>
- 550 González-Alonso, S., Merino, L.M., Esteban, S., López de Alda, M., Barceló, D., Durán, J.J.,  
551 López-Martínez, J., Aceña, J., Pérez, S., Mastroianni, N., Silva, A., Catalá, M., Valcárcel, Y.,  
552 2017. Occurrence of pharmaceutical, recreational and psychotropic drug residues in surface  
553 water on the northern Antarctic Peninsula region. *Environ. Pollut.* 229, 241–254.  
554 <https://doi.org/10.1016/j.envpol.2017.05.060>
- 555 Gröndahl, F., Sidenmark, J., Thomsen, A., 2009. Survey of waste water disposal practices at  
556 Antarctic research stations. *Polar Res.* 28, 298–306. [https://doi.org/10.1111/j.1751-](https://doi.org/10.1111/j.1751-8369.2008.00056.x)  
557 [8369.2008.00056.x](https://doi.org/10.1111/j.1751-8369.2008.00056.x)
- 558 Hodson, A., Nowak, A., Sabacka, M., Jungblut, A., Navarro, F., Pearce, D., Ávila-Jiménez, M.L.,  
559 Convey, P., Vieira, G., 2017. Climatically sensitive transfer of iron to maritime Antarctic  
560 ecosystems by surface runoff. *Nat. Commun.* 8, 14499.  
561 <https://doi.org/10.1038/ncomms14499>
- 562 King, C.K., Riddle, M.J., 2001. Effects of metal contaminants on the development of the common  
563 Antarctic sea urchin *Sterechinus neumayeri* and comparisons of sensitivity with tropical and  
564 temperate echinoids. *Mar. Ecol. Prog. Ser.* 215, 143–154.  
565 <https://doi.org/10.3354/meps215143>
- 566 Koppel, D.J., Gissi, F., Adams, M.S., King, C.K., Jolley, D.F., 2017. Chronic toxicity of five  
567 metals to the polar marine microalga *Cryothecomonas armigera* – Application of a new

- 568 bioassay. *Environ. Pollut.* 228, 211–221. <https://doi.org/10.1016/j.envpol.2017.05.034>
- 569 Koppel, D.J., King, C.K., Brown, K.E., Price, G.A. V., Adams, M.S., Jolley, D.F., 2020. Assessing  
570 the Risk of Metals and Their Mixtures in the Antarctic Nearshore Marine Environment with  
571 Diffusive Gradients in Thin-Films. *Environ. Sci. Technol.* 54, 306–315.  
572 <https://doi.org/10.1021/acs.est.9b04497>
- 573 Kosek K., Luczkiewicz, A., Fudala-Książek, S., Jankowska, K., Szopińska, M., Svahn, O.,  
574 Tränckner, J., Kaiser, A., Langas, V., Björklund, E., Implementation of advanced  
575 micropollutants removal technologies in wastewater treatment plants (WWTPs) – Examples  
576 and challenges based on selected EU countries. *Environmental Science and Policy*, 112  
577 (2020) 213-226, doi 10.1016/j.envsci.2020.06.011
- 578 Kowalik, P., 2011. Chemical pretreatment of formaldehyde wastewater by selected Advanced  
579 Oxidation Processes (AOPs). *Challenges Mod. Technol.* 2, 42–48.
- 580 Kumar Bharti, P., Sharma, B., Singh, R.K., Tyagi, A.K., 2016. Waste Generation and  
581 Management in Antarctica. *Procedia Environmental Sciences* 35, 40-50.  
582 <https://doi.org/10.1016/j.proenv.2016.07.004>
- 583 Lenihan, H.S., Oliver, J.S., 1995. Anthropogenic and natural disturbances to marine benthic  
584 communities in Antarctica. *Ecol. Appl.*
- 585 Lenihan, H.S., Peterson, C.H., Kim, S.L., Conlan, K.E., Fairey, R., McDonald, C., Grabowski,  
586 J.H., Oliver, J.S., 2003. Variation in marine benthic community composition allows  
587 discrimination of multiple stressors. *Mar. Ecol. Prog. Ser.* 261, 63–73.  
588 <https://doi.org/10.3354/meps261063>

- 589 Licínio, M.V.S., Patchineelan, S.R., Evangelista, H.S., Araripe, D.R., 2008. History of heavy  
590 metals contamination in lacustrine sediments of Admiralty bay, King George Island,  
591 Antarctic Peninsula. *Indian J. Mar. Sci.* 37, 391–395.
- 592 Lotfy, H.R., Rashed, I.G., 2002. A method for treating wastewater containing formaldehyde.  
593 *Water Res.* 36, 633–637. [https://doi.org/10.1016/S0043-1354\(01\)00255-X](https://doi.org/10.1016/S0043-1354(01)00255-X)
- 594 Martins, C. de C., Montone, R.C., Gamba, R.C., Pellizari, V.H., 2005. Sterols and fecal indicator  
595 microorganisms in sediments from Admiralty Bay, Antarctica. *Brazilian J. Oceanogr.* 53, 1–  
596 12. <https://doi.org/10.1590/S1679-87592005000100001>
- 597 Martins, C.C., Venkatesan, M.I., Montone, R.C., 2002. Sterols and linear alkylbenzenes in marine  
598 sediments from Admiralty Bay, King George Island, South Shetland Islands. *Antarct. Sci.* 14,  
599 244–252. <https://doi.org/10.1017/S0954102002000093>
- 600 Montone, R.C., Martins, C.C., Bicego, M.C., Taniguchi, S., Albuquerque Moreira da Silva, D.,  
601 Campos, L.S., Weber, R.R., 2010. Distribution of sewage input in marine sediments around  
602 a maritime Antarctic research station indicated by molecular geochemical indicators. *Sci.*  
603 *Total Environ.* 408, 4665–4671. <https://doi.org/10.1016/j.scitotenv.2010.07.012>
- 604 Olkowska, E., Polkowska, Z., Namieśnik, J., 2011. Analytics of Surfactants in the Environment:  
605 Problems and Challenges. *Chem. Rev.* 111, 5667–5700. <https://doi.org/10.1021/cr100107g>
- 606 Olkowska, E., Polkowska, Ż., Namieśnik, J., 2012. Analytical procedures for the determination of  
607 surfactants in environmental samples. *Talanta* 88, 1–13.  
608 <https://doi.org/10.1016/j.talanta.2011.10.034>
- 609 Olkowska, E., Polkowska, Ż., Ruman, M., Namieśnik, J., 2015. Similar concentration of





- 610 surfactants in rural and urban areas. *Environ. Chem. Lett.* 13, 97–104.  
611 <https://doi.org/10.1007/s10311-014-0485-z>
- 612 Pal, C., Bengtsson-Palme, J., Kristiansson, E., Larsson, D.G.J., 2015. Co-occurrence of resistance  
613 genes to antibiotics, biocides and metals reveals novel insights into their co-selection  
614 potential. *BMC Genomics* 16, 964. <https://doi.org/10.1186/s12864-015-2153-5>
- 615 Paulo, A., Rubinowski, Z., 1987. Pyrite mineralization on King George Island (South Shetland  
616 Islands Antarctica): its distribution and origin. *Stud. Geol. Pol.* XC, 38–85.
- 617 Pierpaoli, M., Szopińska, M., Wilk, B.K., Sobaszek, M., Łuczkiewicz, A., Bogdanowicz, R.,  
618 Fudala-Książek, S., 2021. Electrochemical oxidation of PFOA and PFOS in landfill leachates  
619 at low and highly boron-doped diamond electrodes. *J. Hazard. Mater.* 403.  
620 <https://doi.org/10.1016/j.jhazmat.2020.123606>
- 621 Pons, M.N., Spanjers, H., Baetens, D., Nowak, O., Gillot, S., Nouwen, J., Schuttinga, N., 2004.  
622 Wastewater characteristics in Europe - A survey. *Eur. Water Manag. Online.*
- 623 Potapowicz, J., Szumińska, D., Szopińska, M., Polkowska, Ż., 2019. The influence of global  
624 climate change on the environmental fate of anthropogenic pollution released from the  
625 permafrost: Part I. Case study of Antarctica. *Sci. Total Environ.* 651, 1534–1548.  
626 <https://doi.org/10.1016/j.scitotenv.2018.09.168>
- 627 Rakusa-Suszczewski, S., (Ed.) 1993. The maritime Antarctic coastal ecosystem of Admiralty Bay.  
628 Department of Antarctic Biology, Polish Academy of Sciences, Warsaw. pp. 216.
- 629 Sfiligoj, B.J., 2013. Sensitivity of Antarctic marine invertebrates and microalgae to metal  
630 exposure. Ph.D. thesis, School of Life and Environmental Sciences, Deakin University,

- 631 Warrnambool. <http://dro.deakin.edu.au/view/DU:30066160> (accessed 20 April 2021).
- 632 Sladen, W.J.L., Menzie, C.M., Reichel, W.L., 1966. DDT residues in Adelie penguins and a  
633 crabeater seal from Antarctica. *Nature*. <https://doi.org/10.1038/210670a0>
- 634 Smith, J.J., Riddle, M.J., 2009. Sewage Disposal and Wildlife Health in Antarctica, in: *Health of*  
635 *Antarctic Wildlife*. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 271–315.  
636 [https://doi.org/10.1007/978-3-540-93923-8\\_16](https://doi.org/10.1007/978-3-540-93923-8_16)
- 637 Stark, J.S., Corbett, P.A., Dunshea, G., Johnstone, G., King, C., Mondon, J.A., Power, M.L.,  
638 Samuel, A., Snape, I., Riddle, M., 2016. The environmental impact of sewage and wastewater  
639 outfalls in Antarctica: An example from Davis station, East Antarctica. *Water Res.* 105, 602–  
640 614. <https://doi.org/10.1016/j.watres.2016.09.026>
- 641 Stark, J.S., Smith, J., King, C.K., Lindsay, M., Stark, S., Palmer, A.S., Snape, I., Bridgen, P.,  
642 Riddle, M., 2015. Physical, chemical, biological and ecotoxicological properties of  
643 wastewater discharged from Davis Station, Antarctica. *Cold Reg. Sci. Technol.* 113, 52–62.  
644 <https://doi.org/10.1016/j.coldregions.2015.02.006>
- 645 Steber, J., 2007. The Ecotoxicity of Cleaning Product Ingredients, in: *Handbook for*  
646 *Cleaning/Decontamination of Surfaces*. Elsevier, pp. 721–746. [https://doi.org/10.1016/B978-](https://doi.org/10.1016/B978-044451664-0/50022-X)  
647 [044451664-0/50022-X](https://doi.org/10.1016/B978-044451664-0/50022-X)
- 648 Szopińska, M., Namieśnik, J., Polkowska, Ż., 2017. How Important Is Research on Pollution  
649 Levels in Antarctica? Historical Approach, Difficulties and Current Trends, in: *Reviews of*  
650 *Environmental Contamination and Toxicology*. pp. 79–156.  
651 [https://doi.org/10.1007/398\\_2015\\_5008](https://doi.org/10.1007/398_2015_5008)



- 652 Szopińska, M., Szumińska, D., Bialik, R.J., Chmiel, S., Plenzler, J., Polkowska, Ż., 2018. Impact  
653 of a newly-formed periglacial environment and other factors on fresh water chemistry at the  
654 western shore of Admiralty Bay in the summer of 2016 (King George Island, Maritime  
655 Antarctica). *Sci. Total Environ.* 613–614, 619–634.  
656 <https://doi.org/10.1016/j.scitotenv.2017.09.060>
- 657 Tarasenko, S., 2008. Wastewater Treatment in Antarctica. GCAS.  
658 [https://ir.canterbury.ac.nz/bitstream/handle/10092/14196/GCAS\\_11Project\\_Tarasenko.pdf?](https://ir.canterbury.ac.nz/bitstream/handle/10092/14196/GCAS_11Project_Tarasenko.pdf?sequence=1)  
659 [sequence=1](https://ir.canterbury.ac.nz/bitstream/handle/10092/14196/GCAS_11Project_Tarasenko.pdf?sequence=1), [available 05.02.2021]
- 660 The Antarctic Treaty, 1959. The Antarctic Treaty. Conf. Antarct.  
661 <https://www.bas.ac.uk/about/antarctica/the-antarctic-treaty/the-antarctic-treaty-1959/>  
662 [available 05.02.2021]
- 663 Thornton, I., Butler, D., Docx, P., Hession, M., Makropoulos, C., Madeleine, M., Nieuwenhuijsen,  
664 Mark, D., Pitman, A., Rautiu, D.R., Sawyer, R., Smith, D.S., 2001. Pollutants in urban waste  
665 water and sewage sludge, European Commission. ....
- 666 Tjandraatmadjia, G., Cook, S., Gozukara, Y., 2006. Sources of Priority Contaminants in Domestic  
667 Wastewater – a literature review, CSIRO: Water for a Healthy Country National Research  
668 Flagship.
- 669 Tort, L.F.L., Iglesias, K., Bueno, C., Lizasoain, A., Salvo, M., Cristina, J., Kandravicius, N.,  
670 Pérez, L., Figueira, R., Bicego, M.C., Taniguchi, S., Venturini, N., Brugnoli, E., Colina, R.,  
671 Victoria, M., 2017. Wastewater contamination in Antarctic melt-water streams evidenced by  
672 virological and organic molecular markers. *Sci. Total Environ.* 609, 225–231.  
673 <https://doi.org/10.1016/j.scitotenv.2017.07.127>

674 USEPA, 2012. Standard Methods for the Examination of Water and Wastewater 22th Edition,  
675 American Public Health Association, American Water Works Association, Water  
676 Environment Federation.

677 Wild, S., McLagan, D., Schlabach, M., Bossi, R., Hawker, D., Cropp, R., King, C.K., Stark, J.S.,  
678 Mondon, J., Nash, S.B., 2015. An Antarctic Research Station as a Source of Brominated and  
679 Perfluorinated Persistent Organic Pollutants to the Local Environment. Environ. Sci.  
680 Technol. 49, 103–112. <https://doi.org/10.1021/es5048232>

681 Zaborowska, E., Lu, X., Makinia, J., 2019. Strategies for mitigating nitrous oxide production and  
682 decreasing the carbon footprint of a full-scale combined nitrogen and phosphorus removal  
683 activated sludge system. Water Res. 162, 53–63.  
684 <https://doi.org/10.1016/j.watres.2019.06.057>

685 Zhao, G., Pang, Y., Liu, L., Gao, J., Lv, B., 2010. Highly efficient and energy-saving sectional  
686 treatment of landfill leachate with a synergistic system of biochemical treatment and  
687 electrochemical oxidation on a boron-doped diamond electrode. J. Hazard. Mater. 179, 1078–  
688 1083. <https://doi.org/10.1016/j.jhazmat.2010.03.115>

## 689 **10. Web references**

690 The Protocol on Environmental Protection to the Antarctic Treaty,  
691 <https://www.ats.aq/e/protocol.html> (accessed 20 April 2021).

Supplementary Material to

# First evaluation of wastewater discharge influence on marine water contamination in the vicinity of Arctowski Station (Maritime Antarctica)

Małgorzata Szopińska, Aneta Luczkiewicz, Katarzyna Jankowska, Sylwia Fudala-Książek,  
Joanna Potapowicz, Agnieszka Kalinowska, Robert Józef Bialik, Stanisław Chmiel,  
Żaneta Polkowska

*Submitted to the Science of the Total Environment, Elsevier Journal*

February, 2021

**S1.** Additional information regarding the influence of wastewater discharge in Admiralty Bay

**Table S1.** Detailed data regarding water consumption and the number of people in recent years at Arctowski Station.

	daily water consumption [L]			number of people at the station		
	<i>mean</i>	<i>max</i>	<i>min</i>	<i>mean</i>	<i>max</i>	<i>min</i>
<b>2016</b>	153	193	117	14	26	8
<b>2017</b>	138	181	86	16	37	8
<b>2018</b>	152	221	111	13	25	6
<b>2019</b>	153	180	111	16	33	8
<b>mean</b>	149	194	106	15	30	8

**Table S2.** Basic chemical analysis results in wastewater and marine water samples.

PARAMETER	YEAR	RAW WASTEWATER	SEAWATER SAMPLING TIME REFERRING TO THE DISCHARGE TIME									
			<i>sampling point no 1</i>								<i>sampling point no 2</i>	
			<i>before</i>	<i>0 h</i>	<i>0.5 h</i>	<i>1 h</i>	<i>2 h</i>	<i>24 h</i>	<i>48 h</i>	<i>96h</i>	<i>2h</i>	<i>24 h</i>
pH	2017	6.88	8.2	8.1	8.08	8.11	8.11	8.18	-	-	8.17	8.16
[ - ]	2019	7.63	7.36	7.21	-	7.34	7.22	7.24	7.28	7.29	-	-
Conductivity [mS/cm]	2017	1.478	47.8	43.8	53.4	57.8	46.7	58.7	-	-	45	60.2
	2019	1.737	36.7	34.3	-	36.4	47.3	48.3	47.4	37.6	-	-
Redox [mV]	2017	119.8	119.8	120.5	119.5	119.1	118.7	117.7	-	-	118.4	117.4
	2019	152.5	85.6	10.7	-	39.6	47.4	49.6	61.2	70.1	-	-
COD [mgO <sub>2</sub> /L]	2017	2390 (diss. 406)	50.3	58.6	57.6	55.1	52.3	50.5	-	-	49.7	50.0
	2019	1618 (diss. 1019)	73.0	75.4	-	75.2	74.2	73.0	74.5	73.2	-	-
P-PO <sub>4</sub> <sup>3-</sup> [mg/L]	2017	1.12	0.053	0.072	0.059	0.049	0.052	0.055	-	-	0.053	0.058
	2019	2.09	0.069	0.120	-	0.073	0.064	0.059	0.068	0.070	-	-
TP [mg/L]	2017	3.21	0.921	2.10	0.950	0.820	0.850	0.890	-	-	0.085	0.091
	2019	3.44	0.991	1.91	-	0.925	0.825	1.20	0.853	0.655	-	-
N-NH <sub>4</sub> <sup>+</sup> [mg/L]	2017	11.2	<0.015	0.078	0.031	0.068	0.029	0.052	-	-	0.047	0.035
	2019	63.9	0.03	0.06	-	0.04	0.11	0.10	0.06	0.05	-	-



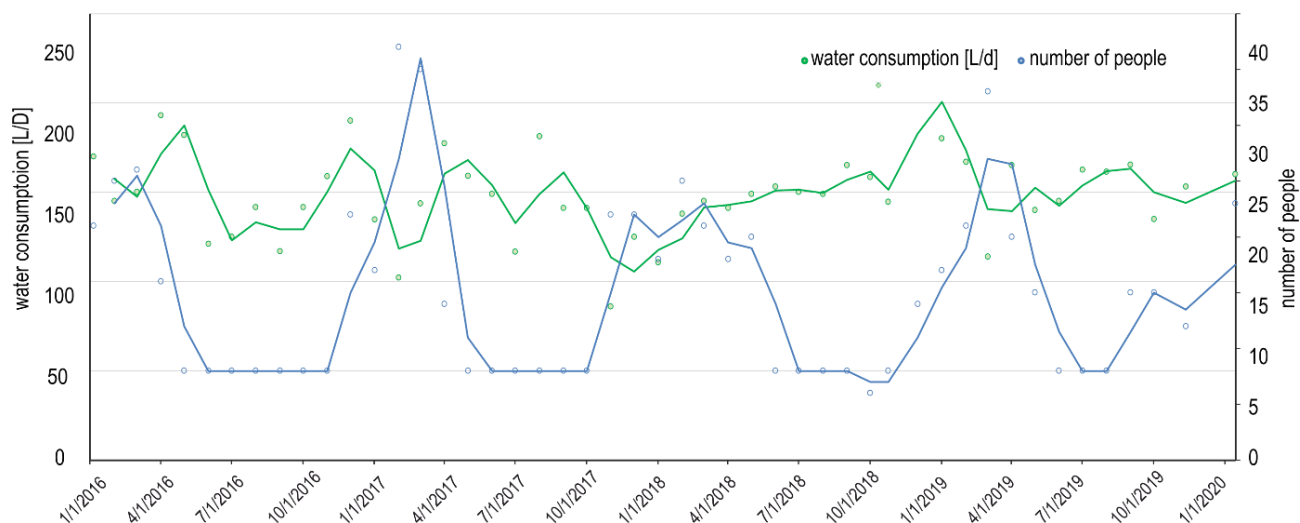
**Table S2. C.D.**

N-NO <sub>3</sub> <sup>-</sup> [mg/L]	2017	1.33	0.126	0.148	0.131	0.126	0.125	0.104	-	-	0.074	0.076
	2019	0.863	0.103	0.128	-	0.112	0.109	0.108	0.106	0.098	-	-
N-NO <sub>2</sub> <sup>-</sup> [mg/L]	2017	0.095	<0.015	<0.015	<0.015	<0.015	<0.015	<0.015	-	-	<0.015	<0.015
	2019	0.035	<0.015	<0.015	-	<0.015	<0.015	<0.015	<0.015	<0.015	-	-
TN [mg/L]	2017	42	0.228	0.312	0.254	0.225	0.213	0.197	-	-	0.179	0.172
	2019	98.2	0.315	1.21	-	0.384	0.239	0.189	0.062	<LOD	-	-

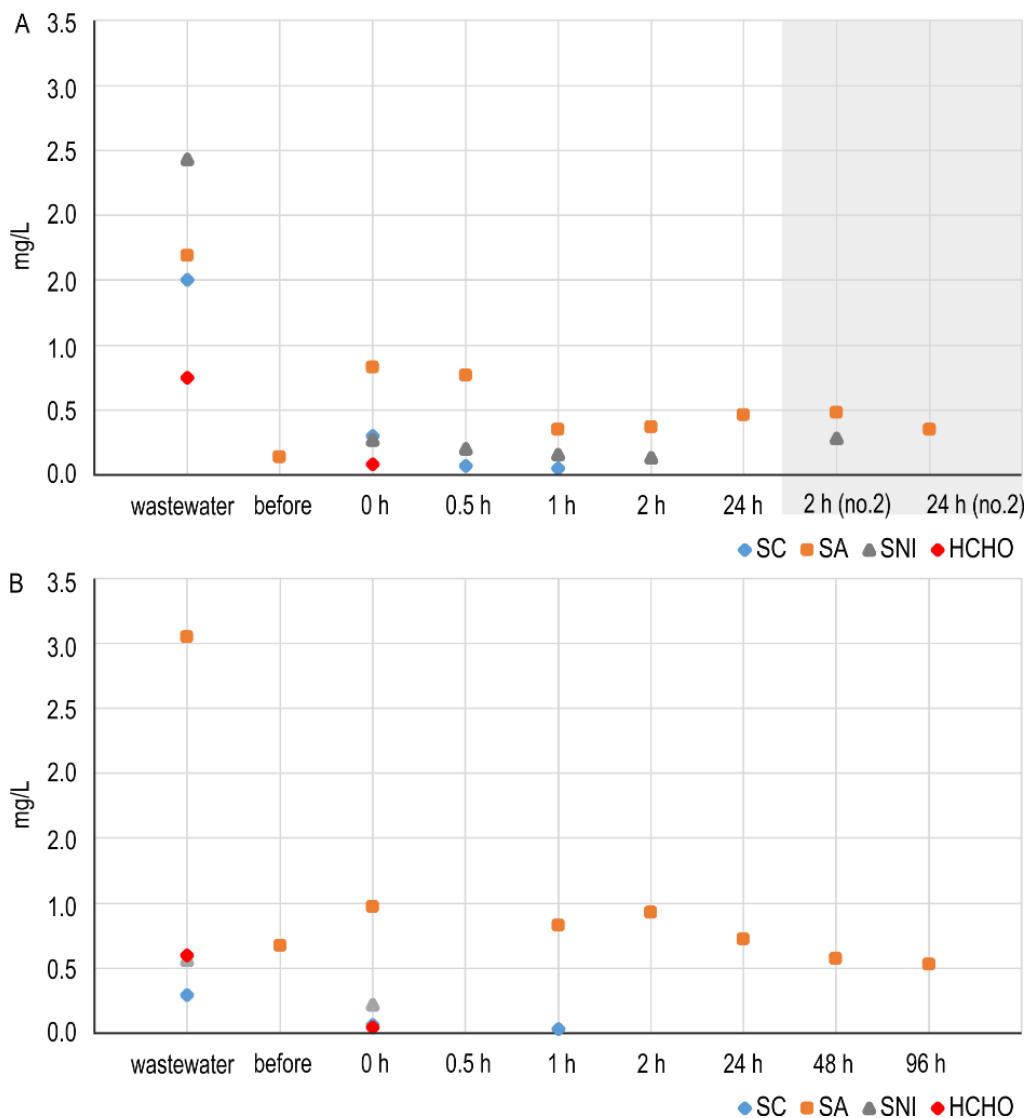
**Table S3.** Influence of wastewater discharge on marine water chemical characteristics in terms of selected heavy metal concentrations in the vicinity of Arctowski Station, Admiralty Bay

HEAVY METALS [µg/L]	YEAR	RAW WASTEWATER	SEAWATER SAMPLING TIME REFERRING TO THE DISCHARGE TIME									
			<i>sampling point no 1</i>								<i>sampling point no 2</i>	
			<i>before</i>	<i>0 h</i>	<i>0.5 h</i>	<i>1 h</i>	<i>2 h</i>	<i>24 h</i>	<i>48 h</i>	<i>96h</i>	<i>2h</i>	<i>24 h</i>
Cr	2017	4.43	0.31	0.34	0.42	0.43	0.38	0.33	-	-	0.35	0.32
	2019	2.67	0.53	0.59	-	0.68	0.64	0.55	0.57	0.79	-	-
Co	2017	1.68	0.02	0.01	0.01	0.01	0.02	0.01	-	-	0.01	0.01
	2019	2.13	0.06	0.14	-	0.03	0.02	0.02	0.02	0.02	-	-
Ni	2017	23.26	0.83	0.61	0.91	0.95	0.64	0.77	-	-	0.55	0.99
	2019	9.06	0.22	0.31	-	0.21	0.28	0.28	0.28	0.33	-	-
Cu	2017	4.27	0.17	0.11	0.17	0.20	0.17	0.10	-	-	0.12	0.09
	2019	8.80	0.53	0.86	-	0.25	0.53	0.89	1.14	1.41	-	-
Zn	2017	37.29	1.16	3.04	2.13	1.94	2.52	2.1	-	-	8.42	3.08
	2019	15.02	0.19	0.98	-	0.21	0.05	0.04	0.06	0.04	-	-
Cd	2017	0.45	0.02	0.01	0.01	0.02	0.01	0.01	-	-	0.01	0.02
	2019	0.03	0.02	0.02	-	0.01	0.01	0.01	0.01	0.01	-	-
Fe	2017	428	0.54	2.01	0.53	0.69	0.48	0.39	-	-	0.44	0.42
	2019	504	3.31	24.42	-	0.43	0.34	0.28	0.24	0.24	-	-
Pb	2017	0.48	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	-	-	<0.01	<0.01
	2019	0.14	<0.01	<0.01	-	<0.01	<0.01	<0.01	<0.01	<0.01	-	-





**Figure S1.** Water consumption in relation to the number of people present at Arctowski Station between Nov 2014 and Jan 2019. Data are obtained from Arctowski Station. Moving-average (period 2) line chart (for both: water consumption – green line, and no. of people – blue line) is applied.



**Figure S2.** Dilution of wastewater in Admiralty Bay at the discharge point at Arctowski Station: A) 2017 and B) 2019. Abbreviations and descriptions: SC- sum of cationic surfactants; SA- sum of anionic surfactants; SNI- sum of non-ionic surfactants; HCHO- formaldehyde; white area – sampling point no. 1; grey area – sampling point no. 2. The error bars for each data point have been omitted to increase the readability of the chart. Data not shown on graph means that concentration are <LOD (applies to all the time series data where there are no points for SC, SNI or formaldehyde, except 0.5 h in B, where was no measurements).



## S2. Detailed information regarding the applied chemical methods

**Table S4.** Basic analytical parameters characterising the applied methods.

PARAMETER/ANALYTE	TEST NAME AND CONCENTRATION RANGE / EQUIPMENT	COMPANY	LOD	LOQ	MEASUREMENT RANGE	CONFIDENCE INTERVAL (cuvette tests)	CONFIDENCE INTERVAL (electronic multimeters)
pH	HL-HQ40d Multimeter	Hach Lange	-	-	0 – 14	-	±0.002
Redox	HL-HQ40d Multimeter	Hach Lange	-	-	-1500 – +1500 mV	-	±0.1 mV
Conductivity	HL-HQ40d Multimeter	Hach Lange	-	-	0.01 µS/cm – 400 mS/cm	-	± 0.5 %
COD, chemical oxygen demand	LCK 1414 5–60 mg/L	Hach Lange	0.6 mg/L	2.0 mg/L	5.0 – 60 mg/L O <sub>2</sub>	± 0.75 mg/L	
P-PO <sub>4</sub> <sup>3-</sup>	LCK 349 0.05–1.5 mg/L	Hach Lange	0.007 mg/L	0.020 mg/L	0.05 – 1.5 mg/L	± 0.010 mg/L	
TP, total phosphorus	LCK 349 0.05–1.5 mg/L	Hach Lange	0.007 mg/L	0.020 mg/L	0.15 – 4.5 mg/L	± 0.010 mg/L	
N-NH <sub>4</sub> <sup>+</sup>	LCK 304, 0.015–2.0 mg/L NH <sub>4</sub> <sup>+</sup> -N	Hach Lange	0.005 mg/L	0.015 mg/L	0.015 – 2.0 mg/L	± 0.012 mg/L	
N-NO <sub>3</sub> <sup>-</sup>	LCK 339 0.23–13.50 mg/L NO <sub>3</sub> <sup>-</sup> -N	Hach Lange	0.210 mg/L	0.629 mg/L	0.23 – 13.5 mg/L	± 0.45 mg/L	
N-NO <sub>2</sub> <sup>-</sup>	LCK 341, 0.015–0.6 mg/L NO <sub>2</sub> <sup>-</sup> -N	Hach Lange	0.012 mg/L	0.037 mg/L	0.015 – 0.6 mg/L	± 0.035 mg/L	
TN, Total nitrogen	Laton Total Nitrogen cuvette test 1–16 mg/L	Hach Lange	0.116 mg/L	0.350 mg/L	1 – 16 mg/L	± 0.229 mg/L	



**Table S4 C.D.**

BOD, Biological oxygen demand	OxiTop, OC 100	WTW	-	-	0 – 4000 mg/L	± 1 %
sum of cationic surfactants	0.05–1.50 mg/L	Spectroquant, Merck	0.027 mg/L	0.05 mg/L	0.05 – 1.50 mg/L	± 0.017 mg/L
sum of anionic surfactants	0.05–2.0 mg/L	Spectroquant, Merck	0.030 mg/L	0.05 mg/L	0.05 – 2.00 mg/L SDSA (calculated as sodium 1-dodecanesulfonate)	± 0.10 mg/L
sum of non-ionic surfactants	0.1–7.5 mg/L	Spectroquant, Merck	0.062 mg/L	0.15 mg/L	0.1 – 7.5 mg/L	± 0.075 mg/L
HCHO-formaldehyde	No. 14678, 0.02–8 mg/L	Spectroquant, Merck	0.040 mg/L	0.10 mg/L	0.10 – 8.00 mg/L	± 0.087 mg/L
Cr						-
Co						
Ni			0.030 µg/L	0.10 µg/L	0.10– 1000 µg/L	0.5-1.5%*
Cu						
Zn	ICP-MS	ICP-MS X Series 2 Thermo Scientific				
Cd			0.002 µg/L	0.006 µg/L	0.01–1000 µg/L	- 0.5-1.5%*
Pb			0.003 µg/L	0.01 µg/L	0.01–1000 µg/L	- 0.5-1.5%*
Fe			0.30 µg/L	0.60 µg/L	0.60– 1000 µg/L	- 0.5-1.5%*

\* relative standard deviation