QUAESTIONES GEOGRAPHICAE 43(3) • 2024

LAKE SEDIMENTS AS MICROPLASTIC SINK: THE CASE OF THREE LAKES FROM NORTHERN AND CENTRAL POLAND

Michał Fojutowski

Department of Environmental Resources and Geohazards, Institute of Geography and Spatial Organization,
Polish Academy of Sciences, Toruń, Poland

Manuscript received: April 9, 2024
Revised version: June 19, 2024

Fojutowski M., 2024. Lake sediments as microplastic sink: The case of three lakes from Northern and Central Poland. *Quaestiones Geographicae* 43(3), Bogucki Wydawnictwo Naukowe, Poznan, pp. 103–112. 7 figs.

Abstract: Microplastic (MP) concentrations were determined in surface samples of bottom sediments collected from three lakes in northern and central Poland, located in catchments with low direct anthropopressure. Between 4 MP and 21 MP particles per kilogram of wet sediment were identified in the lakes studied. These values are small compared to those found in lakes located in urbanised areas and other aquatic environments, but important from the point of view of the threat to local freshwater ecosystems. The differences in the number of MP particles in the three examined lakes are a result of the way their nearest environments are used. Lake Czechowskie, the richest in MP particles found, is partially surrounded by pastures and arable lands, while some of the areas lying by are also seasonally used for recreation. In contrast, Lakes Głęboczek and Gościąż, both completely surrounded by forests, show significantly less MP pollution. The sources of MP in these lakes are primarily attributed to atmospheric transport. A correlation was made between the deepest detected MP particles (ranging from 25 cm to 60 cm) and the rate of sedimentation in the lakes, calculated based on the average annual deposition in sediment traps. Based on this, the attempt was made to determine the exact year of the deepest identified MP particles. The results obtained for each lake – the year 1901 for Lake Czechowskie, 1963 for Lake Głęboczek and 1986 for Lake Gościąż – were interpreted in terms of the sources of MP origin.

Keywords: microplastic, lake sediments, sediment accumulation rate, Central Europe

Corresponding author: Michał Fojutowski; mfojutowski@twarda.pan.pl

Introduction

Plastic, whose mass production began in the 1950s, is an increasingly common environmental pollutant (Xiong et al. 2018). Due to its properties, it is one of the main materials used in the production of packaging, the building and construction industry, the household goods industry or the electronics and electrical industry (Cole et al. 2011, Hidalgo-Ruz et al. 2012, Eerkes-Medrano et al. 2015). It is estimated that >9 billion tons of plastic have been produced worldwide to date. Globally, the total weight of plastic products (without products resulting from the plastic recycling process) was about 367 million tons in 2020. In Europe alone, it was about 55 million tons, but it should be noted that since 2017, when 64.4 million tons were produced, production volume has been slowly declining (PlasticsEurope 2021).

The mass use of plastic items with improper planning and process of recycling has caused them to become ubiquitous in the natural envi-

https://doi.org/10.14746/quageo-2024-0029
ISSN 2082-2103, eISSN 2081-6383

ronment (Harley-Nyang et al. 2023). As a result, plastic pollution has become dangerous to both living and non-living components of the environment (Iroegbu et al. 2021). Objects made of plastic, as a result of improper disposal, end up in the environment through various routes, where they begin to degrade under the influence of factors such as UV radiation, high temperature, mechanical fragmentation during the flow or rippling of water, or biodegradation processes (Weinstein et al. 2016). As a result, they break down into smaller particles, and based on size, they can be divided into macroplastics (>25 mm), mesoplastics (5–25 mm), microplastics (1 μm–5 mm) and nanoplastics (<1 μm) (Hartmann et al. 2019). Currently, the most frequently discussed issue is environmental pollution with microplastics (MPs). In the literature, one can also encounter a classification according to which MPs are particles from 1 μm to 1 mm (Hartmann et al. 2019, Ivleva 2021), but the most widely used classification is the one according to which MPs are particles from 1 μm to 5 mm. MP can appear in the environment in primary or secondary form (Mintenig et al. 2017). The primary form is particles of MP, contained in various types of cosmetics such as creams, scrubs, toothpastes and lipsticks, and in detergents such as powders, gels, laundry capsules, detergents or dishwasher tablets, which are supposed to increase their effectiveness. After human use, they travel through sewer systems to wastewater treatment plants, where, unfortunately, not all of them are caught and end up in the environment. The secondary form of MP is the aforementioned degradation, directly in the natural environment, of plastic objects into smaller particles (Andrady et al. 2022).

In scientific research, the issue of plastic pollution was first addressed when clusters of plastic waste floating on the surface of the Sargasso Sea were described (Carpenter, Smith 1972), while the first study of plastic pollution in lakes was on Lake Huron in North America (Zbyszewski, Corcoran 2011). Pollution of the natural environment by MP is a pervasive problem today (Vaughan et al. 2017). In addition to common examples, such as pollution of seas, rivers, lakes and soil, MP is also found in the air (Gasperi et al. 2015, 2018), at high altitudes (Allen et al. 2019), in the digestive systems of animals (Gurjar et al. 2021) and their faeces (Santillán et al. 2020), in brewed tea (Hernandez et al. 2019) and bottled water (Welle, Franz 2018), in human lungs (Jenner et al. 2022) and blood (Leslie et al. 2022) or even in the bodies of newborn babies (Sripada et al. 2022). MP also enters the environment as a result of everyday human activity involving, for example, opening bottled water or other plastic packaging (Sobhani et al. 2020).

Research on the occurrence of MPs in the environment has for a long time focussed mainly on marine areas, but over the last few years, knowledge about the presence of MPs in freshwater ecosystems has been significantly expanded (Talbot, Chang 2022). By 2021, 98 lakes in the world have been described that are identified with MP pollution (Dusaucy et al. 2021). This number is systematically increasing (D'Avignon et al. 2022, Yang et al. 2022, Nava et al. 2023, Dimante-Deimantovica et al. 2024). In Poland, MP pollution in lakes has so far been the subject of only a few publications (Kaliszewicz et al. 2020, Rogowska et al. 2021, Nava et al. 2023, Pol et al. 2023) and none of them analysed the presence of MP in bottom sediments. Therefore, the research aimed to determine the concentration of MP particles in the bottom sediments of lakes lying outside urban areas. Combined with data on average sedimentation rates in so-called 'Danish' traps, this survey was carried out to determine whether MP could be used as an indicator of sedimentation rates in lakes.

Study area

The Czechowskie and Głęboczek lakes are located in the Tuchola Forest area in northern Poland. The two reservoirs are located within a single catchment, drained by the Struga Czechowska River flowing through the lakes, about 1.5 km apart. Lake Czechowskie has an area of 73 ha and a maximum depth of 32 m, while Lake Głęboczek has an area of 7 ha and a maximum depth of 18 m (Kordowski et al. 2014). Lake Czechowskie is surrounded by forest on the eastern and southern sides, while the northern and western sides are arable land. On the northern shore of the lake, there is a resort open in the summer season, while a small beach is located on the eastern shore. Summer buildings are scattered around the lake. Lake Głęboczek is

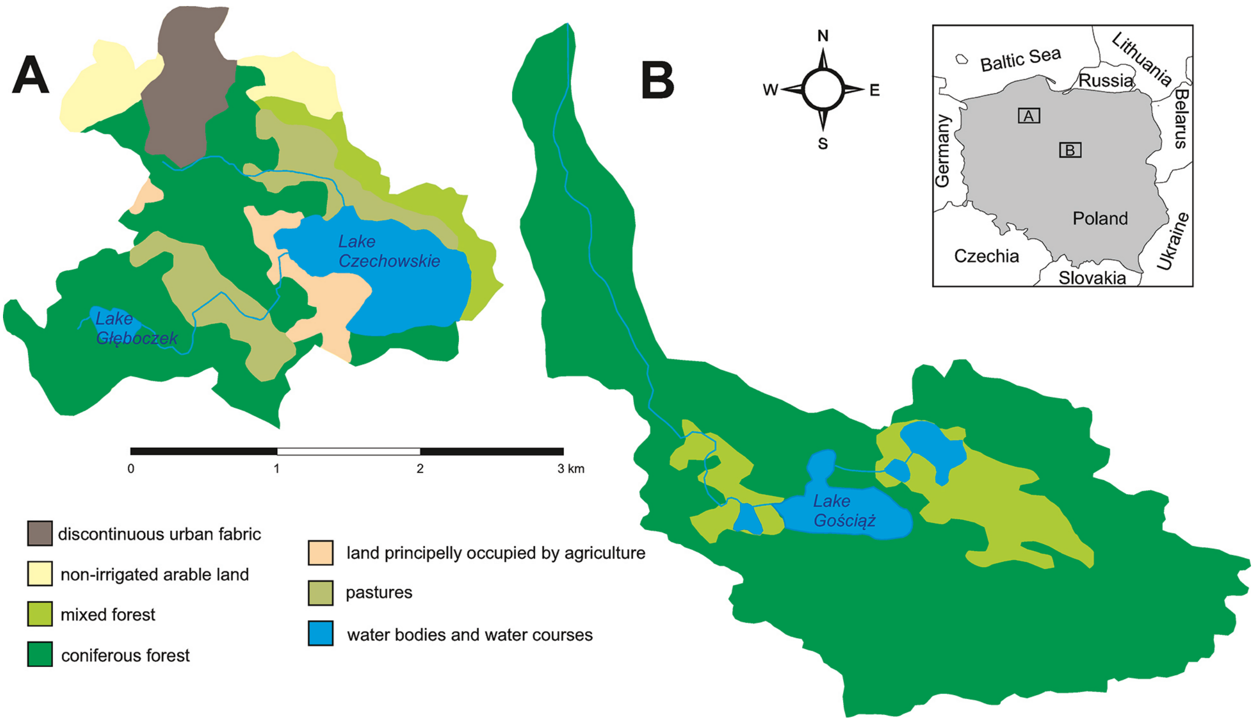

Fig. 1. Study area: A – catchment of Czechowskie and Głęboczek lakes; B – catchment of Gościąż lake (based on Corine Land Cover 2018).

entirely surrounded by forest, and there are several fishing spots on its banks. In the entire direct catchment area of the two lakes, >60% of the area is forest, about 25% is agricultural land, meadows and pastures and <10% is loose buildings (Fig. 1A).

Lake Gościąż is located in central Poland within the Płock Basin, in the Gostynin-Włocławek Landscape Park. The lake itself, due to its annually laminated sediments, has been protected as a nature reserve since 2001. The area of the lake is 43 ha and its maximum depth is 22 m (Fojutowski et al. 2021). The lake is entirely surrounded by forest, dominated by *Querco roboris-Pinetum* communities in wetter habitats and *Peucedano-Pinetum* in drier areas (Kępczyński, Noryśkiewicz 1998). The catchment area is almost 95% covered by coniferous and mixed forests, while the remainder is mainly small lakes (Fig. 1B).

Methodology

Lake sediment cores were taken during field surveys in 2021 and 2022 near the deepest locations. The UWITEC gravity probe with a diameter of 90 mm was used for the sampling. Cores of lengths 93 cm (Lake Czechowskie), 50 cm (Lake Głęboczek) and 80 cm (Lake Gościąż), respectively, were cleaned and stripped of the outer layer to minimise the risk of secondary sediment contamination, and then divided into 5 cm long sections. From each section, 50 g of wet sediment was taken and transferred to a glass flask, to which 100 ml of 25% NaCl was then added. In this way, the density of the solution was $1.2\ \mathrm{g \cdot cm^{-3}}$. The samples thus prepared were placed on a magnetic stirrer and stirred at high speed for 5 min (Duis, Coors 2016). The samples were left to stand for 24 h to allow the entire suspension to settle at the bottom. After this time, the supernatant was carefully decanted and 10 ml of 30% H_2O_2 was added to it. The samples were then heated to 70°C and left at this temperature until the organic matter oxidation was complete. After cooling, the samples were filtered through glass-fibre filters and then dried on glass Petri dishes at 60°C for 4 h (Klein et al. 2015). Only porcelain spatulas and glass pipettes washed with distilled water each time were used to transfer the samples. Before starting work, all working surfaces were cleaned with ethanol, and the work was performed using blue nitrile gloves. Protective clothing of a solid white colour was used to catch any possible ingress of fibres of this colour into the samples to be tested. The prepared samples were examined under a Zeiss Axio Scope

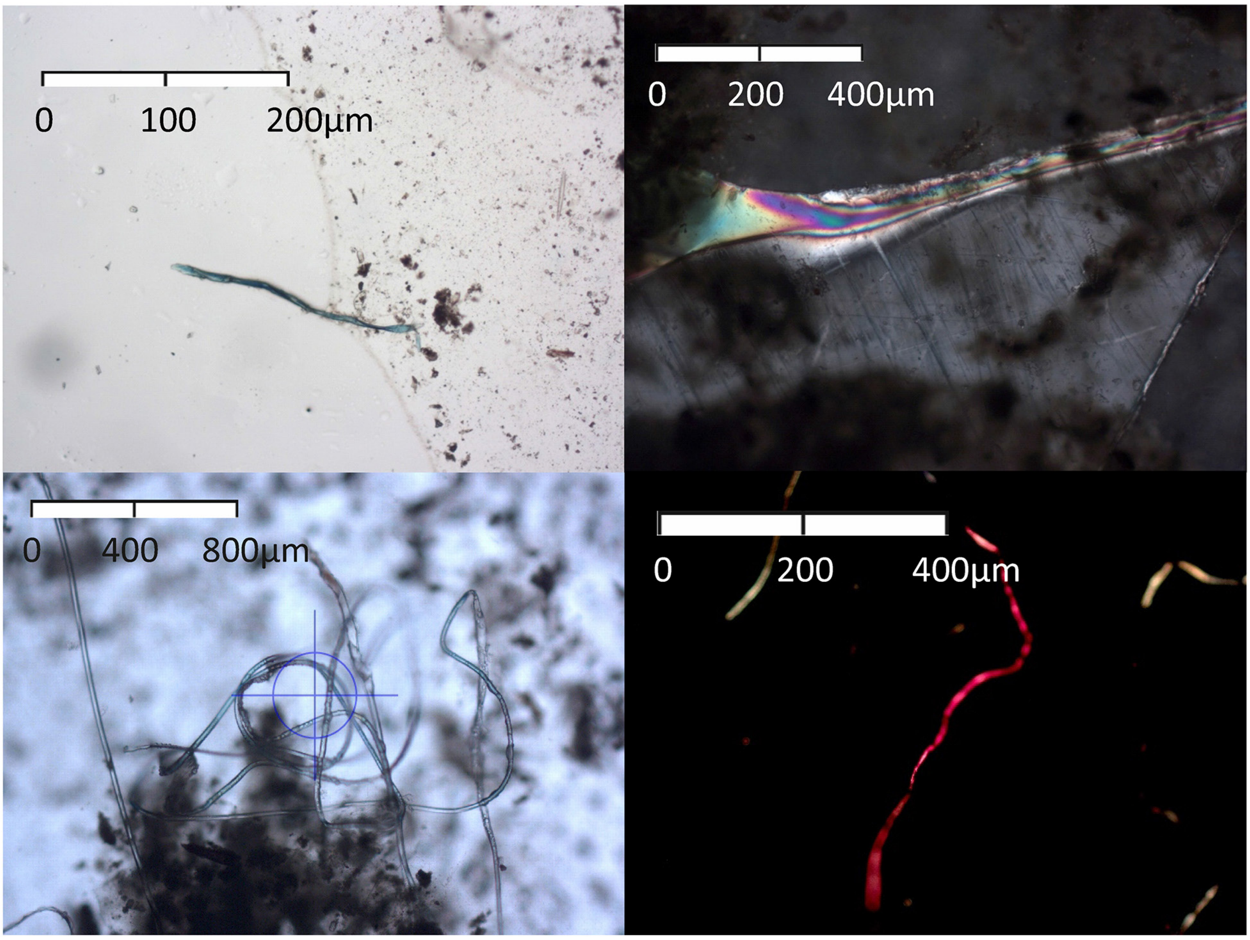

Fig. 2. Microplastic particles (A – blue fibre 0.2 mm, Lake Gościąż; B – transparent fragment 2.0 mm, Lake Głęboczek; C – several transparent fibres, Lake Gościąż; D – red fibre 1.2 mm, Lake Czechowskie).

A1 microscope to identify MP particles (Fig. 2). The identified particles were photographed and classified by form, size and colour.

The sediment material used to determine the average sedimentation rate, and then, to build an age-depth model (Fig. 3), was collected from 'Danish' traps placed in the deepest parts of the studied lakes, approximately 3 m above the bottom. This type of trap consists of four cylinders (each with a diameter of 75 mm, length of 450 mm) and is able to collect all material floating in the depths of the lake. Traps were emptied several times throughout the year. The amount of material was measured in millimetres and then converted to g · m^{-2} · day^{-1}. The data was gathered between 2017 and 2021.

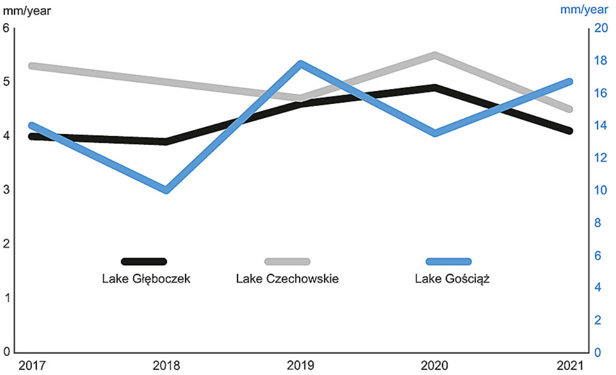

Fig. 3. Average sediment accumulation rate in sediment traps in years 2017–2021.

Maps illustrating the catchment areas were created based on land cover data from the Corine Land Cover database for the year 2018 (EEA 1995).

Results

The highest number of MP particles were identified in the sediments of Lake Czechowskie. A total of 20 particles were found, of which 17 were fibres and the remaining 3 were fragments. The size of the particles was predominantly in the range of 0.1–1 mm (nine identified particles). In the 93 cm long core, contaminants were found at a depth of 0–60 cm. In the 50 cm long core from Lake Głęboczek, 2 MP particles were identified. One was a fragment with a diameter of 2 mm in the upper part of the core (0–5 cm), while the other was a transparent fibre 2.1 mm long found at a depth of 20–25 cm. In the core from Lake Gościąż, which was 80 cm long, 7 MP particles were identified, found in layers from 5 cm to 45 cm deep. In order to systematise the obtained results, the number of identified MP particles per kilogram of wet sediment from which they were extracted was calculated. Thus, there are 21 MP particles in Lake Czechowskie, 4 MP particles in Lake Głęboczek and 9 MP particles per kilogram of wet sediment in Lake Gościąż.

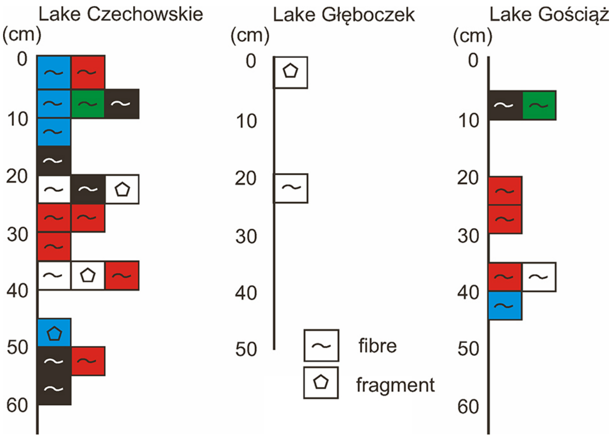

Fig. 4. Particles of microplastic in three bottom sediment cores. The number and colour of the squares correspond to the identified microplastic particles.

Discussion

Most of the studies conducted to date on plastic pollution in lake ecosystems concern lakes located in or near urban areas. The lakes studied by the author belong to a very small group of so-called rural lakes for which such analyses have been carried out (Dusaucy et al. 2021). Even fewer studies have been conducted on the bottom sediments of these lakes. There are only a few such studies, and direct comparisons of the results are difficult due to the different units of measurement. For example, in a small, shallow lake on Spitsbergen, sediment was collected from a rocky bottom for research purposes and 400 MP particles per square metre were identified (Gonzalez-Pleiter et al. 2020). It is therefore difficult to relate these findings to the results obtained by the author. In the deep (maximum depth 34 m) mountain lake Sassolo in Switzerland, 514 MP particles per kilogram of wet sediment were identified in the deepest part of the lake and 34 MP particles per kilogram of wet sediment at the lake outflow (Negrete Velasco et al. 2020). Although the latter value is the smallest, it is >60% higher than the pollution levels found in Lake Czechowskie. Such large amounts of MP in locations far from urbanised and industrialised areas indicate that atmospheric input is an important source of MP input to lakes (Evangeliou et al. 2020, Huang et al. 2021). Brahney et al. (2020) report that in the U.S. 1000 tons of wind- and rain-borne MP fall per year into areas that are protected. Hence, the establishment of an area as a protected area does not eliminate the problem of plastic pollution. This is also confirmed by the results obtained in the sediments of Lake Gościąż, where, despite the establishment of a nature reserve in 2001, a total of 9 MP particles per kilogram of wet sediment were identified (Fig. 4). However, this is a relatively small amount compared to Lake Pinku in Latvia, where, despite its location in a protected area, up to 4.1 MP particles per gram of dry sediment were identified (Dimante-Deimantovica et al. 2024), which corresponds to 4100 particles per kilogram. This also raises the question of direct comparison of the quantities determined, as the measurement here is based on dry sediment. Assuming that the sediment from the lakes investigated by the author was also dried, the number of particles identified would still be significantly lower than in Lake Pinku.

The number of MP particles in the drill core from Lake Czechowskie is similar to the values determined in the coastal sediments of Lake Ełk, which were collected in the vicinity of urbanised and tourist areas (Rogowska et al. 2021). In contrast, significantly fewer MP particles were identified in the sediments of Lake Głęboczek compared to Lake Czechowskie, although the lakes are only 1.5 km apart. Lake Głęboczek is completely surrounded by forest and has only one small tributary, which does not serve as a source of MP inflow into the lake. It can therefore be assumed that the MP particles reached the lake via atmospheric deposition. The immediate surroundings of Lake Czechowskie include not only forests but also agricultural areas, a vacation resort and a small beach, which is used in the summer season. The lake is also used by anglers. Therefore, MP can also enter the bottom sediments through rain runoff and the fragmentation of macroplastics from the coastal sediments.

The size and colour of microplastic particles

In zooplankton-rich lakes, MP particles of 4–5 mm in size proportionally predominate, while in zooplankton-poor reservoirs MP particles of <1 mm in size dominate (Karpowicz et al. 2020, Pol et al. 2023). In the lakes studied, the majority (76%) of the identified MP particles represent sizes <2 mm (Fig. 5). Such a structure may suggest that in these reservoirs the amount of zooplankton is relatively low, or only a small amount of MP consumption by zooplankton occurs (Bellasi et al. 2020, Kvale et al. 2021). As many as 30% of the MP particles found during the study were red in colour (Fig. 6). Marti et al. (2020) suggest that a higher consumption of red particles by aquatic organisms, which confuse them with food, is responsible for the small percentage of this colour in pollution. Thus, such a significant amount of red MP particles in these lakes suggests that these plastics are not, to date, significantly consumed by aquatic organisms.

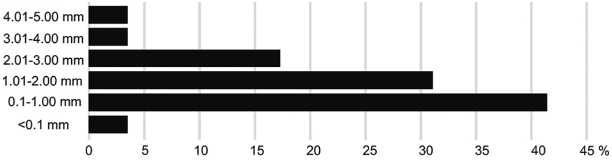

Fig. 5. Percentage distribution of the size of the microplastic particles in all lakes.

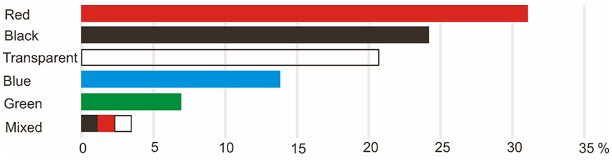

Fig. 6. Percentage distribution of the colour of the microplastic particles in all lakes.

Microplastic as a potential source of information on the age of bottom sediments

Lake sediments serve as a kind of archive in which human activities and their impact on the environment are recorded. Therefore, testing the bottom sediments of lakes for plastic pollution not only allows to determine the concentration of MP but can also become one of the tools to help in determining the sediment accumulation rate. Using additional methods, such as in this case, the average sediment accumulation rate in sedimentation traps, we can determine the moment of potential MP appearance in these lakes. In the case of the three lakes analysed, we can clearly see the boundary below which MP was not found in the sediments. In Lake Czechowskie it is 60 cm, in Lake Głęboczek it is 25 cm, while in Lake Gościąż it is 45 cm. The average sediment accumulation rate for 2017–2021, calculated on the basis of the amount of sediment deposited in sedimentation traps located in the deepest locations of the three studied lakes, is 5 mm $\cdot$ a^{-1} for Lake Czechowskie, 4.3 mm $\cdot$ a^{-1} for Lake Głęboczek and 14.4 mm $\cdot$ a^{-1} for Lake Gościąż (Fig. 3). Assuming that a similar sediment accumulation rate would have persisted over the past few decades, and juxtaposing this with the depths at which MP particles were found, the beginning of plastic accumulation in the lakes studied is 1986 in Lake Gościąż, 1963 in Lake Głęboczek and 1901 in Lake Czechowskie, respectively (Fig. 7). For Lake Gościąż, the age of the first MP particles found corresponds to the start of polyvinyl chloride production at the Anwil nitrogen plant in Włocławek, located about 25 km northwest of the lake, whose installations were built in 1976–1985. Given the prevailing wind directions in the area (Marosz 2016) and the relatively short distance separating the two locations, these pollutants could have been transported to the lake area just by atmospheric means. In Lake Głęboczek, the first MP fragment found was associated with the start of mass production of plastics in Poland, which dates to 1957 (Kochanowski 2017). Here too, in the absence of potential sources of plastic pollution in the immediate vicinity of the lake, it should be expected that they were transported by the atmospheric route. In contrast, in the case of Lake Czechowskie, where the first MP particles were identified at a depth representing 1901, we can speak of intense sediment compaction or potential movement of MP particles into the depths. Dimante-Deimantovica et al. (2024) indicate that MP particles can migrate deep into the sediments, which they supported by dating the sediments using ^{210}Pb. According to these analyses, the first

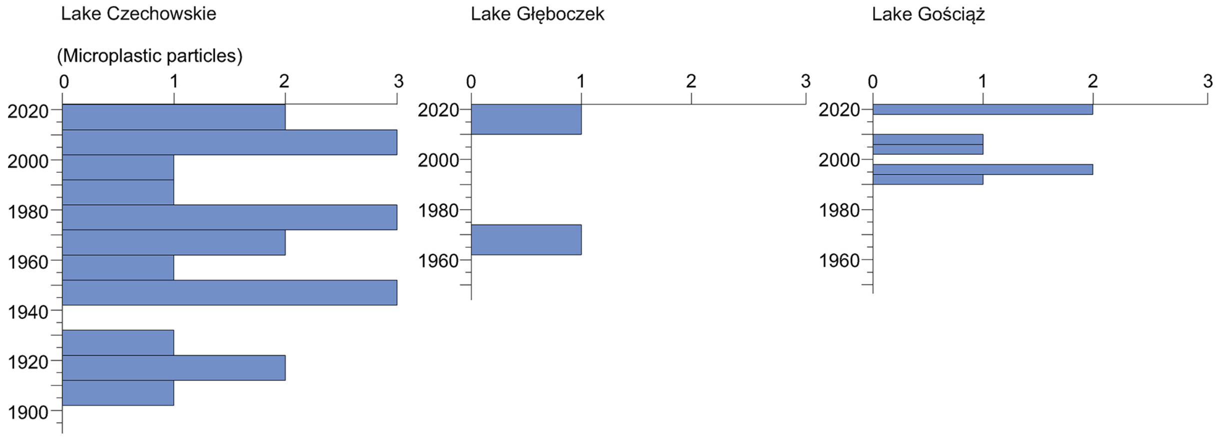

Fig. 7. Dates corresponding to microplastic particles found calculated based on the average annual sedimentation rate from sediment traps (Lake Czechowskie – 5.0 mm · a^{-1}, Lake Głęboczek – 4.3 mm · a^{-1}, Lake Gościąż – 14.4 mm · a^{-1}).

MP particles found in Lake Pinku would date to 1733. Assuming such a scenario, the first appearance of MP in the sediment would not necessarily mean that it dates from the 1950s (the beginning of the mass production of plastic) or later. Given the density of most plastics, which ranges from 0.92 g · cm^{-3} to 1.6 g · cm^{-3} (Hidalgo-Ruz et al. 2012), their ability to penetrate deep into the lake sediment, whose density, depending on its composition and physical properties, ranges from 0.96 g · cm^{-3} to 1.85 g · cm^{-3} (Sekellick et al. 2013, Sowiński et al. 2023), seems to be quite limited, but not out of the question. Especially if the MP particles are rounded fragments rather than fibres and are small in size (Dimante-Deimantovica et al. 2024).

Conclusions

Identification of MP particles in cores taken from all three studied lakes allowed us to confirm that MP is currently a problem not only for marine and freshwater environments with a high impact of anthropopressure but also for small lakes of only local importance, where the impact of anthropopressure is negligible or moderate. The variation in the amount of MP particles in the lakes studied is mainly due to the nature of the immediate surroundings of the lakes. In two of the lakes, which are surrounded by forests, the main source of MP delivery is atmospheric transport. In the third lake, the pollution originates mainly from agricultural and tourist activities. In each of the sediment cores, a clear boundary becomes apparent, below which MP contamination no longer occurs. Juxtaposed with data on sediment accumulation rates in sediment traps, an attempt was made to determine the date of the first appearance of MP in the lakes. The results obtained are consistent with the possible impact of human activities in the case of two lakes, while in the third lake, the question of the possible sinking of MP particles in the sediments remains open, which complicates the interpretation of the age of these sediments. Additional comparative methods are needed to make MP a reliable tool for determining chronology. The studies carried out were of a pilot nature and the results presented are a prelude to further, more extensive analyses. These future analyses will include denser core samples, precise dating and analysis of the identified polymer types by FTIR. In addition, analyses of MP concentrations in the water and coastal zones of these lakes will be conducted.

The process of work implementation has brought dozens of important questions, such as: Can MP migrate deeper into lower layers of bottom sediments, what are the sources and mechanism of its delivery to lakes and what's the seasonal variability of these sources? We suppose that well-planned further research will provide answers to these questions.

Acknowledgements

The author would like to thank the expert anonymous reviewers, and the journal editor for their constructive comments and suggestions.

References

Allen S., Allen D., Phoenix V.R., Le Roux G., Durántez Jiménez P., Simonneau A., Binet S., Galop D., 2019. Atmospheric transport and deposition of microplastics in a remote mountain catchment. *Nature Geoscience* 12: 339–344. DOI 10.1038/s41561-019-0335-5.

Andrady A.L., Barnes P.W., Bornman J.F., Gouin T., Madronich S., White C.C., Zepp R.G., Jansen M.A.K., 2022. Oxidation and fragmentation of plastics in a changing environment; from UV-radiation to biological degradation. *Science of the Total Environment* 851: 158022. DOI 10.1016/j.scitotenv.2022.158022.

Bellasi A., Binda G., Pozzi A., Galafassi S., Volta P., Bettinetti R., 2020. Microplastic contamination in freshwater environments: A review, focusing on interactions with sediments and benthic organisms. *Environments* 7: 30. DOI 10.3390/environments7040030.

Brahney J., Hallerud M., Heim E., Hahnenberger M., Sukumaran S., 2020. Plastic rain in protected areas of the United States. *Science* 368: 1257–1260. DOI 10.1126/science.aaz5819.

Carpenter E.J., Smith Jr, K., 1972. Plastics on the Sargasso sea surface. *Science* 175: 1240–1241. DOI 10.1126/science.175.4027.1240.

Cole M., Lindeque P., Halsband C., Galloway T.S., 2011. Microplastics as contaminants in the marine environment: A review. *Marine Pollution Bulletin* 62: 2588–2597. DOI 10.1016/j.marpolbul.2011.09.025.

D'Avignon G., Gregory-Eaves I., Ricciardi A., 2022. Microplastics in lakes and rivers: An issue of emerging significance to limnology. *Environmental Reviews* 30: 228–244. DOI 10.1139/er-2021-0048.

Dimante-Deimantovica I., Saarni S., Barone M., Buhhalko N., Stivrins N., Suhareva N., Tylmann W., Vianello A., Vollertsen J., 2024. Downward migrating microplastics in lake sediments are a tricky indicator for the onset of the Anthropocene. *Science Advances* 10: eadi8136. DOI 10.1126/sciadv.adi8136.

Duis K., Coors A., 2016. Microplastics in the aquatic and terrestrial environment: sources (with a specific focus on personal care products), fate and effects. *Environmental Sciences Europe* 28: 1–25. DOI 10.1186/s12302-015-0069-y.

Dusaucy J., Gateuille D., Perrette Y., Naffrechoux E., 2021. Microplastic pollution of worldwide lakes. *Environmental Pollution* 284: 117075. DOI 10.1016/j.envpol.2021.117075.

Eerkes-Medrano D., Thompson R.C., Aldridge D.C., 2015. Microplastics in freshwater systems: A review of the emerging threats, identification of knowledge gaps and prioritisation of research needs. *Water Research* 75: 63–82. DOI 10.1016/j.watres.2015.02.012.

EEA [European Environment Agency], 1995. Corine Land Cover, Copernicus Land Monitoring Service, European Environment Agency: Copenhagen, Denmark.

Evangeliou N., Grythe H., Klimont Z., Heyes C., Eckhard T.S., Lopez-Aparicio S., Stohl A., 2020. Atmospheric transport is a major pathway of microplastics to remote regions. *Nature Communications* 11: 1–11. DOI 10.1038/s41467-020-17201-9.

Fojutowski M., Gierszewski P., Brykała D., Bonk A., Błaszkiewicz M., Kramkowski M., 2021. Spatio-temporal differences of sediment accumulation rate in the Lake Gościąż (Central Poland) as a response of meteorological conditions and lake basin morphometry. *Cuadernos de Investigacion Geografica* 47. DOI 10.18172/cig.4724.

Gasperi J., Dris R., Mirande-Bret C., Mandin C., Langlois V., Tassin B. 2015. First overview of microplastics in indoor and outdoor air. In: *15th EuCheMS International Conference on Chemistry and the Environment*.

Gasperi J., Wright S.L., Dris R., Collard F., Mandin C., Guerrouache M., Langlois V., Kelly F.J., Tassin B., 2018. Microplastics in air: Are we breathing it in? *Current Opinion in Environmental Science, Health* 1: 1–5. DOI 10.1016/j.coesh.2017.10.002.

González-Pleiter M., Velázquez D., Edo C., Carretero O., Gago J., Barón-Sola Á., Hernández L.E., Yousef I., Quesada A., Leganés F., 2020. Fibers spreading worldwide: Microplastics and other anthropogenic litter in an Arctic freshwater lake. *Science of the Total Environment* 722: 137904. DOI 10.1016/j.scitotenv.2020.137904.

Gurjar U.R., Xavier M., Nayak B.B., Ramteke K., Deshmukhe G., Jaiswar A.K., Shukla S.P., 2021. Microplastics in shrimps: A study from the trawling grounds of north eastern part of Arabian Sea. *Environmental Science and Pollution Research* 28: 48494–48504. DOI 10.1007/s11356-021-14121-z.

Harley-Nyang D., Memon F.A., Osorio Baquero A., Galloway T., 2023. Variation in microplastic concentration, characteristics and distribution in sewage sludge & biosolids around the world. *Science of the Total Environment* 891: 164068. DOI 10.1016/j.scitotenv.2023.164068.

Hartmann N.B., Huffer T., Thompson R.C., Hassellov M., Verschoor A., Daugaard A.E., Rist S., Karlsson T., Brennholt N., Cole M., 2019. *Are we speaking the same language? Recommendations for a definition and categorization framework for plastic debris*. ACS Publications. DOI 10.1021/acs.est.8b05297.

Hernandez L.M., Xu E.G., Larsson H.C., Tahara R., Maisuria V.B., Tufenkji N., 2019. Plastic teabags release billions of microparticles and nanoparticles into tea. *Environmental Science & Technology* 53: 12300–12310. DOI 10.1021/acs.est.9b02540.

Hidalgo-Ruz V., Gutow L., Thompson R.C., Thiel M., 2012. Microplastics in the marine environment: A review of the methods used for identification and quantification. *Environmental Science & Technology* 46: 3060–3075. DOI 10.1021/es2031505.

Horton A.A., Walton A., Spurgeon D.J., Lahive E., Svendsen C., 2017. Microplastics in freshwater and terrestrial environments: Evaluating the current understanding to identify the knowledge gaps and future research priorities. *Science of the Total Environment* 586: 127–141. DOI 10.1016/j.scitotenv.2017.01.190.

Huang Y., He T., Yan M., Yang L., Gong H., Wang W., Qing X., Wang J., 2021. Atmospheric transport and deposition of microplastics in a subtropical urban environment. *Journal of Hazardous Materials* 416: 126168. DOI 10.1016/j.hazmat.2021.126168.

Iroegbu A.O.C., Ray S.S., Mbarane V., Bordado J.C., Sardinha J.P., 2021. Plastic pollution: A perspective on matters arising: Challenges and opportunities. *ACS Omega* 6: 19343–19355. DOI 10.1021/acsomega.1c02760.

Ivleva N.P., 2021. Chemical analysis of microplastics and nanoplastics: Challenges, advanced methods, and perspectives. *Chemical Reviews* 121: 11886–11936. DOI 10.1021/acs.chemrev.1c00178.

Jenner L.C., Rotchell J.M., Bennett R.T., Cowen M., Tentzeris V., Sadofsky L.R., 2022. Detection of microplastics in human lung tissue using μFTIR spectroscopy. *Science of the Total Environment* 831: 154907. DOI 10.1016/j.scitotenv.2022.154907.

Kaliszewicz A., Winczek M., Karaban K., Kurzydłowski D., Górska M., Koselak W., Romanowski J., 2020. The contamination of inland waters by microplastic fibres under different anthropogenic pressure: Preliminary study in Central Europe (Poland). *Waste Management & Research* 38: 1231–1238. DOI 10.1177/0734242X20938448.

Karpowicz M., Sługocki Ł., Kozłowska J., Ochocka A., López C., 2020. Body size of Daphnia cucullata as an indicator of the ecological status of temperate lakes. *Ecological Indicators* 117: 106585. DOI 10.1016/j.ecolind.2020.106585.

Kępczyński K., Noryśkiewicz A., 1998. Vegetation of the Gostynińskie Lake District. *Lake Gościąż, Central Poland: A Monographic Study, Part* 1: 29–33.

Klein S., Worch E., Knepper T.P., 2015. Occurrence and spatial distribution of microplastics in river shore sediments of the Rhine-Main area in Germany. *Environmental Science & Technology* 49: 6070–6076. DOI 10.1021/acs.est.5b00492.

Kochanowski J., 2017. *Rewolucja międzypaździernikowa: Polska 1956-1957*, Wydawnictwo Znak Horyzont.

Kordowski J., Błaszkiewicz M., Kramkowski M., Słowiński M., Tyszkowski S., Brauer A., Brykała D., Gierszewski P., Lamparski P., Lutyńska M., Mirosław-Grabowska J., Noryśkiewicz A.M., Obremska M., Ott F., Wulf S., Zawiska I., 2014. Charakterystyka środowisk depozycyjnych Jeziora Czechowskiego i jego otoczenia. *Landform Analysis* 25: 55–75. DOI 10.12657/landfana.025.006.

Kvale K., Prowe A.E.F., Chien C.T., Landolfi A., Oschlies A., 2021. Zooplankton grazing of microplastic can accelerate global loss of ocean oxygen. *Nature Communication* 12: 2358. DOI 10.1038/s41467-021-22554-w.

Leslie H.A., Van Velzen M.J., Brandsma S.H., Vethaak A.D., Garcia-Vallejo J.J., Lamoree M.H., 2022. Discovery and quantification of plastic particle pollution in human blood. *Environment International* 163: 107199. DOI 10.1016/j.envint.2022.107199.

Marosz M., 2016. Variability of geostrophic airflow over Poland, 1951-2014. *Bulletin of Geography. Physical Geography Series* 10: 5–18. DOI 10.1515/bgeo-2016-0001.

Martí E., Martin C., Galli M., Echevarría F., Duarte C.M., Cózar A., 2020. The colors of the ocean plastics. *Environmental Science & Technology* 54: 6594–6601. DOI 10.1021/acs.est.9b06400.

Mintenig S.M., Int-Veen I., Löder M.G., Primpke S., Gerdts G., 2017. Identification of microplastic in effluents of waste water treatment plants using focal plane array-based micro-fourier-transform infrared imaging. *Water Research* 108: 365–372. DOI 10.1016/j.watres.2016.11.015.

Nava V., Chandra S., Aherne J., Alfonso M.B., Antao-Geraldes A.M., Attermeyer K., Bao R., Bartrons M., Berger S.A., Biernaczyk M., Bissen R., Brookes J.D., Brown D., Canedo-Arguelles M., Canle M., Capelli C., Carballeira R., Cereijo J.L., Chawchai S., Christensen S.T., Christoffersen K.S., De Eyto E., Delgado J., Dornan T.N., Doubek J.P., Dusaucy J., Erina O., Ersoy Z., Feuchtmayr H., Frezzotti M.L., Galafassi S., Gateuille D., Goncalves V., Grossart H.P., Hamilton D.P., Harris T.D., Kangur K., Kankilic G.B., Kessler R., Kiel C., Krynak E.M., Leiva-Presa A., Lepori F., Matias M.G., Matsuzaki S.S., Mcelarney Y., Messyasz B., Mitchell M., Mlambo M.C., Motitsoe S.N., Nandini S., Orlandi V., Owens C., Ozkundakci D., Pinnow S., Pociecha A., Raposeiro P.M., Room E.I., Rotta F., Salmaso N., Sarma S.S.S., Sartirana D., Scordo F., Sibomana C., Siewert D., Stepanowska K., Tavsanoglu U.N., Tereshina M., Thompson J., Tolotti M., Valois A., Verburg P., Welsh B., Wesolek B., Weyhenmeyer G.A., Wu N., Zawisza E., Zink L., Leoni B., 2023. Plastic debris in lakes and reservoirs. *Nature* 619: 317–322. DOI 10.1038/s41586-023-06168-4.

Negrete Velasco A.D.J., Rard L., Blois W., Lebrun D., Lebrun F., Pothe F., Stoll S., 2020. Microplastic and fibre contamination in a remote mountain lake in Switzerland. *Water* 12: 2410. DOI 10.3390/w12092410.

PlasticsEurope. 2021. Plastics – the Facts. Online: https://plasticseurope.org/wp-content/uploads/2021/12/Plastics-the-Facts-2021-web-final.pdf (acessed 12 January 2024).

Pol W., Stasinska E., Zmijewska A., Wiecko A., Zielinski P., 2023. Litter per liter – Lakes' morphology and shoreline urbanization index as factors of microplastic pollution: Study of 30 lakes in NE Poland. *Science of the Total Environment* 881: 163426. DOI 10.1016/j.scitotenv.2023.163426.

Rogowska W., Skorbiłowicz E., Skorbiłowicz M., Trybułowski Ł., 2021. Microplastics in coastal sediments of Ełckie Lake (Poland). *Studia Quaternaria* 38: 109–116.

Santillán L., Saldaña-Serrano M., De-La-Torre G.E., 2020. First record of microplastics in the endangered marine otter (Lontra felina). *Mastozoología neotropical* 27: 211–215. DOI 10.31687/saremMN.20.27.1.0.12.

Sekellick A.J., Banks W.S., Myers M.K., 2013. Water volume and sediment volume and density in lake linganore between boyers mill road bridge and bens branch, frederick county, Maryland, 2012. US Department of the Interior, US Geological Survey.

Sobhani Z., Lei Y., Tang Y., Wu L., Zhang X., Naidu R., Megharaj M., Fang C., 2020. Microplastics generated when opening plastic packaging. *Scientific Reports* 10: 1–7. DOI 10.1038/s41598-020-61146-4.

Sowiński P., Smólczyński S., Kalisz B., Orzechowski M., Bieniek A., 2023. Variability of some physical properties of Limnic Rendzinas in the Mazurian Lakeland (NE Poland). *Polish Journal of Soil Science* 56: 1–10. DOI 10.17951/pjss/2023.56.1.1.

Sripada K., Wierzbicka A., Abass K., Grimalt J.O., Erbe A., Röllin H.B., Weihe P., Díaz G.J., Singh R.R., Visnes T., 2022. A children's health perspective on nano-and microplastics. *Environmental Health Perspectives* 130: 015001. DOI 10.1289/EHP9086.

Talbot R., Chang H., 2022. Microplastics in freshwater: A global review of factors affecting spatial and temporal variations. *Environmental Pollution* 292: 118393. DOI 10.1016/j.envpol.2021.118393.

Vaughan R., Turner S.D., Rose N.L., 2017. Microplastics in the sediments of a UK urban lake. *Environmental Pollution* 229: 10–18. DOI 10.1016/j.envpol.2017.05.057.

Weinstein J.E., Crocker B.K., Gray A.D., 2016. From macroplastic to microplastic: Degradation of high-density polyethylene, polypropylene, and polystyrene in a salt marsh habitat. *Environmental Toxicology and Chemistry* 35: 1632–40. DOI 10.1002/etc.3432.

Welle F., Franz R., 2018. Microplastic in bottled natural mineral water–literature review and considerations on exposure and risk assessment. *Food Additives & Contaminants: Part A* 35: 2482–2492. DOI 10.1080/19440049.2018.1543957.

Xiong X., Zhang K., Chen X., Shi H., Luo Z., Wu C., 2018. Sources and distribution of microplastics in China's largest inland lake–Qinghai Lake. *Environmental Pollution* 235: 899–906. DOI 10.1016/j.envpol.2017.12.081.

Yang S., Zhou M., Chen X., Hu L., Xu Y., Fu W., Li C., 2022. A comparative review of microplastics in lake systems from different countries and regions. *Chemosphere* 286: 131806. DOI 10.1016/j.chemosphere.2021.131806.

Zbyszewski M., Corcoran P.L., 2011. Distribution and degradation of fresh water plastic particles along the beaches of Lake Huron, Canada. *Water, Air, & Soil Pollution* 220: 365–372. DOI 10.1007/s11270-011-0760-6.