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# Multi-Decadal Impact of Mine Waters in Przemsza River Basin, Upper Silesian Coal Basin, Southern Poland

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**Abstract:** Anthropogenic increases in the salinity of surface waters are referred to as secondary salinization. In surface waters, salinity levels can vary significantly due to various natural and anthropogenic influences. This article presents multi-decadal observations of changes in surface water salinity in the highly industrialized region in southern Poland. The case study of the Przemsza River is an example of the significant impacts of industrial, mainly coal mining, activities that have changed the chemical and biological characteristics of water bodies. The presented research revealed that impacts on salinity and water body status due to mining discharges will be difficult or even impossible to restore, considering the process of transition of the coal sector. In the Przemsza river basin, almost 42% less mine water was discharged in 2023 than in 1991. Parallelly, the salinity of mine waters discharged from deeper levels of active coal mines has increased due to the geochemical gradient (the total load of chlorides and sulfates was 534.8 $MgCl^-{+}SO_4{}^{2-}$ per day in 1991, while in 2023 the total salinity load was 480.1 $MgCl^-{+}SO_4{}^{2-}$ per day). Moreover, of the 19 active mine water discharges in 1991, only 11 remain in 2023, while the observed salinity of surface water in the Przemsza watershed increased rapidly from an average of 2000 $\mu S \cdot cm^{-1}$ to 6700 $\mu S \cdot cm^{-1}$ due to the significant drought and adverse hydrological conditions, which represent low flows never observed before (three times lower flows in the mouth of the Przemsza River in the period 2021–2023 compared to the previous decades 1991–2020). Impacts on water bodies will continue to occur regardless of mining activities in the area—it should be noted that at the end of exploitation, mine water rebound and flooding do not automatically reduce long-lasting impacts on surface waters. Therefore, salinization is a growing threat that might be amplified by climate change. While industrial and urban impacts on surface water change its characteristics, the future challenge of proper water management with a holistic approach is necessary with proper monitoring data collection and river flow-dependent and surface water salinity-dependent discharge of wastewater in the river basin.

**Keywords:** freshwater salinity; mine water; salinization patterns; climate change impact

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## 1. Introduction

Water resource scarcity is a critical issue across Europe and worldwide. It is undoubtedly exacerbated by the documented impacts related to climate change and ensuing extreme drought periods. Water services and environmental stewardship, in terms of diffuse and simple access to clean water, are increasingly important, with their vulnerability being, in the context of a shortage of water resources [1], widely documented [2,3]. Coal mining regions, highly urbanized and industrialized, are significantly affected due to the traditionally long-lasting dewatering and discharge of mine waters, which are documented to have a negative impact on local water resources in several coal regions worldwide, i.e., in the UK [4], Spain [5], Russia [6], Germany [7], as well as worldwide fossil fuel development activities, which are significantly impactful to water resources [8]. Accompanying the transition of EU countries to clean forms of energy and innovative technologies is key to meeting the EU's commitment to environmental sustainability and resilience. Moreover, water quality is a central part of the UN Sustainable Development Goals. Data collection on water parameters has been communicated as an important step for reaching associated water quality targets [9].

The declining use of coal has led to the closing of mines in several regions across Europe. In this context, the closure of mines will undoubtedly and markedly change dewatering systems. Mines abandoned following the cessation of coal exploitation must be continuously dewatered to protect adjacent active mines and aquifer bodies as well as the surface against ensuing hazards [10]. In terms of EU policies, the use of fossil fuels should be decreased and end by 2050. Thus, coal regions are expected to undergo a transformative path leading toward enhanced and sustainable energy efficiency. This path will be strongly connected with mine flooding and regional changes in the water environment. Moreover, climate change is inevitably affecting water balance, with water resources being finite and scarce [11]. This, in turn, hampers the potential to provide effective water services and environmental stewardship. Mine waters discharged into surface waters in highly adverse hydrologic conditions (low flow and hydrological drought periods) severely impact the aquatic environment. Groundwater bodies are impacted (in terms of quantity and quality) by mining drainage and the generation of acid mine drainage due to the cessation of pumping and the ensuing flooding of the excavations. However, the quality and quantity of groundwater are foreseen to be stable within a time frame of several years. Flooding processes of mining excavations and rock mass result in rising of water level and the attainment of a geochemical equilibrium, which would ultimately allow for water resources recovery in particular coal regions [12]. Groundwater level rebound and possible changes in water quality in a flooded region would last at least three decades [13]. Negative impacts of this process will affect water bodies, groundwater intakes, and surface waters across this temporal window [14]. As public awareness of the impacts of mining increases, regulatory and public expectations of the mining industry advance concurrently. As a consequence, environmental laws that regulate the mining industry have become more complex and challenging. Considering the ambitious goals of the Water Framework Directive, which envisions the achievement of a good status of water bodies in the EU within the short time horizon of 2027, as well as current and future changes in water environments due to mine closure and climate changes, issues related to water management in coal regions during transition are unprecedentedly critical and important [15].

In Poland, where coal exploitation is one of the largest within the EU, the transition of the coal sector is in progress. This process results nowadays in the closure of mines and changes in the dewatering infrastructure. About 212 million cubic meters of mine water from abandoned and active underground coal mines are annually discharged into surface waters in the Upper Silesian Coal Basin (southern Poland). Very low amounts (about 3%) are used for technology or drinking supply, and the rest is discharged directly to surface waters [16].

The Upper Silesian Coal Basin, with an area of 7500 km$^2$, including 5500 km$^2$ within the borders of Poland, is one of the largest coal basins in Europe located on the border of watersheds of two main Polish rivers—the Oder (Odra) and Vistula (Wisła) in their headwaters (spring) part—Figure 1. Mining, its range and depth, the duration of mining operations, applied extraction systems, and the activity of the drainage carried out have a fundamental impact on the formation of the underground and surface water regime in the discussed area.

The development of mining on an industrial scale was recorded at the turn of the 18th and 19th centuries. Initially, the exploitation of coal seams was carried out exclusively in the outcrop area using the opencast system and the underground system in the north-eastern part of the USCB (Przemsza River basin) above the groundwater table. With the development of mining technology, coal deposits located deeper were made available to be excavated with continuous dewatering. The most intensive exploitation in the USCB took place in the 1980s and 1990s when coal extraction reached approximately 200 million tons per year. In 1993, the restructuring (nowadays called ‘transition’) of mining in Poland began, and this industry was adapted to the conditions of the market economy. This involved the processes of mine closure and ownership transformations, which were caused by economic factors, the so-called unprofitability of mines, or the depletion of mineral resources. Currently (the end of 2023), coal extraction in the USCB reaches approximately 50 million tons per year [18].

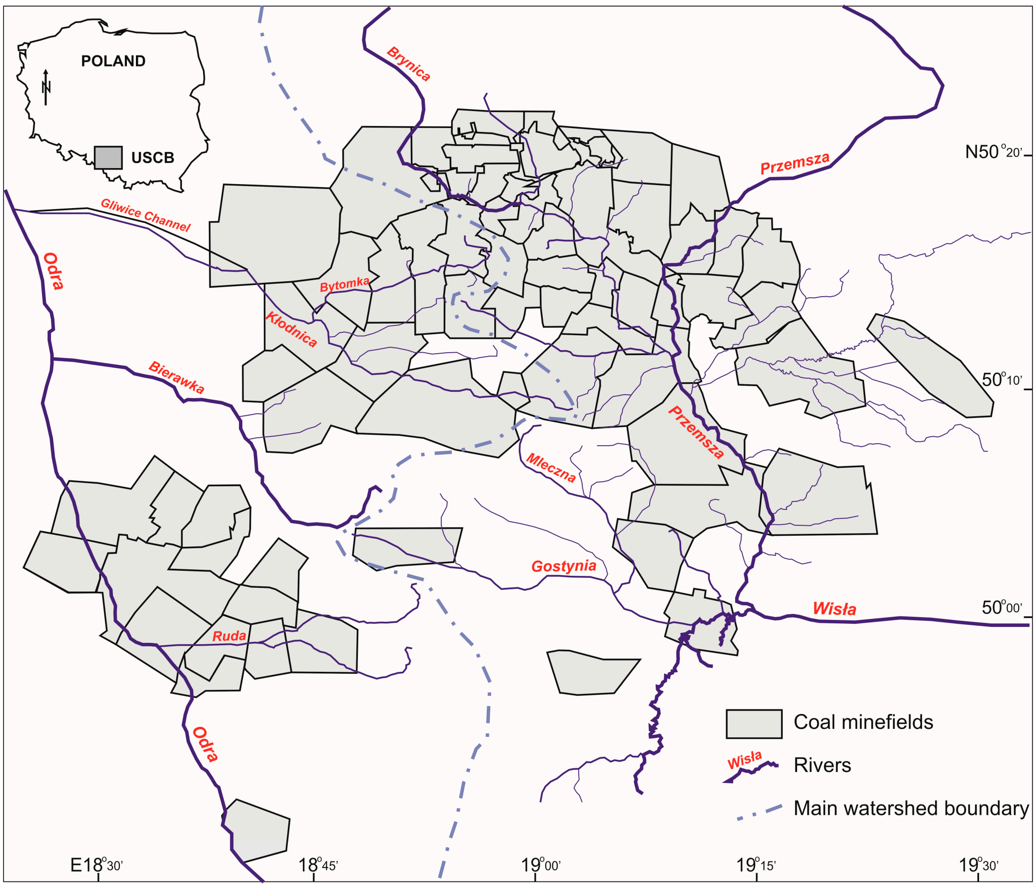

**Figure 1.** Schematic map of coal minefields and rivers in Upper Silesian Coal Basin (USCB), Poland (based on [17]).

The process of mine closure is important while considering the impact on the aquatic environment, as it turned out that it is still necessary to drain abandoned mine workings to protect neighboring deposits in active mines with coal extraction. Most of the mines in the area are hydraulically connected, both through the connecting mine workings and by uncontrolled roads due to caving zones, fault zones, or destroyed boundary pillars. In the abandoned mines or their parts, only the workings located below the level of the existing connections are flooded. From the perspective of the Silesian region, where the impact on surface and underground water bodies has been evident for at least two centuries, it is predicted that the effects of these impacts will continue to be evident long after coal mining has ceased. In terms of climate change impacts, water resource scarcity, and long-lasting drought occurrences, it is necessary to take appropriate measures to manage water resources based on long-term monitoring data. This study presents an analysis of multi-decadal datasets of salinity in surface waters impacted by coal mining discharges and the process of coal industry transition with continuous dewatering as well as changes in the pumping infrastructure of abandoned mines. The study aims to identify the harmful effects of salinization in the Przemsza River basin, possible methods of mitigation of negative impacts, and proper water management in the watershed.

## 2. Materials and Methods

### 2.1. Study Area

Przemsza River is a left tributary of the Wisła River. The catchment area investigated in this study is 1238.8 km$^2$, from the Jeleń water gauge at km 12.8 (from the south) to the Niwka water gauge on Biała Przemsza at km 0.8 (the considered area is limited to the south-east)—Figure 2.

Przemsza River flows from the Karst springs of Upper Jurassic limestone in Bzów, near Zawiercie, at an altitude of 410 m above sea level. It covers a distance of 66.7 km to the Jeleń water gauge. The average slope of the riverbed is 2.9 ‰, and in the lower part it only reaches 1.0 ‰. The lower 25 km section is regulated, and the bottom of the riverbed is paved. Above the reservoir Przeczyce, the river is unregulated with quasi-natural flow, except for the section in Poręba (3 km) and in the area of its sources. Near Katowice, Przemsza receives its largest tributary, the right bank of Brynica, which flows from springs in the village of Huta Szklana at an altitude of 212 m above sea level. The length of Brynica is 57 km, and its average gradient is 1.7 ‰. From the reservoir in Kozłowa Góra, the river has been regulated, embanked, and paved [19].

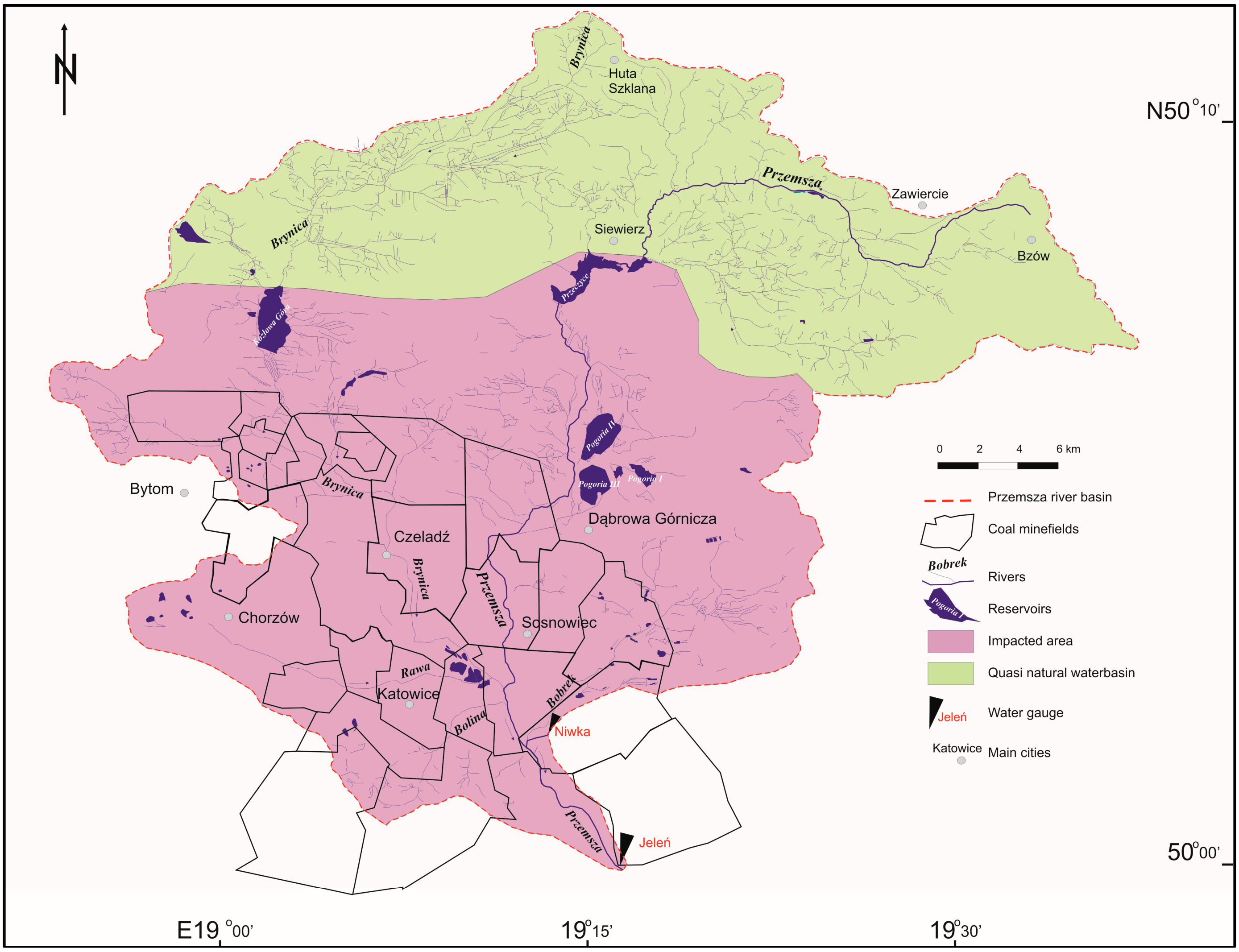

**Figure 2.** Przemsza River basin—case study area (redrawn after Hydroportal [20]).

The development of the Przemsza River basin depends mainly on the specifics of the region, in which, due to the presence of large and diverse mineral resources, the industry developed, and then, due to the enormous economic potential and population, a dense transport network also developed. The most important resources are hard coal, zinc, and lead ores, which were mined out in the Bytom region. Iron ores are largely depleted (Bytom, Siewierz, and Zawiercie). In addition, deposits of limestone, marl, dolomite, clay, sandstone, and refractory shale are exploited. Industrial and urbanized areas cover about 23% of the river basin area in its southwestern part (main cities Dąbrowa Górnicza, Sosnowiec, Katowice, Siemianowice Śl., etc.). Agricultural areas (arable land and green areas) cover 32%, while forests and wastelands cover 34% and are mostly located in the north-eastern part of the studied area. Water reservoirs, communication, etc., cover about 1% of the area. The retention reservoirs are the Przeczyce reservoir with a capacity of 20.74 million m$^3$ and Pogoria with a capacity of 12.03 million m$^3$ on the Przemsza River, and Kozłowa Góra with a capacity of 15.30 million m$^3$ on the Brynica River. Reservoirs have functions mainly for flood protection and are also a source of water supply for the population and industry. The impacts of industrialization and, in particular, hard coal mining, are visible in changes in the land surface (subsidence, creation of floodlands, and heaps), as well as changes in water conditions, especially with harmful effects on water quality and quantity.

### *2.2. Mine Water Discharges—Schemes of Impact on Surface Waters in a Long-Term Period*

For the purpose of the study, a review of mine water discharge locations was prepared, based on data from the author's doctorate thesis [21] and the database of water permits [22] of the Regional Water Management Board. The location of mine water discharge points in the Przemsza water basin is presented in Figure 3. Table 1 presents data on mine water discharges from a particular coal mine in the case study area.

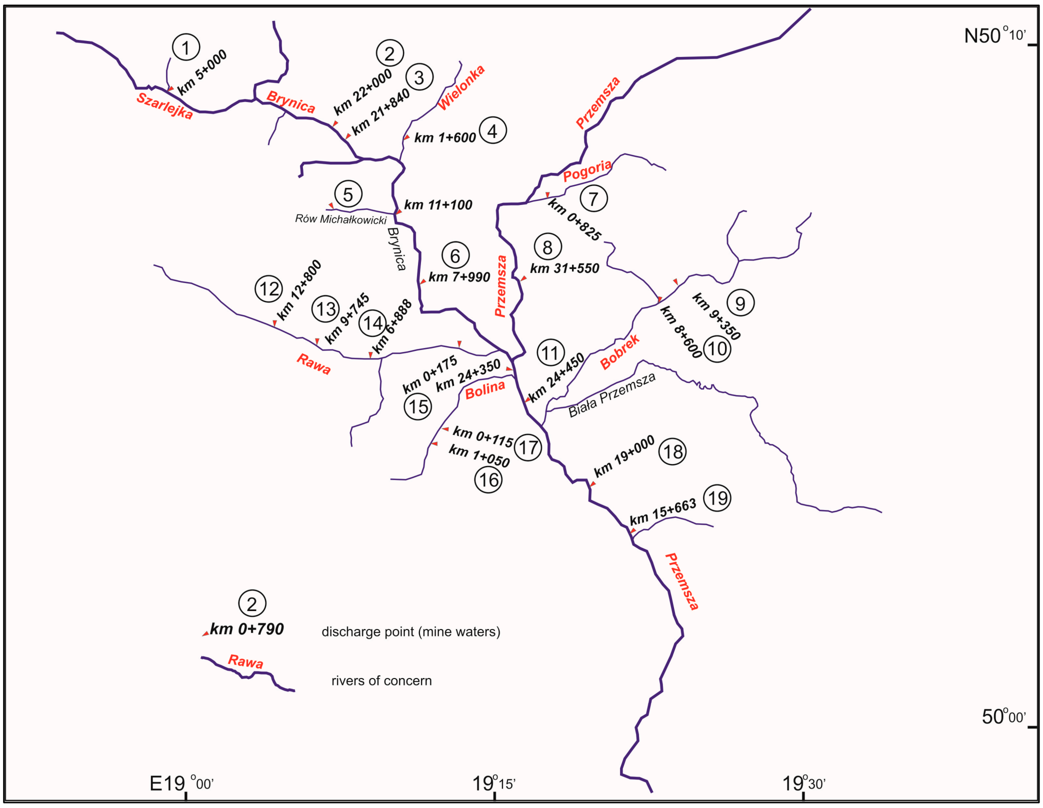

**Figure 3.** Location of mine water discharges in the Przemsza River basin.

**Table 1.** Mine water discharge points—basic data on coal mines and status of dewatering in the period 1991–2023.

| Discharge Point No. | Coal Mine | Period of Operation, Actual Status [1] |
|---|---|---|
| 1 | Powstańców Śl. | 1991–2000 operation, 2001–closure, 2001–2022 abandoned with dewatering, 2022 end of pumping |
| 2 | Piekary | 1991–2018 operation, 2018 closure and flooding |
| 3 | Piekary | |
| 4 | Grodziec | 1991–mine closure, 2000–2005 flooding, 2005–2010 dewatering, 2010–2012 flooding, 2013–2021 pumping, 2021 end of pumping |
| 5 | Siemianowice | 1991–2000 operation, 2001–2023 abandoned with dewatering |
| 6 | Saturn | 1991–2001 operation, 2001–flooding, 2002–2023 abandoned with dewatering |
| 7 | Paryż | 1991–1998 operation, 1999–2020 abandoned with dewatering, 2020–end of pumping |
| 8 | Sosnowiec | 1991–1998 operation, 1999–2014 abandoned with dewatering, 2014 end of pumping |
| 9 | Kazimierz<br>Juliusz | 1991–2016 operation, 2017–closure and end of pumping |
| 10 | Porąbka Klimontów | 1991–2000 operation, 2001–2002 flooding, 2002–2017 abandoned with dewatering, 2017–end of pumping |
| 11 | Niwka<br>Modrzejów | 1991–1997 operation, 1997–2023 abandoned with dewatering |
| 12 | Kleofas | 1991–2004 operation, 2004–2023 abandoned with dewatering |
| 13 | Wujek | 1991–2023 operation |
| 14 | Katowice | 1991–2000 operation, 2001–2023 abandoned with dewatering |
| 15 | Mysłowice | 1991–2020 operation (discharge to Rawa), 2021–closure, flooding, and pumping (to Przemsza River) |
| 16 | Wieczorek | 1991–2021 operation, 2021–2023 closure and flooding, 2023—start pumping |
| 17 | Staszic | 1991–2023 operation |
| 18 | Jan Kanty | 1991–1995 operation, 1995 closure, 1996–2023 abandoned with dewatering |
| 19 | Sobieski | 1991–2023 operation |

Note: [1] by the end of 2023.

Transformation of coal mine water discharges is presented for each decade: 1991–2000, 2001–2010, 2011–2020, and 2021–2023 in the case study area on simplified schemes of water network, discharge, quality, and quantity monitoring points (see Figure 4). Quality and quantity monitoring points were presented, respectively, based on the Polish National Monitoring of Water Quality (Ref. [23], data from 1991 to 2023) and the Polish National Meteorological and Hydrological Institute (IMiGW) [24], data from 1991 to 2023. Data on operation, closure, flooding, and dewatering were collected from entrepreneurs—coal companies, the Polish Mine Restructuring Company, and the database of water permits [22]—data from 1991 to 2023.

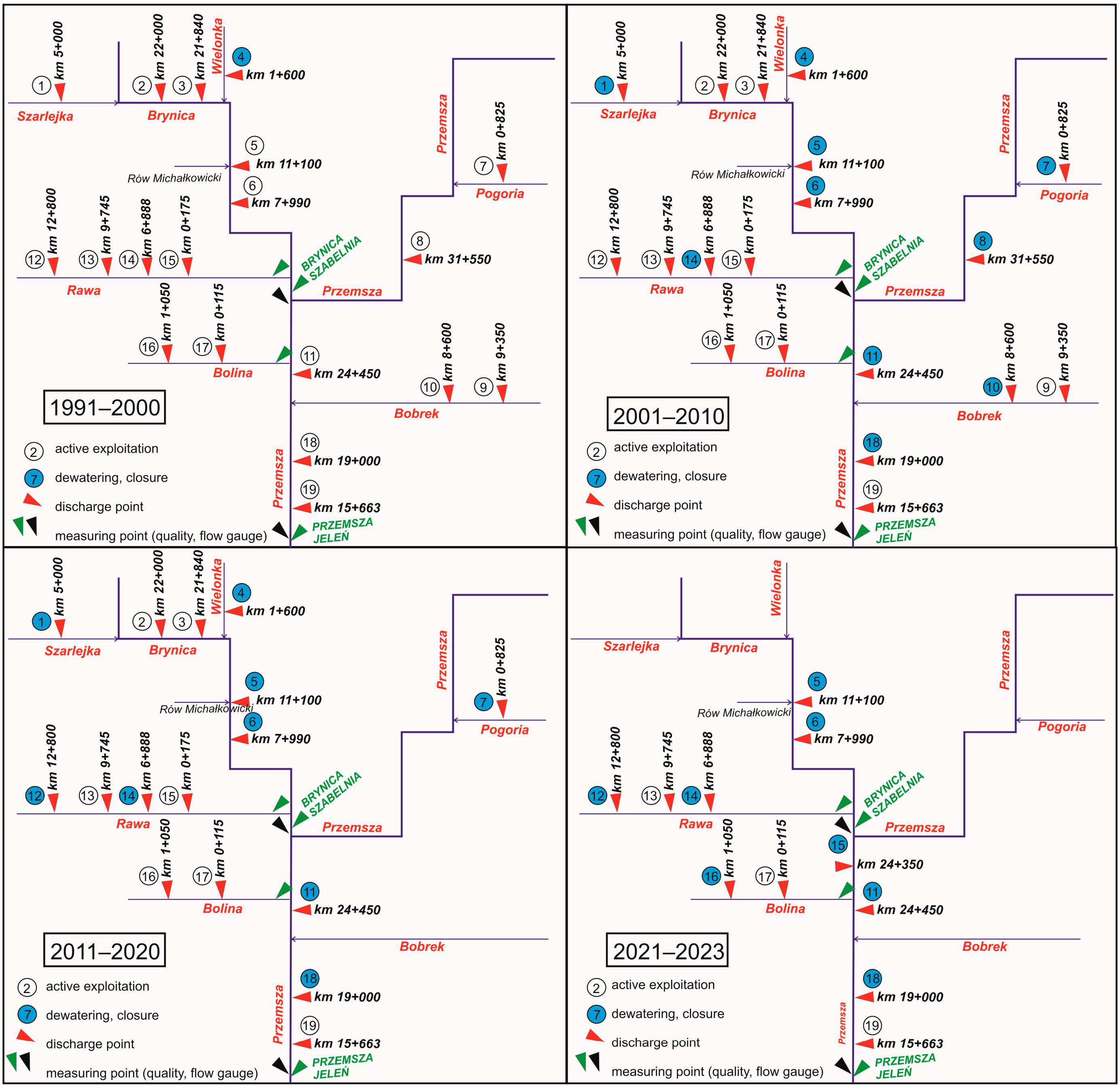

**Figure 4.** Conceptualization of water network in the study area in relevant decades with discharge points of mine water from coal mines and dewatering systems *(numbers of discharges as in Table 1)*.

### *2.3. Collection of Datasets on Surface Water Quality and Quantity*

Datasets on surface water quality—parameters of concern including chlorides, sulfates, TDS, and EC—were collected from the National Inspectorate of Environmental Protection for the period 1991–2023. The results of measurement carried out by the Inspectorate are collected in a database with frequency defined according to the National Monitoring Programme [25]. For the purpose of the study, it is worth mentioning that in the period 1991–2023, spatial distribution, range of measured parameters, and location of monitoring points in the Przemsza River basin have changed due to different requirements for monitoring and implementation of the Water Framework Directive (WFD) into Polish legislation. In 2000, the EU parliament adopted the WFD, which has strongly influenced the monitoring and management of freshwater and coastal habitats across Europe [26]. The primary objective of the Directive was that all water bodies would achieve "good ecological status", defined as a minor deviation only from a reference state with negligible disturbance from human impact, by 2015. Implementation of the WFD by member states resulted in a shift in water management to catchment-based monitoring and restoration, with a greater focus on aquatic ecology and less on surface water quality [15]. Catchment-based monitoring and planning were also implemented in the case study area and resulted in a reduction in the wide monitoring program, frequency of measurements, and range of analyzed parameters. However, few locations with continuous monitoring of flow and chemistry in the period 1991–2023 remain still in the characteristic profile of Przemsza (Jeleń), where relatively coherent data on quantity and quality cover the concerned period.

The datasets on water quality as well as the locations of monitoring points in the Przemsza River basin that are under investigation in this study include Przemsza Jeleń (where flow and quality are measured constantly in the period 1991–2023); this location is representative of the Przemsza River basin. Datasets on water quality and quantity include characteristic parameters related to salinity and reflect all industrial and urban impacts. The location of quality monitoring points is presented in Figure 4 (green triangles) as well as flow gauges (black triangles). Przemsza Jeleń is a complete control cross-section that closes the considered river basin. Bolina outflow to Przemsza and Rawa outflow to Brynica are monitoring stations with constant measures of surface water quality in the period 1991–2023. Bolina and Rawa Rivers are also impacted by mine water discharges during the years; therefore, available data between 1991 and 2023 from monitoring of salinity were collected for profiles located in the outflows of these rivers to Przemsza and Brynica. Data were collected during the same seasons with relevant and coherent frequency and range of parameters (parameters of salinity, main ions, as well as periodically heavy metals and harmful substances, which are not under investigation in this study). Brynica (Szabelnia cross-section), the biggest right tributary of Przemsza, was monitored continuously from 1991 to 2023 by the National Meteorological Institute, while quality data are available from 1991 to 2010. The locations of monitoring points within the Przemsza River basin were established by the National Monitoring Program and include all relevant discharges and characteristics of the quality of surface waters impacted by industrial and urban activity, and particularly, saline mine waters.

## 3. Results

River salinization can have many different causes, and it is obviously derived from the specificity of the region in which surface water services are served. In the Przemsza River basin, the impact of coal mining and discharges of mine waters from the drainage of active and abandoned coal mines is significant, causing several environmental threats. However, the number of active and abandoned but dewatered coal mines decreased significantly through the years due to the transformation of the coal sector. Mine water level rebound in abandoned, flooded coal mines reduces inflows to coal minefields as well as a range of cones of depression. Salinity, due to the geochemical gradient, increases with depth, while after closure and long-lasting flooding, mine water has more sulfur–iron content and then becomes fresher with a lower salt content (chlorides, calcium, sodium, and magnesium) [27]. Therefore, the total amount of mine waters discharged into rivers has been decreasing with time, and the impact of salinization on surface waters is expected to be minimized in the post-closure period. As it was presented in Figure 4, the number of mining water discharges has been reduced due to the continuous process of closure, simplifying dewatering systems, and flooding of abandoned coal mines in the region. The summary of the coal mining closure process and dewatering of abandoned mines in the Przemsza River basin is presented in Figure 5.

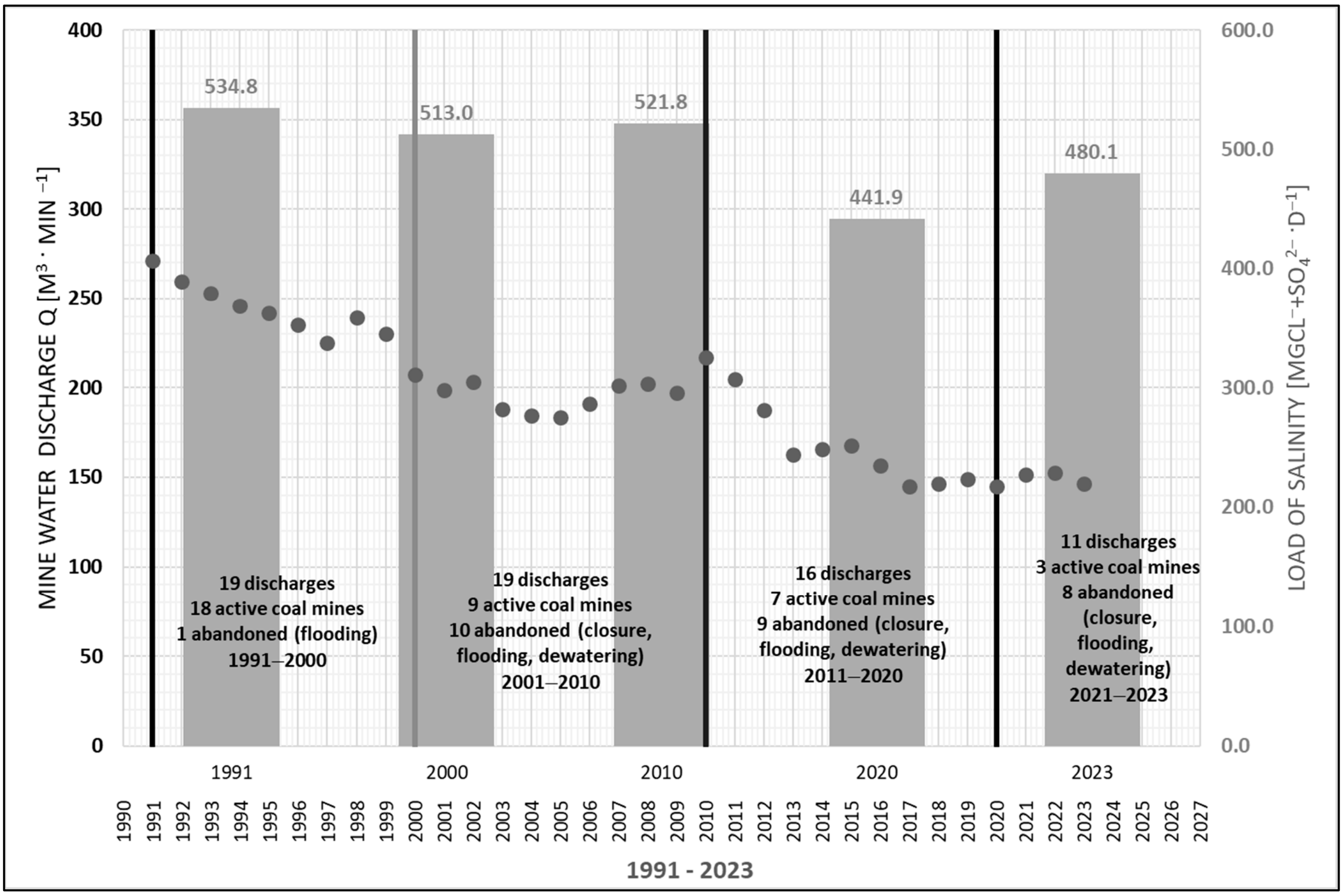

**Figure 5.** Coal mine transformation and dewatering in the Przemsza River basin in relevant decades, with data on quantity and loads of contaminants (salinity) in 1991–2023.

There has been a significant decrease in the number of mine water from 142.5 mln $m^3$/year (271.2 $m^3$/min—1991) to 76.2 mln $m^3$/year (144.2 $m^3$/min in 2020), which gives 47% less mine water discharged into the river basin than it was before the coal closure period. The total loads of chlorides and sulfates in mine waters discharged in the Przemsza River basin in the period 1991–2023 range from 534.8 to 441.9 $MgCl^{-}+SO_4^{2-}$/day [22].

The coal sector transition is analyzed in this study as a background of changes in salinization in surface waters in the Przemsza River basin in the period 1991–2023. As collected data revealed, the total load of contaminants, as the sum of chlorides and sulfates discharged with coal mine waters, has slightly decreased (average level $\cong$ 500 tons of chlorides and sulfates per day), even if the total amount of mine water discharged was less than twice as much as before the coal mine closure in 1991, as well as the number of active discharges (from coal mines where exploitation is ongoing and where dewatering of abandoned mines is continued). It is worth mentioning that all active and abandoned coal mines obtained relevant water permits to discharge mine waters into the rivers or streams in the case study area. However, it should be underlined that discharges are continued without flow-dependent [28] or salinity-dependent discharge management—parameters of quantity and quality of receiver have never been considered as the basis of mitigation of negative salinity impacts in rivers. In this study, particular attention is given to the parameters of surface waters in the scale of the Przemsza watershed, with available data from long-term monitoring of EC [$\mu S \cdot cm^{-1}$], concentrations of chlorides [$mg \cdot L^{-1}$], sulfates [$mg \cdot L^{-1}$], and flows [$m^3 \cdot s^{-1}$]. Additionally, data collection on the concentration of the main ions (calcium, magnesium, sodium, potassium, and bicarbonates) allowed for wider characteristics of chemistry in the surface waters in the concerned basin. The availability of the data for the concerned period in the representative cross-sections mostly covers the relevant decades. Due to the mentioned implementation of WFD, in general, the range of parameters and the number of cross-sections in monitored rivers in the Przemsza River basin were reduced; thus, representative cross-sections monitored continuously in 1991–2023 were chosen for further analysis as follows: Brynica—Szabelnia (salinity parameters 1991–2010, flows 1991–2023), Rawa (outflow to Brynica, salinity parameters 1991–2020), Bolina (outflow to Przemsza, salinity parameters 1991–2023), Przemsza–Jeleń (salinity parameters 1991–2023, flows 1991–2023). Przemsza-Jeleń is a representative cross-section that is monitored (quality and quantity) and closes the area of the Przemsza River basin, which is impacted by mine water discharges. Therefore, in this monitoring point, the overview of the status of water in the river body is assessed by the Water Monitoring Inspectorate for the purpose of Water Management Plans according to WFD.

### *3.1. Changes in Salinity Patterns in Surface Waters of the Przemsza River Basin in 1991–2023*

The changes (deterioration) of surface water quality in the Przemsza River basin are presented in Figure 6. An increase in salinity (measured as EC [µS·cm$^{-1}$] in tributaries of Przemsza; Rawa and Bolina are particularly significant in the last decade 2011–2020 and the period 2021–2023). This results in an increase in water salinity in Przemsza–Jeleń (the closing section of the river basin) in the last period of 2021–2023 and is twice higher than observed in previous decades. Due to data availability for the Brynica River (1991–2010), trends of salinity are presented only for two decades (1991–2000 and 2001–2010) and remain stable in the related periods.

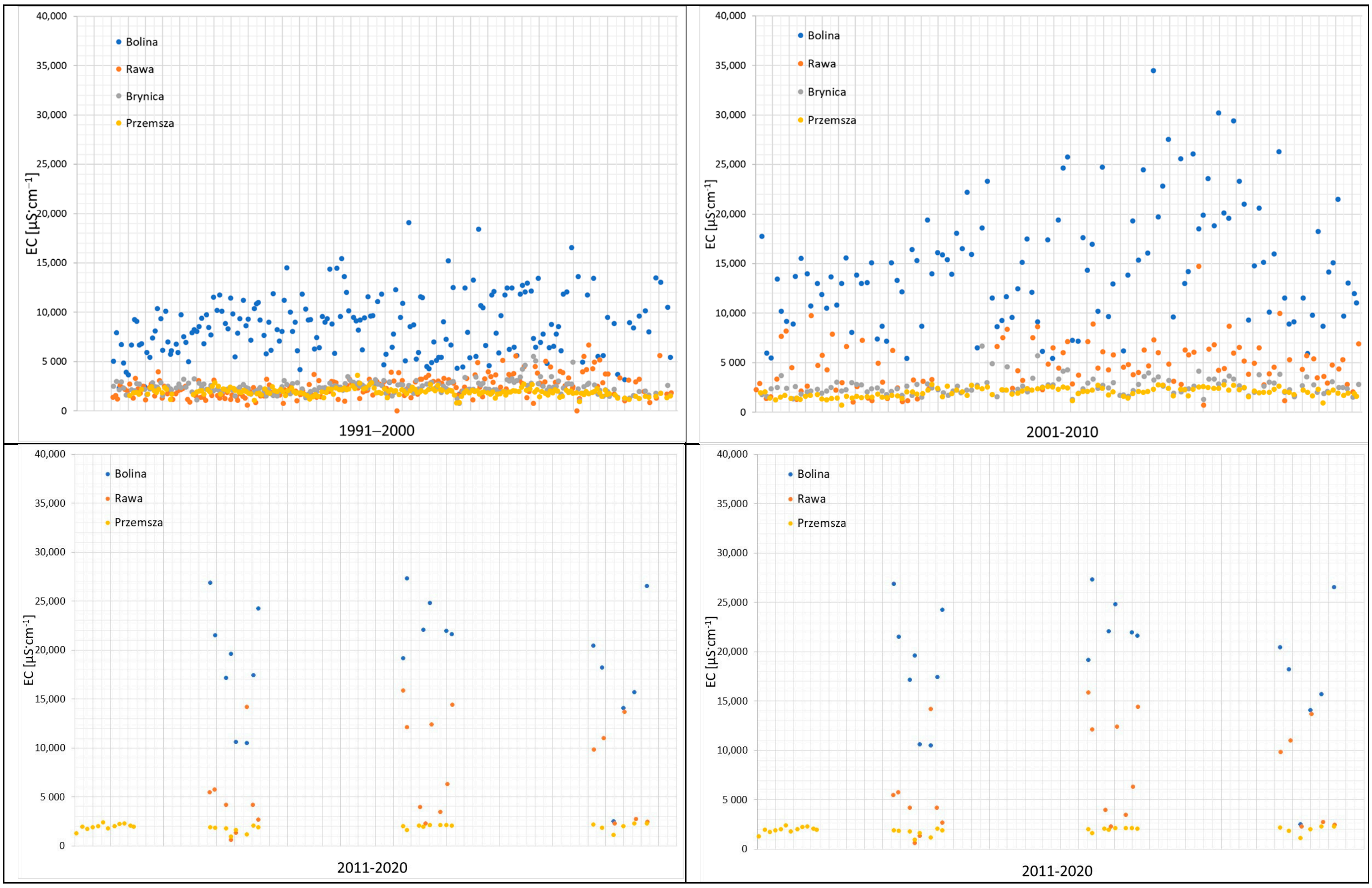

**Figure 6.** Time series of EC [µS·cm$^{-1}$] in surface waters in the Przemsza River basin in relevant decades.

Statistical analyses of the data for salinity parameters EC [µS·cm$^{-1}$] and the concentration of chlorides $Cl^-$ [mg·L$^{-1}$] and sulfates $SO_4{}^{2-}$ [mg·L$^{-1}$] are presented in Table 2. The data revealed that the saline and ultra-saline waters of Rawa and Bolina are mostly chloride-type, with a maximum concentration of 7100 $Cl^-$ [mg·L$^{-1}$] (Rawa) and 31,200 $Cl^-$ [mg·L$^{-1}$] (Bolina). EC, chlorides, and sulfates parameters of waters in Rawa and Bolina significantly increased in the last periods 2011–2020 (Rawa) and 2021–2023 (Bolina). Chlorides values (mean and median) are, in general, below 1000 $Cl^-$ [mg·L$^{-1}$] in the surface waters of Rawa, Brynica, and Przemsza (limit value in mine water discharges in Poland [29]), while good status is defined, in general, as 250 < mg$Cl^-$·L$^{-1}$. Bolina is significantly impacted by saline mine waters, and in the outflow to Przemsza, the salinity concentrations (EC, chlorides, and sulfates) increased in the last 3 years 2–3 times higher than the average.

**Table 2.** Salinity patterns in surface water in the Przemsza River basin in the period 1991–2023.

| **River** | **Brynica** | **Rawa** | **Bolina** | **Przemsza** |
|---|---|---|---|---|
| cross-section | Szabelnia | outflow to Brynica | outflow to Przemsza | Jeleń |
| period | 1991–2010 | 1991–2020 | 1991–2023 | 1991–2023 |
| **Parameter** | **EC [µS·cm$^{-1}$]** | **EC [µS·cm$^{-1}$]** | **EC [µS·cm$^{-1}$]** | **EC [µS·cm$^{-1}$]** |
| n | 324 | 331 | 360 | 378 |
| max | 6670 | 15,880 | 67,470 | 6740 |
| mean | 2465 | 3442 | 12,766 | 2052 |
| median | 2382 | 2810 | 10,329 | 1986 |
| 10th percentile | 1662 | 1315 | 5530 | 1450 |
| 90th percentile | 3269 | 6290 | 23,336 | 2580 |
| min | 776 | 585 | 1692 | 728 |
| **Parameter** | **$Cl^-$ [mg·L$^{-1}$]** | **$Cl^-$ [mg·L$^{-1}$]** | **$Cl^-$ [mg·L$^{-1}$]** | **$Cl^-$ [mg·L$^{-1}$]** |
| n | 324 | 333 | 348 | 346 |
| max | 1735 | 7100 | 31,200 | 1002 |
| mean | 466 | 880 | 4145 | 405 |
| median | 442 | 615 | 3235 | 413 |
| 10th percentile | 245 | 225 | 1548 | 226 |
| 90th percentile | 676 | 1770 | 7704 | 565 |
| min | 114 | 83.3 | 317 | 82.0 |
| **Parameter** | **$SO_4{}^{2-}$ [mg·L$^{-1}$]** | **$SO_4{}^{2-}$ [mg·L$^{-1}$]** | **$SO_4{}^{2-}$ [mg·L$^{-1}$]** | **$SO_4{}^{2-}$ [mg·L$^{-1}$]** |
| n | 324 | 333 | 348 | 346 |
| max | 697 | 817 | 1197 | 623 |
| mean | 404 | 374 | 488 | 254 |
| median | 405 | 374 | 499 | 258 |
| 10th percentile | 299 | 206 | 299 | 200 |
| 90th percentile | 522 | 548 | 636 | 300 |
| min | 109 | 63.2 | 56 | 33 |

A Piper diagram for surface waters in concerned measuring cross-sections in the rivers Przemsza, Rawa, Brynica, and Bolina is presented in Figure 7. The data from the Piper diagram covered the coherent period for concerned monitoring cross-sections (available data from 1991 to 2023, main ion concentrations $Cl^-$, $SO_4{}^{2-}$, $K^+$, $Na^+$, $HCO_3{}^-$, $Mg^{2+}$, and $Ca^{2+}$). Sodium–potassium chloride–sulfate types of surface waters dominate in the Rawa and Bolina Rivers (measured in their outflows to Brynica and Przemsza). This is evident from the mine water impacts of continuous discharges from coal mines in the river basins. No dominant type is characteristic for surface waters in Brynica and Przemsza; however, for Przemsza in the last period (2021–2023), increased impact of the tributaries Rawa and Bolina is visible as prevailed sodium chloride type of water in Jeleń measuring point.

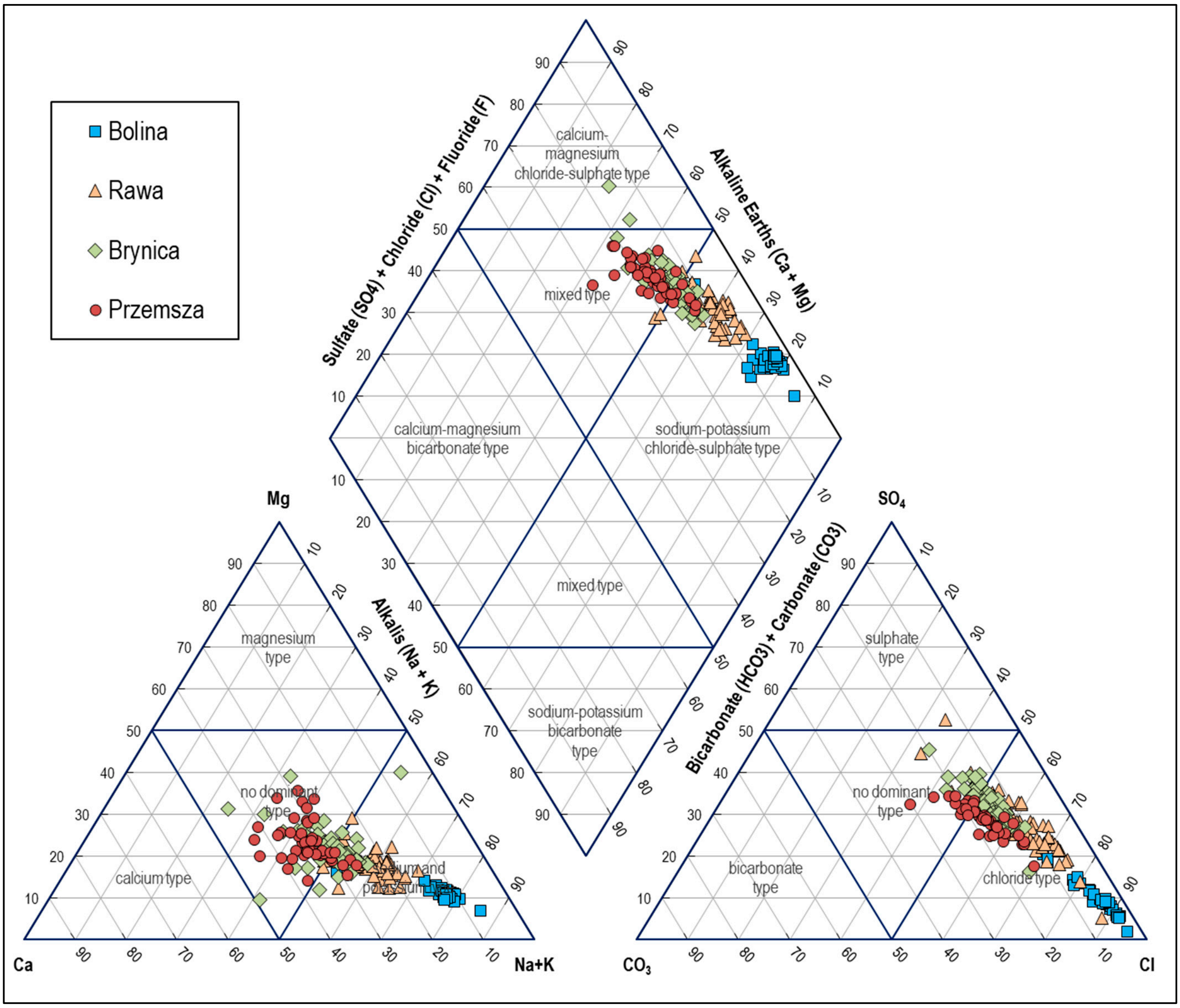

**Figure 7.** Piper diagram for characteristic measuring points of surface waters in the Przemsza River basin.

### 3.2. Changes in Flows in 1991–2023 in the Przemsza River Basin

Climate change impacts surface waters in many regions worldwide, which is generally defined as drought with increased frequency and long lasting periods. It is undoubtedly environmental threat for water resources which are at scarce. The increase in salinization of surface waters should be then analyzed parallelly with quantity of water resources in the river basin—time trends of flows should be at particular concern to implement appropriate measures and management.

On Figure 8 time series of mean monthly low flows from Polish National Meteorological and Hydrological Institute (IMiGW) [24] are presented for two representative (and available) cross sections: Brynica Szabelnia and Przemsza Jeleń.

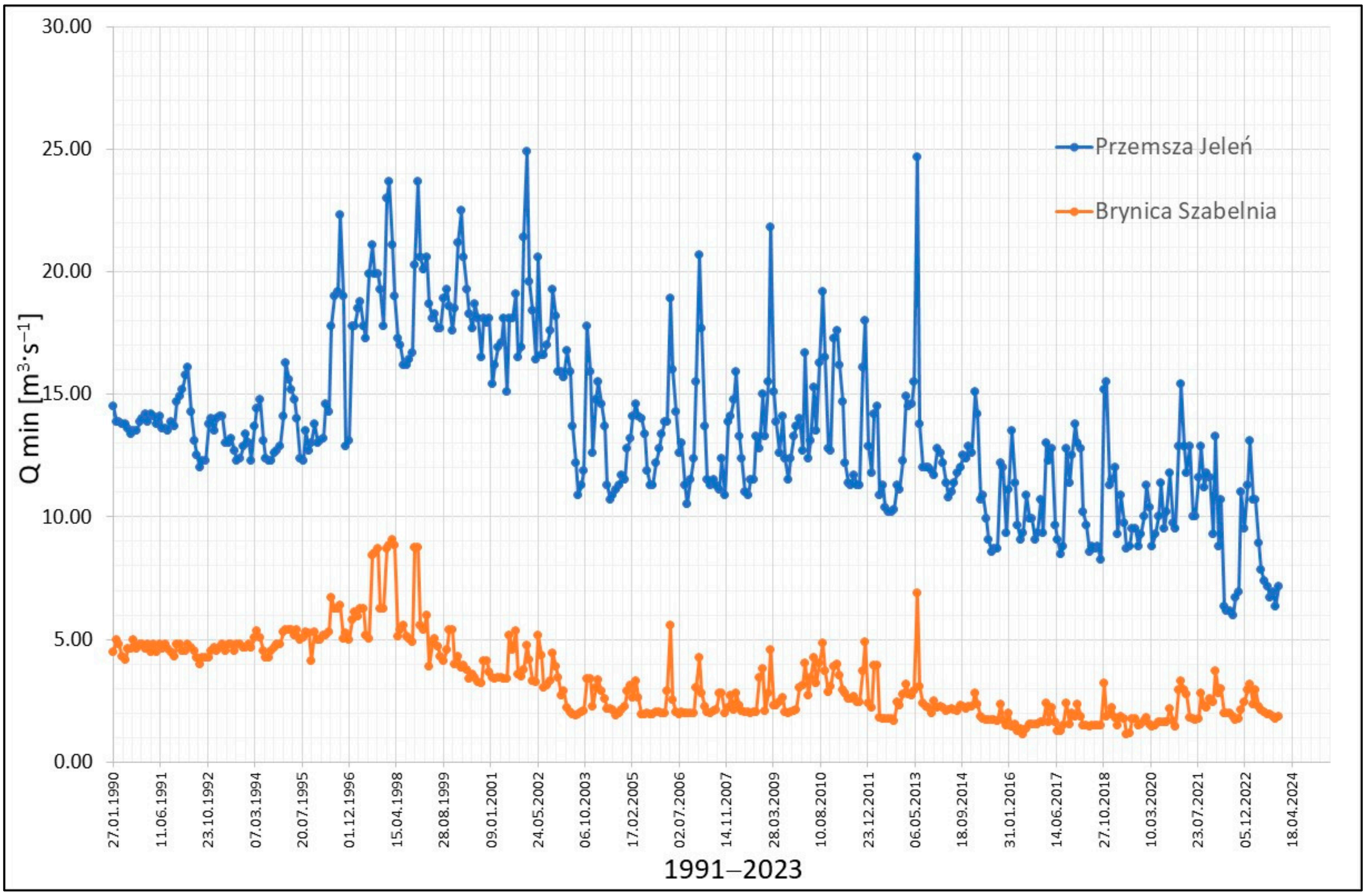

**Figure 8.** Mean monthly low flows in two characteristic flow measuring points in Przemsza River basin (Przemsza Jeleń, Brynica Szabelnia, 1991–2023).

A significant decrease in low flows in the Przemsza River basin occurred in the last decade (2013–2023). During this period, a significant and long-lasting drought period affected surface water resources in Poland. Low flows in Przemsza and Brynica were noted as the lowest in the history of measurements ($Q_{min1991–2023}$ = 1.12 [$m^3 \cdot s^{-1}$] in Brynica and $Q_{min1991–2023}$ = 5.96 [$m^3 \cdot s^{-1}$] in Przemsza, while average flows were 16 [$m^3 \cdot s^{-1}$] and 57.6 [$m^3 \cdot s^{-1}$], respectively).

In the Przemsza River basin, as a case study of significant salinization of surface waters due to industrial activity, even if in its phase-out period, analysis of the quality and quantity were not carried out as a part of management plans for mitigation of climate change, industrial, and urban impacts. Monitoring is performed as a part of the assessment of water body status, which is generally defined as bad, with the necessity to decrease its limits for good status. Therefore, the holistic approach is presented with the minimum possible analysis of the quantity and quality of surface waters. In Figure 9, the graphs present time series and overlapping measurements of salinity and flows in Przemsza–Jeleń as representative measuring points for the river basin.

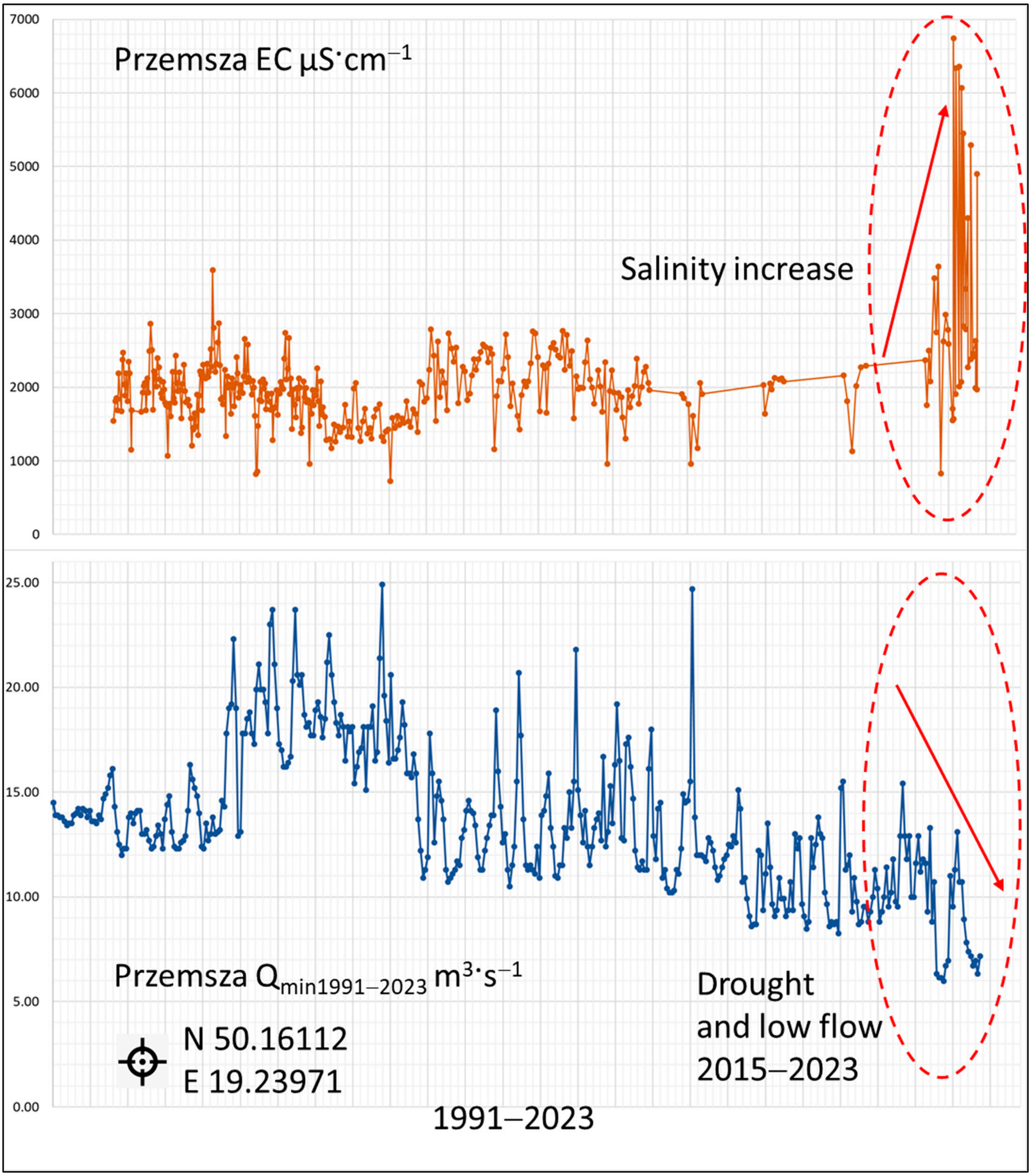

**Figure 9.** Adverse salinity and hydrological conditions in the Przemsza River basin (with coordinates of the Przemsza–Jeleń monitoring cross-section, 1991–2023; red circles and arrows indicate significant increase of salinity and decrease of flows in drought period).

## 4. Discussion

Water management practices and legislation in Poland lack mechanisms of proper discharge management in terms of sewage systems, with particular attention to saline discharges—up to now, flow-dependent and salinity (quality)-dependent discharge management has not been legally established. However, as mentioned in the legal act [29], there are requirements for saline discharges (limits for chlorides 1000 $mgCl^{-} \cdot L^{-1}$ and 500 $mgSO_4^{2-} \cdot L^{-1}$) but there are possible derogations in the case of mine waters with higher values (concentrations) allowable in water permits, which are commonly implemented. Considering mine water impact as increasing salinization of surface waters, it should be underlined that climate change impact results in significant and long-lasting drought periods. This multiplies the deterioration of surface water resources, and in turn, the mining impact expected to be reduced due to the phase-out of the coal process is in fact more significant and harmful to the water environment.

The changes (deterioration) in the chemical condition of surface waters identified in this study increased susceptibility to eutrophication and are derivative of changes in the quantitative status of waters. Therefore, for users of water services in water bodies, in particular those discharging industrial, municipal, and social-domestic sewage, this may result in restrictions on the quantity and quality of sewage due to the need to protect the water resources of a specific stream or river basin.

It is also necessary to emphasize that in relation to the water management in the Upper Oder and Little Vistula regions, the specific nature of water environment transformations resulting from high urbanization, industrialization, and intensively transforming mining exploitation should be taken into account. The number and significance of pressures on the water environment occurring in the Silesian region in terms of the need to achieve good status or good potential necessitates sustainable management of water resources.

These resources will be significantly depleted in the near future, so a number of parallel actions should be taken to reduce pressure and increase the water resources of these regions. It should also be noted that the condition and status of water bodies covered by significant mining impacts should be verified both currently and in the future, i.e., in the perspective of 2027, term of WFD for the achievement of good status in water bodies, and further, 2049, term of complete phasing out of coal in Poland.

Forecasts regarding changes in water conditions after the closure and flooding of mines were discussed in a number of works, but the determination of the expected changes in the aquatic environment as a result of the cessation of dewatering in coal mines could only be approximate. However, the analysis of both chemical conditions (salinity) and quantity (flows in rivers) presented in this study revealed that an increase in salinity and a significant decrease in flows in rivers result in multiple negative impacts in the aquatic environment—salinity levels are three times higher and have never been observed before in the Przemsza River basin.

In the Przemsza River basin, almost 42% of mine water was less discharged in 2023 than in 1991. The salinity of mine water, as a total load of chlorides and sulfates, was at 534.8 $MgCl^{-}+SO_4^{2-}$ per day in 1991, while in 2023 it was at 480.1 $MgCl^{-}+SO_4^{2-}$ per day. The total loads of salts in mine water are directly related to the depth of exploitation; therefore, more saline mine water is pumped out from active coal mines. Moreover, of the 19 active mine water discharges in 1991, only 11 remain in 2023, while observed salinity of surface water in the Przemsza watershed increased rapidly from an average of 2000 $\mu S \cdot cm^{-1}$ to 6700 $\mu S \cdot cm^{-1}$ due to significant drought.

The adverse hydrological conditions represent low flows never observed before (three times lower flows in the mouth of the Przemsza River in the period 2021–2023 compared to previous decades 1991–2020).

As of 2023, the closure of hard coal mines is ongoing. Mine water quantity is relatively two times less than 30 years ago (in periods of active coal mining). The salinity of surface waters in impacted areas increased significantly, which is the result of both mine water discharges and the deterioration of water resources due to droughts, as a result of climate change. Thus, proper measurement and management actions are urgent and necessary to mitigate negative impacts on water bodies. These actions are focused mainly on proper discharge management, which is directly dependent on the flow and salinity of surface waters measured upstream of the discharge point from a coal mine. Such systems are not legally required in Poland yet but are under investigation, and engineering works in river basin management are underway. Flow-dependent and salinity-dependent discharge of mine waters as well as hydrotechnical systems with available retention volume (mine water ponds) are optimal solutions to mitigate salinity impact on surface waters. These systems were implemented in Mid-Germany with improved wastewater treatment and flow-dependent discharge management [28]. However, in the current status of the coal sector transformation in Poland, mine water management in the aspect of climate change and salinization of surface waters is going to be one of the most important issues in future legislation changes.

## 5. Conclusions

The long-lasting impact of coal mines on surface water bodies is evident and known in many regions across the EU and worldwide [30]. While industrial and urban impacts on surface water remain unsustainable, the future challenge of proper water management with a holistic approach is necessary [31].

Proper measurement and data collection from representative sampling points on a regular basis is crucial for decision-making in water management. Requirements of impact assessment based on reliable data should be implemented not only in water management plans but into legal requirements with a focus on the continuous decision-making process in the management of sewage discharge (here, mine waters). Flow-dependent discharge of saline mine waters would mitigate negative impacts on surface waters, but this requires available retention volumes and accurate hydrological prognosis on the time and frequency of low flows in the rivers.

The overlapping impacts in mining regions have caused and continue to cause significant transformations of the aquatic environment, including primarily those water bodies to which mine water is discharged. Therefore, it is necessary to apply derogations and lower environmental requirements for water bodies (underground and surface) in the applicable water management plans. However, this should be reconsidered in relation to climate change and the global increase in surface water salinity. This is particularly important in mining-impacted areas, with significant salinization of surface waters—legal requirements on controlled flow. Dependent discharge is one of the possible mitigation actions during low flow and long-lasting drought periods to protect surface waters against rapid increases in salinity.

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**Data Availability Statement:** Data supporting the reported results can be found as follows: (https://energy.instrat.pl/en/mining/production-sales-hard-coal/ accessed 11 September 2024), The data presented in this study are openly available in database of Chief Inspectorate of Environmental Protection of Poland, The surface water quality portal: https://wody.gios.gov.pl/pjwp/ (accessed 22 April 2024). Detailed data on mine water discharges are not publicly available due to the coal companies' restrictions.

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