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Assessment of Groundwater (Main Usable Aquifer) Vulnerability to Seawater Intrusion in the Polish Baltic Coastal Region

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Abstract: The inflow of saline water reduces water quality and limits its use as drinking water. The risk of seawater intrusion into groundwater along the Polish coastline was assessed using two methods. The vulnerability method (GALDIT) considered six aquifer parameters. The second method focused exclusively on the chemical parameters of groundwater: EC, seawater mixing index (SMI), $rHCO_3/rCl$, rNa/rCl, and the concentrations of Cl^- and Br. The analysis focused on monitoring results collected from points located within 5 km of the Baltic Sea coastline. Both risk assessment methods used a division into three risk classes (low, moderate, and high), but the results differed between the two approaches. A comparison of the results from both classification methods was conducted, followed by a comprehensive risk assessment integrating the outcomes of both approaches. No straightforward relationship was observed between individual threat assessment parameters and distance from the sea. However, when the overall assessment, incorporating multiple parameters, was considered, such a relationship emerged. The classes of seawater intrusion risk differ in terms of the medians and ranges of individual parameters. Ratios such as $rHCO_3/rCl$, rCa/rMg, and Cl/Br play a significant role in risk assessment, whereas the rNa/rCl ratio has a relatively smaller impact. Seawater intrusion risk should be assessed based on multiple parameters. The highest risk of seawater intrusion occurs within approximately 800 m of the coastline.

Keywords: coastal groundwater; seawater intrusion; GALDIT; seawater mixing index (SMI); hydrochemical ratios; Polish Baltic coastal region

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1. Introduction

Seawater acts as a discharge area for coastal groundwater. In coastal regions, groundwater and saline seawater exist in a state of hydrodynamic and hydrogeochemical equilibrium. However, the natural balance between freshwater and seawater is vulnerable to disruption. Groundwater in coastal areas is at risk of seawater intrusion. The vulnerability of groundwater to seawater intrusion is influenced by hydrogeological conditions, including aquifer parameters, distance from the coastline, and water circulation [1–3]. An increase in Cl^- ion concentrations in coastal groundwater can result from changes in aquifer recharge, influenced by sea-level fluctuations, as well as by groundwater table-lowering due to water abstraction. Variations in the state of seawater significantly impact groundwater, particularly in shallow aquifers. Rising ocean levels driven by climate change exacerbate the risk of seawater intrusion [4,5]. The disruption of hydrodynamic equilibrium, leading to the influx of higher salinity waters, can also result from human activities. This is

primarily due to changes in the hydrodynamic field in coastal areas caused by excessive exploitation of groundwater resources [6–11]. The assessment of groundwater vulnerability to seawater intrusion has been the focus of numerous scientific studies [11]. These studies encompass various approaches, including multi-criteria risk analysis supported by GIS-vulnerability tools [12,13], hydrodynamic modeling of equilibrium conditions in coastal regions [6,9,14–16], and studies on changes in water chemistry [17–21].

The GALDIT method, a type of multi-criteria risk analysis, considers the hydrogeological parameters of aquifers [12]. It has been applied in studies of coastal groundwater in Portugal [22], India [12], South Korea [23,24], Kenya [25], Iran (Caspian Sea region) [26], Greece [27,28], and other regions. The method has been utilized in its basic form, in modified versions, and with additional parameters considered [27]. The acronym GALDIT was derived from the initial letters of terms describing the key factors influencing seawater intrusion [22].

The intrusion of seawater affects the chemistry of groundwater, making it possible to assess the current state of coastal groundwater based on its chemical composition, including the concentrations of individual components and their interrelationships (hydrogeochemical indices). This issue has been explored in various studies, including those on the Mediterranean coast [18,29,30], the Red Sea [31], the Indian Ocean [21,32,33], and the Pacific Ocean [17,34,35]. Another parameter used to evaluate the degree of risk of intrusion is the seawater mixing index [17]. The application of this parameter has been presented in numerous studies, including research on the coasts of the Indian Ocean [19,20,36] and the Mediterranean Sea [37]. To the best of our knowledge, this parameter has not yet been used in studies concerning the Baltic Sea.

In the Baltic Sea region, the risk of saltwater intrusion has been assessed using the value-weighing factor method. Such assessments were conducted on Öland Island (Sweden) [13]. Model studies of seawater intrusion were also performed on Falster Island in southeastern Denmark [38]. Additionally, the impact of the Baltic Sea on groundwater conditions at water abstraction sites has been studied in Latvia [39].

The impact of seawater intrusion on groundwater conditions in Poland has also been addressed in scientific publications [7,8,14–16,40–42]. Studies on the origin of chloride anomalies in groundwater along the Polish Baltic coast were conducted by Krawiec [43]. Pruszkowska-Caceres [42,44] analyzed the variability of groundwater chemistry in the areas of Ustka and Władysławowo. Modeling studies to determine the impact of sea-level rise on groundwater conditions in the cliff coast region (Jastrzębia Góra area) were carried out by Lidzbarski and Tarnawska [16]. Research on the influence of seawater on groundwater conditions in Poland has primarily focused on local situations. However, there is a lack of studies that assess the risk along the entire coastline using the GALDIT method or compare potential risk assessments with the current groundwater chemistry.

In the Baltic coastal region, there are several dozen monitoring points that are systematically and thoroughly sampled as part of groundwater monitoring programs carried out by the Polish Geological Institute—National Research Institute [45]. The aim of this article was to assess the risk of seawater intrusion into groundwater based on monitoring data from the Baltic coastal region. The assessment was conducted using two methods, including the aquifer vulnerability to seawater intrusion method, GALDIT [12]. The GALDIT method assessment resulted in the classification of monitoring points into three risk groups for seawater intrusion. The second method focused exclusively on the chemical parameters of the groundwater. Electrical conductivity, hydrochemical ratio values, and the seawater mixing index (SMI) [17] were used as the basis for categorizing groundwater into three risk classes for seawater intrusion. Monitoring data from the past several years were analyzed (with most points providing results from the last two years).

A comparison of the results obtained from both classification methods was conducted, followed by a comprehensive risk assessment that combined the outcomes of both approaches. This evaluation resulted in the classification of monitoring points into five groups with varying degrees of vulnerability to seawater influence and the identification of areas most at risk of seawater intrusion.

2. Materials and Methods

2.1. Groundwater in the Baltic Coastal Region

The Polish section of the southern Baltic coast is approximately 500 km long. This coastline features diverse geological structures. It predominantly consists of high cliff coasts, which span 65 km, accounting for 20% of the total coastline length, as well as dune coasts. The cliff coasts are dispersed along the coastline in segments ranging from 0.5 to 10 km. Dune coasts are associated with the outlet sections of former glacial troughs and valleys, as well as with sand spits [46].

In the Polish Baltic coastal region, there are two, and locally three, exploitable aquifer systems. These include Quaternary, Neogene, and Cretaceous aquifers (in the Gdańsk area), as well as Triassic and Jurassic aquifers (in the Kamień Pomorski area). Across most of the coastline, the Quaternary aquifer system holds primary significance for water use, while the other mentioned aquifers are of local importance (Figure 1). The water table in the Quaternary aquifer is generally unconfined but can be confined in some areas. In the strata underlying the Quaternary aquifer, confined aquifers are present [47].

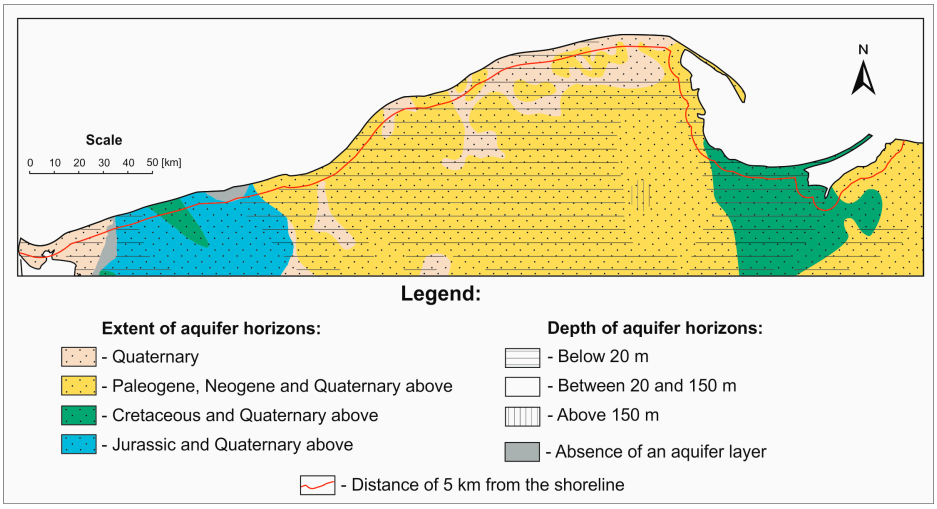


Figure 1. The main usable aquifers in the area of the Polish part of the Baltic coast according to [48], modified and simplified.

The aquifers of the Quaternary system mainly consist of fluvial and glaciofluvial accumulation deposits. The Quaternary aquifer system occurs within Holocene and Pleistocene formations. In the western coastal region, Quaternary aquifers are found at depths of approximately 30–40 m, while in the eastern coastal region, they extend to depths of up to 100 m, and locally even as deep as 300 m. In the Quaternary aquifer system, two aquifer levels are present: the Pleistocene and the Holocene. The Holocene aquifer is found in the sandspit areas (Hel and Vistula Spits). The upper Pleistocene aquifer layer is continuous across the entire eastern coastal region (in the Pomeranian Voivodeship area) and occurs at depths of 10–40 m below ground level. It consists of glaciofluvial sands of varying grain sizes from the Vistulian glaciation, with filtration coefficients ranging from 0.04 to 8.3 m/h (0.96–199.2 m/d). The water table is unconfined or slightly confined and ranges from 1 m above sea level (a.s.l.) to 0 m a.s.l. along the coastline. The lower Pleistocene aquifer layer

is widespread, except in the Vistula Spit, occurring at depths of 30–50 m below ground level. It is composed of fine- and medium-grained sands from the South Polish and Middle Polish Glaciations. This layer has a confined water table that stabilizes around 1 m a.s.l. along the coastline, with filtration coefficients ranging from 0.3 to 0.72 m/h (7.2–17.28 m/d). In some areas, this layer connects with Miocene aquifers, forming a combined aquifer with a significant spatial extent, thickness, and yield.

In areas where the sandspits are wide and dunes reach heights of several dozen meters, unconfined groundwater is present, with the water table ranging from 0.5 to 5 m a.s.l. and filtration coefficients between 0.3 and 1.1 m/h (7.2–26.4 m/d) [43,47–50].

The Neogene (Miocene aquifer system) is the primary exploitable aquifer in the northernmost part of the Polish coastline (Rozewie Cape). The aquifer consists of Miocene sands of varying grain sizes, which lie beneath South Polish Glaciation clays with a thickness of 10–40 m. These sands are located at a depth of approximately 20 m. The water table is confined and stabilizes at a level close to the sea level [50,51].

Low-mineralized groundwater in deeper aquifer systems is found only locally. Examples include Cretaceous aquifers in the Gdańsk region and Jurassic aquifers in the Pobierowo and Trzęsacz areas.

In the Uznam and Wolin Islands area, groundwater from the Cretaceous aquifer is of the Cl-Na type. The Upper Cretaceous formations have a mineralization of approximately 15 g/L, while the Lower Cretaceous formations exhibit a mineralization level of approximately 45 g/L and are utilized for therapeutic purposes. Chloride–sodium waters from the Jurassic aquifer are extracted in the Kamień Pomorski area (with a mineralization level of 34 g/L) and in Kołobrzeg (ranging from 52 to 62 g/L). In Międzywodzie, Cl-Na waters from the Triassic aquifer exhibit a mineralization level of 93 g/L [52,53].

In the zone of interaction between groundwater and surface water, both submarine and coastal drainage occur. Submarine free drainage takes place when the seabed cuts through the aquifer, allowing saline seawater to come into direct contact with fresh groundwater. The zone of direct contact extends from several dozen to up to 300 m inland [47]. The extent of the contact zone is influenced by human activity, particularly the extraction of groundwater. Lowering the water table in the aquifer causes the contact zone between groundwater and seawater to shift inland, resulting in groundwater salinization. Such cases have occurred in the Polish coastal region, for example, on the Hel Peninsula [7] and the islands Wolin and Uznam [14,15]. Groundwater extraction can also lead to the upward migration (ascent) of saline water, as observed in the Słowiński coast region [54] and on Uznam Island [14]. Groundwater salinization also occurs due to hydraulic contact with surface water. This phenomenon is exacerbated by storm surges [42,44]. Salinity in the Baltic coastal region can result from both seawater intrusion and the upwelling of mineralized waters from deeper aquifers. Coastal saline lakes can also influence groundwater salinity.

In the Kołobrzeg area, salinity is almost exclusively the result of upwelling from the Mesozoic substratum. Seawater intrusion processes are evident in the lower reaches of river valleys. The Quaternary cover of the Kołobrzeg anticline is an area of saline water upwelling, where saline springs with mineralization exceeding 50 g/L discharge to the surface.

In some areas with multiple aquifer levels, salinity in the shallowest aquifer (Holocene or Holocene–Pleistocene) is associated with seawater intrusion. In contrast, salinity in deeper Pleistocene or Pleistocene–Miocene aquifers is considered a result of ascending from the Mesozoic aquifer system. This is observed in the Mielno-Rowy and Łeba areas. In Pleistocene and Holocene formations on sandspits, freshwater lenses overlay saline groundwater [43].

2.2. Monitoring Studies of the Polish Baltic Coast

The impact of the sea on groundwater conditions was assessed using data from chemical monitoring conducted by the Polish Geological Institute. The nationwide monitoring program forms a groundwater observational and research network that covers the entire country, including all exploitable aquifer levels and groundwater tables (Polish Geological Institute—Groundwater Monitoring) [45].

The purpose of these monitoring studies is to document the chemical state, composition, and quality of ordinary groundwater. Both confined and unconfined aquifers are monitored using various sources, including wells, boreholes, piezometers, and springs. Two types of monitoring are conducted: diagnostic and operational. Diagnostic monitoring is conducted nationwide every three years and provides a comprehensive assessment of groundwater conditions. Operational monitoring is carried out in the years between diagnostic monitoring, focusing on specific areas and issues identified during the diagnostic phase.

2.3. Scope of the Study

The analysis focused on monitoring results (including chemical composition determinations) collected from points located within 5 km of the Baltic Sea coastline (Figure 1). According to the classification of uniform groundwater bodies (JCWPd), the monitoring points were situated within 10 JCWPd areas. The dataset included data from 61 monitoring points (32 piezometers and 28 drilled wells).

In most cases (51), samples were taken from Quaternary aquifers, while two samples came from the Paleogene–Neogene aquifer, one from the combined Paleogene–Neogene and Quaternary aquifer, one from the combined Paleogene–Upper Cretaceous aquifer, and three from the Cretaceous aquifer. The monitoring points were located at distances ranging from 12 m to 4172 m from the coastline.

In 28 cases, the water table was unconfined, and in 33 cases, it was confined. At points with an unconfined water table, the depth to the water table generally did not exceed 10 m below ground level, with a minimum of 0.3 m below ground level. In only two cases were greater depths recorded, at 23.2 m and 30.5 m b.g.l. (Figure S1). Relative to sea level, the water table elevation ranged from below sea level (−0.26 m) to 15.78 m above sea level (a.s.l.). For confined conditions, the tops of the Quaternary aquifers were found at depths ranging from 1.3 m to 103 m b.g.l. In contrast, the top of the Upper Cretaceous–Paleogene formations was at a depth of 118 m, the Upper Cretaceous formations at 134 m, and the Lower Cretaceous formations at 225 m b.g.l.

Monitoring points where waters from unconfined Quaternary aquifers were sampled were located at distances of 12 m to 1850 m from the coastline. Points sampling confined Quaternary aquifers were situated at distances of 80 m to 4172 m, while waters from aquifers older than the Quaternary were sampled at distances of 383 m to 2257 m (Figure S1).

The data on groundwater chemistry covered the period from 2002 to 2023, with the majority originating from 2022 and 2023. In 2023, samples were collected from 20 monitoring points, while in 2022, 22 points were sampled.

The risk assessment utilized two methods: the GALDIT method [12] and a method based on the chemical composition of groundwater. The GALDIT method considers six aquifer parameters: Each parameter is assigned a specific weight. This method has been thoroughly described in studies [12,24,25].

The method based on groundwater chemistry involved the analysis of chemical parameters, including electrical conductivity (EC), chloride ion concentrations, hydrochemical ratios, and the seawater mixing index (SMI), calculated using the concentrations of ions: Na^+, Mg^{2+}, Cl^-, and SO_4^{2-} [20]. Hydrochemical ratios such as $rHCO_3/rCl$, rNa/rCl, and

Cl/Br were calculated and analyzed. The chemical parameters at monitoring points were compared with the characteristic values of seawater to assess potential seawater intrusion.

3. Results and Discussion

3.1. Risk Assessment Based on the GALDIT Method

The GALDIT method assesses the risk of seawater intrusion based on hydrogeological conditions. In the GALDIT method the most important factors controlling seawater intrusion were found to be the following: groundwater occurrence, aquifer hydraulic conductivity; depth to groundwater level above the sea; distance from the shore, impact of existing status of seawater intrusion in the area ($rHCO_3/rCl$ ratio); and thickness of the aquifer [12].

The GALDIT index (*GI*) is calculated by multiplying the weights with the rating parameters assigned to each data point.

$$GI = \frac{\sum_{i=1}^{6}(W_i \cdot R_i)}{\sum_{i=1}^{6} W_i} \quad (1)$$

where W_i is the weight of the i's parameter, R_i is the importance rating of the i's parameter.

There are four importance ratings for each parameter with scores of 2.5, 5, 7.5, or 10. The results are three GALDIT vulnerability classes: high vulnerability, $GI \geq 7.5$; moderate vulnerability, *GI* values from 5 to 7.5; and low vulnerability, $GI < 5$. Details of the weighting and scoring system are presented in Table S1. The table with the output data is also included (Table S2).

The risk classification in the GALDIT method was conducted using data from monitoring points. The data for these parameters were derived from information collected at groundwater monitoring points [54]. Due to the lack of precise data on hydraulic conductivity at the monitoring points, its value was represented by the upper limit of the average values reported for the respective JCWPd (Groundwater Management Units) area [55]. Throughout the entire area, the value of hydraulic conductivity did not exceed 3×10^{-4} m/s^3 (28 m/d), which corresponded to an importance rating of 7.5. However, in the Vistula Spit region, the value was three times lower, corresponding to an importance rating of 5. In this article, the factor "groundwater occurrence (aquifer type)" was assessed based on the level of the drilled water table relative to the stabilized water level. If the stabilized water level corresponded to the drilled water table, it was classified as an "unconfined aquifer". If the stabilized water level was above the drilled water table, it was classified as a "confined aquifer". The seal integrity of the aquifers was not evaluated.

3.2. Risk Assessment Based on Groundwater Chemistry

3.2.1. Major Components of Groundwater

The electrical conductivity (EC) of the analyzed waters ranged from 142 to 33,389 µS/cm. At 12 monitoring points, EC exceeded 1000 µS/cm. Among the anions, bicarbonates (HCO_3^-) predominated, while calcium (Ca^{2+}) and sodium (Na^+) were the dominant cations:

- Bicarbonate-dominated waters (HCO_3^-): In 13 cases, the HCO_3^- ion constituted more than 72% of the milliequivalents, classifying these waters as HCO_3-Ca (Na) type;
- Mixed bicarbonate–chloride waters: A group of 13 samples was identified as HCO_3-Cl (Na-Ca) type, with 1 case also including magnesium (HCO_3-Cl-Na-Mg);
- Chloride-dominated waters (Cl^-): At five points, Cl^- exceeded HCO_3^-, classifying the waters as Cl-HCO_3-Na (Ca) type;
- Bicarbonate–sulfate waters: Five samples were classified as HCO_3-SO_4-Ca (Mg) type;

- Five-ion waters: Two samples represented complex five-ion waters classified as HCO_3-Cl-SO_4-Ca-Na type.

The chemical composition of the groundwater was visualized on a Piper diagram, incorporating the distances of sampling points from the coastline to assess the spatial relationship between water chemistry and proximity to the sea (Figure 2). The distance from the coastline does not influence the water type.

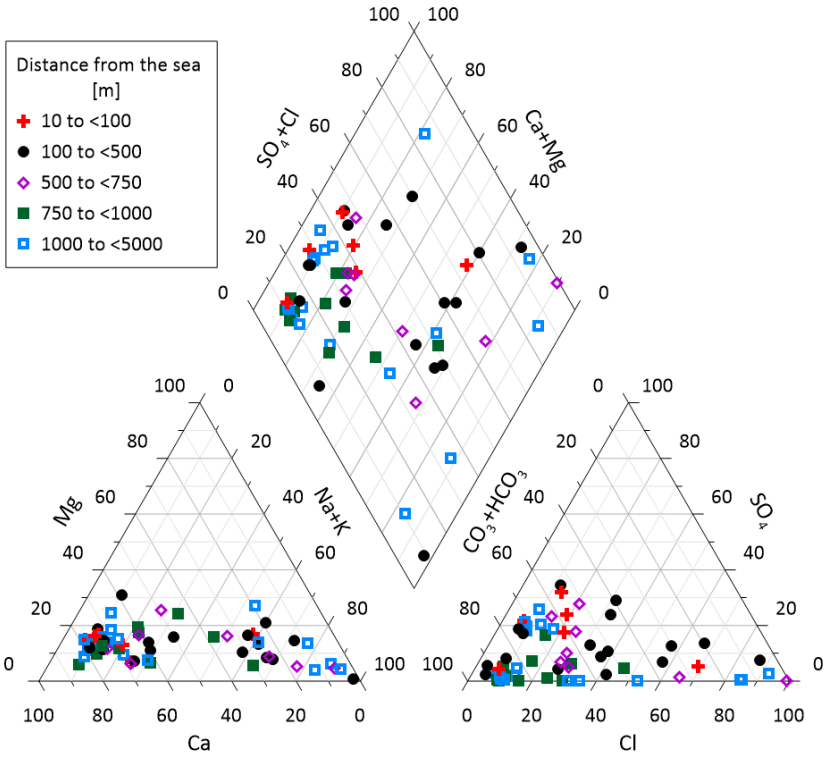


Figure 2. Piper diagram of groundwater from monitoring points.

3.2.2. Seawater Mixing Index

The assessment of seawater influence on groundwater in coastal regions can be conducted using the seawater mixing index (SMI). This method was proposed by Park et al. [17] in studies of the western coast of South Korea. It has also been applied in research on the coasts of India [19,36,56,57] and Sri Lanka [58]. Additionally, it has been used for the Mediterranean coast [37], the Red Sea [31], and other regions. To the best of the authors' knowledge, this method has not yet been applied to the coastal regions of the Baltic Sea. The SMI value can quantitatively reflect the extent of seawater influence by considering the relative ion concentrations in seawater, weighted against the enrichment factor of the sample relative to the regional threshold.

The SMI is based on the concentrations of four major ion constituents in seawater and is calculated following the methodology outlined by [17].

$$\mathrm{SMI} = a \cdot \frac{C_{Na}}{T_{Na}} + b \cdot \frac{C_{Mg}}{T_{Mg}} + c \cdot \frac{C_{Cl}}{T_{Cl}} + d \cdot \frac{C_{SO_4}}{T_{SO_4}} \quad (2)$$

where the constants a, b, c, and d represent the relative concentrations of Na, Mg, Cl, and SO_4 in seawater:

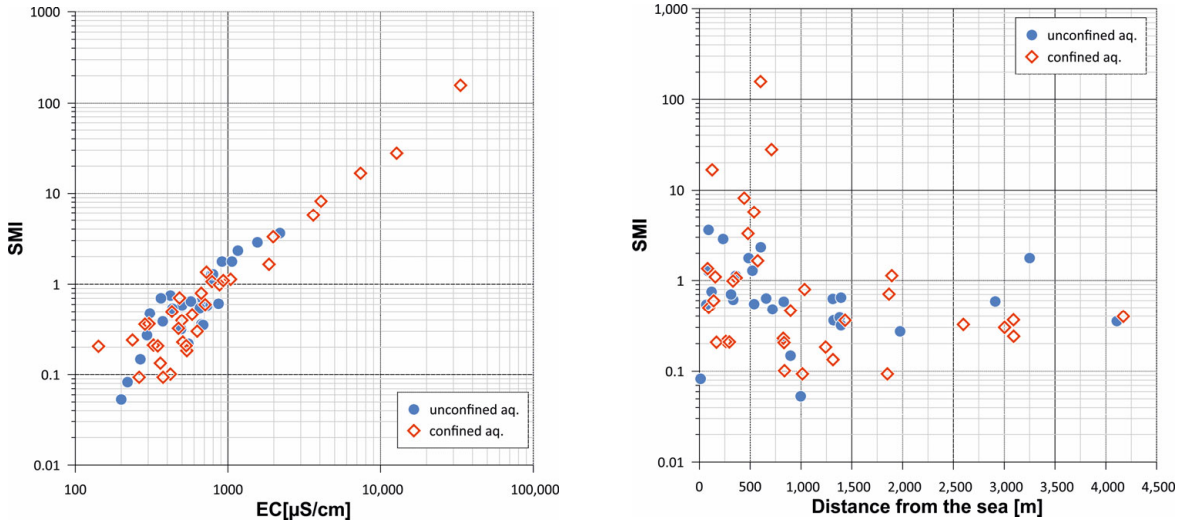
$a = 0.31$, $b = 0.04$, $c = 0.57$, $d = 0.08$

C_{Na}, C_{Mg}, C_{Cl}, and C_{SO4} represent the concentrations [mg/L] of sodium (Na), magnesium (Mg), chloride (Cl), and sulfate (SO_4) ions, respectively, in water collected from monitoring points.

The regional threshold values (T_{Na}, T_{Mg}, T_{Cl}, and T_{SO4}) were determined based on cumulative probability curves, as described in the methodology of [17]. Data from 61 monitoring points were used to construct cumulative probability curves. The inflection point was determined based on the distribution of the points on the graph. The T value corresponds to the concentration of a selected ion at the inflection point. The regional threshold values used in the seawater mixing index (SMI) calculation were as follows: T_{Na} = 165 mg/L, T_{Mg} = 25 mg/L, T_{Cl} = 115 mg/L, T_{SO4} = 10 mg/L (Figures S2–S5).

A calculated SMI value greater than one may indicate that seawater influences groundwater chemistry. The SMI value calculated based on the concentrations of major ions in seawater from the Ustka and Władysławowo regions, as reported in studies [42,44], was 22 and 23, respectively.

SMI values greater than 1 were observed at 19 monitoring points. These included 11 points with a confined water table and 8 points with an unconfined water table. This group also included three monitoring points from aquifers older than the Quaternary. All waters with an EC > 1000 µS/cm exhibited SMI values greater than 1 (Figure 3a). In all waters where the SMI was greater than 1, chloride ion concentrations exceeded 115 mg/L. For the waters located more than 2000 m from the coastline, SMI values were below 1, with one exception. In contrast, waters located within 2000 m of the coastline exhibited SMI values both above and below 1 (Figure 3b).



(**a**) (**b**)

Figure 3. Seawater mixing index in groundwater: (**a**) versus electrical conductivity; (**b**) versus distance from the sea.

Studies of coastal areas in various regions of the world indicate that waters with an SMI value exceeding 1 can occur locally at significant distances from the coastline. Park et al. [17] reported that along the southern coast of Korea, this zone extends up to 4 km inland. On the coast of the Bay of Bengal, the range extends to 10 km [59], 12 km [19], and in some areas even up to 20 km [21] from the shoreline. Ezeldin [37] indicated that for the Egyptian Mediterranean coast, this zone extends up to 12.5 km inland.

3.2.3. Hydrochemical Ratios

- $rHCO_3/rCl$ ratio

In the assessment of saline and freshwater, the relative proportions of HCO_3^-, CO_3, and Cl^- are often considered. In waters with a pH below 8, carbonates are not present [60]. For such waters, the $rHCO_3/rCl$ ratio is typically analyzed. In the studied waters, carbon-

ates were present at only one monitoring point. In this case, the r(HCO_3 + CO_3)/rCl ratio was calculated to account for both bicarbonates and carbonates in the evaluation.

In zones associated with natural water circulation, carbonates are the dominant component, and their concentration increases due to the dissolution of $CaCO_3$ until saturation is reached. When chloride content increases, the value of the rHCO_3/rCl ratio decreases.

The rHCO_3/rCl ratio can serve as an indicator of the degree of water interaction with the recharge zone. Higher values suggest stronger contact with recharge areas, while lower values indicate increasing influence from external saline sources, such as seawater intrusion [61]. The rHCO_3/rCl ratio for seawater ranges from 0.02 to 0.05 [62]. For Baltic Sea waters near Władysławowo and Ustka, the value was 0.02 [42]. In the analyzed waters, the rHCO_3/rCl ratio values ranged from 0.008 to 11.84.

For waters with an EC < 1000 µS/cm, no correlation was observed between the EC and the rHCO_3/Cl ratio. However, for waters with an EC > 1000 µS/cm, an inverse proportional relationship was identified (Figure 4a).

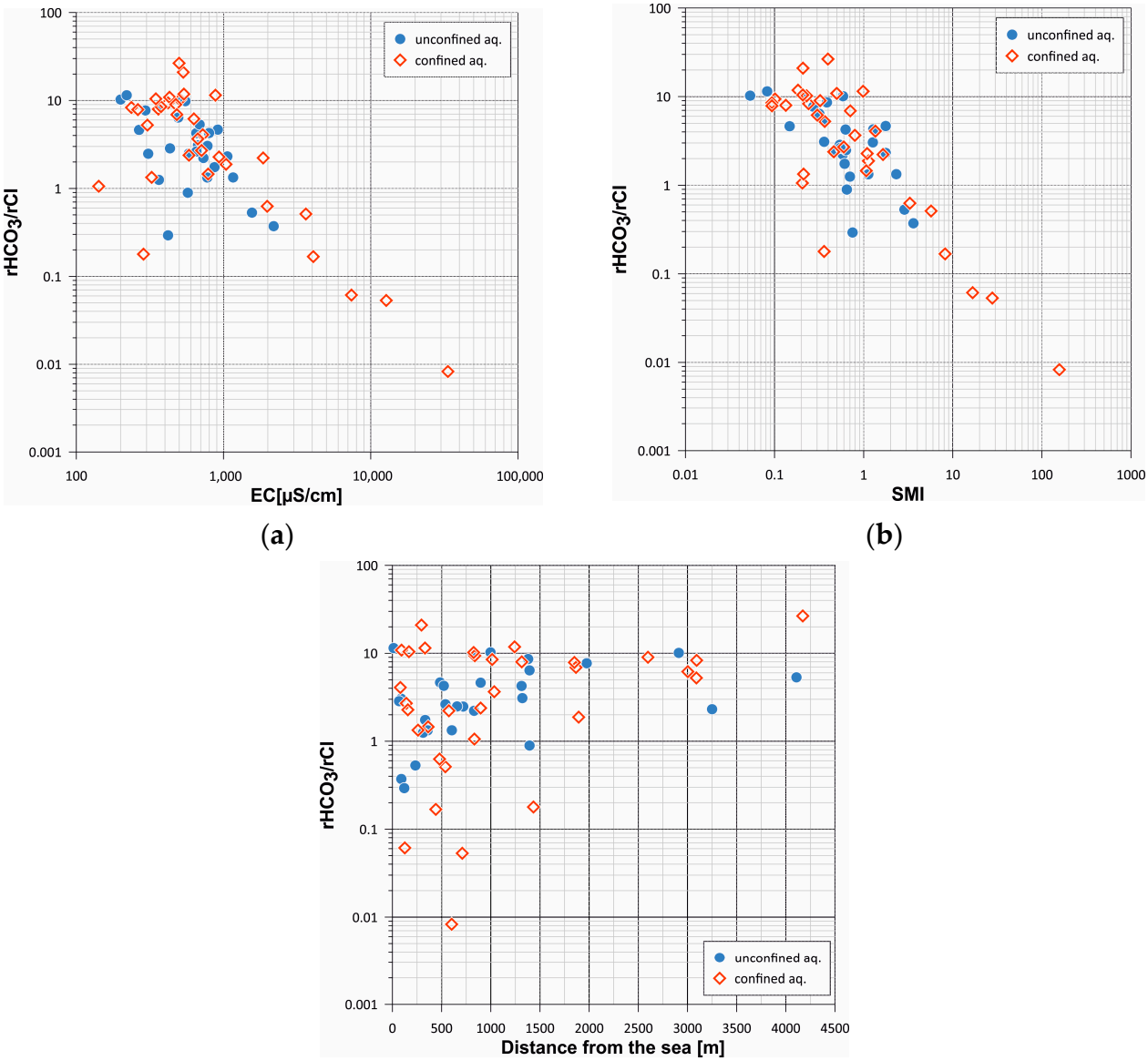


Figure 4. rHCO_3/rCl in groundwater: (**a**) versus EC; (**b**) versus SMI; (**c**) versus distance from the sea.

Additionally, for waters with an SMI > 1, an inverse proportional relationship was also observed between the SMI parameter and the $rHCO_3/rCl$ ratio (Figure 4b). At distances greater than 2000 m from the coastline, waters with $rHCO_3/rCl < 1$ were not observed. Waters located closer than 2000 m to the coastline exhibited $rHCO_3/rCl < 1$ ratio values both above and below 1 (Figure 4c).

The inflow of saline waters affects the $rHCO_3/Cl$ ratio, making it a commonly used parameter in groundwater studies in coastal regions. The influence of seawater, as indicated by the values of this ratio, based on various researchers [12,63–65], is summarized in Table 1. The presented data indicate that $rHCO_3/Cl$ ratio values above 2 may suggest no influence of seawater, while values below 0.15 indicate a significant (alarming) impact of seawater intrusion.

Table 1. Impact status of existing seawater intrusion (according to [12,63–65]).

Range of Values [63] (Number of Points)	Influence of Seawater	Range of Values [12] (Number of Points)	Influence of Seawater	Range of Values [64,65] (Number of Points)	Influence of Seawater
≥2 (42)	Not affected			>2 (42)	Not affected
2–≥0.77 (9)	Slightly contaminated	>1 (50)	Very low	2–0.15 (16)	Slightly affected
		1–0.7 (1)	Low		
0.77–≥0.36 (4)	Moderately contaminated				
		0.5–−0.7 (3)	Medium		
		<0.5 (7)	High		
0.36–≥0.15 (3)	Injuriously contaminated				
0.15–≥0.06 (1)	Highly contaminated			<0.15 (3)	Strongly affected
<0.06 (2)	Severely contaminated				

- rCa/rMg ratio

The rCa/rMg ratio for seawater is 0.2. The rCa/rMg ratios for fresh water range between 0.5 and 5 in sedimentary rocks and from 0.25 to 0.5 in cases of seawater intrusion [66,67]. In Baltic Sea waters, this ratio is also 0.2. In groundwater sources where seawater intrusion is not detected, the ratio is slightly above 1 [42]. For the analyzed waters, the rCa/rMg values ranged from 0.7 to 13.94. These values do not indicate the presence of seawater intrusion. Therefore, this ratio was not included in the risk assessment. Additionally, no correlation was found between the distance from the coastline and the rCa/rMg ratio (Figure 5). It should be noted that the inflow of seawater with a low rCa/rMg value (e.g., 0.2) into fresh water reduces this indicator's value in the affected waters. The lower the value of this indicator, the higher the likelihood of seawater intrusion. For this reason, rCa/rMg values in different marine intrusion risk classes were subject to analysis.

- rNa/rCl ratio

The rNa/rCl ratio for seawater is 0.87, while in the waters of the Baltic Sea, it is 0.86 [51]. In groundwater from the western coastal region studied by Krawiec et al. [41], it ranged from 0.56 to 4.15, and in groundwater from the Ustka region, it ranged from 0.89 to 1.07 [42]. In the vast majority of the analyzed waters, the rNa/rCl ratio ranged from 0.22 to 2.00, and its value was not correlated with the distance from the coastline (Figure 6).

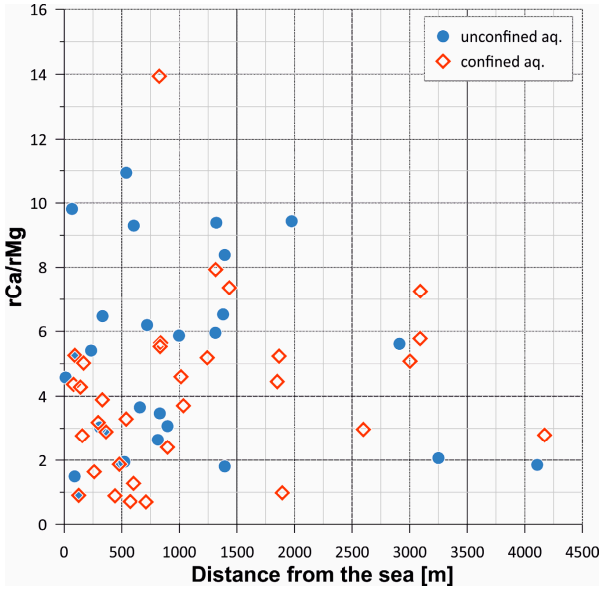


Figure 5. rCa/rMg versus distance from the sea.

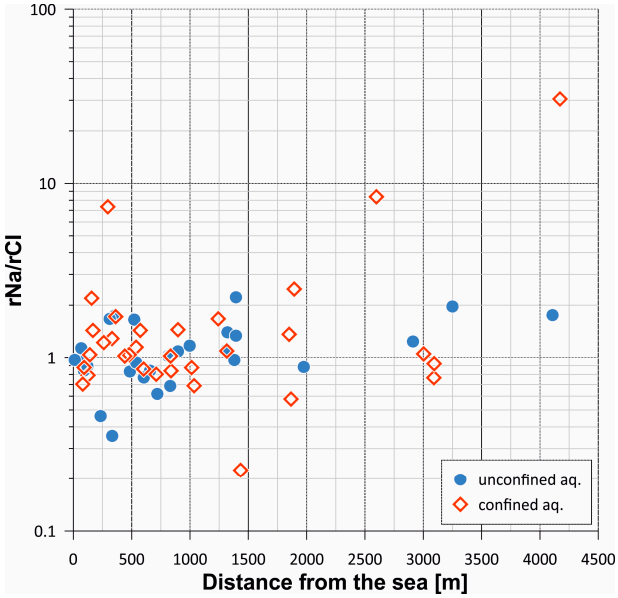


Figure 6. rNa/rCl ratio versus distance from the sea.

- Cl/Br-ratio

The natural environment for bromide ions includes ocean water and saline groundwater in isolated structures, such as hydrocarbon deposits. The average concentration of bromide ions in ocean water is approximately 65 mg/L, while in the Baltic Sea, it is around 23 mg/L. The mass ratio of chloride ions to bromide ions known as the Cl/Br ratio typically reaches values of about 290 in ocean water and 297 in Baltic Sea waters [42]. Brines with a Cl/Br ratio value up to 400 are regarded as primary, meaning their salinity results from the presence of seawater. Brines with Cl/Br values between 400 and 1000 are described as mixed waters, while those with values above 1000 are considered secondary, where salinity originates from the dissolution of salt minerals [68]. In numerous studies on coastal water regions, and beyond, the Cl/Br ratio plays a significant role in identifying the causes of water salinity [69–71].

A reduction in the Cl/Br ratio value in formation waters compared to seawater indicates that the waters have undergone evaporation, compaction, and have acquired

bromide from the diagenesis of sedimentary organic matter [72]. In low-mineralized waters that are not contaminated, bromide ion concentrations are typically below or slightly above the detection limit. Elevated bromide ion concentrations in low-mineralized waters, along with low Cl/Br values (<200), may result from the presence of organic matter [73] and pollution from agrochemical [69]. In groundwater from coastal regions, Cl/Br ratio values range from 220 to 315, as reported in studies from Spain and Portugal [74]. Groundwater from the Greek coastline affected by seawater intrusion exhibited Cl/Br values ranging from 270 to 320 [75]. In the groundwater of the western Polish Baltic coast, bromide concentrations ranged from below the detection limit to 150 mg/L, with Cl/Br ratio values ranging from 125 to over 1000 [41]. In the Ustka region, bromide concentrations ranged from 0.11 to 0.91 mg/L, while the Cl/Br ratio values varied between 328 and 372 [42].

Bromide concentrations above the detection limit were identified at 17 monitoring points, ranging from 0.11 mg/L to 6.06 mg/L [76]. The Cl/Br ratio at these points ranged from 211 to 818. At the points where bromides were detected, the Cl/Br values suggested primary salinity in 11 points and mixed salinity in 6 points (Figure 7a,b).

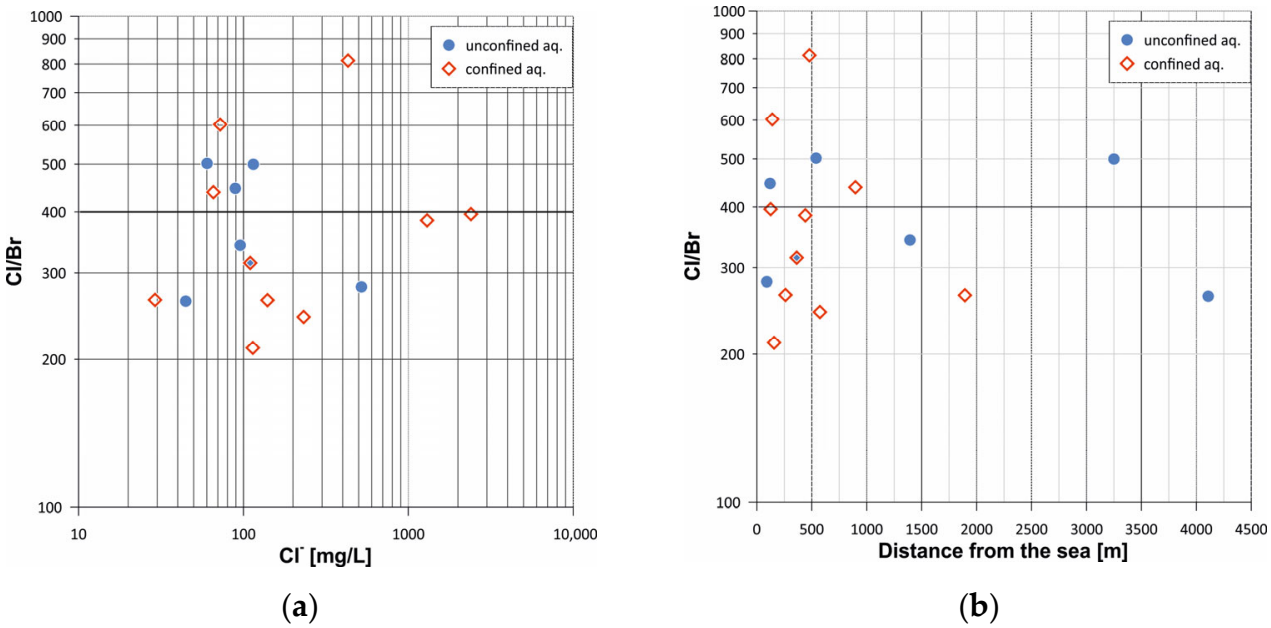


Figure 7. The Cl/Br ratio: (**a**) versus Cl^{-}; (**b**) versus distance from the sea.

The presence of bromides and the Cl/Br ratio values indicated the likelihood of seawater intrusion. It is worth noting that waters containing bromides and characterized by Cl/Br ratio values between 280 and 510 exhibited a wide range of chloride concentrations, including low levels (<115 mg/L) (Figure 7a). Additionally, these waters often had $rHCO_3/rCl$ ratio values >1, and even above 2, as well as rNa/rCl values exceeding 1.

3.2.4. Risk Assessment Based on Chemical Parameters

The chemical method assesses the risk solely based on water chemistry, considering selected chemical parameters. The classification of waters in terms of seawater intrusion risk was conducted using a point-based scale developed from the values of key parameters: EC, SMI, $rHCO_3/rCl$, rNa/rCl, and the concentrations of Cl^{-} and Br^{-}. Six criteria were established to identify waters unaffected by seawater intrusion. Waters meeting the following conditions were classified as free from seawater influence:

- EC < 1000 µS/cm;
- Chloride concentration < 115 mg/L;
- $rHCO_3/rCl > 1$;

- rNa/rCl > 1;
- SMI < 1;
- Absence of bromide ions.

The values of EC and chloride concentrations were determined using cumulative probability plots for 63 samples. The points of intersection on these plots can serve as regional threshold values to distinguish samples influenced by seawater mixing within the study area. The point of intersection, marked on the figures as the "inflection point," represents a regional threshold value (Figures S4 and S6). Furthermore, it should be noted that EC < 1000 µS/cm indicates the absence of seawater intrusion [23,24].

Studies on groundwater from other regions of the world typically report higher threshold values. For the western coast of South Korea, T_{EC} is reported as 1780 µS/cm and T_{Cl} as 316 mg/L [35]. Park et al. [17] reported a T_{Cl} value of 300 mg/L. For the coasts of Sri Lanka, T_{Cl} values range from 318 to 318.9 mg/L [58]. Conversely, Lee and Song [34] reported lower values for the southern and western coasts of South Korea: T_{Cl}—65 mg/L; and T_{EC}—366 µS/cm.

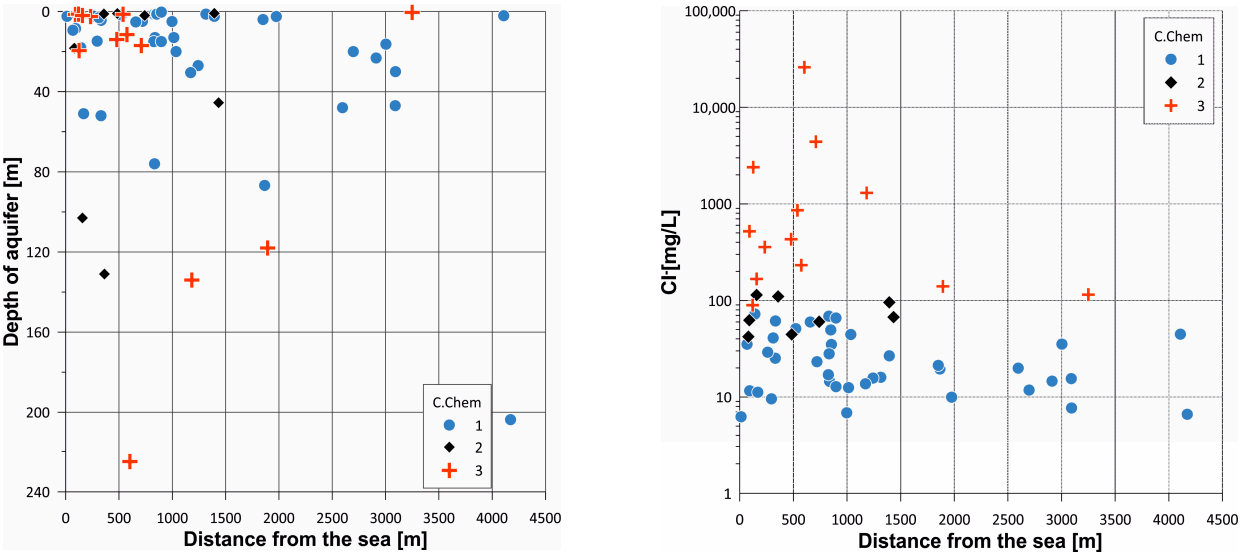
Research from the Mediterranean region indicates threshold values of T_{Cl}: 225 mg/L for Algeria [77] and 7700 mg/L for Egypt [37]. For the Baltic Sea coast (Latvia) [39], a T_{Cl} value of 131.6 mg/L was adopted, which is slightly higher than the threshold used in this study.

Failure to meet any of the six criteria listed above resulted in the assignment of one point to the total risk assessment score. However, if $rHCO_3/rCl < 0.36$, this was assigned two points. The total number of points indicates how many parameters contributed to classifying the water as potentially affected by seawater intrusion. A higher number of points signified a greater likelihood of seawater intrusion affecting the water. Each water sample from the studied locations could receive a score ranging from 0 to 7 points. Based on the total score, three risk classes for seawater intrusion were established.

- Low Risk: A maximum of one parameter exceeded the established threshold (1 point). Waters in this category showed minimal risk of seawater intrusion;
- Moderate Risk: Two or three parameters did not meet the specified criteria. These waters were classified as having a moderate influence from seawater;
- High Risk: Four or more parameters failed to meet the specified conditions. These waters were classified as being at high risk of seawater intrusion.

Generally, waters classified into Risk Classes 2 (moderate) and 3 (high) were located within 800 m of the coastline (Figure 8a). However, some points classified as Risk Class 3 were situated farther away, at distances exceeding 1800 m from the coastline. Two points often sampled water from deeper depths (Figure 8a), where the probable cause of salinity was the ascension of waters from deeper aquifers (Figure 8b). The third of these points represents water from the Quaternary aquifer, located at a close distance (235 m) from surface waters.

Three points in Risk Class 3, located more than 800 m from the coastline, were found near surface coastal waters. These include one point located 334 m from Lake Wicko, one point located 37 m from Lake Jamno, and one point located 235 m from the Świna River. It should be noted, however, that the chloride (Cl^-) concentrations in groundwater near these lakes were higher than the upper chloride concentrations observed in the lakes themselves. In Lake Jamno, Cl^- concentrations range from approximately 120 to 250 mg/L, and in Lake Wicko, Cl^- concentrations range from approximately 40 to 60 mg/L [78].



(**a**) (**b**)

Figure 8. Classes of risk base on chemical parameters: (**a**) depth of aquifers versus distance from the sea; (**b**) Cl^- versus distance from the sea.

3.3. Seawater Intrusion Risk Based on Both Classifications: Comparison of Groundwater Risk Assessments

In both risk assessment methods, the division into three risk classes (low, moderate, and high) was applied. However, the classification of monitoring points was not identical between the two methods. The differences in the evaluation results of the two classifications are presented in Tables 2 and S2, and visualized on the accompanying map (Figure 9). The risk assessment was consistent across both classifications for 22 monitoring points, including 8 classified as low risk, 4 as moderately at risk, and 10 as high risk. A value of "0" indicates agreement between the GALDIT and chemical classifications. Positive values (1, 2) indicate that the GALDIT classification assigned a higher risk category (by one or two classes) compared to the chemical classification. Negative values (−1, −2) indicate that the chemical classification assigned a higher risk category (by one or two classes) compared to the GALDIT classification.

Table 2. Number of monitoring points by seawater intrusion risk class.

		GALDIT			
Chemical	classes	1	2	3	total
	1	8 [1]	14	17	39
	2	0	4 [1]	5	9
	3	1	2	10 [1]	13
	total	9	20	32	61

Note: [1]—number of monitoring points included in the same class in both classifications.

Generally, it should be noted that along the entire coastline, there are points where the risk assessments from both classifications align. However, in the central part of the coastline, the differences between the GALDIT and chemical classifications are smaller (Figure 9). It should be noted that only in the case of three points located in the western part of the coastline did the chemical classification indicate a higher risk class than the GALDIT classification. For one of these points, the water originates from a sub-Quaternary aquifer with a top layer at a depth of 118 m. This fact, along with the significant distance

from the sea, suggests that the salinity is unrelated to seawater intrusion, and the GALDIT classification provides an accurate assessment for this point.

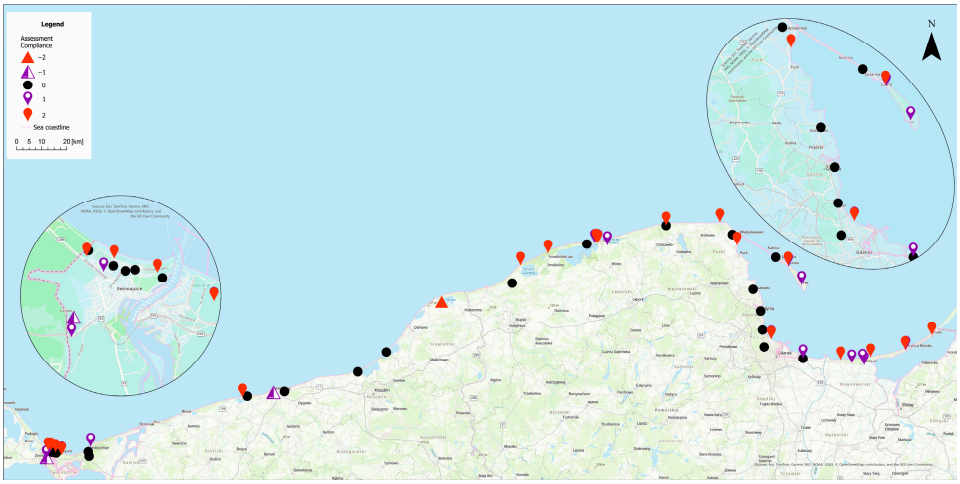


Figure 9. Assessment of compliance between two methods (GALDIT and chemical) for monitoring points.

According to the GALDIT classification, the majority of points (32) were placed in Risk Class 3 (high risk), whereas the chemical classification identified only 13 points in this class. The chemical classification presents a less pessimistic view of seawater intrusion risk. The differences between the two classifications likely stem from the fact that the GALDIT method considers potential risk, based on hydrogeological vulnerability factors, while the chemical classification reflects the current state of groundwater, as determined by measured chemical parameters. The altered chemical composition of groundwater may result from seawater intrusion. However, for points classified as at risk of seawater intrusion but without actual saline water inflow, the water chemistry may not yet show significant changes. The chemical classification indicates that groundwater at these points has already undergone slight changes in chemical composition due to seawater intrusion, reflecting the current state of the water. This approach focuses on assessing the present condition, rather than potential risk.

The points classified according to the GALDIT classification as Class 3 (high risk) are located within 1000 m of the Baltic Sea coastline (Figure S7) and exhibit a wide range of SMI values (Figure S8). On the other hand, points belonging to Class 1 (not threatened by seawater intrusion) are located more than 800 m from the coast (Figure S7) and are characterized by EC < 1000 µS/cm and SMI $\leq$ 1 values (Figure S8).

The application of the GALDIT method in other regions of the world has demonstrated that areas at risk of seawater intrusion vary significantly and can extend up to several kilometers from the coastline. In the Mediterranean region, this range is 1–2 km along the Algerian coast [29,79] but extends to 1–4.5 km on the Tunisian coast [80]. In the northern part of Greece, it reaches up to 500 m in the eastern part of the Chalkidiki Peninsula [27] and up to 3 km in the coastal Rhodope region [28].

Studies in the Indian Ocean coastal regions indicate a range of up to 1.5 km, such as along the Kenyan coast [25] and similarly on Jeju Island (South Korea) [23]. It is worth noting that modifications to the GALDIT method, including the introduction of new parameters, allow for greater precision in risk assessment. These modifications account for the influence of saline surface waters and the impact of the current salinization status [27,28].

In the Baltic Sea region, a risk assessment was conducted using a method similar to, but slightly different from, the GALDIT approach. The study focused on the island of Öland (Sweden). The risk assessment incorporated parameters such as distance to the

coast, distance to the lake, soil type, elevation in meters above sea level, and precipitation. The risk value and weight factors differed from those used in the GALDIT method. The weighted risk value index ranged from 0 to 22, and the area with the highest risk scale extended up to approximately 500 m from the coastline [13].

The assessment of the threat was carried out by considering the results of both classifications. The results of both classifications were summed in the following manner. In each classification, the lowest category (low risk of seawater intrusion—Class 1) was assigned 1 point. Medium risk was assigned 2 points, while high risk was given 3 points. By summing the points from both classifications, each monitoring point could be assigned a score ranging from 2 points (lowest risk, first group of susceptibility to intrusion) to 6 points (fifth group, highest risk of seawater intrusion).

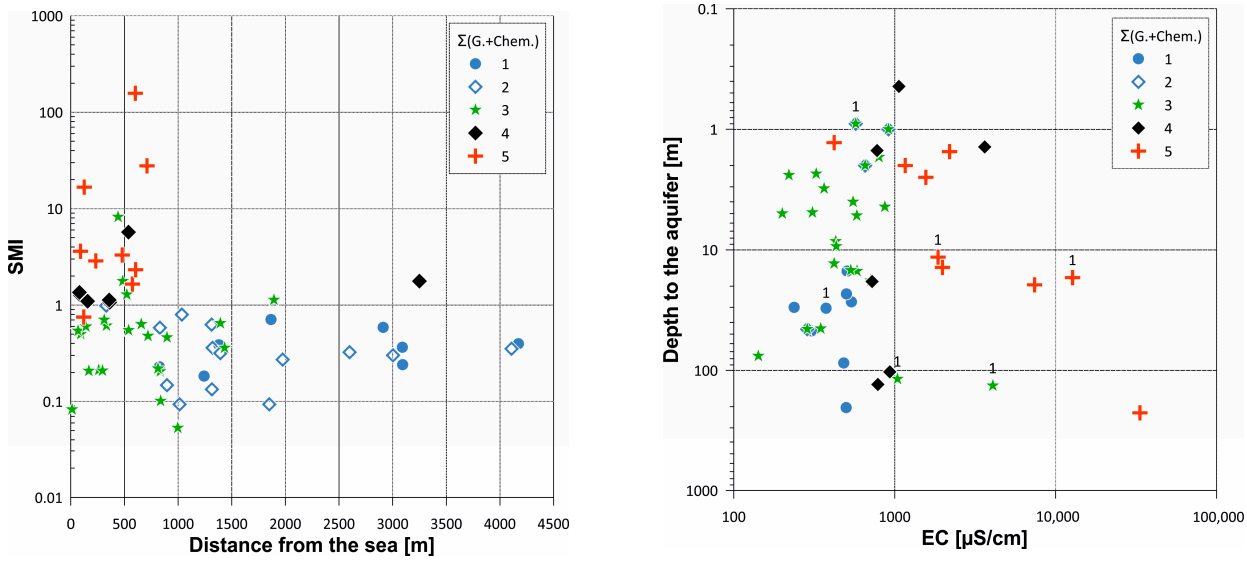
The exact method for creating the assessment based on the sum of both classifications is presented in Table 3.

Table 3. Risk assessment based on the cumulative classification (classes). → (in rows − GALDIT classes) ↓ (in columns − chemical classes).

GALDIT (classes) →	1	2	3
Chemical (classes) ↓	points (class)		
1	2 (1 class)	3 (2 class)	4 (3 class)
2	3 (2 class)	4 (3 class)	5 (4 class)
3	4 (3 class)	5 (4 class)	6 (5 class)

The assessment carried out based on the new cumulative classification confirms, but also refines, what was previously shown by the analysis of individual parameters.

The group with the lowest risk consists of points located 826 to 4172 m from the sea. Points classified into the second class include 14 points located from 331 m to 4108 m from the sea. The largest group is the third class of threat (23 points), with distances ranging from 12 m to 1894 m from the coastline. The fourth risk class consists of 7 points located from 80 m to 3250 m away. The fifth class is for waters located from 90 m to 710 m from the coastline (Figure 10a).



(**a**) (**b**)

Figure 10. The results of both classifications (five risk classes): (**a**) SMI versus distance from the sea; (**b**) depth of the aquifer versus EC.

In each class of risk, there are points that represent both confined and unconfined groundwater. In the distance up to 800 m from the coastline, there are no waters classified in the lowest risk category (Group 1). All waters in Class 5, all but one in Class 4, and most waters in Class 3 are located within this distance. In the case of a point classified as Class 4, located over 3000 m from the coastline and more than 2000 m from surface waters (Świna), the possible influence of saline water ascent from lower levels with elevated salinity may occur, which has been observed in the past [81]. There is no correlation between the risk class and the depth at which the aquifer occurs (Figure 10b).

The threat of seawater intrusion is related to the distance from the coastline (Figures 10a and 11g).

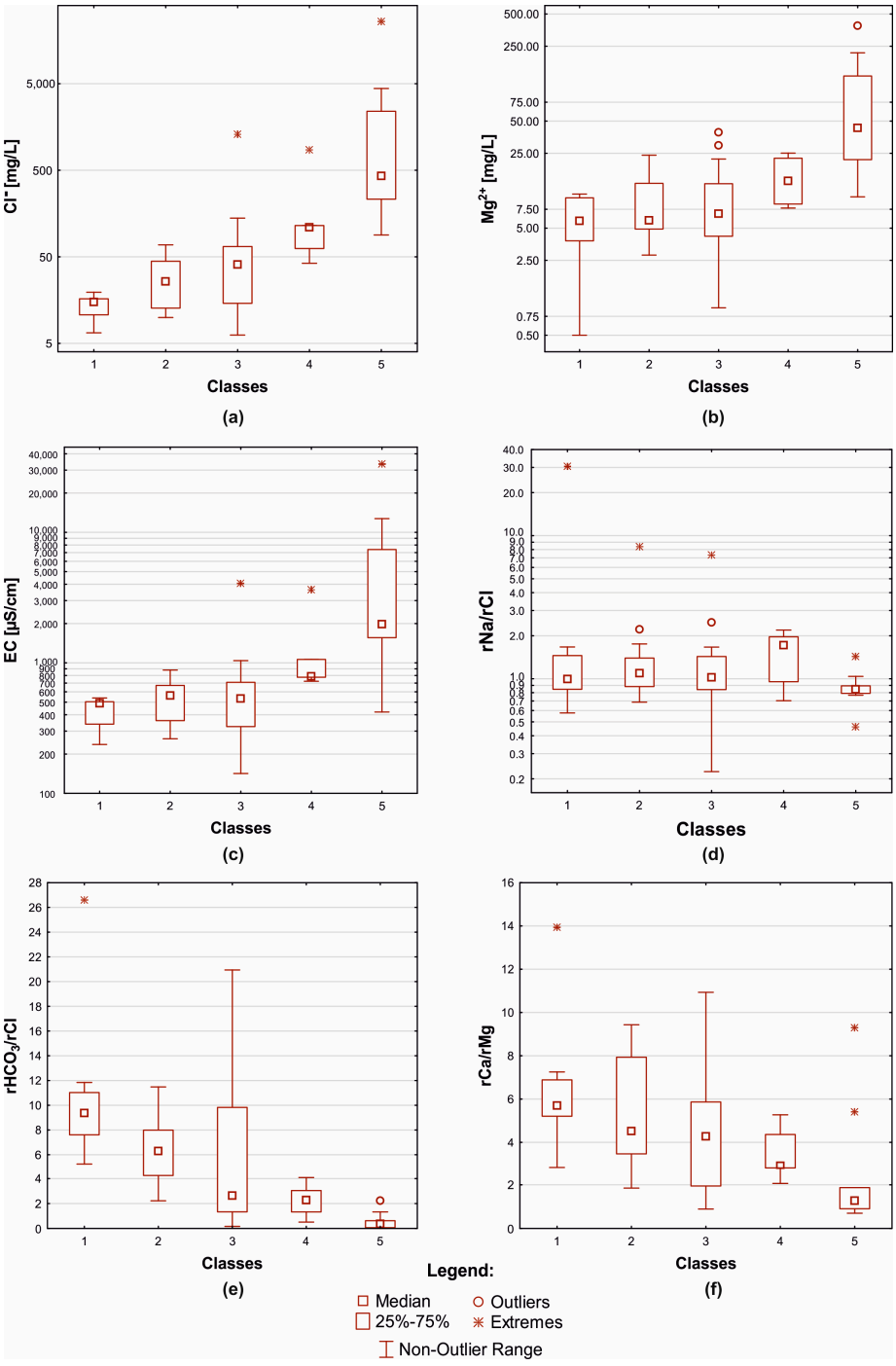


Figure 11. *Cont.*

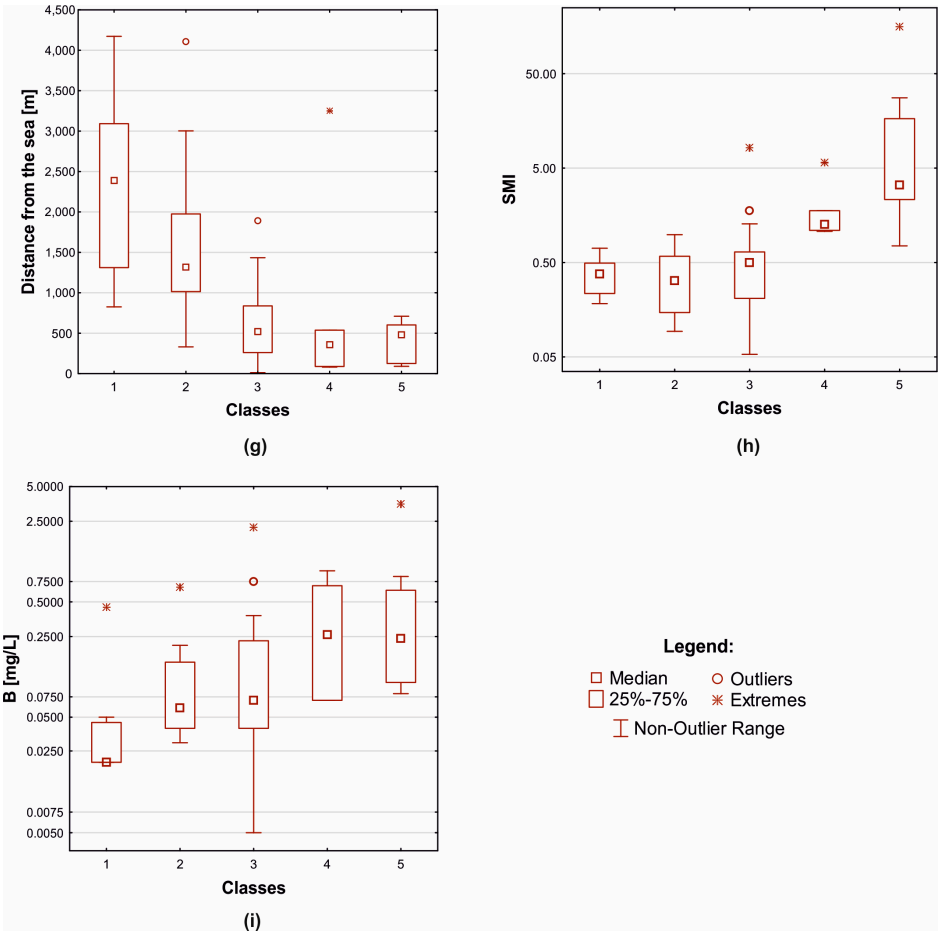


Figure 11. Box plot of data from groundwater monitoring points for five risk classes: (**a**) (Cl^{-}), (**b**) (Mg^{2+}), (**c**) EC, (**d**) rNa/rCl, (**e**) $rHCO^{3}$/rCl, (**f**) rCa/rMg), (**g**) Distance from the sea, (**h**) SMI, (**i**) B.

The variability of the analyzed parameters is presented in box plots, showing that in groups differing in risk classes, there is a clear differentiation in the parameters: Cl^{-}, Mg^{2+}, EC, SMI, $rHCO_3$/rCl, and rCa/rMg (Figure 11a–c,e,f,h). However, there is no differentiation according to the rNa/rCl ratio (Figure 11d).

It should be noted that the individual risk classes also differ in the median boron concentration (Figure 11i). One of the sources of boron in groundwater may be seawater intrusions [82]. An increase in boron concentration towards the coastline has been observed in coastal areas [83,84].

For the individual parameters that contribute to the threat assessment, no simple relationship is observed between their values and the distance from the sea. However, when considering the overall assessment, which includes multiple parameters, such a relationship does exist. The classes of seawater intrusion risk differ in the median and ranges of individual parameters.

The threat increases with rising chloride ion concentrations (Cl^{-}), electrical conductivity (EC), and decreasing values of the indicators $rHCO_3$/rCl and rCa/rMg. However, despite these correlations, it should be noted that in the groups with high threat (Classes 4 and 5), individual parameters may indicate the absence of seawater influence. Therefore, a comprehensive analysis considering several parameters is essential.

Values of the HCO_3/Cl ratio > 2, which indicate no seawater intrusion, are not a determining factor that rules out the possibility of saline water intrusion. The assessment of the risk of seawater intrusion at individual monitoring points is shown on the map (Figure 12). The uneven distribution of monitoring points means that the assessment is

focused on a few regions along the coast, leaving some areas unexamined (including the area from Wolin Island to the town of Rogowo). Figure 12 shows that the threat exists along the entire Baltic Sea coastline, but it is not uniform; it varies even in points located at relatively short distances from each other.

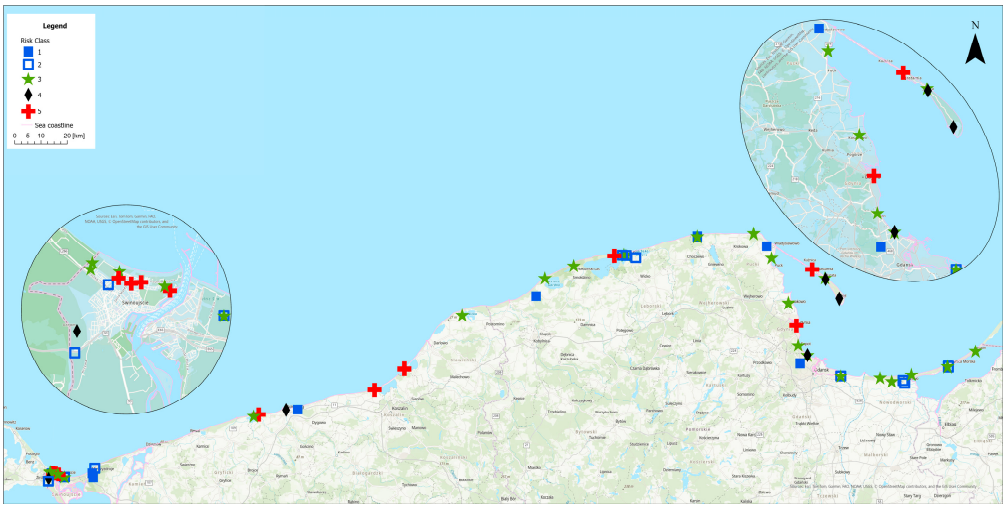


Figure 12. Assessment of the risk of seawater intrusion in monitoring points based on five risk classes.

Both in the eastern and western parts of the coastline, monitoring points exhibit different risk classes. Nevertheless, based on the average risk class (determined by the GALDIT method and the chemical method), some distinctions can be observed. The average risk class for waters in the western part of the coastline is higher than for those in the eastern part, amounting to 3.17 in the west and 2.73 in the east.

In the western coastal area, Quaternary deposits lie directly on Mesozoic formations, where Neogene and Paleogene claystones and siltstones have been eroded. Saline waters occur within the Mesozoic layers. The inflow of saline waters from the Mesozoic levels is due to higher pressures compared to Quaternary layers, as well as the presence of dislocations. There is no effective confining layer in this region.

On the eastern coast, however, poorly permeable Neogene and Paleogene deposits lie beneath Quaternary formations, impeding the upward flow of brackish waters from the subsurface [43].

The differences in the average risk class suggest that the threat of saline water inflow is greater in the western part; however, considering the hydrogeological conditions, this risk is not solely due to marine intrusion but is also influenced by the upward migration of saline waters from deeper Mesozoic formations.

The impact of this upward migration is evident in areas where points closer to the shoreline have lower risk classes, whereas points farther inland show higher risk classes (e.g., around Uzam Island). High threats are associated with areas where the influence of surface saline waters is possible (such as near lakes and river mouths).

3.4. Risk Classification of Saline Water Intrusion and Water Quality Assessment

Water quality is assessed based on a broad range of chemical parameters, whereas the evaluation of the risk of saline water inflow relies only on specific chemical criteria. A comparison was made between the risk classification (divided into five classes) and the water quality classification as defined by the relevant regulation [85]). In general, it should be noted that the higher the risk class of saline water inflow, the lower the water quality class. The waters in the highest risk class correspond to Quality Classes V and IV (and in one instance, Class III). Meanwhile, water not threatened by marine intrusion fell into

Quality Class II, with one exception being Class III. The medium-risk category for saline water inflow contained waters spanning various quality classes (I–V).

From this comparison, it follows that one cannot assess the risk of saline water inflow solely based on water quality class. For example, Class III water can be either not threatened or highly threatened by marine intrusion. The quality of drinking water is regulated by the Regulation of the Minister of Health [86] which considers numerous chemical parameters. In groundwater from coastal areas, exceedances of the parametric values for Fe and Mn concentrations, as well as other parameters not analyzed in this study, have been reported (based on monitoring data). However, only in the fifth class of saline water intrusion risk were exceedances of parametric values for EC, Cl, and Na recorded. It is worth noting that in two waters within this class, elevated values of these parameters were not observed.

Water quality is influenced by multiple factors, including the inflow of saline waters. While water quality assessment is related to risk evaluation, poor quality does not necessarily result from marine intrusion. High-quality water in hydrogeological conditions favorable to the inflow of saline water could deteriorate over time. Therefore, points assessed as being at medium risk should be subject to further investigation.

4. Conclusions

Using two distinct methods, an assessment was conducted to evaluate the threat posed by the inflow of saline seawater to groundwater along the Polish coastline. Parameters indicative of the risk of marine intrusion were also identified. The study provides a conceptual overview of the threat of marine ingress, offering a general depiction of the situation along the Polish coast. The research is constrained by certain limitations, primarily the relatively small number of sampling points compared to the size of the study area.

The highest risk of seawater intrusion occurs within approximately 800 m of the coastline. In this zone, groundwater may not yet show changes in chemical composition indicative of saline water inflow. Both confined and unconfined groundwater in this area are equally vulnerable. It is important to note that confined aquifers do not necessarily represent completely sealed structures that prevent the infiltration of saline water. In coastal regions, groundwater salinity can also result from the inflow of surface water with elevated salinity or, in the absence of adequate insulation of deeper saline aquifers, from the upward migration (ascent) of these waters. While proximity to the shoreline is a critical factor, the risk assessment should also account for other sources of elevated salinity, including surface waters and deeper aquifers.

The effects of salinity on groundwater are reflected in the variability of chemical parameters (SMI, EC, Cl concentrations, and hydrogeochemical ratios). The classes of seawater intrusion risk differ in terms of the median and range values of various parameters. For example, ratios such as HCO_3/Cl, Ca/Mg, and Cl/Br play an important role in risk assessment, while the rNa/rCl ratio has a smaller impact. Seawater intrusion risk should therefore be assessed based on multiple parameters.

The differences between the results of the two classification stem from their distinct focuses. The GALDIT classification evaluates hydrogeological conditions, while the chemical classification assesses the physico-chemical properties of water. GALDIT primarily reflects potential risk, whereas the chemical classification captures current conditions. Consequently, the chemical classification often provides a more favorable perspective on the threat of marine intrusion. A high risk class in the chemical classification, but a low one in the GALDIT classification, may result from the influx of saline water unrelated to seawater intrusion. The flexibility of the GALDIT method, including its capacity to incorporate modifications to parameters such as the water table height relative to sea level, makes it a useful tool for forecasting the risk of marine intrusion.

The comparison of both classifications highlighted regions where the scale of the threat is unequivocal, as well as areas where discrepancies suggest no immediate risk but a potential increase in the future. In regions with conflicting results, detailed analysis of local hydrogeological conditions is necessary, ideally supported by a denser network of sampling points.

Employing a modified GALDIT classification that incorporates additional factors—such as proximity to surface waters, vadose zone characteristics, and other site-specific parameters—could enhance the precision of risk assessments. Moreover, analyzing trends in the chemical parameters discussed in the study could provide further insights and improve the accuracy of threat evaluations.

Assessing the risk of seawater intrusion is crucial for the sustainable management of groundwater resources in coastal areas. The inflow of saline water compromises water quality and limits its suitability for consumption. Applying both risk assessment methods and comparing their results can offer valuable insights for regional hydrogeological studies of coastal regions.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/w17030336/s1. Figure S1. Characteristics of monitoring points in the aquifers PgNg (Paleogene–Neogene aquifer); Cr (Cretaceous aquifer); without labels Quaternary aquifers; Figure S2. Cumulative probability curves for the concentrations of Na; Figure S3. Cumulative probability curves for the concentrations of Mg; Figure S4. Cumulative probability curves for the concentrations of Cl; Figure S5. Cumulative probability curves for the concentrations of SO_4; Figure S6. Cumulative probability curves for EC; Figure S7. Classes of risk base on GALDIT method-depth of aquifer versus distance from the sea; Figure S8. Classes of risk base on GALDIT method SMI versus EC; Table S1. Evaluation criteria for GALDIT parameters; Table S2. Evaluation by chemical and GALDIT methods (Reference [12] is cited in the Supplementary Materials).

Author Contributions: Conceptualization, B.W. and M.M.; methodology, B.W.; validation, B.W. and M.M.; formal analysis, B.W. and M.M.; investigation, B.W.; resources, B.W. and M.M.; data curation, B.W. and M.M.; visualization: B.W. and M.M.; writing—original draft preparation, B.W. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data supporting the findings of this study were obtained from the Chief Inspectorate of Environmental Protection under the framework of the State Environmental Monitoring (PMŚ) and from the Polish Geological Institute—National Research Institute (PGI-NRI) under the Polish Geological Survey (PSH) tasks defined by the Water Law Act. These datasets are not publicly available but can be requested directly from the respective institutions.

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