

INTRODUCTION

The deterioration of groundwater resources due to seawater intrusion is a significant problem for the water supply in coastal areas. Seawater intrusion is mostly a result of sea-level rise and groundwater overexploitation that causes coastal aquifers severely vulnerable to salinization. This phenomenon has a degrading influence on the availability of fresh water, ecosystems condition, coastal infrastructure and tourism. Potential implications of sea-level rise for coastline in Poland has been subject of several studies (Pruszkowski and Zawadzka 2008; Moskaiewicz 2016; Paprotny and Terefenko 2017).

In order to control seawater intrusion in coastal aquifers, a number of management strategies and prevention methods have been developed (Chachadi and Lobo-Ferreira 2001; Kallioras et al. 2012; Trabelsi et al. 2016). One of the principal approaches to predict the influence of seawater intrusion to groundwater is analysis of vulnerability maps. In this paper, GALDIT method was used to assess seawater intrusion in the coastal aquifer of the inner Puck Bay (Southern Baltic Sea). The impact of potential sea-level rise to groundwater vulnerability for years 2081-2100 was also considered.

AREA OF STUDY

The research area is situated along the coastline of the inner Puck Bay, in the eastern part of the Kashubian Coastland and western part (13 km) of the Hel Peninsula, covering an area of 85,2 km² (Fig. 1). The vicinity of Baltic Sea creates a specific marine climate in this region, which characteristic features are moderate winters and mild summers. The annual temperature is around 7.4°C and the average amount of precipitation does not exceed 700 mm. The income of local inhabitants comes mainly from agriculture, fishery and tourism, related to the seaside location and unique environmental values of this region.

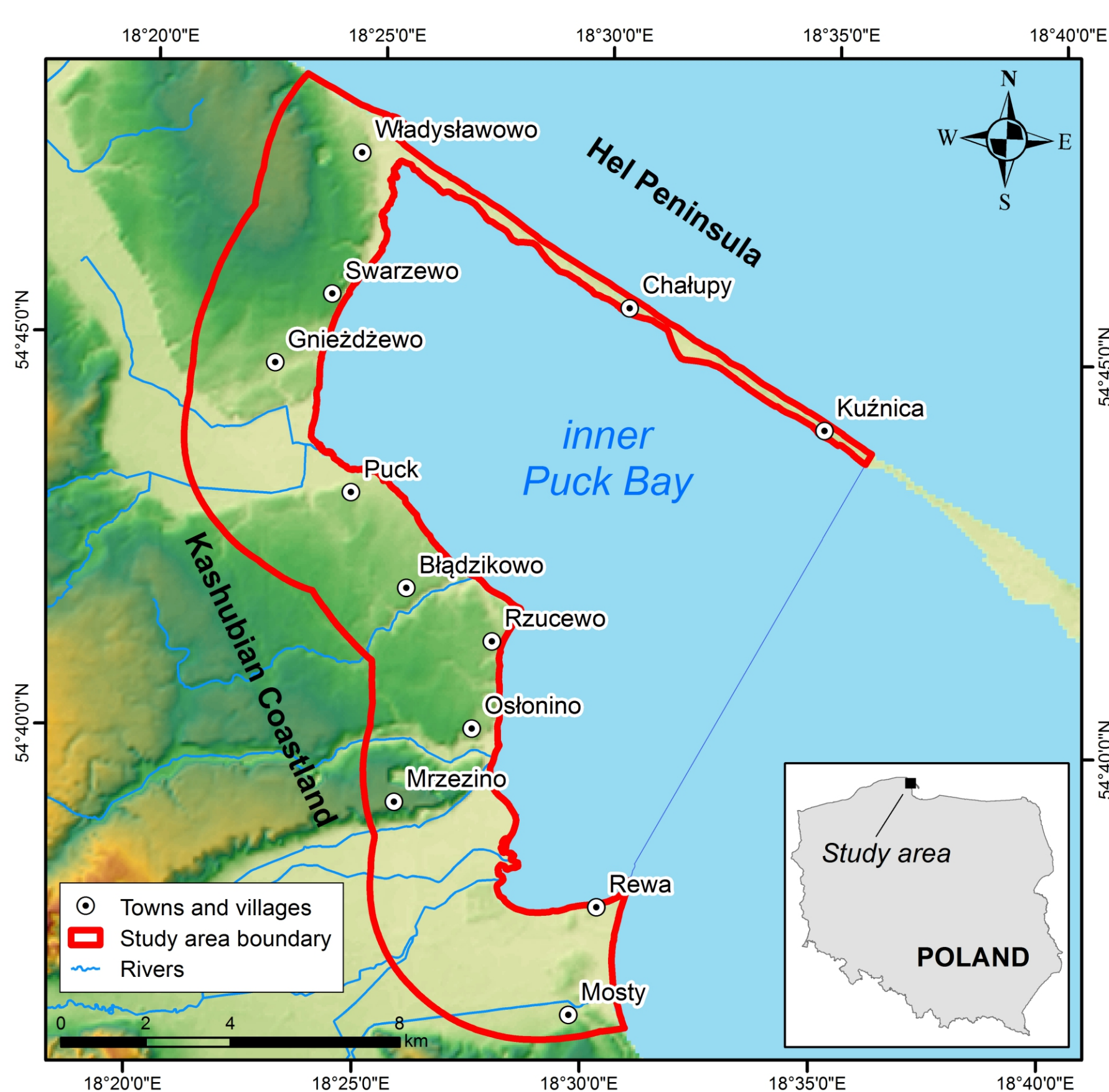


Figure 1. Research area.

The Kashubian Coastland mesoregion has a varying topography, typical for young glacial landscape. Morainic uplands are separated by deeply cut ice marginal valleys. Moraines consist of till deposits, which are divided by series of fluvioglacial sands and gravels. Glacial valleys are covered by extensive peat wetlands and consist of fluvioglacial sediments. The Hel Peninsula was formed during the Holocene under the influence of aeolian and marine processes. This structure is a sandbar, which separates the Puck Bay from the open Baltic Sea. With reference to the coastal system classification (©Eucc), the landscape of Hel Peninsula is a wave-dominated sedimentary plain with dune coasts in microtidal zone (Furmańczyk 2004).

In the Kashubian Coastland two aquifers have been identified (Frączek 1998). They consist of fluvioglacial sediments series (sands and gravels) which separate till deposits. Both aquifers are hydraulically connected.

In the Hel Peninsula fresh groundwater occurs as a lens in sandy aquifer, which directly overlies pleistocene silty sand sediments. This groundwater cannot be used for water supply, however it is exploited locally and temporally.

APPLIED METHODOLOGY AND MATERIALS

Analysis has been carried out using GALDIT method. Proposed by Chachadi and Lobo-Ferreira (2001), GALDIT method is a numerical ranking system, based on the most important map-able factors that control the seawater intrusion: (G) groundwater occurrence, (A) aquifer hydraulic conductivity, (L) height of groundwater level above sea level, (D) distance from the shore, (I) impact of existing status of seawater intrusion and (T) thickness of the aquifer. Relative importance of seawater intrusion influence is determined by weight established for each factor and assigned numeric rating, based on its susceptibility to seawater intrusion (Tab. 1). Applying the related weight and importance rating thematic maps were generated for each GALDIT parameter (Fig. 2). The final map of groundwater vulnerability to seawater intrusion (Fig. 3) was obtained by overlying six weighted maps with the following equation (Chachadi and Lobo-Ferreira 2007):

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

The investigation was carried out using data from the Central Hydrogeological Data Bank – The HYDRO Bank of Polish Geological Institute – National Research Institute: 235 boreholes, digital elevation model (DEM) and hydrogeological maps.

Spatial distributions of each GALDIT parameter in 3 km buffer of the inner Puck Bay coastline were integrated with GIS environment and mapped using geostatistical interpolation techniques and GIS analyst tools. Final vulnerability index were estimated by using *raster calculator* tool.

where W_i is the weight of the i th indicator and R_i is the importance rating of the i th indicator. The final GALDIT index ranges from 2.5 to 10 and is divided into three vulnerability classes: high (>7.5), moderate (5-7.5) and low (<5).

Table 1. Summary of GALDIT parameter weight, rates and ranges.

Indicator	G	A	L	D	I	T	Importance Rating
Weight Unit	1	3	4	4	1	2	
	[-]	[m/d]	[m]	[m]	[epm]	[m]	
Indicator variables	Confined Aquifer	>40	<1.0	<500	>2.0	>10	10
	Unconfined Aquifer	10-40	1.0-1.5	500-750	1.5-2.0	7.5-10	7.5
	Leaky confined Aquifer	5-10	1.5-2.0	750-1000	1.0-1.5	5-7.5	5
	Bounded Aquifer	<5	>2.0	>1000	<1.0	<5	2.5

RESULTS AND DISCUSSION

Groundwater occurs (G) as confined as well as unconfined aquifers. The hydrogeological system is confined mainly in the upland area and in that part the highest vulnerability rank – 10 was assigned. Aquifers in the remaining area are unconfined thus in this part rating of 7.5 was applied (Fig. 2-G). The aquifers hydraulic conductivity (A) varies from 6 to 120 m/d. Therefore, the study area was classified into three classes of vulnerability with ranges 5, 7.5 and 10 (Fig. 2-A). The major part of studied area was rated with 7.5 and locally within upland area with 5 or 10. In reference to the height of groundwater level above mean sea level (L), the considered coastal area was categorized into four classes of vulnerability and rated between 2.5-10 (Fig. 2-L). The lowest values of rating are observed in upland area and increases in discharge area direction (Bay of Puck, open Baltic Sea and glacial valleys). The distance from the shore (D) was estimated according to three distances to the coastline ranges: 500, 750 and 1000 m. The maximum value (10) is assigned for areas situated close to the coast (distance lower than 500 m), whereas it decreases as distance inland increases (Fig. 2-D). According to poor availability of groundwater quality data it was difficult to reliably estimate impact of existing status of seawater intrusion (I) in entirely area. To evaluate this parameter the ratio of Cl^- / HCO_3^- (Lobo-Ferreira et al. 2007) were considered instead of recommended Revelle index ($Cl^- / [HCO_3^- + CO_3^{2-}]$) (Chachadi and Lobo-Ferreira 2007). The impact of parameter I was divided into four classes and rated from 2.5 to 10 (Fig. 2-I). According to the available data the maximum ratio of Cl^- / HCO_3^- was observed at the Hel Peninsula and northern part of the Kashubian Coastland. In the major part of the Kashubian Coastland the minimal value was adopted. In terms of the aquifer thickness (T), study area can be divided into two parts. The thickness of aquifer in the Hel Peninsula is 6 m and it was rated with 5 value, while aquifer thickness in the remaining area is higher than 10 m and thus it was rated with the highest score (Fig. 2-T).

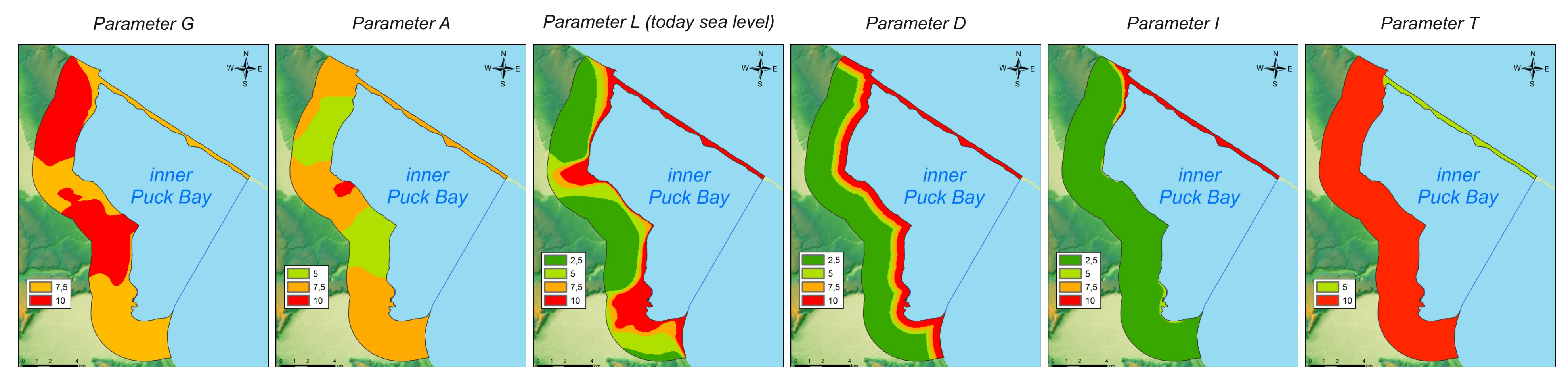


Figure 2. Thematic maps of GALDIT method parameters.

As the Polish coastline is thought to be the most susceptible to sea level rise in Europe (Paprotny and Terefenko 2017) the impact of predicted sea-level rise to groundwater vulnerability was checked. Actual trends of sea level changes may cause increase of coastal aquifers vulnerability to seawater intrusion in the future. According to the KLIMAT project (Wibig and Jakusik [eds.] 2012), the mean sea level of the inner Puck Bay in the period 2081-2100 is predicted to exceed the current level by 0.28 m (the most pessimistic scenario). The prediction was estimated based on the greenhouse gases emissions (A2), the impact of circulation factor and expected changes in the global sea level according to the IPCC. The scenario of sea water level rise was included in GALDIT method by decreasing the height of groundwater level above sea level by 0.28 m – L parameter.

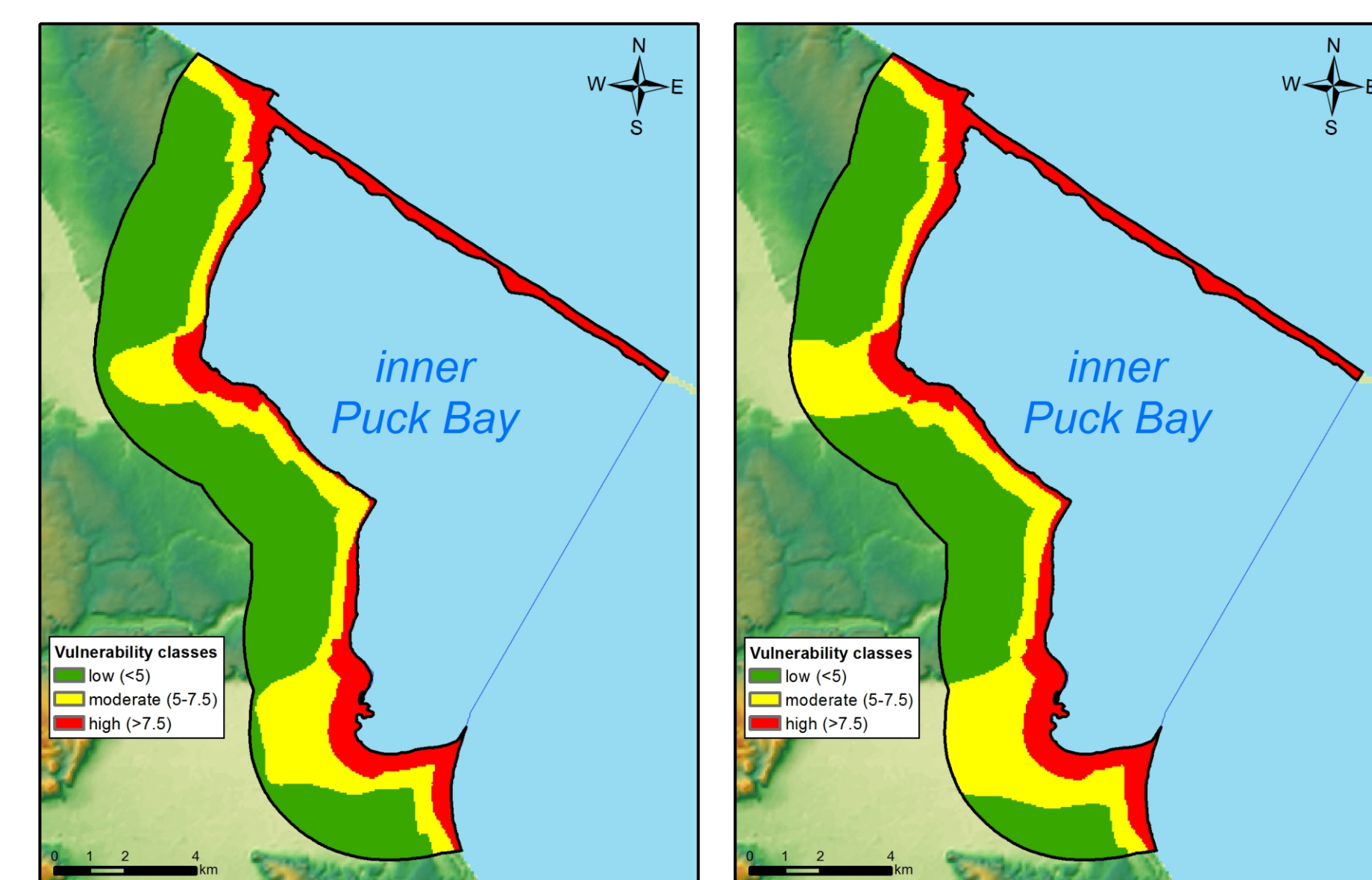


Figure 3. Comparison between GALDIT index for the current and future sea levels (left – current sea level; right – predicted sea level in 2081-2100 years with rise +0.28 m).

Table 2. Areal comparison of vulnerability classes.

Vulnerability classes	Current sea level		Predicted sea level in 2081-2100 years (+0.28 m)	
	[km ²]	[%]	[km ²]	[%]
Low	47.5	55.8	41.5	48.7
Moderate	21.6	25.3	26.0	30.5
High	16.1	18.9	17.7	20.8

CONCLUSIONS

Assessment of the inner Puck Bay coastal aquifer vulnerability to seawater intrusion has been conducted using GALDIT method. The most vulnerable areas are the Hel Peninsula and northern part of the Kashubian Coastland. Increased class of aquifer vulnerability was also obtained for glacial valleys.

Differences between actual and future aquifer vulnerability are noticeable. The predicted sea level rise of 0.28 m in the scenario for period 2081-2100 will increase vulnerability to seawater intrusion on 7% of the research area. It will be particularly significant in glacial valley areas, where the groundwater table is only slightly above the sea level.

The final map of vulnerability can be a useful tool for management of the coastal zone of the inner Puck Bay.

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