

## **D2.1 Sites thematic maps of vulnerability**

# DATASET

**“Groundwater sAlinizaTion and pollution AsseSsmEnt Tool”**



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### EXECUTIVE SUMMARY:

The deliverable **D 2.1 Site thematic maps of vulnerability** presents the application of the DATASET Index methodology to five pilot sites in Europe and South Africa, providing groundwater vulnerability maps for agricultural leaching (AGL) and salinization processes (SP) using the Automated DATASET Index (ADI).

D 2.1 is intended for use by DATASET project researchers only.

# Table of Contents

<b>1</b>	<b>General information .....</b>	<b>4</b>
1.1	<b>The DATASET Index Structure .....</b>	<b>5</b>
1.1.1	Automated DATASET Index (ADI).....	6
<b>2</b>	<b>Pilot Sites .....</b>	<b>10</b>
2.1	<b>Campania Plain (Italy) .....</b>	<b>11</b>
2.2	<b>Po Delta Plain (Italy) .....</b>	<b>15</b>
2.3	<b>Puck Bay Catchment (Poland) .....</b>	<b>19</b>
2.4	<b>Vistula Spit (Poland).....</b>	<b>22</b>
2.5	<b>Cape Flats (South Africa).....</b>	<b>25</b>
<b>3</b>	<b>ADI results - Agricultural Leaching and Salinization Processes .....</b>	<b>30</b>
3.1	<b>Campania Plain (Italy) .....</b>	<b>30</b>
3.2	<b>Po Delta Plain (Italy) .....</b>	<b>33</b>
3.3	<b>Puck Bay Catchment (Poland) .....</b>	<b>37</b>
3.4	<b>Vistula Spit (Poland).....</b>	<b>41</b>
3.5	<b>Cape Flats (South Africa).....</b>	<b>44</b>
<b>4</b>	<b>References .....</b>	<b>48</b>

# 1 General information

The goal of DATASET is to create an efficient tool that helps protect and manage the use of water resources in coastal aquifers, even under changing and challenging conditions. To achieve this goal, DATASET focuses on three main objectives:

**OBJ 1** - Better tools for better protection developing a new method to create vulnerability maps of coastal aquifers.

**OBJ 2** – Innovative water management forcing a paradigm shift in water governance by making data, models, and management tools available online.

**OBJ 3** – Raising awareness highlighting the importance of groundwater and its vulnerability to climate change and extreme events.

To reach these three objectives, DATASET follows a multidisciplinary approach. This means bringing together expertise from different fields to identify the environmental factors that can harm groundwater quality. Using the best available knowledge, we also gather data from open-access databases to build a comprehensive picture of the challenges that coastal aquifers must face [D.1.1].

The research has led to the creation of a new index designed to evaluate groundwater vulnerability specifically to salinization and agricultural leaching [D1.3]. This index uses a simple and accessible formula that allows the use of global data, making it easier for researchers, planners, and policymakers to assess risks anywhere in the world. Moreover, to test the reliability of the DATASET index, several coastal areas have been chosen around the world, characterized by different hydrogeological and climatic characteristics to calibrate parameters classification [D2.2]. The purpose of Deliverable D 2.1, Sites thematic maps of vulnerability, is to review the work carried out at the five pilot sites and to present the results obtained through the application of the Automated DATASET Index (ADI). This deliverable proposes site characterization and conceptual modeling efforts and provides thematic vulnerability maps for agricultural leaching (AGL), supported by graphical outputs and interpretation. The results demonstrate the applicability and robustness of the DATASET methodology across different hydrogeological and climatic conditions.

## 1.1 The DATASET Index Structure

As stated in the D1.3, the DATASET index is designed to establish a standardized methodology for evaluating groundwater vulnerability assessment (GVA) to both saltwater intrusion (SP) and agricultural leaching (AGL) pollution, ensuring global accessibility and affordability for researchers.

The selection of key factors follows two mandatory criteria:

1. **Global Data Availability** – Factors must be accessible from open databases with worldwide coverage to enable broad applicability.
2. **Ease of Use** – The methodology should be straightforward to implement while maintaining a balance between accuracy and usability.

This index offers flexibility by allowing users to assess either SP or AGL by simply toggling relevant parameters on or off (Fig. 1). The selected parameters are based on systematic reviews (D1.1) and refined from established models such as DRASTIC, GOD, SINTACS and GALDIT, focusing on the most impactful, quantifiable factors while incorporating additional parameters used in specific global assessments.

- **For SP assessment**, key parameters include distance from salt/freshwater sources, recharge, groundwater head, hydraulic conductivity, elevation, hydraulic gradient, salinity origin, and soil properties.
- **For AGL assessment**, factors related to pollutant transport and aquifer characteristics are prioritized, such as depth to the water table, recharge, elevation (slope), hydraulic conductivity, hydraulic resistance, background pollutant levels, and soil properties.

The DATASET index will be divided into two sub-indices: an Automatic DATASET Index (ADI) and an Improved DATASET index (IDI).

### 1.1.1 Automated DATASET Index (ADI)

ADI is a fully automated tool that enables effortless groundwater vulnerability assessment (GVA) for SP and AGL, eliminating the need for manual input.

- **Fully Automated** – Relies exclusively on open-source data provided by the DATASET team for global accessibility.
- **Effortless Screening** – Users can generate vulnerability maps worldwide by selecting parameters from a predefined list.
- **Standardized Input Data** – Ensures consistency by utilizing parameters available through the DATASET Project Website.

The ADI includes **six parameters for SP assessment** and **five for AGL assessment**, aiming to provide a robust screening phase that is both accessible and sufficiently detailed, avoiding oversimplification (Foster et al., 2013).

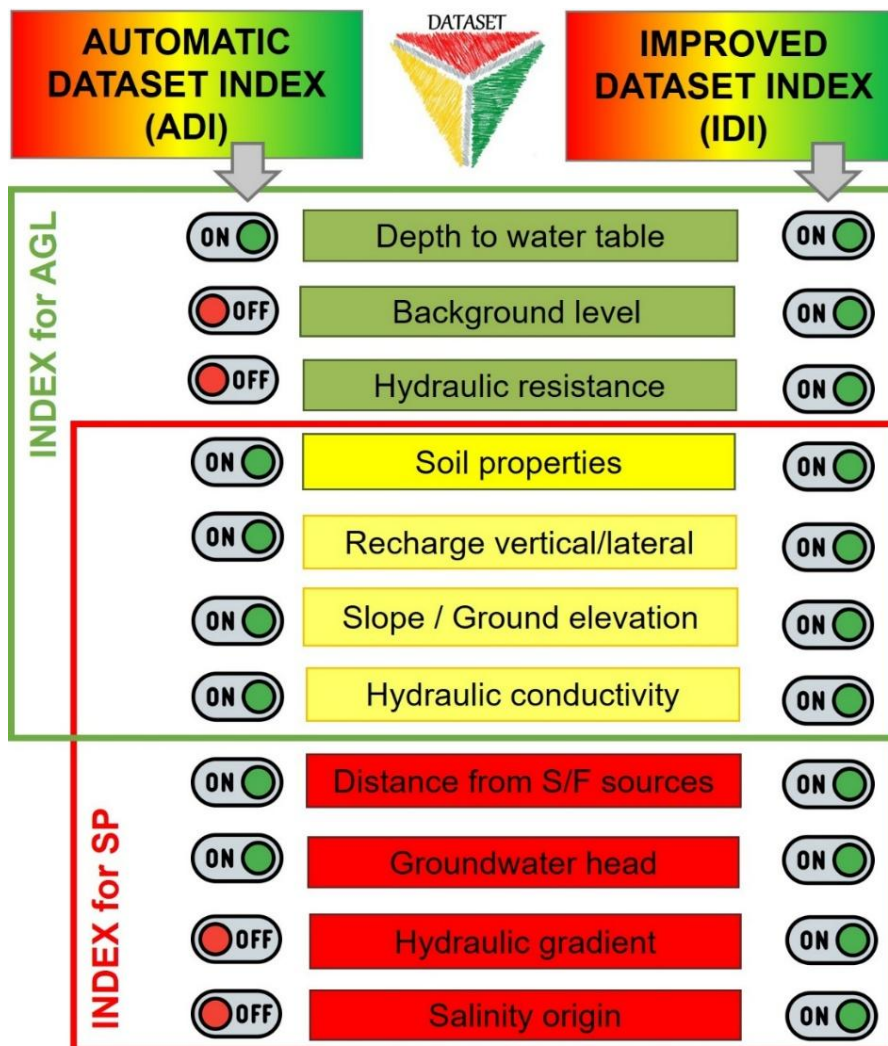


Figure 1: General concept of the DATASET index.

- *Parameters for the AGL assessment.*

**Depth to water table (D):** This parameter represents the thickness of the unsaturated zone, which determines the distance that recharge water must travel to reach the aquifer. Lower values indicate a higher vulnerability to contamination, as pollutants have a shorter path to infiltrate. The shallower the water table, the greater the risk of contamination from surface sources (Busico et al., 2020).

**Vertical Recharge (R):** it refers to the amount of meteoric water that infiltrates the soil and reaches groundwater reservoirs. It serves as the primary transport mechanism for hydrovehiculated contaminants introduced at the surface, directly influencing the chemical composition of groundwater (Liu et al., 2023).

**Hydraulic conductivity (C):** it is a crucial parameter in hydrogeology, determining how easily water can move through aquifer materials. Higher conductivity values indicate more permeable materials like sand and gravel, which allow rapid groundwater flow, while lower values correspond to less permeable materials, like clay, which restrict movement.

**Slope (E):** it affects water movements on the surface and thus the likelihood of pollution moving towards an underlying aquifer, and groundwater velocity within the aquifer. Higher slope, trigger runoff, reducing infiltration while flat morphology incentive infiltration along with likelihood of pollutant leaching.

**Soil properties (S):** it is one of the factors affecting recharge rate and consequently water availability. In areas with fine textures such as silt and clay, the relative permeability of the soil is reduced and as a result, the migration of contaminants is limited (Busico et al., 2020). For example, the amount of clay, silt or sand can be used to assess groundwater vulnerability.

The final formulation for the ADI index to AGL will be as follows:

- $$ADI_{AGL} = D_{rating} * D_{weight} + R_{rating} * R_{weight} + E_{rating} * E_{weight} + C_{rating} * C_{weight} + S_{rating} * S_{weight}$$

- *Parameters for the SP assessment.*

**Distance from salt/freshwater (L):** salt and freshwater sources, both superficial and underground can influence SP. The main source of saltwater is surely the sea and generally, the shorter the distance from the coastline, the greater the seawater intrusion, and the shorter this distance, the higher the probability of aquifer salinization (Luoma et al., 2017). Moreover, a dynamic interaction can be seen between sea water and coastal water bodies, which can be affected by the inflow of sea water because of tides and storms (Kazakis et al., 2019). In general, water bodies stretch close to the shoreline and located in a depressed area (ground elevation) could be a source of saltwater due to tides and waves action, while at higher elevation and far from the shoreline they could be represent source of freshwater, accelerating or mitigating SP, respectively (Tosi et al., 2022)

**Groundwater head (G):** it has a significant effect on seawater intrusion (Boufekane et al., 2022), since a groundwater level below sea level can increase aquifers' vulnerability to seawater intrusion while groundwater level above sea level can push back the sea water (Trabelsi et al., 2016).

**Vertical and lateral Recharge (R):** it maintains freshwater pressure in aquifers, helping to prevent both lateral salinization coming from seawater intrusion and vertical salinization due to paleo seawater. A decrease in recharge, whether from natural or human-induced causes, can make aquifers more susceptible to contamination by saltwater (Costall et al., 2020).

**Ground elevation (E):** it reflects several aspects related to GVA to SP. As previously described, it influences the role of water bodies as source of salt/freshwater and is helpful in defining the lateral recharge as conditioning factor. Moreover, depressed morphology (e.g. subsident) can trigger SWI.

**Hydraulic conductivity (C):** in the context of seawater intrusion, it determines how easily seawater can move into and spread through freshwater aquifers. High hydraulic conductivity allows seawater to intrude more easily and quickly, especially when groundwater pressure is reduced, while low hydraulic conductivity slows or prevents the spread of seawater.

**Soil properties (S):** Soil properties can play a crucial role in either facilitating or resisting SWI. The movement of saline water into coastal aquifers and soil depends on factors like permeability, porosity, texture, structure, hydraulic conductivity and chemical composition. These properties determine how easily SWI infiltrates, spreads, and affects groundwater. Soil hydraulic conductivity also plays a role in defining the interaction among superficial water (possible path of SWI) and groundwater. In the case of layers and lenses with low hydraulic conductivity (e.g. clay and silt) the interaction is limited. On the contrary wise, when coarse grain material occurs then the interaction is significantly higher.

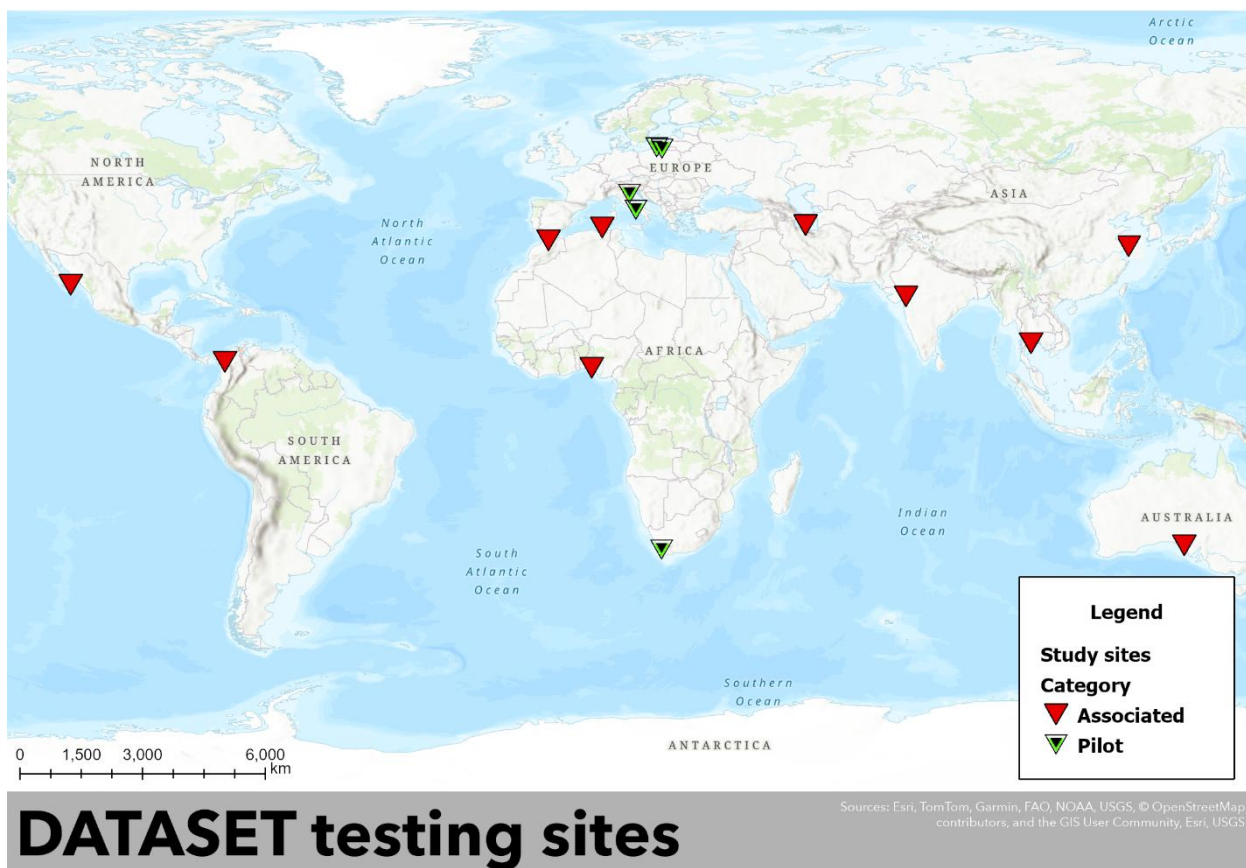
The final formulation for the ADI index to AGL will be as follows:

- $ADI_{SP} = L_{rating} * L_{weight} + G_{rating} * G_{weight} + R_{rating} * R_{weight} + E_{rating} * E_{weight} + C_{rating} * C_{weight} + S_{rating} * S_{weight}$

## 2 Pilot Sites

The DATASET methodology has been developed and calibrated in 15 sites around the world: 5 under consortium responsibility and 10 selected by open literature (Fig. 2). These sites are in five continents with different hydrogeological, climatic, and land-use conditions. The selected pilot sites are the Campania Plain (Italy), the Po Delta Plain (Italy), the Puck Bay Catchment (Poland), the Vistula Spit (Poland), and the Cape Flats Aquifer System (South Africa). This diversity allows for a comprehensive evaluation of the DATASET methodology and supports the assessment of its robustness and applicability under different environmental conditions.

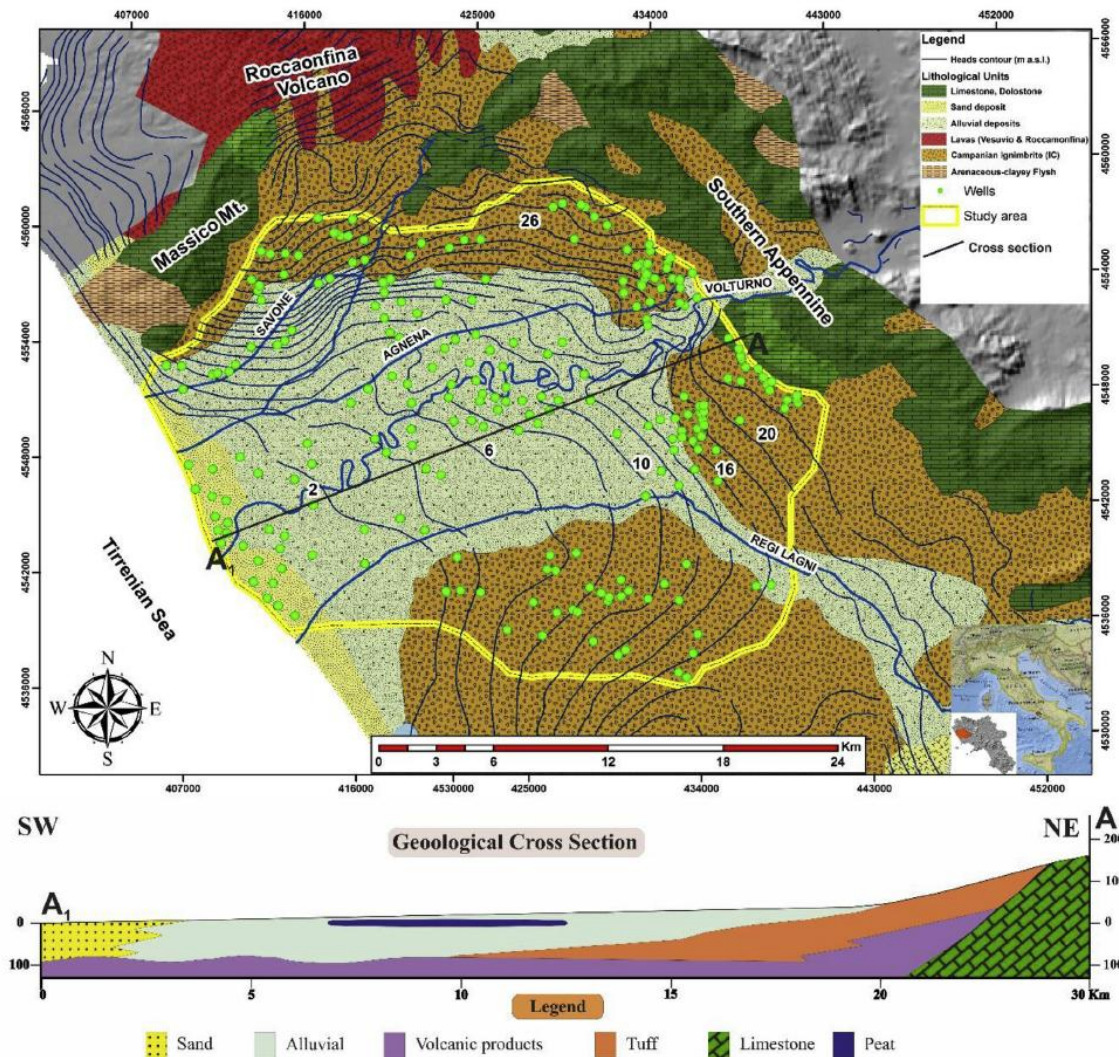
For each pilot site is provided a description, including geological and hydrogeological conditions, recharge mechanisms, and natural and anthropogenic pressures. The information provided supports the interpretation of the Automated DATASET Index (ADI) results presented in the next sections. Figure 2 shows the geographic distribution of the pilot sites.



**Figure 2:** Pilot sites and associated sites

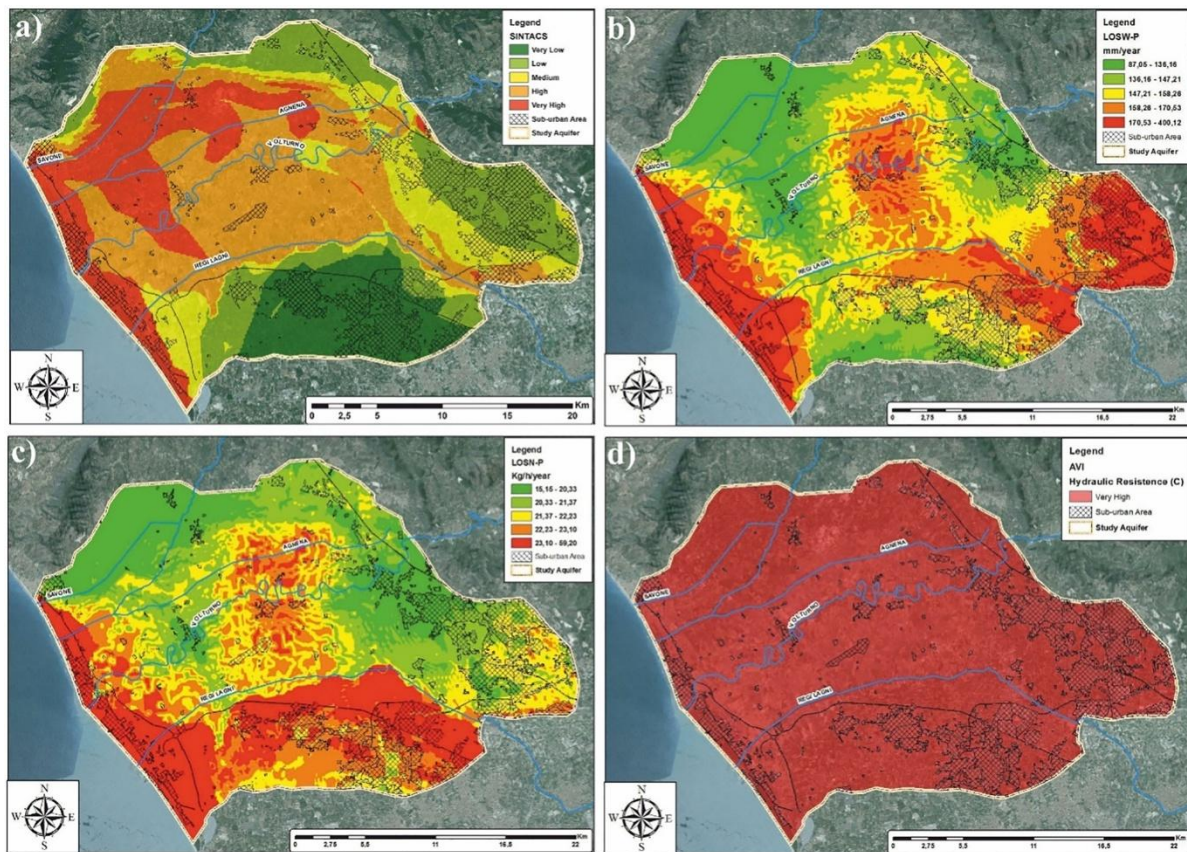
## 2.1 Campania Plain (Italy)

The Campania Plain, located in southern Italy, is a large coastal and alluvial depression extending along the Tyrrhenian margin of the Southern Apennines. It is bounded to the west by the Tyrrhenian Sea, to the north by the Massico Massif and the Roccamonfina Volcano, to the east by the carbonate ranges of the Maggiore, Tifatini and Avella Mountains, and to the south by the volcanic systems of the Phlegrean Fields and Mt. Vesuvio. The climate is a typical Mediterranean climate, with hot, dry summers and wet winters. The mean annual rainfall is 800 mm occurring mainly in the wet period (October–May), and the mean annual temperature is 17 °C. The Campania plain covers an area of approximately 700–780 km<sup>2</sup>, and hosts more than one million inhabitants, with highly heterogeneous land use: about 20% urbanized areas, more than 70% agricultural land, and the rest of the area is occupied by deciduous woods and forests.



**Figure 3:** Geological setting of Campania Plain (Busico et al.,2018)

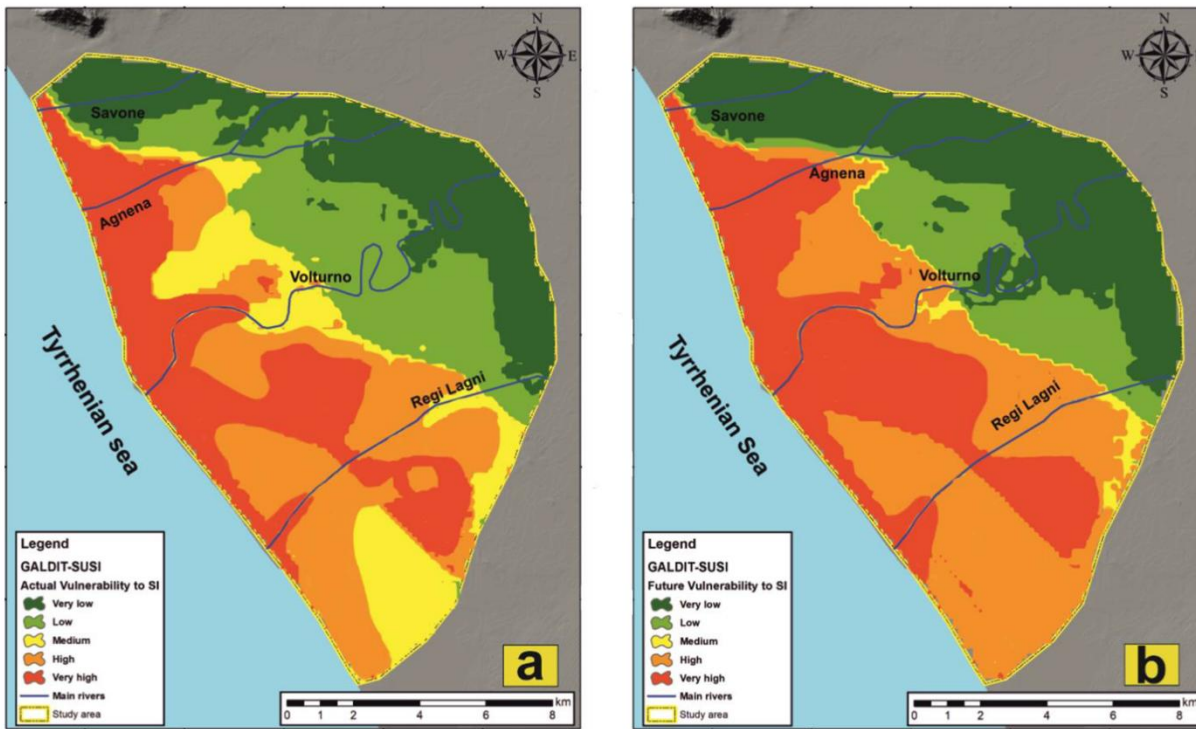
The Campania plain is a big graben that developed in Upper Pliocene–Lower Pleistocene generating a disruption and decline of the Apennine Mezo-Cenozoic carbonate units, creating a graben which is filled by marine, continental, and volcanic deposits. Specifically, alluvial deposits consist of a mixture of sand, silt, and clay deposited by the Volturno and Garigliano rivers (Busico et al., 2019, 2020), while volcanic materials consist of tuffs and other volcanic products produced by several explosive events of the Campi Flegrei caldera and minor events of the Somma-Vesuvio volcano (Milia and Torrente, 2015). The shallow, unconfined aquifer of the Campania Plain is hosted within volcanic deposits and the alluvial formations of the Volturno River plain. The alluvial formations, including gravel and sand, are characterized by high hydraulic conductivity. However, clay and peat also occurred, especially in the lowland area located in the central part of the Volturno River plain. Recharge occurs primarily through local rainfall infiltration and lateral groundwater inflows from the karst aquifers of the Apennine reliefs and the volcanic aquifers to the north and south. Regional groundwater flow is oriented from east to west toward the Tyrrhenian coast. Groundwater levels range from 0 to 70 m below ground surface, with the water table reaching its highest level in May or April and its lowest level in September-October. The predominant water types of groundwater are from Ca-HCO<sub>3</sub> in recharge zones, and, moving into the plain it changes in Na-K-HCO<sub>3</sub> and Na-Cl in coastal area. The Campania plain is one of the most anthropized areas of Southern Italy, with extensive agriculture (orchards, vegetables, vineyards, maize, and wheat), dense urban settlements, and industrial zones. In the coastal Volturno delta plain, which represent the main testing area, reclaimed lands have promoted the development of farming, and strong urban expansion since the mid-20th century, leading to landscape fragmentation, groundwater overexploitation, and degradation of sensitive habitats such as dunes, lagoons and wetlands. Nitrate (NO<sub>3</sub><sup>-</sup>) concentrations in the Campania Plain are mainly influenced by lithology and groundwater flow conditions. In the central Volturno River plain, NO<sub>3</sub><sup>-</sup> levels are below detection limit due to the presence of peat-rich sediments that create reducing conditions and favor nitrate removal. Instead, higher NO<sub>3</sub><sup>-</sup> concentrations occur in areas characterized by tuff formations, especially in sub-urban zones. The stronger influence of salinization is located near the coastal area, where shallow marine sediments in proximity of the Volturno River mouth together with the actual seawater intrusions increase EC, pH, Na<sup>+</sup> and Cl<sup>-</sup> in groundwater. Cl<sup>-</sup> concentrations in the area range from a minimum of 9 mg/L to as much as 19,400 mg/L for the Tyrrhenian Sea.



**Figure 4:** Distribution of SINTACS intrinsic vulnerability in the study area (Busico et al., 2019)

According to the existing literature, there are different sources of  $\text{NO}_3^-$  in the pilot site that make the Campania plain vulnerable beyond agricultural land. The presence of shallow unconfined aquifers hosted in permeable volcanic and alluvial deposits, combined with intensive agricultural and sub-urban activities, facilitates the downward transport of  $\text{NO}_3^-$  toward the groundwater system. Although reducing conditions locally attenuate  $\text{NO}_3^-$  concentrations, fractured tuff formations and areas with high recharge enhance pollutant migration.

Figure 4a shows the SINTACS groundwater vulnerability map of the Campania Plain (Busico et al., 2019). High vulnerability classes are mainly observed in the coastal and central part of the plain, where groundwater level is shallow and the aquifer is composed of highly permeable alluvial and volcanic deposits. In contrast, low vulnerability classes are in the southern and eastern parts of the plain, where thicker pyroclastic deposits, finer-grained materials in the vadose reduce vertical-permeability and limit the downward movement of contaminants.

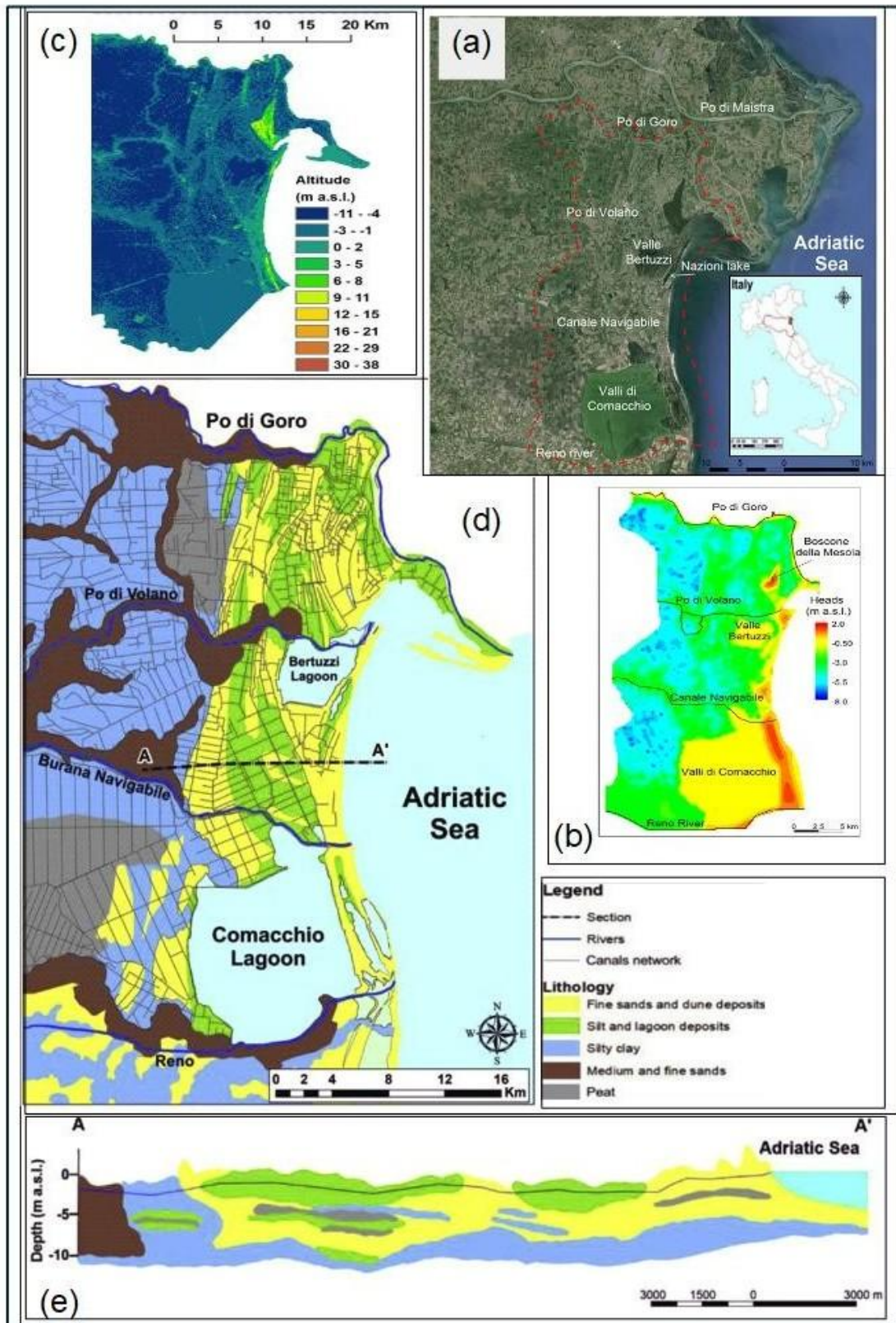


**Figure 5:** Actual (a) and future (b) vulnerability to seawater intrusion (SI) calculated according to the GALDIT-SUSI methodology (Busico et al., 2021)

According to Busico et al. (2021) the GALDIT-SUSI methodology, the Campania Plain shows high vulnerability to seawater intrusion, mainly controlled by the aquifer type, groundwater depth, lithology, and elevation. High vulnerability classes are observed in the coastal zone and in the terminal stretches of the Volturno, Agnena, and Regi Lagni rivers, up to 4.0 km from the shoreline. In these areas, rivers and drainage canals act as preferential pathways for seawater intrusion, especially where ground elevation is close to or below sea level. The low elevation, together with the high salinity index, and the unconfined aquifer condition are responsible for the natural high vulnerability to salinization. In inland, more than half of the plain is characterized by medium to high vulnerability due to low piezometric values, ranging from +1.0 to +3.0 m. a.s.l., and limited aquifer thickness. The low and very low vulnerability areas are presented to the northern part of the pilot site, at least 5 km from the coastline, where groundwater levels are higher and finer-grained vadose materials reduce seawater penetration. These processes define the spatial distribution of groundwater vulnerability to  $\text{NO}_3^-$  pollution and seawater intrusion and provide the basis for comparison with the Automated DATASET Index (ADI) presented in the following section.

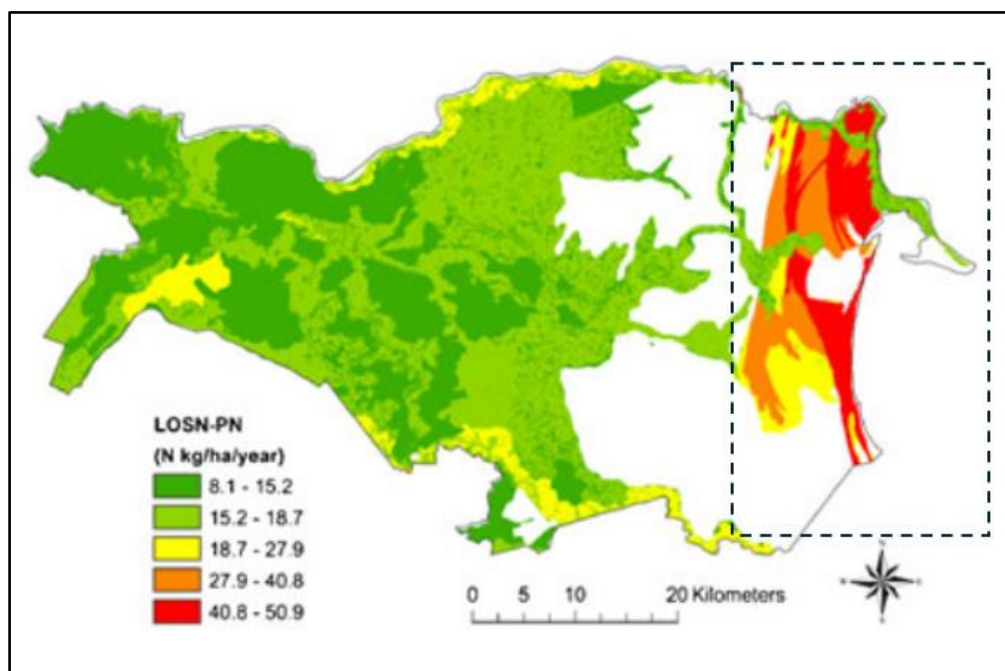
## 2.2 Po Delta Plain (Italy)

The Po Plain site is located along the northern Adriatic coast in the Ferrara Province (Northern Italy), extending between the southern margin of the Venice Lagoon and the Province of Ravenna (Fig. 6a). It corresponds to the low-lying coastal floodplain of the Po River and covers approximately 750 km<sup>2</sup>, from the present shoreline up to about 20 km inland. The climate is temperate subhumid, with a mean annual air temperature of about 13.3 °C and an average annual precipitation of approximately 650 mm. Land use is dominated by intensive agriculture over most of the inland areas, while coastal zones are subject to strong seasonal pressure related to tourism during summer months (June–September). Brackish coastal lagoons (Valle Bertuzzi, Lago delle Nazioni, and the Valli di Comacchio), major river branches (Po di Goro, Po di Volano, Canale Navigabile, and the Reno River), and an extensive artificial drainage and irrigation system dominate the hydrological setting. Surface water levels are artificially maintained at approximately –0.5 m a.s.l. to meet agricultural requirements. Excess water is pumped into collector channels and discharged into the Adriatic Sea (Colombani et al., 2016). The landscape is characterised by flat topography, with elevations commonly at or below sea level. The only morphological reliefs consist of coastal dune systems, palaeodunes, abandoned beach ridges, and riverbanks, reflecting the recent Holocene evolution of the deltaic plain (Fig. 6c). From a lithostratigraphic perspective, the shallow subsurface consists predominantly of permeable sandy deposits arranged in a seaward-thickening wedge, deposited in shallow-marine and littoral environments, with frequent intercalations of silty layers and peat horizons (Fig. 6e). These deposits are locally overlain by foreshore and beach sands and by aeolian dune systems along the coast (Amorosi et al., 2003). Landward, fine-grained silts and clays become increasingly dominant, forming laterally extensive low-permeability units (Fig. 6d and 6e). The complex stratigraphic architecture results in a complex aquifer geometry. The main shallow aquifer is hosted within littoral sands and shallow-marine sandy wedge deposits and is underlain by fine-grained silty–clayey sediments (Fig. 6e). The aquifer is predominantly unconfined, although locally semi-confined conditions occur due to fine-grained interlayers. The horizontal hydraulic gradient (0.1–0.5 %) and the horizontal flow velocity (7–10 m/year) are mainly controlled by canals and drains of the reclamation works (Mastrocicco et al. 2013).



**Figure 6:** Po River lowland overview. (a) location of the study area, (b) groundwater level map, (c) topography map, (d) geological map, and (e) cross-section. The figures were retrieved from Colombani et al., 2016 (a and b), Mastrocicco et al., 2013 (c), Kazakis et al., 2019 (d and e)

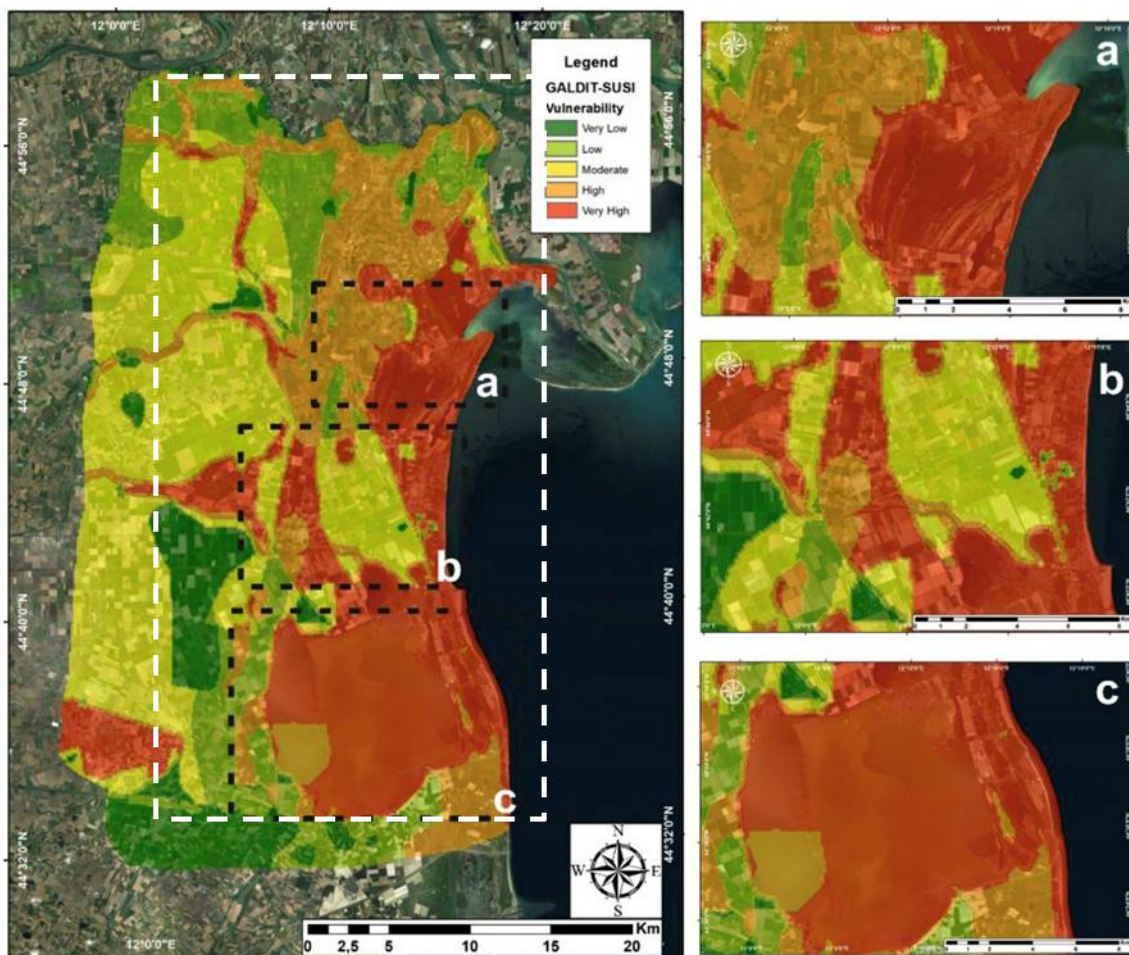
Groundwater quality is strongly influenced by both paleoenvironmental conditions and present-day hydraulic management. Monitoring spatiotemporal  $\text{NO}_3^-$  pollution in the shallow aquifer, by Soana et al. 2022, shows homogeneous  $\text{NO}_3^-$  concentrations at the spatial scale, with only a few hotspots in correspondence to groundwater samples belonging to Po River paleo-channels and coastal paleo-dunes sandy soils. On the other hand, Aschonitis et al. (2013) calculates the average intrinsic nitrogen loss rates in Ferrara Province (Fig. 7). They report that elevated rates are mainly found in the eastern coastal region and along riverbanks, as well as in the paleochannels and crevasse splays of the Po and Reno rivers, where the soil texture consists primarily of alluvial deposits from dunes and paleo-dunes (characterized by very high  $K_s$ ). The lowlands of the Po River exhibit high to very high annual intrinsic nitrogen loss rates through percolation (LOSN-PN) across most of the area. A small area with medium nitrogen losses is present in fine sand and dune deposits close to the Comacchio lagoon.



**Figure 7:** Annual intrinsic rates of nitrogen losses through percolation ( $\text{kgN ha}^{-1}\text{year}^{-1}$ ) in Ferrara Province (retrieved from Aschonitis et al., 2013)

According to Mastrocicco et al. (2012) the aquifer overall displays fresh water (salinity  $<0.5\text{g/l}$ ) in the uppermost section and a transition zone of brackish water (from  $0.5$  to  $30\text{g/l}$ ) with a thickness ranging from  $1$  to  $4\text{m}$ . Finally, saline (from  $30$  to  $50\text{g/l}$ ) to hypersaline ( $>50\text{g/l}$ ) water is present in the remaining thickness of the aquifer (Barlow 2003). The hydrogeochemical investigations by Giambastiani et al. (2013) demonstrate that the hyper-salinity found in the deepest portion of the aquifer cannot be associated with conventional lateral intrusion or upconing of present seawater but suggests the presence of relict seawater trapped in the back-barrier dunes

and lagoonal environments during the Holocene interglacial phases. Kazakis et al. (2019) proposed GALDIT-SUSI methodology to assess the aquifer vulnerability to seawater intrusion (Figure 8). According to them, very high vulnerability characterizes the coastline up to 5 km inland and close to two big lagoons, Comacchio and Bertuzzi. High vulnerability is mainly connected to rivers, especially close to the discharge area where the vadose zone is characterized by high conductivity sediments. The presence of high vulnerability areas 20 km far from the coast is mainly due to the flat topography and to the existence of depressed areas. The rest of the territory is characterized by medium vulnerability with a small percentage of Low and Very Low vulnerability where higher elevation values are present.

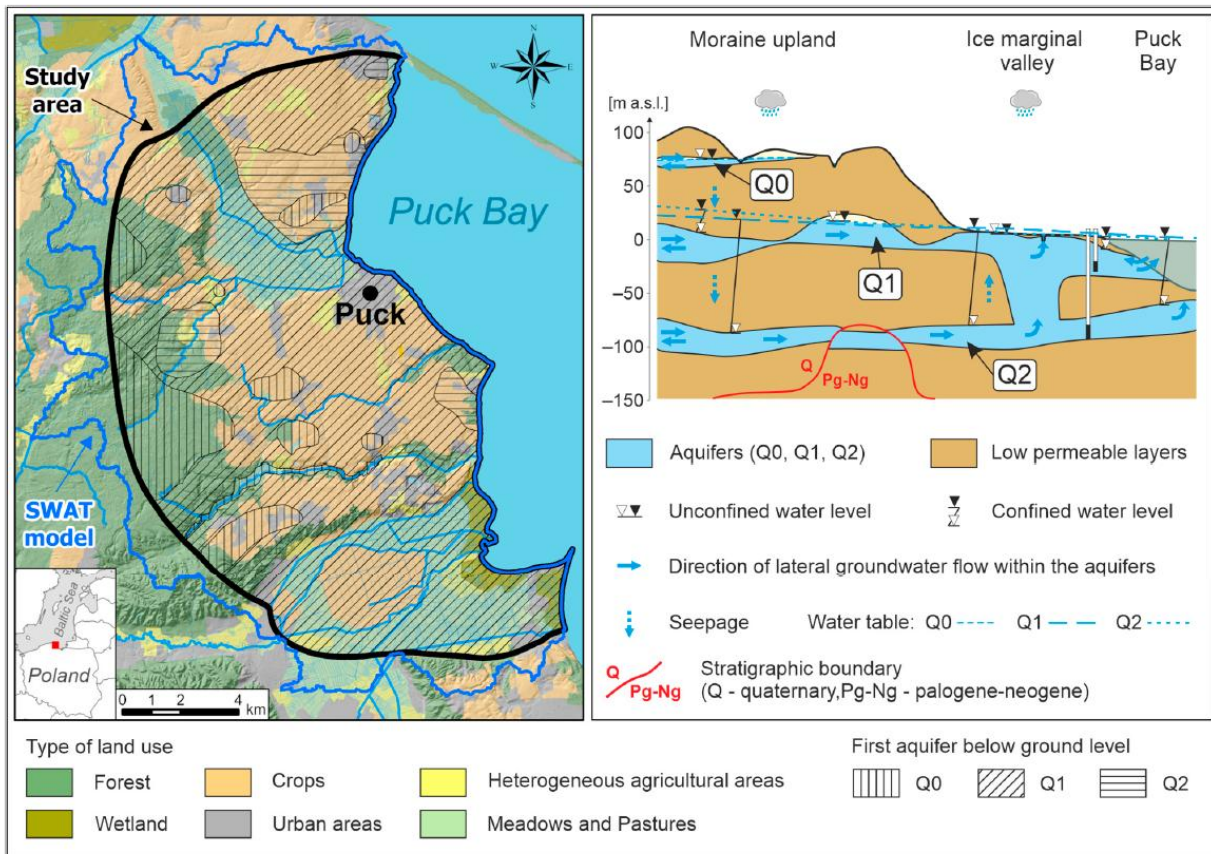


**Figure 8:** Distribution of the vulnerability classes according to the GALDIT-SUSI method in the Po River lowland. Detailed maps for the Lagoons of Bertuzzi and Comacchio (a and c) and for the Canale Navigabile (b) are also shown (retrieved from Kazakis et al., 2019). The white dashed box corresponds to the boundaries of our study area.

The study area is affected by several natural and anthropogenic pressures, including land subsidence, groundwater salinisation, saltwater intrusion along river channels, and diffuse agricultural pollution (Mastrocicco et al., 2013). Reduced recharge associated with climate change, together with increasing groundwater abstraction and continuous drainage, is expected to enhance inland migration of the freshwater–saltwater interface. These processes are further facilitated by buried sandy paleochannels and relict coastal ridges. Additionally, the upconing of ammonium-rich palaeo-seawaters, trapped within peat-bearing layers deposited during the Holocene maximum transgression, may intensify due to sustained artificial drainage (Giambastiani et al., 2013; Mastrocicco et al., 2013).

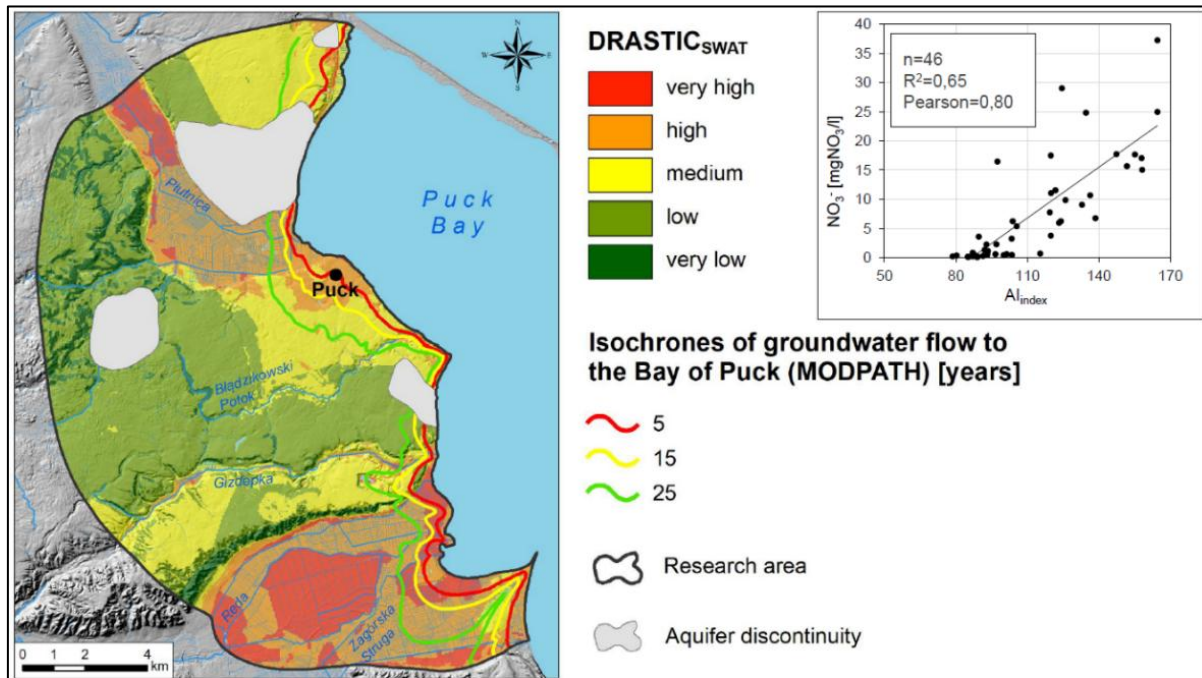
### 2.3 Puck Bay Catchment (Poland)

The Puck Bay catchment area is in northern Poland, on the southern coast of the Baltic Sea, and covers an area of 200 km<sup>2</sup>. It has a distinct marine climate, with relatively moderate winters and mild summers. The mean annual rainfall in the area corresponding to the hydrological years from 2001 to 2010 has been estimated at approximately 646.5 mm. The Puck Bay catchment is characterized by a typical young postglacial landscape with relatively high relief, ranging from -0.5 to 113.5 m above the sea level. Agricultural land (51%) is the dominant land use, in addition to forests (28%), permanent meadows and grasslands (12%), and low-density urban areas (9%). From a lithological point of view, the area consists of moraine plateaus separated by deeply incised ice-marginal valleys formed during the last glaciation. The region is entirely covered by Quaternary deposits, mainly composed of glacial till interlayered with sand and gravel, as well as fluvioglacial and fluvial sands occurring within valleys. Peat deposits are present locally, especially in larger river valleys. Groundwater occurs within a complex multi-layer aquifer system developed in Quaternary deposits (Fig. 9). Shallow groundwater is present in small, perched aquifers (Q0) and in sand lenses enclosed in moraine deposits. These shallow aquifers (Q0) do not play a key role in regional water supply, but they are exploited locally by farms and summer houses. The two main deeper aquifers in the study area are the inter-moraine (upper) aquifer (Q1) and the sub-moraine (lower) aquifer (Q2), both hosted in Quaternary sand and gravel deposits. The thickness of inter-moraine (Q1) aquifer is about 20 m, locally reaching up to 50 m, while the sub-moraine aquifer (Q2) has a thickness ranging from 10 to 35 m. Shallow groundwater is recharged by the infiltration of rainwater. Deeper aquifers are influenced by inflow from the west and take the seepage water from the layers above.



**Figure 9:** Map of Puck Bay region and general scheme of groundwater flow in the pilot site (Potrykus et al., 2026)

The entire groundwater system is drained by the Baltic Sea (Bay of Puck), either directly via submarine groundwater discharge or indirectly via streams and rivers. The Quaternary aquifers are the main source of water supply in the region (Szymkiewicz et al., 2020). The presence of pollutants in groundwater occurs locally and shows specific vertical geochemical inversion. The highest concentrations of nitrogen compounds, phosphates and potassium are observed in shallow groundwater, indicating a local impact of agricultural activities, as well as an influence of municipal waste from households and farms (e.g., poor sanitary conditions, animal husbandry, storage, and distribution of organic fertilizers) (Potrykus et al., 2020).

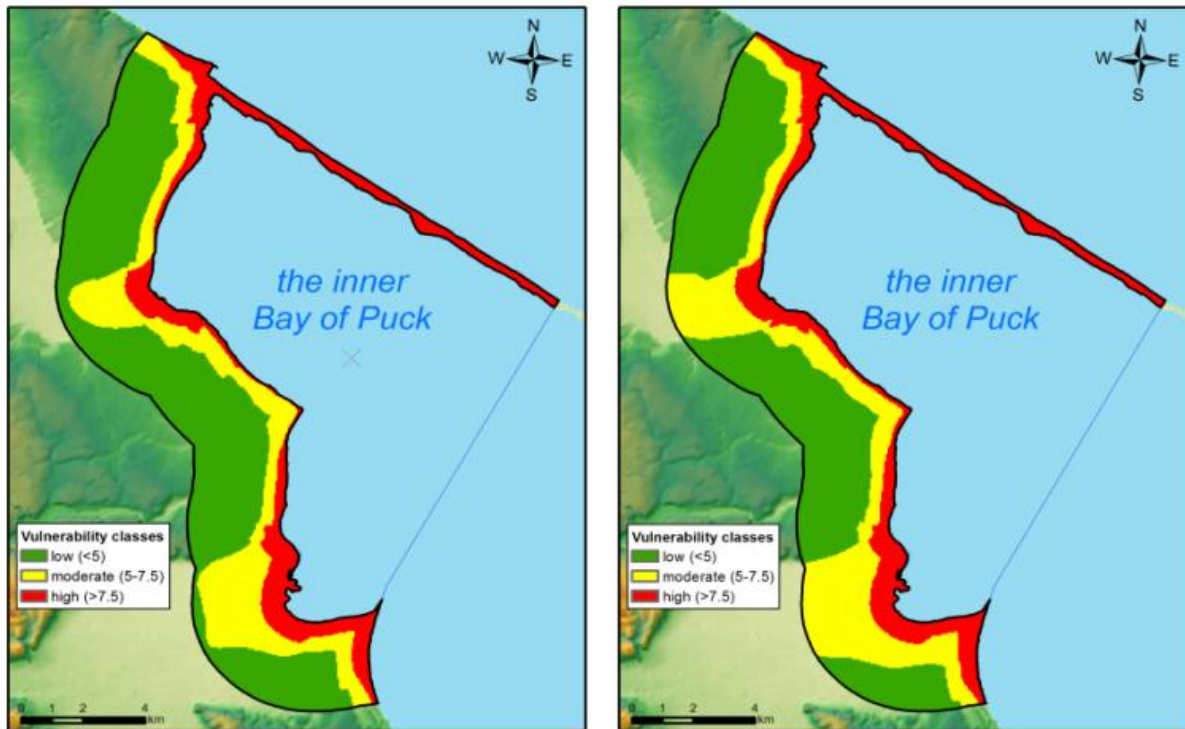


**Figure 10:** Distribution of DRASTIC-SWAT groundwater vulnerability and nitrate concentrations in the Puck Bay catchment (Potrykus D. 2022)

Nitrate (NO<sub>3</sub><sup>-</sup>) concentrations in groundwater of the Puck Bay catchment show clear differences between shallow and deeper aquifers. The highest NO<sub>3</sub><sup>-</sup> concentrations are observed in shallow groundwater, indicating a strong influence of surface-derived pollution. In the perched aquifers (Q0), nitrate concentrations range from 2 to 49 mg/L, with a median value of 26 mg/L. In the upper Quaternary aquifer (Q1), concentrations vary widely from below detection limit (<0.1 mg/L) up to 92 mg/L, with a median of 10 mg/L. In contrast, the deeper Quaternary aquifer (Q2) shows very low nitrate concentrations, ranging from below detection limit to 1 mg/L, with a median of 0.3 mg/L (Potrykus et al., 2020). As a result, high N-NO<sub>3</sub> loads are discharged to the Bay of Puck from the upper aquifer, which is more vulnerable to pollution migration from ground surface. The observed NO<sub>3</sub><sup>-</sup> distribution in the pilot site is consistent with the spatial pattern of groundwater vulnerability identified by the DRASTIC-SWAT assessment (Fig. 10).

Groundwater vulnerability to seawater intrusion in the Puck Bay area has also been previously assessed using GALDIT method (Fig. 11). According to Potrykus et al. (2018), the inner Bay of Puck was classified into three groundwater vulnerability classes: high (>7.5), moderate (5-7.5) and low (<5). The percentage distribution of low, moderate and high vulnerability zones for the current sea level are 55.8, 25.3 and 18.9 %, respectively. High vulnerability values characterize the coastline, in the Hel Peninsula and the northern part of the Kashubian Coastland. Increased aquifer vulnerability is also observed in glacial valleys. The low to moderate vulnerability areas are

presented in inland, where the influence of the sea decreases and natural hydrogeological protection of the aquifer increases.

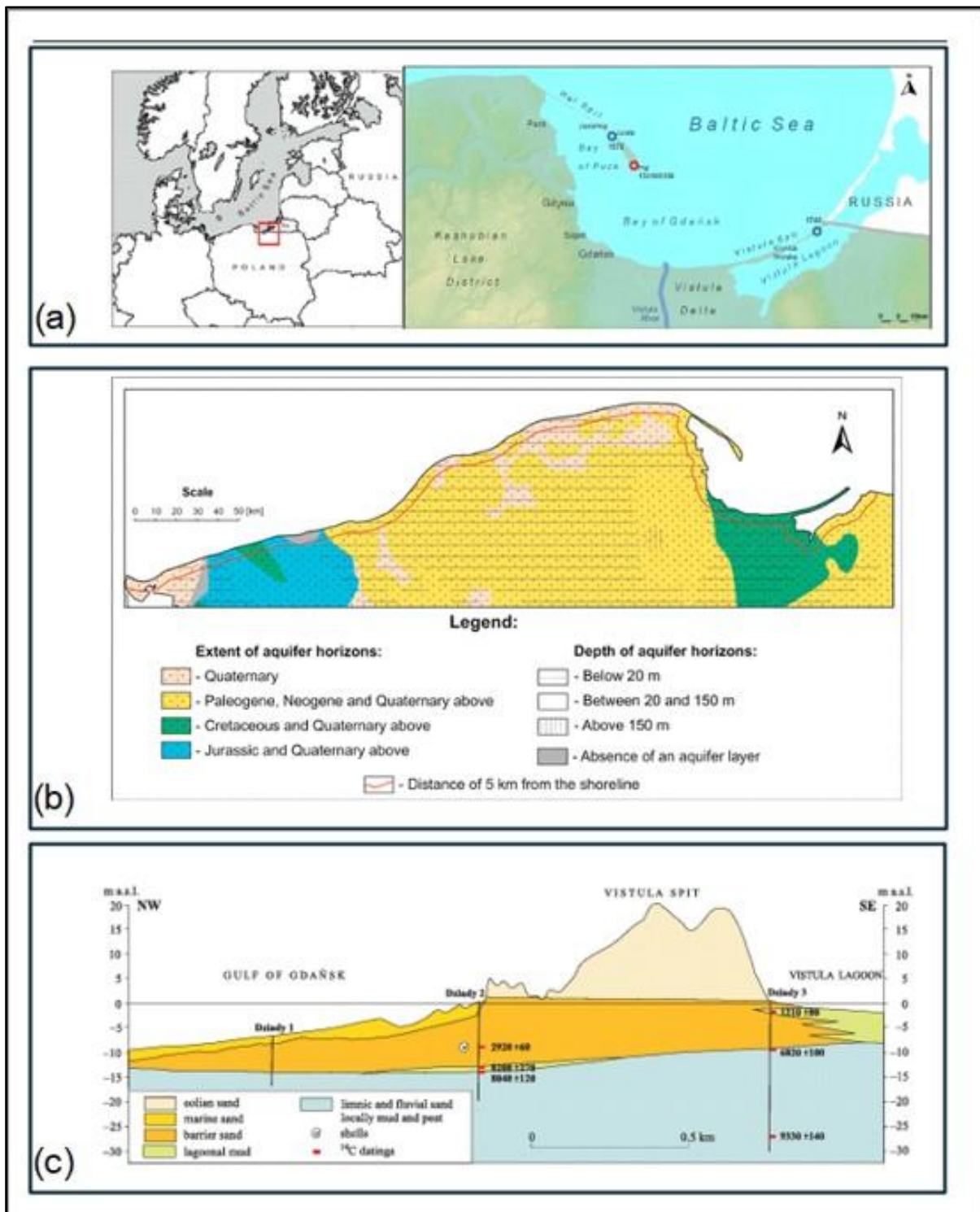


**Figure 11:** Comparison between GALDIT index for the current and future sea levels (Potrykus et al., 2018)

## 2.4 Vistula Spit (Poland)

The Vistula Spit is one of the largest sandbars along the southern Baltic coast. It extends to approximately 90 km in total length, and has a width ranging from 0.7 to 2 km. The spit separates the Vistula Lagoon—characterized by brackish waters with salinity ranging from 0.2 to 7‰ (average ~3‰)—from the eastern part of the Gulf of Gdańsk, where salinity typically reaches 7–8‰, and it connects westward to the Vistula Delta (Fig. 12). The climate of the area is temperate and strongly influenced by maritime conditions. Observations from the Hel meteorological station indicate a mean annual air temperature of 8.1 °C for the period 1951–2015. According to the 1991–2020 climate normal, mean annual precipitation amounts to 598.1 mm. Snow cover is generally limited, persisting for an average of 39 days per year. The landscape is dominated by several generations of dune ridges, largely covered by pine forest (Mojski, 1995). The oldest dune forms are isolated, relatively high ridges (up to ~10 m), located at the greatest distance from the modern coastline. Moving seaward, these are followed by low aeolian ridges known as “brown dunes,” situated approximately 2 km inland from the present shoreline. These dunes have a sub-latitudinal orientation and are characterised by well-developed ferruginised podzolic soils. Closer to the coast,

a group of younger, high dunes (>30 m) forms the so-called “yellow dunes,” which contain deep deflation depressions and weakly developed soils. The youngest dune forms are the modern avandunes and dune bars (“white dunes”), which are oriented parallel to the present coastline and lack soil cover (Uścińowicz et al., 2021). The upper part of the Holocene sedimentary succession is composed mainly of marine (barrier) and aeolian sands, with locally developed peat layers formed within interdune depressions (Uścińowicz et al., 2021). The base of the aeolian deposits occurs at least 2 m below present sea level (Badyukova et al., 2011), while the barrier sands are predominantly medium- to fine-grained, with locally occurring coarse-grained fractions (Uścińowicz et al., 2021). The oldest Pleistocene deposits consist of glacial tills, glaciofluvial sands and gravels, and clayey sediments of ice-marginal lakes. Sediments from the Eemian Interglacial comprise fine- and medium-grained marine sands with thicknesses reaching up to 30 m. Deposits related to the Vistulian glaciation—mainly sands and gravels—are preserved only locally and are of limited thickness. Following ice-sheet retreat, fluvial and lacustrine sediments, and locally peat, were deposited. Pre-Quaternary strata consist mainly of Upper Cretaceous (Campanian) and Eocene–Oligocene marine deposits, while small patches of Miocene limnic and fluvial sediments occur locally in the western part of the study area near Gdańsk. After postglacial glacio-isostatic rebound, the area is tectonically relatively stable (Uścińowicz, 2003), with present-day vertical crustal movements along the southern and south-eastern Baltic coast ranging between 0 and  $-1$  mm/yr (Uścińowicz et al., 2021). Hydrogeologically, the spit hosts a shallow, unconfined Quaternary sandy aquifer resting on low-permeability sediments at depths of approximately 40 m below mean sea level. The water table depth ranges from about 1.4 m below ground level (b.g.l.) in low-lying areas to as much as 24 m b.g.l. beneath dune ridges (Gumuła-Kawęcka et al., 2024). The aquifer exhibits filtration coefficients between 0.3 and 1.1 m/h (7.2–26.4 m/d) (Winid & Maruta, 2025). Recharge occurs exclusively through precipitation, rendering the aquifer highly sensitive to climatic variability. Groundwater flows towards and discharges into both the eastern Gulf of Gdańsk and the Vistula Lagoon. Groundwater abstraction from the spit aquifer supplies the municipality of Krynica Morska, which has a permanent population of approximately 1,284 inhabitants but experiences markedly increased water demand during the summer tourist season. Groundwater intake rates range between 30 and 50 m<sup>3</sup>/h (Gumuła-Kawęcka et al., 2024), with a long-term average extraction of about 1,600 m<sup>3</sup>/day (Krawiec, 2021).

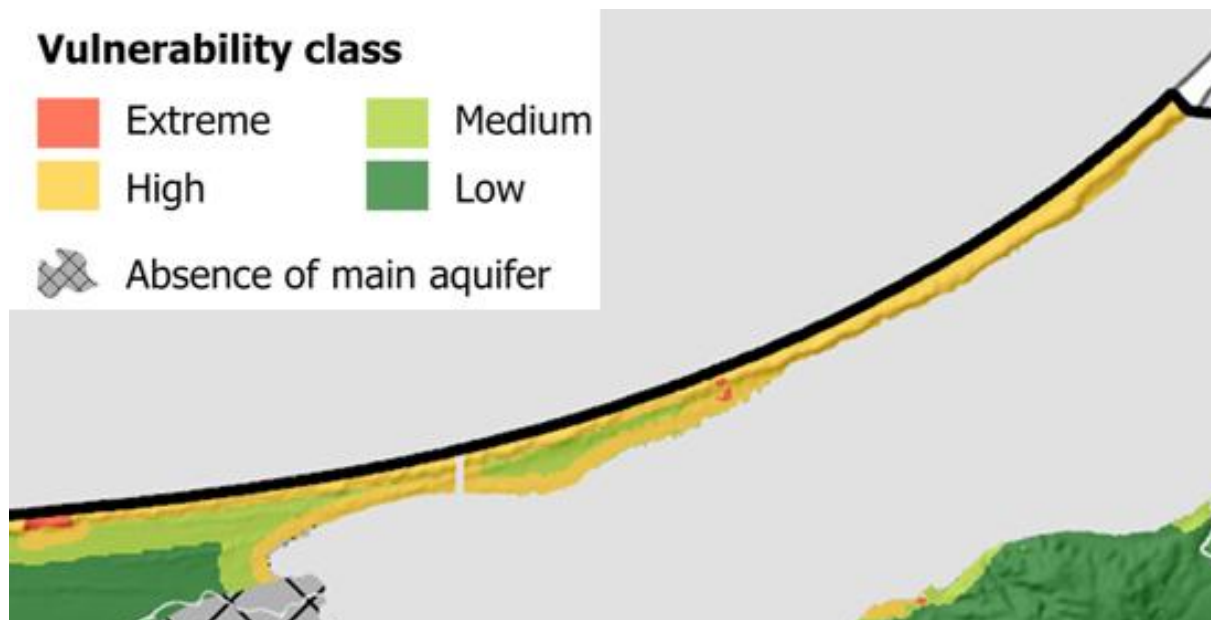


**Figure 12:** Vistula spit overview. (a) location of the study area, (b) the main usable aquifers in the Polish part of the Baltic coast, and (c) cross-section. The figures were retrieved from Gumuła-Kawęcka et al. 2025 (a), Winid & Maruta 2025 (b), and Uścińowicz 2003 (c)

Due to generally low hydraulic heads in the exploited aquifer, often exacerbated by intensive pumping, freshwater resources on the Vistula Spit are highly vulnerable to seawater intrusion (Gumuła-Kawęcka et al., 2024). Climate change projections for the 21st century indicate increasing precipitation totals and a significant rise in air temperature, leading to enhanced evapotranspiration. Tide-gauge measurements from the Hel station reveal a pronounced sea-level rise trend of approximately 8 mm/yr. Along the southern Baltic coast, where subsidence related to glacial isostatic adjustment persists, relative sea-level rise is therefore higher than the global average, further increasing the vulnerability of the Vistula Spit aquifer system (Gumuła-Kawęcka et al., 2024).

Two overlay index methods were developed: the INTRUSFLD method, tailored to determine the vulnerability of the shallow aquifer (the first aquifer below the ground surface) to seawater intrusion resulting from coastal flooding and the INTRUSEXPL method to assess the vulnerability of the main (exploited) aquifer to seawater intrusion, considering groundwater pumping. An overlay index structure has been used in both cases assigning ratings and weights to several representative factors. All the analysis were processed using GIS tools.

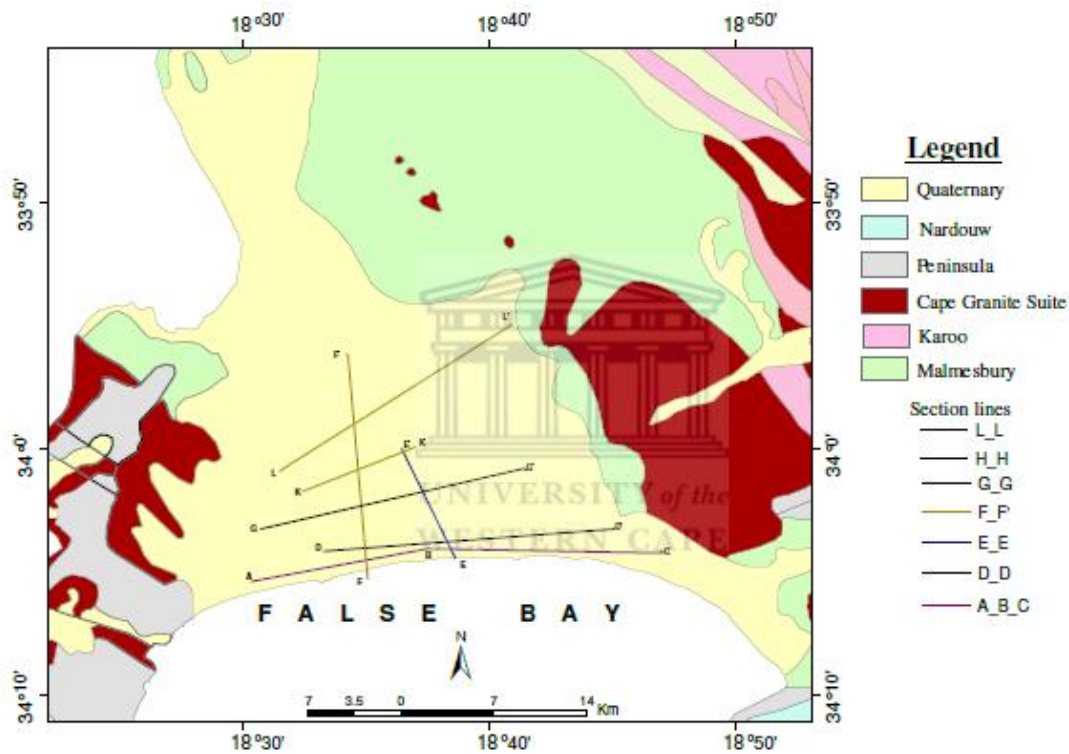
The results show significant heterogeneity in groundwater vulnerability to seawater intrusion in the Polish coastal area. Approximately 807 km<sup>2</sup> of coastal aquifers were found to be highly vulnerable to seawater flooding, and approximately 496 km<sup>2</sup> are highly vulnerable due to groundwater extraction



**Figure 13:** INTRUSFLD method developed to assess SWI in Vistula Spit (Potrykus et al. 2025).

## 2.5 Cape Flats (South Africa)

The Cape Flats are in south-western South Africa, between False Bay to the south and the Tygerberg range to the north and cover an area of approximately 450 km<sup>2</sup>. They are found within quaternary catchments G22C, G22D and G22E (Berg-Olifants Water Management Area) with a topography typical of coastal plain and dune fields. The climate is Mediterranean with wet winters and dry summers. The mean annual rainfall ranges between approximately 600-650 mm, occurring mainly during the winter months, while summers are warm and dry.



**Figure 14:** Geological map of the area around the Cape Flats. (Adelana et al., 2010)

The Cape Flats Aquifer consists of fluvial, marine and aeolian Quaternary sedimentary deposits of the Sandveld Group (Fig. 14). These sediments reach a maximum thickness of about 55 m, underlain by low-permeability basement rocks of the Malmesbury Group and the Cape Granite Suite. The unconfined Witzand formation and the semi-confined Springfontyn formation dominate the area with localized occurrences of calcrete and peaty clay lenses. Groundwater flows from NE to SW and discharges into False Bay. The groundwater table is shallow (2-4 m), which often causes flooding during the winter season. Groundwater chemistry is dominated by Na-Cl and Ca-Cl to calcium-alkaline with EC and pH values ranging from about 40 to 125 mS/m and from 5.8 to 8.4, respectively. High NO<sub>3</sub><sup>-</sup> concentrations are observed locally in parts of the Cape Flats aquifer, mainly in shallow groundwater, reflecting the influence of agricultural activities, and urban land use. This confirms the vulnerability of the unconfined aquifer to surface-derived

contamination, in intensively cultivated and urbanized areas. Groundwater quality in the Cape Flats is also locally influenced by salinity. Chloride ( $\text{Cl}^-$ ) concentrations show that aquifer's resources meet the WHO drinking water guideline of 250 mg/L, primarily in the north and along the dune sand in areas of the southwest. However, higher  $\text{Cl}^-$  concentrations occur in specific locations, mainly along the coastline and near selected sites. The accumulation of salts in the Cape Flats was due to the agricultural activities, the evaporation process from the open water bodies (pond waters) and the natural movement of groundwater through the geological formation of the area, with high  $\text{Cl}^-$  concentrations associated with human activities such as waste disposal, industrial and agricultural practices, while current studies showed only a limited role of widespread inland seawater intrusion (Adelana et al., 2010). The land cover is dominated by agriculture (Philippi Horticultural Area, PHA) and urban areas (residential, industrial, business), with grassland covered sand dunes and sand mining. Groundwater is the main source of irrigation water to PHA, especially in the dry season, and the biggest water user of the Cape Flats Aquifer. Nonetheless the PHA is an important part of the City of Cape Town's food security with approximately 64% of land being used for food production by 30 active farmers. As a result of high spatial-temporal variability of rainfall and resulting diminishing surface water bodies, the City of Cape Town is looking to augment its municipal water supply with groundwater (Adelana et al., 2010) through managed aquifer recharge and maintenance of storm water basins. Groundwater has been used by schools and hospitals for irrigation of sports grounds, and the locals also find well-points a cheaper alternative to municipal water supply. For this reason, it is critical that this aquifer's integrity be maintained to ensure its sustainable use. Another dynamic to the problem is that climatic changes and variability could potentially add more stress to the groundwater resource by reducing the much-needed rainfall recharge which helps in diluting salinity. The proximity of the ocean exacerbates the risk of salinization as it may result in seawater intrusion if groundwater levels are lowered due to increased abstraction and reduced recharge. The reduction in water quality will not only impact farmers but also residents and it will increase remediation costs if intended to be used by the City of Cape Town for water supply augmentation. A vulnerability assessment was carried out using DRASTIC-L and DRASTL (Hunink et al., 2024). The Cape Flats aquifer underlying the southern and central suburbs, towards Cape Town CBD has been classified as high on the vulnerability index. The analysis of the vulnerability maps (Fig. 15a and 15b) indicates that the areas of high vulnerability predominate in the central part of the study area, while the surrounding high-elevation areas are characterized by moderate-low vulnerability. The areas, where vulnerability is higher than average, are associated with shallow groundwater levels, porous aquifer media, sandy soils, shallow slopes, a permeable vadose zone, and high-risk land use types (Hunink et al., 2024). In contrast, the moderate to low vulnerability surrounding the

Cape Flats Aquifer (CFA) is mainly linked to a deeper water table, crystalline aquifer media, fine-grained soils, steep slopes, a low permeability vadose zone, and moderate to low-risk land use types. Based on its hydrogeological conditions and land-use characteristics, the CFA exhibits significant vulnerability to groundwater contamination. Shallow groundwater levels in unconfined sandy aquifers, combined with intensive agricultural and urban activities, provide the basis for the application of the Automated DATASET Index (ADI) for agricultural leaching and salinization, the results of which are presented in the following section.

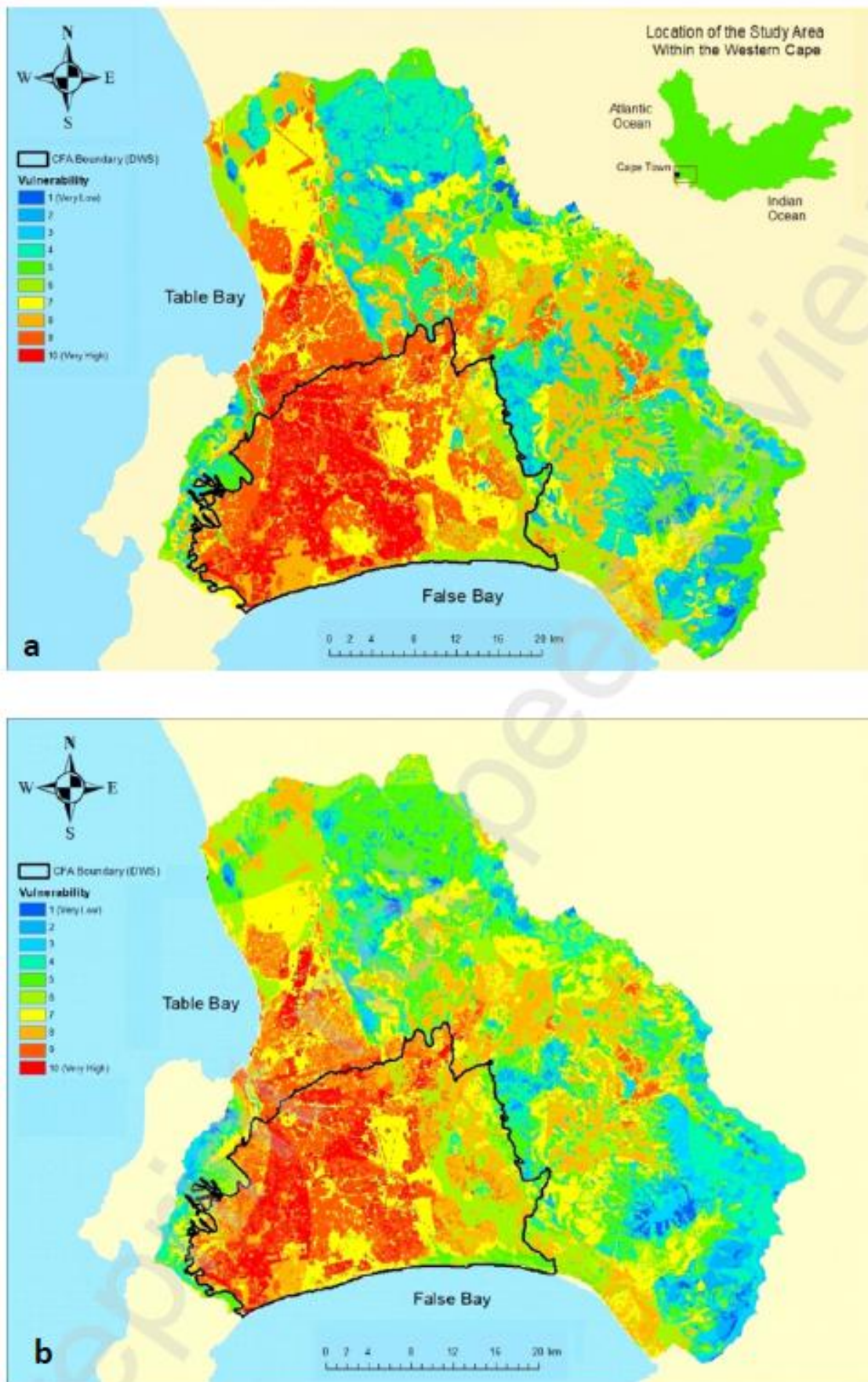
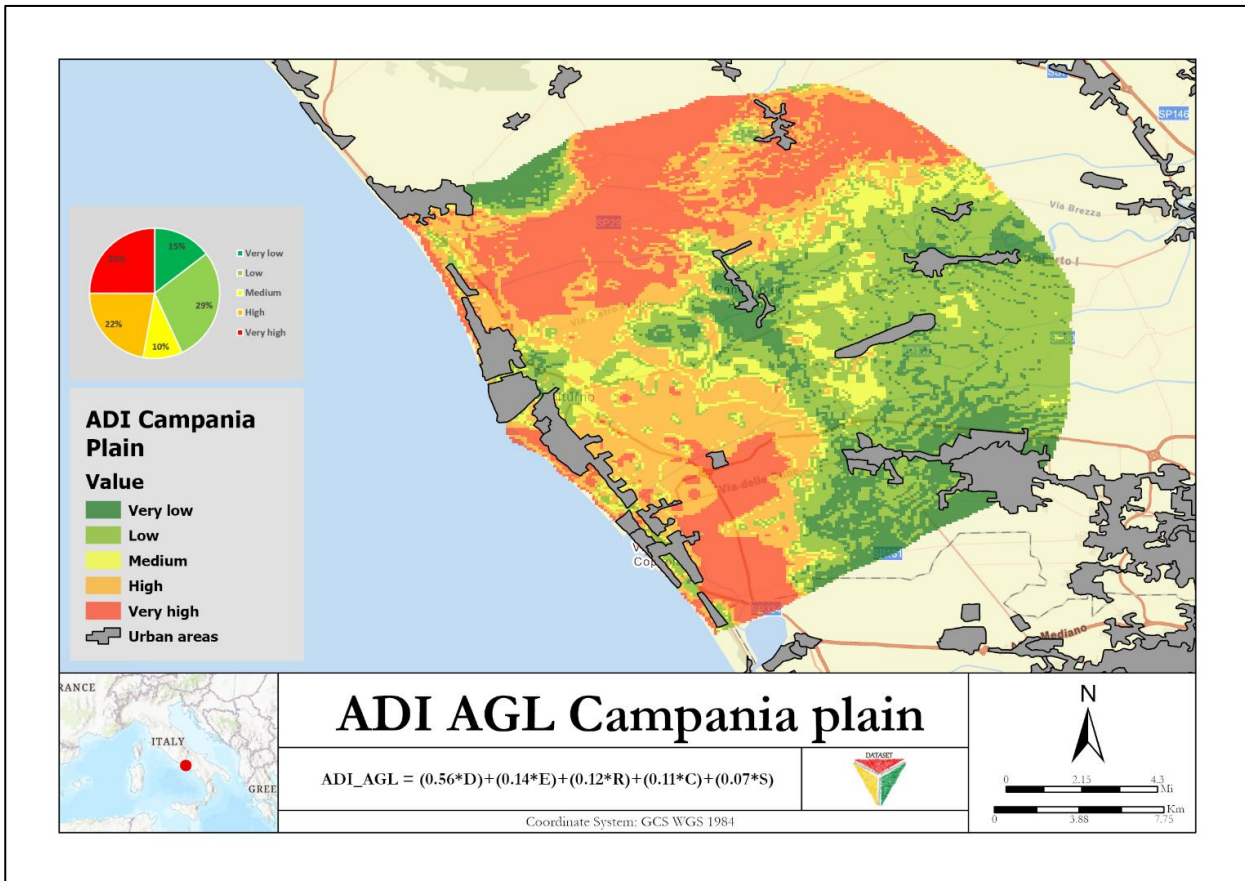


Figure 15: Aquifer vulnerability map of the Cape Flats: a) DRASTIC-L, and b) DRASTL (Hunink et al. 2024)

### 3 ADI results - Agricultural Leaching and Salinization Processes

This section presents the results of the Automated DATASET Index (ADI) for groundwater vulnerability to agricultural leaching (AGL) and salinization processes (SP) for the pilot sites.

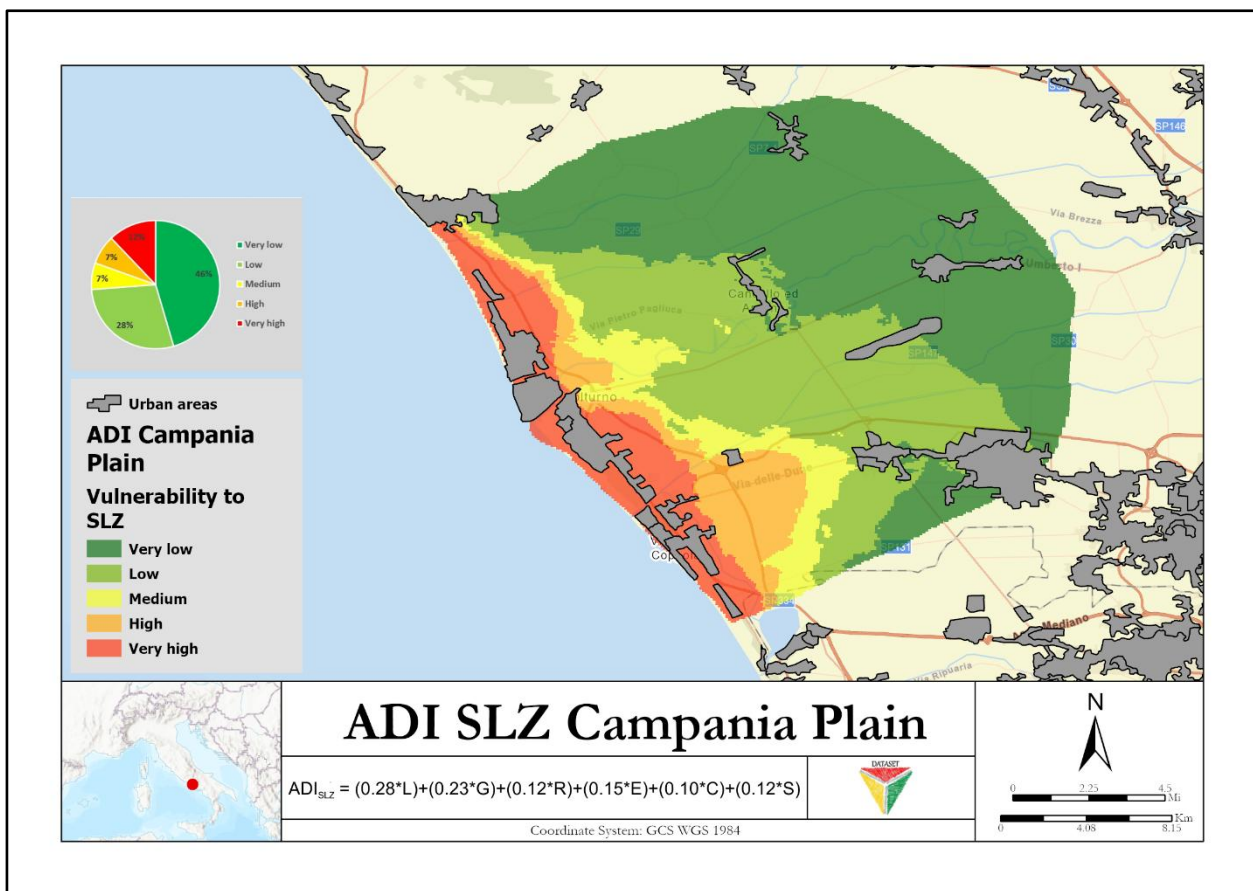
#### 3.1 Campania Plain (Italy)



**Figure 16:** ADI Index groundwater vulnerability map to agricultural leaching (AGL) for the Campania Plain.

The ADI results for groundwater vulnerability to AGL in the Campania plain are mainly controlled by aquifer type, depth to groundwater, and recharge conditions (Fig. 16). The high and very high vulnerability classes are observed in the central and coastal areas of the plain, where shallow groundwater levels coincide with permeable volcanic and alluvial deposits. These conditions favor the migration of  $\text{NO}_3^-$  from the soil zone to groundwater. The low and very low vulnerability classes mainly occur where finer-grained sediments (such as clay and peat-rich deposits) are present. According to the ADI vulnerability assessment, very low vulnerability areas cover 15% of the Campania plain, while low vulnerability zones account for 29%. Medium vulnerability represents 10% of the pilot site, whereas high and very high vulnerability classes cover 22% and 25%, respectively, indicating a susceptibility of groundwater to agricultural leaching processes.

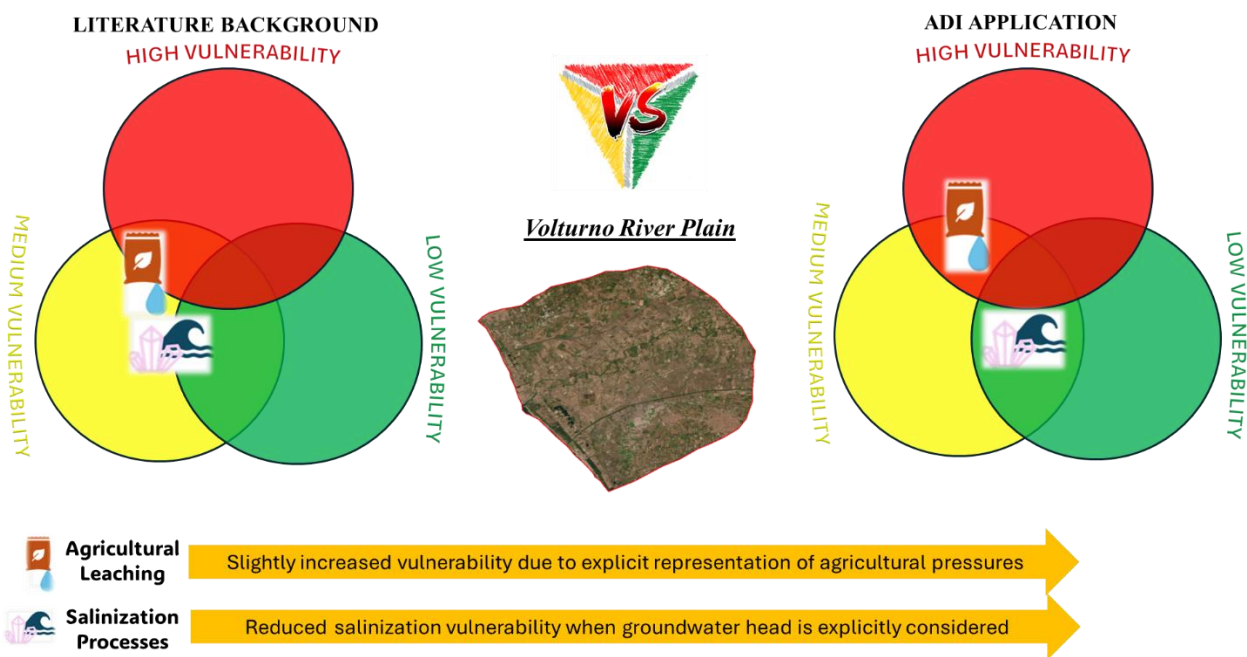
Overall, the high proportion of high vulnerability percentages in Campania Plain indicates a susceptibility of groundwater to agricultural leaching. The comparison between the ADI vulnerability map for AGL and the SINTACS results from previous studies shows a high degree of agreement. Both approaches classify the central and coastal areas of the Campania Plain as areas of high to very high vulnerability where areas are characterized by shallow groundwater levels, high hydraulic conductivity, and intense human activities. In contrast, lower vulnerability is related to less permeable deposits, and thicker vadose zones. Minor differences between the two assessments are related to the differences in parameter selection and weighting schemes. The similarity in vulnerability maps supports the reliability of the ADI vulnerability assessment for the Campania Plain.



**Figure 17:** ADI Index groundwater vulnerability map to salinization (SLZ) for the Campania Plain.

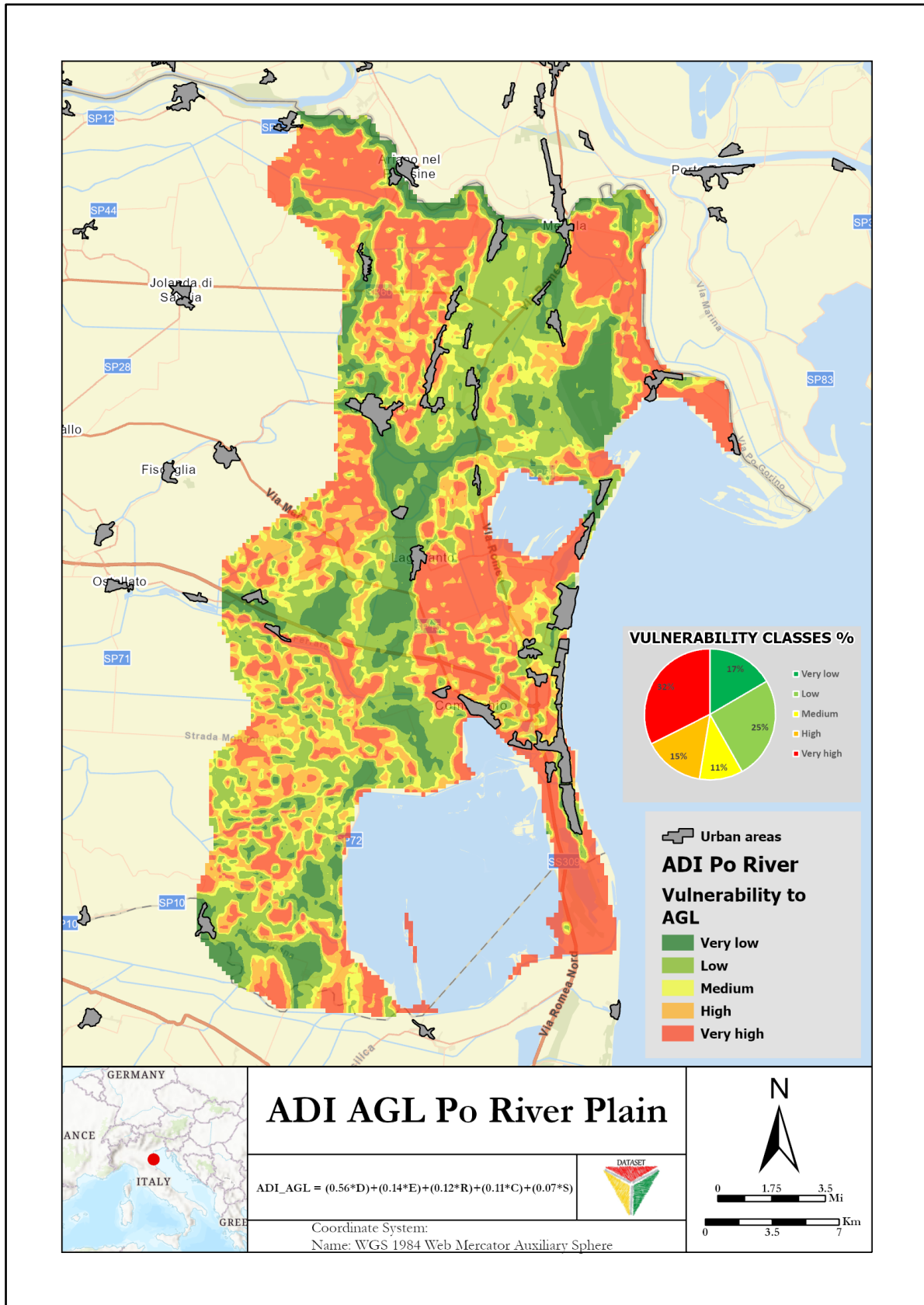
The ADI results for groundwater vulnerability to SLZ indicate that salinization vulnerability in the Campania Plain is influenced by distance from the coastline, groundwater depth, and local hydrogeological conditions (Fig. 17). Most of the area is characterized with very low to low vulnerability, where the aquifer is naturally better protected due to higher groundwater levels and reduced influence of seawater intrusion. The index also identifies some areas characterized by high

vulnerability more inland due to process of paleo seawater upconing (Schiavo et al., 2023). Very low vulnerability covers 46% of the plain, while low vulnerability areas account for 28%. Medium vulnerability represents only 7% of the pilot site. In contrast, high and very high salinization vulnerability is presented in coastal zone and to river mouths, where shallow groundwater levels, low elevations, and direct hydraulic interaction with the sea favor salinity intrusion. These higher vulnerability classes together account for 19% of the plain (7% high and 12% very high). The comparison between the ADI vulnerability map for SLZ and results from previous studies based on the GALDIT-SUSI methodology shows a high degree of agreement. Both approaches classify as highly vulnerable the coastal zone and the mouth of the Volturno, Agnena, and Regi Lagni rivers, while as low to very low the inland areas. Minor differences between AGL and SLZ are related to the different weighting of parameters. The similarity in vulnerability maps supports the reliability of the ADI vulnerability assessment for the Campania Plain. Figure 18 summarizes the conceptual comparison between literature-based and ADI-based vulnerability assessments for the Campania Plain.



**Figure 18:** Conceptual comparison of literature-based and ADI-based vulnerability assessment for the Campania Plain

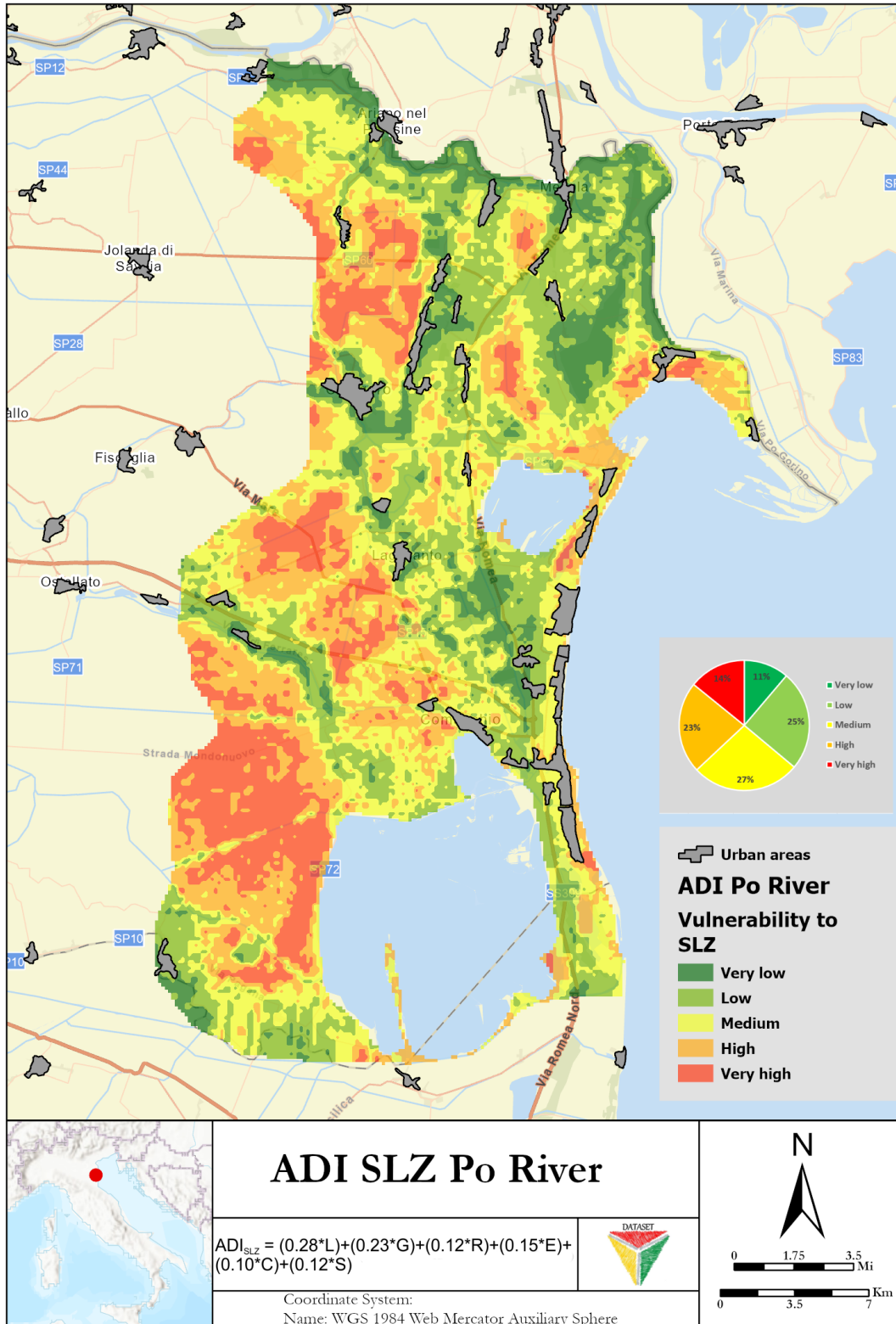
### 3.2 Po Delta Plain (Italy)



**Figure 19:** ADI Index groundwater vulnerability map to agricultural leaching (AGL) for the Po Delta Plain.

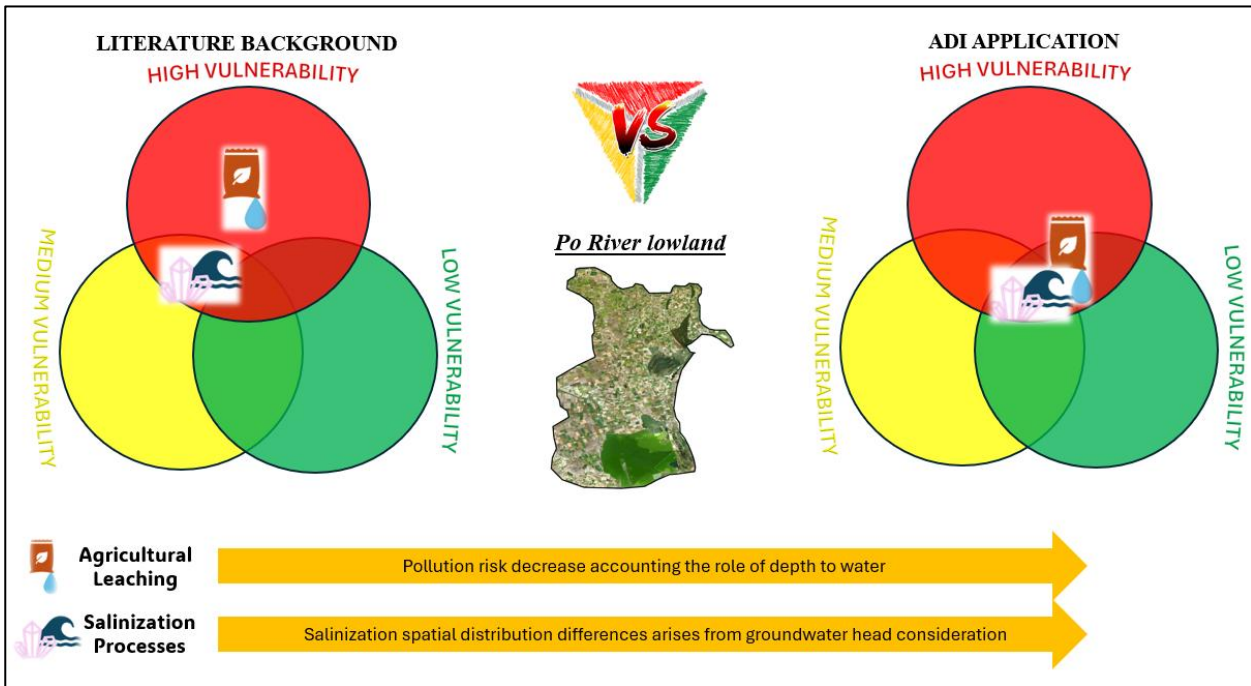
As shown in Figure 19, agricultural leaching vulnerability classes in the Po River Delta are mainly controlled by soil type, which determines hydraulic conductivity, and by depth to water. Accordingly, near the coastline, the high Vulnerability class occurs predominantly in fine sands and dune deposits combined with shallow water table. Across the rest of the territory, high vulnerability is also observed in medium and fine sands, and part of its spatial extent can be attributed to the presence of depressed areas. Those areas also explain the occurrence of the high vulnerability class farther inland. The medium vulnerability class is limited to 11% of the study area. The remaining territory corresponds to the low vulnerability (25%) and very low vulnerability (17%) classes, which mainly occur in silty clay deposits combined with medium depths to groundwater. The ADI-AGL vulnerability assessment for the Po River Lowland indicates that 47% of the study area falls within the highest vulnerability classes (Very High and High), compared to more than 70% reported in the vulnerability map for nitrogen loss through percolation in Ferrara Province by Aschonitis et al. (2013). This discrepancy arises because the latter map represents the potential for nitrogen percolation from the surface to the subsurface, rather than the intrinsic vulnerability of the aquifer itself. Consequently, it does not account for depth to groundwater, which represents more than 50% of the weighting in the ADI-AGL index.

Figure 20 presents the vulnerability to salinization processes assessment in the Po River lowland based on the ADI index. The Very High and High vulnerability classes extend to over 14% and 23% of the territory, respectively, while 27% corresponds to the medium vulnerability class. Finally, the Very Low and Low vulnerability classes cover 11% and 25% of the study area, respectively. The spatial distribution of vulnerability classes is mainly controlled by groundwater head and distance from saline and freshwater sources. The highest vulnerability classes occupy a coastal strip approximately 3 km wide, parallel to the shoreline. In addition, a substantial portion of these classes extend inland over depressed areas characterized by negative groundwater heads (down to  $-8$  m a.s.l.). The distribution of the lower vulnerability classes is mainly explained by soil properties and hydraulic conductivity.



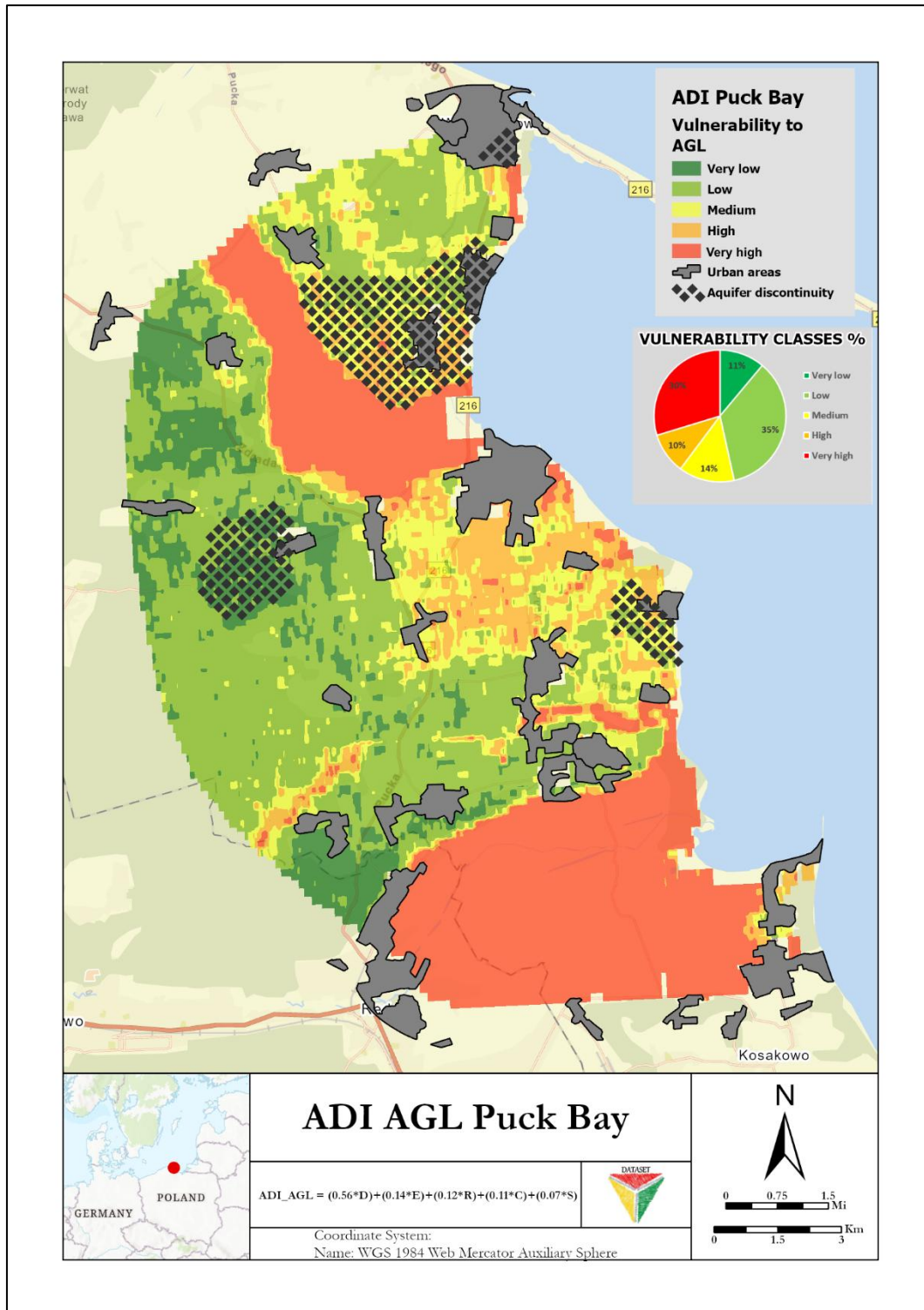
**Figure 20: ADI Index groundwater vulnerability map to salinization (SLZ) for the Po Delta Plain**

A comparison between the ADI-SLZ results and the previous study by Kazakis et al. (2019) shows good agreement in terms of the areal extent of vulnerability classes (Fig. 21). In both studies, the coastal zone up to 3 km inland is classified as Very High and High vulnerability. However, the occurrence of these classes farther inland is more limited in Kazakis et al. (2019). In contrast, the ADI-SLZ assessment identifies a larger inland extent affected by Very High and High vulnerability classes, corresponding to depressed areas and primarily explained by very low groundwater heads below sea level (down to  $-8$  m a.s.l.).



**Figure 21:** Conceptual comparison of literature-based and ADI-based vulnerability assessment for the Po River Lowland

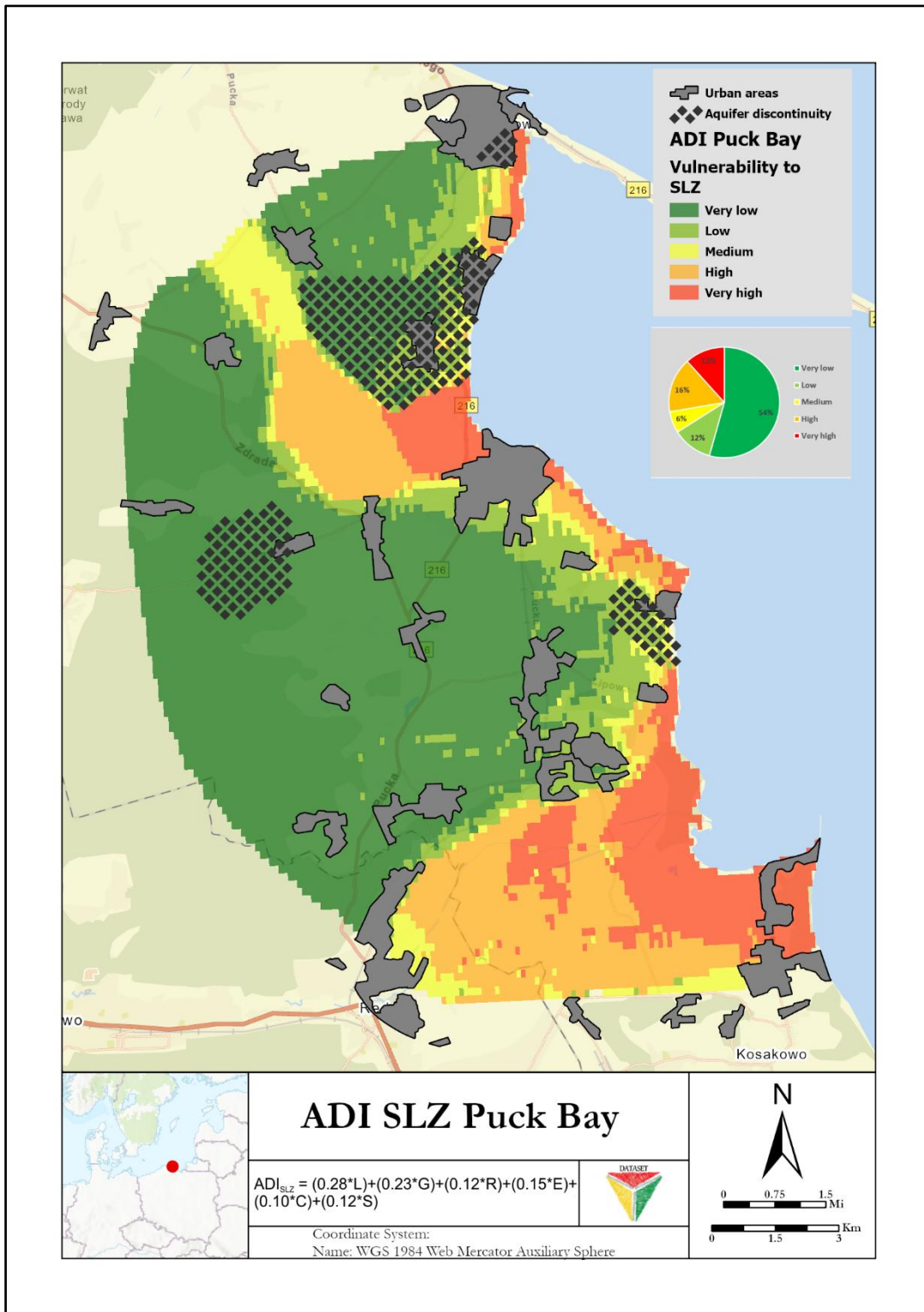
### 3.3 Puck Bay Catchment (Poland)



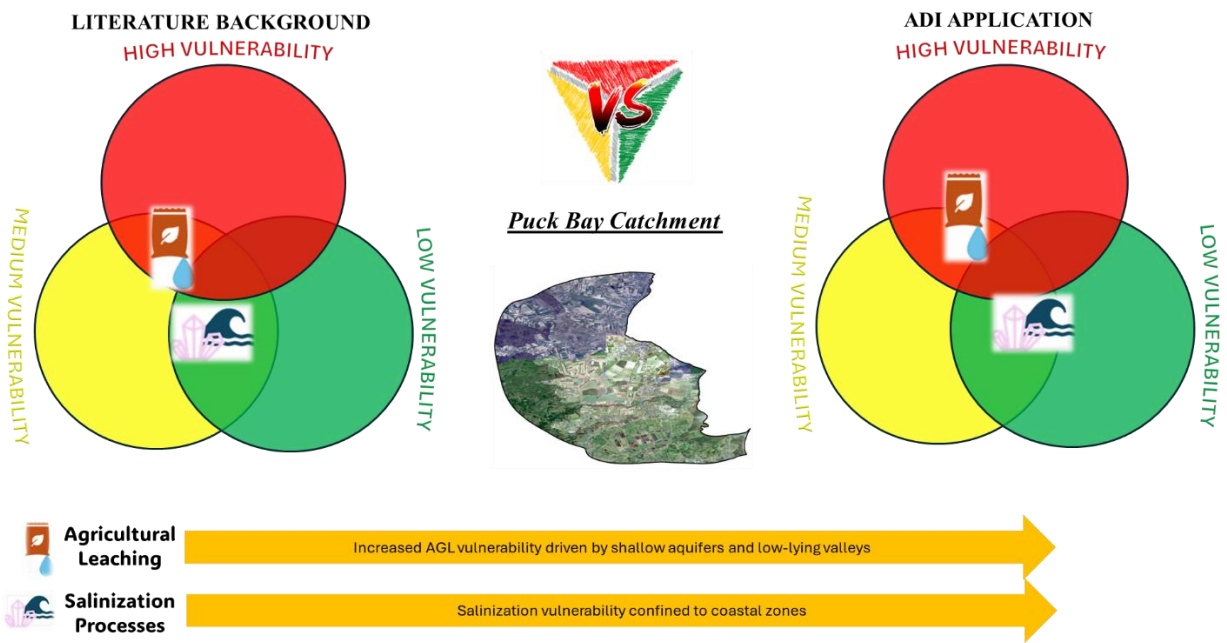
**Figure 22:** ADI Index groundwater vulnerability map to agricultural leaching (AGL) for the Puck Bay Catchment

As shown in Figure 22, agricultural leaching vulnerability classes in the Puck Bay catchment are mainly controlled by the presence of shallow unconfined aquifers, depth to groundwater, and the contrast between moraine uplands and low-lying ice-marginal valleys. High and very high

vulnerability classes are observed in coastal and low-lying areas, where shallow unconfined aquifers hosted in permeable sandy and glaciofluvial deposits favour the migration of nitrates from the unsaturated zone to groundwater. Low and very low vulnerability classes mainly occur in areas characterized by thicker unsaturated zones and the presence of low-permeability moraine deposits. According to the ADI vulnerability assessment, very low vulnerability areas account for 11% of the catchment, while low vulnerability zones represent 35%. Medium vulnerability covers 14% of the study area, whereas high and very high vulnerability classes account for 10% and 30%, respectively. Overall, about 40% of the Puck Bay catchment falls within high to very high vulnerability classes, indicating a susceptibility of groundwater to agricultural leaching. The comparison between the ADI vulnerability map for AGL and DRASTIC-SWAT results from previous studies shows a good degree of agreement. Both approaches identify coastal and low-lying areas as high to very high vulnerability areas, where shallow unconfined aquifers and permeable sandy and glaciofluvial deposits prevail. On the other hand, lower vulnerability classes are associated with moraine uplands characterized by thicker unsaturated zones and low-permeability deposits. Overall, the similarity of the spatial vulnerability patterns supports the reliability of the ADI vulnerability assessment for the Puck Bay catchment, while minor differences between the two assessments are related to the differences in parameter selection and weighting schemes. The ADI results for groundwater vulnerability to salinization in the Puck Bay catchment show that high and very high vulnerability classes span the coastal zone, where shallow groundwater levels and highly permeable sandy deposits facilitate seawater intrusion (Fig. 23). In inland, salinization vulnerability decreases, with most of the area characterized by very low to low vulnerability. According to the ADI classification, very low vulnerability accounts for 54% of the catchment, while low vulnerability represents 12%. Medium vulnerability accounts for 6% of the pilot site and occurs in areas between the coastal zone and the inland part of the catchment. In contrast, high and very high vulnerability together cover 28% of the study area (16% high and 12% very high), indicating that salinization vulnerability in the Puck Bay catchment is confined to coastal areas rather than across the region. The comparison between the ADI vulnerability map for salinization (SLZ) and results from previous studies based on the GALDIT methodology shows a good degree of agreement. Both approaches identify the coastal zone of the Puck Bay catchment as an area of high to very high vulnerability in Hel Peninsula and northern part of the Kashubian Coastland. The lower vulnerability classes are observed inland, where increased distance from the coastline, higher elevation, and reduced marine influence provide greater natural protection. The agreement of the spatial vulnerability distribution supports the reliability of the ADI SLZ vulnerability assessment for the Puck Bay catchment, while minor differences between the two assessments are related to differences in parameter selection and weighting schemes.

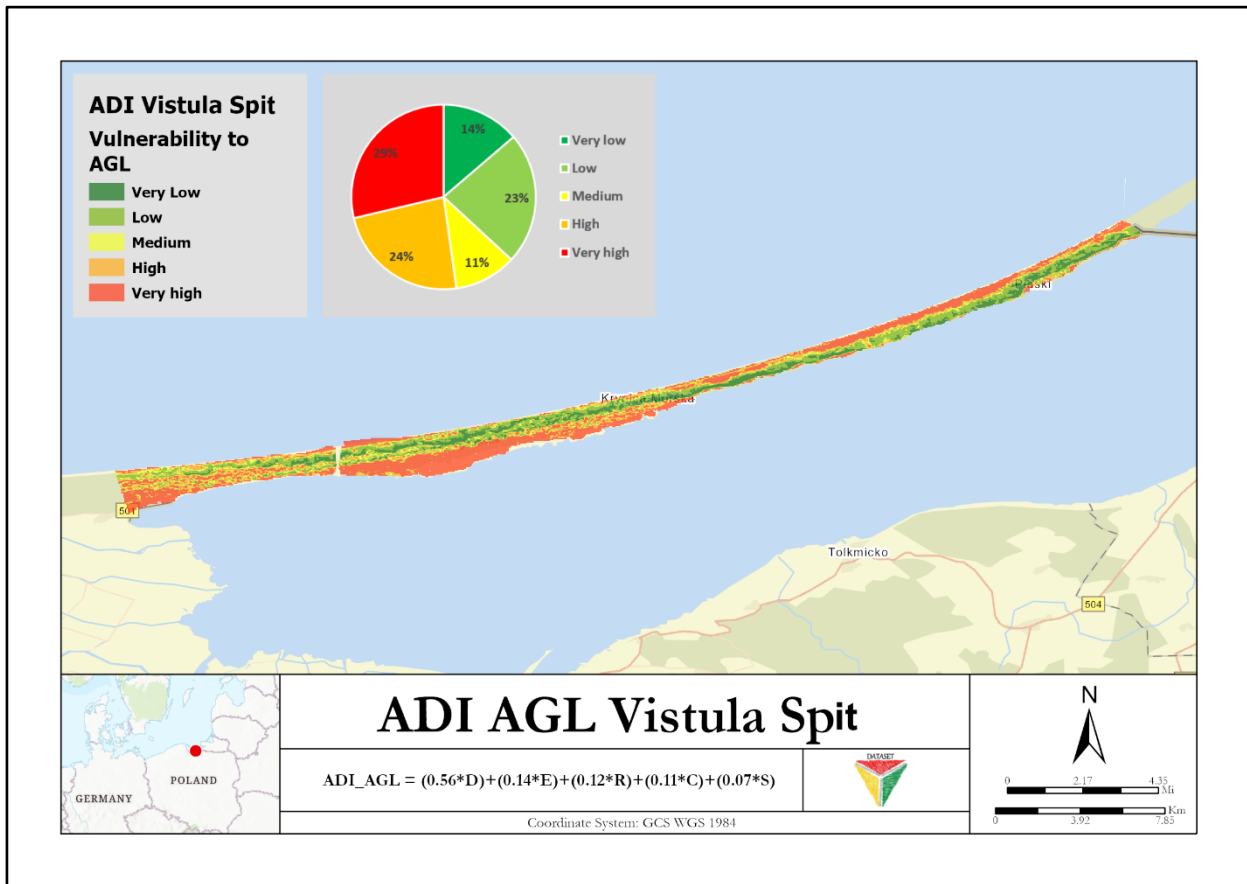


**Figure 23:** ADI Index groundwater vulnerability map to salinization (SLZ) for the Puck Bay Catchment



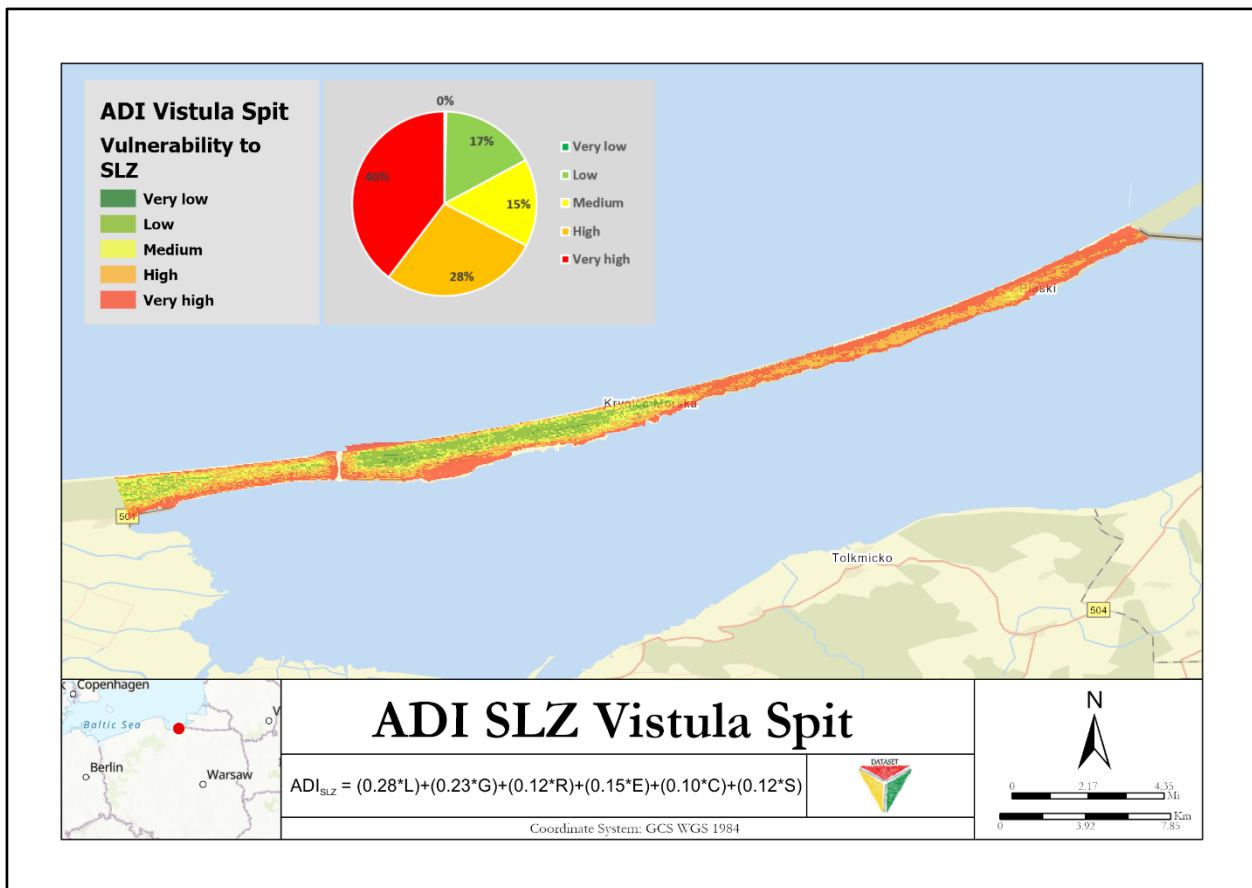
**Figure 24:** Conceptual comparison of literature-based and ADI-based vulnerability assessment for the Puck Bay catchment

### 3.4 Vistula Spit (Poland)



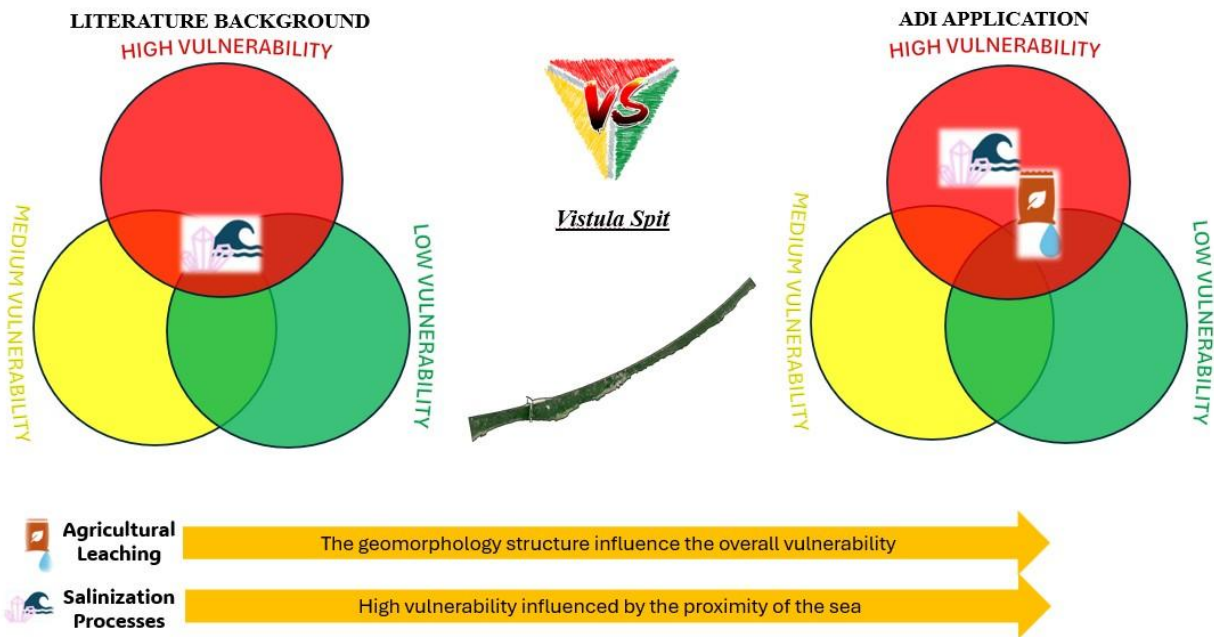
**Figure 25:** ADI Index groundwater vulnerability map to agricultural leaching (AGL) for the Vistula Spit

The distribution of vulnerability classes in Vistula Spit is broadly parallel to the shoreline (Fig. 25). The Very Low vulnerability class is mainly located in the central part of the spit. Moving seaward, it is followed by the Low and Medium vulnerability classes. Closer to the coastline, the High vulnerability class and, predominantly, the Very High vulnerability class occupies the largest extent. This spatial distribution mirrors the geomorphological structure of the Vistula Spit. The Very Low vulnerability class mainly corresponds to the oldest dune systems, which are relatively elevated (> 10 m) and where the depth to the water table is greatest (up to 24 m below ground level). The Low and Medium vulnerability classes are associated with low aeolian ridges (brown dunes). The Very High vulnerability class occurs in low-lying areas, where the depth to water is approximately 1.4 m below ground level. The presence of Very Low and Low vulnerability classes close to the coast, locally interspersed with High vulnerability spots, can be explained by the occurrence of yellow dunes (high dunes > 30 m) containing deep deflation depressions.



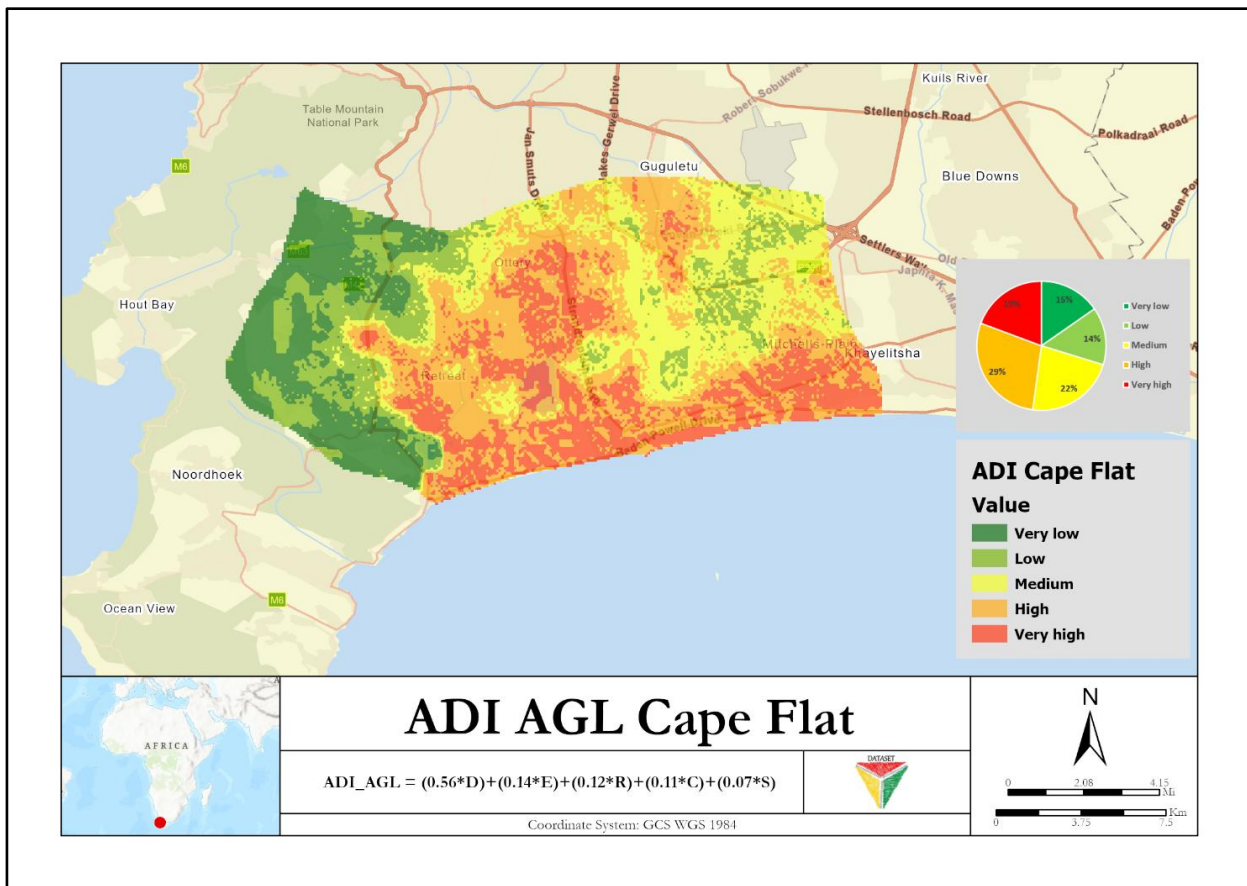
**Figure 26:** ADI Index groundwater vulnerability map to salinization processes (SP) for the Vistula Spit

The vulnerability assessment to salinization processes in Vistula Spit using the ADI index indicates that 40% of the territory falls within the Very High vulnerability class and 28% within the High vulnerability class (Fig. 26). The Very Low vulnerability class is not represented in the study area, while the areal extent of the Low vulnerability class is limited to 17%. The remaining 15% of the territory corresponds to the medium vulnerability class. The sandbar width ranges from 0.7 to 2 km and separates the brackish waters of the Vistula Lagoon from the Gulf of Gdańsk. This morphological setting explains why most of the study area (68%) is characterized by Very High to High vulnerability conditions and accounts for the absence of the Very Low vulnerability class. The Low vulnerability class is restricted to the central part of the widest sections of the spit (approximately 2 km wide), where the distance from saltwater sources is greater and elevation and groundwater heads are higher.



**Figure 27:** Conceptual comparison of literature-based and ADI-based vulnerability assessment for the Vistula Spit (to be completed depending on available literature).

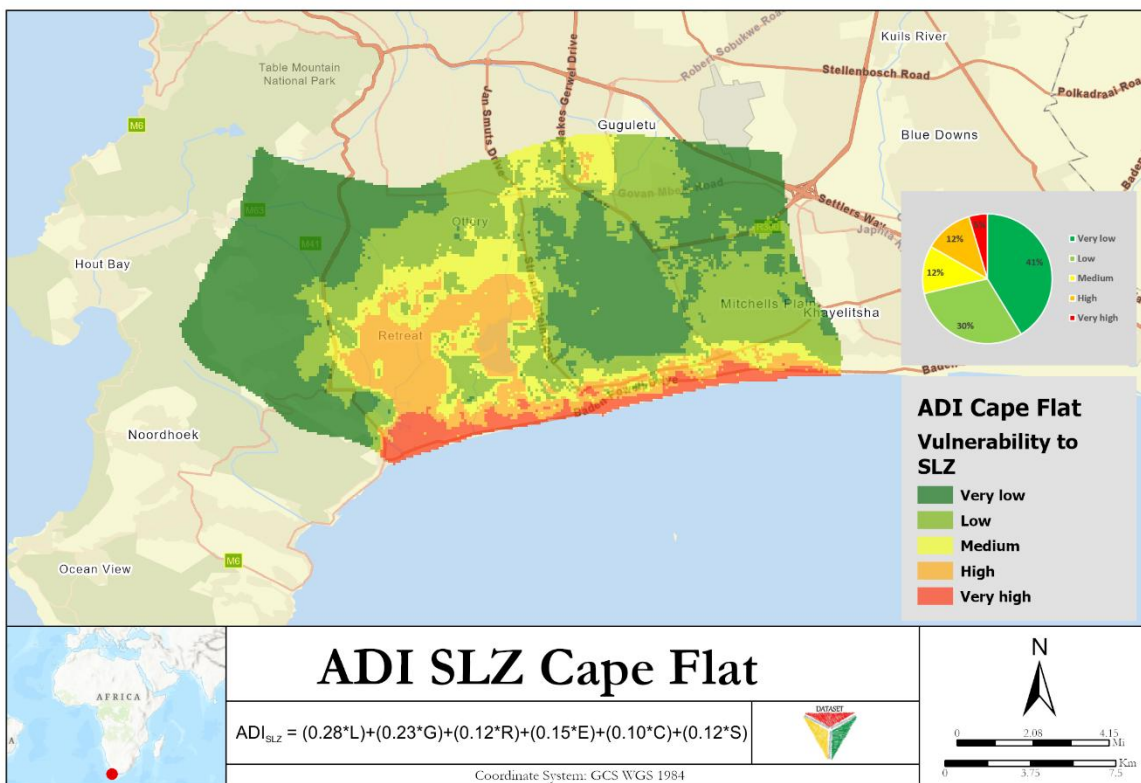
### 3.5 Cape Flats (South Africa)



**Figure 28:** ADI Index groundwater vulnerability map to agricultural leaching (AGL) for the Cape Flats

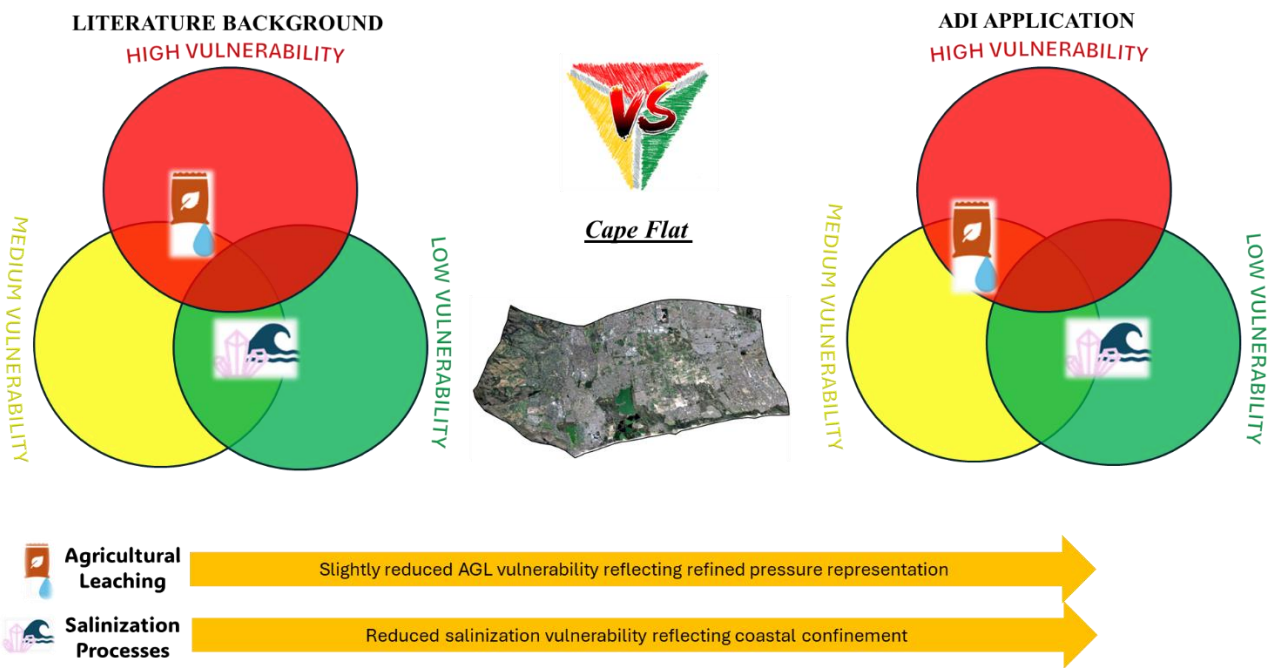
The ADI results for groundwater vulnerability to agricultural leaching in the Cape Flats Aquifer indicate that high and very high vulnerability classes are observed in the coastal zone and the central part of the pilot site, aligned with the land uses occurring in these area, where shallow unconfined sandy aquifers with shallow groundwater levels coincide with predominantly urban land use (Fig.27). According to the ADI classification, very high vulnerability accounts for 19% of the pilot site, while high vulnerability represents 29%, indicating that nearly half of the Cape Flats Aquifer (48%) is characterized by high susceptibility to agricultural leaching. Medium vulnerability covers 22% of the area and is observed in the central intensive agricultural area (PHA) and eastern parts of the pilot site. In contrast, low and very low vulnerability classes account for 14% and 15% of the study area, respectively, and are observed in the western part of the Cape Flats, which is a mountainous protected nature reserve of the Table Mountain range. A comparison between the ADI results for agricultural leaching and previous vulnerability assessments, using DRASTIC-L and DRASTL methods, shows a general agreement in the spatial distribution of groundwater vulnerability in Cape Flats Aquifer. All approaches identify the central part of the pilot site and the coastal zone as areas of high to very high vulnerability, associated with shallow

groundwater levels, unconfined sandy aquifers, high soil permeability, and predominantly urban land use. However, the DRASTIC-L and DRASTL assessments tend to classify a larger extent of the central and southern parts of the aquifer as high to very high vulnerability. In contrast, both the ADI results and the DRASTIC-based assessments indicate medium vulnerability conditions in the eastern part of the pilot site. The reason for the discrepancy could be explained through the interpretation of land use in the eastern part of the domain, to the south of Cape Town International airport. Although land use is not agricultural, these eastern parts in Fig. 28 are characterized by densely populated informal settlements, poor water and wastewater services, shallow groundwater (often <2 m) and flat topography, which renders them prone to flooding and high groundwater vulnerability. The eastern coastal strip in Fig. 28 is likely to be less vulnerable to agricultural pollution because it is characterized by rehabilitated sand dunes. However, groundwater monitoring data in these parts of the domain are too scarce to corroborate the assessment. The ADI results further distinguish areas of lower vulnerability mainly in the western part of the Cape Flats, where groundwater levels are relatively deeper and local hydrogeological conditions provide increased natural protection in the mountainous nature reserve. Minor differences between the assessments are related to differences in parameter selection and weighting schemes.



**Figure 28:** ADI Index groundwater vulnerability map to salinization (SLZ) for the Cape Flats

As shown in Figure 29, the ADI SLZ results indicate that salinization vulnerability in the Cape Flats aquifer is controlled by coastal proximity, groundwater depth, and local hydrogeological conditions. A large part of the pilot site (71%) is characterized by very low and low vulnerability, covering 41% and 30% of the aquifer, respectively, where inland location, dune sands, and higher groundwater levels provide natural protection against salinity intrusion. It can be noted in the map in Fig. 28 that the western high-lying areas of the Table Mountain National Park have very low vulnerability to seawater salinization. Likewise, in the central parts of the domain, the silhouette of the Zeekoevlei Lake is recognizable with low vulnerability due to the positive water pressure of the lake, as well as the PHA (very low vulnerability) where irrigation return flow on sandy soils may represent a barrier to seawater intrusion. Medium vulnerability represents 12% of the Cape Flats. The high and very high salinization vulnerability are observed in coastal and low-lying zones, where shallow groundwater levels and closer hydraulic interaction with the sea favor saltwater intrusion. The higher vulnerability classes together account for 17% of the aquifer (12% high and 5% very high). Past studies do not provide a salinization vulnerability map for the Cape Flats aquifer, but they offer a clear picture of the processes controlling groundwater salinity. These studies show that salinity is mainly confined to coastal areas, while inland zones are characterized by lower salinity levels, with the exception of localized areas where natural salts occur, clay lenses with low permeability and salts derived from urban sources. These results confirm the ADI SLZ results, which identify higher vulnerability along the coastline and low vulnerability inland. The agreement between the ADI results and the process-based evidence from the literature confirms the reliability of the ADI approach for assessing salinization vulnerability in the Cape Flats. Figure 30 summarizes the conceptual comparison between literature-based and ADI-based vulnerability assessments for the Cape Flats.



**Figure 29:** Conceptual comparison of literature-based and ADI-based vulnerability assessment for the Cape Flats

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