

Blaž Repe*, Tina Pavlin*



SUBAQUEOUS SOIL SEQUENCE IN MARINE WATERS OF THE STRUNJAN BAY

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Abstract

Soil research focuses mainly on soils on land, but the process of soil formation also takes place in shallow waters. Subaqueous soils form below the water surface, mainly on the bottom of shallow, stagnant waters such as bogs, swamps, lakes, and shoals in the sea. Three subaquatic soil profiles were investigated in the Strunjan Bay to study them in detail. The sites for the soil investigation were selected after observing the movement of seawater and thus its possible influence on subaquatic soils. All the soils studied are permanently and year-round under water. Therefore, all soil samples were collected under water using drainage pipes and by excavation. The samples were slowly drained in the pipes to prevent mixing of the material and to keep the horizons as intact as possible. Visual observations and standard analyses were carried out in the laboratory according to the identified horizons. During the investigation, we found that apart from water properties and movement, most soil-forming factors can be considered constant, so we investigated and presented a soil hydrosequence. According to the WRB classification, the subaqueous soils in the waters of the Strunjan Bay were divided into the reference groups Gleysols and Leptosols.

Keywords: soil geography, subaqueous soils, soil forming factors, WRB soil classification, the Strunjan Bay, Slovenia

⋮ * Department of Geography, Faculty of Arts, University of Ljubljana, Aškerčeva cesta 2,
⋮ SI-1000 Ljubljana, Slovenia
⋮ e-mail: blaz.repe@ff.uni-lj.si, tinkara.pavlin@gmail.com
⋮ ORCID: 0000-0002-5530-4840 (B. Repe)

GENETSKO ZAPOREDJE PODVODNIH PRSTI V STRUNJANSKEM ZALIVU

Izvleček

Raziskovanje prsti se v glavnem osredotoča predvsem na prsti na kopnem, vendar se pedogenetski procesi nastajanja prsti pojavljajo tudi v plitvih vodah. Podvodne prsti nastajajo pod vodno gladino, predvsem na dnu plitvih, stoječih voda, kot so barja, močvirja, jezera in morske plitvine. V Strunjanskem zalivu smo proučevali tri podvodne profile prsti z namenom, da bi jih podrobneje raziskali in predstavili. Lokacije za raziskavo prsti so bila izbrane glede na opazovanje gibanja morske vode in posledično njenega možnega vpliva na podvodne prsti. Vse proučevane prsti so stalno in vse leto pod vodo, zato so bili vsi vzorci tal zbrani pod vodo z drenažnimi cevmi in s pomočjo izkopa. Vzorce smo počasi izsušili v samih ceveh in s tem preprečili mešanje gradiva in ohranitev horizontov. V laboratoriju smo opravili vizualna opazovanja in standardne analize za vsakega od prepoznanih horizontov. Med raziskavo smo ugotovili, da lahko poleg lastnosti vode in njenega gibanja večino pedogenetskih dejavnikov smatramo za konstantne, zato smo proučili in predstavili pedogenetsko hidrosekvenco prsti. Podvodne prsti pod vodo Strunjanskega zaliva so bile po mednarodni WRB klasifikaciji prepoznane in uvrščene v referenčni skupini *Gleysols* in *Leptosols*.

Ključne besede: geografija prsti, podvodne prsti, pedogenetski dejavniki, WRB klasifikacija, Strunjanski zaliv, Slovenija

1 INTRODUCTION

Soil is an unconsolidated mineral or organic material on the immediate surface of the earth that serves as a natural medium for the growth of land plants (Gregorich et al., 2001). When we think of soils, we generally think of soils on land. Agricultural soils in particular are usually found on land, but soils also occur in shallow waters. Subaqueous soils form below the water table, especially at the bottom of shallow standing waters, e.g. in bogs, swamps and lakes (Bufon et al., 2005) and are very poorly studied. There are several reasons for this. Research (especially soil sampling) is extremely difficult, these soils have little economic value, and there are differing opinions as to whether this material is soil at all. Although some researchers (Goldschmidt, 1958; Kubiěna, 1953; Mückenhausen 1965) recognised this underwater material as soils as early as the middle of the last century, most researchers (geologists, biologists) consider them to be merely underwater sediments (Demas et al., 1996). The pioneering study of underwater material in the Maryland area (Demas, 1998) led to a change in definitions in soil taxonomy in 1999 (Payne, Turenne, 2009). The International WRB

Classification included subaqueous soils with the definition that *any material within 2 m from the Earth's surface that is in contact with the atmosphere, with the exclusion of living organisms, areas with continuous ice not covered by other material, and water bodies deeper than 2 m* (IUSS Working Group WRB, 2006).

In 1972 Folger (1972) described the primary factors that influence the composition and distribution of estuarine sediments. Together, therefore, the factors of Jenny and Folger form a (new) equation (Balduff, 2007):

$$p_e = f(p, cl, o, t, B, F, W, E) + H$$

in which subaqueous soils (p_s) are a function (f) soil forming factors: climate (cl), organisms (o), bathymetry (B), waterflow properties (F), parent material (p), time (t), chemical properties of water (W) and extreme events (E). The latter two factors were added later (Balduff, 2007) and human (H) influences were added separately. By examining the soils and the forming factors, we aimed to determine a hydrosequence. A soil hydrosequence refers to a series or sequence of soils arranged in a specific order, typically associated with variations in moisture content, drainage patterns and other hydrological factors. These sequences are often found in landscapes where water availability varies, such as wetlands, floodplains, or coastal regions. Soils within a hydrosequence have different characteristics and properties that are influenced by their location in the landscape and their relationship to water movement and availability. Typically, a hydrosequence includes soils adapted to different levels of water saturation, from well-drained soils in higher elevations or drier areas to poorly drained or waterlogged soils in lower elevations or wetter areas (Lin, 2012).

The main goal of the research was to investigate the soils on a certain location (the Strunjan Bay) at the Slovenian coast that are permanently under water, their inventory, and describe a soil hydrosequence.

1.1 A brief introduction to the classification of subaqueous soils

The sediments deposited in the water were mainly studied by geologists and biologists. The first initiative that some of the material was also the subject of pedology appeared in 1862, when von Post proposed the terms “*gyttja*” and “*dy*”, which are still used today (von Post, 1862, cited in Demas, 1998). Research continued 100 years later. Kubiěna (1953) included subaqueous soils in his classification of European soils and divided them into two categories: 1. young soils that are constantly flooded with water and do not form peat, and 2. young subaqueous soils that form peat. Mückenhausen (1965) contributed to the classification of German soils by identifying subaqueous soils as sub hydric and dividing them into four groups (protopedon, *gyttja*, sapropel and *dy*). Soil Taxonomy of subaqueous soils includes specific taxa within Entisols and Histosols, such as “Wassents” and “Wassists” (Soil Survey Staff, 2010). The latest

version of the WRB classification (Repe, 2018) does not have a special subaqueous group but defines it with specific material and qualifiers within Histosols, Technosols, Cryosols, Leptosols, Gleysols, Arenosols and Fluvisols. Among others, there are certain diagnostic features such as horizons (anthraquic, histic, hydric), properties (gleyic, stagnic), materials (fluvic, limnic, organic) that indicate the possible presence of subaqueous soils. There are also some qualifiers directly (Floatic, Subaquatic, Tidalic) or indirectly (Fibric, Hemic, Sapric) associated with subaquatic soils (IUSS Working Group WRB, 2022). Subaqueous soils were included in the Yugoslav classification (Antić et al., 1982; Škorić, 1977) as subaquatic or subhydric, which was also adopted by the Slovenian classification (Prus, 2000; Repe, 2010), but without any serious research (Repe, Pristovšek, 2022; Repe, Pristovšek, Pavlin, 2019).

Figure 1: Research area of the Strunjan Bay.



2 METHODS

For the study, we chose subaqueous soils along the coast of the Slovenian Sea. We were looking for an accumulative, lagoonal coastal type (Bat et al., 2003; Radinja, 1990), which is constantly submerged and has different seawater influences, to study the soil hydrosequence. This means that three sites were selected in the waters of the Strunjan Bay (Strunjanski zaliv) (Figure 1).

2.1 Research area, soil forming factors and processes

The selected area of the Strunjan Landscape Park covers 428.6 ha and 4 km of the shore of the Gulf of Trieste. The park includes the Strunjan peninsula from Simon's Bay (Simonov zaliv) to the mouth of the Strunjan – Roja river, including a 200-metre-long strip of sea and the inner part of the Strunjan Bay. The Strunjan peninsula is located in the flysch landscape on the Slovenian coast. Flysch is a mechanically quite unstable rock, so the cliff areas are exposed to strong lateral processes. Large boulders and coarse material quickly accumulate directly on the coast and underwater, so the chances of soil formation are very low. Fine material is carried away by sea currents or waves, or accumulates under boulders. A large part of the Strunjan Bay consists of salt marshes that continue into the Strunjan Valley. The geomorphology of the Strunjan Peninsula is largely determined by geological features. The predominant material is flysch from the Eocene, generally consisting of alternating layers of lapis and sandstone. The lack of resistance of the rocks emphasises mechanical and chemical weathering). An important element of the park is the Stjuža, the only marine lagoon on the Slovenian coast. More than 200 years ago, this lagoon was an open bay, which was then closed by a dike. This cut off the direct connection to the sea. Today, the only connection to the sea is via a channel (Hoyer et al., 1986). It is divided into the Great Lagoon and the Transitional Lagoon (DOPPS, 2018). Since it is closed, the name Stjuža also derives from the Italian word *chiusa* – closed. The water movement is tidal, there are no waves or currents in the lagoon (Hoyer et al., 1986).

According to the Köppen climate classification, the coastal zone up to an altitude of 350 m is classified as a temperate warm-humid climate with hot summers (Cfa). Compared to the Mediterranean climate (Cs), there is more precipitation distributed more evenly throughout the year, less pronounced dryness in summer and generally lower temperatures throughout the year. In the coastal zone there is a so-called temperate Mediterranean coastal climate (locally known as the climate of the olive tree, *Olea europaea*) or sub-Mediterranean climate (Ogrin, 1993; 1996; 2012).

Shallowness is an important feature of the Slovenian Sea (Bat et al., 2003; Ogrin, Plut, 2009; Radinja, 1990). The Gulf of Trieste descends rapidly and irregularly along the Slovenian coast. Sea water temperatures in the Gulf of Trieste typically reach their lowest point in February (8–9 °C) and their highest point in August (about 24 °C).

Therefore, the average annual amplitude is 15–16 °C. The average annual water temperature is about 16 °C, 2–3 °C higher than the average annual air temperature. The sea never freezes over. The Gulf of Trieste has a salinity of 37–38‰, which is higher than in the oceans. The salinity varies according to the seasons and the freshwater inflow into the bay. During the rainy season, the salinity of the water at the mouths of rivers and streams can fall below 20‰ (Kolbezen, 1998; Ogrin, Plut, 2009). The Slovenian Sea is characterised by high turbidity (poor transparency) due to its muddy and fine sandy bottom, shallow water depth, and high nutrient and plankton load. Many dead particles and transitions between water layers with different temperatures and salinities also contribute to higher turbidity and poorer visibility in the lower layers. Typical visibility at the surface is 6–8 m (Ogrin, Plut, 2009). The currents in the Gulf of Trieste are rather weak and already turn mostly to the west along the southern coast of Istria. The current that reaches the Gulf of Trieste flows north and northwest along the Slovenian coast before returning to the southern Adriatic along the Italian coast. The speed of the current is generally no more than 1.5 km/h. The tidal range off the Slovenian coast is a mixed type, with two tides alternating on a lunar day (24 hours and 50 minutes). The average tidal range is 66 cm in Koper and 88 cm in the Gulf of Trieste. Very high waves with destructive force are generated by strong local winds (especially storms) (Maček, Žabkar, Ušeničnik, 2002). The Stjuža lagoon hosts salt-loving (halophytic) vegetation that has developed on a silty substrate, mainly due to salinity, water availability, the soil type itself and microtopography. The halophytic and brackish vegetation started to develop when the bay was closed with dykes and the lagoon was created. Due to changes in hydrological dynamics, sediment deposition and anthropogenic influences, the vegetation cover has expanded throughout the area (Šajna, Kaligarič, 2005). Most of the Stjuža is covered by seagrass, namely *Cymodocea nodosa*, and there is also some *Zostera marina*. The waters of the Stjuža are home to a variety of animal species, mainly shrimps. These are swimming species of decapod crustaceans that play a very important role in the food web of the lagoon ecosystem. In the mud, one of the most abundant species is *Upogebia littoralis*, known to the locals as “škaradobola”. This crustacean lives in small vertical tunnels in the mud bottom (Lipej, 2004) and is responsible for the vertical mixing of the bottom material (Figure 2).

Like terrestrial soils, subaqueous soils are also subject to pedogenesis. In fieldwork we have the following processes:

- Translocation of material within the soil profile: Diffusion is an important process where the entry of oxygen from seawater into the soil causes the surface horizons to become coated with iron oxides and take on a brown colour. In the case of impermeable cover by dead vegetation, this influx is stopped, and reduction takes place (grey and blackish hues). Bioturbation is also important, where organisms (marine worms and crabs) move organic material mainly downwards, up to half a metre into the bottom profile.

- Transformation of material: Mineral material is transformed very little under anaerobic conditions. As a result, larger, sandy particles are abundant in our subaqueous soils. Organic material is subject to anaerobic microbial decay processes that prevent oxygen from reaching the soils. The putrefaction processes lead to sulphidisation (anaerobic formation of iron sulphide compounds (FeS , Fe_3S_4 , FeS_2) (Demas, Rabenhorst, 1999) and the release of gases (H_2S) with a distinctly unpleasant odour.
- Inputs of pedogenesis. These are mainly mineral (weathered rock debris carried in by terrestrial waters) and biogenic substances. Of the latter, organic matter is the most important and contributes significantly to the high proportions of poorly weathered organic matter. Biogenic matter also includes fine shell particles, which contribute to the higher CaCO_3 content. The mineral and organic fractions are mixed by seawater movement and often overlap at the surface.
- Outputs of pedogenesis. The most common output in subaqueous soils is related to subaqueous erosion, where wave action and currents carry material from surface horizons to deeper areas of the seabed. Another important output in subaqueous soils is the decomposition of organic material.

Figure 2: Animal (crab) burrow that enables vertical movement of oxygen and soil material (photo: B. Repe).



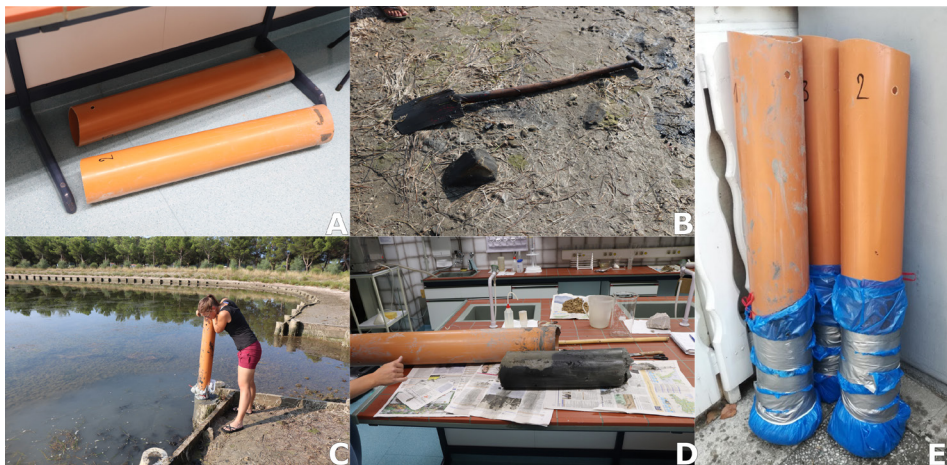
2.2 Soil sampling and analysis

For our investigation we selected three different sites in the Strunjan Landscape Park. The first soil sample was taken in the Stjuža lagoon, the second in the transition area – the channel between Stjuža and the seashore – and the last on the seashore of the Strunjan Bay.

We used sewage pipes with a diameter of 16 cm and a length of 1 m. We drilled holes in the upper part of the pipes and put a metal rod through them to facilitate pushing the pipe into the soil as deep as possible. Under water we excavated the area around the inserted pipe. Then the pipes with the samples were carefully and slowly lifted out of the water, taking care that the soil did not slip out of the pipe. The lower (opened) parts of the pipes were tightly sealed with plastic bags and held together with cable ties and tape. We drilled tiny holes in the bags so that the water could slowly seep away without disturbing the structure of the profile. In this way, the samples were dried outdoors for a month and in the laboratory at room temperature for a week. Later, the samples were pushed out of the pipes, cut lengthwise and the horizons for each sample were determined. An extremely unpleasant odour (rotten eggs) was present. As expected, the odour was most intense in the first sample, only faintly perceptible in the second sample and odourless in the third sample. The dried samples from each horizon were then crushed and sieved and prepared for laboratory analysis. A standard soil analysis was carried out for each horizon of each sample. Electrical conductivity was also measured, and the percentage of shells estimated.

The soil samples were collected in August 2018 and the laboratory analysis was carried out in October 2018. As the processes of formation and change in soil properties

Figure 3: Soil sampling. A) Sewage pipes for taking soil samples; B) Spade for excavating pipes containing samples; C) Soil sampling; D) Extracting the sample from the pipe; E) Drying of soil samples (photos A–D: B. Repe; photo E: T. Pavlin).



are often measured over a period of at least several decades, it is unlikely that the situation investigated to date has changed significantly. An exception could be major human intervention, which was not detected last year (2022).

3 RESULTS

Based on the field observations and measurements as well as the laboratory analyses (Tables 1, 2 and 3), we described the profiles (determining the diagnostic horizons, properties and materials as well as all qualifiers) and finally gave a full name of the soil according to the WRB classification (IUSS Working Group WRB, 2022).

Table 1: Horizon designations and the results of the field measurements and laboratory analysis for the sample No. 1, the Stjuža lagoon.

HOR	DEP	SHEL	COLM	COLD	Sa	Si	Cl	TEXT
C	0,2–0	/	/	2,5Y 5/2	/	/	/	sand
2H _a C _{r1}	0–9	1	N1,5/0	5Y 5/2	37,3	47,3	15,4	loam
2H _a C _{r2}	9–21	5	N2/0	5Y 5/1	33,3	44,2	22,5	loam
3AC _{r1}	21–28	1+	7,5GY 2/1	5Y 5/1	34	51,5	14,5	silt loam
3AC _{r2}	29–46	15	5GY 2/1	5Y 5/1	22,7	54,8	22,5	silt loam
3AC _{r3}	46–	10	2,5GY 3/1	5Y 5/1	16,5	48,5	35	silt clay loam

HOR	pH	OM	CaCO ₃	Ece	H	S	CEC	V
C	/	/	33,96	/	/	/	/	/
2H _a C _{r1}	6,89	19,23	47,21	7,97	1	50	50,65	98,72
2H _a C _{r2}	6,95	20,43	42,24	13,13	2	50	51,3	97,47
3AC _{r1}	7,36	22,01	35,61	16,08	1	50	50,65	98,72
3AC _{r2}	7,17	18,28	43,07	8,72	2	50	51,3	97,47
3AC _{r3}	7,32	15,33	27,33	12,91	2	50	51,3	97,47

HOR – horizon name; DEP – horizon depth; SHEL – % of biogenic shells; COLM – colour in wet state; COLD – colour in dry state; Sa – % of sand fraction; Si – % of silt fraction; Cl – % of clay fraction; TEXT – texture class; pH – PH value; OM – % of organic matter; CaCO₃ – % of free calcium carbonate; Ece – electric conductivity (dS/m); H – hydrolytic acidity (mekv); S – sum of all basic cations (mekv); CEC – cation exchange capacity (mekv/100g); V – base saturation (%).

Table 2: Horizon designations and the results of the field measurements and laboratory analysis for the sample No. 2, the channel to the Stjuža lagoon.

HOR	DEP	SHEL	COLM	COLD	Sa	Si	Cl	TEXT
C	3–0	/	5Y 3/2	5Y 5/2	31,7	51,8	16,5	silt loam
C _g A _{h1}	0–4	1	5Y 3/1	5Y 5/1	29,2	49,9	20,9	loam
C _g A _{h2}	4–7	1	5Y 2/2	5Y 5/1	34,8	43,4	21,8	loam
C _{r1}	7–15	5+	5Y 2/2	7,5Y 5/1	46,3	39,2	14,5	loam
C _{r2}	15–25	3+	5Y 2/2	5Y 5/1	42	41,7	16,3	loam
C _{r3}	25–	10	5Y 2/2	5Y 5/1	38,6	44,9	16,5	loam

HOR	pH	OM	CaCO ₃	Ece	H	S	CEC	V
C	7,18	16,63	35,41	28,6	3	50	51,95	96,25
C _g A _{h1}	7,2	16,59	31,4	25,2	2	50	51,3	97,47
C _g A _{h2}	7,49	16,69	38,83	20,3	2	50	51,3	97,47
C _{r1}	6,95	16,89	40,49	12,92	2	50	51,3	97,47
C _{r2}	7,18	17,32	42,96	11,7	3	50	51,95	96,25
C _{r3}	7,09	16,1	45,44	9,53	2	50	51,3	97,47

HOR – horizon name; DEP – horizon depth; SHEL – % of biogenic shells; COLM – colour in wet state; COLD – colour in dry state; Sa – % of sand fraction; Si – % of silt fraction; Cl – % of clay fraction; TEXT – texture class; pH – PH value; OM – % of organic matter; CaCO₃ – % of free calcium carbonate; Ece – electric conductivity (dS/m); H – hydrolytic acidity (mekv); S – sum of all basic cations (mekv); CEC – cation exchange capacity (mekv/100g); V – base saturation (%).

Table 3: Horizon designations and the results of the field measurements and laboratory analysis for the sample No.3, seashore of the Strunjan Bay.

HOR	DEP	SHEL	COLM	COLD	Sa	Si	Cl	TEXT
O _i	1–0	/	/	5Y 5/2	87,5	5,7	6,8	loamy sand
AC	0–4	/	2,5Y 3/3	2,5Y 5/2	93,9	1,4	4,7	sand
C _g	4–7	3	5Y 3/2	2,5Y 5/2	88,4	5,2	6,4	loamy sand
C _r	7–9	/	5Y 3/3	5Y 5/2	90,6	1,8	7,6	sand
O _e C _{r1}	9–9,5	/	5Y 2/1	5Y 5/2	/	/	/	/
O _e C _{r2}	9,5–	/	5Y 3/1	5Y 5/2	87,2	7,1	5,7	loamy sand

HOR	pH	OM	CaCO ₃	Ece	H	S	CEC	V
O _i	7,87	/	75,37	6,5	/	/	/	/
AC	7,04	11,56	70,4	18,52	1	50	50,65	98,72
C _g	8,07	15,3	67,91	1,395	1	50	50,65	98,72
C _r	8,01	16,06	59,63	0,0115	1	50	50,65	98,72
O _e C _{r1}	7,9	/	72,05	8,87x10 ⁻³	/	/	/	/
O _e C _{r2}	7,79	12,94	62,11	8,23x10 ⁻³	1	50	50,65	98,72

HOR – horizon name; DEP – horizon depth; SHEL – % of biogenic shells; COLM – colour in wet state; COLD – colour in dry state; Sa – % of sand fraction; Si – % of silt fraction; Cl – % of clay fraction; TEXT – texture class; pH – PH value; OM – % of organic matter; CaCO₃ – % of free calcium carbonate; Ece – electric conductivity (dS/m); H – hydrolytic acidity (mekv); S – sum of all basic cations (mekv); CEC – cation exchange capacity (mekv/100g); V – base saturation (%).

Site No. 1, the Stjuža Lagoon

Figure 4: Sampling site 1 (photo: B. Repe).



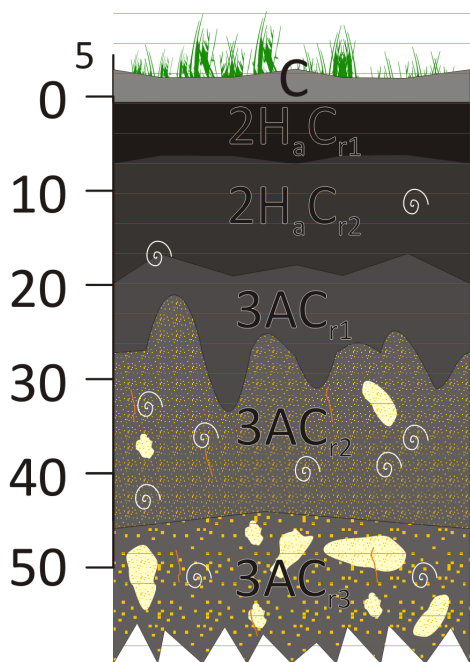
Site description: Location: NW part of the Stjuža Lagoon, N45°31'53.0", E13°36'10.4". Parent material: alluvial silt sediment of the flysch origin. Water conditions: permanently saturated with water, protected from wind, waves and currents; slow vertical tidal movement of water. Vegetation: *Cymodocea nodosa*, *Zostera marina*. Human influences: artificial formation of the lagoon by dike, possible illegal liquid waste deposits – sewage.

Diagnostic horizons: mollic (structure not massive or hard when dry, more than 0.6% organic carbon and more than parent material, moist colour value is lower than 3, base saturation is higher than 50%, it is more than 20 cm thick), salic (electric conductivity is higher than 15 dS/m, the product of ECe in thickness is higher than 450, it is more than 15 cm thick).

Diagnostic properties: gleyic (has reductimorphic colours (N), more than 5% of the oximorphic mottles around root channels).

Diagnostic materials: calcaric (strong effervescence (more than 50% of CaCO₃), structure is not disrupted, no concretions, nodules, coatings etc. present), limnic (material partly deposited by water, partly from aquatic plants), mineral (soil properties are dominated by mineral components), hyposulfidic (extreme odour, high pH value, does not cause acidification).

Figure 5: Soil profile 1.



Reference soil group: GLEYSOL (a layer is more than 25 cm thick and starts less than 40 cm from surface, it has gleyic properties throughout, it has reducing conditions in every sublayer).

Principal qualifiers: Subaquatic (permanently under water), Mollic (has a mollic horizon), Calcaric (has a calcaric material throughout), ~~Hyper~~eutric (because of Calcaric, Eutric is redundant).

Supplementary qualifiers: Loamic (dominant loamic texture), Humic (more than 1% of organic carbon), Limnic (has limnic material), Salic (has a salic horizon and ECe more than 30 dS/m), Sodic (does not have a natric horizon and has more than 15% of Na; not confirmed, but most probably), Hyposulfidic (has hyposulfidic material more than 15 cm thick and starting less than 100 cm from the soil surface).

Figure 6: Soil sample 1 (photo: B. Repe).



Complete WRB name: Calcaric Mollic Subaquatic GLEYSOL (Loamic, Humic, Salic, Sodic, Hyposulfidic).

Site No. 2, channel to the Stjuža Lagoon

Figure 7: Sampling site 2 (photo: B. Repe).



Site description: Location: middle section of channel leading from the Strunjan Bay to the SW part of the Stjuža Lagoon, N45°31'41.9", E13°36'16.2". Parent material: alluvial silt and sandy sediment of the flysch origin. Water conditions: permanently saturated with water, protected from wind, waves and currents; slow vertical tidal movement of water; according to the tide, slow lateral movement of water in and out of the lagoon). Vegetation: *Cymodocea nodosa*, *Sarcocornetea fruticosa*, *Salicornia europaea*. Human influences: artificial formation of the channel by dike, local port for very small boats.

Diagnostic horizons: mollic (structure not massive or hard when dry, more than 0.6% organic carbon and more than parent material, moist colour value is lower than 3, base saturation is higher than 50%, it is more than 20 cm thick), salic (electric conductivity is higher than 15 dS/m, the product of E_{Ce} in thickness is higher than 450, it is more than 15 cm thick).

Diagnostic properties: gleyic (has reductimorphic colours (N), more than 5% of the oximorphic mottles around root channels), stagnic (mottles of reducti- and oxymorphic).

Diagnostic materials: calcaric (strong effervescence (more than 50% of CaCO_3), structure is not disrupted, no concretions, nodules, coatings etc. present), mineral (soil properties are dominated by mineral components).

Reference soil group: GLEYSOL (a layer is more than 25 cm thick and starts less than 40 cm from surface, it has gleyic properties throughout, it has reducing conditions in every sublayer).

Principal qualifiers: Subaquatic (permanently under water), Mollic (has a mollic horizon), Oxygleyic (within 100 cm soil does not meet diagnostic criterion 1 of the gleyic properties), Calcaric (has a calcaric material throughout), ~~Hypereutric~~ (because of Calcaric, Eutric is redundant).

Supplementary qualifiers: Loamic (dominant loamic texture), Humic (more than 1% of organic carbon), Limnic (has limnic material), Salic (has a salic horizon and ECe more than 30 dS/m), Sodic (does not have a natric horizon and has more than 15% of Na; not confirmed, but most probably).

Figure 8: Soil profile 2.

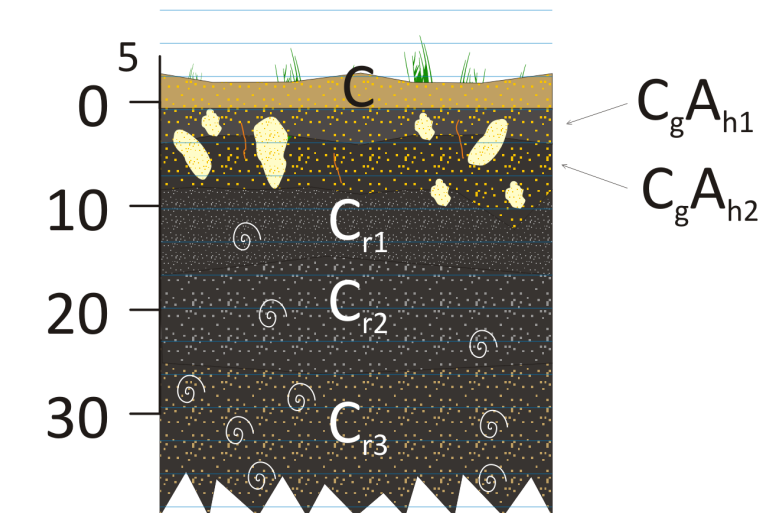
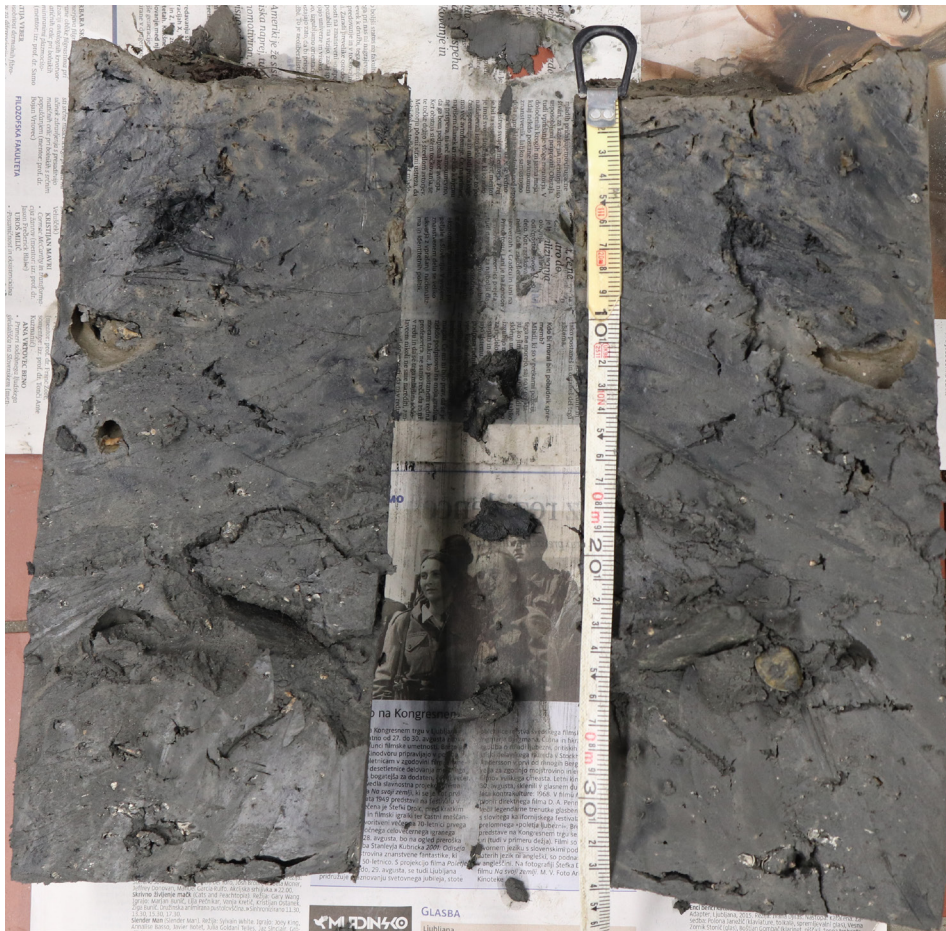


Figure 9: Soil sample 2 (photo: B. Repe).



Complete WRB name: Calcaric Oxygleyic Mollic Subaquatic GLEYSOL (Loamic, Humic, Salic, Sodic).

Site No. 3, seashore of the Strunjan Bay

Figure 10: Sampling site 3 (photo: B. Repe).



Site description: Location: E part of the Strunjan Bay, seashore, N45°31'41.6", E13°36'12.2". Parent material: alluvial sandy sediment over large of the flysch origin, covering large flysch blocks and boulders. Water conditions: permanently saturated with water; active movement of water by wind, waves, currents, and tide. Vegetation: *Cymodocea nodosa*. Human influences: bank of the shore and swimming resort.

Diagnostic horizons: /

Diagnostic properties: continuous rock (hard rock that cannot be penetrated by tools), gleyic (has reductimorphic colours (N), more than 5% of the oximorphic mottles around root channels).

Diagnostic materials: calcaric (strong effervescence (more than 50% of CaCO_3), structure is not disrupted, no concretions, nodules, coatings etc. present), fluvial (material of marine origin and has visible strata with alternating organic matter content).

Reference soil group: LEPTOSOL (has a *continuous rock* starting less than 25 cm from the soil surface).

Principal qualifiers: Lithic (has continuous rock less 10 cm from the soil surface), Subaquatic (permanently under water), Calcaric (has a calcaric material throughout), *Hypereutric* (because of Calcaric, Eutric is redundant).

Supplementary qualifiers: Akrofluvic (has fluvic material, but they are less than 25 cm thick), Arenic (dominant sandy texture), Ochric (more than 0.2% of organic carbon in the upper 10 cm), Limnic (has limnic material).

Figure 11: Soil profile 3.

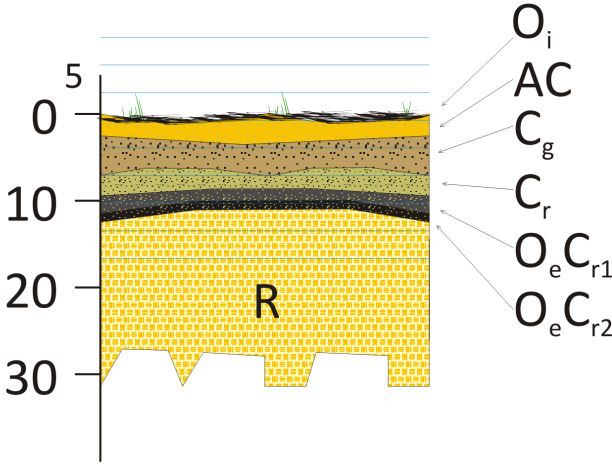


Figure 12: Soil sample 3 (photo: B. Repe).



Complete WRB name: Calcaric Subaquatic Lithic Leptosol (Akrofluvic, Arenic, Ochric).

According to old classifications, the first soil sample would be classified as sapropel, the second as gyttja and the third with properties between protopedon and gyttja (Mückenhausen, 1965).

4 DISCUSSION

The study of subaqueous soils is not a new field of research in soil science. However, the research is still quite rare for two main reasons. Rarely do these studies have application value (e.g., the mapping and analysis of Dutch polder soils prior to dam construction) (Demas et al., 1996), and the research is even more demanding and expensive than it already is. During our work, similar problems arose. Fieldwork, especially underwater sampling, proved to be very time-consuming, tedious, and demanding. As no professional and expensive field equipment was available, we were forced to improvise, which made the work even more difficult. Nevertheless, we managed to get all the results, successfully named the soils, and thus came to some important conclusions. On the other hand, the knowledge gained, and information collected has very limited application value.

In a study carried out in the Gulf of St Bartholomew (Repe, Pristovšek, 2011), a soil hydrosequence was established referring to the intertidal zone, the time of inundation with seawater or the time when the soil was exposed to air. In fact, the hydrosequence showed a correlation between soil properties and distance from the coastline. Consequently, in simplified terms, the soil groups followed the following sequence: Solonchaks (land, with saline groundwater) – Histosols (intermittent flooding with seawater at low tide, the flooding duration is shorter than the duration of air exposure) – Gleysols (intermittent flooding with seawater at high tide, the flooding duration is longer than the duration of air exposure) – Arenosols (permanent water flooding). It should be noted that the thickness of the sandy flysch sediment is so great that the hard parent rock does not come to the surface). This is then related to the predominant vegetation, with mainly reeds (*Phragmites sp.*) growing on the shore, mainly salt-loving vegetation (*Salicornia europaea*, *Arthrocnemum glaucum*, *Crithmum maritimum*, *Limonium angustifolium*, *Juncus maritimus*) in the intertidal zone, and Neptune grass (*Cymodocea nodosa*) in the permanently flooded zone.

We have once again examined the hydrosequence in the waters of Strunjan Bay. The surface is flat, the parent substrate is flysch, the climate is sub-Mediterranean, the plants are dominated by seagrasses and the soils are all young and influenced by recent soil formation processes. However, this hydrosequence differs to some extent from the previous one. The main difference is that this time all sites are permanently under water and never in contact with atmospheric air. As a result, the vegetation is also submerged, with seagrasses dominating at all sites.

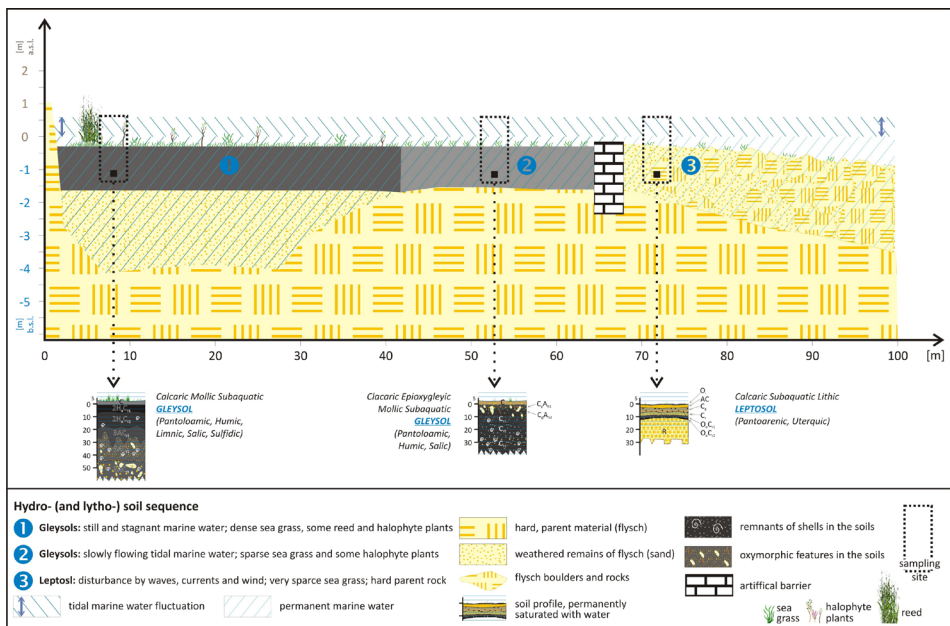
Figure 13: Coarse biogenic and sandy flysch material (photo: B. Repe).



The main difference between the three selected sites in this study is the effect of the sea water. At the first site (the Stjuža lagoon), the seawater is practically stagnant. Only depending on the tides is there a daily vertical fluctuation of the seawater level. The site is completely protected from external influences such as wind, waves or currents. As a result, all organic residues end up on the soil surface, where they slowly decompose anaerobically. The organic layer completely prevents the oxygen dissolved in the water from reaching the soil, so that the soil is heavily gleyed, the material completely reduced and grey in colour. The material is heavily transformed to a depth that can be sampled. The organic material is sulphidised and sulphur compounds are present, resulting in an unpleasant odour. Wastewater discharged or dumped into the lagoon is most likely a contributing factor. At the second site (artificial channel to the lagoon), seawater flows slowly in and out of the lagoon every day in accordance with the tides. The soil is also protected from external influences. The water flow is not turbulent and therefore does not cause displacement (inflow or erosion) of material or mixing of material in the upper horizons. The main process is still reduction and gleying. The main difference from site 1 is that the soils are flooded daily with fresh, oxygenated water, which can be seen in the brownish mottles (oxidation) in an otherwise predominantly grey soil matrix. The soils are highly altered up to a depth of 35 cm, after which coarser biogenic material occurs (Figure 13). There is no decay due to the

decomposition by oxygen and consequently little odour. The biggest difference is at the third site (the shore of the Strunjan Bay), which is completely exposed to the action of waves, currents and wind and therefore shows intense displacement of mineral and organic material. The tides do not play a role. Another difference is that the very shallow soil is underlain by hard flysch bedrock, as the finer material is continuously carried away by seawater. The surface of the soil is covered with poorly weathered seagrass remains, followed by coarse, sandy, poorly altered mineral material that is gleyed only in the lower part. This is followed by a new organic layer (not a horizon!), another gleyed layer and then a thin layer of unaltered flysch sand lying directly on the hard flysch bedrock. The soil is young, poorly developed, and shallow. The texture of the first two samples is predominantly loamy, with an organic horizon present in both samples and the humus is mollic. The third soil is distinctly sandy, organic matter is in ochric form. All three samples are calcareous (above average free carbonate content), all are naturally saline, and the reaction is high (on average the pH is above 7 or even above 8). The base saturation is close to 100%.

Figure 14: Schematic soil hydro sequence of the Strunjan Bay.



Despite the modest number of samples, it can be concluded that the submarine soils of the Slovenian shallow coastal sea are quite similar, with the expected dominance of Gleysols. The closer the soils are to the coast, the more organic material is present and the stronger the gleying process. As the distance from the coast increases,

the strength of the gleying decreases, while the proportion of sand fraction increases. At a point between 50 and 100 m from the coast (depending on the width of the submarine shelf), Arenosols begin to appear. At a still undetermined distance from the coastline, but certainly at a depth of more than three metres, only unaltered, flyschy, sandy material appears (Figure 14).

In order to obtain a complete overview of the soil types of the Slovenian offshore seabed, it would be necessary to investigate the areas below the cliffs, where the rocky seabed predominates, and shallow soils are very likely to prevail in the cracks between the boulders. In any case, the places where rivers flow into the sea should also be investigated, as the water there is less saline and the input of material from the coast is greater.

The continuation and completion of research on the underwater soils of the Slovenian coast will provide a comprehensive pedological and geographical overview of an area about which we know very little. And, more importantly, it will add one of the last pieces of the mosaic that is still missing to fully understand the ecological conditions for underwater flora and fauna to thrive. This in turn will provide a scientific basis for understanding and adequately protecting this fragile and unique habitat in Slovenia.

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GENETSKO ZAPOREDJE PODVODNIH PRSTI V STRUNJANSKEM ZALIVU

Povzetek

Glavni cilj raziskave je bil proučiti prsti na izbrani lokaciji (Strunjanski zaliv) na slovenski obali, ki so stalno pod vodo, ustrezno opisati in poimenovati prsti ter opisati hidrosekvenco. Za ugotavljanje hidrosekvence prsti smo iskali akumulacijski, lagunski obalni tip, ki je stalno potopljen in ima različne vplive morske vode. Posledično smo izbrali tri lokacije v vodah Strunjanskega zaliva. Prvi vzorec prsti je bil opisan v laguni Stjuža, drugi na prehodnem območju – kanalu med Stjužo in morskobalo, in zadnji na morskobali Strunjanskega zaliva. Za vzorčenje smo uporabili kanalizacijske cevi premera 16 cm in dolžine 1 m. V zgornji del cevi smo izvrtali luknje, skozi katere smo vstavili kovinsko palico, da smo cev potisnili kolikor je mogoče globoko v prst. Pod vodo smo izkopali območje okoli vstavljene cevi. Nato smo cevi z vzorci previdno in počasi dvignili iz vode, pri čemer smo pazili, da vzorec ni zdrsnil iz cevi. Spodnje (odprte) dele cevi smo tesno zaprli s plastičnimi vrečkami in jih povezali z vezicami in lepilnim trakom. V vrečke smo izvrtali majhne luknjice, da je lahko voda počasi odtekala, ne da bi se pri tem porušila zgradba profila. Na ta način smo vzorce en mesec sušili na prostem in en teden v laboratoriju pri sobni temperaturi. Kasneje smo vzorce potisnili iz cevi, jih vzdolžno razrezali in za vsak vzorec določili horizonte. Ob izpostavljenosti zraku se je pojavil izjemno neprijeten vonj (po gnilih jajcih). Kot je bilo pričakovati, je bil vonj najintenzivnejši v prvem vzorcu, v drugem vzorcu je bil le rahlo zaznaven, tretji vzorec je bil brez vonja. Posušene vzorce iz vsakega horizonta smo nato zdrobili in presejali ter jih pripravili za laboratorijsko analizo. Za vsak horizont vsakega vzorca je bila opravljena standardna analiza tal. Izmerjena je bila tudi električna prevodnost in ocenjen odstotek školjčnih lupin. Vzorci prsti so bili odvzeti avgusta 2018, laboratorijske analize pa so bile opravljene oktobra 2018.

V raziskavi, ki je bila opravljena v zalivu Sv. Jerneja (Repe, Pristovšek, 2011; 2022), smo ugotovili hidrosekvenco, ki se je nanašala na bibavični pas, čas zalitosti z morskobalo oziroma čas, ko so bile prsti izpostavljene zraku. Dejansko je hidrosekvenco kazala na povezavo med lastnostmi prsti in oddaljenostjo od obalne linije. Posledično so si poenostavljeno skupine prsti sledile v naslednjem zaporedju: *Solonchaks* (kopno, s slano podtalnico) – *Histosols* (občasna zalitost z morskobalo ob plimi, obdobje zalitosti je krajše od obdobja izpostavljenosti z zrakom) – *Gleysols* (občasna zalitost z morskobalo ob plimi, obdobje zalitosti je daljše od obdobja izpostavljenosti z zrakom) – *Arenosols* (stalna zalitost z vodo). Ob tem je treba povedati, da je debelina peščenega flišnega sedimenta takšne debeline, da trda matična kamnina ne pride blizu površja. Na to se nato navezuje tudi prevladujoče rastlinstvo, kjer na obali uspeva predvsem trstičje (*Phragmites* sp.), v pasu plime in oseke predvsem slanopljudno rastlinstvo (*Salicornia europaea*, *Arthrocnemum glaucum*, *Crithmum maritimum*,

Limonium angustifolium, *Juncus maritimus*), v stalno zalitem delu pa morska trava (*Cymodocea nodosa*). Tudi tokrat smo v vodah Strunjanskega zaliva proučevali hidrosekvenco. Površje je povsod uravnano, matična podlaga flišnata, podnebje submediteransko, med rastlinami prevladujejo morske trave, vse prsti so mlade, podvržene recentnim procesom. Se pa tokratna hidrosekvenca od prejšnje do določene mere razlikuje (zaporedje tipov prsti ni povsem identično). Najpomembnejši vzrok za to razliko je, da so tokrat vse lokacije stalno pod vodo in nikoli ne pride do stika z atmosferskim zrakom. Posledično je tudi rastlinstvo podvodno, na vseh lokacijah prevladujejo morske trave.

Med tremi izbranimi lokacijami je glavna razlika v delovanju morske vode. Na prvi lokaciji (laguna Stjuža) morska voda praktično miruje. Le v skladu s plimo in oseko se pojavlja dnevno, vertikalno nihanje gladine morske vode. Lokacija je povsem zaščitena pred zunanjimi vplivi vetra, valov ali morskih tokov. Posledično vse odmrlo gradivo konča na površini prsti, kjer počasi anaerobno gnije. Organska plast povsem prepreči dostop v vodi raztopljenega kisika, zato so prsti močno oglejene, gradivo povsem reducirano in sive barve. Gradivo je močno preoblikovano do globine, do koder je bilo mogoče odvzeti vzorec. Organska snov se sulfidizira, zato so prisotne žveplove spojine in posledično neprijeten vonj. Zelo verjetno k temu prispevajo tudi odplake, ki so bile speljane v laguno. Na drugi lokaciji (umetni kanal v Stjužo) morska voda dnevno, v skladu z delovanjem plime in oseke počasi teče enkrat v laguno in nato spet izven nje. Prsti so prav tako zaščitene pred zunanjimi vplivi. Vodni tok ni turbulenten, zato ne povzroča premeščanja (dotok ali erozija) gradiva niti mešanja gradiva zgornjih horizontov. Glavni proces je še vedno redukcija in oglejevanje. Bistvena razlika z lokacijo št. 1 je, da dnevno prsti preliva sveža, s kisikom bogata voda, kar je moč opaziti v procesih oksidacije, ki se marmorirano pojavlja v rjavkastih odtenkih, v sicer pretežno sivemu matriksu. Prsti so močno preoblikovane do globine 35 cm, potem pa se že pojavlja bolj grobo in skeletno gradivo. Zaradi kisika ne prihaja do gnitja, neprijeten vonj je komajda zaznaven. Največja razlika pa je na tretji lokaciji (obala Strunjanskega zaliva). Lokacija je povsem izpostavljena delovanju valov, morskih tokov in vetru, zato se pojavlja intenzivno premeščanje mineralnega in organskega gradiva. Plimovanje ne igra nobene vloge. Dodatna razlika je, da se plitvo pod površjem pojavlja trda flišna podlaga, saj drobno gradivo sproti odnaša morska voda. Površino prsti prekrivajo slabo prepereli ostanki morske trave, čemur sledi grobo, peščeno, slabo preoblikovano mineralno gradivo, ki je oglejeno šele v spodnjem delu. Temu sledi nov organski sloj, ponovno oglejen sloj in nato tanek sloj nepreoblikovanega flišnega peska, ki leži neposredno na trdi flišni podlagi. Prsti so mlade, slabo razvite in plitve. Tekstura prvih dveh vzorcev je prevladujoče meljnata, pri obeh se pojavijo organski horizont, humusni je moličen. Tretje prsti so izrazito peščene, organska snov nastopa v ohrični obliki. Vsi trije vzorci so kalkarični (nadpovprečna količina prostih karbonatov), vsi so seveda slani, reakcija je visoka (v povprečju nad 7 ali celo nad 8). Zasičenost z bazami je blizu 100 %.

Kljub skromnemu številu vzorcev lahko vseeno zaključimo, da so si podvodne prsti slovenskega plitvega obalnega dna precej podobne, saj prevladujejo glejsoli. Glede na pedogenetske dejavnike jih upravičeno lahko pričakujemo tudi drugod, vendar bomo morali to še potrditi. Bližje ko se prsti nahajajo obali, več je organskega gradiva in hkrati močnejši je proces oglejevanja. Z oddaljevanjem od obalne črte se moč oglejevanja zmanjšuje, obenem pa se povečuje delež peščene frakcije. Med 50 in 100 m stran od obale (odvisno od širine podvodne morske police) se začno pojavljati arenosoli. Vsekakor pa se globlje od treh metrov pojavlja le še nepreoblikovano, flišno, peščeno gradivo. Za popolno pedološko sliko slovenskega priobalnega dna bi bilo treba proučiti še območja pod klifi, kjer prevladuje kamnito dno in prevladujejo zelo verjetno plitve prsti, v razpokah med skalnimi bloki. Vsekakor pa bi bilo treba proučiti tudi mesta, kjer se reke izlivajo v morje, saj je voda manj slana, dotok gradiva z obale pa večji.

Z nadaljevanjem in zaključkom raziskovanja podvodnih prsti slovenske obale bomo dobili celovit pedološki in geografski pregled območja, o katerem vemo izjemno malo. Še pomembneje je, da bomo z zaključkom dodali enega zadnjih kamnov v mozaiku naravnih dejavnikov, ki še manjkajo, da bomo lahko v celoti razumeli ekološke razmere za uspevanje podvodnega rastlinstva, pa tudi živalstva. To pa bo dalo znanstveno podlago za razumevanje in ustrezno varovanje krhkega ter v Sloveniji edinstvenega življenjskega okolja.