Physical and chemical properties in relation to soil permeability in the area of the Velika Gorica well field

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Abstract

Hydraulic parameters affect the behaviour of various ions in soils. The goal of this paper is to get a better understanding of the relationship between physical and chemical properties and soil permeability at the location of the case study soil profile Velika Gorica, based on physical and chemical data. The soil profile is situated in the Eutric Cambisol of the Zagreb aquifer, Croatia. The Zagreb aquifer represents the only source of potable water for inhabitants of the City of Zagreb and the Zagreb County. Based on the data obtained from particle size analysis, soil hydraulic parameters and measured water content, unsaturated hydraulic conductivity values were calculated for the estimation of soil profile permeability. Soil water retention curves and unsaturated hydraulic conductivities are very similar for all depths because soil texture does not change significantly through the depth. Determination of major anions and cations on soil samples was performed using the method of ion chromatography. The results showed a decrease of ions concentrations after a depth of 0.6 m. SAR distribution in the soil profile shows that SAR values are not significantly changing in the soil profile. The highest CEC and EC values are determined in the horizon Bw developed at a depth of 0.6 m which is consistent with the highest SAR value and ion concentrations. All results suggest that physical and chemical properties of the investigated profile are related to soil permeability.

1. Introduction

Due to human activity, groundwater composition and quality can be affected by various contaminants. The unsaturated zone mostly presents a barrier for many contaminants, although in some cases, it can act as a medium for the transport of potential contaminants to groundwater bodies. Throughout history, numerous equations were suggested for the construction of soil water retention curves. **Buckingham (1907)** calculated the first equations and created SWRC. Among the most used equations are those of **Brooks & Corey (1964)**, **Van Genuchten (1980)** and **Fredlund et al.** (1994). Analyses have shown that water flow through soil is directly proportional to the hydraulic conductivity (**Fredlund et al., 1994**). Theoretical soil water retention curves (SWRC) and associated unsaturated hydraulic conductivities can be used for the estimation of soil permeability based on the variation of water content (**Ružičić et al., 2017**). Even though different values of hydraulic conductivity can be used as a boundary between permeable and impermeable materials, in this research, the

value of 1E-9 m/s was used, as suggested by **Terzaghi & Peck (1967)**. The sodium adsorption ratio (SAR) can be used as an indicator of the potential damaging effects of calcium, magnesium and sodium ions on soil structure and permeability (**Subramani et al., 2005**). Sodium is a unique cation because of its effect on soil as it causes adverse physicochemical changes in the soil, particularly to the soil structure (**Rosu et al., 2014**). Excessive sodium ions on the exchange complex enhance swelling and dispersion which may have profound effects on soil structural stability of the soil matrix and a decrease in permeability (**Keren & Ben-Hur, 2003**) with a decrease in electrolyte concentration, particularly with increased SAR. For example, an increase in SAR values can cause soil structural deterioration through clay swelling and dispersion, and by slaking of silt-sized micro-aggregates (**Abu-Sharar et al., 1987**) blocking the water conducting pores. Among SAR, cation exchange capacity (CEC) and electrical conductivity (EC), in combination with other physical and chemical soil properties (soil texture, organic matter, etc.), can be related to soil permeability. **Chaudhari et al. (2014)** found high correlations between electrical conductivity and physical properties of soils. Soils with higher CEC values have a smaller per-
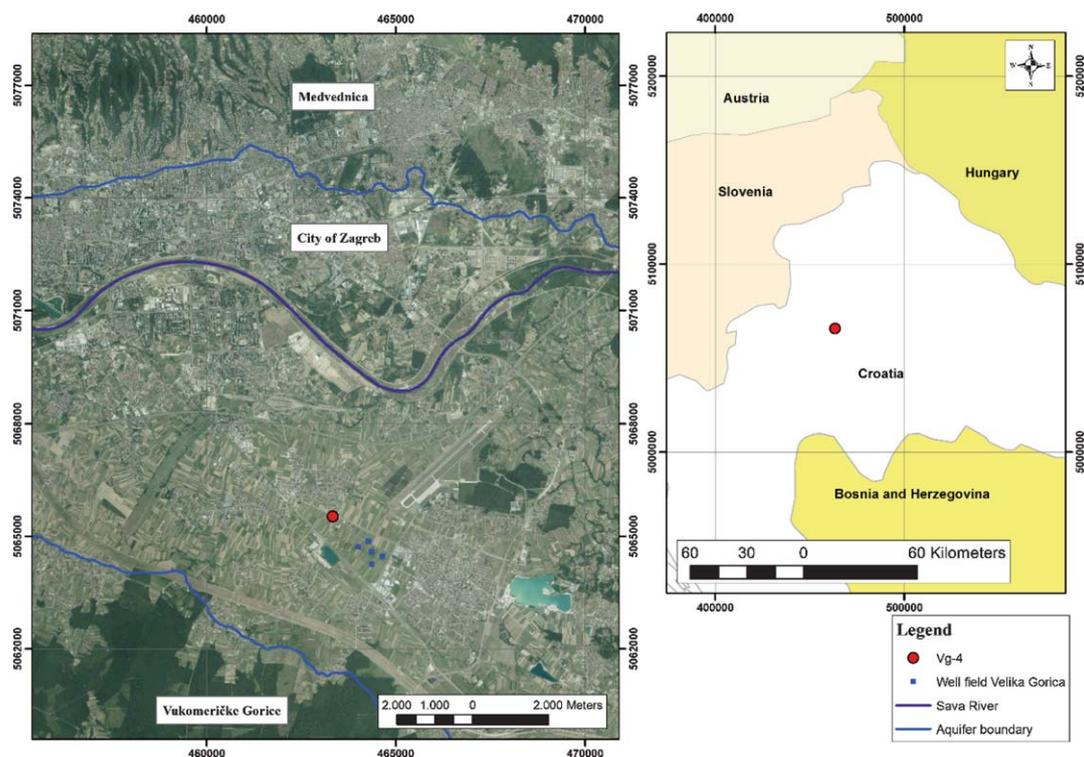
Figure 1: Location of the study area and soil profile Vg-4

meability. **Ružičić et al. (2016)** found the minimum CEC value in soil horizon with maximum hydraulic conductivity.

The main objectives of the investigation were: (1) to estimate soil profile permeability using particle size distribution and related hydraulic parameters, determined water contents and associated unsaturated hydraulic conductivity values; and (2) to examine whether physical and chemical properties are related to soil permeability.

2. Area description

2.1. Location

The study area is in the vicinity of well field Velika Gorica, which is located in the southeastern part of the Zagreb aquifer (**see Figure 1**). The well field consists of five wells drilled to a depth of 35.8 m up to 46 m. These wells provide water supply for the City of Zagreb and the City of Velika Gorica.

Variable lithology, pedological features (**Bogunović et al., 1996**) and land use characterize the study area. The study area consists of a large alluvial plain that has two marked geomorphological features: the raised sealed terrace of the Sava River (varying in width down the rivers length), and a Holocene terrace (**Nakić et al., 2013**). Numerous meanders of the Sava River inundated fluvial cones and numerous bowl-shaped depressions abound in the alluvial plain. According to the **Zaninović et al. (2008)** in the study area, a moderate continental climate prevails. The summers are hot and dry and the winters are

cold. Meteorological station Pleso is located about 3 km from the well field Velika Gorica. The measurements were carried out at the Pleso station in the period from 1981 to 2008. According to the measured data in the observed period, the average annual air temperature was 11 °C. At the meteorological station Pleso, the amount of precipitation was also measured. For the observed period, the average annual rainfall was 929.6 mm.

2.2. Geological and hydrogeological characteristics

The Zagreb aquifer is built from three types of deposits that are predominantly consisting of sand, gravel and silts or silty clays. These deposits were mainly formed during the Pleistocene and the Holocene. Eroded material was carried by the streams and deposited in the lakes and the swamps (**Velić & Saftić, 1991**). At the beginning of the Holocene, the climatic and tectonic processes enabled the penetration of the Sava River which began to transport materials from the region of the Alps (**Velić & Durn, 1993**). The transport of materials was with a variable intensity because of the frequent climate changes. During the hot and humid period, transport was intensive, while its intensity subsided during dry and cold periods. Apart from the climate change, tectonic movements also influenced the processes of deposition (**Velić et al., 1999**). The main consequences of this condition of deposition were extreme heterogeneity and anisotropy of the aquifer and the uneven thickness of the deposits. For this reason, the thickness of the aquifer is variable, with the main trend of increasing thickness from the west to the east.

The study site consists mainly of Quaternary deposits. These deposits are consisting of Pleistocene non-carbonate loess, Holocene alluvium of the first terrace of the Sava River, flooding sediments and alluvium splay sediments (**Basch, 1981**).

Deposits of the Pleistocene non-carbonate loess are a product of aeolian transport type, mainly transport of silty particles on the surface. Clayey silt is deposited over time under the influence of atmospheric conditions, underground water regime and changes in temperature. Deposits of the second Sava terrace were formed as a result of the accumulation and the erosion activity of water flow in the Holocene. These deposits are mainly made of gravels, sands and sandy/silty clays.

Flooding sediments were created by the deposition of fine-grained material after floods and restoring the river flow in the riverbed. They are sandy-clayey or clayey silts with a transition in the silty clays in grain size. At the top of these deposits, they transferred into a pedological cover under the influence of material decomposition.

Alluvium splay sediments are cut off old meanders of abandoned flows of the Sava River and smaller water flows like the Lomnica River. Abandoned riverbeds are formed as a result of the regulatory work on the impermeable terrains composed of the swamp loess sediments and as a result of natural processes on permeable surface composed of Sava alluvial sediments. These sediments are fine-grained, non-coherent rocks that are composed of clayey silts and silty clays with a significant amount of organic matter (**Basch, 1983**).

There are two different water-bearing layers: the first water-bearing layer with the dominantly alluvial sediments of the Sava River and other water-bearing layer with the dominantly lake – pond deposits. The thickness of the first water-bearing layer is varying from 5 to 10 meters in the western part and up to 40 meters in the eastern part of the layer. This layer contains Holocene alluvial deposits (**Velić & Durn, 1993; Velić et al., 1999**).

The thickness of the second water-bearing layer rises up to 20 meters in the western part of the system, while in the eastern part of the system the thickness is considerably larger and rises up to 60 meters in the Črnkovec area. According to **Velić & Durn (1993)** and **Velić et al. (1999)** the second water-bearing layer contains Pleistocene lacustrine-marshy deposits. Even though they present one hydrogeological unit, geochemical stratification along the depth is recognized (**Marković et al., 2013**).

The general direction of the groundwater flow is from the west to the east/southeast. The groundwater levels mostly depend on the stream-aquifer interaction, which is particularly pronounced in the vicinity of the Sava River (**Posavec et al., 2017**). Apart from this, groundwater levels are also the consequence of the infiltration from precipitation; the infiltration of the porous water-supply and sewage network; the inflow from the Samobor-Zaprešić aquifer in the west; and the inflow

from the southern border of the aquifer in the area of the Vukomeričke Gorice (**Posavec, 2006**).

2.3. Pedology

The study area consists of three main pedological units: Fluvisols, Stagnosols and Eutric Cambisols on the Holocene deposits (**Ružičić, 2013**). According to **Bogunović et al. (1998)**, the pedological profile is situated in Eutric Cambisols on the Holocene deposits. According to **FAO (2006)**, the texture of this soil is mainly silt, in some parts silty loam. According to **Ružičić at al. (2012)**, the thickness of the unsaturated zone in the Zagreb area varies from 2 meters in the SE part to 8 meters in the NW part.

Cambisols occur due to a specific combination of the pedogenetic factors that enable the transformation of the mineral portion of the soil in the zone below the developed humus-accumulation horizon, with the formation of secondary clay minerals and the formation of the cambic horizon (**Husnjak, 2014**). The presence of the clayey cambic horizon with the structure of pedological profile A– (B) v-C is characteristic for the specified soil. In the area of the Zagreb aquifer, Cambisols were developed at fluvial loamy deposits where groundwater reaches a depth of 1 m. It is characterized by good air-water relations and weak, acid reaction of the soil (**Husnjak, 2014**).

3. Materials and methods

Field research was conducted in the spring of 2016 in the area of the well field Velika Gorica, which is located west of Velika Gorica City. The field research consisted of borehole drilling, sampling, description of the pedological profile and morphological description of the soil horizons.

Six disturbed soil samples for laboratory analysis were collected from soil horizons. Soil samples were air-dried and passed through a 2 mm sieve for laboratory analysis. The laboratory analysis included water content determination, particle size distribution, electrical conductivity determination and quantification of anions and cations by the ion chromatography method with the Dionex Ion Chromatography system (ICS-90). Water content was obtained by the gravimetric method of **Black (1965)**. Soil particle size distribution was determined by the pipette method with sieving and sedimentation after dispersion with sodium pyrophosphate, and interpreted according to **FAO (2006)**. Electrical conductivity of soil was measured in water with a 1:5 soil to water ratio using a Mettler Toledo MPC 227 EC meter.

Ion chromatography is a technique with which the ions can be separated and detected. The ICS-90 system performs isocratic ion analyses by using suppressed conductivity detection. This method was used to determine the concentrations of sodium (Na^+), potassium (K^+), am-

monium (NH_4^+), magnesium (Mg^{2+}), calcium (Ca^{2+}), chlorides (Cl^-), nitrates (NO_3^-), nitrites (NO_2^-) and sulphates (SO_4^{2-}) in each soil horizon. The steps of sample preparation for ion determination are described in detail. Each soil sample (10 g) was put in a 100 mL glass and diluted with ultra-pure water (conductivity less than 1 µS/cm) to rest overnight. After that, samples were put on a shaker for 1 hour. Suspensions were then centrifuged at 3000 rpm for 20 min and filtrated.

Particle size analysis results for every pedological horizon are shown in **Table 1**, while soil hydraulic parameters are shown in **Table 2**. Rosetta Lite software (**Schaap et al., 2001**) was used to estimate soil hydraulic parameters without taking into account bulk density of the soil. Theoretical soil water retention curves and estimated unsaturated hydraulic conductivities (**Van Genuchten, 1980**) were constructed and calculated using **Equations 1-4**:

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + \left(\alpha |\Psi| \right)^n \right]^m} \quad (1)$$

$$n = \frac{1}{1-m} \quad (2)$$

$$\alpha = \frac{1}{h_b} \left(2^{1/m} - 1 \right)^{1-m} \quad (3)$$

$$K\left(\theta \right) = K_s S_e^{1/2} \left[1 - \left(1 - S_e^{1/m} \right)^m \right]^2 \quad (4)$$

Where:

θ_r – residual water content (m^3/m^3),
θ_s – saturated water content (m^3/m^3),
h_b – bubbling pressure (m),
$K(\theta)$ – unsaturated hydraulic conductivity (m/day),
K_s – saturated hydraulic conductivity (m/day),
S_e – effective saturation (%),
ψ – matric potential (m),
α – (1/m), n and m are parameters which depend on the slope of the curve (**Van Genuchten, 1980; Fetter, 1999**).

Unsaturated hydraulic conductivities were placed into function of determined water content for each horizon, while the hydraulic conductivity value of 1E-9 m/s was used as a boundary for the definition of impermeable and permeable soils. SAR was calculated using **Equation 5** (**Sposito & Mattigod, 1997**) where cation concentrations are represented in meq/L.

$$SAR = \frac{\left(Na^+ \right)}{\sqrt{\frac{\left(Mg^{2+} \right) + \left(Ca^{2+} \right)}{2}}} \quad (5)$$

Cation exchange capacity (CEC) is a measure of the soil's ability to hold positively charged ions. This soil property influences soil structure stability, nutrient availability, soil pH and the soil's reaction to fertilisers and other ameliorants (**Hazleton & Murphy, 2007**). The steps of sample preparation for CEC determination are described in detail. All soil samples (150 mg) were put in a 50 mL glass along with 1M NH_4Ac to rest overnight. The prepared solution was filtrated (0.45 µm) and 50 mL of 1M NH_4Cl was added. The solution was then filtrated again and 50 mL of isopropyl alcohol was added. After that, the samples on the filter paper were air dried. For moisture loss, samples were dried in an oven at 70°C for 1 hour. Determination of CEC was carried out using an ammonia electrode according to **Busenberg & Clemency (1973)**.

The CECs of the samples were obtained from the **Equation 6**:

$$CEC = \frac{c(NH_3) * V(suspension)}{w(sample) * f} \quad (6)$$

Where:

CEC – Cation Exchange Capacity (cmol(+)/kg),
c – concentration of ammonia (mol/L),
V – volume of water added (L),
w – weight of the sample (g),
f – a conversion factor, $f=10^{-5}$.

4. Results and discussion

According to **Table 1** water content is the highest in Bw horizon, from 0.2 to 0.4 meters, while it is the lowest in Bw horizon, from 0.6 to 0.8 meters. In Bw horizon from 0.2 to 0.4 meters, the sandy component is smaller than in the horizon from 1 to 1.2 meters.

Figure 2 shows theoretical soil water retention curves for each pedological horizon. Curves were constructed using soil hydraulic parameters (**see Table 2**). According to the results, soil water retention curves are very similar for all depths because soil texture does not change significantly through the depth.

Figure 3 shows theoretical unsaturated hydraulic conductivity at different depths of pedological profile. Theoretical unsaturated hydraulic conductivity ranges are also similar because of almost the same soil content at different depths. **Figure 3** suggests that at water content about 0.2, the soil becomes impermeable. Due to very low water content (from 4 to 7 %) at the time of sampling, very low values of the unsaturated hydraulic conductivities were obtained, which suggests that, at the sampling time, the soil was impermeable. Saturated hydraulic conductivity (K_s) in studied soil horizons were in the range from 1.9E-6 m/s to 3.3E-6 m/s. According to **Horel et al. (2015)** Cambisol has K_s of 2.2E-6 m/s in the first 0.1 meters which is in line with this study where Ks is 2.2E-6 m/s.

Table 1: Water content and soil texture for analysed soil horizons

Soil horizon	Depth (m)	Water content (-)	Sand (%)	Silt (%)	Clay (%)	Soil texture
A	0-0.2	0.0464	2.42	87.43	10.15	silt
Bw	0.2-0.4	0.0740	1.80	89.54	8.65	silt
	0.4-0.6	0.0521	1.46	87.59	10.95	silt loam
	0.6-0.8	0.0414	2.72	84.97	12.32	silt loam
C	0.8-1	0.0468	4.77	82.00	13.23	silt loam
	1-1.2	0.0415	3.84	89.78	6.37	silt
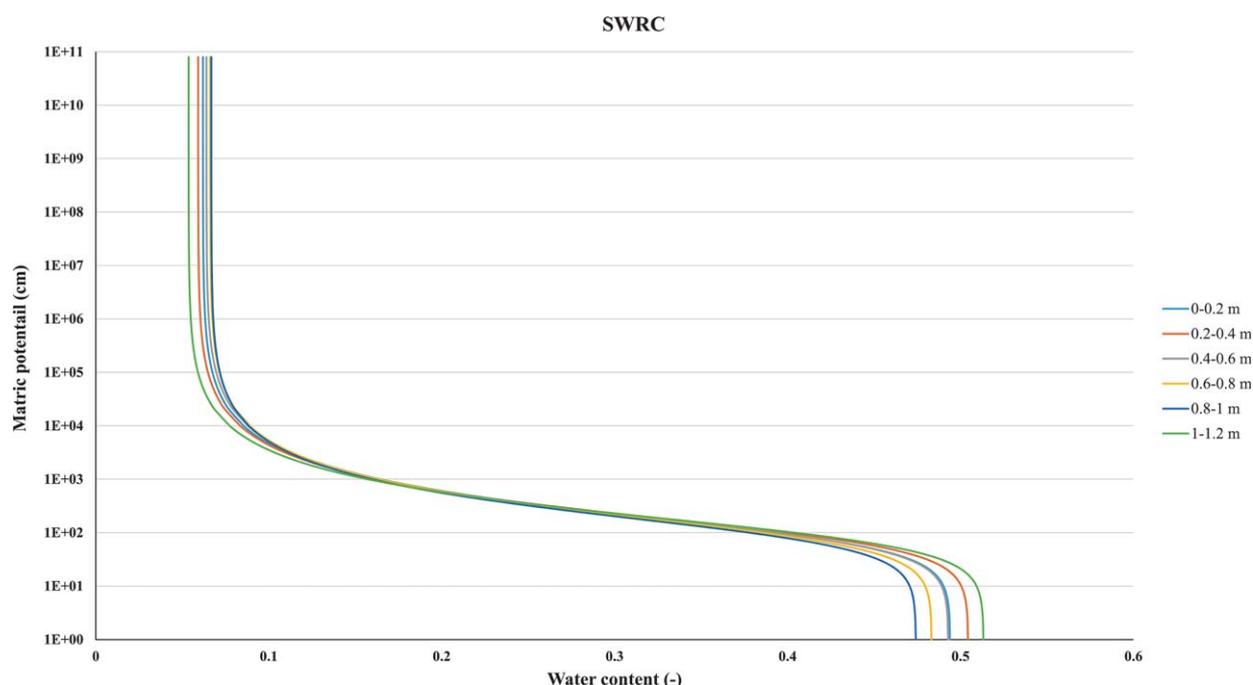
Figure 2: Theoretical SWRC (without bulk density) for all pedological horizons

Table 2: Soil hydraulic parameters of the soil profile Vg-4 in the area of the Velika Gorica well field

Soil horizon	Depth (m)	θ_r	θ_s	α (1/cm)	n	m	K_s (m/s)
A	0-0.2	0.062	0.4940	0.0076	1.6328	0.3876	2.2E-6
Bw	0.2-0.4	0.0592	0.5044	0.0081	1.6319	0.3872	2.3E-6
	0.4-0.6	0.0640	0.4929	0.0077	1.6261	0.3850	1.9E-6
	0.6-0.8	0.0661	0.4833	0.0071	1.6295	0.3863	1.9E-6
C	0.8-1	0.0668	0.4742	0.0065	1.6381	0.3895	2.0E-6
	1-1.2	0.0537	0.5133	0.0081	1.6437	0.3916	3.3E-6

Figures 4 and **5** show the distribution of the anions and cations in the soil profile according to the results of ion chromatography (**see Table 3**). Cations and anions have higher concentrations up to a depth of 0.6 m, while deeper depths have decreasing concentrations. Elevated concentrations of calcium could be derived from different types of chemical fertilizers and manure as reported in **Puckett & Cowdery (2002)** and **Kaown et al. (2007)**. High concentrations of chlorides could be related to ag-ricultural activity (**Rodvang et al., 2004**), but also to urban pollution sources such as leaking sewage systems (**Jeong, 2001; Moratalla et al., 2009**) or infiltration of waste water from landfills (**Nakić et al., 2007**). It seems that particle size distribution and very low water content level, which is in line with very low unsaturated hydrau-lic conductivity values, are associated with the general decrease of most ion concentrations in the lower part of the soil profile. However, the lowest *Ks* values are found

at Bw/C boundary which suggests the potential existence of some kind of barrier, which is in line with generally the lowest concentrations of almost all observed ions.

Calculation of the Sodium Adsorption Ratio (SAR) is shown in **Table 4**. SAR distribution in the soil profile shows that SAR values are not significantly changing in the soil profile. For all depths, SAR values were <3. The maximum SAR value (2.41) is at the depth between 0.4

and 0.6 m (**see Figure 6**), where SAR value changes from 1.50 to 2.41, which is consistent with a decrease in ion concentrations. According to **Richards (1954)** classification, all the samples belong to the excellent category.

The highest CEC, CaCO$_3$ and EC values are also determined in horizon Bw from 0.4 to 0.6 meters (**see Table 4**) which is in correlation with SAR values and ion concentrations. **Guang-Ming et al. (2006)** found that SAR influenced EC of the soil-water extract to a differ-
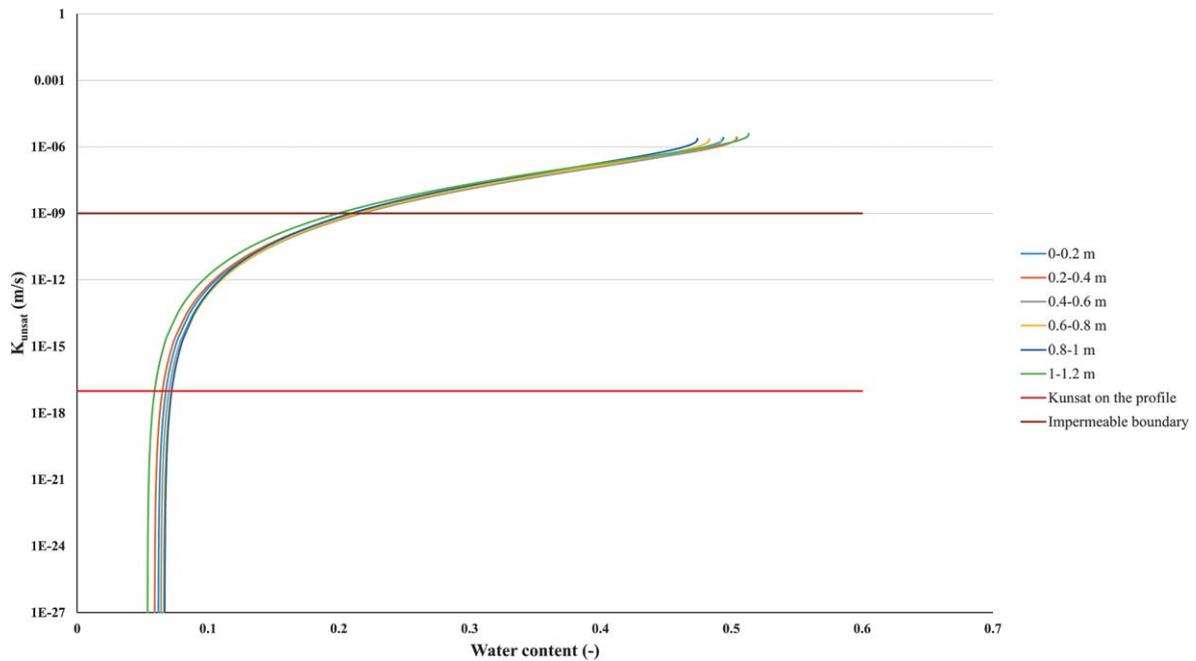

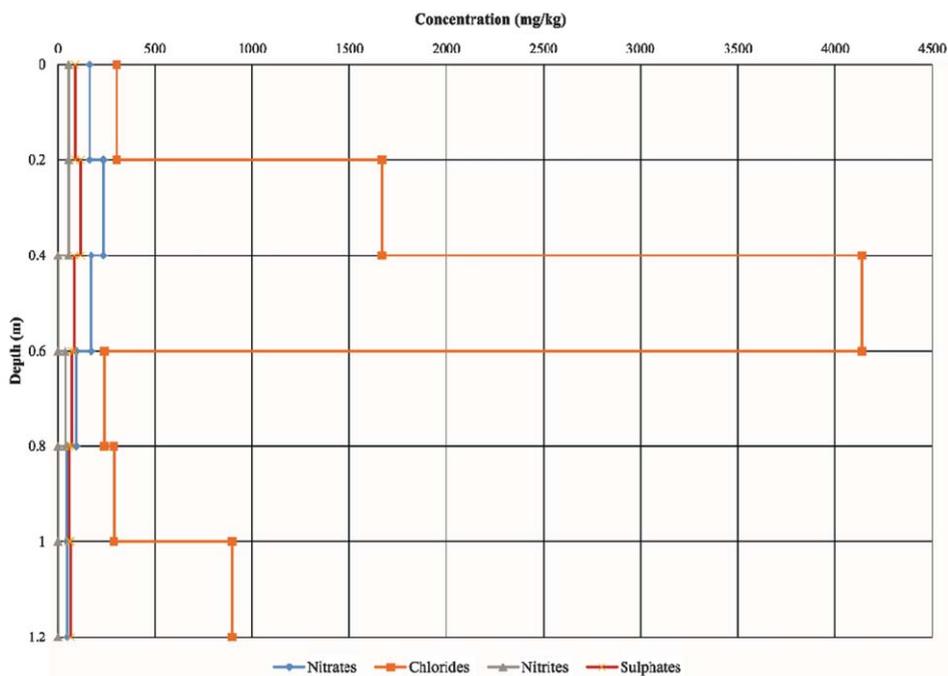**Figure 3:** Theoretical unsaturated hydraulic conductivity at different depths

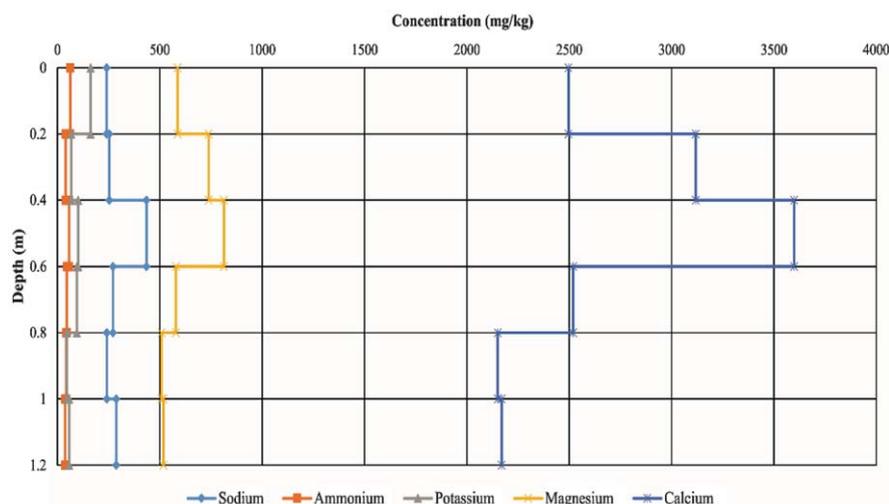**Figure 4:** Distribution of the anions (NO$_3^-$, Cl$^-$, NO$_2^-$, SO$_4^{2-}$) in the soil profile

Figure 5: Distribution of the cations (K^+, Na^+, NH_4^+, Ca^{2+}, Mg^{2+}) in the soil profile

Table 3: Distribution of cations and anions by depth in the soil profile Vg-4. All units are in mg/kg.

Soil horizon	Depth (m)	NO_3^-	Cl^-	NO_2^-	SO_4^{2-}	Na^+	NH_4^+	K^+	Mg^{2+}	Ca^{2+}
A	0-0.2	164.11	302.87	57.83	90.49	241.13	63.81	162.57	587.25	2496.26
Bw	0.2-0.4	234.91	1668.41	57.79	117.2	253.28	39.4	67.92	739.38	3117.91
	0.4-0.6	173.65	4140.04	0.00	85.57	435.26	56.47	102.13	813.68	3598.69
	0.6-0.8	95.34	239.16	39.04	73.27	271.15	46.69	94.87	578.96	2518.98
C	0.8-1	48.41	289.07	0.00	60.55	241.99	42.88	46.34	508.16	2151.49
	1-1.2	50.90	897.19	0.00	67.21	287.67	38.08	57.29	517.50	2169.68

Table 4: Chemical soil properties of soil profile Vg-4

Soil horizon	Depth (m)	Na^+ (meq/L)	Mg^{2+} (meq/L)	Ca^{2+} (meq/L)	SAR (meq/L)	CEC (cmol(+)/kg)	EC (µS/cm)	$CaCO_3$ (%)	OM (%)	pH ($CaCl_2$)
A	0-0.2	10.49	12.08	31.14	1.60	22.91	196.6	7.5	8.06	6.88
Bw	0.2-0.4	11.02	15.21	38.90	1.50	25.71	210.0	14.3	11.46	7.10
	0.4-0.6	18.93	16.74	44.90	2.41	39.78	248.3	19.4	4.6	7.19
	0.6-0.8	11.79	11.91	31.43	1.79	25.78	180.4	13.8	4.07	7.16
C	0.8-1	10.53	10.45	26.84	1.72	35.76	241.3	7.2	12.72	7.14
	1-1.2	12.51	10.65	27.07	2.04	34.01	293.0	5.3	3.77	7.14

ent extent. According to **Grisso et al. (2009)** soil electrical conductivity may influence on CEC values. In this horizon, the proportion of sand and K_s are the lowest, which is also in correlation with all the results. The average CEC value is 30.65 cmol(+)/kg. **Hudec & Feszterová (2013)** in their study of variability in chemical properties of Eutric Cambisol determined CEC values of 31.8 cmol(+)/kg.

5. Conclusion

Particle size distribution and soil hydraulic parameters were used for the construction of soil water retention curves which are very similar for all depths because soil content does not change significantly through the depth. The theoretical unsaturated hydraulic conductivities range is also similar because of almost the same soil water contents at different depths. In addition, low water content values and associated K_{unsat} values suggest that percolation to the aquifer in this study soil profile is very low. Analysed cations and anions generally have higher concentrations to 0.6 m depth of soil profile, while after that depth, concentrations are decreasing. SAR distribution in the soil profile shows that SAR values are not significantly changing in the soil profile. However, the highest CEC and EC values are determined in horizon Bw, from 0.4 to 0.6 meters, which is consistent with generally the highest SAR values and ion concentrations.
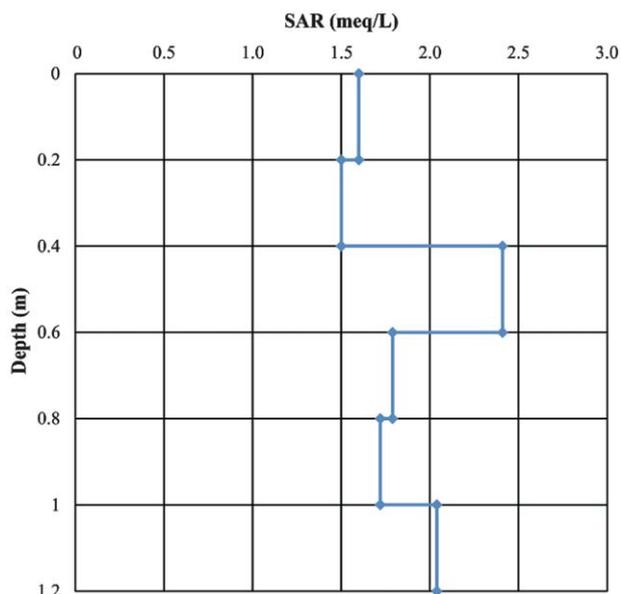
Figure 6: SAR distribution in the soil profile Vg-4

The main difference in chemical properties, generally ion concentrations, CEC and OM, can be seen between 0.4 to 1 m. Due to very small changes in hydraulic conductivities along the soil profile, especially between depths of 0.4 and 1 m, it can be assumed that the mobility of ions is more related to chemical properties of the investigated soil. To conclude, all results of this study suggest that physical and chemical properties are related to soil permeability.

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SAŽETAK

Fizička i kemijska svojstva tla te njihova povezanost s propusnosti tla na području Velike Gorice

Hidraulički parametri utječu na ponašanje različitih iona u tlima. Cilj ovoga rada bio je prikazati odnos između fizičkih i kemijskih svojstva te propusnosti tla u svrhu boljih spoznaja njihove interakcije na području Velike Gorice. Profil tla smješten je u južnome dijelu zagrebačkoga vodonosnika. Zagrebački vodonosnik predstavlja glavni izvor pitke vode za stanovnike grada Zagreba i Zagrebačke županije. Na temelju podataka o teksturi i hidrauličkim parametrima tla te izmjerenim sadržajima vode u tlu izračunate su vrijednosti nesaturirane hidrauličke vodljivosti koje su korištene za procjenu propusnosti tla. Krivulje zadržavanja vode u tlu i nesaturirane hidrauličke vodljivosti slične su za sve dubine. Sadržaj aniona i kationa u tlu određen je pomoću ionske kromatografije. Rezultati su pokazali pad koncentracije iona nakon 60 centimetara dubine, što se slaže s izračunanim vrijednostima nesaturirane vodljivosti koje upućuju na dominantno nepropusno tlo. Najveće vrijednosti CEC-a i EC-a određene su u horizontu Bv ispod 60 cm, što je u skladu sa najvećim vrijednostima SAR-a i koncentracijama iona. Svi rezultati upućuju na to da su fizička i kemijska svojstva istraživanoga profila tla povezana s propusnosti tla.

Ključne riječi
kapacitet izmjene kationa, sadržaj vode u tlu, propusnost tla, eutrično smeđe tlo

Authors contribution

Stanko Ružičić was main author of this paper. He made goals and gave possible conclusions of this research. **Zoran Kovač** made retention curves, calculated unsaturated hydraulic conductivities, and contribute in results interpretation. **Dražen Tumara** did field work and made laboratory measurements of analysed parameters.