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Soil water and stable isotopes in the unsaturated zone profile – field observations and analysis

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Abstract. In this review, we provide research data emphasizing the role of groundwater table and hydrometeorological parameters variation on soil water fluctuations in the unsaturated soil profile. We focused on soil water content, air temperature, precipitation and groundwater table observations. The ThetaProbe Soil Water Sensors basing on changes in the apparent dielectric constant were used for soil volumetric water content measurements. The sensors were installed at the different depths of the unsaturated zone profile under natural atmospheric conditions. The observations lasted more than five years (14 November 2013 – 31 December 2018). Groundwater table data was obtained using Diver data loggers, which continuously recorded water pressure and temperature. For more detailed investigations of water and mass transport at the Maišiagala radioactive waste repository site water, stable isotopes as environmental tracers were used as well.

Keywords: *volumetric water content; groundwater table; Diver data loggers*

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INTRODUCTION

The unsaturated zone is an important part of the water circulation cycle and an environmental compartment for many hydrological and hydrogeological factors and processes. Soil water variability during hydrological processes was studied in various aspects, see e. g. Rodriguez-Iturbe 2000; Eagleson 1978; Zhang, Schilling 2005; Corradini 2014; Basile, Coppola 2019; Keith *et al.* 2008; Kutilek, Nielsen 1994; Ali *et al.* 2010; Schilling *et al.* 2008, Anctil *et al.* 2008. Soil water is an essential component of the atmospheric water cycle both on a large scale in relation to the transfer of water from the land surface to groundwater and vice versa and on a small scale when it comes to agricultural issues. The role of soil processes in relation to the function of the earth system was discussed in Robinson *et al.* (2009).

The effect of spatial variability of initial soil water and soil hydraulic properties on the runoff was assessed using a rainfall runoff model (Merz, Plate 1997). The influence of land cover on water table, soil water and evapotranspiration has been studied under various land cover scenarios by Zhang, Schilling (2005). It has been evidenced that land cover has a significant effect on soil water and groundwater table. The main method for measuring soil water content is a gravimetric method. However, gravimetric sampling disturbs the soil structure and makes it impossible to repeat measurements on the same soil sample. Indirect methods use a device placed in soil to measure a specific characteristic of the soil related to its water. Indirect methods are widely used in studies as an alternative to gravimetric determination. These methods are called “indirect” because they cannot measure the amount of soil water directly, but they do measure the values of some other variables from which the amount of soil water can be calculated. The data obtained from the measurements are immediately available, and the measurements can be repeated several times in the same place, can be recorded continuously and controlled by a computer. Over the past decades, many datasets have been produced on soil water using various instruments (Owe *et al.* 2001; Njoku *et al*. 2003; Naeimi *et al.* 2009; Huisman *et al*. 2001; Cardell-Oliver *et al.* 2005; Kerr *et al*. 2001; Robock *et al.* 2000; Pablos *et al.* 2016; Alvarez-Garreton *et al.* 2014). Remote sensing is a valuable tool for measuring soil water on a global scale (Robock *et al.* 2000), but in situ measurements are needed for the calibration and validation of the data on soil water (Zazueta, Xin 1994; Gardner 1986; Tanrıverdi 2005; Zhou *et al*. 2014). The quality of measurements was studied in many research works (Su *et al*. 2013; Albergel *et al.* 2012). The methodology to combine VUA-NASA passive microwave and TU-Wien active microwave soil water retrievals to produce an improved global long-term soil water dataset has been presented in Liu *et al.* (2012). Such a multi-decadal and growing combined remotely sensed soil water record is expected to help further understanding of the role of soil water in water energy and carbon cycles. Using remote sensing it is possible to see seasonal and short-term changes in soil water. The daily pattern of changes in water content in the upper soil layers and the mechanism by which water is added to the soil was studied in Agam, Berliner (2004). The possibility to use soil water content to estimate evapotranspiration and root water uptake profiles was presented in Guderle, Hildebrandt (2015). The results of the study showed that highly resolved (temporal and spatial) measurements of soil water content contain a great deal of information which can be used to estimate the sink term when an appropriate approach is used.

In this study, our objective was to find out soil water content fluctuation under natural conditions and the factors influencing it. To achieve this, we provided unsaturated zone characterization, a detailed record of soil volumetric water content and groundwater table, as well as measurements of stable isotopes of soil water.

ENVIRONMENTAL SETTINGS, METHODS AND MATERIAL

Our study focused on the analysis of the spatial – temporal variability of soil water content data collected from the soil profile at the Maišiagala radioactive waste repository site, Lithuania. The Maišiagala repository site (Fig. 1; 54°53'19"N, 24°57'28"E, WGS) is located in the 53rd quarter of the Green Forest District in Bartkuškis Forest, Širvintos district. It is about 7 km northwest of the town of Maišiagala and about 30 km in the same direction from the capital Vilnius.

The Quaternary glacial deposits occur on the top of sedimentary cover. The deposits were settled by

Fig. 1 Site location (54°53'19"N, 24°57'28"E, WGS) is marked in red square and given in a simplified scheme of the investigated profile together with locations of 6 ThetaProbe sensors for soil moisture measurement and Diver data logger for groundwater level observation (blue triangle and number show the average depth of groundwater table over the entire observation period)

glacier melt waters and consist of sand, gravel, pebble, loam and sandy loam. The thickness of the Quaternary formation is 100–120 m (Juodkazis 1979). Eolian fine grained sands are present in the region with the thickness of more than 10 m. The experimental measurements of the volumetric water content in the soil at the site of the repository were carried out using a Soil Water Logger with 6 ThetaProbe sensors. The groundwater table and water temperature records were obtained using the Baro-Diver P7422 data logger that measures and records atmospheric pressure, and the Diver P7693 data logger that measures and records pressure and temperature in a piezometer. The data recording was started on 28 October 2013 using a data logger P7693 for recording pressure and temperature in the piezometer and a sensor P7422 for recording atmospheric pressure and temperature. The equipment consists of a data logger for measuring water pressure and water temperature, a memory storage device, and a battery. The data loggers capture the pressure (water pressure + atmospheric pressure), which can be expressed in meters, centimetres, kPa, etc. In order to calculate water table fluctuations based on the pressure readings in a piezometer, it is necessary to monitor atmospheric pressure data. After performing pressure compensation for atmospheric pressure fluctuations, this method is the most accurate way to monitor changes in water table. In order to get additional information, stable isotope composition of soil water was determined. To perform pore water extraction from unsaturated core samples for isotopic analyses, a water extraction system was designed as described in IAEA (2005). The water stable isotope analysis was carried out using IRMS DELTA V Advantage or Picarro L2120-i Cavity Ringtown Spectrometer in the Laboratory of Isotope-Palaeoclimatology of the Institute of Geology at Tallinn University of Technology, Estonia. The isotope data were reported as $\delta^{18}O$ and $\delta^{2}H$ values and expressed as per mille deviations with respect to the international standard (V-SMOW) with the reproducibility of ±0.1‰ for $\delta^{18}O$ and ±1‰ for $\delta^{2}H$ (Coplen 1996).

RESULTS AND DISCUSSION

The data on grain size distribution and hydraulic properties of unsaturated soil of the investigated profile at the Mašiagala repository site are presented in detail in Table 1 and Figs 2–3.

Based on grain size analysis data, the soil of the unsaturated zone is characterized by fine (0.063–0.2 mm) to medium (0.2–0.63 mm) sands (Table 1, Fig. 2). The hydraulic conductivity of the soil under full saturation conditions was determined according to the scheme of the falling head method, when water flow is laminar. The values of saturated hydraulic conductivity (Ks) are in the range of 1.5–3.9 m/day, with an average value of 2.3 m/day (Skuratovič 2013). Based on these grain size distribution and hydraulic properties data, the unsaturated zone soil at the Maišiagala repository site is homogeneous.

The unsaturated zone has no low permeability soil layers. The saturated hydraulic conductivity changed insignificantly from 0.9 to 3.9 m/day (Fig. 3).

The highest hydraulic conductivity was observed at the depths of 120–140 cm and 450–500 cm with values of 3.9 and 3.7 m/day, respectively. The lowest Ks (0.9 m/day) was observed at a depth of 400–450 cm. However, even the lowest Ks value was relatively high in terms of water permeability. Due to high permeability of soil in the unsaturated zone of the Maišiagala repository site, the water transit time in the studied soil profile was short and the unsaturated zone became saturated very quickly. The sandy profile of the unsaturated zone did not hold much water because particles acted as single grains. Sandy soils have a relatively large pore space between par-

Table 1 Grain size distribution and hydraulic properties of the investigated soil profile at the Mašiagala repository site

Depth cm	Ks m/day	<0.002	0.002–0.0063	0.0063–0.02	0.02–0.063	0.063–0.2	0.2–0.63	0.63–2	>2
		mm							
0–20	2.3	0	0	0	0.29	62.23	37.39	0.09	0
20–40	2.2	0	0	0	0.15	43.42	56.18	0.25	0
40–60	2.3	0	0	0	0.16	54.19	40.43	0.02	0
60–80	2.4	0	0	0	0.16	54.19	44.63	0.94	0
80–100	2.9	0	0	0	0.30	57.41	41.78	0.51	0
120–140	3.9	0	0	0	0.71	84.61	14.60	0.08	0
140–160	2.1	0	0	0	0.59	79.75	19.45	0.21	0
200–220	2.3	0	0	0	0.48	80.32	19.12	0.08	0
280–300	1.7	0	0	0	1.31	77.39	21.08	0.19	0
340–360	1.5	0	0	0	0.53	74.97	24.36	0.12	0
360–380	1.8	0	0	0	0.77	63.73	35.38	0.12	0
400–450	0.9	0	0	0	1.03	63.89	34.67	0.41	0
450–500	3.7	0	0	0	1.34	71.34	27.03	0.39	0

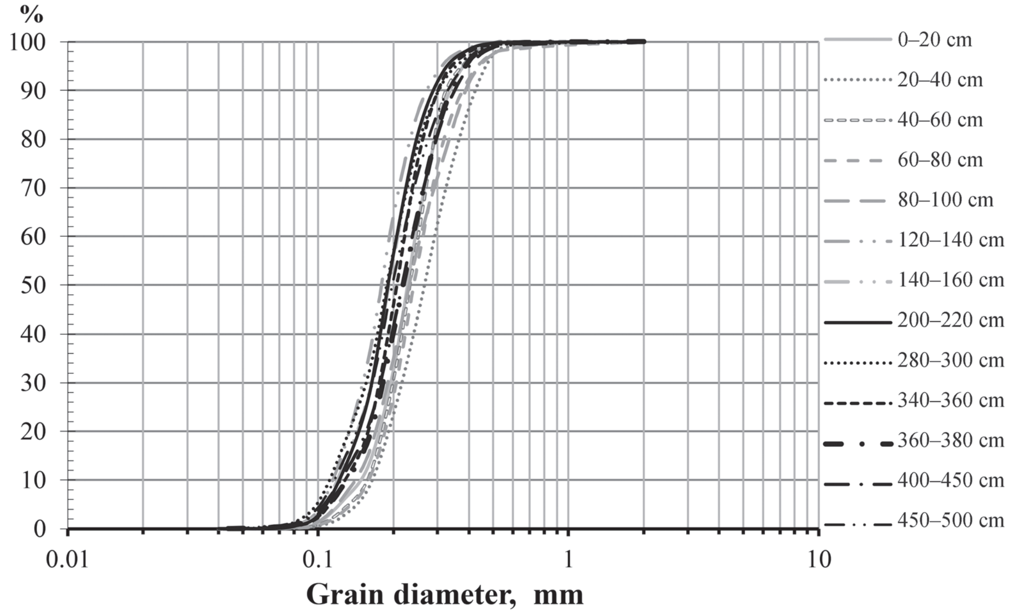

Fig. 2 Grain size distribution curves at different depths of the soil profile at the Maišiagala repository site

ticles, which provides rapid downward percolation of water.

The water content in the soil profile was measured and stored using 6 ThetaProbe sensors during the observation period 14 November 2013 – 31 December 2018 (Fig. 4).

The most variable water content was at the upper boundary of the soil profile; deeper in the profile, the change in water content became more and more smooth. Basing on soil water content and its variation over time, three characteristic sub-zones can be distinguished in the soil profile. The first sub-zone is attributed to the upper boundary of the soil profile and can be characterized by water content features of two depths, 50 and 100 cm. This sub-zone is obviously under the influence of evaporation, precipitation, and soil freezing resulting in water content variations with a high frequency and a fairly large amplitude.

The water content at the depths of 250 and 300 cm did not change much over time, except for 2018. The water content at a depth of 300 cm reacted markedly to changes in the groundwater table during the period of 2018, when the groundwater table reached its highest position. The temporal variability of soil water at a depth of 400 cm and with the greatest amplitude at a depth of 470 cm was found to be significantly correlated with fluctuations in the groundwater table (Fig. 4).

In addition to the time series analysis, we compared the vertical distribution of soil water content in the unsaturated zone profile (Fig. 5).

As in the time series of water content, three distinct above-mentioned zones with different responses to environmental conditions could be seen in water content distribution along the soil profile. The soil water content fluctuations at a depth of 50 cm correlated with air temperature changes in January, February and March (Fig. 6). In summer, especially in June and August, it was the amount of precipitation that exerted the main influence on fluctuations in soil water at a depth of 50 cm (Fig. 7). The highest values of water content at the 50 cm depth occurred in the periods after air temperature changed from negative values to above 0°C. Data on the depth of soil freezing are attributed to a number of applications (Bayard *et al.* 2005; Vasilyev 1994). According to various studies, it can take from 2 to 3 weeks from the start of thawing for the frozen layer to dissipate. The soil wa-

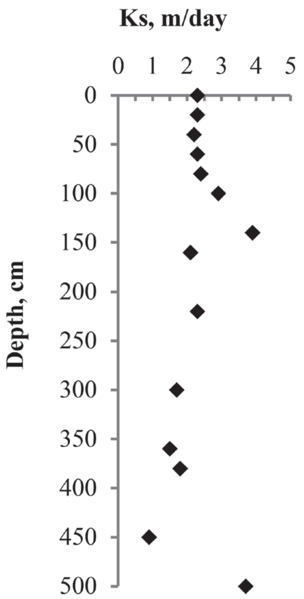

Fig. 3 Saturated hydraulic conductivity (K_s (m/day)) variation with depths of the soil profile at the Maišiagala repository site

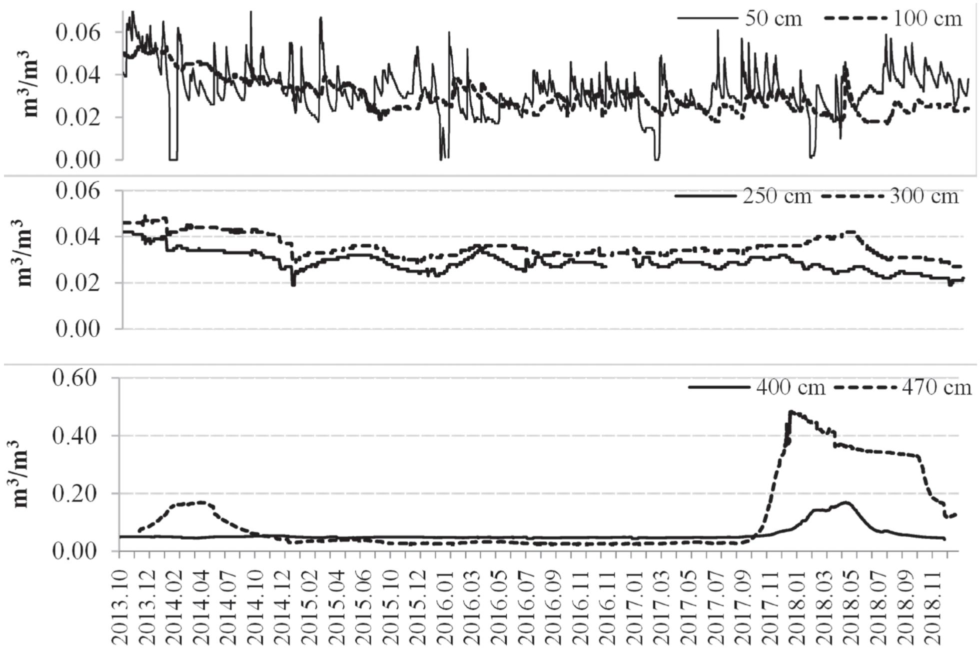

Fig. 4 Temporal changes in volumetric water content at different depths of the soil profile in the period 2013–2018

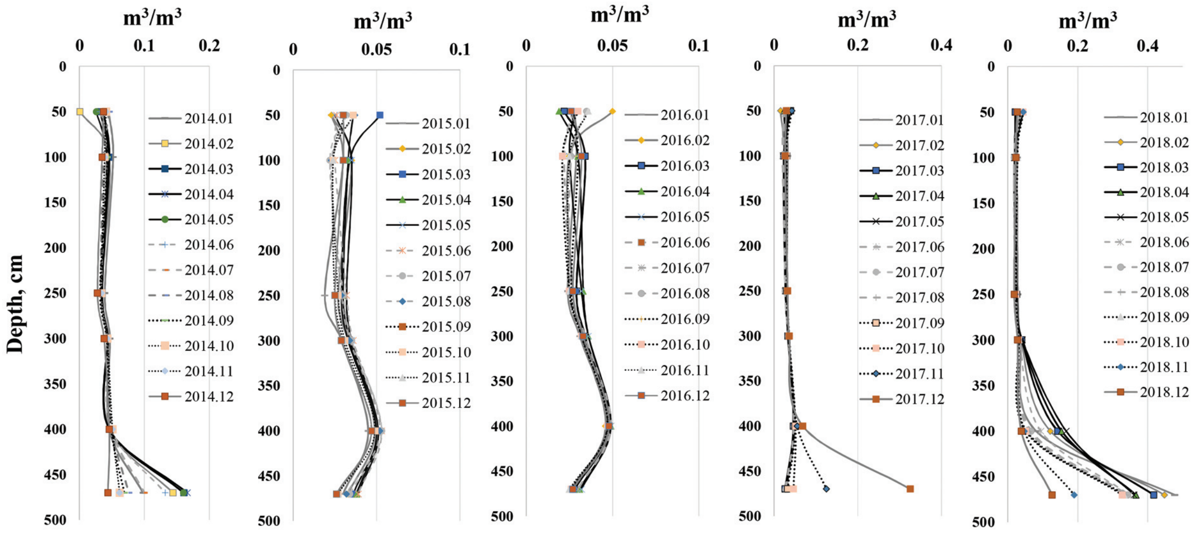

Fig. 5 Volumetric water content distribution versus depth in 2014–2018 (curves correspond to the first day of the month)

ter dynamics also varies with the time and thickness of snow cover, as presented in Iwata *et al*. (2010).

The performed observations showed the dependence of water content both on the number of days with negative air temperature and on its values. During the observation period, water content equal or close to 0 m^3/m^3 was measured 4 times: in January–February 2014, January 2016, February 2017, and January 2018. When soil temperature decreases, liquid water content also decreases, which affects the decreasing of the measurement signal. During the freezing period, the soil water curve had a sharp decline at a temperature of about –10°C (Fig. 6). The curve roses again as soon as air temperature rose above 0°C and water content reached water table prior to soil freezing. The highest values of water content were measured in winter and summer periods (0.065 m^3/m^3 and 0.075 m^3/m^3, respectively), while the mean value was 0.033 m^3/m^3 for the entire observation period (Table 2).

The daily measured precipitation data are shown in Fig. 7. The largest amount of precipitation during the observation period was in summer from June to August.

The water content at a depth of 100 cm ranged from 0.017 m^3/m^3 to 0.054 m^3/m^3 with an average value of 0.030 m^3/m^3 (Fig. 4, Table 2). There were no pronounced changes in soil water content between seasons, with the lowest values of soil water content recorded in winter, late spring, and early summer. There was a downward trend in water content values,

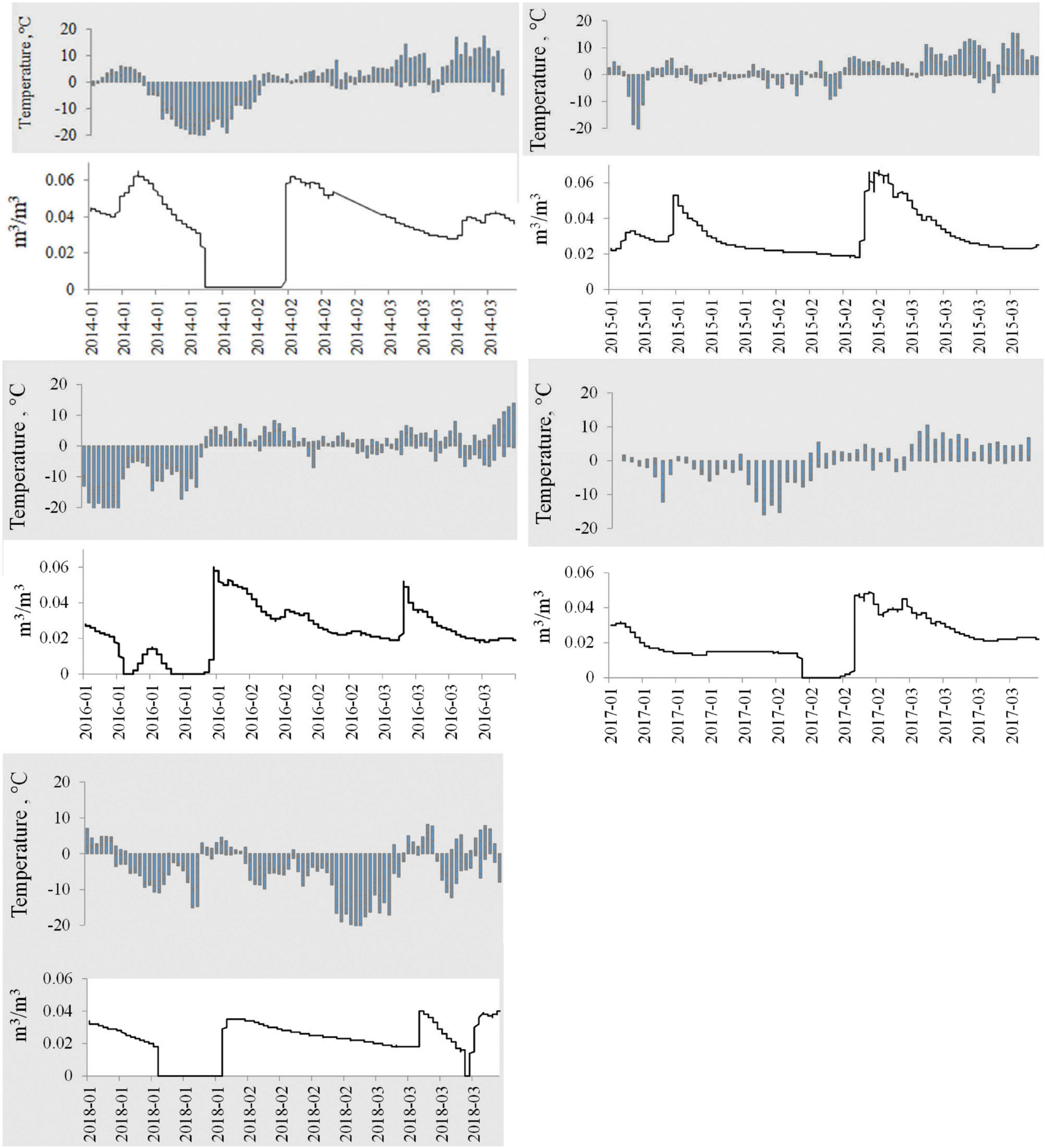

Fig. 6 Changes in volumetric water content at a depth of 50 cm and air temperature in January, February and March

starting from the highest position observed in October 2013 till July 2015; very similar trends were observed annually.

At a depth of 250 cm, fluctuations in soil water content were not of a large amplitude. The mean value was 0.029 m^3/m^3, which was very close to the value measured at a depth of 100 cm. A minimum value (0.019 m^3/m^3) was measured in 2014, 2015, and 2018. The highest value of soil water content (0.042 m^3/m^3) was observed in 2013; in other years, water content did not exceed 0.034 m^3/m^3. The depth of 250 cm was characterized by the lowest average water content and the smallest amplitude compared to other depths over the entire observation period.

According to a logger installed at a depth of 300 cm, the water content values varied from 0.027 m^3/m^3 to 0.049 m^3/m^3. The largest difference between the lowest and highest values was measured in 2018, when a noticeable effect of groundwater table fluctuations was observed. The mean value of water content at a depth of 300 cm was 0.036 m^3/m^3.

At a depth of 400 cm, water content ranged from

Table 2 Statistical parameters of volumetric water content data recorded by 6 sensors installed at different depth

Year	Depth	Mean value	Standard deviation	Minimum	Month minimum	Maximum	Month maximum
	cm	m^3/m^3	m^3/m^3	m^3/m^3		m^3/m^3	
2014	50	0.038	0.009	0*	January–February	0.075	August
	100	0.041	0.005	0.028	December	0.053	January
	250	0.033	0.003	0.019	December	0.038	January
	300	0.042	0.003	0.029	December	0.048	January
	400	0.048	0.002	0.045	December	0.051	September–October
	470	0.105	0.047	0.030	December	0.105	April
2015	50	0.033	0.008	0.018	February	0.067	February
	100	0.030	0.005	0.019	February	0.039	March
	250	0.028	0.003	0.019	July	0.032	April–June
	300	0.033	0.002	0.029	January	0.036	May–June
	400	0.050	0.002	0.045	January	0.053	May–July
	470	0.033	0.005	0.026	November–December	0.040	April–June
2016	50	0.055	0.009	0*	January	0.060	January
	100	0.050	0.004	0.021	July	0.039	February
	250	0.040	0.003	0.023	January	0.034	April
	300	0.046	0.001	0.031	January	0.036	March–June
	400	0.044	0.001	0.045	January	0.048	March–July
	470	0.084	0.002	0.025	October–November	0.028	May–June
2017	50	0.029	0.009	0*	February	0.061	June
	100	0.026	0.004	0.018	June–July	0.034	January
	250	0.029	0.002	0.026	June–July	0.032	November–December
	300	0.034	0.001	0.032	February–March	0.036	October–December
	400	0.051	0.008	0.043	January	0.081	December
	470	0.080	0.115	0.025	January	0.486	December
2018	50	0.033	0.010	0*	January	0.059	July
	100	0.023	0.004	0.017	May	0.043	April
	250	0.024	0.002	0.019	October–November	0.029	January
	300	0.034	0.005	0.027	December	0.042	April–May
	400	0.091	0.430	0.038	December	0.169	April
	470	0.329	0.098	0.117	December	0.477	January
2014–2018	50	0.033	0.011	0*		0.075	
	100	0.030	0.008	0.017		0.054	
	250	0.029	0.004	0.019		0.042	
	300	0.036	0.005	0.027		0.049	
	400	0.057	0.026	0.038		0.169	
	470	0.113	0.132	0.025		0.486	

*Corresponds to freezing period. (Data for 2013 is not included in the table as it only covers October, November and December).

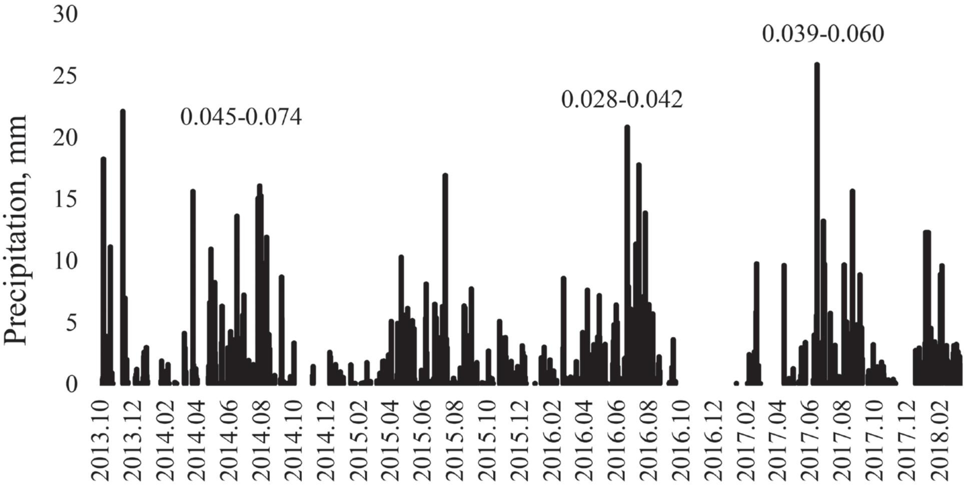

Fig. 7 Precipitation amount measured at the Maišiagala repository site (data provided by the Radioactive Waste Management Agency). Numbers show the highest volumetric water content changes due to precipitation events (August 2014, August 2016 and June 2017) at the 50 cm depth

0.038 m^3/m^3 to 0.169 m^3/m^3, with the mean value of 0.057 m^3/m^3. The soil water content started to increase in September 2017 and reached its maximum value in April 2018. The water content values were stable until 2017, and fluctuations between the minimum value and the maximum position were insignificant (Figs 4, 5). Soil water content at a depth of 400 cm was higher than at a depth of 470 cm when no effect of groundwater table was observed (period 2015 – 2016) and the situation changed under the influence of fluctuations in groundwater table (Figs 4, 5).

At a depth of 470 cm, soil water content ranged from 0.028 m^3/m^3 to 0.486 m^3/m^3, with the mean value of 0.113 m^3/m^3. In 2018, water content reached the value of the soil saturation state, which is the maximum amount of water that the soil can store. The water content reached its highest values in April 2014 and January 2018.

The soil interval directly above the groundwater has a close hydraulic connection with groundwater, and as the groundwater table decreases, the capillary rise zone also decreases, and, vice versa, when the groundwater table rises, the capillary zone also rises up. The lower boundary of the unsaturated zone was limited by the variable table of groundwater over the entire observation period (Table 3, Fig. 8).

The change in the table of groundwater at the lower boundary of the unsaturated zone determined low-frequency and high-amplitude water variations at the depths of 400 and 470 cm. Traces of groundwater table fluctuations were also visible in the unsaturated zone at a depth of 300 cm in 2018 (Fig. 4). The height of capillary rise in soil is inversely proportional to pore size. In natural environments, a significant capillary rise can occur in soils with a grain size of 0.03 to 0.075 mm. The pores can be completely saturated in the vadose zone, where larger pores (>0.075 mm) will be emptied by gravity drainage (Brewer 1964). The height of water capillary rise in soil depends in a complex way both on soil and pore water properties.

The groundwater table fluctuations are an important aspect in terms of predicting the position of the groundwater table for the entire period of long-term operation of structures in many engineering calculations (Chaudhary 2012). Comparison of the results of models analyzing options with and without groundwater showed that models can much more accurately describe the change in water content when groundwater effects are included in the modelling (Xi Chen, Qi Hu 2004).

The groundwater table fluctuates not only seasonally, but also over a long-term cycle. The amplitude of long-term fluctuations in the groundwater table can exceed the amplitudes of seasonal fluctuations and reach significant values. Under natural conditions, the groundwater table is characterized by an undisturbed regime, which is formed mainly under the influence of meteorological, hydrological and geological factors. They cause seasonal and long-term fluctuations in the groundwater table. Seasonal fluctuations in the groundwater table are caused by precipitation and changes in air temperature throughout the year.

In our study, the groundwater table in the piezometer was recorded using the data logger with a 60–min interval for the period from 28 November 2013 to 31 December 2018. According to the P7693 piezometer, the depth of groundwater from the surface varied from 428 to 587 cm during the observation period (Table 3, Fig. 8). The unsaturated zone at the Maišiagala repository site was limited by the groundwater table at an average depth of 521 cm (Fig. 8).

The difference between the highest and lowest groundwater tables – the amplitude of table fluctuations – was 159 cm.

Table 3 Statistical parameters of groundwater table fluctuation

	Average value cm	Minimum cm	Month minimum	Maximum cm	Month maximum
2014	512	482	April	553	December
2015	546	520	May	581	December
2016	561	530	May	587	December
2017	518	449	December	564	January
2018	465	428	April	504	December
2014–2018	521	428		587	

(Data for 2013 is not included in the table as it only covers November and December).

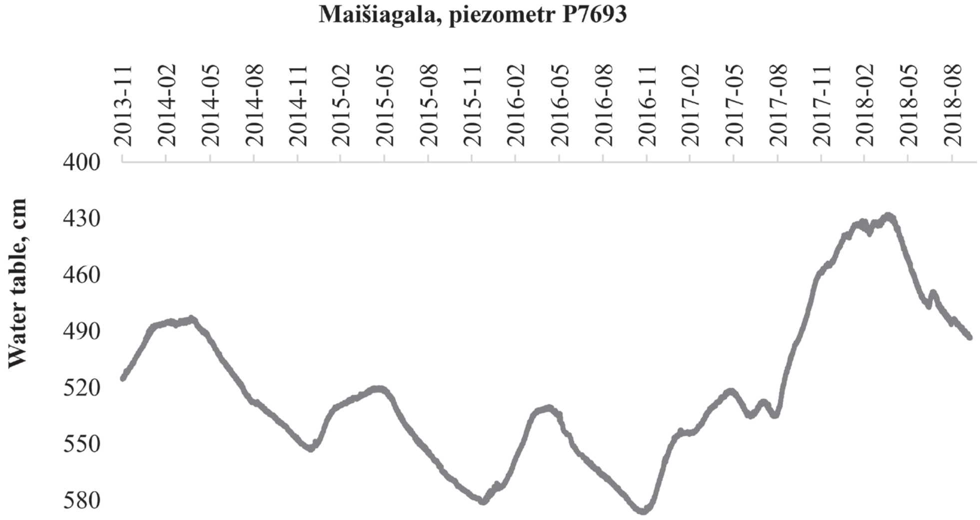

Fig. 8 Groundwater table fluctuations at the Maišiagala repository site recorded by P7693 piezometer

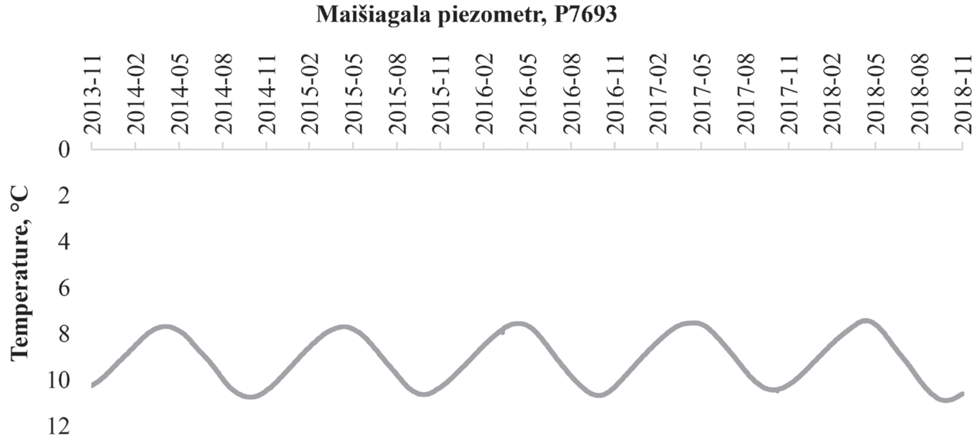

Fig. 9 Groundwater temperature fluctuations at the Maišiagala repository site recorded by P7693 piezometer

The groundwater table was closest to the ground surface in April and May in all years of observation, with the exception of 2017, when the table reached its maximum in December. The groundwater table was closest to the surface in April 2018 and reached a depth of 428 cm. The lowest groundwater tables were in December, except for 2017 (Table 3, Fig. 8). Over the entire 5-year observation period, we had 3 cycles of groundwater table fluctuations with the same trend and peak position in spring time (Fig. 8). The highest position of the groundwater table was observed in 2018 (Fig. 8).

Along with the groundwater table, groundwater temperature was recorded in the same piezometer. According to the data logger P7693, the temperature of the water in the piezometer varied very regularly with the seasons. The lowest temperature was in May and the highest in November (Fig. 9). Summariz-

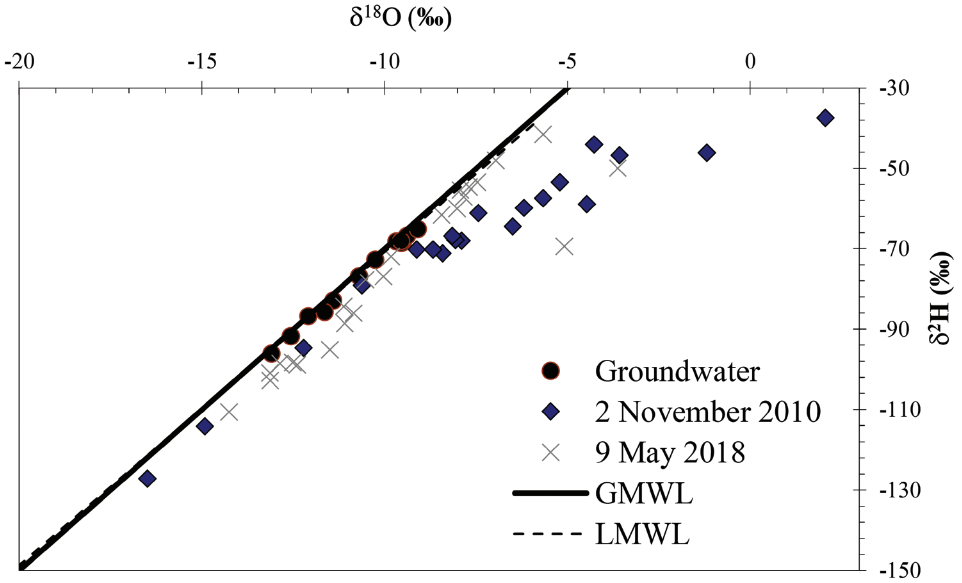

Fig. 10 Relationship between mean δ^{18}O and mean δ^2H in precipitation, which is defined as the local meteoric water line (LMWL) with the equation ($\delta^2H = 7.8\times\delta^{18}O + 7.2$, $R^2 = 0.9$). Together, data on the isotope composition of soil water for two periods are plotted

ing the data, groundwater temperature varied from +7.4 ºC to +10.9 ºC with the average value of 9.1 ºC (Fig. 9). In the annual groundwater temperature regime, two main periods can be distinguished – the warming phase and the cooling phase.

The results of observations showed that the water content regime of the unsaturated zone was affected by both atmospheric conditions and fluctuations in the groundwater table.

Environmental tracer techniques (δ^{18}O, δ^2H) are increasingly being used to evaluate water flow processes in the environment. Variations of stable isotopes in water can give important information on unsaturated zone processes such as infiltration, evapotranspiration, mixing and recharge. The groundwater stable isotope issues of Lithuania were studied in Mokrik (2003). The dependence of meteoric waters δ^{18}O and δ^2H on continental, latitude, altitude, and other effects was analyzed in Mokrik, Mažeika (2006) and Skuratovic *et al.* (2016).

Stable isotope ratios of groundwater in the Maišiagala repository site were close to the annual isotopic composition of precipitation in Lithuania. The weighed annual means of δ^{18}O and δ^2H for atmospheric precipitation were -9.9 and -70‰, respectively. The δ^{18}O and δ^2H values for groundwater varied from -12.1 to -9.3‰ and from -82 to -70‰, respectively (Skuratovic *et al.* 2016).

The isotopic composition of groundwater was close to the annual isotopic composition of precipitation in Lithuania. The majority of groundwater samples in the diagram are situated near the global meteoric water line (GMWL) and local meteoric water line |(LMWL) indicating groundwater recharge by modern atmospheric precipitation (Skuratovič *et al.* 2016). The soil water δ^{18}O and δ^2H values of the Maišiagala unsaturated zone vertical profile for autumn (2 November 2013) and spring (9 May 2018) seasons are presented according to Skuratovič *et al.* (2016) (Fig. 10).

The δ^{18}O and δ^2H values of water in the Maišiagala unsaturated zone profile varied within wide ranges: from -5.6 to -14.3‰ and from -41 to -110‰, respectively, in the spring 2018 profile and from +2.1 to -9.1‰ and from -37 to -70‰, respectively, in the autumn 2010 profile. The isotope composition of soil water is plotted with an excursion to the right of the LMWL (Fig. 10).

The soil water from the profile investigated in November was more isotopically enriched compared to the soil water sampled in May. A more depleted profile (May) contained water from winter and spring precipitation, and a more enriched profile (November) contained water from summer and autumn precipitation (Fig. 11).

According to the values of stable isotopes, it is also possible to distinguish the above-mentioned sub-zones in the profile of the unsaturated zone with different responses to environmental conditions and with certain differences in stable isotope composition. Large fluctuations with higher values of δ^{18}O and δ^2H were observed in the upper sub-zone (approx. 60 cm) than in deeper sub-zones. The soil water near the ground surface was influenced by precipitation infiltration and evapotranspiration, resulting in highly variable and often enriched δ^{18}O and δ^2H values compared to deeper sub-zones (Fig. 11).

The influence of precipitation and evapotranspi-

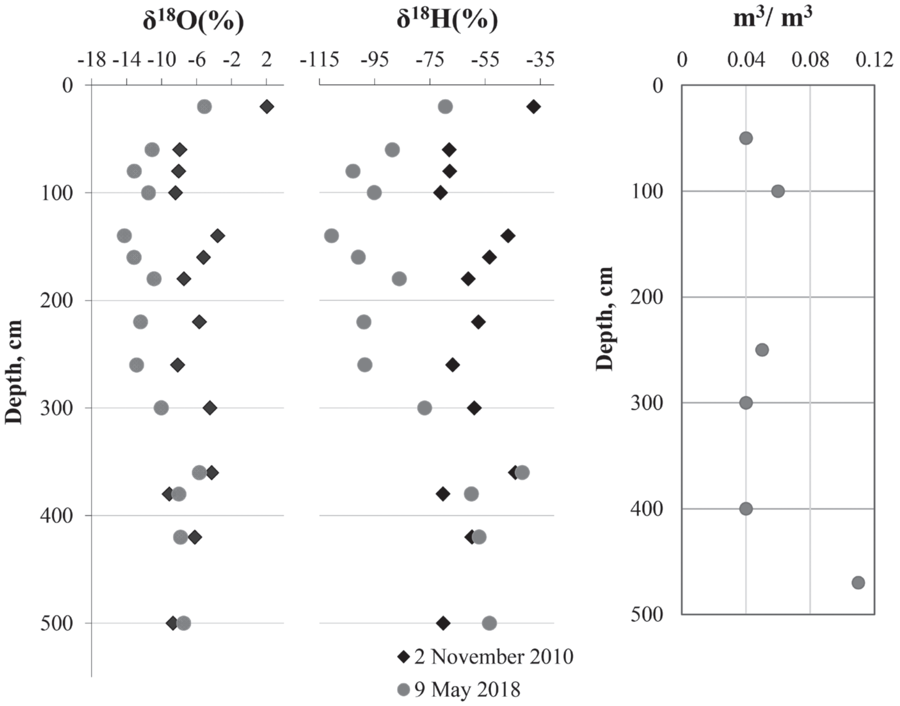

Fig. 11 Values of soil moisture $\delta^{18}O$ and δ^2H and volumetric water content in the profile of the unsaturated zone of the Maišiagala repository site for autumn (2 November 2010) and spring (9 May 2018) seasons. Groundwater level was 493 cm at the time of sampling in autumn and 436 cm in spring, groundwater temperature in spring was 7.4°C

ration on the composition of stable isotopes in soil waters weakens with increasing depths, and delta values become more negative. The sandy profile at the Maišiagala repository site does not retain much water, because sand particles act as individual grains. Sandy soils have relatively large spaces between particles, allowing for rapid movement of water. Starting from depths of 60 to 300 cm (approx.), differences in stable isotope values of soil water may be the result of infiltration of precipitation pushing older water portions downward. There were also peaks in both isotopic profiles. This may be due to the fact that older water is forced down by new water which penetrates into the deep layer, and mobile soil water replaces the previously infiltrated soil water, pushing it downward, while some of soil water remains immobile. As can be seen from a comparison of the $\delta^{18}O$ and δ^2H values of two profiles (spring and autumn), the same trend in the distribution of stable isotope values was observed below a depth of 300 cm. At depths greater than 350 cm, the delta values were less variable and mainly depended on fluctuations in the groundwater table over time (Fig. 11).

CONCLUSIONS

We analysed high-resolution variations of soil water content at different depths of the unsaturated zone profile from 2013 till 2018 in line with groundwater table fluctuations, groundwater temperature and stable isotope distribution. As can be seen both in the time series of water distribution and in the profile of water and composition of stable isotopes, there were three characteristic sub-zones of the unsaturated zone with different responses to environmental conditions.

The first sub-zone was attributed to the upper soil layer and was evidently affected by evaporation, precipitation, and soil freezing, resulting in high frequency and rather large amplitude of water variations. Changes in soil water content and values of stable isotopes were the result of changes in atmospheric conditions and decrease in the liquid water content in January, February, and March, depending both on the number of days with negative air temperature and its values.

When the soil temperature decreases, the liquid water content also decreases and this influences the decrease in recording signal. The results of this study provide an interesting way to monitor soil freezing using a series of spatial and temporal water content records of ThetaProbe Soil Water Sensors.

The water content remained almost constant at the depths of 250 and 300 cm, except for 2018. In 2018, at a depth of 300 cm, there was a noticeable increase in water content associated with a change in the groundwater table, when it reached its highest position. At the depths less than 300 cm (approx.) the differences in soil water stable isotope values could be the result of precipitation infiltration pushing older portions of water down.

At the depths greater than 350 cm, stable isotope values were less variable and mainly depended on fluctuations in the groundwater table over time. The soil water from the profile investigated in November was more isotopically enriched compared to the soil water sampled in May. A more depleted profile (May) contained a fraction of water from winter and spring precipitation, and a more enriched profile (November) contained a fraction of water from summer and autumn precipitation.

The groundwater table affected the change in water content at a depth of 400 and 470 cm, resulting in low-frequency and high-amplitude water content fluctuations. In 2018, at a depth of 470 cm, the water content reached the value of the soil saturation state, which is the maximum amount of water that the soil can store. Over a 5-year observation period, three cycles of groundwater table fluctuations were observed with the same trend and peak position in spring. The difference between the highest and the lowest groundwater table was 159 cm. The temperature of groundwater varied very regularly with the seasons. In the annual temperature regime of groundwater, two main periods were distinguished – the warming phase and the cooling phase.

The results gave information about the processes and factors influencing volumetric water content changes in the unsaturated zone and provide guidelines for further long-term or short-term monitoring strategies as an important factor in the hydrological budget. Soil water content, air temperature, precipitation and groundwater table observations together with environmental tracer techniques play an important role in helping to understand the transport processes with advances in environmental modelling methods.

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