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Distribution and development conditions of karst phenomena in Estonia

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Abstract

Nearly half of Estonia's territory is underlain by Silurian and Ordovician carbonate rocks, which host extensive shallow karstified aquifers that contribute nearly a third of the annually abstracted domestic groundwater. Due to glacial erosions, the short duration of the post-glacial evolution of the territory and for other reasons, karst topography has generally modest dimensions in Estonia. Despite of the relative youth of the majority of the karst formations, karstification is widespread and affects a large fraction of the population daily mostly by means of shallow groundwater quality. Moreover, Estonian karst, with its peculiarities, offers a rare glimpse into the (re)initiation phase of karst in intensively eroded topography, which can still surprise with occasional remnants from the previous times. In this paper a brief overview of the distribution and development of Estonian karst are presented.

Key words

Karst, groundwater, cuesta-like topography, geomorphology, springs, caves.

The Savalduma karst lake in the heart of the Pändivere karst region. The lake has been receiving poorly treated wastewater from the nearby town of Tamsalu for almost 50 years. (cliché : Oliver Koit).

Introduction

As Estonia is located in the transition zone of the Baltic Sea maritime and continental climate regions (Cfb and Dfb according to Köppen-Geiger climate classification (Kottek et al. 2006)), humid and cool climate prevails. The mean annual amount of rainfall (727 mm) exceeds the average rate of evapotranspiration (430–450 mm according to Kink (2007)) in Estonia. Thus, there is a significant excess of recharge for the development of sufficient groundwater resources. Consequently, groundwater is among the most important source of potable water. The hydrogeological context of Estonia is defined by its location in the NW part of the East-European platform. In Estonia, the low-lying platform consists of Neoproterozoic and Paleozoic sedimentary rocks. Silurian and Ordovician carbonate rocks outcrop on the northern half of the platform in Estonia forming

extensive plateaus (figure 1). The widespread carbonate rocks host mostly unconfined shallow aquifers of the Silurian-Ordovician aquifer system, which account for 33% of the annually abstracted domestic groundwater (Olesk, 2016). While providing a vital source of potable groundwater, the carbonate aquifers also feature widespread karstification, which often entails challenges in water management. Following, a brief overview of the development, distribution and peculiarities of the karst in Estonia is presented. All of the major karst regions in Estonia will be addressed in terms of their most specific characteristics.

Figure 1. The geological map of Estonia, showing the main karst regions according to Kink (2006), major karst areas/springs (from the EELIS database) and the bedrock geology. The author includes the unlisted Adavere-Põltsamaa karst

region among the ones distinguished by Kink (2006). The basemap and the geological data provided by the Estonian Land Board (p. 50).

The development and distribution of karst in Estonia

Repeated glaciations during the Pleistocene epoch most likely resulted in the destruction of the majority of pre-glacial karst formations, as the glaciers have been estimated to erode a 50–60 m thick layer from the bedrock surface (Makkaveyev, 1976; Isachenkov, 1982). However, in many cases the interstadial and even stadial karst formations might have developed and survived (Heinsalu, 1977; 1978a; 1980; 1984; 1987; Karukäpp, 2005) and in some cases could have formed the basis for the karstification in the Holocene. The latter was more likely to occur near the old buried valleys, which have been estimated (Puura, 1980) to form already in the Late Palaeogene. Seldom palaeokarst occurrences from the Middle Palaeozoic Era up until Palaeogene and Neogene could be witnessed in the oil shale mines of Northeastern Estonia and elsewhere (Heinsalu, 1977; Bauert, 1989; Pirrus, 2007; Söstra & Kallaste, 2008; Sokman et al., 2008; Kelp, 2014). Presumably, the ongoing karstification epoch started soon after the withdrawal of the last Pleistocene glaciation (approximately 10 000–14 000 years ago) and the gradual regression of the Baltic Sea in the Holocene (Pirrus, 2007). Thus, much of the active karst today is rather young and modest in size when compared to the world's most famous karst areas.

The spatial distribution and the intensity of the karst phenomena in Estonia is primarily controlled by the extent of tectonic disturbances and the lithological characteristics of the host rock, but also by the type and thickness of the Quaternary cover mantling the bedrock (Heinsalu, 1967; 1977a). Vertically the karstification is the most developed in the depths of 5–10 m but in some cases can reach 30 m (Heinsalu, 1967; 1977a). In the Pandivere Upland and tectonic fault zones karstification can reach depths up to 75 m (Bauert & Kattai, 1997; Karst ja allikad..., 2002). Therefore karstification has not developed uniformly everywhere on the carbonate rock outcrops (figure 1). Based on the prominence and abundance of karst phenomena, Heinsalu (1977a) and Kink (2006) distinguished six karst regions in Estonia (figure 1): Kohila, Pandivere, Kohtla-Järve, North-Pärnumaa and West-Estonian Archipelago. To a smaller extent, Upper Devonian carbonate rocks outcropping in southeastern Estonia, feature

karstification, thus the Southeast Estonian karst region was also distinguished by Kink (2006). Although previously not differentiated, the Adavere-Põltsamaa is another karst region neighboring the Pandivere Upland in the south that should be noted (region 7* in figure 1).

The postglacial neotectonic uplift and the regression of the Baltic Sea in the Holocene determined where the karstification could start first. Thus, there was probably a notable difference of several thousand years between the karstification initiation between the South-Estonia and the Pandivere Upland versus the West-Estonian Lowland (Heinsalu, 1977a). Consequently, the karst in the West-Estonian Lowland and the lower western islands is generally the youngest. On the contrary, the West-Saaremaa Upland (54.5 m asl) was emerged from the Baltic Sea already after the drainage of the Baltic Ice Lake (Saarse et al., 2007; 2009), which means that there was more time for the karst to develop compared to the rest of the West-Estonian Lowland. There may be also some peculiar exceptions like in the case of the Salajõe karst system, located just NE from the Haapsalu Bay (figure 1) in the West-Estonian Lowland. The system with the throughput capacity of 1.7 m³/s according to Heinsalu (1984) features an impressive 600 m long and up to 100 m wide blind valley and multiple permanent baseflow and intermittent overflow springs. As the elevation of the system is only 1–7 m a.s.l., it was still submerged under the Baltic Sea approximately 2000–3000 years ago (Saarse et al., 2003). Thus, it is likely example of a karst system that is developed based on a preglacial remnant.

The cuesta-like topography and mires

In the relatively flat topographic context of Estonia, karst formations commonly developed near the foot of bedrock uplands, escarpments, hillocks and buried bedrock valleys that would provide crucial vertical circulation for karstification (Heinsalu, 1977a; Pirrus, 2005). Moreover, the combination of the gentle regional southward dip (0.15°–0.19° according to Puura & Mardla (1972) and Puura et al. (1999)) of the monoclinical bedrock strata, repeated glacial erosions, neotectonic crustal uplift and significant sea level fluctuations and the accompanying coastal processes in the Holocene resulted in the development and pronouncement of the cuesta-like bedrock topography (Tavast, 1997; Tuuling, 2009). The roughly E-W or NE-SW oriented escarpment ridges, each one

of which features a steeper northern scarp face and a gentler southern dip slope, form a system of descending "cascade" of cuestas when heading towards N-NW across the carbonate outcrops. The latter, along with other positive bedrock landforms, laid the topographic foundation for the karst development in Estonia.

During the Holocene, climatic conditions and flat topography favored the formation of mires in Estonia, which spread on roughly 22% of the surface (Oru, 1992; Ilomets, 1997; Masing et al., 2000). Mires, especially the successive raised bogs would also play an important role in the development of the Estonian karst in the Holocene. Primarily, the mires would provide an abundant source of chemically aggressive recharge to the majority of the karst rivers (Kink et al., 1998) on the carbonate outcrops. Later, as the raised bogs grew taller in thickness, they could also become local or even regional groundwater divides providing elevated hydraulic head for the surrounding areas.

Although not yet studied in detail, the author hereafter provides a likely scenario how the effect of the neotectonic crustal uplift and the formation of mires affected the karst development in the Estonian cuesta-like topography. The crustal uplift rate (approximately 3 mm/y according to Vallner et al. (1988) and Ekman (1996)) is higher in the NW Estonia compared to the SE Estonia (0 to -1 mm/y according to Ekman (1996)). Thus, there is a progressing crustal tilt perpendicular to the NE-SW hinge line of the platform (according to Miidel & Vaher (1997) the azimuth of the tilt is between 130-155° as also shown in figure 2). Due to the tilting of the surface, the initial lakes (in case of limnogeneous mires) and the successive mires could have gradually become "trapped" at the end of the S-SE dip slopes of the cuestas. Consequently, the initial surface drainage was forced to gradually cut through the cuesta escarpment to reach for their base level. If preconditions were favorable, the initial surface stream would develop an underground karst drainage network.

Figure 2. Sample area from the Kohila karst region (see Figure 1) illustrating the effect of the progressing neotectonic crustal uplift, cuesta topography and mire drainage on the karst development in the case of Tuhala and Aandu karst areas. The green dashed arrows in the map symbolize the azimuth of the crustal tilt according to Miidel & Vaher (1997). The cuesta escarpment 1 (red dashed line) roughly corresponds with

the coastal formations of the Baltic Ice Lake after Suuroja et al. (2003). The cuesta escarpment 2 roughly coincides with another escarpment that based on the elevation could correspond with the Yoldia Sea stage coastline according to Suuroja et al. (2012). Based on the surface LIDAR data by the Estonian Land Board, the artistic impressions of cross sections are provided for the Tuhala (profile A-B-C) and Aandu karst areas (profile D-E) (p. 52).

The aforementioned scenario could be exemplified by the case of the Tuhala and Aandu karst areas located in the Kohila karst region (figures 2, 3). In the recent years, the hydrological, hydraulic and hydrochemical functioning of the Tuhala karst area has been thoroughly studied by the author (Koit, 2016a; 2016b; Koit et al., 2017; Koit et al., 2018). The Tuhala karst area features a dry surface valley (1 in figure 3a) situated to W-NW from the currently active perennial spring group (3 in figure 3a). An intermittent overflow spring group (2 in figure 3a) is situated in-between the dry valley and the perennial spring group. Such conditions are probably the result of the progressing neotectonic crustal tilt that first caused the initial surface stream (1 in figure 3a) to gradually seek for more effective drainage path towards the base level in the Pirita River valley (see in figure 2). Consequently, the Tuhala River found a new drainage path through the karst system (2 in figure 3b). As the tilt progressed even further, the preferential karst flow path gradually shifted even more to NE-E towards its current base level at the Pirita River valley, leaving the previous mains spring to function as an overflow spring. Also noteworthy is the gradual upstream shifting of the main sink of the system (figures 3a).

Figure 3. The overview maps of the proposed development scenario for the Tuhala karst area (a) and the Aandu karst area (b) in the Kohila karst region. Their locations and extents are noted with white boxes in Figure 2. Both karst areas feature dry surface valleys that could have been the initial main drainage paths in the early phase of the development of the karst in the area. Due to the progressing crustal tilt, both streams developed karst drainage networks to reach for regional base level represented by the buried bedrock valleys of the Pirita and Keila Rivers located NE from the systems. The base-map is provided by the Estonian Land Board (p. 54).

Although not studied in detail, The Aandu karst area (figure 3b) located some 14 km to W-SW from Tuhala, features characteristics similar to the Tuhala karst area based on the remote and field observations. First, there is the prominent dry valley with baseflow springs in the downstream half (1 in figure 3b; figure 4). Similarly to the Tuhala karst area, the main karst drainage has been shifting towards the local base level in NE in response to the progressing crustal tilt (2 in figure 3b). Thus, it is reasonable to assume that similar forces compared to the Tuhala karst area generally affected the development of the Aandu karst area.

Figure 4. A spring fen in the downstream part of the dry valley of the Aandu karst system (p. 55).

Pandivere Upland – the holy grail of Estonian karst

The Pandivere Upland (highest elevation 166 m asl) is one of the most karstified regions in Estonia (figure 1) (Heinsalu, 1963a; 1967; 1977a). There are more than 350 documented karst occurrences in the upland, most commonly dolines, blind valleys and springs (Karst ja allikad..., 1994). The karst in the upland is presumably based on the preglacial remnants. Mires were not as significant affecting the Holocene karst development on the upland compared to the Lower Estonia. Highly fractured and karstified bedrock, thin Quaternary cover, great relative elevation and thick vadose zone are favorable for intensive infiltration of precipitation and surface water. Thus, there are very little surface rivers, lakes and mires in the central part of the upland covering approximately 1375 km² (Pandivere..., 2006). However, the peculiarity of the upland is the high incidence of intermittent karst lakes sometimes forming complex sequences of hydraulically linked systems. Most noteworthy are the Jalgsema, Assamalla, Võhmetu-Lemküla-Porkuni, Saksi, Roosna and Savalduma (figure 5) intermittent karst lakes (Joonuks, 1974).

The Pandivere Upland acts as a major regional groundwater divide covering an area of approximately 5440 km² (Eipre, 1987). The infiltration is rapidly transferred to the extensive overflow and baseflow spring belts surrounding the upland. There are more than 200 water-rich springs or groups organized into three belts at different elevations on the slopes of the Pandivere Upland (Heinsalu, 1977b). Altogether, these mainly autogenic springs discharge approximately 250 million m³ of groundwater annually (Aruja et al.,

1976). Moreover, these water-rich springs form the headwaters for many of the major North-Estonian rivers.

On the contrary, good drainage conditions in the upland also attract intensive agricultural activities. Due to the widespread use of fertilizers and pesticides, the safe threshold values for agricultural contaminants in the shallow groundwater of karstified carbonate aquifers are frequently exceeded (Aruja et al., 1976; Leisk, 2017; Leisk & Rebane, 2018). In order to implement special water protection measures to handle the agricultural pollution load in the upland, the Nitrate Vulnerable Zone of Pandivere and Adavere-Põltsamaa was established in 2003 (Pandivere..., 2006). Although the domestic wastewater management in the upland has improved a lot since the re-independence of Estonia in 1991, it still presents challenges due to complex hydrogeological conditions and inefficient wastewater treatment in the small towns and dispersed settlements (figure 5) (Koit & Vainu, 2017).

Figure 5. The Savalduma karst lake in the heart of the Pandivere karst region. The lake has been receiving poorly treated wastewater from the nearby town of Tamsalu for almost 50 years (p.56).

Technogenic karst in the Kohtla-Järve karst region

Kohtla-Järve karst region coinciding the Jõhvi Upland (81 m asl) (figure 1) in North-eastern Estonia, has also encountered significant anthropogenic impact. At least 49 karst occurrences have been documented in the region commonly associated with the many fault zones encountered in the bedrock (Heinsalu, 1977a; 1978b; Kink, 1997). In the region, oil shale has been mined on the surface and in the subsurface for more than 100 years. The mining activities have been accompanied by the intensive pumping and dewatering of the shallow carbonate aquifers hosting the oil shale, collapsing of the chambers of the abandoned mines, extensive modification of the surface topography and alteration of the natural hydrographic network (Bauert & Kattai, 1997; Perens & Vallner, 1997; Toomik & Liblik, 1998; Gavrilova et al., 2005; Perens et al. 2006).

Decades of mining has affected the natural hydrodynamics of the surface water and shallow carbonate aquifers in the Kohtla-Järve region, this resulted in the formation of the so-called anthropogenic or technogenic karst (Gavrilova et al., 2005, Perens et al.

2006). The typical example of technogenic karst during the mining phase is the drying of surface streams and karst springs (Heinsalu, 1978b). When the dewatering is stopped, the combination of the recovering groundwater tables and the gradual inundation of the extensive network of underground mines with fissured and weakened overburden may result in collapse dolines on the surface, anthropogenically enhanced secondary and tertiary porosity and numerous artificial and spontaneous overflow springs (Sepp, 2017).

Decades of mine drainage and the industrial wastewater discharging into surface water bodies and shallow aquifers has negatively affected the hydrochemistry of the waters in the region (Vallner & Sepp 1993; Gavrilova et al., 2005). Although located just outside of the western border of the the Kohtla-Järve karst region, the Purtse River catchment illustrates the impact of the oil shale industry. Since the beginning of the 20st century, The Purtse River and its tributaries have received mine drainage, untreated wastewaters from the oil shale industry and leachates from the semi-coke landfills (Jürgenson, 1958; Pahkla, 1969; Gavrilova et al., 2005; Tamm, 2008). A tributary called the Erra River terminally sinks into the Uhaku karst system (figure 1) in its lower course, to discharge into the Purtse River 400 m to the east from the sink. Another tributary for the Purtse River, the Kohtla River, was known for losing water to the Kohtla underground mine (Heinsalu, 1978b) through numerous karst sinks. As the pollution in the surface streams has remained through decades (figure 6) (Tamm, 2008), it can be presumed that an unknown amount of the waste that was discharged into the shallow aquifers through karst sinks is preserved to this day.

Figure 6. Solid bituminous layer in the bottom of the Uhaku karst sink resulting from the decades-long discharge of wastewaters from the oil shale industry (Photo: Blaž Kogovšek) (p. 57).

Kohila karst region

The area covering about 2700 km² in the Harju Plateau surrounding Kohila is the most karstified region in the Western Estonia (figure 1). The region is characterized by the occurrence of numerous bedrock hillocks, cuesta escarpments and buried bedrock valleys. The lower areas in-between the positive landforms often host mires that supply the numerous karst areas with the recharge as described above. Thus, in the Kohila karst region, the above-described cuesta-uplift-mire type of karst systems are widespread. The

latter is also characterized by the abundance of the intermittent overflow spring groups of the karst systems resulting from the gradual changes in the base level (Bakalowicz, 2005). In total, several hundred karst occurrences have been documented in the region (Heinsalu, 1977a; Kink, 1997). The region comprises the Aandu (figures 2, 3b, 4, 7), Hageri, Kuivajõe, Kuimetsa, Kurevere, Pae and Palamulla karst areas among which the abovementioned Tuhala (figures 2, 3a) and Kadaka karst areas (Koit, 2014; 2015) have been more thoroughly studied during the recent years (figure 1).

Figure 7. The main sink in the blind valley of the Aandu karst area (p. 58).

Karst caves

By chance, the Kohila karst region also comprises the majority of the known karst caves (24 karst caves according to Heinsalu (1977a)) in Estonia. Estonian karst caves dominantly develop along the joint and bedding plane intersections. Due to the almost flat homoclinal bedding, caves usually feature nearly horizontal long profiles. As the more clayey beds often “sandwich” the more soluble cave hosting beds, caves commonly feature low (up to 2.5 m in height) and wide (up to 12 m in width) rectangular cross profiles (figure 8). Joint-controlled, vertically elongated sections of caves, can reach up to 4.4 m in height or more (Heinsalu, 1977a). Commonly Estonian caves feature both vadose and phreatic cave elements due to being close to the groundwater table. Thus, depending on the hydrological conditions, they can be completely submerged, partly flooded or dry.

Figure 8. A rectangular bedding plane controlled section in the Virulase karst cave in the Tuhala karst area (p. 59).

Tuhala, Kuimetsa and Pae karst areas (figure 1) feature the most prominent known karst caves in Estonia. The main passage of the Virulase cave (figure 8) in the Tuhala karst area is known to be at least 58 m long (Palumets & Proosa, 2003). After the collapse of a suffosion sinkhole in 1973 near the main sink of the Tuhala karst system, another cave was revealed. The uncovered cave featured a 4.4 m high vertical section up to 1.6 m wide and passable in the length of 5 m (Maastik, 1973). The latter refers, that both vertical and horizontal feature-dominated sections form concurrently if the preconditions are met.

There are at least twelve documented karst caves in the Kuimetsa karst area (figure 1) (Heinsalu, 1963b; 1987) among those at least nine are accessible to explore. All of the known accessible caves seem to be part of the same larger cave network system. Unofficially the longest accessible part of the Kuimetsa system is the "Suur koobas" or "Big cave", featuring more than 80 m long main passage. The Kuimetsa "Big cave" has developed along the vertical joints in the well soluble thick to massive-bedded Hirnantian Stage carbonate rocks. Structurally supported by the massive bedding. In Estonian context, the cave has shaped into remarkable dimensions: up to 12 m in width and in some cases more than 4-5 m in height in the joint controlled sections of the cave (figure 9).

Figure 9. A joint controlled near- vertical section in the Kuimetsa "Big cave" which leads into a siphon (p. 60).

Secret rivers

Active karst cave and conduit systems provide flow paths for the underground karst streams, which according to the Estonian folktales are often referred to as the so-called "secret rivers". Approximately 40–50 sinking and springing secret rivers have been documented in Estonia (Heinsalu & Vallner, 1995). As all secret rivers do not start at a sink nor end at the springs, the proposed number of actual secret rivers could be in the hundreds when we consider all the karst areas in Estonia. Kohila karst region comprises many noteworthy examples, among others, Tuhala, Kuivajõe, Kuimetsa (figure 10), Kadaka, Aandu, Hageri and Kurevere. The throughput capacity of the secret river of the Tuhala karst system (see figures 2, 3a) for example has been estimated to be more than 3 m³/s (according to Koit (2016), Koit et al. (2017) and the latest unpublished results). Moreover, in spite of the modest hydraulic gradient of less than 4 meters for the distance of about 1.3 km, the karst groundwater can travel with the velocity up to 800 m/h (Koit et al., 2017). The Kostivere karst area (figures 1, 11) is not included in the major karst regions, but features a secret river with the throughput capacity of up to 6 m³/s (Heinsalu, 1958). Other remarkable examples are the secret rivers of the Uhaku karst area in Northeast-Estonia (throughput up to 3 m³/s according to Heinsalu (1977b)) and the Sala-jõe karst area in West-Estonia.

Figure 10. One of the so-called secret rivers in the Kuimetsa cave system (Photo: Blaž Kogovšek) (p. 60).

Figure 11. The Kostivere karst area during spring flood (p. 61).

The Island of Saaremaa in the West-Estonian Archipelago karst region (figure 1) features 38 documented karst areas/occurrences (Kink, 1997b). Based on the slopes of the West-Saaremaa Upland, the ridges of coastal formations captivate numerous wetlands and lakes, which in addition to the autogenic recharge, provide allogenic provide recharge for the karst systems. To reach the local base level, which in most cases is the sea, the flow bypasses the coastal formation ridges through karst drainage systems as secret rivers. Among others, Küdema, Lepakõrve and Kalja karst areas feature prominent secret rivers. Peculiar for the West-Estonian Archipelago karst region is that often due to the great thickness of the marine sandy overburden and the position near the feet of the coastal formations, karst sinks have developed unexpectedly steep slopes and great depth. The somewhat less known and studied Southeast Estonian karst region (figure 1) associated with the Upper-Devonian carbonate outcrop features mostly karst lakes but also few karst systems with known secret rivers. Near the villages of Keerba, Palo and Kastamara, numerous streams sink into karst to resurface again in at least three major spring groups to north of the Meremäe village.

Bare and alvar karst

The more glacially eroded landscapes of the Kohila, West-Estonian Archipelago, Pandivere and Põhja-Pärnumaa karst regions often feature shallow or absent soil cover. Consequently, there are numerous remarkable bare karst areas in these regions. Bare or thinly mantled karst areas usually feature a large variety of karren formations. The most prominent karren micro- and mesoforms are featured on one the Estonia's westernmost island Vilsandi and its neighboring Vaika islets (figure 12). Remarkable limestone pavement landscape with clints and grikes can be seen in the Kostivere, Kuimetsa, Lipstu and Palamulla karst areas (figure 13) among others. These bare karst areas could be also referred to as alvar karst because of the distinct alvar grassland or forest habitats (figure 13) featuring a variety of rare and endangered species (Paal et al. 2009; Kink & Petersoo, 2010). Due to the abundance of remarkable alvar forests in the surroundings of Märjamaa in the Kohila karst region (S-SW sector of the karst region), Kink & Petersoo (2010) named it "the country of the alvar forests".

Figure 12. A large variety of karren micro- and mesoforms can be seen on the beaches of the Vilsandi Island (p. 61).

Figure 13. Alvar forest in the Palamulla karst area (Photo: Blaž Kogovšek) (p. 62).

The karst springs and potable groundwater

The journey of karst waters ends in the springs. Vilbaste (1936) and Tšeban (1975) documented approximately 3700 and 1312 springs respectively in Estonia. According to Heinsalu (1977b) the majority of those documented and estimated are karst springs. If taken into account that in many cases karst springs occur in groups due to being related to tectonic joint sets, Heinsalu (1977b) assumed that in reality there could be somewhere between 5000 to 15000 springs depending on the hydrological conditions. At earlier times, springs were essential water sources, near which settlements were established.

In modern Estonia, karst springs are not commonly used directly for water supply because of their unstable and uncertain quality. The latter is especially an issue in case the spring is fed by allogenic recharge. In many cases the karst spring water features high concentration of humic substances (originating from the mires) which in low concentrations is not hazardous but reduces the aesthetics of the water. Another reason, why the karst springs are seldom used for water supply these days is the fact that carbonate groundwater usually lays in shallow depths. Thus, it is more convenient to abstract groundwater through drilled or dug wells, which in principle, would provide better protection from the potential superficial contaminants. In reality, depending on the thickness of the mantling quaternary cover, the shallow carbonate aquifers of Estonia are generally vulnerable to all kinds of anthropogenic effects because of karst. Whether caused

by the intensive agricultural activities, poor wastewater management, residual pollution from the soviet era, water table controlling or mine discharge (Vallner, 1994).

Figure 14. Probably the most famous Estonian karst "spring" in the world called the "Witch's Well". It resembles a dug well built in a suffosion sinkhole in the overflow spring group of the Tuhala karst area (see Figures 1, 2, 3a, 4). The springs starts to overflow during high flow conditions (p. 63).

Conclusion

Regardless of being generally young in geologic time scale and the relatively small in size when compared to the world's other spectacular karst areas, the intensity and multiformity of the Estonian karst still makes an impression. Here we can witness the karst at the beginning of its development. At the same time we can also conclude, that the karst development in previously glaciated areas is not so linear and straightforward as one would like to imagine. The question of survival and reactivation of the remnant karst forms still remains. Regardless of the size, the karstification is widespread almost everywhere on the carbonate outcrops where the crucial preconditions are met. Furthermore, shallow carbonate aquifers hosting the karst provide water for nearly a third of the population of Estonia. These karstified shallow aquifers normally provide excellent quality groundwater for daily use, at the same time are highly susceptible to anthropogenic or naturally induced contamination. This means that karst daily affects the population on almost half of the land territory of Estonia.

References (p. 65)