since 1961

Baltica

BALTICA Volume 33 Number 1 June 2020: 71–84
https://doi.org/10.5200/baltica.2020.1.7

Hydrogeological assumptions for stormwater management in Tallinn

Rein Perens, Arvo Käärd, Anto Raukas

Perens, R., Käärd, A., Raukas, A. 2020. Hydrogeological assumptions for stormwater management in Tallinn. *Baltica, 33 (1),* 71–84. Vilnius. ISSN 0067-3064.

Manuscript submitted 12 March 2019 / Accepted 14 April 2020 / Published online 25 June 2020

Abstract. Most cities in temperate climate zones, including Tallinn, face the threat of torrential rains and resultant floods, which cause extensive damage to city economies. The main causes of floods are climatic; however, unreasonable building activity and insufficiently developed and maintained drainage systems also contribute to this problem. The percentage of impervious pavement has increased with the consolidation of buildings and road networks. Rainwater drainage is an important issue in a number of different areas of human activity ranging from town planning and environmental protection to building, maintenance and operation of rainwater drainage systems. Hence, to deal with the rainwater drainage issue, it is necessary to develop an integrated and scientifically justified strategy. The present study represents a constituent part of the relevant strategy development process. The authors pay special attention to options for increasing rainwater percolation in different environmental conditions, including geological setting, topography and different soil filtration properties.

Keywords: *floods; rainwater drainage system; town planning; buried valleys; vulnerability*

✉ *Rein Perens, Maavarauuringud OÜ, Iva 2, 12618 Tallinn, Estonia; Arvo Käärd (akaard@hot.ee) Tallinn University of Technology, Estonian Maritime Academy, Kopli 101, 11712 Tallinn, Estonia; Anto Raukas (anto.raukas@mail.ee) Tallinn University, Institute of Ecology, Uus-Sadama 5, Tallinn, Estonia*

INTRODUCTION

Most cities in temperate climate zones face flood problems, which accompany torrents of rain and cause extensive damage to city economies, and Tallinn, the capital of Estonia, is no exception. To deal with rainwater drainage, which is an important issue in a number of different areas of human activity ranging from town planning and environmental protection to building, maintenance and operation of rainwater drainage systems, it is necessary to develop a scientifically justified strategy. In June 2011, the Tallinn City Council passed the decree “Environmental Strategy of Tallinn until Year 2030”, which set a clear task to develop an integrated environmentally suitable solution for minimizing the damage caused by stormwater. The current study is a constituent part of the ongoing more extensive research aiming at fulfilling the above task. This paper focuses on a qualitative description of options for increasing rainwater percolation in different environmental conditions, including heavy stormwaters.

Meteorological monitoring, including precipitation measuring, is part of the national weather service activities guided by manuals of the World Meteorological Organization (WMO), international cooperation pacts and national laws and regulations. Precipitation quantity is defined as the thickness of the water layer that forms on a horizontal ground surface provided that no water flows away, seeps into the soil or evaporates. Rain intensity is a measure of the amount of precipitation per time unit: the average annual precipitation amount in Estonia is 672 mm, being higher in inland areas and lower in coastal regions. The climate and precipitation regime of Tallinn is determined by the proximity of the Gulf of Finland (Tarand *et al*. 2013). According to the Tallinn-Harku weather station data, the average annual amount of precipitation in the city is larger than the national average, and in 1981–2010 it was 704 mm. The yearly and daily

Fig. 1 Flood caused by a strong downpour on Laagna Road, northern Tallinn. Photo by Hannes Vaga

distribution of precipitation is highly variable. For example, on 15 August 1954, 83 mm of rain came down in Tallinn, and on 18 July 1964, in a little more than two hours, 61 mm of rain fell in some districts. In 1961–2010, the recorded maximum daily amount of precipitation was 78.3 mm. On 16–17 June 1982, the longest continuous rain lasting for more than 35 hours was recorded in Tallinn. Downpours like this (Fig. 1) disturb and interfere with traffic and operation of different enterprises, and mitigation of their adverse impacts requires considerable financing.

Causes of floods can be natural and anthropogenic. Although downpours cannot be prevented, it is possible to reduce the amount of impervious pavement, avoid construction activities in low-lying areas as well as in the areas where water draining is complicated, upgrade drainage systems and ensure that their use is more efficient.

The drainage system of Tallinn comprises 21 separate and 7 combined drainage basins. One of the city's stormwater management problems is routing of runoff into combined sewer systems. It is aggravated since the natural receiving waters (rivers, streams, ditches) running through the city are small and in bad condition. Another problem is the scarcity and uneven distribution of stormwater percolation areas.

Overflows of combined sewer systems must protect treatment equipment from excessive hydraulic load and city streets from floods. The conditions for the overflow must be regulated so that the treatment equipment is not hydraulically overloaded, and the pollution load directed into the environment is minimal. In addition, the overflow must guarantee that the sediment load entering a water body is minimal, and, also, it must be designed so that the safety of use is guaranteed. Development of the stormwater sewer system in Tallinn has been proceeding for a long period of time. In the city centre, all stormwater is channelled into combined sewers; however, in the newer residential districts (Mustamäe, Haabersti, Lasnamäe), sewers are mostly separated, and in the areas of mostly private residences (Lilleküla, Kakumäe, Merivälja), storm and drainage water is redirected via ditches. Until now, it has not always been sufficient.

SOIL PROPERTIES IN THE TALLINN AREA

All soils contain mineral particles, organic matter, water and air. Their combinations determine such soil properties as texture, structure, porosity, chemistry and colour. The speed at which precipitation reaches the groundwater and the sea strongly depends on soil properties that govern the parameters of soaking, infiltration, and permeability. Aquifer properties are essentially predetermined by its composition. The most important properties of the aquifer are porosity and specific yield, which, in turn, characterise its capacity to release water from soil pores and the flow rate through the soil. The apparent groundwater velocity is the distance covered by groundwater in the saturated zone per unit of time (Table 1).

Water yield is the quantity of water that can be collected from surface or groundwater sources for a given use in a basin in a given time interval. The level of the water yield coefficient depends on the grain size distribution and porosity of the rock.

Infiltration or soaking of precipitation happens under the action of capillary forces and gravity and depends on particle size and soil structure. Infiltration of water occurs only if lower layers of the soil are dryer than the upper ones. Initially, the rate of infiltration is fast, but as soon as water penetrates into the soil and its pores are filled with water, it rapidly decreases. At the moment when the penetrating water fills all the pores in the soil, infiltration stops and groundwater flow begins.

The infiltration rate is the speed at which water enters the soil. It is usually measured by the depth (in mm) of the water layer that can enter the soil in an hour (Table 2). The infiltration rate depends on soil texture (size of soil particles) and soil structure (arrangement of soil particles).

Table 1 Hydraulic conductivity of the most common soil types according to Plotnikov (1979)

Soil types in Tallinn	Hydraulic conductivity, m/day
Sand mixed with gravel, sandy gravel, coarse sand	10–100
Mixed-grained sand with sporadic gravel and medium sand	1–10
Fine sand, sandy loam	0.1–1.0
Loam	0.001–0.1
Clay	less than 0.001 m/day

Table 2 Basic infiltration rates of various soil types (Anon, 2009 b)

Characteristic soil types in Tallinn	Basic infiltration rate (mm/hour)
Sand	> 30
Sandy loam	20–30
Loam	10–20
Clayey loam	5–10
Clay	1–5

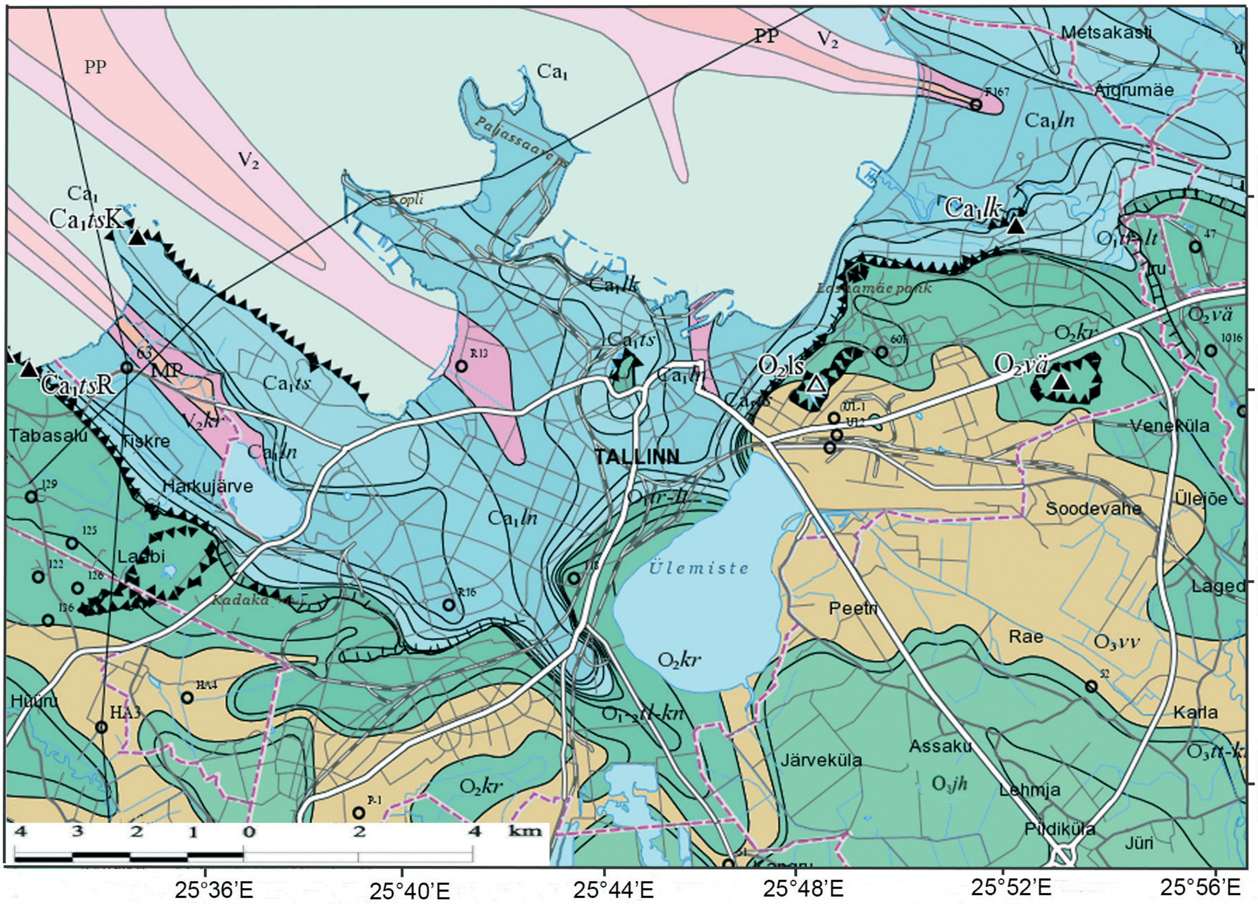
FACTORS INFLUENCING STORMWATER PERCOLATION AND DISCHARGE

One of the most common and effective methods for dealing with stormwater is percolation that facilitates water discharge, reduces stormwater system load and helps to improve the hydrological regime. When percolating stormwater, it is necessary to comply with the requirements set out in ”Water Act”, which was passed on 30.01.2019 and is in force as of 01.10.2019. To meet these requirements, it is necessary to have good knowledge about the geological setting and hydrogeological conditions in the area.

The main features of the geological setting

The water regime of Tallinn as well as the mitigation of flood water effects largely depend on the geological structure, geomorphology and topography of the sub-Quaternary surface, mainly on buried valleys. These data were thoroughly discussed in (Soesoo 2010). Therefore, in this paper, we present only the data necessary for gaining the understanding of environmental flood impacts. Tallinn is located on the southern slope of the Fennoscandian Shield of the East-European craton, and its geological stratification is rather simple (Fig. 2). The surface of crystalline basement lies at 100–160 m below the sea level (b.s.l.). It does not outcrop and has a southward inclination of 2–3 m/km. The upper 1–20 m layer of the crystalline basement is weathered, forming the crust of weathering. The crystalline basement is covered by Neoproterozoic and Palaeozoic rocks with a great temporal gap.

The thickness of the sedimentary bedrock increases from 110–120 m in the northern part of Tallinn to ca 180 m in its southern part. Ediacaran (Vendian) rocks belong to the Neoproterozoic era (ca 630–542 Ma) and are represented in Tallinn by a 40–60 m thick layer of sand-, silt- and claystones. They are covered by Cambrian and Ordovician rocks, transgressively overlaying older formations. The Cambrian system is represented by clastic rocks (sand-, silt- and claystones) and is about 100 m thick. These rocks outcrop mainly in the klint area, where the following four formations can be distinguished (from the bottom): Lontova, Lükati, Tiskre and Ülgase. From the standpoint of hydrogeology, the most important is the Lontova Formation (Ŗ1ln), which is 65–80 m thick and consists of greenish-grey to multi-coloured clay (“blue clay”), which is an important aquitard. The sandstone of the Tiskre Formation (Ŗ1ts) (11–20 m) is an important water-bearing layer. The Ordovician system outcrops southwards of the North-Estonian Klint. Its thickness increases from the north (20–30 m) to the south (ca 50 m). The Lower Ordovician system (with a thickness of 8–12 m) comprises three stages (Pakerort, Varangu and Hunneberg) and four formations: obolus-sandstone or phosphorite (Kallavere Formation (Fm.)), graptolite argillite or “Dictyonema shale” (Türisalu Fm.), glauconite-rich bentonite clay (Varangu Fm.), and glauconite sandstone (Leetse Fm.). The Middle Ordovician system (thickness in the area 15–20 m) is represented by carbonate rocks divided into six stages (Billingen, Volkhov, Kunda, Aseri, Lasnamäe and Uhaku) and the following six formations (from the bottom): Toila, Sillaoru, Loobu, Aseri, Väo and Kõrgekalda. Important building stone of the Väo Fm. (O2vä) (thickness in the area 7–9 m) belonging to the Lasnamäe Stage is excavated in Väo and Harku quarries. The abandoned Lasnamäe and Ülemiste quarries could be potentially used as water reservoirs and saturating grounds. The Upper Ordovician is mostly represented by the Viivikonna Fm. (O3vv) (thickness 9–11 m) belonging to the Kukruse Stage. It includes kukersite layers and outcrops near the southern border of Tallinn.



LEGEND

System	Subsystem	Series	Regional stage	Formation	Index	Rock description
ORDOVICIAN	Upper	Caradoc	HALJALA	JÕHVI	O_3jh	*Argillaceous limestone*
				VASAVERE, TATRUSE	$O_3tt\text{-}vsv$	*Argillaceous limestone*
			KUKRUSE	VIIVIKONNA	O_3vv	*Limestone, oil shale*
	Middle	Llanvirn	UHAKU	KÕRGEKALDA	O_2kr	*Argillaceous limestone*
			LASNAMÄE	VÄO	$O_2v\ddot{a}$	*Limestone*
		Arenig	ASERI, KUNDA, VOLHOVI, BILLINGENI	KANDLE, LOOBU, SILLAORU, TOILA	$O_2tl\text{-}kn$	*Glauconite limestone*
	Lower	Tremadoc	HUNNEBERGI, VARANGU, PAKERORDI	LEETSE, VARANGU, TÜRISALU	$O_1tr\text{-}lt$	*Dictyonema shale, glauconite sandstone*
CAMBRIAN	Upper			KALLAVERE, TSITRE, ÜLGASE	$Ca_3\ddot{u}l\text{-}O_1kl$	*Biodetritic quartzose sandstone*
	Lower		DOMINOPOLI	TISKRE	Ca_1ts	*Quartzose sandstone*
				LÜKATI	Ca_1lk	*Silty claystone with interbeds of sandstone*
			LONTOVA	LONTOVA	Ca_1ln	*Claystone*
VENDIUM	Upper		KOTLINI	KROODI	V_2kr	*Sandstone*
MESOPROTEROZOIC				NAISSAARE	MP	*Rapakivi-like granite*
PALEOPROTEROZOIC				JÄGALA	PP	*Metamorphic rocks: gneisses, amphibolites*

Quarry   a b *Escarpment in bedrock: a) exposed; b) buried* Ca_1lk *Stratotype of a geological unit*

Fig. 2 The bedrock map of Tallinn. Simplified and modified by R. Perens, based on the Geological base map of Estonia, 1:50 000, List 6334 (Suuroja 2003)

Bedrock topography

In the bedrock topography, it is possible to distinguish the foreklint lowland with deep ancient valleys, the klint and the limestone plateau.

Foreklint lowland

Deep buried pre-Quaternary valleys are important for the recharge of the deep-lying Cambrian-Vendian aquifer system. E. Tšeban and E. Sepp (Tšeban 1975; Sepp 2002) described the following four valleys: Mustamäe–Pelguranna (Lilleküla), Kesklinna, Harku, and Mähe. According to the information presented in the latest overview (Vaher et al. 2010), the Central Valley (Tallinna Keskorg) is split into three branches: Harku, Lilleküla, and Kadriorg depressions. In the east, they are adjoined by the Mähe valley (also known as Pirita or Merivälja valley). Altogether, there are ten valleys and depressions in Tallinn and its surrounding areas: Harku, Lilleküla, Kadriorg, Pirita, Saku-Nõmme, Saku-Vääna, Nabala, Saku, Sausti-Raudalu and Rae (Künnapuu et al. 1981). The valleys differ in shape, structure and orientation. They are filled with glacial and glacial meltwater deposits, with marine sediments found in their upper parts (Fig. 3).

The deepest among them is Harku valley (144 m near Lake Harku), which is about 800 m wide. However, the valleys are deep only in the foreklint lowland, while on the limestone plateau, they are just some 10–15 m deep and have gentle slopes. There, they are not river valleys but just relatively low depressions of glacial origin. The depressions are separated by drumlin-like ridges (Fig. 3), the largest of which are: Kakumäe, Kopli, Pirita and the Central elevation (Künnapuu *et al*. 1981). The Central elevation, which was apparently shaped by the Ancient Neva River streams, is 4–5 km long and 0.5–1.5 km wide. In its northernmost part, there is a Toompea hillock (relative height 27 m and altitude 44 m a.s.l), while in its southern part, there is a low (2–4 m) oval-shaped Tõnismäe elevation, which reaches 26.9 m a.s.l.

Limestone plateau

Elevations on the limestone plateau differ in their orientation and shape. Harku, Sõjamäe and Lehmja elevations consist of two layers with one (or sometimes more) oval hummock on a gently sloping base. Sõjamägi (51.9 m a.s.l.) and Lehmja (56.5 m a.s.l.) are the highest hillocks on the Viru-Harju Plateau. Also, there are several oval elevations of simple structure that are 2.5–3.8 km long, 1.5–2.6 km wide and rise up to 44.1–47.6 m above the sea level. The largest of them is Mõigu elevation (relative height 11.0 m). Every new advancing glacier destroyed or reshaped the bedrock elevations and the earlier topography.

North-Estonian Klint

The Klint is the most impressive bedrock form dividing Tallinn into the limestone plateau and the

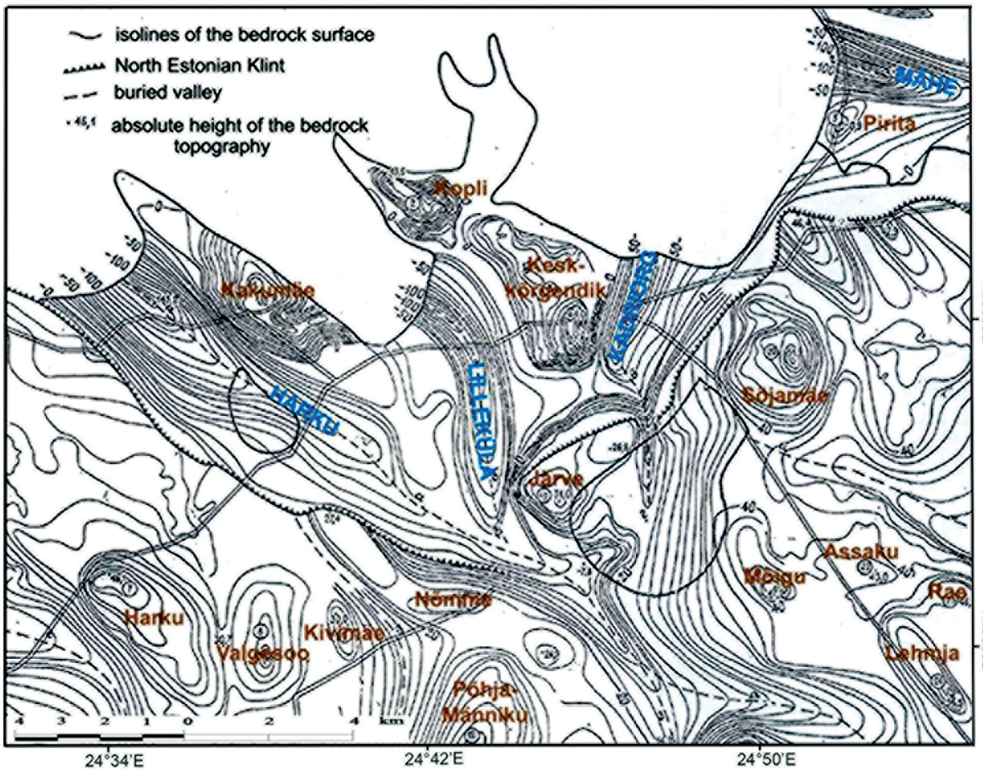


Fig. 3 Topography of the bedrock surface in Tallinn and its immediate surroundings according to A. Raukas and E. Tavast (2010) with supplements by the authors. Names of buried valleys are given in blue font, and those of bedrock elevations in brown font

foreklint lowland. On the territory of Tallinn and in its immediate vicinity, most of the klint is buried under Quaternary deposits (Künnapuu, Raukas 1976). In Tallinn, the klint forms two escarpments: the upper, which is usually represented by a 3–4 m high limestone scarp with a 5–8 high talus below it, and the lower, which is mainly a 4–5 m high sandstone scarp buried under sand. The sandstone slope is particularly impressive at Maarjamäe, where it reaches its maximum relative height (30 m) and the greatest altitude (47 m a.s.l.). Between the scarps there is a terrace, which is up to 400 m wide.

The Quaternary cover of Tallinn

According to the geological data, the Tallinn area was covered by continental ice at least six times; however, deposits older than the last glaciation has not survived. The till of the last glaciation (gIIIjr3) varies in colour and composition. In front of the klint, till does not contain carbonates, while on the limestone plateau, carbonate clasts prevail. In front of the klint, the thickness of till can reach 10 metres, while on the plateau, its thickness is less than 2 m. Ice-marginal formations of the Palivere Stade, represented by Nõmme and Männiku glaciofluvial deltas (Raukas 1992), which are suitable areas for precipitation percolation (Fig. 4), stretch through Tallinn. The Nõmme delta is more than 5 km long and ca 2 km wide, the thickness of glaciofluvial gravel and sand is 20–25 m. The Männiku delta is the most important sand deposit in the environs of Tallinn, its present reserves are estimated at 5.5 million m3. In the ice lakes located in front of the continental ice sheet (Raukas 1992a), there have accumulated varved clays, their thickness reaching up to 10 m. Sediments and coastal formations of the earlier Baltic Sea (Baltic Ice Lake, Yoldia Sea, Ancylus Lake and Litorina Sea) formation stages are widespread in Tallinn.

These sediments (mostly sands and silts) are highly variable. The sands and silts of the Litorina Sea are found practically throughout the foreklint area, making it unsuitable for construction.

Aeolian and bog deposits are quite common, while river and lake sediments are rather infrequent. There are three major bogs in Tallinn, i.e. Tondi (116 ha), Sõjamäe (102 ha), and Rae (1092 ha), with peat thickness reaching up to 7 m. Most of natural landforms in Tallinn have been more or less altered during the construction of roads and buildings or have been buried under a cultural layer. On bastions (Linda Hill, Harju Hill, Great Coast Gate), the thickness of technogenic sediments reaches 15 m, 1–8 m on average. On Toompea Hill and in Vabaduse Square, the cultural layer is 2–8 m thick, in the region of Rataskaevu and Suur-Karja streets, its thickness is 2.5–6 m, and in the surroundings of Viru Square – its thickness reaches 2–2.5 m (Künnapuu, Raukas 1976).

The Tallinn area topography has been highly controlled by land uplift that has been proceeding throughout the whole historical time and is still going on; however, at present, its rate has decreased to only a couple of millimetres per year (see, e.g., Harff et al. 2017 and references therein).

Main features of hydrogeology

The hydrogeology of Tallinn has been quite well studied (Perens 2010; Fig. 5). In addition to the geological and hydrogeological mapping (Perens 2002; Suuroja et al. 2003), there are groundwater vulnerability maps at a scale of 1:20 000 (Savitskaja et al. 1998) and engineering geological maps at the scale of 1:5 000 and 1:20 000 (Arbeiter 1998).

Groundwater in Quaternary deposits is recharged by precipitation. The distribution of water-bearing layers, which are quite thin and contain little water, is limited. Only the groundwater that is in deposits of glaciofluvial deltas and in interbeds of gravel and sand inside tills in ancient buried valleys is of practical value. Due to the thin aeration zone, the groundwater in Quaternary deposits is generally weakly protected against surface pollution.

The water-bearing layer of peat deposits in Pääsküla, Tondi and Sõjamäe bogs has the thickness mostly less than 1 m and the natural water level lies at a depth of 0.3–0.5 m. Hydraulic conductivity of peat is 0.3–1 m/d.

The water-bearing layer of marine deposits spreads across the foreklint lowland and mostly are composed of fine and medium sand and silt with relatively weak permeability. Hydraulic conductivity of marine deposits is mostly 1–3 m/d. The water level is 0.5–2.0 m below the ground surface.

The water-bearing layer of sandy gravelly glaciofluvial deposits is related to Nõmme and Männiku outwash plains and buried valleys. The specific capacity of wells is 0.8–5.8 l/s. Depending on the grain size, hydraulic conductivity of these deposits is 8–15 m/d. Water level is mainly at a depth of 3–7 m, less often at a depth of 12 m. Water in buried valleys is confined.

The water-bearing layer of glacial deposits is firstly related to lenses of sand inside tills. The more clayey varieties of till form local aquitards. Depending on the terrain, water lies at a depth of 0.3–5.5 m.

The Ordovician aquifer system spreads to the south of the North Estonian Klint (Fig. 5). In Tallinn, it occurs in Middle Ordovician limestones, argillaceous limestones, marls and dolostones. The thickness of carbonate rocks varies from 5 m near the klint up to 30–40 m in Männiku. Water-abundance in the Ordovician complex is dependent on fracturing and composition of rocks and is considerably variable. In Männiku, some bored wells have specific

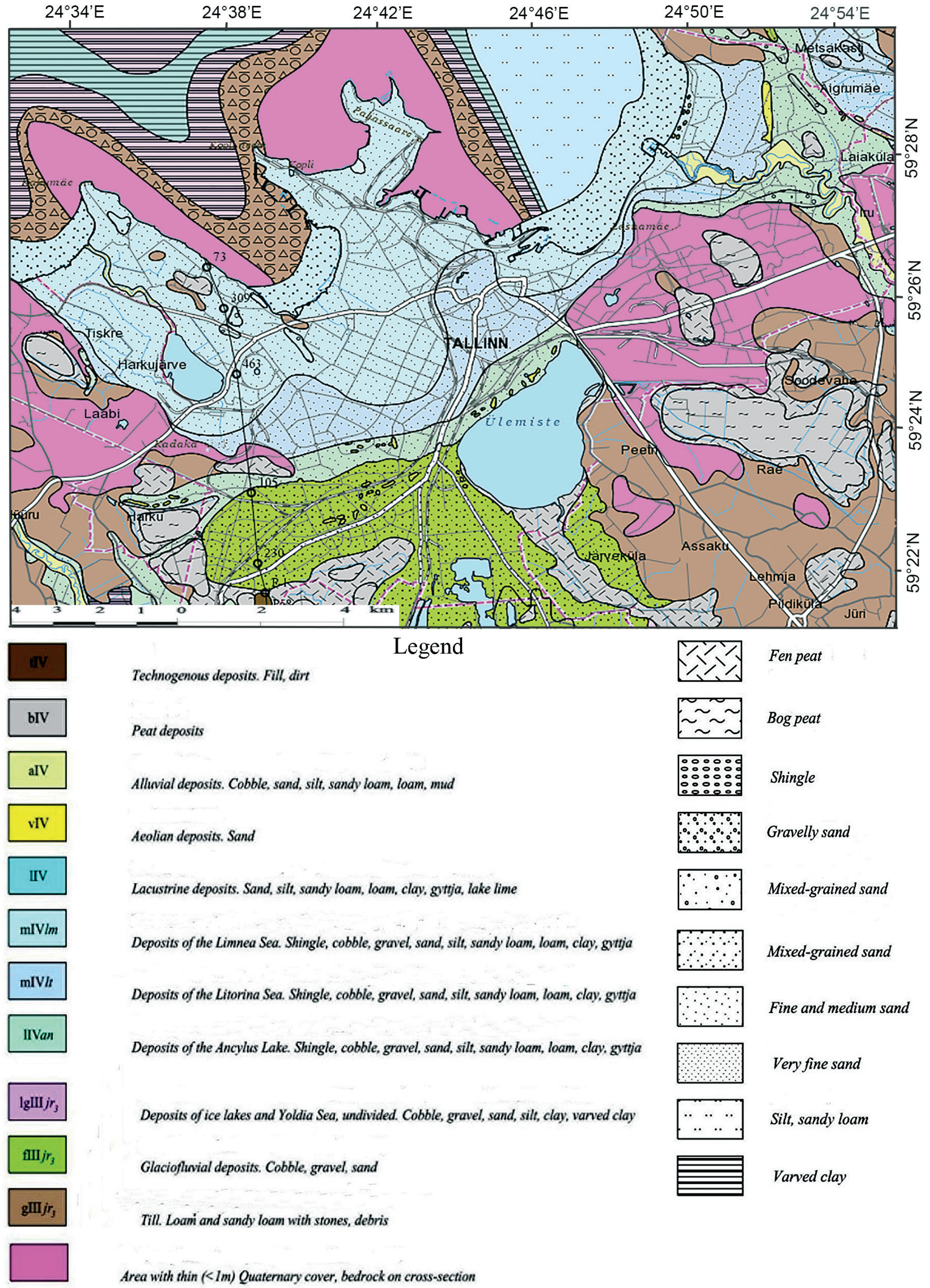


Fig. 4 The Quaternary deposits map of Tallinn. Simplified and modified by R. Perens, based on the Geological base map of Estonia, 1:50 000, List 6334 (Morgen 2003)

capacity of 5.3–16.0 l/s·m. At the foot of the klint, there are many springs, the best known of which is the Varsaallika spring in Kose district. The chemical composition of the groundwater is HCO3-Ca-Mg, with mineralization of 0.2–0.7 g/l. The water is fresh, moderately hard, with pH 7.0–8.5. The content of iron in the groundwater is high (>1 mg/l).

The Ordovician-Cambrian aquifer system spreads almost throughout the territory of Tallinn, except the ancient buried valleys (Fig. 6). The water-bearing rocks are Lower-Ordovician and Upper- and Lower-Cambrian fine-grained sand- and siltstones, their total thickness is up to 25–30 m. The lower aquitard is represented by Cambrian clay- and siltstones that are 50–60 m in thickness. The groundwater is confined. As a result of intense water consumption in the Nõmme district and in the nearest environs of Tallinn (Saku, Saue, etc.), there have formed local drawdown cones. Water-abundance in the aquifer system is rather uniform, specific capacity of wells is up to 0.3 l/s·m, with no lateral regularities in its variation being identified. The groundwater is fresh, its chemical composition is HCO3-Cl-Ca-Mg, mineralization is low (average 0.3 g/l), it is moderately hard; the content of nitric compounds in the groundwater is usually small. In more than half of wells, the content of iron exceeds the maximum permissible level for drinking water, i.e. 0.2 mg/l.

The Cambrian-Vendian aquifer system is the main source of groundwater supply to Tallinn. The aquifer system spreads over the major part of the city's territory. The water-bearing rocks are Lower Cambrian and Vendian sand- and siltstones that overlie the weathering crust of the crystalline basement. The

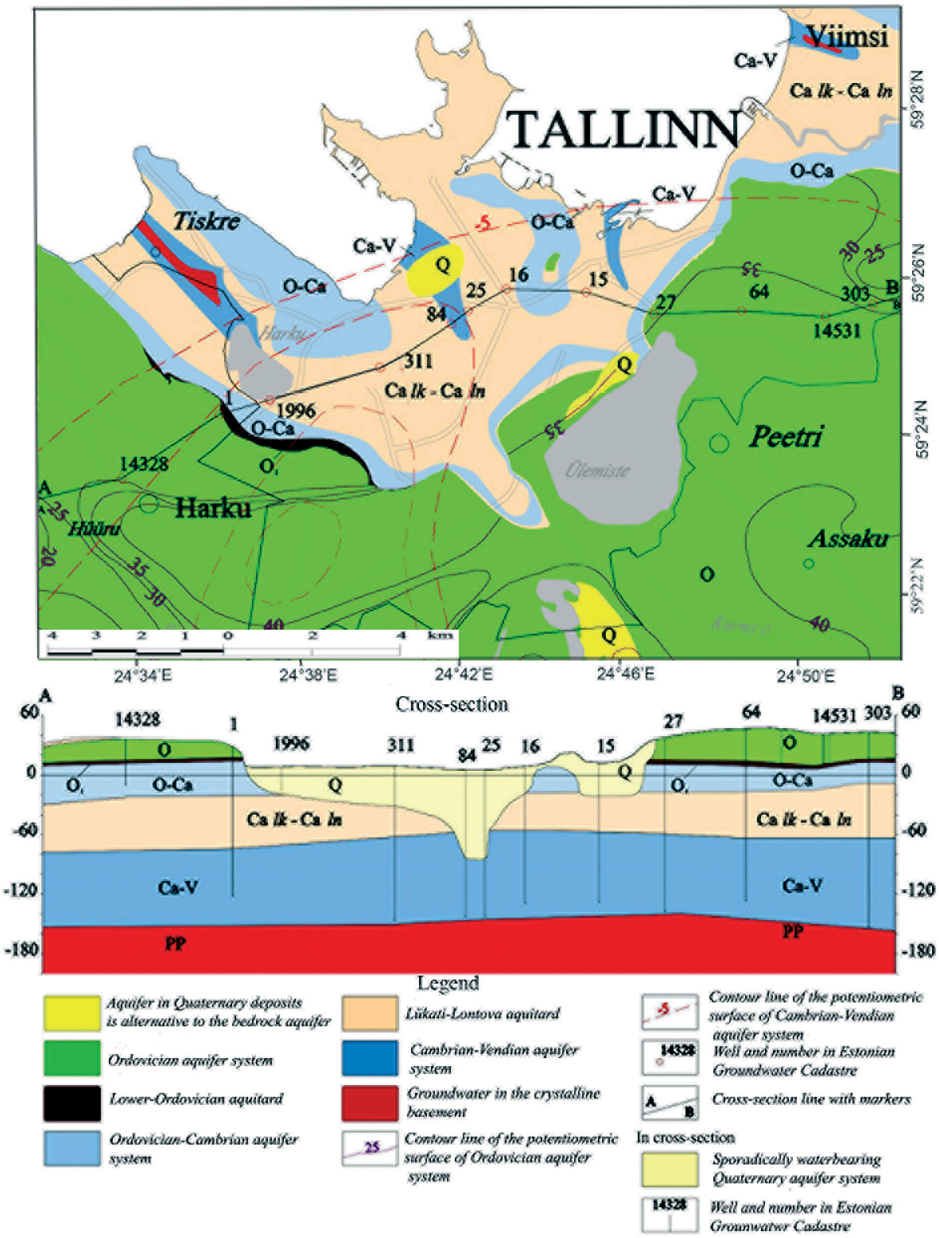


Fig. 5 The hydrogeological map and cross-section of Tallinn according to Perens (2010), modified by the author

aquifer system is overlain by a thick layer of blue clay. Due to the proximity of the Gulf of Finland (few kilometres), intrusion of brackish seawater into the groundwater is possible. The thickness of the complex varies quite largely, reaching 100 m in some wells. The groundwater is confined, but as a result of extensive consumption, its potentiometric level has lowered below the sea level and extensive drawdown has formed, with its centre located in the area of the city centre and in the Nõmme district. In the 1980s, when the groundwater of this aquifer system was intensively consumed, its potentiometric level in Tallinn descended 28 m below the sea level, or up to 30 m below the primary level. A considerable decrease in groundwater consumption during the last decade has resulted in the rise of the groundwater table that has minimized the danger of sea water intrusion into the groundwater.

In the weathering crust and fissured zone of crystalline basement, groundwater spreads throughout the territory of Tallinn. The groundwater flows in fissures of gneisses, amphibolites and other basement rocks. The role of the aquifer in the public water system is insignificant, but it demands attention due to its high mineralization. In the regions of intensive water consumption, the groundwater related to the basement may intrude into the Cambrian-Vendian aquifer system and increase water mineralization, first of all, the content of chlorides.

Groundwater recharge and regime. Depending on the amount of precipitation and bedding conditions of aquifers, their recharge may vary considerably. The recharge areas of Quaternary and Ordovician aquifers generally coincide with their distribution. Annual fluctuation in their levels shows two clearly expressed maximums: snowmelt in March–April and autumn rains in October–November. Minimum levels commonly occur in late summer and in early spring before snowmelt. The amplitude of annual fluctuation seldom exceeds 0.5–l.5 m.

GROUNDWATER VULNERABILITY IN STORMWATER DRAINAGE BASINS

Groundwater vulnerability is dependent on natural, technogenic and physical-chemical factors (Vrba, Zaporozec 1994). The most important natural factors are the thickness of the sediment layer covering the water-bearing layer, sediment grain-size distribution, the thickness of the aeration zone and its sorption. Technogenic factors include the ways in which pollution reaches the groundwater, i.e. due to damage in sewerage network equipment or infiltration from a percolation field. Physical-chemical factors are special characteristics of the contaminant: migrational capabilities, chemical durability and the time of decomposition, “waste-rock-groundwater” synergy. The vulnerability of groundwater to contamination depends mostly on natural factors. As far as stormwater is concerned, the most important factor is the intensity of groundwater recharge or the time of infiltration.

On the limestone plateau, where water-bearing fissured limestone or dolostone beds are exposed or outcrop just beneath a thin surface layer, pollution can rapidly enter the groundwater. Thus, in these areas, groundwater is unprotected (Fig. 6).

Stormwater drainage basins in foreklint lowland

In areas of protected groundwater, the uppermost aquifer is covered by a regional aquitard. In most part of the foreklint lowland, the uppermost is the Cambrian–Vendian aquifer system, which is covered by the 65–90 m thick Lükati–Lontova regional aquitard. The Mähe stream, Lepiku-Laiaküla, the Kloostrimetsa stream and Pirita-Kose are the local drainage basins where a large part of the territory is protected (Fig. 6). In areas of relatively protected groundwater, the aquifer is covered by a more than 20 m thick layer of till, or a layer of clay or that of loam that is more than 5 m thick. The common feature of these areas is the presence of water-bearing glaciofluvial deposits in the geological sequence of buried valleys. Despite great thickness and mostly clayey composition of Quaternary deposits, the groundwater, which is positioned deeper, is not completely isolated. Till alternates with water-bearing glaciofluvial deposits (sands and gravel), and, therefore, in the course of time, pollution can reach the Cambrian–Vendian aquifer system.

In areas of medium protected groundwater, the aquifer is covered by a 10–20 m thick layer of till or a 2–5 m thick layer of clay or loam. The potentiometric surface of confined groundwater should constantly remain near the ground surface and reach minimum 2 m above the aquifer in the clayey soil. The estimated infiltration time of pollutants is 200–400 days.

In areas of weakly protected groundwater, the aquifer is covered by a 2–10 m thick layer of till, or by a clay or loam layer that is up to 2 m thick, or by a layer of sand or gravel up to 20–40 m thick. The estimated infiltration time of pollutants is 30–200 days, which means that potentially contaminating objects should not be established in weakly protected groundwater areas without thorough research. In these areas, percolation of contaminated stormwater should be avoided as well.

Stormwater drainage basins on the limestone plateau

Unprotected groundwater areas include karst areas and alvars, and, also, the areas where the aquifer

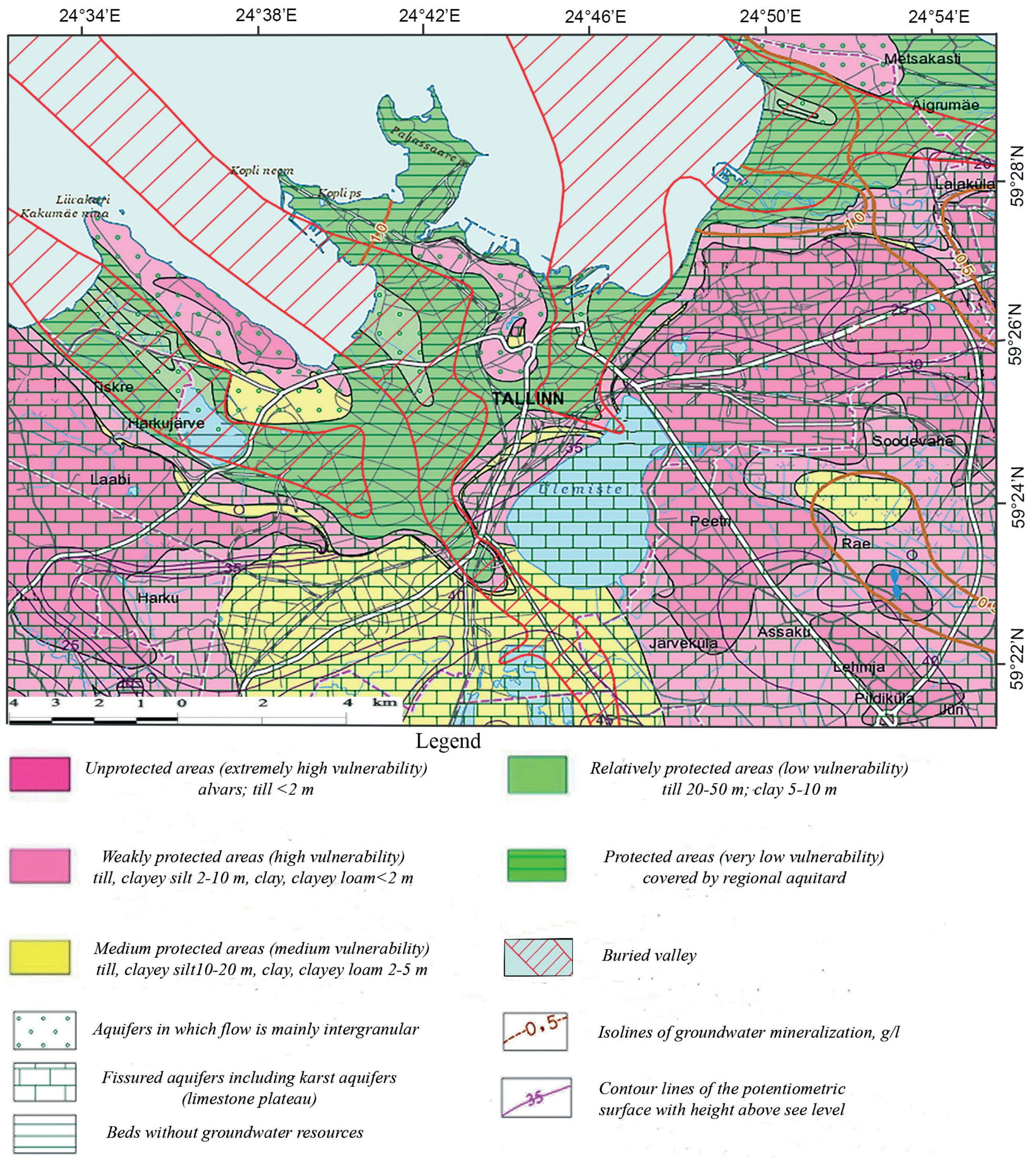


Fig. 6 The groundwater vulnerability map of Tallinn. Simplified and modified by the author, based on the Geological base map of Estonia, 1:50 000, List 6334 (Perens 2002)

is covered by a layer of till up to 2 m thick, or a layer of sand or gravel up to 20 m thick. The characteristic time of pollutants’ infiltration is up to 30 days. Areas of weakly protected groundwater are scarce in the study area. Areas of medium protected groundwater are the largest in Nõmme and Männiku outwash plains, where beneath sand and gravel, there is a 2–5 m thick layer of clay.

STORMWATER IMPACT MITIGATION

The basic principles of stormwater management are well known (Maharjan et al. 2016; Maimone et al. 2011) but applied differently in different countries and cities. For example, in Germany, the most important method for stormwater management is percolation. In Denmark, stormwater is diverted into wetlands, ponds and sedimentation basins. In France, Holland and Sweden, stormwater must be purified before runoff (Pachel 2014).

The primary tasks in stormwater management are to prevent the occurrence of heavy water flows in the areas where they are formed, and to avoid stormwater contamination. This basically means that several actions have to be carried out: stormwater collection, percolation, use, equalization of drainage, separate collection of clean stormwater, etc. If possible, stormwater should be percolated on the spot taking into consideration soil characteristics, stormwater quality, relevant legislation and other circumstances. If it is not possible to percolate stormwater or its stay in the area is prolonged, stormwater must be conducted forward via such obstructive and percolation delaying systems as ditches, artificial cavities and depressions, where it can infiltrate into the soil or evaporate as fast as possible. Part of the precipitation falling on the ground surface and percolating into the soil supplements groundwater reserves. The water remaining from the spring–autumn period can fast percolate into the ground when the groundwater level is deep enough and the soil itself has good absorption capabilities. In Estonia, the average annual precipitation is 600–800 mm, the drainage of surface water accounts for about 40% of that amount (about 260 mm). On average, about 70 mm or 10% of the average annual precipitation amount recharges groundwater. This part of infiltrated water forms net infiltration, on the basis of which, groundwater reserves are formed. In the region of Tallinn, net infiltration is about 60 mm per year. Intensive infiltration into groundwater takes place in spring, during autumn rains and during winter thaws, especially when the frozen surface thaws and the water from melting snow percolates through the soil and reaches the groundwater near the ground surface. In summer, most precipitation evaporates, while in winter, it remains on the ground surface as snow.

Very intensive rains are called downpours. In Estonia, a strong downpour or an especially dangerous amount of precipitation is understood as rain of high intensity with the rainfall reaching 30 mm or more in an hour or a shorter period of time, and 50 mm or more in 12 hours or less.

If stormwater cannot be percolated or channelled away from its point of origin via obstructive and percolation delaying systems, it must be drained off by pipes, thus implementing water flow retardation in ponds and purification before reaching a recipient when needed. In case stormwater cannot be percolated or detained before runoff, it must be channelled into a separate communal sewer system. If the area has no such a system, stormwater can be routed into a combined sewer system with permission from the water entrepreneur. Of course, wastewater cannot be diverted therein. If possible, stormwater should be diverted into ponds and ditches, which allow accumulating water flows in case of downpours, detaining stormwater runoff and localizing possible contamination. Ditches, ponds and containers must be easy to maintain (Fig. 7).

Stormwater draining via pipelines excludes infiltration of stormwater into the ground. Yet, pipelines form an important part of the whole drainage system in cities. In conditions of fast drainage, the maintenance of the vegetation-moisture regime may be problematic. Side by side with water drainage systems, different countries have developed and implemented other environment-friendly solutions for avoiding different environmental hazards. One possibility is to plan land use so that the percentage of fully developed area is as small as possible and the percentage of water impervious surfaces in traffic areas and parking spaces is reduced to minimum. The application of environment-friendly methods in stormwater management reduces the amount of stormwater that needs purification, and prolongs the time of stormwater runoff confluence.

The possible options for safe and environmentally friendly stormwater treatment include pervious soil coatings, grass-covered roofs, roof gardens, ponds, artificial wetlands, infiltration systems, open ditches and canals. When developing or reconstructing impervious surfaces, on-site stormwater treatment or maximum flow rate buffering must be carried out. The use of stormwater as a resource for vegetation watering and other domestic purposes should be considered as well.

POSSIBLE STORMWATER PERCOLATION AREAS IN TALLINN

In addition to geological and hydrogeological factors, stormwater accumulation is influenced by precipitation intensity, rain duration and the duration of the preceding dry period. One of the most common ways of stormwater management is its percolation, which allows reducing the drainage system load and improving the hydrological regime. Besides, percolation also compensates for the groundwater level lowering caused by building activity. The prerequisite for this is that the stormwater is not contaminated and the districts suitable for percolation are situated in areas of protected (very low vulnerability) or medium protected (medium vulnerability) groundwater.

Groundwater quality may significantly suffer due to stormwater percolation. If the groundwater level is high, stormwater can reach and adversely impact groundwater. The percolation depth of wastewater and stormwater must be at least 1.2 m above the high-

Fig. 7 Drainage canal in Kadriorg Park, Tallinn. Photo by Arvo Käärd

est annual level of the groundwater and at least 1.2 m above the bedrock surface. More favourable conditions for stormwater percolation are in the areas with higher terrain. Percolation is difficult to apply in the compactly built-up central part of the city, where land is expensive, and in the areas covered by roads or other facilities. However, the amount of stormwater flows can be minimized and the confluence of stormwater runoff can be delayed in such free planning areas as Mustamäe and Õismäe. Suitable for stormwater percolation are such districts with small private residences as Nõmme and Merivälja. It should be noted that conditions for percolation vary depending on the time of the year.

Percolation of the rainwater falling from roofs should be considered as an important task, especially in Nõmme, Mustamäe, Haabersti and Lasnamäe districts. Attention should be paid to creating rooftop gardens on the buildings under construction and on renovated buildings, as they reduce the need for percolation fields or new separate or combined sewer systems in densely inhabited city spaces.

In apartment building districts, the main attention must be paid to the percolation of stormwater from inner roads and roofs, favourable conditions for which are in Mustamäe and Õismäe. Stormwater channelling to areas with impervious coating, from where it quickly flows into drainage systems, increases the maximal capacity of the stormwater management system. Finding a solution to the problem of stormwater percolation from inner roads and roofs is especially acute in densely built-up areas. If in such areas the percentage of imperviously paved areas increases, the capacity of stormwater percolation increases accordingly. As a result, the present pipeline system may be unable to receive large amounts of water. Stormwater from additional inner roads must be percolated maximally. To reduce the amount of drained water, water from the roofs of existing buildings must be percolated into the soil. This is possible, for example, by replacing flat roofs with gable roofs and installing new rainwater pipes so as to route rainwater to verdant areas, not to roads.

As a result of intensive building, renovation and insulation, the amount of imperviously coated areas in districts of private residences (Nõmme, Merivälja Mähe, Kristiine) considerably increases, thus reducing the amount of naturally infiltrating water and increasing the amount of drained water. Therefore, when coordinating and approving local plans it must be required that stormwater should be percolated on the premises.

When constructing inner-block roads, sidewalks, bicycle roads and parking spaces, the fast increasing number of cars must be taken into consideration. The roads and parking spaces built in the last century do not provide enough parking spaces for additional cars; as a result, real-estate owners reduce the amount of green areas and build additional imperviously coated parking spaces. Water from these areas must be mostly percolated (e.g. gaps must be left between kerbstones) and only in extreme cases drained into existing drainage systems. All construction projects must also include stormwater drainage solutions.

CONCLUSIONS

The water regime of Tallinn as well as the mitigation of flood-water effects largely depends on the geological structure, geomorphology and hydrogeological conditions. The geological stratification of the Tallinn area is rather simple: a crystalline basement is covered by Neoproterozoic and Palaeozoic sedimentary rocks. In the bedrock topography, the foreklint lowland with deep ancient valleys, the klint and the limestone plateau can be distinguished. The klint is the most impressive bedrock form, which divides Tallinn into the limestone plateau and the foreklint lowland. The area discussed in this paper was covered by continental ice at least six times. Ice marginal formations, which are suitable areas for the infiltration of precipitation and stormwater, extend across Tallinn. Sands and silts of the Baltic Sea development stages are found throughout the foreklint area. Groundwater in Quaternary deposits is recharged by precipitation and usually overlaps with the recharge area. Due to the thin aeration zone, the groundwater in Quaternary deposits is generally weakly protected against surface pollution. There are no proved reserves of the Ordovician aquifer system, because the aquifer system is highly vulnerable. Ordovician–Cambrian and Cambrian–Vendian aquifer systems are the main sources of groundwater supply to Tallinn. Vulnerability of groundwater is mainly predetermined by natural factors. From the viewpoint of the potentially adverse impact of stormwater on groundwater quality, the most important factor is the intensity of groundwater recharge or the time of infiltration. On the limestone plateau, where water-bearing fissured limestone or dolostone beds are exposed or outcrop just beneath a thin surface layer, pollution can rapidly enter the groundwater. Hence, these are the areas where groundwater is unprotected. In these areas, percolation of contaminated stormwater should be avoided as well. The causes of floods can be natural and anthropogenic. Downpours cannot be prevented; however, the amount of impervious pavements can be reduced, construction in low-lying areas as well as in locations where draining of water is complicated can be avoided, drainage systems can be upgraded and used more efficiently. One of the most common and effective methods used in stormwater management is percolation that facilitates water discharge, reduces the stormwater system load and helps to improve the hydrological regime. A set of problems related to the city's stormwater management includes water routing into combined sewer systems, scarcity and uneven distribution of stormwater percolation areas.

The primary task in stormwater management is to prevent the occurrence of vast water flows in the areas where they are formed, and to avoid stormwater contamination. If possible, stormwater should be percolated on the spot, taking into consideration soil characteristics, stormwater quality, relevant legislation and other circumstances. In case stormwater cannot be percolated or its runoff cannot be delayed, it must be routed into a separate communal sewer system. Stormwater treatment options include pervious soil coatings, grass-covered roofs, roof gardens, ponds, artificial wetlands, infiltration systems, open ditches and canals. In Tallinn, it is necessary to enhance the efficiency of drainage systems and to raise the possibilities of stormwater percolation into the soil. The fast increase in hard-coated areas must be avoided and local planning requirements must be made stricter.

ACKNOWLEDGEMENTS

The authors thank the Tallinn City Government for raising the problem and financing the study. The authors express sincere gratitude to two anonymous reviewers for their constructive comments and suggestions regarding quality improvement of this paper.

REFERENCES

Anon 2009. Basic infiltration rates for various soil types. In: Gyamera E.A. 2014. Hydrological studies of the university of Cape Coast School of Agriculture research station at Twifo Wamaso. *Global Research Journal of Geography 2 (1),* 010–066.

Arbeiter, K. 1998. Engineer-geological map of Tallinn in the scale 1:5000. In: Estonian engineering geology fund.

Harff, J., Deng, J., Dudzińska-Nowak, J., Fröhle, P., Groh, A., Hünicke, B., Soomere, T., Zhang, W. 2017. What determines the change of coastlines in the Baltic Sea? In: Harff, J., Furmańczyk, K., von Storch, H. (eds), *Coastline changes of the Baltic Sea from South to East. Past and future projection*. Coastal Research Library 19, Springer, Cham, 15–35, doi: 10.1007/978-3-319-49894-2_2.

Künnapuu, S., Raukas, A. 1976. Geomorphology and Quaternary cover. In: Pullat, R. (compiler). *History of Tallinn till 1860*. *Estonian Book*, 20–36. Tallinn. [In Estonian].

Künnapuu, S., Raukas, A., Tavast, E. 1981. The bedrock relief of Tallinn and its vicinity. *Proceedings of the Estonian SSR Academy of Sciences*. *Geology 30 (4),* 167–172. [In Russian].

Maharjan, B., Pachel, K., Loigu, E. 2016. Towards effective monitoring of urban storm water for better design and management. *Estonian Journal of Earth Sciences 65 (3)*, 176−199.

Maimone, M., O'Rourke, D.G., Knighton, J.O., Thomas, C.P. 2011. Potential impacts of extensive stormwater infiltration in Philadelphia. *Environmental Engineer: Applied Research and Practice* 29–39.

Morgen, E. 2003. Geological base map of Estonia in the scale 1: 50 000, List 6334 Tallinn: *Quaternary deposits*, *Geological Survey of Estonia*. Estonian Geological Fund.

Pachel, K. 2014. *Prospective solutions of the precipitation water sewer system*. Tallinn University of Technology, 60 p. [In Estonian].

Perens, R. 2002. Geological base map of Estonia 1: 50 000, List 6334 Tallinn: *Groundwater vulnerability. Hydrogeology. Geological Survey of Estonia*. Estonian Geological Fund.

Perens, R. 2010. Public water supply and groundwater in Tallinn. In: Soesoo, A., compiler. *Geology of Tallinn*. NORIA books. Tallinn, 56–69.

Plotnikov, N. 1979. The mean values of hydraulic conductivity of some rock types. In: V. Maksimov (ed.). *Handbook for hydrogeologists*, vol. 1. *Nedra,* 512. [In Russian].

Raukas, A. 1992. Ice marginal formations of the Palivere zone in the eastern Baltic. *Sveriges Geologiska Undersökning Ser. Ca 81*, 277–284.

Raukas, A. 1992a. Evolution of Ice-Dammed Lakes and Deglaciation of the Eastern Peribaltic. In: Billwitz, K., Jäger, K.-D., Janke, W. (eds). *Jungquartäre Landschaftsräume (Aktuelle Forschungen zwischen Atlantik und Tienschan)*. Berlin-Heidelberg, Springer Verlag, 42–47.

Raukas, A., Tavast, E., 2010. Bedrock topography in Tallinn. In: Soesoo, A., compiler. *Geology of Tallinn*. NORIA books, Tallinn, 90–101.

Savitskaja, L., Savva, V., Jaštšuk, S. 1998. *Tallinn groundwater protection maps in the scale 1:20 000*. Estonian Geological Fund. [In Estonian].

Sepp, E. 2002. *Water of Tallinn yesterday, today and tomorrow*. Rebellis AS, Tallinn, 244 p. [In Estonian].

Soesoo, A. (compiler). 2010. *Geology of Tallinn*. Tallinn, NORIA Books, 286 p.

Suuroja, K. 2003. Geological base map of Estonia 1: 50 000, List 6334. In: *Estonian geological fund*. Tallinn: Bedrock, Geological Survey of Estonia.

Suuroja, K., All, T., Kaljuläte, K., Kõiv, M., Morgen, E., Ploom K. 2003. Compilation and digitalization of the geological-geophysical basic map of Tallinn (6334) and Rohuneeme (7312). Estonian Geological Survey. In: *Estonian geological fund*. Tallinn. [In Estonian].

Tarand, A., Jaagus, J., Kallis, A. 2013. *Estonian climate in the past and nowadays*. Publishing House of Tartu University, Tartu, 631 p. [In Estonian].

Tšeban, E.1975. *Groundwater and its use in Estonian SSR*. Tallinn, Valgus, 166 p. [In Estonian].

Vaher, R., Miidel, A., Raukas, A., Tavast, E. 2010. Ancient buried valleys in the city of Tallinn and adjacent area. *Estonian Journal of Earth Sciences 59 (1),* 37–48.

Vrba, J., Zaporozec, A. (eds.) 1994. Guidebook on Mapping Groundwater Vulnerability. *International Contributions to Hydrogeology 16 (1994),* 131.

Water Act. Passed 30.01.2019 and in force from 01.10.2019. RT I, 22.02.2019, 1.