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On the occasion
of the 32nd International Geographical Congress

Cologne
26–30 August 2012

ESTONIAN GEOGRAPHICAL SOCIETY

ESTONIA

GEOGRAPHICAL STUDIES
11

ESTONIAN ACADEMY PUBLISHERS
TALLINN 2012

Edited by Anto Raukas, Kalev Kukk and Tiit Vaasma

All the papers of this periodical issue have been peer-reviewed by at least two referees. The editors thank all reviewers.

ISBN 978-9985-50-419-2
ISSN 1406-6092

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PREFACE

The Estonian Geographical Society published the first collection of papers *Estonia. Geographical Studies* in 1972 for the 22^{nd} International Geographical Congress in Montreal. Since then the Estonian Geographical Society has published collections containing different geographical materials on Estonia that may be interesting for foreign readers on the occasion of all International Geographical Congresses.

The Estonian Geographical Society represents the Estonian National Committee in the International Geographical Union since 1992. Thus it was 20 years ago, in the 27^{th} International Geographical Congress in Washington when Estonia became member of the Union. This book, which contains nine papers that cover quite a wide area of topics on economic and political changes in Estonia and natural geography, is dedicated to the small anniversary.

After regaining its independence in 1991, Estonia has been rapidly transforming into a society based on democracy and a free-market economy. In spring 2004, after twelve years of strenuous, demanding and fundamental transformational reforms, Estonia achieved its long-term goal of becoming a full-fledged member of the European Union, including the euro zone, and NATO, which gave us back political and economic stability and security. Rapid political and economic advances have attracted investors and have begun to bring prosperity to Estonian people.

In 2011 Tallinn, the capital of Estonia, was the European capital of culture and in 2006 Tallinn initiated the idea of the title 'European Green City'. Estonia is trying to set an example, increasing awareness about issues related to the environment, introducing modern technologies in waste handling and energy. Our landscapes are variegated and relatively young. They have specific features reflecting their formation and development. These are interesting objects of research and therefore the contributions published in this book pay much attention to their development, diversity and changes.

The Estonian geographical Society thanks the Institute of Ecology at Tallinn University for the financial support.

Editors

LAND RESTITUTION AND THE RETURN OF HISTORY IN POST-SOVIET ESTONIA

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After declaring independence from the Soviet Union in 1991, Estonia began to rapidly transform into a society based on democracy and free-market economy. Membership in NATO and the EU one and a half decades later signalled, as it were, the completion of 'the return' of Estonia to her proper place in the West. The transformation was carried out, largely, through the implementation of a number of statutory reforms. In general, these worked towards the liberalisation and decentralisation of economic and political structures, including a far-reaching privatisation of state-owned enterprises and other assets. Undeniably, at an aggregate level of analysis the metamorphosis was striking.

Yet, 'the return' symbolised not only the removal of Soviet-period barriers and the return to the free world. In the midst of forward-oriented reforms, there was also in Estonia and other countries in the region a 'return of history', that is a narrative about the past which had been suppressed by communist and Soviet ideology (Lagerspetz, 1999; Müller, 2002). Thus, even if the policies of reform contained elements of 'shock therapy', these had to be sensitive to the prevalence of facts and ideals inherited from the past. This was true, not least, for the privatisation of property. Given the acknowledgement of the Soviet period as an unlawful occupation of the independent Estonian state, restitution (i.e. the return of lost or stolen property to the proper owners) was to play a crucial part in the privatisation process. Restitution was a pivotal issue in most post-communist countries (Blacksell & Born, 2002; Kuti, 2009), and its potential consequences and moral implications quickly became subjects of intellectual debate. Some scholars cautioned that the decision to restore property rights, made in several post-communist countries, was itself based on a selective interpretation of the past (Elster, 1992; Judt, 2002). Restitution, they feared, *could* lead to the replacement of one form of oppression or injustice by another, often dictated by nationalist objectives. Critics argued that restitution would favour some groups of people at the expense of others, by selecting which type of ‘losses’ qualified for restitution and by selecting the historical ‘baseline dates’ that determined whether a taking was illegal or not (Offe & Bönker, 1993). These concerns constitute the point of departure for the present paper, which focuses on the Estonian Land Reform Act of 1991. Indeed, the reform called for the privatisation of land, primarily through restitution according to the baseline date of 16 June 1940 (the final day of independence before the Soviet takeover).

The aim of this paper is to examine the idea of the ‘return of history’ through the post-Soviet land reform and its spatial implementation. Thus, the paper does not focus on the economic rationales of the land reform, but rather on the way it addressed the role of the past in the making of the post-Soviet property structure in particular, and Estonian society in general. Indeed, the land reform and its drawn-out implementation cannot be made sense of unless it is placed in a wider historical context. The paper, which focuses on rural rather than urban areas, is guided by three questions:

(1) Given the baseline date of 16 June 1940, what characterised the pre-Soviet land ownership situation and which ideals did the property structure express?
(2) Given the elimination of private property in land in 1940, did private land ownership matter during the Soviet decades and if so, how?
(3) What happened after the passing of the 1991 Land Reform Act when ‘frozen’ pre-Soviet land rights encountered a social and physical space that had changed during the Soviet period?

In posing these questions we will get a better understanding of the nature of land restitution in Estonia, and therefore also of the ‘return of history’. From the geographer’s perspective it is interesting to note that the ‘return of history’ was, fundamentally, a spatial process: ‘correcting’ history meant putting things in the correct or proper place, as it were. Yet, as becomes clear when reading this paper, the search for the proper place of land rights has been a recurrent theme in the history of Estonia, a fact that the land reform of 1991 could not circumvent.

Pre-Soviet Estonia: the making of a cohesive property regime

As mentioned above, the Estonian Land Reform Act of 1991 allowed for a restoration of property in land according to the pre-Soviet situation. Thus, let us address our first question and imagine, for a moment, that it would be possible to reverse time and to return to the pre-Soviet years: What was the character of land ownership and the property structure at the time?

Firstly, as far as rural Estonia is concerned, we would encounter a property structure adjusted to agricultural production; more precisely, the structure reflected the subsistence needs of rural households. Indeed, at the time, around 70% of the population lived in rural areas (Kuddo, 1996). A second observation would be that land ownership as a concept was readily associated with the idea of 'land to the tiller'. A third observation would be the strong connection between land ownership (farm ownership) and Estonian national identity. However, these traits were not 'ready-mades' in the pre-Soviet nation. They had become intertwined over time, a process that was still ongoing during the pre-Soviet years, as summarised below.

At the beginning of the 19th century, agricultural land and forests were owned almost exclusively by the powerful German-speaking nobility of Estland and Livland (the German name for South Estonia and the northern part of Latvia), their oldest roots extending back to the medieval crusades in the Baltic region (Fig. 1). From the early 18th century the rights of the nobility were generally protected by the Russian emperors (even if the latter repeatedly challenged the privileges of the Baltic-German nobility during the 19th century). However, the members of the nobility amounted to around 1% of the total population in what was to become Estonia (Whelan, 1999). The land itself was cultivated by a predominantly Estonian-speaking peasantry. The latter was emancipated from serfdom in the early 19th century, but it was only in the second half of that century that peasants were provided financial assistance and the legal means required to purchase the land that they tilled. This was also an intense period of land consolidation and enclosure of commons, which served to rationalise farming and to individualise ownership (Troska, 1987; Lust, 2005). These agrarian reforms coincided with the movement for national awareness among ethnic Estonians. Indeed, nationalist-oriented intellectuals and an increasing number of agricultural societies and cooperatives advised the burgeoning freeholder class on how to manage the redeemed land in a proper way (Eellend, 2007: 48–69). On the eve of the First World War, there were more than 50 000 freehold farms in the province of Estland and the northern half of the province of Livland, controlling 42% of the land; most of the rest, including nearly all of the productive forests and 23 000 tenant farms, still belonged to the 1149 estates (Pool, 1926).

By the time of Estonia's declaration of independence in 1918, a number of agrarian-based political parties were already in place. The thrust of the agrarian–national movement, in combination with events during and after the Russian revolutions, the First World War and the Estonian War of Independence, ensured that the nature and distribution of land was to be one of the most urgent and politically volatile issues to be solved. This brings us to the fourth observation, namely, that land ownership was in a state of reform right up to the Soviet takeover in 1940. Thus, as described below, the property structure that existed in June 1940 was, in many places, very recent and hardly 'settled in'.

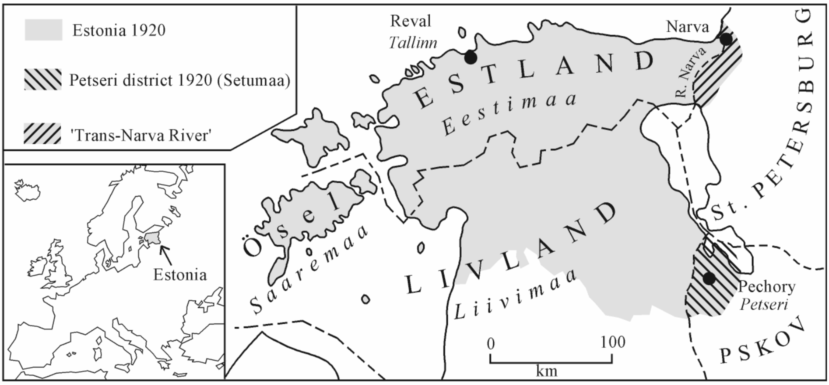

Fig. 1. Estonia in 1920. The map shows the different provinces within the Russian empire out of which the independent state of Estonia was formed. The power of the German-speaking nobility was confined to Estland and Livland (and Kurland further south). Source: Maandi, 2010.

When Estonia was created as a unified territory, out of entire or parts of former tsarist-Russian provinces, the new state inherited a property regime characterised by diversity. The reforms of the 19th century that were mentioned above concerned only part of the lands occupied by the peasantry and then only on estates belonging to specific categories. Thus, regional and local variations in ownership, customary practices as well as land-taxation procedures were profound. The new, central government could not administer the situation in an efficient way. Furthermore, during the First World War and its violent aftermath, Bolsheviks, Estonian nationalists and Germany-oriented reactionaries had, in different ways, used various segments of rural society, as well as specific categories of land, as springboards for their respective ideological agendas. Thus, the Estonian nationalists and democrats, who came out of the turmoil as winners, launched a series of reforms that served not only to improve agricultural production, but to standardise the property structure across the territory and to neutralise potential threats to national stability. This process, which involved four substantial land reforms, has been detailed elsewhere, and a summary will suffice here.[1]

The first reform, based on the Land Law of 1919[2], targeted the estates that were still in the hands of, primarily, the Baltic German nobility (for background and results of the reform see also Lipping, 1980; Kõll, 1994;

1 If nothing else is stated, the summary of the land reforms of the pre-Soviet period, as well as their political context, is based on Maandi, 2010.

2 The Land Law, *Maaseadus*, was published in Riigi Teataja [State Gazette], 1919.

Pilve, 2008). The estates were expropriated generally without the consent of the owners, who would receive compensation less than the market value of the land. Some former owners would later regain a limited part of their land, but most of the nationalised land was divided into medium-sized family farms, as exemplified in Fig. 2. Forests were generally kept in state ownership. The reform produced around 50 000 new farms on the former manors. The farmers, of whom many had qualified for land as war veterans on the nationalist side in the Estonian War of Independence, initially rented the land on the condition that they actually cultivated the same; later, they could pay a purchase fee granting them full ownership. In addition, the 23 000 tenant farms on the expropriated estates were transferred to state ownership, but became owner-occupied once a redemption fee was paid. Thus, the reform generated more farms, but it was also argued that the reform prevented frustrated rural inhabitants from joining the Bolshevik cause (Pool, 1926), as had happened in Finland.

If the first reform treated the 'Baltic German' problem, another round of reform targeted the 'Russian problem' confined to the eastern borderlands of the new state. The region-specific reform was known as the Act of Land Adjustment in Petseri District of 1920, which was later amended to include the so-called Trans-Narva area.[3] During the War of Independence, Estonia had acquired parts of provinces that had never been within the Baltic German sphere, and which were thus part of 'Russia proper' (Fig. 1). The population consisted of ethnic Russians and Setu, the latter speaking an Estonian dialect but belonging to the Russian Orthodox Church (unlike most Estonians, who were Lutherans). The Russian tradition of village communes was widespread. Unlike villages in the traditionally Estonian areas, villages here often constituted one cadastral unit since the emancipation of serfs in Russia (in 1861, around four decades after emancipation in the Baltic provinces), which was owned in common by the households. Each household cultivated a number of strips of land that were found intermixed in common fields, the strips being redistributed from time to time as the households varied in size. These villages were now subjected to land consolidations and enclosures, sometimes without the consent of villagers, who were not accustomed to ideas of independent ownership. Estonian politicians and intellectuals readily described these measures as a way to dissolve 'Russian' communal traditions and to pull the region into closer resemblance with the Estonian heartland. This would also, it was argued, make the inhabitants of this geopolitically

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[3] The original act was known as *Seadus talumaade korraldamise kohta Petseri maakonnas* (Riigi Teataja, 1920). The amended act was known as *Seadus talumaade korraldamise kohta Petseri maakonnas ja Viru maakonna Naroova taguses osas* (Riigi Teataja, 1921).

sensitive region less susceptible to Soviet–Bolshevik propaganda. The implementation of this reform continued through the interwar period.

A third land reform, the Land Consolidation Act of 1926, targeted the remaining communal tenure systems wherever they were found in Estonia (i.e. not region-specific), by facilitating consolidation of dispersed fields and enclosure of commons.[4] This reform was carried out, where relevant, jointly with a fourth reform, popularly known as the 'Crofter Act' (*Popsiseadus*) of 1926.[5] The latter implied that crofters or tenants on freehold or common land were provided the legal means to carve out a piece of land to be held as private property. This reform was preceded by fierce political debate. Freeholder-supported parties opposed the reform, arguing that the state should obey the rule of law and protect private property, not violate it. Parties supported by the rural poor argued that the land should be owned by the actual tiller, the same argument with which the freeholders had confronted the former Baltic German landlords in the latter half of the 19th century. In any case, these reforms proved to be very time consuming and a number of villages were still in the process of reform when the Soviet occupation changed the situation altogether.

Thus, I have addressed the first question about the structure and nature of land ownership in pre-Soviet rural Estonia. According to the agricultural census of 1939 (Riigi statistika keskbüroo, 1940), there were nearly 140 000 farms (mostly family-run) in Estonia, with more than 1 ha of land. The majority (64%) were medium sized (10–50 ha). While small farms (less than 5 ha) amounted to 12.7%, the share of farms with more than 100 ha was negligible (0.7%). In terms of farm size, the distribution of land was relatively equal, if compared to for example Hungary where very large and small farms dominated or Bulgaria with a large share of very small farms (for Eastern European comparisons see Taagepera, 1972 and Kõll, 1994). Yet, as we have seen, in some regions and localities, a property structure reflecting individual farming and private ownership was a recent phenomenon in 1940. Indeed, when we consider the entire period from 1918 to 1940, private ownership was something in the making rather than a taken-for-granted fact. Furthermore, in justifying acquisition for land, different politico-philosophical arguments were called upon: for example rule of law, land to the tiller, communal membership or risking life through participation in war (the veterans). Yet, despite differences in argument, there was a widespread principle that one had to qualify for land ownership, primarily by actually using, and labouring on, the land. The state was deeply involved in reorganising land ownership. The state's interest was

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4 The act was known as *Maakorralduse seadus* (Riigi Teataja, 1926b).

5 The official name of the 'Crofter Act' was *Kogukonna-, asutuste- ja erarendimaade korraldamise seadus* (Riigi Teataja, 1926a).

not agricultural alone but also geopolitical. The reformation of land ownership was a weapon against pending threats from reactionaries and communist revolutionaries. It has been suggested that the creation of a spatially cohesive property regime was part of a wider policy of territorial integration in the new nation (Maandi, 2010). For the first time in history, the entire territory (with the exception of areas where the reforms had not yet reached completion) was united under one and the same official land regime, dominated by individualised relationship between the owner and the land. This relationship was a primary target of the following Soviet reforms.

The Soviet period and the suspension of private land ownership

It is easy to judge the Soviet period on the basis of what we know today, in particular that it actually came to an end. That fact was not available at the time. The second question in our inquiry, therefore, is to what extent and in what manner private land ownership was articulated in the Soviet period, given that private property in land was abolished as of the summer of 1940.

Just as the pre-Soviet independence period saw successive changes in the distribution and nature of land rights, so was the Soviet period characterised by a mixture of radical and gradual reforms. The wholesale nationalisation of land in 1940 had few immediate practical consequences on the part of the farmers. They maintained the rights of usage to a maximum of 30 ha (three quarters of all farms had less land), but were prohibited to use hired labour, in accordance with the regime's anti-capitalist ideology. The part exceeding the upper limit was redistributed to landless farm labourers and smallholders. The redistribution reform was upturned by the German authorities (1941–1944), but resumed by the Soviets upon their return in the autumn of 1944. Thus, on the face of it, despite arrests of 'Nazi collaborators' and other persons who were considered anti-Soviet, the first reform seemed to confirm the Soviet leaders' commitment to family farming; farmers were even provided an official document that gave them perpetual right of usage to the land.

Nevertheless, in 1947 the Soviet leadership in Moscow declared that the farms in the Baltic Soviet republics were to be collectivised, just as in Russia in the preceding decades. The pressure on family-managed farms increased, for example by the imposition of ever greater taxes and compulsory food deliveries to the state. The formation of collective farms speeded up after the mass deportation in March 1949 of more than 20 000 rural inhabitants, including elderly and children, to Siberia and certain parts of Central Asia. By the early 1950s, collectivisation was completed; as production entities, the 140 000 family farms were amalgamated to form around 2900 collective farms (kolkhozes) or state farms (sovkhozes) (for an overview of the creation and continuous amalgamation of 'Soviet' farms see Kasepalu, 1991).

The early kolkhozes usually consisted of one or two villages, but they were soon amalgamated into larger units, a process that continued until around the year 1980. Whether classified as collective or state enterprises, these large farms were closely monitored by the Communist Party and the five-year plans. That the process of collectivisation was in most cases accompanied by harassments and socio-economic hardship is well known and does not need repetition. Large numbers of people left the countryside for more attractive jobs and the relatively less supervised life in the towns. However, major investments were made in the agricultural and rural sector in the 1960s and 1970s, the most visible results being land amelioration, drainage of wetlands, demolition of many farmhouses and the construction of standardised apartment blocks and service centres for rural inhabitants. As the farms grew in size, they attained many of the social service functions associated with rural municipalities (Raagmaa & Kroon, 2005). Although some farms were well managed with relatively high living standards, and even if rural life periodically did attract townspeople, the general picture was one of gradual deterioration. With notable exceptions agricultural production was in general hampered by lack of spare parts, poor maintenance of machinery and lack of enthusiasm on the part of the workers.

Thus, Soviet policies had done much to erode the sense of ownership to a particular piece of land. Yet, opportunities to cultivate a sense of ownership did not vanish completely. One reason is the slow transformation of the landscape. The major transformations occurred only in the late 1960s and the 1970s, as mentioned above. Analyses of cultural landscape changes indicate that these changes were not uniform across rural Estonia (compare e.g. the cases presented in Palang et al., 1998; Peil, 1999; Hellström, 2002: 76–95; Maandi, 2005: 210; Palang, 2010). Acknowledging regional and local variations, traces from the pre-Soviet past nevertheless remained relatively intact well into the 1970s and even beyond. However, did this landscape continuity matter from an ownership perspective?

To the extent that pre-Soviet families remained in, or maintained their ties to, the pre-Soviet farmstead and village, the landscape did indeed function as an *aide memoire* (Maandi, 2009; see also Grubbström, 2011). Even if far from a concerted effort, and seldom publicly expressed, there are numerous examples of how people kept an eye on landscape elements that were, or could serve, as boundary markings well into the late Soviet period. In some areas, many of the official boundary markings from the pre-Soviet period remained in place, if they did not get in the way of tractors and the amelioration of fields. In quiet, people would often mumble their dissatisfaction when they found out that someone had made hay or picked berries or mushrooms for personal use on 'their' land. Bribes were sometimes paid to make sure that officials did not order, for example, the cutting of trees on what someone considered his or her land.

Another way of cultivating the sense of ownership was provided, ironically perhaps, by Soviet law. The latter protected – and relatively strongly so – the citizen's right to a home and to other things that fulfilled direct subsistence needs (to be held in 'personal ownership' rather than as 'private property').[6] The right to 'own' a dwelling (up to a certain size) meant that the house could be sold and change hands.[7] In addition, members of collective farms had the right to cultivate around 0.5 ha for personal use (as a rule, 0.15 ha for members of state farms). Like most house owners, those who remained in their single-family house were usually designated their plot in the immediate vicinity of the house; thus, they had direct access to, and benefitted from, part of their pre-Soviet property. Studies demonstrate that people used the land very efficiently and that these gardens generated more output per area unit than the collectivised fields (Hedlund, 1989). However, fences that served no apparent practical function, and eye-catching embellishment of the plots, were generally viewed upon with great distrust by local authorities (Maandi, 2005).

To repeat, the second question was whether private ownership mattered in the Soviet period and if so, how? Research suggests that many rural inhabitants, especially if they maintained their ties to their native place, were at one and the same time anchored in a pre-Soviet past as well as a Soviet present. They recognised the official changes in ownership, but did not necessarily accept them. Land ownership was put in a state of suspension rather than destroyed. This is not to say that private ownership lingered on as a full-bodied concept. Rather, in the oppressive environment the meaning of privately owned land was increasingly transformed into a memory of the past, the manifestations of which were personal and symbolic, as well as increasingly isolated, rather than public and practical. This varied geographically, largely depending on the extent to which people remained attached to their pre-Soviet home. As people had lost any realistic hope of getting their land rights back in the foreseeable future, such memory-reproducing behaviour may have served, increasingly, as some kind of identity-confirming practice. Had not the overall situation changed in the late 1980s, it is questionable whether the property-related memories and practices would have survived much longer.

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6 For an overview of private and personal ownership rights in Central and Eastern Europe, see Marcuse, 1996.

7 Peculiarly, a family could stay in the family's old farm house, while the other buildings that once belonged to the farm, and which were deemed excessive in accordance with the new ideology, were taken over by the collective farm. Such buildings, which were often found in the immediate vicinity of the dwelling house, often deteriorated once the collective farm considered the buildings obsolete.

Re-privatisation: socioeconomic need or a call for justice?

By the mid-1980s the socio-economic situation was deteriorating in the Soviet Union, including the rural areas of Estonia. The official *glasnost* policy was an attempt to find a way out of the disillusionment, not least by publicly sharing information about the situation in different sectors of the economy and by suggesting proper changes (*perestroika*). In Estonia, this led among other things to an open critique of the large-scale farms, especially their inefficiency and harmful effects on the environment. In 1987, a group of Estonians seized the opportunity and presented an economic development programme for Estonia, which challenged the policies advocated by the central power in Moscow. Parts of the programme were later adopted as official policy in the Estonian SSR. In this context, calls were made for a restored possibility of running family farms (for an early account of the experience of family farming, see Abrahams, 1996). The first family farms started to operate on an experimental basis in 1987. Their establishment was facilitated through the ratification of a series of acts in 1988–1989, which regulated farming in individualised form, the most well-known being the Farm Act of the Estonian SSR from 1989.[8]

The situation did not, however, mean the resurrection of private property in land, which was still prohibited by Soviet law. The family farms had to lease land on a long-term basis from the collective or state farms, the land being assigned by local authorities and the leaders of the concerned kolkhozes or sovkhozes. Neither did it automatically lead to the restoration of pre-Soviet farms within their pre-Soviet boundaries (even if only with usage rights to the land). The initial act and decrees did not mention restitution or restoration at all. However, a decree passed in February 1989, shortly after the declaration of sovereignty by the Supreme Council of the Estonian SSR, stated that things taken from persons by means of repression in the 1940s and 1950s were to be returned or compensated (land excluded).[9] Hence, the subsequent 1989 Farm Act stated, for example, that persons who still owned and lived in their pre-Soviet rural home and who were interested in family farming were to be compensated for equipment and other assets (apart from land) that had once been handed over to the kolkhoz. In addition, compensation was due also on the basis of the years of work that the farmer had done on (or for) the collective farm. The person now also had pre-emptive right of usage to the farm's former land (a limit was set at a maximum of 50 ha) if such an arrangement was practically possible. In most cases, it was not; houses had changed owners (see

[8] The Act is known as *ENSV Taluseadus* (ENSV ÜVT, 1989b).

[9] The decree is known as *Massirepressioonide läbi kannatanutele vara tagastamise ja kahju hüvitamise korra kohta* (ENSV ÜVT, 1989a).

previous section), and directors of the kolkhozes and sovkhozes often argued that individual farming within pre-Soviet boundaries would obstruct the daily work of the large-scale farms. Moreover, farming on an individual basis was conditional, at least officially. For example, the right of usage was to be withdrawn if agricultural production had not commenced within two years, or if the head of the household was unable to work for a longer period of time (due to e.g. illness or imprisonment).

Thus, in the early days of the transition period, the rationale behind the Farm Act was primarily agricultural and socio-economic. Even if it contained an element of historical justice (as a kind of 'return of history'), the Farm Act was still constrained by basic fundamentals of Soviet law (and by the potential threat exerted by the Soviet leadership). To the extent that individual ownership was indeed publicly discussed it seems that the general understanding was that ownership was reserved to the user, to the person who labours on the land. The situation changed quickly, however. In March 1990, the Estonian Supreme Council (by now and for the first time in its Soviet history, more or less popularly elected) declared its intention to restore Estonian independence on principles of continuity (i.e. the de jure continuity of the pre-Soviet republic). All legal acts issued by the Estonian Supreme Council were now attuned to this goal, and the justice aspect became evident. As a result, the nationalisation of land in 1940 was declared unlawful and restitution of *land* (not merely of the farm as a production entity) became a matter of justice and rule of law rather than of agriculture and personal labour.

Restoration of rights, not land

Let us move on to our third question about the encounter between land rights originating in the pre-Soviet period and the geographical situation as it existed in 1991. Because the ownership of so many types of assets, including land, buildings and enterprises, had to be sorted out, it was decided that a general ownership reform was needed, on which subsequent asset-specific reforms would depend. During the summer of 1991, after intensive debates in the Estonian Supreme Council and two months before the actual declaration of (full) independence, the Act on the Principles of Ownership Reform was passed (hereafter referred to as the Principles of Reform).[10] Its purpose was to secure the inviolability of property, to support free enterprise and to restore or compensate those whose ownership rights had been violated during

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[10] The Act, known as *Eesti Vabariigi Omandireformi Aluste Seadus*, was first published in Riigi Teataja, 1991a. Like many reform acts of the period, it was amended several times. The original text as well as amendments made between 1991 and 1999 are published in Justiitsministeerium, 1999a.

the Soviet years. Importantly, it also stated that restitution or compensation must not violate the legally protected rights of other individuals, or lead to new violations in general. Basically, and with our purposes in mind, the Act stated (1) that pre-Soviet property rights existed de jure, (2) that former (pre-Soviet) owners or their heirs could apply for a physical return of the property or else compensation and (3) it listed a number of restrictions on the physical return of property. In essence, primacy was given to the restoration of *rights* to an object, rather than the return of the object itself (to the former owner).

In October the same year, the Land Reform Act was passed, which was in accordance with the Principles of Reform.[11] Just as many other privatisation acts, its implementation turned out to be complicated and the Act was therefore amended several times (though the basic principles remained the same). Even in 2011, 20 years after the initial ratification of the reform, 16.3% of the land had not yet been registered in the national cadastre (Estonian Land Board, www.maaamet.ee, accessed 21.09.2011). While pre-Soviet rights to land had existed de jure throughout the Soviet period, some form of official recognition had to be given to certain interests that originated in the Soviet period, lest the Act would cause new injuries. For example, what about those who had bought a house in the Soviet period – or built a new one – and now found out that the land on which the house was located belonged to someone else? What about those who had set up a family farm in accordance with the Farm Act of 1989 (indeed, in spirit a non-Soviet act) and acquired a long-term lease for land only to find that the land was claimed by the rightful owner? In such cases, the house owner's and new farmer's claims were in theory based on *actual usage* of the asset, and their possession was, it can be assumed, for the most part based on good faith (they had not obtained the asset through conscious violation of other people's rights). These interests were protected in the Principles of Reform, and therefore also in the Land Reform Act. On the other hand, some pre-Soviet owners who realised that their de jure rights would not give them back all their land would regard this as a second-time repression, this time underpinned by the independent Estonian state. The complexity of the privatisation reforms and the immense bureaucracy associated with their implementation, had a delaying effect on the privatisation process. Thus, Owners by Title (*Eesti Õigusjärgsete Omanike Liit*), a public organisation and lobby group, argued that it was difficult for ordinary people to sort out which agencies were responsible for the various parts of the reforms, which in turn opened up for

[11] The act is known as *Maareformi Seadus* (Riigi Teataja, 1991b). The original text as well as amendments made between 1991 and 1991 are published in Justiits-ministeerium, 1999b.

dishonest privatisations at the expense of many entitled owners.[12] Clearly, once the pre-Soviet property space was recognised again as legal, a morally and practically complicated situation arose, when different interests, originating in different political and legal circumstances, made claims to the same space.

A prerequisite behind the ownership reforms was the decision to regard nationalised assets (e.g. land) as the property of the Estonian state (or the public) until the private claims had been solved. This meant that if a specific piece of land could not be returned to the rightful ('pre-Soviet') owner through physical restitution, the state was to compensate the owner in the form of privatisation vouchers (*erastamisväärtpaberid*, abbreviated as EVP). These could be used for example when buying one's apartment in one of Tallinn's Soviet-period suburbs (where apartment blocks were being privatised), to buy more land around one's house as the law permitted or to buy stocks in privatised state enterprises. The amount of vouchers issued in compensation for a parcel of unreturned land was determined, in a rather coarse way, by a specific act dealing with the value of different categories of land (compensation was not, though, granted for lost income opportunity caused by the Soviet nationalisation or expropriation). The flexibility of the voucher system meant that the law basically treated land as a ubiquity. In other words, converted to a monetary rather than usage value, land and other property could, in a manner of speaking, easily be relocated from one economic sector to another and from the countryside to town and vice versa. Moreover, a person's years of work (*tööstaaž*), which also included years in deportation, politically motivated imprisonment and compulsory service in the Soviet armed forces, were converted into a share of the so-called 'public capital' (*rahvakapital*). This share was issued in the form of public capital bonds (*rahvakapitali obligatsioonid*). These bonds could likewise be used in the privatisation of various assets, thus adding not only to the dynamics in the flow of capital and property rights but also increasing the number of people potentially involved in the land reform. It is worth noting that this also included Russians and other nationals who had moved into Estonia during the Soviet period and who were now Estonian citizens or had permanent residence permits.

Thus, the new property structure is a result of a combination of different privatisation modes. Hence, even if only a minor part of the land in a particular village was privatised through direct restitution, in itself that cannot be taken as a sign of failure on the part of the Land Reform Act. On the contrary, although restitution was a prioritised goal, restitution implied

[12] The arguments of Owners by Title, and the organisation's efforts to influence the reform process, are summarised in Ulas, 2006 and Ulas, 2010.

the recognition of the *legal right*, whether that right materialised as a return of a particular piece of land or as compensation. Thus, in a village where much of the land was privatised through pre-emptive right of purchase (e.g. by the owner of a house) or public sale of unclaimed land, some of these properties are likely to have been privatised at least partly by using EVPs obtained from restitution processes elsewhere. Moreover, because the law protected some legal interests originating in the Soviet period (e.g. house owners or those who made use of the Farm Act of 1989), obstacles to direct restitution were anticipated right from the beginning.

Figure 3 depicts the property structure and the modes of privatisation in the rural settlement of Sikeldi (Rapla County, North-Central Estonia), as it appeared in 2003. The contemporary property pattern has some similarities with the pre-Soviet predecessor (Fig. 2), but is considerably less uniform; larger property units are mixed with very small ones, and the boundaries display a greater degree of irregularity. This is a result of the limited degree of direction provided by the law (in terms of shape and use of landed property) and the greater emphasis on negotiation between potentially colliding claims. Clearly, this negotiation was historically contingent. In most cases the outcome of the reform depended on more than one period in history, as becomes evident when we map the mode of privatisation, as in Fig. 3.

Concluding remarks: land reform as a return of history?

Was the post-Soviet land reform part of the general 'return of history'? The answer is affirmative in the sense that pre-Soviet land rights were explicitly declared as (still) valid in 1991. We may refer, here, to what an elderly woman is reported to have said: 'It isn't a land reform really. We are just getting back what has been ours all along' (Maandi, 2005: 15). A telling practical implication of the 'return of history' is that land consolidations which were ongoing but abruptly called off in the 1940s were in some cases taken up again after the enactment of the 1991 land reform, albeit within a new legal framework (Maandi, 2005: 230–231). However, if we look at the actual Land Reform Act and the modes of privatisation as they materialised in situ, it is clear that the 'return of history' was most often severely held back as well as subjected to compromise – right from the beginning. A glimpse at the national land cadastre (Estonian Land Board) gives us an indication: the state is the owner of 35.5% of the registered land (this is expected, just as during the pre-Soviet period this area is primarily forest); 38.8% of the registered land was privatised through direct restitution (i.e. more than half of the non-state land), 16.2% through pre-emptive right of purchase, 8.8% through restricted or open public sale and the rest is in municipal ownership (numbers are valid for 31.12.2010).

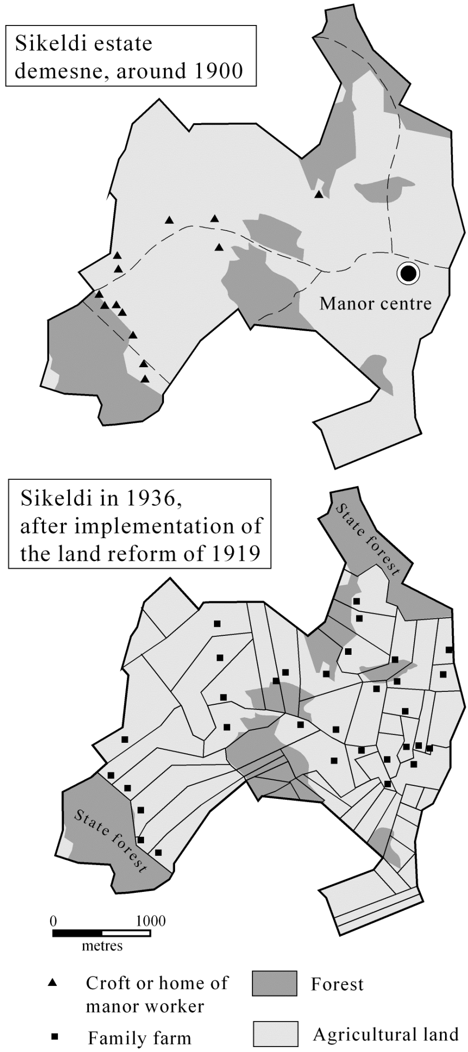

Fig. 2. Sikeldi manor before and after the Land Reform of 1919. In the early 1920s, the former manor demesne was subdivided into family farms, with an average area of 28.4 ha. On the face of it, hierarchical tenure systems had been abolished and the dispersed farms, which managed their land on an individual basis, symbolised the dominant agrarian ideal. Source: Adapted from Maandi, 2010.

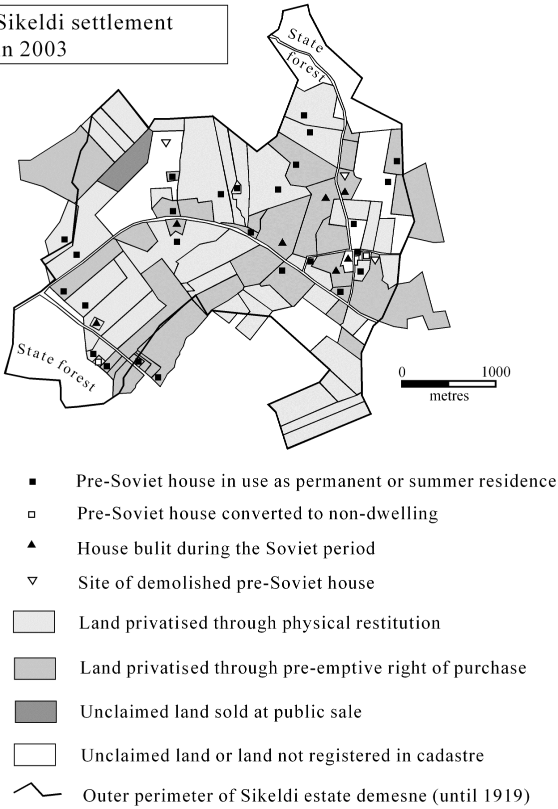

Fig. 3. The Sikeldi settlement after the implementation of the Land Reform Act of 1991. The mode of privatisation, the fate of pre-Soviet farmsteads, as well as the sites of houses built in the Soviet period, are indicated. Source: Adapted from Maandi, 2005.

It can be argued that the 'return of history' is evident also in the very urge to individualise land ownership, which is an echo of the post-Tsarist Estonian state formation. To get some historical perspective it may be useful to compare the Land Reform Act of 1991 with its post-Tsarist predecessors, discussed earlier. This will also shed light on the meaning of land ownership then and now. Thus, even if politically motivated, the post-Tsarist land reforms could not be understood without the primacy given to the improvement of rural living conditions and agriculture. Each of the reforms targeted specific 'problems' and sought to cure them with more or less the same recipe: for example individualisation of farming, enclosure of commons and redistribution of agricultural land among those who cultivated it. Certainly, the post-Tsarist reforms were complex in that they addressed socio-economic, political and agro-technical issues; yet the clear guidance given by the state meant that the property structure, as depicted in cadastral maps, became ever more uniform across the rural space of Estonia. The post-Soviet land reform on the other hand had, in principle, nothing to do with agriculture. Indeed, it was explicitly *separated* from agricultural considerations; agriculture was left to the Agricultural Reform Act of 1992, which basically stated how the assets (apart from land) of the collective farms were to be privatised. Moreover, the post-Soviet land reform was *not* explicitly rural: it concerned every square metre of Estonian soil, whether rural, urban, industrial etc., making the number and type of interested parties very large.

A final difference was the open-ended character of the post-Soviet land reform. In other words, privatisation was a clearly stated and paramount goal, but the reform act did not really determine what should be the proper outcome in terms of size or shape of holdings, in terms of land use, or the landowner's degree of activity or presence on the land. Such considerations had been very central to the post-Tsarist reforms. To be sure, the Land Reform Act of 1991 contained a few paragraphs that related the right of possession to a particular usage of the land, but these were generally removed from the Land Reform Act after a few years. Examples include § 17, which prohibited subdivision of privatised land into units smaller than 10 ha (this echoed an agriculturally motivated legal restriction from 1938, as noted by Virma, 2000; see also Virma, 2004), and § 18 stating that land classified as agricultural must be taken into agricultural use within five years unless the land's use definition is changed. These paragraphs, which can be directly associated to agricultural concerns, were annulled between 1993 and 1996. Indeed, many land owners today do not live on, or off, the land; research indicates that many keep the land for emotional reasons, which in turn may hinder a more efficient use or consolidation of the land (Grubbström, 2011). This is in contrast to the underlying ideas of the pre-Soviet and Soviet land reforms, which addressed land as a physical object with an intended use (e.g. agricultural) and user (e.g. farmer). The focus of the 1991 land reform was primarily land *rights*.

Thus, claims originating in different time periods and legal regimes were negotiated into the new property regime and property structure. The spatial outcome of the post-Soviet land reform depended, therefore, on whether pre-Soviet owners wanted a direct return of property or compensation, whether there were other claims to the land that originated in the Soviet period and on the material landscape (e.g. new houses built on the land could be used as a basis for a land claim). Thus, even if the Estonian historical narrative of an unlawful Soviet occupation and expropriation of land played a central role in the post-Soviet transformation, we can only speak of a fragmented return of the pre-Soviet past. The actual privatisation of propertied space is clear evidence of this. Indeed, once the narrative of the unlawful expropriation was to be materialised in a particular place and landscape, it became clear that that place and landscape were claimed also by other narratives of the past. Whether successful or not, the law advocated a compromise solution. As a result, if one learns how to decipher it, the spatial property structure (e.g. as expressed in the cadastral map) provides an entry into the long history of the contested nature of land rights in Estonia.

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ESTONIA BETWEEN THE SOVIET ROUBLE AND EURO (A MACROECONOMIC APPROACH)

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Introduction

According to the official version, the Soviet economy, including that of the Estonian SSR, was a flourishing one at least in the 1980s. This economy was characterised by remarkably high natural production figures, which potentially gave Estonia very high places based on per capita production in world ranking lists, for instance by the production of electricity (11 188 kWh in 1988; the figures for Finland, Sweden and the Federal Republic of Germany were 10 848, 20 104 and 7101 kWh, respectively); meat (145 kg vs. 73, 67 and 96 kg), milk (818 kg vs. 556, 406 and 405 kg), butter (20.7 kg vs. 11.0, 8.1 and 6.9 kg), cement (762 kg), mineral fertilisers (156 kg), cotton fabrics (122 m^2) etc. (Eesti statistika aastaraamat, 1990).

Even in 1988, when the Soviet economy started to go also statistically downhill, Aleksandr Fedotov from the Institute of Economics of the Academy of Sciences of the Latvian SSR published in the leading economics monthly of the USSR *Voprosy ékonomiki* a (official) conclusion that the per capita national income of Latvia made up more than 70% of the USA level (Fedotov, 1988). Insofar as the national income (net material product according to the Soviet statistical system) of Estonia was practically the same as in Latvia (2593 and 2633 roubles, respectively), this 70% had to be characteristic of Estonia as well (Ékonomicheskoe …, 1990).

Such an ideological overestimation from the Soviets found believers also in the Western world. PlanEcon Report (1990) estimated the per capita GNP in Estonia in 1989 at 6240 USD (according to purchasing power parity, ppp) and in the USSR on average at 5000 USD. The background of these figures had to be the CIA, but actually these were based on the official statistics of the USSR (see also e.g. Götz, 1991). Irresponsible overestimation was typical not only in the case of the USSR. The same myth characterised all socialist countries.

At the same time, the shops emptied and general shortage prevailed. In winter 1990, ration coupons were introduced for many foodstuffs and main consumer goods like TV sets, furniture, soap, etc. After gradual (1990–1992) liberalisation of wages and prices, inflation started to rise and reached 87.5% (cost-of-living index; month-on-month basis) in January 1992, the same figure on year-on-year basis was 728% and culminated with 1254% in September although the 'backbone' of hyperinflation was broken already.

The USSR and the Soviet central planning system collapsed. Estonia restored its independent statehood in August 1991. The figures of material production continued to fall like in all (post-) socialist Europe. Their products were not wanted by anybody. The most curious example in this context is the former German Democratic Republic: in the first year after the reunification of Germany (1991), the percentage of new federal lands, that is the territory of the former GDR, in Germany's exports to the leading advanced economies (EEC and EFTA countries, USA, Canada, Japan, Australia) amounted to 0.8% only (Wirtschaft in Zahlen ′92, 1992).

During the Soviet period, Estonia's economic relations were extremely unidirectional due to the autarkic economic policy of the Soviet Union. Isolation from the world market and the ensuing adaptation to the ease to please the Soviet domestic market and absolute protection against any possible competition from the world market (guaranteed by the state monopoly of foreign economic ties in the Soviet Union and inconvertibility of the rouble) ultimately brought about technological and economic backwardness of production and deteriorating production culture in Estonia and decreasing competitiveness of its goods on the world market. In the 1980s, only 2–3% of the Estonian industrial output was delivered outside the Soviet Union (so-called external export), of which two thirds went to the COMECON countries. Moreover, there was no geographical or economic logic in the distribution of Estonia's external exports: annual fluctuations were huge; in the 1970s, the most important target for Estonian external exports was, for example, Cuba (Kukk, 2000).

The aim of this paper is to analyse the changes in the Estonian economy during two decades: from the regaining of national independence and discarding the Soviet central planning system at the beginning of the 1990s and joining the euro zone in 2011. As a comparative background the Central and Eastern European post-socialist countries and the successor states of the former USSR are used.

Goodbye, socialism!

The events at the turn of 1991 and 1992 (regaining of national independence, hyperinflation in the rouble zone, collapsing of the former Soviet markets) and self-evident reluctance to join the newly established Commonwealth of Independent States (CIS) made Estonia to act on the ad hoc principle. There was no time to discuss the topic 'gradual reforms versus Big Bang reforms and shock therapy' although the advantages and disadvantages of both approaches were well known from Polish examples at the beginning and end of the 1980s. The developments in Estonia in the early 1990s were amasingly similar to the events in Poland in the early 1980s albeit with a nine-year lag. The year 1990 in Estonia was a kind of analogue to the year 1981 in Poland. Furthermore, the line between gradualism and shock therapy was quite hazy then.

It was very difficult to believe that Estonia and the other Baltic countries could find a short way back to Western Europe after 50 years of Soviet annexation. Open scepticism dominated in the thinking of politicians, economists and sovietologists. The economy of the USSR, as already mentioned, was an autarkic one. Its goods, with the exception of raw materials, were not competitive on the world market.

In the rating of the economic potential of independence by Jürgen Corbet and Andreas Gummich (Deutsche Bank) the Baltic countries scored 77 from 120 and came second after Ukraine among the former Soviet republics (Corbet & Gummich, 1990). In this calculation, the authors gave to the Baltic countries zero points out of ten possible for mineral resource capacity and hard currency-earning capacity of raw materials. Hard currency-earning capacity of agricultural products and industrial goods received 3 and 5 points, respectively. The Baltic countries had to be 'saved' for business-mindedness and proximity to Europe.

Such pessimism is summarised by Nötzold (1993):

> The destruction of a unitary monetary system and an economic area with an integral economic system leads to the decline in production and income and to increasing socioeconomic destabilization caused by the collapse of the planned economy. It may be assumed that at least half of the decline in outputs has been caused by the interruption of trade between the descendant countries of the Soviet Union. … The marketing of their [Baltic countries] products remains dependent on the CIS markets. The exports of animal products can be reoriented to Western Europe but only if open markets can be found there. In industrial good exports, nothing can replace the CIS markets. The continuing economic decline in the CIS countries and the insufficient qualification of industry for export in the West leads the Baltic countries to continuous economic stagnation. The maintenance of economic relations with the successors of the Soviet

Union, primarily with Russia, need not mean membership in some economic or monetary alliance, but association agreements with Russia are still indispensable.

According to estimates of the European Comparison Program, Estonia's per capita GDP at current prices was only 5% of the Austrian level in 1993. On the ppp basis, the difference from Austria was 5-fold. Such a large gap was typical of all European post-socialist countries (Table 1). According to Statistics Estonia (2012), the per capita GDP of Estonia was 976 euro or 1155 USD in 1993 (at current prices).[1]

The collapse of the socialist planning system and the Soviet Union led to an increasing disequilibrium and decline of production in all former European socialist countries and newly independent countries. The transition period was relatively painless only for three countries (Czech Republic, Slovak Republic and Hungary), which succeeded in avoiding the steep fall of production and hyperinflation (Tables 2 and 3). The bottom year of the transition crisis (depression) in Estonia was 1994. According to estimates of the European

Table 1

Per capita GDP in some European post-socialist countries compared to Austria in 1993 (Austria = 100)

Country	On ppp basis	At current prices
Slovenia	48	28
Czech Republic	44	13
Hungary	31	16
Slovak Republic	30	9
Belarus	26	6
Russia	26	2
Poland	24	10
Bulgaria	22	6
Croatia	20	11
Estonia	**20**	**5**
Lithuania	19	3
Romania	19	5
Ukraine	17	3
Latvia	16	4
Moldova	12	1

Source: Wirtschaftslage …, 1996.

[1] The statistical data from the electronic databases used in this paper (Statistics Estonia, Bank of Estonia, Eurostat, EBRD, IMF) are presented as of 1 March 2012.

Table 2

Growth rates (%) of real GDP in some European post-socialist and CIS countries in 1990–1998

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1998 (1989=100)
Estonia	**–6.5**	**–13.6**	**–14.2**	**–8.8**	**–1.6**	**2.8**	**5.7**	**11.7**	**6.7**	**81**
Latvia	2.9	–10.4	–34.9	–14.9	2.2	–0.9	3.6	8.3	4.8	61
Lithuania	–5.0	–5.7	–21.3	–16.2	–9.8	1.2	5.1	8.5	7.5	66
Poland	–11.6	–7.0	2.6	3.8	5.2	7.0	6.2	7.1	5.0	118
Czech Republic	–1.2	–11.6	–0.5	0.1	2.2	5.9	4.0	–0.7	–0.,8	96
Slovak Republic	–0.4	–15.9	–6.7	–3.7	6.2	5.8	6.1	4.6	4.2	98
Hungary	–3.5	–11.9	–3.1	–0.6	2.9	1.5	1.3	4.6	4.8	95
Slovenia	–7.5	–8.9	–5.5	2.8	5.3	4.1	3.7	4.8	3.9	101
Croatia	–7.1	–21.1	–11.7	–8.0	5.9	6.8	5.8	6.8	2.1	78
Bulgaria	–9.1	–11.7	–7.3	–1.5	1.8	2.9	–9.4	–5.6	4.0	68
Romania	–5.7	–12.9	–8.8	1.5	3.9	7.1	3.9	–6.1	–4.8	79
Russia	–3.0	–5.0	–14.8	–8.7	–12.7	–4.0	–3.6	1.4	–5.3	56
Belarus	–3.0	–1.2	–9.6	–7.5	–11.7	–10.4	2.8	11.4	8.4	79
Ukraine	–4.0	–10.6	–9.7	–14.2	–22.9	–12.2	–10.0	–3.0	–1.9	39
Moldova	n.d.	n.d.	n.d.	n.d.	n.d.	0.0	–5.9	1.6	–6.5	n.d.
Georgia	–12.4	–20.6	–44.8	–25.4	–11.4	2.4	10.5	10.6	2.9	33
Armenia	–7.4	–11.7	–41.8	–8.8	5.4	6.9	5.9	3.3	7.3	57
Azerbaijan	–11.7	–0.7	–22.6	–23.1	–19.7	–11.8	0.8	6.0	10.0	43
Kazakhstan	–0.4	–11.0	–5.3	–9.2	–12.6	–8.2	0.5	1.7	–1.9	61
Uzbekistan	1.6	–0.5	–11.1	–2.3	–4.2	–0.9	1.6	2.5	4.3	91
Kyrgyzstan	5.7	–7.9	–13.9	–15.5	–20.1	–5.4	7.1	9.9	2.1	64
Turkmenistan	2.0	–4.7	–5.3	–10.0	–17.3	–7.2	–6.7	–11.3	6.7	56
Tajikistan	–0.6	–7.1	–29.0	–16.4	–21.3	–12.4	–16.7	1.7	5.3	34

n.d. = no data.
Source: EBRD, 2012.

Bank for Reconstruction and Development (EBRD), the GDP (real GDP) in that year was 62% of the level of 1989 (EBRD, 2012). Still, the fall in Estonia was even one of the smallest on the territory of the former Soviet Union (but very high in comparison with post-socialist Central European countries) and Estonia was one of the first to take up a new growth. We should also take into consideration that these comparisons do not reflect changes in the quality of production.

Two core reforms

Estonia was one of the first among the former republics of the USSR to launch market reforms. The key role in transition processes was played by monetary reform, external liberalisation, privatisation (ownership reform) and tax and budgetary reforms. Because the two last ones were essentially first and foremost institutional reforms these are not discussed in this paper.[2]

Table 3

Inflation in some European post-socialist and CIS countries in 1990–1998 (change in annual average consumer price level, %)

	1990	1991	1992	1993	1994	1995	1996	1997	1998
Estonia	**23.1**	**211**	**1076**	**89.8**	**47.7**	**29.0**	**23.1**	**11.2**	**8.1**
Latvia	10.5	172	951	109	35.9	35.9	25.0	17.8	8.4
Lithuania	8.4	225	1021	410	72.1	39.6	24.6	8.9	5.1
Poland	586	70.3	43.0	35.3	32.2	27.8	19.9	14.9	11.8
Czech Republic	9.7	52.0	11.1	20.8	9.9	9.6	8.9	8.4	10.6
Slovak Republic	10.8	61.2	10.0	23.2	13.4	9.9	5.8	6.1	6.7
Hungary	28.9	35.0	23.0	22.5	18.8	28.2	23.6	18.3	14.3
Slovenia	552	115	207	32.9	21.0	13.5	9.9	8.4	8.0
Croatia	610	123	666	1518	97.6	2.0	3.5	3.6	5.7
Bulgaria	26.3	334	82.0	73.0	96.3	62.0	123	1082	22.2
Romania	5.1	170	210	256	137	32.3	38.8	155	59.1
Russia	5.6	927	1526	875	311	32.3	38.8	147	59.1
Belarus	4.7	94.1	970	1190	2221	709	52.7	63.9	72.9
Ukraine	4.2	91.0	1210	4734	891	377	80.0	15.9	10.6
Moldova	n.d.	n.d.	n.d.	n.d.	n.d.	29.9	23.5	11.8	7.7
Georgia	3.3	79.0	887	3125	15607	163	39.4	7.1	3.6
Armenia	10.3	274	1346	1822	4962	176	18.7	14.0	8.7
Azerbaijan	7.8	107	912	1129	1664	412	19.7	3.5	–0.8
Kazakhstan	n.d.	78.8	1381	1662	1892	176	39.1	17.4	7.1
Uzbekistan	4.0	110	645	534	1568	305	54.0	70.9	29.0
Kyrgyzstan	n.d.	85.0	855	772	181	43.5	31.9	23.4	10.5
Turkmenistan	4.6	103	493	3102	1748	1005	992	83.7	16.8
Tajikistan	5.6	112	1157	2601	350	613	419	88.0	43.2

n.d. = no data.
Source: EBRD, 2012.

Currency reform

The Estonian currency reform took place on 20 June 1992, that is exactly 44 years after the classic currency reform of the German western zones. Although, unlike the Estonian currency reform, the German reform was directly based on the administrative restriction of monetary overhang and its impact on the technological side of the Estonian reform was minimal, the

[2] On the privatisation in Estonia (obviously the most successful case of the large-scale privatisation among the post-socialist countries) see e.g. Terk (2000) and on tax and budgetary reform Kukk (2003).

‘ideology’ of the German currency reform played a significant role in the Estonian reform.

The denominational currency reform (10 roubles equalled 1 kroon) removed the roubles from circulation. The kroon was pegged to the German mark under the currency board arrangement, and based on the original gold and foreign currency exchange reserves[3] as well as the demand and supply of foreign currency at that time. The exchange rate was set at 1 German mark = 8 kroon (formally, the official buying and selling rates of the rouble were devalued at the moment of the currency reform in view of simplifying later revaluations by 9.6% and 2.4%, respectively).[4] In principle, the kroon was at that moment actually pegged also to the future euro: since 1 January 1999, the Estonian kroon has been re-pegged to euro at the exchange rate 1 euro = 15.64664 kroon and in 2011 the euro was adopted with the same exchange rate. Each permanent resident of Estonia could exchange up to 1500 roubles worth of cash at the exchange rate 10 : 1. This ‘starting pocket’ was equal to 18.75 German mark only. All bank deposits (these were ‘eaten up’ by inflation later) and liabilities were converted into kroons at the same rate.

Estonia was the first among the former Soviet republics to carry out a genuine currency reform with leaving the rouble zone. Unlike Latvia and Lithuania, Estonia jumped over the nominal parallel, that is the interim currency stage. This gave Estonia a lead in comparison with Latvia and Lithuania, which has persisted until today. Lithuania introduced the litas as

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[3] In 1992–1993 the pre-war gold deposits (11.3 tonnes of gold) in different Western banks were returned to Estonia in either gold or in the form of monetary compensation.

[4] Actually the introduction of the Estonian kroon on 20 June 1992 was only one moment in the evolutionary monetary reform in Estonia. Estonia was the first in the former Soviet Union who ‘legalised’ with gradual liberalisation of prices and wages starting in 1990 the so far hidden and restricted inflation. Accordingly, the roubles circulating in Estonia cheapened, as elsewhere in the Soviet Union the prices were still frozen. In addition to striving for so-called preventive inflation (substantially, beggar-my-neighbour policy), another main monetary policy phenomenon in Estonia’s economic policy of those years was the encouraging of dollarisation, thus creating an alternative foreign currency circulation and attracting foreign currency (first and foremost Finnish markka, Swedish krona and US dollar) into Estonia. In March 1991, the newly (re)established Bank of Estonia, whose role was a symbolical one at that time, started independently quoting the Soviet rouble, based on the black market exchange rates. In essence, this meant local devaluation of the Soviet rouble in Estonia. Thus, the years 1990–1991 can be regarded as the first, so-called interim currency stage of the stretched currency reform when the ‘official medium of payment’ in Estonia was the ‘own’ rouble, which was outwardly identical to the Soviet rouble but had lower purchasing power and brought Estonia’s price structure closer to the international price structure (see Kukk, 2007).

single currency on 1 August 1993 and Latvia the lat on 18 October 1993. Latvia came to fixing the exchange rate in February 1994 (to the special drawing rights, SDR) and Lithuania in April 1994 (to the US dollar under the currency board arrangement). The previous fixing of the kroon's exchange rate at the economically accepted level was definitely a reason why Estonia was in the first period of reforms undeniably more successful than Latvia and Lithuania, not to speak of the CIS countries. As early as in 1995, Estonia rose in terms of the per capita inflow of cumulative foreign direct investments (FDI) with 413 US dollars after Hungary (1113 USD) and the Czech Republic (532 USD) and before Slovenia (253 USD) to the third place among the post-socialist countries (EBRD, 1996). Some empirical studies have demonstrated the currency board arrangement to be more effective than other fixed exchange rate systems both in suppressing inflation and in ensuring faster economic growth (Ghosh et al., 1998).

However, it is necessary to underline that currency reform with the choice in favour of currency board arrangement was successful because it was followed by other reforms and managed to comply with certain 'rules of game' (conservative fiscal and banking policies, liberal foreign trade and foreign exchange policies, readiness to implement structural reforms). The Estonian case with the currency board is obviously the best example of the implementation of the main principles of such a monetary system.[5] On the other hand, the Estonian currency reform and monetary policy framework represented a non-traditional approach in the Central and Eastern European countries.[6]

The earlier introduction of 'hard' currency helped Estonia restructure its foreign trade, attract foreign investment and turn to new growth. The stable currency played a significant role also in the privatisation.

External liberalisation and integration into the Western economy

As regards secessional foreign trade reform, which meant external liberalisation in Estonia, we can speak of spontaneous and at the same time explosive changes, that is not gradual reform and development but simply a

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[5] Estonian monetary system was not an orthodox currency board arrangement. It did not completely rule out an independent monetary policy, but the monetary policy decisions taken by the Bank of Estonia could be only restrictive, not expansive (see e.g. Kukk, 2007).

[6] Currency board was in international financial quarters regarded then mostly as a bygone monetary system. This was according to a 'definition' in *The New Palgrave. A Dictionary of Economics* by Alan Walters, 'Once ubiquitous in the colonial regimes of Africa, Asia and the Caribbean, currency boards now survive only in such small countries as Singapore, Brunei and Hongkong' (Walters, 1987).

constrained-by-circumstances ad hoc action. This is obviously a reason why the processes in this sphere, unlike, for instance, monetary reforms and privatisation, have attracted little attention in other world as ‘Estonian *case*’ (Feldmann & Sally, 2001). The re-establishment of independence automatically meant the end of any kind of state monopoly in foreign trade. Such an approach was essentially facilitated by everyday life, because with the overall deficit and low purchasing power of the population it was inconceivable to introduce any kind of import restricting measures. Estonia’s choices and options differed in this respect considerably from those of the Central European countries (see e.g. Hungary …, 1990). However, in order to temporarily restrict exports of local resources, favoured by the strongly undervalued exchange rate of the rouble as well as of the kroon on ppp basis, for some time export quotas continued to be exposed on some goods that were in short supply in the domestic market.

Estonia’s foreign economic policy has been aimed primarily at opening access to foreign markets and promotion of foreign investment in the Estonian economy. This included primarily intensive activity to conclude agreements on free trade, investment protection and avoidance of double taxation. In 1992–1994, free trade agreements were enacted with Finland, Sweden, Norway and Switzerland. Trilateral free trade agreements between the Baltic States came into force on 1 April 1994 (for agricultural produce on 1 January 1997). A free trade agreement with the European Union was concluded on 18 July 1994 and came into force on 1 January 1995. Unlike Latvia and Lithuania, Estonia did not apply for any transition period (Latvia 4 years and Lithuania 6 years). Already before, Estonia had got a preferential regime under the Generalised System of Preferences (GSP). These were mostly so-called unilateral agreements, because unlike Estonia, the other party in the agreement retained the right to impose custom duties, especially on agricultural produce.

A free trade agreement between Estonia and Russia was initialled on 7 September 1992, which Russia did not enact on a purely political pretext. Moreover, from 1 July 1994 Russia also abolished the so far de facto working most favoured nation regime for Estonia, which meant double customs tariffs on Estonian products. In the early 1990s, Estonia hoped that a free trade agreement with Russia might ‘soften’ Estonia’s landing in market economy, providing thus at least some market for enterprises so far oriented to the Soviet Union’s internal market (electric motors, amelioration excavators etc.). Actually Russia with its double tariffs and economic uncertainty did the greatest favour to the Estonian economy, accelerating the structural changes and reorientation to the West, primarily to European Union markets.

Estonia established then an essentially unilateral free trade regime, which has been estimated to be quite unique. According to Feldmann (2000), ‘a policy of unilateral free trade was adopted, which is an extremely rare feature in the world political economy … Estonia can be thus described as a country approximating the open economy of economics textbooks.' Estonia was deemed to belong among the countries with the most liberal trade regime in the world (Lainela & Sutela, 1994; Berengaut & Lopez-Claros, 1998; Feldmann, 2000; Feldmann & Sally, 2001; Laaser & Schrader, 2003; etc.), which is clearly indicated also by various economic freedom as well as national competitiveness indices. Such a choice was induced by the small size and openness of the Estonian economy (Table 4).

The most momentous qualitative change (so-called geographical reform) in Estonian foreign trade has been the restructuring of markets. The withdrawal from the Russian market, if to evaluate this process with changes in the geographical distribution of Estonian foreign trade, happened essentially within a year – in 1992 (Table 5). This was induced by the relatively soft blockade imposed by Russia early in 1992 and the loss of trust in the Russian market (clearing of accounts did not work, buyers there proved insolvent). These changes were sealed with the currency reform, which secured convertibility of the Estonian kroon for current transactions. The subsequent years and especially the Russian crisis of 1998–1999 further strengthened this tendency (Kukk, 2000). These developments can be summarised in two drastic changes: the share of the former Soviet Union (CIS and Baltic countries, i.e. 'Eastern market') decreased in Estonian export in 1991–1993 from 94.7% to 44.3% while the share of EU-15 countries increased from 3.9% to 50.2% (Table 5).

Table 4

Development of Estonia's foreign trade and openness of its economy in 1993–2010

	1993	1995	2000	2005	2008	2009	2010
Export and import of goods[a]							
Export (bn euros)	0.7	1.2	3.4	6.2	8.5	6.5	8.7
Export (% of GDP)	44.8	44.0	55.9	55.5	52.0	46.9	61.2
Import (bn euros)	0.7	1.8	4.6	8.2	10.9	7.3	9.3
Import (% of GDP)	50.0	63.4	74.9	73.6	66.8	52.5	64.7
Export and import of goods and services (according to balance of payments)							
Export (bn euros)	1.0	1.9	5.2	9.0	12.1	9.7	12.2
Export (% of GDP)	66.6	68.0	84.4	80.1	74.1	70.3	85.3
Import (bn euros)	1.0	2.1	5.4	9.7	13.0	8.9	11.1
Import (% of GDP)	70.7	75.6	87.7	86.5	79.5	64.4	77.9

[a] Different years are not comparable.

Sources: Statistics Estonia, 2012; Bank of Estonia, 2012.

Table 5

Changes in the geographical distribution of Estonia's (external) export and import before and after regaining independence (1990–1993; general trade; as percentage)

	1990	1991	1992					1993
			Year	1st quarter	2nd quarter	3rd quarter	4th quarter	
Export (total)	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**
of which								
Eastern market	***94.1***	***94.7***	***47.0***	***59.1***	***57.4***	***47.3***	***35.3***	***44.3***
of which								
Latvia	5.7	7.7	10.6	8.5	9.2	13.1	10.4	8.9
Lithuania	3.1	3.8	1.5	2.3	1.8	1.3	1.5	3.8
CIS-12	*85.3*	*83.3*	*34.9*	*48.3*	*46.4*	*32.9*	*23.4*	*316*
of which								
Russia	55.0	56.5	20.8	32.0	27.0	17.2	15.9	23.6
Western market	***5.9***	***5.3***	***53.0***	***40.9***	***42.6***	***52.7***	***64.7***	***55.7***
of which								
EU-15	n.d.	*3.9*	*43.2*	*32.2*	*34.3*	*41.0*	*54.0*	*50.2*
of which								
Finland	1.1	2.3	21.2	14.4	20.2	17.5	27.4	21.5
Sweden	0.4	0.5	7.7	6.7	4.7	7.9	10.3	9.9
Germany	0.3	0.2	3.9	2.5	3.0	3.9	4.9	8.3
Import (total)	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**
of which								
Eastern market	***82.0***	***84.7***	***45.4***	***54.5***	***58.1***	***38.2***	***46.9***	***27.2***
of which								
Latvia	4.7	5.1	1.7	3.8	1.8	1.2	1.4	2.6
Lithuania	3.2	6.3	3.6	3.0	6.9	3.4	0.6	3.6
CIS-12	*74.1*	*73.3*	*40.1*	*47.4*	*49.4*	*33.6*	*44.9*	*21.0*
of which								
Russia	51.8	45.9	28.4	36.2	32.3	21.9	40.7	17.0
Western market	***18.0***	***15.3***	***54.6***	***45.5***	***41.9***	***61.8***	***53.1***	***72.8***
of which								
EU-15	n.d.	*6.0*	*44.6*	*37.4*	*38.5*	*48.5*	*46.9*	*69.8*
of which								
Finland	1.6	2.0	22.6	21.8	21.4	25.8	22.5	37.6
Sweden	0.1	0.8	5.9	5.1	4.5	6.7	6.9	10.0
Germany	2.3	0.8	8.3	4.2	7.0	8.0	9.4	9.1

n.d. = no data.
Note: 1990 and partially 1991 on the basis of domestic market prices.
Sources: Kukk, 1994; Statistics Estonia, 2012.

‘Shining star from the Baltics’, ‘Baltic tiger’, ‘*Musterknabe* [paragon]’

These are only some of the pet names attributed to Estonia and the other Baltic countries in global economic and political literature during the last 15 years, excluding 2008–2009. Since 1995 it is possible to follow a continuous growth of the GDP, with a short exception in 1999 when, caused by the Russian crisis, the GDP declined by 0.3%. Exports to Russia fell by 43% that year (total exports by 0.6%). However, the Estonian economy overcame the Russian crisis quickly and the growth rate for the year 2000 was already 9.7%, which was the highest figure among the post-socialist Central and Eastern European countries. This cyclical growth lasted until the year 2008. In this period essential structural changes took place in the economy as a whole (Table 6) as well as in industry (Table 7). High employment rates in agriculture and industry and under-development of the tertiary sector showed that at the end of the 1980s the structure of the Estonian economy was 20–30 years behind that of the Scandinavian countries. In 1995–2010, the percentage of agriculture in value added decreased more than 5-fold while that of services increased 1.5-fold. In the structure of manufacturing the shares of the food and textile industries fell whereas the share of the production of machinery and equipment increased.

The turn to the growth in 1995 did not mark an end of transition in the economy. Large-scale privatisation culminated in the period from the fourth quarter 1993 to the first quarter 1995 and ended essentially in 1997 (large-scale privatisation was first and foremost oriented to attracting foreign capital as FDI into Estonian economy); for the first time inflation (year-on-year) fell below 10% (8.2%) in 1998. The year 1997 can be regarded as the end of basic capitalist-market oriented reforms: then the European Commission claimed that Estonia is a functioning market economy: ‘Estonia can be regarded as a functioning market economy. It has radically liberalised foreign

Table 6

Structural changes in the employment in 1990–2010 (% of total employment)

	1990	1995	2000	2005	2008	2009	2010
Primary sector	19.5	10.3	7.1	5.2	3.9	4.0	4.2
of which							
agriculture	*15.8*	*8.2*	*4.9*	*3.7*	*2.6*	*2.9*	*3.0*
Secondary sector	37.4	34.4	33.4	33.8	35.4	30.7	30.5
of which							
manufacturing	*25.6*	*24.9*	*22.3*	*22.3*	*20.6*	*19.1*	*19.0*
construction	*8.4*	*5.6*	*7.1*	*8.0*	*12.3*	*9.8*	*8.4*
Tertiary sector	43.1	54.8	59.5	61.0	59.4	65.3	65.3

Source: Statistics Estonia, 2012.

Table 7

Structural changes in industry (% of total industrial production; current prices)

Industry	1995	2000	2005	2008	2009
Electricity, steam and hot water supply	13.5	9.9	6.1	6.3	8.0
Mining	4.5	3.6	2.9	3.4	4.1
Manufacture of food products and beverages	28.9	18.6	15.3	15.1	17.6
Manufacture of textiles, apparel and leather products	10.6	11.7	7.2	5.2	5.3
Manufacture of wood and wood products, incl. furniture	11.4	17.5	21.0	16.4	16.0
Manufacture of chemical products	9.2	7.1	9.9	11.2	10.0
Manufacture of fabricated metal products	3.8	6.4	9.5	11.6	9.7
Manufacture of machinery and equipment	8.8	12.6	13.4	16.5	16.0

Source: Statistics Estonia, 2012.

trade and privatised the public sector. Prices have been liberalised to a very large extent. The currency board system and the prudent fiscal stance have helped to reduce inflation. The legislative framework is largely in place' (Agenda 2000, 1997). The year 1997 may also be fixed as the conditional end of the secessionist (post-Soviet) transition period (Ennuste, 2007). The symbolic end of this period was the including of Estonia into the first, so-called Luxembourg group of the next enlargement of the European Union together with some other post-socialist countries (Czech Republic, Hungary, Poland and Slovenia) in 1997. Since November 1999, Estonia is a member of the WTO.

Economic policy at the turn of the century was oriented to accession to the European Union (1997–2003 can be seen as harmonisation period) and the euro area. The accession to EU on 1 May 2004 and NATO a month earlier gave an additional impulse to rapid economic growth, which however ended with overheating in 2007. The growth rates of the GDP doubled or nearly doubled: 8.9% in 2005 and 10.1% in 2006; the average annual growth rate of the real GDP (arithmetic mean) was 7.3% in the period of 1996–2007. These figures were among the highest in post-socialist Europe (Table 8). Supported by extensive foreign money inflow new jobs were created, but first and foremost in the closed sectors such as construction, real estate business and retail trade. Estonia achieved full employment. The labour market turned into an employee's market. The wages skyrocketed and started to generate additional inflation. In the context of growth theory it was a so-called 'big push' (first and foremost growth impulse from outside); on the other hand, however, it was an unbalanced growth. According to the EBRD, the cumulative inflow of FDI per capita into Estonia was the second largest among the post-socialist countries after the Czech Republic (5960 and 6337 USD, respectively, in 1989–2007), followed by Hungary (4829), the Slovak

Republic (4366), Croatia (4168) and others (EBRD, 2008). Geographical proximity to Finland and Sweden supported very strongly rapid re-orientation of the Estonian economy towards Western markets. At the turn of the centuries these two countries together accounted for more than 50% of Estonia's exports (Table 9). Besides, Sweden and Finland were in the 1990s and 2000s the main foreign investors into the Estonian economy, for example their percentage of all FDI (cumulative total) into the Estonian economy was 68.1% and 58.4% in 2003 and 2010, respectively.

Such an extensive growth after joining the EU was not sustainable. The imbalances in the economy deepened. The external imbalance was reflected in a very high deficit of the current account (15.3% and 16.2% of the GDP in 2006 and 2007, respectively) and internal imbalance in the acceleration of inflation (harmonised index of consumer prices, HICP, reached 10.6% in 2008). The first attempt to join the euro area in 2007 failed because Estonia was not able to fulfil the Maastricht inflation criterion. The imbalance in the labour market was expressed in the labour market turning more and more into an employee's market.

The expected slowdown in economic growth started. On the other hand, the external environment has been considerably more unfavourable for the Estonian economy since the mid-2007. The turmoil on the global financial markets (in particular the 'examples' of small countries like Iceland and later Hungary and New Zealand) increased risks involved in investing into Estonia. In the last quarter of 2007, the GDP fell against the previous quarter and in the first quarter of 2008 also on a year-on-year basis. The volume of industrial output turned to fall in the second quarter of 2008. Unemployment started to increase in the fourth quarter and employment to decrease in the first quarter of 2009.

Table 8

Growth rates (%) of the real GDP in European post-socialist countries that joined the EU in 2004

Country	2004	2005	2006	2007	2008	2009	2010	2007 (2003 = 100)	2010 (2003 = 100)
Estonia	**6.3**	**8.9**	**10.1**	**7.5**	**–3.7**	**–14.3**	**2.3**	**137**	**116**
Latvia	8.9	10.1	11.2	9.6	–3.3	–17.7	–0.3	146	116
Lithuania	7.4	7.8	7.8	9.8	2.9	–14.8	1.4	137	122
Poland	5.3	3.6	6.2	6.8	5.1	1.6	3.9	124	137
Czech Republic	4.7	6.8	7.0	5.7	3.1	–4.7	2.7	126	128
Slovak Republic	5.1	6.7	8.3	10.5	5.9	–4.9	4.2	134	141
Hungary	4.8	4.0	3.9	0.1	0.9	–6.8	1.3	113	108
Slovenia	4.4	4.0	5.8	6.9	3.6	–8.0	1.4	123	119

Source: Eurostat, 2012.

Table 9

Changes in the geographical distribution of Estonia's foreign trade in 1995–2010 (special trade; % of total export and import)

Country	1995	2000	2005	2008	2009	2010
Export						
Finland	23.3	32.3	26.4	18.4	18.5	17.0
Sweden	11.8	20.5	13.1	13.8	12.6	15.6
Russia	16.4	2.4	6.5	10.4	9.3	9.7
Latvia	7.4	7.0	9.1	10.0	9.5	8.9
Germany	7.3	8.5	6.1	5.1	6.1	5.2
Lithuania	4.4	2.8	4.6	5.7	4.8	5.0
USA	2.5	1.3	3.1	4.8	4.2	3.8
Denmark	3.3	3.4	3.2	3.3	3.5	2.5
France	0.8	1.4	1.2	1.4	2.3	2.5
Netherlands	4.4	2.5	2.4	2.3	2.5	2.3
Others	8.4	17.9	24.3	24.8	26.7	27.5
Import						
Finland	39.3	37.6	19.7	14.1	14.4	14.9
Germany	8.5	9.5	14.0	13.4	10.7	11.3
Latvia	3.0	4.1	4.8	9.1	10.5	11.0
Sweden	9.2	10.5	8.8	10.0	8.4	10.9
Russia	14.4	8.0	9.2	7.6	8.2	8.3
Lithuania	2.0	2.0	6.0	8.9	10.9	7.8
Poland	0.7	2.0	3.7	4.6	5.7	6.3
Netherlands	3.4	3.1	3.4	3.3	3.5	3.3
China	0.1	0.5	2.1	2.1	2.0	3.0
Italy	2.3	2.4	2.6	2.6	2.3	2.4
Others	17.1	20.3	25.7	24.3	23.4	20.8

Source: Statistics Estonia, 2012.

In autumn 2008, a global financial crisis broke out. The inflow of foreign capital stopped (at the end of 2010, the net foreign liabilities of commercial banks were 1/3 smaller than at the end of 2008). The first 'victims' of the crisis were real estate business and construction. However, the main setback hit exports. The precipitous decline of the import demand on the main Estonian export markets led to a rapid fall of industrial production: in the fourth quarter 16.4% over the corresponding period in the previous year. There was no hope of a soft landing. It is a fact that the main export markets of Estonia – Finland, Sweden, Russia, Latvia, Lithuania and Germany, whose share in Estonian exports was 63.4% in 2008 – proved to be the greatest losers in Europe.

At the same time, the weakness of external and domestic demand started to press down the inflation. The deflation tendencies in Western Europe reached also Estonia. From May 2009 to February 2010 the inflation rates (HICP; y-on-y) were negative. Such a situation gave Estonia a unique opportunity to fulfil all Maastricht criteria, including the inflation criterion: as satisfying deficit (general government fiscal deficit has to be lower than 3% of the GDP) and public debt (general government debt less than 60% of GDP) criteria depended only on the country's own acting (e.g. in 1996–2010 Estonia did not fulfil the deficit criterion only in 1999 and always fulfilled the debt criterion – Table 10), a higher level of inflation at the fixed exchange rate policy (in Estonian case the currency board arrangement) in open catching-up economies where the price level is considerably lower than in old members of the EU is theoretically inevitable (Balassa-Samuelson effect).[7] Estonia managed to meet the criteria and was the 17th country to join the euro area on 1 January 2011.

Table 10

Fulfilling Maastricht criteria by Estonia in 1996–2010

Year	General government fiscal balance, % of GDP	General government debt, % of GDP	Inflation (HICP), %	Exchange rate stability
1996	–0.2	8.2	23.1	1 DEM = 8 EEK
1997	2.2	7.0	11.2	1 DEM = 8 EEK
1998	–0.7	6.2	8.2	1 DEM = 8 EEK
1999	–3.5	6.6	3.3	1 EUR = 15.6466 EEK
2000	0.2	5.1	3.0	1 EUR = 15.6466 EEK
2001	–0.1	4.8	5.8	1 EUR = 15.6466 EEK
2002	0.3	5.7	3.6	1 EUR = 15.6466 EEK
2003	1.7	5.6	1.3	1 EUR = 15.6466 EEK
2004	1.6	5.0	3.0	1 EUR = 15.6466 EEK
2005	1.6	4.6	4.1	1 EUR = 15.6466 EEK
2006	2.5	4.4	4.4	1 EUR = 15.6466 EEK
2007	2.4	3,7	6.6	1 EUR = 15.6466 EEK
2008	–2.9	4.5	10.4	1 EUR = 15.6466 EEK
2009	–2.0	7.2	–0.1	1 EUR = 15.6466 EEK
2010	0.3	6.7	3.0	1 EUR = 15.6466 EEK

Note: The figures in the column 'Inflation' are not 12 months average (Maastricht criterion) but annual percentage change.
Source: Eurostat, 2012.

[7] The comparative price level of Estonia in 2004 and 2010 was 60% and 72% of the average of EU-15 and 51% and 61%of the Finnish average level, respectively (Eurostat, 2012). Higher inflation in post-socialist member states reflects the price convergence between EU member states.

At the end of 2009 or beginning of 2010, several European economies turned to a rise. For Estonia this meant first of all a recovery of external demand. After having decreased for nine quarters, in the second quarter of 2010 the GDP turned to growth in annual figures like in most European countries. The recovery of demand in foreign markets, above all in Nordic markets (Finland and Sweden), was followed by a rapid growth of industrial output and exports. The number of employed persons started to increase and unemployment to decrease. The GDP increased 2.3% in 2010 and 7.6% in 2011. After a 23% fall of exports in 2009 the growth in 2010 was 35% and in 2011, 37% (preliminary data). The crisis of 2009 was (statistically) one of the deepest and the amplitude of quarterly growth and fall rates of the GDP on year-on-year basis in Estonia was the highest among the EU countries in the period of 2008–2010.

Conclusions

During the 20 years after regaining national independence, Estonia has witnessed huge changes in its economy. From the country annexed and incorporated by the Soviet Union for half a century and totally isolated from the world market it has since 2004 become a member of the European Union and NATO. Since May 2010, Estonia is a member of the OECD and from 1 January 2011, the euro is the legal tender in Estonia. These processes have been followed by a rapid economic growth, with the exception of crisis years 2008–2009, and huge structural changes. In 2010, the per capita GDP in Estonia at current prices was still 32% of the Finnish figure (10 700 and 33 600 EUR, respectively), in 1995 it had been 10% only. According to the purchasing power parity (purchasing power standard), the difference was 1.8-fold (15 700 and 28 300 EUR, respectively) and in 1995 3.0-fold (see also Table 11). The former Soviet republic had grown into a typical European capitalist country. In April 2011, the International Monetary Fund included Estonia for the first time among advanced economies. Of the post-socialist countries only Slovenia, the Czech Republic and the Slovak Republic are in this category besides Estonia.

Table 11

Per capita GDP in some post-socialist countries in Central and Eastern Europe and in successor states of the USSR (in USD)

Central and Eastern Europe				Successor states of the USSR			
	1995	2009	2010		1995	2009	2010
Estonia	**2 600**	**14 400**	**14 400**	Russia	2 100	8 500	10 400
Latvia	2 000	11 400	10 700	Belarus	300	5 200	5 800
Lithuania	n.d.	11 100	11 000	Ukraine	700	2 600	3 000
Poland	3 600	11 300	12 300	Moldova	300	1 500	1 600
Czech Republic	5 300	28 200	18 300	Georgia	400	2 500	2 600
Slovak Republic	3 700	16 200	16 100	Armenia	400	2 600	2 800
Hungary	4 400	12 800	13 000	Azerbaijan	300	4 800	6 000
Slovenia	10 500	24 400	12 600	Kazakhstan	1 100	7 100	9 000
Croatia	5 000	14 300	13 800	Kyrgyzstan	300	900	800
Bulgaria	1 600	6 400	6 400	Uzbekistan	700	1 200	1 400
Romania	1 500	7 600	7 500	Turkmenistan	1 400	3 500	3 700
				Tajikistan	100	700	700

n.d. = no data.

Note: According to the official statistics of the USSR, the per capita national income (according to the Soviet method) in the Soviet republics in comparison with Russia (= 100%) was as follows: Latvia 102, Estonia 99, Belarus 99, Lithuania 92, Ukraine 75, Armenia 75, Moldova 70, Georgia 67, Kazakhstan 61, Azerbaijan 59, Turkmenistan 49, Kyrgyzstan 46, Uzbekistan 38 and Tajikistan 33 (Ékonomicheskoe …, 1990).

Source: IMF, 2012.

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ENERGY CRISIS AND THE OIL SHALE INDUSTRY

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Introduction

Energy crisis is visible. It is difficult to pay attention to anything else when we do not have the energy that we need. It drives economic growth all over the world; it gives us comfort and security. Growth of energy prices has created global interest in oil shale resources for oil and power production. Some forecasts indicate that oil shale can account for more than a third of the growth in the use of unconventional oil by 2030. Oil shale deposits range from Early Palaeozoic to Cenozoic in age. The reserves of oil shale in the world are immense, some 10^{13} tonnes, exceeding the resources of other solid fuels (coal, lignite, brown coal) all taken together (Veiderma, 2003). Over 600 deposits are known located in more than 30 countries on all continents (Liive, 2007). The largest resources are known in the USA (220–240 billion tonnes), Brazil (110–120 bn t), Russia (ca 70 bn t), China (ca 68 bn t), Australia (ca 35 bn t) and Jordan (ca 20 bn t). More than 80 deposits have been identified in Russia. In addition to the Leningrad deposit, the best fields for exploitation are those in the Volga-Petchyorsk oil shale province including the Perelyub-Blagodatovsk, Kotchebinsk and Rubezhinsk.

Evaluation of oil shale resources is difficult because of the wide variety of analytical units that are reported (Dyni, 2003). The grade of a deposit is often expressed in U.S. or Imperial gallons of shale oil per short ton (gpt), litres per metric ton (l/t), barrels, or short tons or metric tons of shale oil, kilocalories per kilogram of oil shale, or gigajoules per unit weight of oil shale. To bring some uniformity into this assessment, oil shale resources are mostly reported in metric tons of shale oil and in U.S. barrels of shale oil. By-products may add considerable value to some oil shale deposits. Uranium, vanadium, zinc and sulphur are only some potential by-products of oil shales. For example, graptolitic argillite in Estonia contains several rare elements, among them molybdenum (up to 600 g/t), vanadium (up to 1200 g/t) and uranium (300–400, in some places up to 1000 g/t). From 1949 to 1952 graptolitic argillite was mined at Sillamäe in NE Estonia for the production of uranium. More than 60 tonnes of uranium compounds were produced of some 250 000 tonnes of ore unearthed. The spent shale after retorting is used in the manufacture of cement in some regions, notably in Germany and China.

Composition of oil shale

Oil shales are fine-grained sedimentary rocks containing relatively large quantities of organic matter, known as 'kerogen'. World oil shales vary widely in their content and composition. Presently there is no unanimously accepted lower limit of the percentage of sapropelic organic matter for oil shales. The lower limit varies from 5% to 10% and the upper limit from 60% to 70%. It is difficult to find two analogous oil shales, mainly because of their extremely variable deposition conditions as well as postsedimentation alterations. For this reason there is a need for specific solution for every type of oil shale. Dyni (2003) gave an overview of the geology and resources of world oil shale deposits and mentioned a large variety of names that have been used, such as alum shale, cannel coal, boghead coal, lamosite, marinite, tasmanite, wollongite, torbanite, kukersite and others. The deposits of marinites and lamosites are the largest and most abundant.

Marinite is a dark-grey to black oil shale of marine origin in which the main organic components are lamalginite and bituminite derived from marine phytoplankton with varied admixtures of bitumen, telalginite and vitrinite. The Devonian-Mississippian oil shales of the eastern United States are typical marinites.

Lamosite is pale brown and greyish-brown to black oil shale in which the main organic constituent is lamaginite derived from lacustrine planktonic algae. Other minor components include vitrinite, inertinite, telalginite and bitumen. The Green River oil shale deposit in western United States and a number of the Tertiary lacustrine deposits in eastern Queensland, Australia, are lamosites.

Kukersite, which takes its name from Kukruse manor in NE Estonia where the rock was first described, is a light-brown marine oil shale whose principal organic component is telalginite derived from the green alga *Gloecapsomorpha prisca.* The Estonian and Leningrad oil shale deposits of Ordovician age along the southern coast of the Baltic Sea are kukersites. They contain organic matter, carbonate and clastic materials in various proportions. The carbonate material consists mainly of pore-filling micritic carbonate mud together with a variable content of fine to coarse skeletal debris. The carbonate content (mainly calcite) ranges in different kukersite seams from 20% to 70% and the organic matter content from 10–15% to 50–60%. The clastic matrix is composed mainly of silt-size quartz and illite, the minor clastic minerals are feldspars and chlorite, pyrite is a rather common authigenic mineral (Bauert & Kattai, 1997).

Several countries, including Canada, the USA, Scotland, Spain, Sweden, France, Australia, Jordan and South Africa, have had notable oil shale industries in the past, but they have been closed for economic reasons. Currently the largest miners are China and Estonia. Remarkable oil shale deposits are located in the United States (Dyni, 2006), which according to some forecasts account for up to 77% of the world's resources. The largest of the deposits is the Eocene Green River Formation in north-western Colorado, north-eastern Utah and south-western Wyoming.

The Estonian experiment

The Baltic Oil Shale Basin is situated mostly in the north-eastern part of Estonia and extends eastwards into Russia, covering a total area of over 50 000 km^2. The basin is administratively divided into the Estonia and Leningrad fields, comprising two currently mineable (Estonia and Leningrad) deposits and the prospective Tapa deposit (Fig. 1). The Estonia deposit is the largest explored and commercially exploited oil shale deposit in the world; its total resources exceed 7 billion tonnes of oil shale. The energy rating of the bed is 15–45 GJ/m^2. The oil shale reserve, based on an economic profitability classification, is about 5.0×10^9 t, where 1.5×10^9 t is classified as active and 3.5×10^9 t is passive (Valgma, 2003). About 4% of the total oil shale active reserve is located under building areas (Kattai et al., 2000).

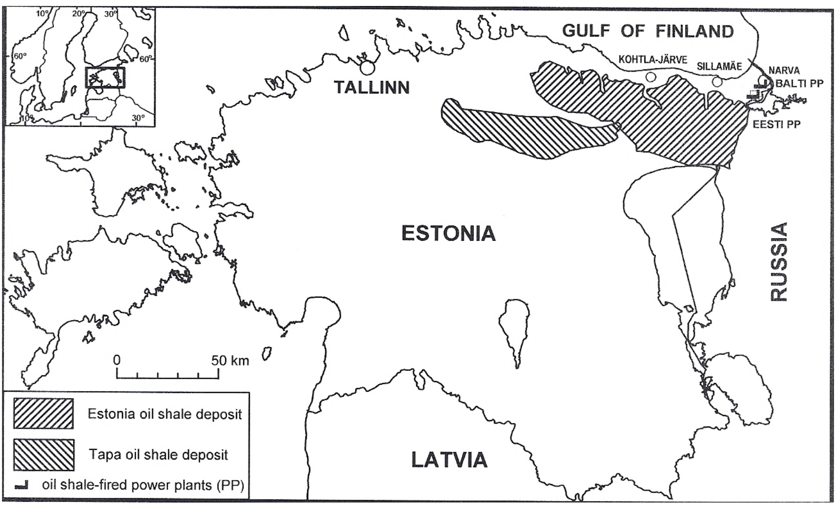

Fig. 1. Location of Estonia and Tapa oil shale deposits and Narva Power Plants.

The reserves of the Tapa deposit (2.6×10^9 t) have not been extracted. The seam thickness there varies from 1 to 2 m, with an average energy rating of 6.1 GJ/t. The area of the Tapa deposit is 1150 km^2 (Kattai et al., 2000).

The oil shale complex accounts for 4% of the Estonian gross domestic product, employs over 8000 people and is responsible for generating the largest part of the wastes polluting air, water and soil in Estonia. At present oil shale is used for electricity generation in power plants, shale oil production and in small amounts also for cement production. Oil shale mining is performed in Estonia using an opencast method (at 5–20 m depth) and an underground method (20–70 m depth).

In Estonia technologies of oil shale mining and exploitation have been continuously developed during more than 80 years. Since the 1960s, Estonia has been the greatest oil-shale producer and consumer in the world (Fig. 2). Up to 1960, the main oil shale consumers were the Kohtla-Järve and Kiviõli shale oil plants and the railway. Fine oil shale was used as a fuel at local power stations. Later large power stations using oil shale were launched in Narva: Balti Thermal Power Station in 1966 and Eesti Thermal Power Station in 1973. This altered the structure of oil shale consumption: about 80% of the mined oil shale was used for producing energy. Oil shale production reached its peak in 1980, when 31.3 million tonnes was mined. By now oil shale production has stabilised at a level of some 15–17 million tonnes per year.

Currently, kukersite oil shale in Estonia is mined in four underground mines (Estonia, Viru, Sompa and Ojamaa) and in nine opencast pits. Up to the 1990s longwall mining, where the bed was mined with a coal cutting shearer–loader, was widely used in underground mining. The roof was temporarily supported by hydraulic jacks. The method was rather productive but capital-intensive and it caused noticeable changes in land surface.

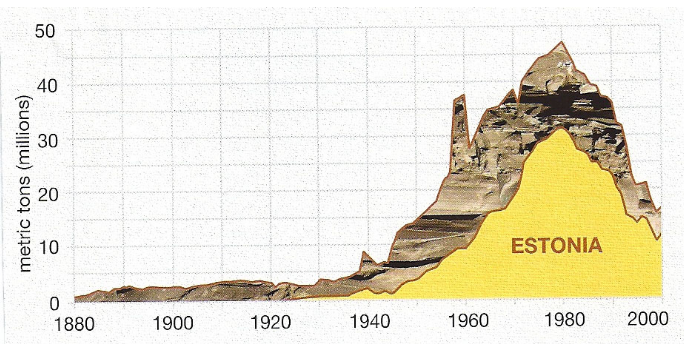

Fig. 2. Oil shale production in Estonia and the rest of the world in 1880–2000. Compiled by H. Bauert after Dyni, 2003.

These were the reasons for abandoning longwall mining in the 1990s, to be replaced by pillar mining, where the roof and mined-out land are supported with pillars of unextracted oil shale (averaging 25% of the reserve). As a result the ground does not subside but the losses of oil shale are rather large (Fig. 3).

In the surface mining technology developed after the Second World War the greatest in Europe bucket excavators (with bucket holding capacity of 35 m^3) EVG35/65, weighing up to 4021 tonnes, began to be used (Fig. 4). Both the overburden and the bed were at first broken up by blasting. Stripping was done with smaller excavators in opencasts with a thin overburden using front end loaders and hydraulic excavators. The overburden was transported with front end loaders and trucks.

During the last decades mining companies have had to apply new methods of mining to threaten the environment as little as possible and to obtain products of good quality. One of such methods involves the use of a Wirtgen 2500 SM surface miner (Fig. 5), which breaks, crushes and loads material in

Fig. 3. In pillar mining, the roof and the mined-out land are supported with pillars of unextracted rock, with some 25% losses of oil shale. Photo by Heikki Bauert.

Fig. 4. Largest in Europe bucket excavator EVG35/65 with bucket holding capacity of 35 m^3 and weighing 4021 t in the Aidu opencast. Photo by Ingo Valgma.

one operation. The surface miner enables environmentally sustainable mining of oil shale, reduction of losses and improvement of oil shale heating value. The surface miner can cut limestone and oil-shale seams separately and more exactly than rippers with 1-cm deviations. It is estimated that precise cutting enables the surface miner to increase the output of oil shale up to 1 tonne per 1 m^2 (Väli, 2011). This means that in the case of using a Wirtgen 2500 SM oil-shale losses can be reduced from conventional 12% to about 5%. This technology increases the oil yield by 30%, up to 1 barrel per tonne during the oil shale retorting, because of a better quality of the mined material. Also oil shale burning at power plants is more efficient because of a smaller content of limestone in oil shale.

The bulk of oil shale mined in Estonia today is used as a feedstock for the production of energy. Eesti Energia AS (Estonian Energy) with its 500 000 customers and more than 8000 employees is the leading Baltic energy utility as well as one of the largest companies in Estonia, which generates 95% of the electric power produced in the country. Since 2004 a new, circulating fluidised bed boiler technology is used for electric power generation. The performance and efficiency of boilers have risen and the percentage of harmful industrial contaminants emitted has substantially fallen and is now below


Fig. 5. Wirtgen 2500 SM surface miner in the Põhja-Kiviõli opencast. Photo by Heikki Bauert.

EU permissible limits. About 1.4 kg of oil shale is burnt in older boilers (pulverised combustion) of the Narva Power Plants to generate 1 kWh of electric power. The new technology has decreased the figure to 1.17 kg, resulting in substantial fuel saving (Liive, 2007).

The total oil resource in the Estonian deposit amounts to 985.7 million tonnes (Kattai, 2006). Presently shale oil is mainly used for producing fuel oil, and small amounts go to the production of calcined petroleum coke and road asphalt. Also phenols, resins, glues, impregnators, tanning agents, mastic and other products are made. Today two main technologies, Kiviter and Galoter (known also under different names such as Enefit, Petrosix, ATP, Petroter and Fushun technologies), are used in industrial production of shale oil in Estonia. The Kiviter process (vertical retorts with internal heating, some 1000 t oil shale per day) with the use of enriched high-calorific oil shale ensures 15–17% oil yield. Unfortunately, large amounts of organic matter get lost with harmful semicoke, which accumulates in large waste piles (Fig. 6).

The Galoter or TSK-140 process with a solid heat carrier in which poorer fine oil shale is used has lower environmental impacts. The process is based on introducing dried oil shale less than 25 mm in size into an aerofountain drier where it is mixed with hot (590–650 °C) shale ash produced by the combustion of oil shale semicoke (at 740–810 °C). The oil yield is 11.5–13% in

Fig. 6. Kohtla-Järve semicoke piles in May 2001. Photo by Arvo Käärd.

the Galoter process, which is 3–5% less than in the Kiviter process, but advantages are that ash is less harmful to the environment, the concentration of organic substances is below 1% and unriched oil shale of lower calorific value can be used (Veiderma, 2003).

In 2010 the output of shale oil in Narva, Kohtla-Järve and Kiviõli plants was over 555 thousand tonnes. The Narva Power Plants plan to install two new TSK-140 and two TSK-280 devices under the name Enefit. The Viru Keemia Grupp in Kohtla-Järve started to install two TSK-140 devices under the name Petroter. This will cause a high demand for oil shale in the coming future, because to obtain one million tonnes of shale oil 8 million tonnes of oil shale is needed. Enefit and Petroter are rather friendly technologies in the struggle with CO_2 emissions. They do not generate organic waste and do not use extensive amounts of water.

The mineral matter content of the commercial-grade oil shales is much higher than of typical coal. Therefore the large-scale use of oil shale will cause large amounts of combustion waste.

Environmental problems

During the years under Soviet regime the production of electric power, mainly on the basis of oil shale, increased nearly 100 times in Estonia. The development of the oil shale industry was the main priority in the Estonian SSR, and mining capacities skyrocketed. This was primarily needed for supplying the city of Leningrad with power and oil shale gas. By the end of 1954 more than 227 000 flats accommodating a total of 2.5 million people had been gasified on the basis of Estonian oil shale (Kukk, 2005). No attention was paid to environmental protection. Underground mining caused subsidence of the ground above shafts in an area covering thousands of hectares. This became an obstacle to the further management of the region. The hollows resulting from the collapse of rocks from the mine roof hindered the runoff of surface water as a result of which the plant cover perished. The total mined-out area was 424 km^2, which comprised 12.6% of Ida-Viru County's territory. About 8.4% of the county's area had been disturbed by mining using the underground method and 4.2% by the opencast method (Kattai et al., 2000). Of the area disturbed by underground mining about 87 km^2 was classified as subsided, where the topography had changed as a result of the failing of underground pillars, 36 km^2 was defined as stable and 150 km^2 was defined as unstable, liable to subside in the coming decades (Reinsalu et al., 2002).

The timing of oil shale and peat excavation was often poor. In several regions the speed of oil shale mining was so high that there was no time to take the overlying peat into use and large amounts of this valuable mineral resource ended up in wasterock dumps. A serious problem was related to great mining losses, which reached 50% even in the Estonian SSR's best-operating Estonia mine (Baukov & Tubli, 1976).

However, the fact that during Soviet time the mineral resources had no price was much more important. Yet economic calculations of their mining (non-mining) or environmental damage caused by mining can only be made by means of money price. The price system based on administrative grounds was voluntaristic. The price of Estonian oil shale was arbitrary: oil shale was cheap and it was donated to neighbouring regions. At the same time, in Estonia land was spoilt, people were driven out from villages as it happened, for instance, before the Aidu (former October) open-pit mine was put into operation. All the pollution generated by the oil shale industry remained in Estonia. Besides, the oil shale industry was based on workers recruited from other regions of the Soviet Union. This accelerated assimilation of the local population.

Harmful environmental impacts of oil shale use are well known and now thoroughly studied (Raukas & Punning, 2009). Oil shale combustion in power plants and retorting in the oil shale chemical industry for the production of shale oil and combustible gas generate huge amounts of waste – oil shale ash and semicoke. In power plants the ash that remains after combustion makes up 45–48% of the oil shale dry mass (Bauert & Kattai, 1997). Only a small percentage of ash finds its way to secondary use, either in construction materials, in agriculture for liming acid soils or in road construction as a stabilising agent of roadbeds. The amount of ash annually deposited in waste plateaus ranges between 5 and 7 Mt and the total ash waste volume is close to 300 Mt (Mõtlep, 2010).

The thermal combustion of oil shale in power plants will lead to increasing amounts of heavy metals, including radioactive ones, in the ash deposited on ash fields or emitted into the atmosphere. So the concentration of radioactive isotopes in the oil shale dumps, which cover more than 20 km^2 in NE Estonia, is many times higher than the background values in soils, reaching 5.5 g/T. Annually about 50 tonnes of uranium was transported with ash to the ash fields. In 1970–1990 more than 200 000 tonnes of fly ash was emitted into the atmosphere annually (Punning & Alliksaar, 1997).

Oil shale mining is accompanied by the lowering of the water level and discharge of mine water into bodies of surface water. Mining activities have a direct influence on groundwater quality due to the use of machinery, blasting, fuel and oil residues, etc. Exhausted underground mines are flooded. These abundant mine caves comprise a total area of 220 km^2, with 170×10^6 m^3 of water within them. The sulphate content of the water increased sharply from 300–600 mg/l to 1200–1500 mg/l in the two years following flooding as a result of the oxidation products of pyrite leaching from carbonate rocks. The sulphate content has later decreased, but still remains higher than the natural background (Erg, 2005).

Mine water is pumped out and discharged through pipelines to natural sedimentation ponds from where water polluted with sulphates flows into rivers. Mine water is also polluted by nitrogen, phosphorus and phenols. Because of mine water pumping sulphate concentration is high in most rivers in the region, as well as in nearby lakes, including picturesque lakes in the Kurtna Landscape Reserve (Erg, 2005).

To conclude, we can say that oil shale mining and processing have exerted and are still exerting a complicated impact on the surrounding landscapes, on their ecological state and matter cycling.

Summary and the outlook

The energy system is the single largest source of anthropogenic greenhouse gases, therefore it is no surprise that decarbonising the supply of energy services is a key element of climate change policy. The world is facing a global energy dilemma: can we have secure, reliable and affordable supplies of energy and, at the same time, manage the transition to a low-carbon energy system? The International Energy Agency forecasts a 40% increase in global energy demand between 2007 and 2030 and identifies China and India as the main focuses of growth. As we know, China is one of the greatest miners of oil shale in the world and the biggest polluter of the environment. However, we are not sure that there will be global warming in the coming future and its main reason will be anthropogenic carbon dioxide, and that we should make substantial investments in renewable energy technologies and nuclear energy, free of carbon emissions. It is now widely recognised that the current carbon-based energy system is unsustainable and costly (financially and environmentally). We should take it into consideration in Estonia as well and a reduction of oil shale-based energy here is unavoidable.

Although in today's world market oil shale is not competitive with petroleum and natural gas, it is still used and will be used in several countries as a cheap fossil fuel. The most important factor that will determine today's large-scale development of the shale oil industry is the price of petroleum.

World oil shale science and technology have a long history, but with considerable ups and downs. Depletion of oil reserves and emphasis on energy security can be expected to give an impetus to oil shale research in the coming future.

We cannot afford energy and oil at any cost. This means that we have to ensure that we take good care of the environment and society as well. Countries with great oil shale resources, such as the USA, China and Jordan, have made already large investments in oil shale research and technology. Estonia has a good knowledge in this field. In view of the great resources of oil shale in the world, we should develop international cooperation to exchange advanced oil shale know-how between countries.

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POTENTIAL USE OF UNDERGROUND MINE WATER IN HEAT PUMPS

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Introduction

The Estonian oil shale deposit comprises ten closed mines that are fully or partly filled with water. Eight mines in the central part of the deposit (Ahtme, Kohtla, Kukruse, Käva, Sompa, Tammiku, mine No. 2 and mine No. 4) form one underground water body. Ubja mine and Kiviõli mines are located in the western part of the deposit, away from the other mines.

In Estonia on average 9 TWh of heat is produced a year for the district heating network. Heat production differs in summer and winter about five times (Statistics Estonia, 2010). In the eastern part of Estonia, where closed oil shale mines are located, it would be useful to get part of the required heat from water. Water has a certain temperature throughout the year. To produce heat from mine water a heat pump has to be used (Leonardo Energy, 2008; Estonian Heat Pump Association, 2010). The first heat pump based on mine water was put into operation at Kiikla in 2011 (Karu, 2011).

The main aims of this research were to find parameters of water and the factors that influence the amount and availability of energy in the Estonian oil shale underground mining area and to analyse possibilities of using mine water as a heat source in heat pumps.

Oil shale mining area

Underground oil shale mining has been performed in the north-central part of the Estonian deposit (Figs 1 and 2) for 90 years. In this part of the deposit the depth of the oil shale layer is lower and its thickness is greater and quality better than in other parts of the deposit. This was the reason why in 1916 mining started from Kukruse, moving towards the wings of the deposit where mining conditions are worse. In the northern part of the

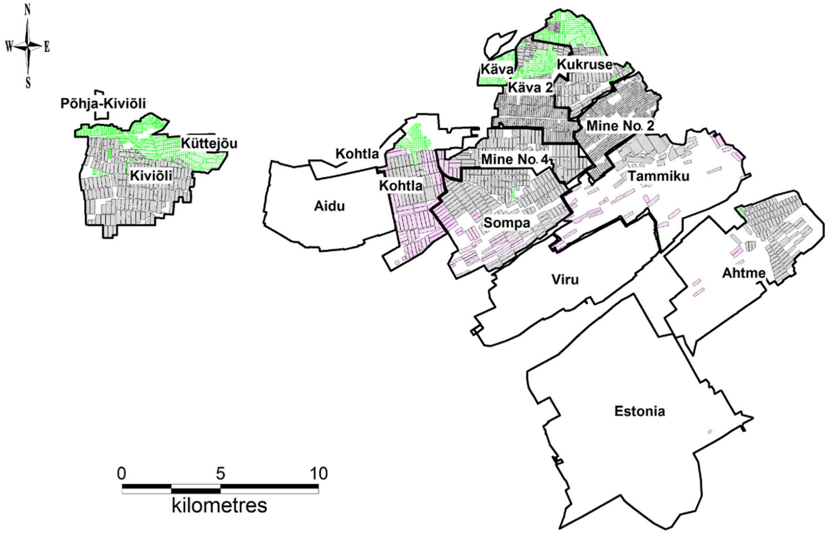

Fig. 1. Hand-mined (longwall, rooms) (green) and mechanised longwall (pink) mining areas.

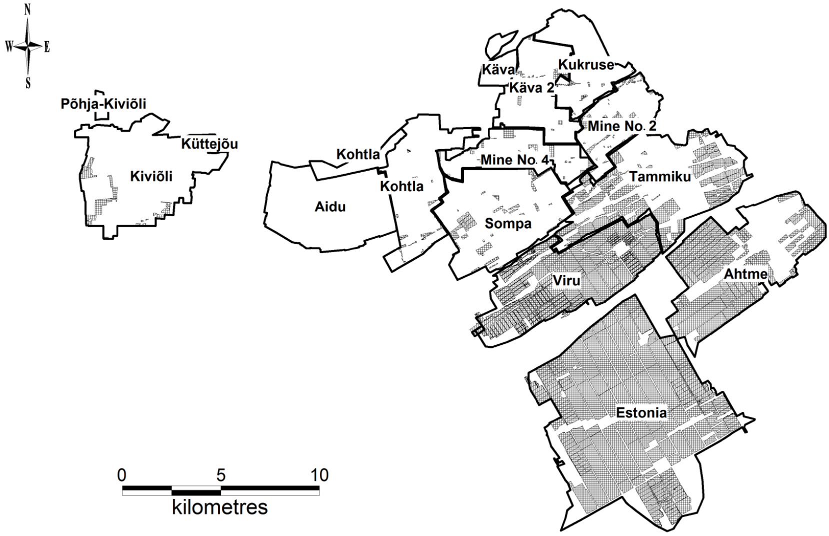

Fig. 2. Room and pillar mining areas (light grey).

deposit mostly the hand-mining technology with longwall mining was used (Fig. 1). In newer mines, launched in the 1950s–1960s, mostly the room and pillar mining method has been used (Fig. 2).

Groundwater

Groundwater accumulation and movement in sedimentary rocks is possible due to fissures. Fissures in sedimentary rocks determine the main properties of the rock, such as hydraulic conductivity, permeability, specific storage and specific yield. Also strength properties of rocks depend on fissures (Ojaste, 1974). The amount of water in fissures depends on the season. The temperature of the water in active circulation belts is mostly determined by the air temperature, and the temperature of groundwater depends on the geological conditions and bedding depth (Ojaste, 1974). The quality of the water in closed mines is improving. The contents of sulphates and iron in mine water decrease and in about five years after the closure of a mine are below the maximum level permitted in drinking water (Erg, 2005; Reinsalu et al., 2006; Karu, 2010).

Aquifer horizontal hydraulic conductivity, aquitard vertical hydraulic conductivity, ratio of aquifer vertical and horizontal hydraulic conductivities, rock-specific yield and artesian storativity depend on the material and layer thickness (Walton, 1987). The permeability of a porous medium is the ease with which a fluid can flow through that medium. It depends on the physical properties of the porous medium: grain size, shape and arrangement and pore interconnections. Water permeability is largely affected by the geological disturbances of the Earth's crust, which makes the aquifer highly anisotropic (Reinsalu et al., 2006). The permeability of rocks is determined by the size of the pores between the rock particles (Walton, 1987; Permeability of rocks, 2010). If the rock has small pores, water cannot easily infiltrate into it and this means that the rock is impermeable. On the other hand, if the rock has large pores, water can easily infiltrate and thus the rock is permeable. When water flows through an area of impermeable rock, little water infiltrates in the ground, as a result there is high surface runoff, leading to a high volume of water flow (Kresic, 1997; Permeability of rocks, 2010).

Water quality is also important. The sulphate content in the water filling up mines is high but in the closed mines it is low (Erg et al., 2007; Statistics Estonia, 2010).

During the pumping of water from underground mines a cone of depression forms around mining areas. The quantity of water pumped out from mines depends highly on the amount of precipitation and to a smaller extent also on groundwater and the water infiltrating from closed mines. According to the measurements and calculations performed, precipitation accounts for up to 70% of the water pumped out of mines (Reinsalu et al., 2006; Robam & Valgma, 2010). If the hydraulic conductivity of the streambed is high, the cone of depression may extend only partway across the stream. If the hydraulic conductivity of the streambed is low, the cone of depression may expand across and beyond the stream (Walton, 1987). There are two water levels in ground: dynamic and static water level. Dynamic water level is the level that forms during continuous pumping. Static water level is the initial natural water level.

Rock parameters

The moisture content is the ratio of the weight of water in the sample to the weight of solids. Saturation degree is expressed by the saturation index, which is the percentage of sample voids filled with water. Effective porosity is the volume of interconnected voids that allow free water flow divided by the total sample volume (Walton, 1987). Effective porosity (Table 1), vertical and horizontal hydraulic conductivity (Table 2) and permeability are hydrogeological parameters that greatly depend on the size of sediment grains and the percentage of various sediment fractions. Porosity is given as the ratio of the volume of voids to the total initial volume of the specimen before drying, which includes both voids and solids. For example, the average porosity of sandstone is 10%, of sands 35% and of clay 50% (Ojaste, 1974). Generally, if the water content increases, the porosity will also increase. If the water content decreases, the porosity will decrease.

All these properties (Tables 1–4) vary in the mined out area. They depend upon the rock type and the mining method that was used (Figs 3 and 4); therefore the used mining technology has to be known.

Table 1

Representative porosity values for sedimentary rocks (Walton, 1987)

Rock type	Porosity, %
Sandstone	14–49
Siltstone	21–41
Claystone	41–45
Shale	1–10
Limestone	7–56
Dolostone	19–33
Till	25–40

Table 2

Representative horizontal and vertical hydraulic conductivity values (Walton, 1987)

Rock	Horizontal hydraulic conductivity, m/d	Vertical hydraulic conductivity, m/d
Gravel	4.075×10^1–1.223×10^3	
Limestone	8.15×10^{-4}–8.15×10^{2}	
Sand and gravel	8.15×10–2.038×10^2	
Sandstone	4.075×10^{-1}–2.038×10^1	
Clay	8.15×10^{-1}–8.15×10^{-2}	2.038×10^{-5}–4.075×10^{-4}
Shale	4.075×10^{-7}–4.075×10^{-3}	4.075×10^{-9}–4.075×10^{-5}
Clay, sand and gravel		8.15×10^{-4}–2.445×10^{-3}
Sand, gravel and clay		4.075×10^{-3}–4.075×10^{-2}

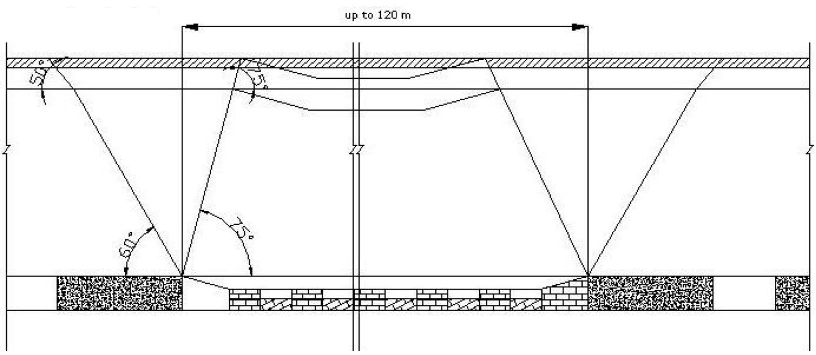

Fig. 3. Cross-section of a mine with the hand-mining technology.

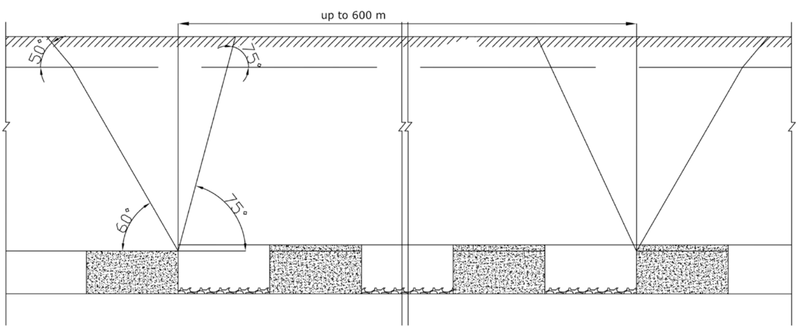

Fig. 4. Cross-section of a mine with the room and pillar mining technology.

Table 3

Specific water yield of common rocks (Walton, 1987)

Material	Specific yield, %
Silt	20
Clay	6
Limestone	14
Coarse gravel	21
Medium gravel	24
Fine gravel	28
Coarse sand	30
Medium sand	32
Fine sand	33
Fine-grained sandstone	21
Medium-grained sandstone	27

Hydraulic conductivity depends on the properties of both the porous medium and the fluid. Hydraulic conductivity (K) defines the specific discharge of a porous medium under a unit hydraulic gradient: $q = KI$. Hydraulic gradient (I) is hydraulic head loss per distance: $I = dh/dl$. Horizontal conductivity is generally 10–100 times higher than vertical conductivity (Perens, 2009). Specific storage (S_s) is the volume of water released from storage from a unit volume of aquifer per unit decline in hydraulic head. Specific yield (S_y) is the volume of water released from storage by an unconfined aquifer per unit surface area of aquifer per unit decline of the water table (Table 3). Specific yield is a dimensionless value (Walton, 1987). Transmissivity (T) is the product of hydraulic conductivity (K) and saturated thickness (b): $T = Kb$.

As a result of mapping, modelling and simulating, bases for a geometrical model, a groundwater model and a subsidence model were constructed. The geometrical model shows higher storage in the abandoned underground mining area where water flows towards the wings of the oil shale deposit. The water level has recently risen in the north-central part of the Estonian deposit (Valgma et al., 2010).

Methods

For calculating the potential amount of water the underground space and its properties should be defined. Since underground space forms from mine workings, roof structure and related water channels or tubes, this situation has to be mapped in 3D. Hydrogeological parameters have to be created and evaluated for defining the properties of the underground space and classifying the used mining technologies. Classification helps to define the space that is available for water in abandoned mines.

The main tools for analysing the amount of water in abandoned oil shale mines are computational modelling with spreadsheet models and designing the water flow with ModFlow. For the computational modelling it is necessary to know how the oil shale bed was mined (mining technology), how much space is in the old mine drifts and how water is moving between the mines. The model enables to assess the water levels in different mines and their border areas and to make assumptions and predictions about the water movement directions (Reinsalu et al., 2006).

Geometrical and hydrological properties of the water body

The geometrical parameters for the model are the bottom height of the oil shale seam; roof height, length and width; height of pillars and workings in the mines and thickness of overburden that is divided into the required number of sublayers by different storativity values. The main tools chosen for spatial modelling were spreadsheets and MS Access databases for systematising and querying data, MapInfo for georeferencing, Vertical Mapper for interpolating and grid calculations and ModFlow for pumping simulation. With the help of the interpolated grids, surface elevations (Fig. 5) and layer thicknesses the required properties were calculated. The modelled result shows that the bottom of the flat oil shale layer is sloping southwards (Fig. 6). Rapid changes in elevation indicate geological fault zones (Fig. 6).

The initial data obtained by grid calculation for the base model show that the average thickness of oil shale is 2.5 m, varying from 1.5 to 3.2 m. The thickness of the overlying rocks is from 3 to 66 m (Table 4).

Considering that the hydrogeological situation has changed relatively fast because several mining operations have been closed down and pumping has stopped in these regions, a dynamic model has to be created, simulating groundwater level, amount of water in working and abandoned underground mines and potential productivity of wells to be put into operation for energy extraction. The main hydrogeological parameters for a hydrogeological model are porosity, vertical and horizontal hydraulic conductivity, infiltration rate, storage and information about aquifers. The dynamic model has to be checked with a spreadsheet as well as the amount of water to find the suitable areas for heat pumps, using the same parameters to be entered in the hydrogeological ModFlow model (Table 5; Fig. 7).

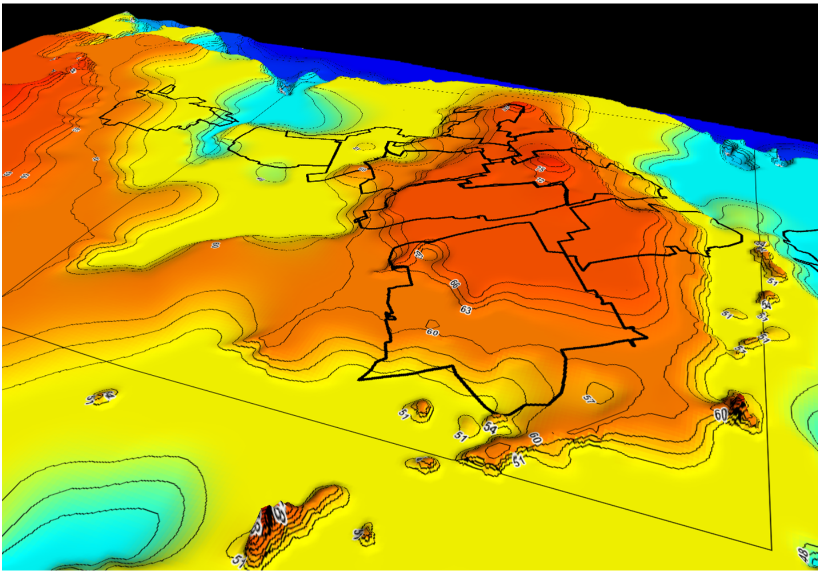

Fig. 5. Surface elevations of the study area.

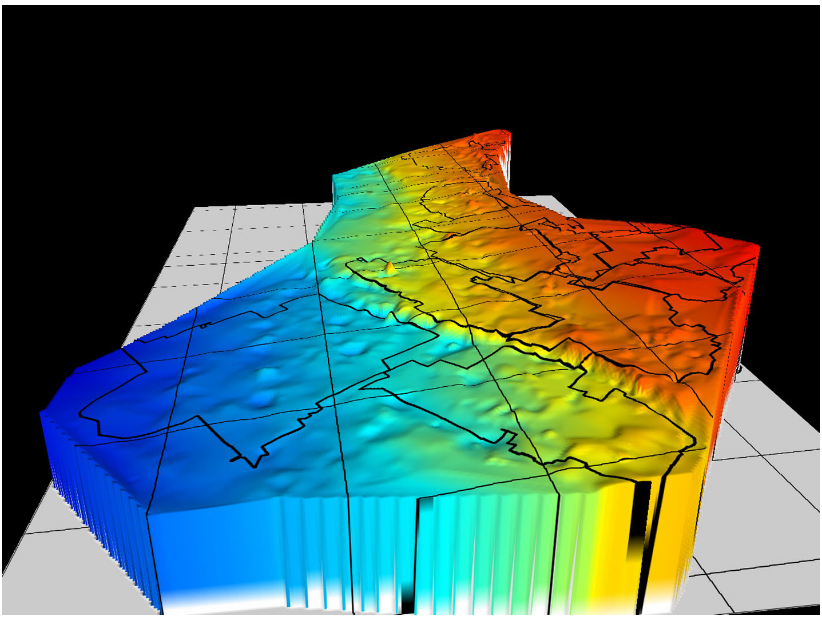

Fig. 6. Oil shale layer is flat and lowers 3 m per 1 km.

Table 4

Data on the mines located in the study area

Mine	Overburden thickness, m			Oil shale thickness, m			Ground surface, m		
	min	avg	max	min	avg	max	min	avg	max
Tammiku	10.7	23.1	43.3	2.8	2.8	2.8	50.0	67.4	80.0
Kukruse	9.4	11.3	12.4	2.8	2.8	2.9	59.9	70.5	79.5
Mine No. 2	9.3	12.7	21.9	2.8	2.8	2.8	58.2	70.0	75.9
Mine No. 4	4.1	11.9	20.5	2.8	2.8	2.8	49.9	61.7	72.5
Sompa	12.4	23.3	34.4	2.7	2.8	2.8	50.0	62.1	71.5
Viru	31.8	41.6	50.4	2.7	2.8	2.8	57.0	69.4	72.0
Estonia	49.3	56.8	65.8	2.6	2.7	2.8	50.0	63.4	70.0
Kohtla	2.6	15.0	54.1	2.7	2.8	2.8	49.8	51.1	60.0
Käva 1	15.0	21.0	30.0	2.8	2.8	2.8	51.8	59.5	62.0
Käva 2	7.2	9.6	12.8	2.8	2.8	2.8	58.9	66.1	77.8
Ahtme	13.3	37.1	54.9	2.8	2.8	2.8	42.3	63.8	71.2

Mine	Water level in 2000, m			Water level in 2004, m			Water level in 2008, m		
	min	avg	max	mi	avg	max	min	avg	max
Tammiku	25.1	35.4	41.8	34.9	47.8	51.1	28.2	45.0	47.4
Kukruse	51.0	52.1	53.9	49.4	50.0	50.1	51.2	52.1	57.7
Mine No.2	39.2	45.9	51.8	49.2	50.0	51.5	42.6	46.8	51.9
Mine No. 4	21.0	39.2	47.5	40.9	42.0	49.7	41.0	42.5	47.8
Sompa	19.8	22.6	38.7	41.4	42.0	45.0	32.6	41.8	45.0
Viru	11.5	24.0	37.0	17.3	26.4	50.0	11.3	24.6	44.8
Estonia	–15.0	1.0	52.2	–18.5	–0.8	25.6	–15.1	0.6	41.5
Kohtla	22.2	34.9	44.2	37.8	41.6	44.4	30.8	40.7	47.5
Käva 1	49.4	51.4	53.3	49.7	50.0	50.5	50.5	51.5	52.1
Käva 2	40.8	51.3	52.7	43.8	50.0	50.8	43.2	51.3	52.4
Ahtme	7.8	20.5	34.8	18.1	26.8	28.6	19.4	42.0	45.1

Table 5

Parameters for the hydrogeological model in ModFlow

Rock	Horizontal hydraulic conductivity, m/d	Vertical hydraulic conductivity, m/d	Porosity, %	Specific yield, %
Limestone	8.15×10^{-4}–8.15×10^{-2}	8.15×10^{-6}–8.15×10^{-4}	7–56	14
Clay	8.15×10^{-1}–8.15×10^{-2}	2.038×10^{-5}–4.075×10^{-4}	41–45	6
Oil shale	4.075×10^{-7}–4.075×10^{-3}	4.075×10^{-9}–$4.075 \text{ x } 10^{-5}$	1–10	

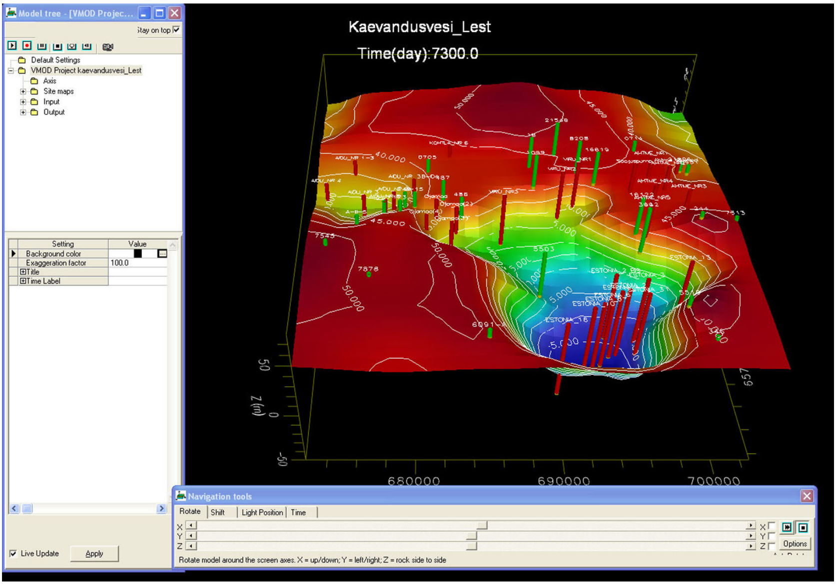

Fig. 7. Screenshot of the dynamic water flow model of mine water.

Limits for locating energy spots

The areas, underground workings or outflows, where energy extraction is possible could be called energy spots. For locating the energy spots certain limiting factors should be taken into account and spatial queries should be made. These are: water protection and environmental protection areas, restricted zones and areas, technological networks (pipelines, cables, etc.) and other objects.

Heat source calculations

Heat can be defined as energy transferred between matters because of differences in temperature. The ability of matter to transfer heat depends on its mass and temperature. In this research the primary analytical tools were spreadsheet models and GIS data analysis tools.

To calculate transfers of heat energy, the following equation can be used:

$$Q = m \cdot c \cdot \Delta t \text{ (kW)} \tag{1}$$

where Q – heat absorbed or released, kW;
m – water mass, kg/s;
c – specific heat capacity, kJ/kgK (4.19 for water);
Δt – change in temperature, ^{o}C.

To analyse the situation, the water volume for the heat pump has to be known in addition to the degrees of the temperature that will be decreased in the heat pump and the coefficient of performance (COP) (Calculating COP, 2010). Water volume for a heat pump is the amount of water that is pumped through the heat pump (m^3/h). Change in temperature t depends on how much heat will be taken away from water (°C). Coefficient of performance (COP) depends on how much electricity the heat pump complex consumes. Water volume and change in temperature are interdependent. Water can quickly heat up in the Earth's crust (if the water is returned to the mine, it depends on the technological solution).

COP is the ratio of energy output to energy input. For instance, a COP of 1 means that for every one unit of energy that the heat pump uses (such as 1 watt) it produces an equivalent unit of heat (1 watt of heat). A COP of 2 means that the heat pump can produce twice as much heat as it takes in to work, discounting small expenditures in its motor. Normal heat pumps have COPs that range between 2 and 5, depending on their efficiency. To know how much electricity has to be spent to get heat with the heat pump, we have to know COP and then we can calculate the electricity needs. The equation is:

$$\mathrm{COP} = \frac{Q_{\text{heat out}}}{Q_{\text{electricity in}}} \tag{2}$$

where $Q_{\text{heat out}}$ – quantity of heat production by heat pump, kW;
$Q_{\text{electricity in}}$ – quantity of electricity for heat production, kW.

In this study the potential of underground water pools for using heat pumps is analysed for the case COP = 3.

An example of calculations for heat pumps

Mine water that is used as a heat source for heat pumps has to produce 10 MW heat. The initial water temperature is 8 °C and the final water temperature is 7 °C (change in water temperature is 1 °C). To calculate the water mass, we have to transform Eq. (1) to the following equation:

$$m = \frac{Q/(c \cdot \Delta t)}{\rho} \tag{3}$$

where Q – heat absorbed or released, kW;
m – water mass, kg/s;
c – specific heat capacity, kJ/kgK (4.19 for water);
Δt – change in temperature, °C;
ρ – density of water, kg/m^3.

The water mass needed is calculated as follows:

$$m = \frac{10000/4.19 \cdot 1}{1000} = 2.39 \frac{m^3}{s} \Rightarrow 8604 \ m^3/h$$

Thus, in order to produce 10 MW of heat, 8604 m^3/h mine water passing the heat pump is needed.

As COP = 3 in the case of heat pumps, $\frac{10000}{3} = 3333 \text{ kW}$. So for the production of 10 MW of heat 3333 kW of electricity is spent.

Results

A spreadsheet model was used to determine the amount of water in different seams. Taking into account the porosity and thickness of the seams, the water amount in the overburden of the oil shale layers was calculated. The used mining technology and the thickness of the oil shale layer determine the free space in the mine that would be filled with mine water (Table 6). Taking into account these factors, the amount of water in the extracted oil shale layer was calculated (Table 6). Calculations showed that the amount of water is the largest in the Ahtme mine (Fig. 8; Table 6). Most of the water in the mining area is located in the extracted oil shale seam (Fig. 9; Table 6).

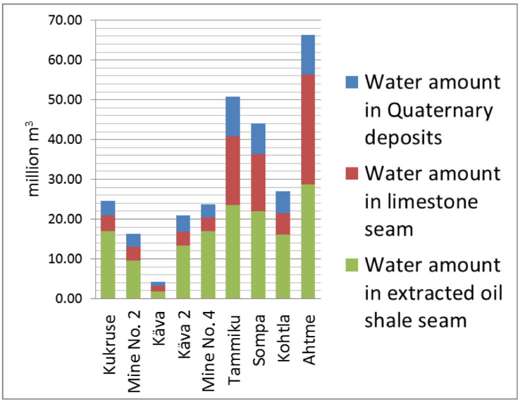

Fig. 8. Amount of mine water by seams.

Table 6

Properties of mines in the study area and mine water amount

	Kuk-ruse	Mine No. 2	Käva 1	Käva 2	Mine No. 4	Tam-miku	Som-pa	Koht-la	Aht-me
Mine opening	1921	1949	1924	1924	1953	1951	1948	1937	1948
Mine closing	1967	1973	1972	1972	1975	1999	1999	2001	2001
Working time, years	46	24	48	48	22	48	51	64	53
Field area, km^2	13.20	12.30	3.47	14.05	12.70	40.00	33.60	18.30	43.30
Mined field area, km^2	15.13	8.57	1.84	11.72	10.43	19.26	18.14	12.14	26.36
Unmined area, km^2	–1.93	3.73	1.63	2.33	2.27	20.74	15.46	6.16	16.94
Thickness of over-burden, m	11	13	21	10	12	23	23	15	37
Thickness of oil shale seam, m	2.83	2.81	2.83	2.82	2.8	2.8	2.77	2.76	2.79
Geological space in oil shale seam, mln m^3	**42.82**	**24.08**	**5.22**	**33.05**	**29.20**	**53.92**	**50.24**	**33.52**	**73.53**
Mined oil shale seam thickness, m									
Hand-mined face	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
Hand-mined rooms	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
Room and pillar	2.83	2.81	2.83	2.82	2.8	2.8	2.77	2.76	2.79
Drifts	2.83	2.81	2.83	2.82	2.8	2.8	2.77	2.76	2.79
Longwall face	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Mined field area, km^2									
Hand-mined face	11.28	6.87		9.16	7.71	4.36	12.70	3.80	6.33
Hand-mined rooms	3.50	0.00	1.84	1.73	0	0	0.06	1.36	0.05
Room and pillar	0.29	1.70		0.79	1.08	11.81	1.86	0.55	19.22
Drifts	0.06	0.00	0.00	0.04	0.69	0.36	0.00	0.02	0.30
Longwall face	0	0		0	0.95	2.74	3.52	6.41	0.46
Total mined area	15.13	8.57	1.84	11.72	10.43	19.26	18.14	12.14	26.36
Mine water amount, mln m^3									
Water amount in Quaternary deposits	3.66	3.37	1.04	4.19	3.34	9.94	7.76	5.48	9.96
Water amount in limestone seam	3.94	3.40	1.37	3.56	3.47	17.32	14.46	5.30	27.61
Water amount in oil shale extracted seam	17.05	9.54	1.74	13.29	16.92	23.51	21.93	16.14	28.75
Total	**24.65**	**16.30**	**4.14**	**21.04**	**23.74**	**50.77**	**44.15**	**26.91**	**66.32**
Mine water amount distribution in seams, %									
Water amount in Quaternary deposits	14.8	20.7	25.0	19.9	14.1	19.6	17.6	20.4	15.0
Water amount in limestone seam	16.0	20.8	33.0	16.9	14.6	34.1	32.7	19.7	41.6
Water amount in oil shale extracted seam	69.2	58.5	42.0	63.2	71.3	46.3	49.7	60.0	43.3

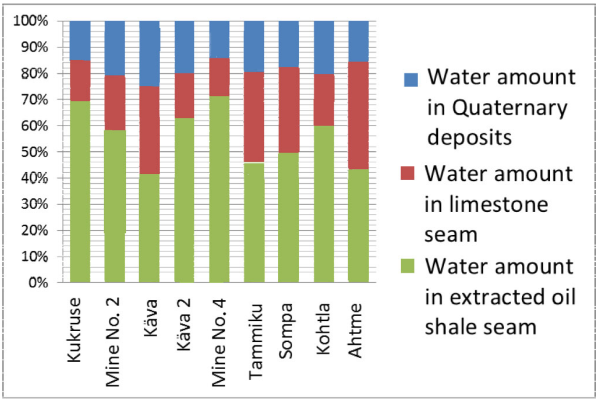

Fig. 9. Distribution of mine water in seams.

Water requirements for heat pumps

A possible location of a heat pump is on the top of the Ahtme oil shale mine (Fig. 10) in the vicinity of the Ahtme thermal power plant. The heat pump would use the Ahtme underground water pool for heat production. The amount of mine water in the Ahtme mine is 69 mln m^3. The heat requirement for consumption is 10 MW in summer and 50 MW in winter. Knowing the required heating capacity and applying equations (1) and (3), the spreadsheet model is used to calculate the necessary water amount for the heat pump (Table 7).

Table 7

Water requirements depending on water temperature reduction (initial water temperature is 8 ^{O}C) and heat production

Heat requirement, MW	Change in temperature, °C	Final water temperature after heat pump, °C	Water requirements, m^3/h
10	1	7	8 604
10	2	6	4 302
10	3	5	2 868
10	4	4	2 151
50	1	7	43 021
50	2	6	21 511
50	3	5	14 340
50	4	4	10 755

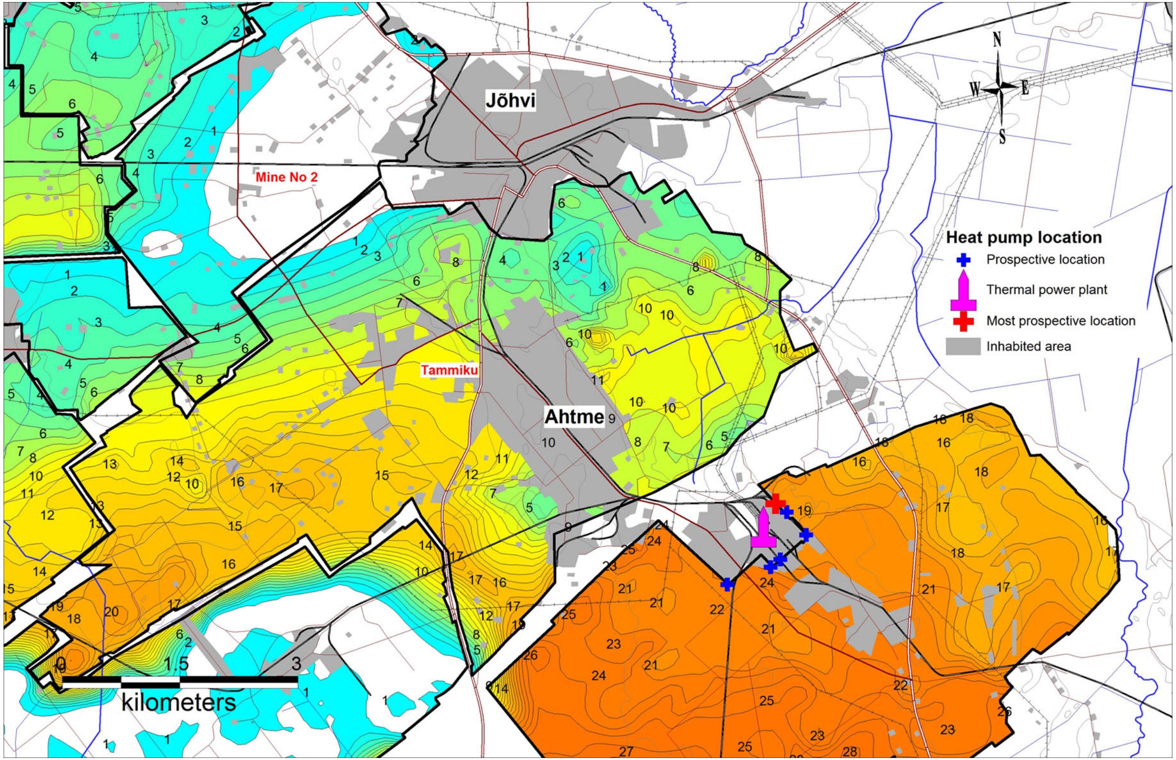

Fig. 10. Prospective locations for heat pumps in the Jõhvi and Ahtme areas. The figures show the height of the water from the bottom of the oil shale seam.

The best possible technical solution for using mine water in heat pumps is to pump the water through a drill-hole onto the ground surface (Fig. 11). After lowering the temperature of mine water in the heat pump by about 1–4 °C, the water will be directed back to the mine or to the water source. If underground water pools are used, the recommended temperature reduction is at least 4 °C. When the temperature is lowered less, large volumes of mine water have to be used, which would change the land and pillar stability situation in the mine.

In areas where groundwater is abundant and easily accessible, groundwater is extracted from a well and circulated through the cold side of the heat pump. Groundwater can be used either directly via circulation through the evaporator or indirectly via the use of an intermediate heat exchanger. An intermediate heat exchanger is the preferred option in most cases, as groundwater may cause corrosion or clogging of the evaporator. After leaving the heat exchanger, the cold groundwater will be directed back into the ground via an injection well.

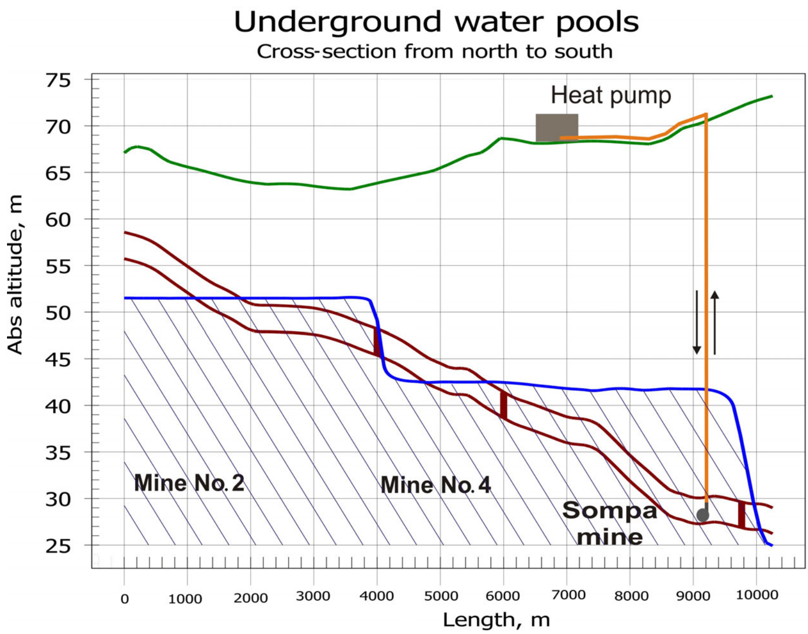

Fig. 11. North–south cross-section of the underground mining area with Sompa mine from where mine water for the pilot project performed at Kiikla was extracted and an example of heat pump installation.

A heat pump complex that produces 10 MW of heat, uses 2151 m^3/h mine water, produces 87 650 MWh heat per year and 29 217 MWh of electricity is consumed (COP = 3). A heat pump complex that produces 50 MW of heat uses 10 755 m^3/h mine water. The best possible solution would be to build a 10 MW heat pump complex as it allows optimum heat production through the year. In winter it would be necessary to use also a thermal power plant for heat production. The best location for a heat pump is near the Ahtme thermal power plant (potential locations are shown in Fig. 10). Then the existing district heating network can be used and in case the temperature in the heating network needs to be raised, the thermal power plant can be used.

Conclusion

Technological and hydrogeological modelling allows calculating the amount of water in the mines. However, the free flow in underground workings depends on the subsidence and closing practice of mines. Therefore, pumping tests should be made to check the flow. Groundwater and underground pool water can be used as the heat source for a heat pump complex.

In underground mines filled with water the water has a stable temperature all over the year. The water subjected to a heat pump and returned underground is warmed up by the heat of the Earth and mixing with warmer water. Use of mine water for a heat pump complex is unique in the world. The first heat pump complex as a pilot project was opened at Kiikla, NE Estonia, in 2011.

Acknowledgements

The reported research is related to Estonian Science Foundation grant No. 7499 'Conditions of sustainable mining' and No. 8123 'Backfilling and waste management in Estonian oil shale industry' and a study of the local power supply in Ida-Viru County.

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LANDSCAPES OF NORTH ESTONIAN ISLANDS AND THEIR CHANGES IN THE 20th CENTURY

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Introduction

Landscape investigations have become diverse due to the multiple possibilities of comprehending and interpreting landscapes. When performing these investigations, landscapes are increasingly treated as being a result of changing and manifold relationships of man and the environment. In recent decades the concept of landscape has considerably extended and it is approached simultaneously as ecological, cultural, economic as well as socio-spatial evidence (Mander & Antrop, 2003).

In the investigations of the relatively young landscapes of Estonia much attention has been paid to their development, diversity and changes. The landscapes at lower hierarchical levels are more easily comprehended and their investigations are more detailed. The investigations carried out on small islands, too, are detailed, considering the vulnerability of the object as compared to larger objects situated on the mainland. From the standpoint of landscape science integrated investigations of the nature of small islands are valuable, enabling to elucidate relationships between the different components and the development of landscapes. Transformation in the landscapes of islands depends on natural factors as well as socio-economic conditions (MacArthur & Wilson, 1963).

The coastal sea of Estonia is extremely rich in small islands. These islands belong to different landscape regions. A characteristic feature of North Estonian islands is their position in the area of the neotectonic land uplift (Vallner et al., 1988), due to which these islands are young and their development is rapid. The land uplift explains the occurrence of coastal formations of different age on the islands at different elevations and distances from the present-day shoreline. The higher and generally also older parts of the islands are mostly related to glacial landforms. Land uplift causes also changes of soils as well as hydrological properties of the substrate. As a result, the growth conditions of plants alter, which is accompanied by replacement of one association with another, thus forming plant successions that differ by islands (Vartiainen, 1980). Some landscape types have reached a stage of balance on islands, while others are in an early stage of development.

The youngest landscapes, which are subject to the greatest and fastest changes, generally occur close to the shoreline, where wave activity and salinity of seawater are among the major impactors (Ratas et al., 2003). Development of the islands is closely connected with the surrounding sea; therefore insular landscapes differ from those on mainland areas.

The landscape is a result of dynamic relationships between various elements, which may be abiotic and biotic, including the influence of man. Chemical and physical properties of the substrate affect the development of the biotic component of the islands' ecosystem. Besides, the water regime plays an important role, influencing the development of soils, availability of nutrients and evolution of vegetation (Ratas & Nilson, 1997). The development of the landscape of small islands has been strongly influenced by human activity. The most intensive exploitation of small islands is connected with the formation of permanent settlements. Before that, the islands were used as hayfields, most of them also as summer pastures (Ratas & Puurmann, 1995).

The way and intensity of using the islands play an important role in landscape changes. The social and economic changes as well as trends of political development and the accompanying type of landed property are of great importance, too. The changes in society trigger changes in economy, which are directly reflected in land use and density of population (Kaur & Palang, 2005).

The character of land use is above all determined by its suitability for utilisation. The possibilities of land use on an island depend primarily on the percentage of marine (directly affected by seawater) and supramarine zones (not under a direct impact of seawater), which is closely related to the geomorphology of an island (Ratas & Nilson, 1997). Fields have been located on higher parts of islands, covering mostly just a small area of arable land. Pastures were situated mostly on sodded shores, pebble–gravel beach ridges and sandy areas poor in nutrients, while hayfields spread on sodded shores and lower Gleysol parts of sandy plains. Forests covered higher stony and sandy sites, sometimes occurring also on paludified areas. Dwellings were situated on higher sites somewhat farther from the shoreline. In addition to tillage and cattle breeding, also fishing and seal hunting were among major sources of subsistence of the islanders.

The geographical position of the islands has been an important factor from the standpoint of using them. Many of the islands were situated close to important seaways and several seamarks have been established there. Some islands were located in strategically important places and were therefore used for military purposes in different times (Nerman, 2008). In the middle of the 20^{th} century most Estonian islands were included in the Soviet border zone and therefore using and visiting them was restricted, in places even forbidden. The ways of using the islands changed in the last decades of the 20^{th} century when Estonia regained its independence, ownership forms were altered and tourism began to develop on islands.

Nature protection has played an important role in the development of insular landscapes. In Estonia relevant activities began a century ago on the Vaika islets (Leito et al., 2008). Today, the majority of small islands are located on the territory of nature reserves. Many are included also in the Natura 2000 network, which highlights their nature values, stresses the need for protection and helps to preserve important habitat types and habitats of species within their natural distribution areas. An important issue in the use of islands is the need to preserve the characteristic semi-natural habitats that are valuable from the standpoint of nature protection on one hand, and the desire to develop the islands as recreational areas on the other hand (Gladh, 2005).

General characterisation of the studied islands

In the Estonian coastal sea there are more than 1500 islands and islets. In the territorial waters of Estonia in the Gulf of Finland there are about 100 small islands belonging to the landscape region of the North Estonian Coastal Lowland (Linkrus, 1998). These islands are different from the West Estonian ones, which are situated in the area of outcropping Ordovician and Silurian calcareous rocks.

Eight inhabited (formerly or nowadays) islands of the North Estonian coastal region were investigated (Fig. 1, Table 1).

Most of them are situated close to the mainland, being a direct continuation of the peninsulas on the North Estonian Coastal Lowland via underwater banks. The topography of the islands is flat; the dominating accumulation–abrasion plains are dissected by low beach ridges, scarps and dunes.

The studied islands are higher parts of north-west–south-east oriented drumlin-like landforms, which have risen above sea level as a result of land uplift (Karukäpp & Malkov, 1993). Differences in the development of coastal areas are caused also by the differences in the land uplift in post-glacial time. The present rate of the land uplift in North Estonia is about 2 mm per year (Vallner et al., 1988). The oldest island of this area is Naissaar, which started to emerge from the sea about 7500–7700 ^{14}C years ago (Punning et al., 1998), while the remaining islands under discussion emerged during the Limnea Stage and this process continues also nowadays. The land uplift at Estonian coasts has created a series of different development stages of islands (Orviku & Sepp, 1972).

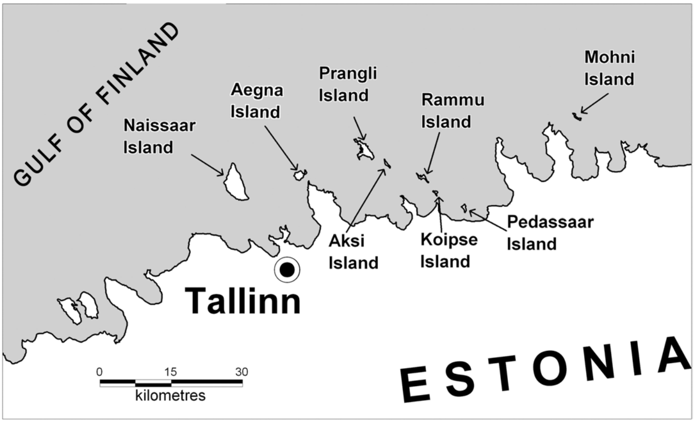


Fig. 1. Location map of the studied islands in North Estonia.

Table 1

Numerical characteristics of the investigated islands

Island	Area, km^{2*}	Max elevation, m a.s.l.**	Shoreline		Distance from mainland, km
			length, km*	dissection coefficient*	
Naissaar	18.56	27.0	24.4	1.58	8
Prangli	6.44	11.5	26.4	2.94	10
Aegna	2.91	12.8	10.1	1.67	2
Rammu	1.02	4.0	11.5	3.12	4
Pedassaar	0.90	13.0	5.2	1.54	1.5
Mohni	0.63	10.1	6.0	2.14	5
Aksi	0.59	4.3	5.1	1.87	5
Koipse	0.34	7.0	4.5	2.17	1.5

* After Loopmann (1996); ** after Loopmann (1996) and topographic maps.

The studied small islands are located not far from the coast, on the morphologically strongly dissected southern coastal slope of the Gulf of Finland (Kiipli et al., 1993). The crystalline basement is covered with Vendian and Cambrian sedimentary rocks, which are overlain with Quaternary deposits. On Prangli Island the Quaternary deposits (50–120 m) lie directly on the crystalline basement. Quaternary deposits are represented mainly by tills. On Prangli the stratotype section of the last Eemian interglacial has been established at a depth of 66–78 m (Kajak, 1961; Raukas & Kajak, 1997). Analyses have revealed that the marine sediments between the tills formed in relatively warm waters of the Eemian Sea in the course of the interglacial. The interglacial deposits are overlain with several till beds and lacustrine, glaciofluvial and marine sediments. The occurrence of natural gas on Prangli, Aksi, Rammu and Koipse is probably connected with interglacial organic deposits.

The network of inland waters is poorly developed because the islands are small and geologically young. Shallow permanent bodies of water (lakes) can be found only on Rammu and Aksi.

The soils of the investigated islands are thin and just in the early phase of development, due to which their profile is simple. Soils are entirely missing in sandy areas, pebbly beach ridges and recent shore. Seaweed mounds serve as habitats suitable for vegetation. The soil parent material is mostly sand and gravel poor in carbonates.

In the phytogeographical division by Lippmaa (1935) the studied islands belong to the northern subdistrict of the Estonian island and coast district (*Estonia maritima borealis*). Many species on the islands are at the southern boundary of their distribution area. The number of plant species on each island depends, in addition to the variation of edaphic conditions, on the area of the island as well as its location (Rebassoo, 1974). The abundance of species on the islands under discussion is not high, but rare and interesting plant species can be found, several at the boundary of their distribution area. The number of plant species ranges from 516 (Naissaar) to 201 (Aksi) (Ploompuu, 2009). The vegetation of the islands varies from coastal open plant communities to forests. Most of Estonian forest types (except alvar forests) are represented on these islands. Heath with *Empetrum nigrum*, seashore meadows and northernmost mires of Estonia are also noteworthy. Some types of coastal vegetation, such as seashore grasslands, are semi-natural plant communities, which exist and develop only when there is periodic mowing or grazing.

Settlement of islands

In the early 13th century the coastal areas of Estonia were not permanently inhabited; there were just fishermen's shacks used during the summer fishing season (Peil, 1999). The earliest written record mentioning Naissaar and Aegna dates back to 1297. In this document Erik Menved, the King of Denmark, forbids logging on these islands as well as on the Karl's Islands (Meikar, 1998). In the late 14th century historical documents mention Prangli Island (*Rango, Wrangoe*). After the Great Northern War, in 1716, altogether 16 families inhabited Prangli (Viidas, 1992). They were mainly engaged in fishing and to some extent also in seal hunting. In 1726 three families lived on Aegna. Aksi was inhabited at approximately the same time. Before that, Aksi and Prangli were temporary stopping places of fishermen. Among the islands of Kolga Bay, Rammu was inhabited the longest, since the early 18th century. The first inhabitants of Koipse came from Rammu Island in the late 18th century (Peil, 2002). In the 19th century the population of the islands grew explosively. Since ancient times, Mohni has sheltered castaways and fishermen from neighbouring areas. There was also one farmstead on Mohni, which perished only after the First World War (Juske, 2004).

The population of the investigated islands was the most numerous at the beginning of the 20th century. In connection with the lessons from the Russo–Japanese War, Naissaar and Aegna became part of the Russian defence system and were turned into military islands, from which the local inhabitants were forced to leave (Gustavson, 1998). During the Second World War and the Soviet occupation period the coastal population drastically decreased and their way of life substantially changed. After the Second World War people left also Rammu and Koipse islands (Peil, 1999), only Prangli remained permanently populated. By the mid-20th century, 83 families lived on this island and the number of permanent residents was 296, that is 47 persons per square kilometre (Koskor, 1964).

The 1990s together with the re-independence of Estonia brought along new changes. The military base on Naissaar was liquidated (Martin, 1999). By now, some summer cottages have been built on Rammu and Koipse. During the Soviet period (from the late 1960s) institutional holiday homes were established on Aegna, but these ceased to function when Estonia regained its independence (Nerman, 2008). Presently the number of inhabitants on Prangli is about 140. Today the islands are suitable for recreational purposes. The potential of tourism on these islands is related to day-trips and overnight visits during the summer season. Many of the studied islands have been taken under nature protection. Mohni Island belongs to Lahemaa National Park (established in 1971), Rammu and Koipse to the Kolga Bay Islets' Landscape Reserve (1991) and Aksi to the Prangli Landscape Reserve (1999). The Aegna Landscape Reserve was formed in 1991 and the Naissaar Nature Reserve in 1995.

Material and methods

The current study is based on interpretation of data from the literature, analysis of various maps and field investigations carried out in 2002–2005. The objects of investigation of landscape studies were localities, which are one of the smallest typological units in landscape science. For the research of the landscape of the islands, the main classical research methods were used: large-scale landscape (locality) mapping (1 : 10 000) and the methods of landscape complex profiles. By *locality* we understand the natural territorial complex connected with the mesorelief and mechanical composition of the deposits. To characterise landscape structure the following quantitative parameters were used: number of landscape units (localities), number of landscape types and edge index (Forman, 1995). The landscape fragmentation within the localities is expressed by vegetation site type.

The landscape profiles showing cross-sections of different landscape units were used for studying the landscape structure and interrelationships between their components. The impact of human activity on the islands' landscapes is expressed via land cover. Each land cover unit reflects the character of vegetation generated by land use (grassland, wooded land, arable land and others). The land cover units are based on the CORINE system (Meiner, 1999). Maps identifying land cover are available back to the beginning of the 20th century, and in some cases even earlier.

Landscapes of islands and landscape fragmentation

The landscapes of the North Estonian islands have been developing on noncalcareous parent rocks surrounded by the deeper sea and having a more continental climate than the westerly islands (Ratas et al., 1996; Kokovkin & Loodla, 1998). The landscape structure of the studied islands is rather diverse and is characterised by applying small typological units – localities. On the studied islands 17 types of localities were distinguished (Table 2). The diversity of landscape structure is mainly connected with the size and age (height) of the island. More localities generally appear on greater and older islands, for example on Naissaar (12 locality types). However, on the smaller Prangli Island with more variable edaphic conditions the landscape fragmentation is greater. The landscape structure of Pedassaar Island is the simplest.

The landscape structure on Naissaar, Aegna and Prangli islands is rather similar. The prevalent part of the islands is occupied by localities associated

Table 2

Landscape characteristics of the investigated islands

Island	Number of locality types	Edge index, m/ha	Area under the influence of the sea, %	Inland part of island, %	Number of vegetation types
Naissaar	12	61.3	6.2	93.8	7
Aegna	9	100.3	6.3	93.7	14
Prangli	14	114.7	19.2	80.8	16
Aksi	5	163.1	30.5	69.5	7
Rammu	7	123.7	34.5	65.5	9
Koipse	6	133.3	23.6	76.4	4
Pedassaar	4	59.3	11.4	88.6	4
Mohni	8	134.3	30.0	70.0	6

with plain areas indented by localities of sandy and pebbly beach ridges, dunes as well as fens and transitional fens. The landscape structure of Prangli Island is characterised by a greater share of the locality of sodded lowshore (19%).

Owing to the military use of Naissaar Island, there are also artificial localities (1%). On Rammu and Koipse islands the locality of sandy plain predominates (47–60%). Of considerable significance are also localities of pebbly beach ridges (on Rammu Island 13%, on Koipse Island 10%) and paludified sandy plains (0.7% on Rammu and 6% on Koipse). On Aksi Island pebbly beach ridges dominate (35%), alternating with localities of paludified areas. On Rammu and Aksi islands also a locality of lake (4%) occurs (Fig. 2).

The geomorphology of the islands causes differences in their landscape structure. On islands that have developed by the joining of several small islands the landscape structure is much more complicated due to the diversity of geological–geomorphological features. On larger and higher islands terrestrial processes dominate, which results in the occurrence of localities of paludified areas and mires as well as the locality of dunes (Kiimann et al., 2007; Ratas et al., 2007). On Naissaar, Pedassaar and Aegna localities above the marine zone occupy most of the islands' interior parts (94%) while the proportion of recent shore localities is small (ca 6%) (Table 2). On lower and smaller islands, which are younger, the proportion of recent shore localities is large, ranging from 20% to 35%.

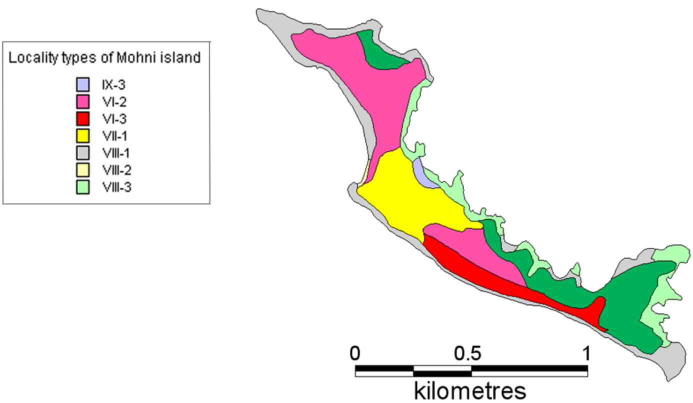


Fig. 2. Landscape (locality) map of Mohni Island. Landscape (locality) types: IV-3, pebbly–sandy plains; VI-2, sandy beach ridges; VI-3, pebbly beach ridges; VII-1, dunes; VIII-1, pebbly seashores; VIII-2, sandy seashores; VIII-3, sodden lowshores; IX-3, paludified sandy plains.

The diversity of an island's landscape is characterised by edge index (Table 2). The edge index is the highest on Aksi (163.1 m/ha), followed by Mohni (134.3 m/ha) and Koipse (133.3 m/ha) islands, showing the complexity of landscapes that have developed from two or more islands. The value of the edge index is smaller on Pedassaar (59.3 m/ha) and Naissaar (61.3 m/ha), indicating a simple landscape structure of the islands that have developed as one island.

The landscape fragmentation within the localities is expressed by the number of vegetation types (Fig. 3), spotlighting the connections between abiotic and biotic complexes. For example, on Mohni Island the vegetation on the localities of ancient beach ridges is the most variable (Figs 2 and 3). The localities of sandy beach ridges are covered with pine forests of *Cladina*

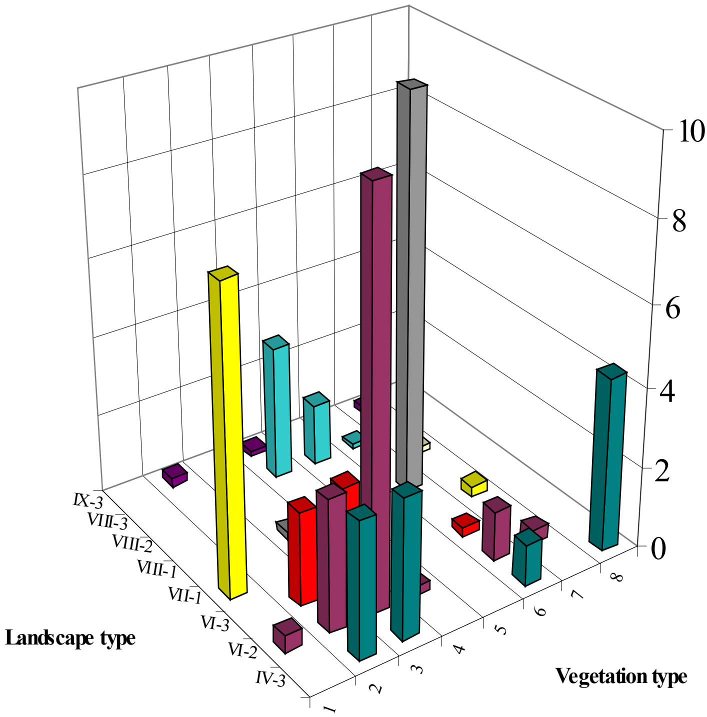


Fig. 3. Distribution of vegetation types in different localities on Mohni Island. The vertical axis indicates the number of particular vegetational units in a certain locality. Vegetation types: 1, *Cladina* site type pine forest; 2, *Vaccinium myrtillys* site type pine forest; 3, shrubbery; 4, seashore meadow; 5, reed bed; 6, sparsely vegetated area; 7, sandy area ; 8, artificial area. For landscape (locality) types see Fig. 2.

site type and initial vegetation. On the localities of pebbly beach ridges juniper shrubberies and pine forest of boreal type dominate. On moister parts of the sandy plain localities the forests of *Filipendula* site type dominate. Dry heath pine forests prevail on dunes. The localities of sandy and pebbly shores are characterised by pioneer communities. Seashore meadows and reed beds prevail in the localities of sodded lowshore.

Landscape fragmentation clearly reflects connections between different habitats and the edaphic characteristics and the topography of islands. Landscape fragmentation is expressed on several landscape profiles of the islands (Fig. 4). Generally, the topography and Quaternary cover determine the area's moisture regime, on which the soil–vegetation complex and land use depend.

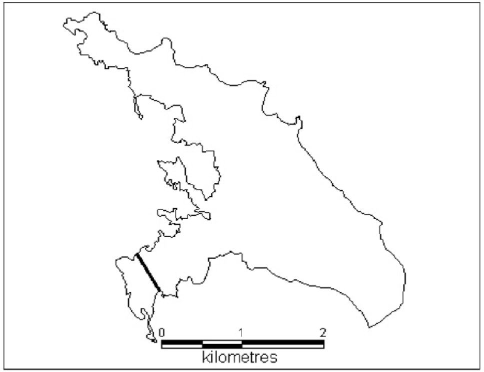
The landscape profiles show that the landscape units are represented by belts parallel to the shoreline and also describe the relations between different landscape components. For example, the Naissaar landscape profile (400 m) crosses a sandy plain where on the higher parts pine forests of *Calluna* site type on Podsols occur and on moister and lower parts of sandy plains pine forests of *Vacciniun myrtillus* site type on Gleyic Podsols prevail. The 800 m long Prangli landscape profile crosses recent shores and a system of ancient beach ridges and hollows between them, where juniper shrubberies on Podsols and paludified grassland on Gleysols prevail (Fig. 4).

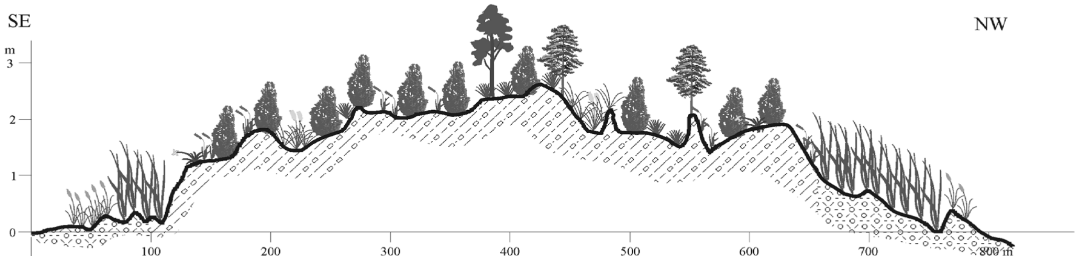
Tendencies of changes in insular landscapes in the 20th century

On small islands the changes in landscapes occur rather fast, especially on recent shores. This study enabled us to distinguish the following development trends of localities determined by the land uplift on the investigated islands:

- enlargement of flat areas (formation of sodded shore localities, e.g. on Prangli and Rammu);
- transition of sodded shore localities into localities of sandy marine plains or abraded till plains (e.g. on Mohni);
- formation and development of new coastal formations (e.g. recent beach ridge localities);
- transition of recent beach ridge localities into old beach ridge localities;
- growing over of coastal lakes and paludification of depressions between beach ridges (e.g. on Aksi, Rammu and Koipse).

Human activity has played an important role in the changes of insular landscapes. Rather detailed investigations of changes were carried out during the 20th century when government systems alternated several times and so did the forms of landed property. The tendencies of changes on the investigated islands were elicited by comparing the land cover maps compiled on the ground of maps from different years. On the land cover maps of the islands





Azimuth°	110			120			125	
Landform	shore	beach ridges and depressions between them						shore
Deposits	till	pebble sand/gravel						till
Soil type	Salic Fluvisols	Cambic Podsols	Gleysols	Gleyic Podsols	Gleysols	Cambic Podsols		Salic Fluvisols
Vegetation type	seashore grassland	dry boreal grassland	shrubbery		paludified grassland	shrubbery		seashore grassland
Landscape type	sodden lowshore	ancient pebbly beach ridges						sodden lowshore

Fig. 4. Landscape profile of the south-western part of Prangli Island.

altogether 11 land cover types were distinguished. Among these woodlands and grasslands dominate. These were in turn divided into subtypes.

The land cover of the discussed islands was quite different in the 20th century. Pedassaar, Aegna and Naissaar were typical wooded islands where since the early 19th century **wooded land** was the predominant land cover type (Fig. 5). On Pedassaar, too, the area of wooded land was stable throughout the century. On Naissaar and Aegna the share of wooded land increased just by 4–6% throughout the century. The two major reasons for the large percentage of wooded land on these islands were soils unsuitable for farming and military activities (actually non-activities as the forest was simply preserved as a buffer zone, useful for camouflage). On Rammu, Koipse, Aksi

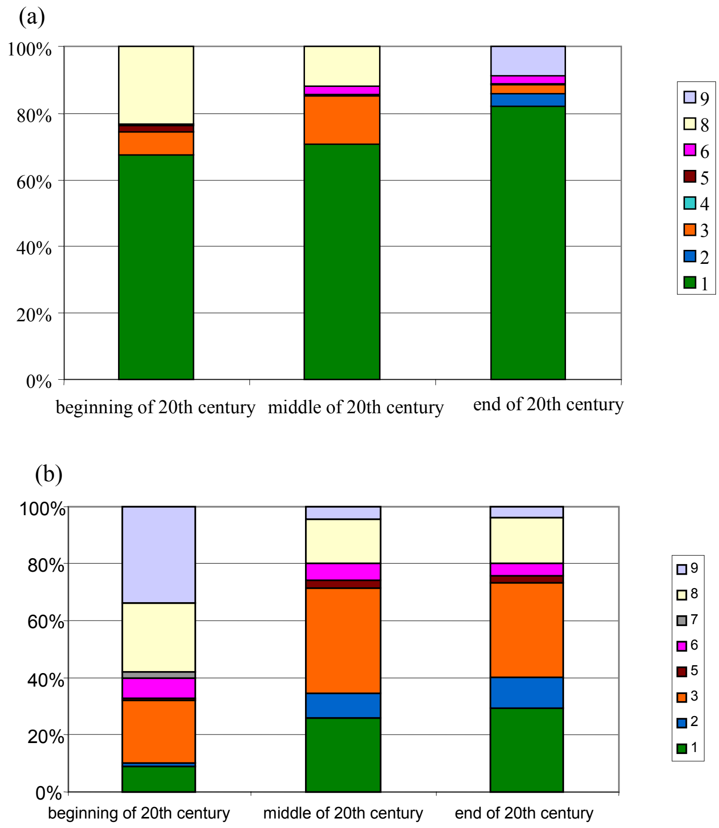


Fig. 5. Land cover change on Aegna (a) and Prangli (b) islands during the 20th century. Land cover types: 1, forest; 2, shrubbery; 3, grassland; 4, reed bed; 5, swamp; 6, households; 7, arable land; 8, sandy area; 9, sparsely vegetated area.

and Mohni the forest was missing or just a few larger tree groups (coppices) occurred, which is due to denser population and more intensive use of land, mainly for grazing and haymaking. By the end of the 20th century, wooded land had become the dominating land cover type on Mohni and Aksi islands. Like on Koipse, on Rammu Island the percentage of forested land increased because of afforestation in the 1980s. Growth of the percentage of wooded land can be observed also on Prangli: in the early 20th century forests covered only 9.3% of the island's area, but since the middle of the century their share has increased and has reached 26.3% (Klimenko, 2005). This happened because traditional land use perished during the Soviet period, and most of the land grew over with bushes and forest.

Shrubberies (mainly junipers) and **bushland** (willow and young alder) were not observed on the islands under discussion in the 20th century except on Aksi, where the percentage of shrubberies was as high as 10%. Presently, due to a considerable decrease in the number of livestock, they cover rather large areas on Koipse and Prangli where they grow on abandoned grasslands, former households and sparsely vegetated areas.

Grassland presently dominates on Rammu and Prangli. On Prangli, its percentage changed little during the 20th century (Fig. 5), but its distribution altered considerably: the percentage increased on the shores and decreased inland. In the land cover of Rammu Island the percentage of grassland considerably increased during the 20th century. At the beginning of the century it covered 28% of the island, but at the end it spread already on 66% of the territory. This is explained by the leaving of the residents and sodding of the areas formerly overexploited by pasturing. On Koipse, too, the percentage of grassland increased during the century (from 6% to 26%). On Aksi the area of grassland remained almost the same (ca 10%), but on Naissaar and Aegna as well as on Mohni an abrupt decrease occurred. On these islands grasslands turned into wooded land or shrubberies.

The area of **reed beds** was very small on the islands, being somewhat more widely spread only on Aegna and Mohni. In recent years also the coastal grasslands of Prangli Island have considerably become covered with reed. Reed beds spread mainly on waterside areas where the sea is shallow.

Paludified grasslands covered small areas on larger islands (Naissaar, Prangli and Aksi) in the 20th century. By today most of them have turned into wooded land; exceptionally, the land cover type of paludified grasslands has preserved in the overmoist central part of Aksi Island.

Mires are present only on larger islands (Naissaar, Aegna and Prangli). Their percentage is the highest (4%) on Naissaar.

An obvious trend on all investigated islands is falling importance of **households** and on Prangli Island also the area of **arable land** has decreased due to changes in economic policy and the leaving of residents. In the early 20th century households covered as much as 0.6% to 7% of the area of the islands discussed. On Prangli arable land made up 2.2% in the south-eastern part of the island.

On most islands the percentage of **sandy areas** decreased. In the early 20th century they covered some 20% of the islands' territory but at the end of the century they made up only 2% (Mohni and Aksi) to 16% (Prangli).

At the beginning of the 20th century the land cover type of **sparsely vegetated area** dominated on Aksi, Rammu, Koipse and Prangli, spreading on almost half of their territories. Nowadays it covers considerably smaller areas, mostly due to sodding of several areas (on Prangli and Rammu) and turning into bushland (Koipse and Aksi).

Lakes occur on Aksi, Mohni and Rammu. By the time of the investigations the lake on Mohni Island had grown over, but on Aksi and Rammu the lakes have maintained more or less the same areas throughout the centuries.

The general tendency of changes in land cover on the islands is increasing percentage of grasslands, forests, shrubberies and bushland and decreasing proportion of sparsely vegetated areas and households. Figuratively this can be described as follows:

- sparsely vegetated area → grassland;
- arable land and households → grassland;
- grassland → shrubbery → forest;
- sparsely vegetated area → forest (partly due to afforestation).

The land cover pattern on small islands depends on the intensity and character of land use. Most likely during the next decade no major land-cover change can be expected. Most of the islands have been taken under protection, but this has not preserved the traditional forms of human influence and overgrowing of grasslands is continuing. Nowadays small islands are a popular destination for recreational activities and there has been growing pressure on their capacity.

Conclusion

The unique nature of small islands is reflected primarily in their landscape structure. Landscape diversity of the islands is based on their variable topography and sediments, hydrological regime as well interrelations between land and sea. Under the influence of these factors various soils and plant communities have developed. The time factor is of great significance, determining the whole development process in the uplifting areas. Changes in the landscape of islands are caused both by the inner development of the localities themselves and by human impacts on the landscape.

The changes in insular landscapes in the 20th century were due to three main reasons: decrease in population, perishing of farming and development of tourism on the islands. The changes in landscapes are above all caused by altered land use resulting in changes of land cover. The increase of forested land and bushland characterises the land cover changes on the whole territory of Estonia (Palang, 1998), but on the studied islands also expansion of grasslands due to the sodding of shores was recorded. Grassland and bushland have started to spread also on former households and arable land because inhabitants have left and the fields have been left fallow. The geographical position also has played a significant role in the land use on small islands. At the same time, military activities on Naissaar Island and contraction of traditional land use have led to an increase in the percentage of wooded land on the islands.

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FORMATION OF AEOLIAN LANDSCAPES IN ESTONIA

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Introduction

Aeolian landscapes have formed as a result of the interaction of geological, biological and climatic processes as well as human activities. Every landscape has a specific structure reflecting its formation and development. Coastal aeolian landscapes are strongly affected by initial deposits and moisture conditions. Coastal areas are highly dynamic and fragile systems. The specific influences of the marine coastal areas are heavy winds, salt spray and lack of nutrients (van der Maarel, 1997). Forest cuttings and fires, military activities and other human activities may trigger the movement of surface sand, but wet environmental conditions, sparse population and rapid spreading of vegetation have prevented extensive redistribution of loose sandy sediments by wind in recent decades.

In Estonia different aeolian landforms such as coversand hillocks, blowouts, deflation hollows, foredunes, inland and coastal dunes and wind-eroded plains occur (Fig. 1). The aeolian redistribution of fine glacio-lacustrine and beach material is highly controlled by land uplift, human impacts, re-advance of ice-dammed lakes, the Baltic Sea and Lake Peipsi, initial deposits and palaeoclimatic parameters (wind direction and activity, soil moisture a.o.). The stratigraphy and palaeoclimates of the Holocene (Raukas et al., 1995 a.o.) and Late Glacial (Pirrus & Raukas, 1996 a.o.) are in Estonia rather well studied. Oldest coversands are largely restricted to areas with periglacial conditions favouring aeolian activity. In North-East Estonia

Fig. 1. Distribution of aeolian landforms in Estonia.

inland parabolic and transversal dunes formed in the severe climate of the Younger Dryas (Figs 2 and 3). It is assumed that inland dunes started to develop here immediately following the re-advance of ice-dammed lakes, after source deposits became available. Dune formation was stopped after the stabilisation of the sand movement by vegetation (Raukas, 2011). Presently, the inland dunes are covered by pine forest and display Podsols.

The distribution and morphology of coastal dunes largely depend on the exposition of beach ridges in the conditions of gradual land uplift. The biggest dunes are associated with the transgression phases of the Baltic Sea (Raukas, 1997 a.o.). Because of the neotectonic uplift of the Earth's crust (Vallner et al., 1988) coastal dunes are nowadays situated at some distance from the contemporary shore and at different absolute heights (Eltermann & Raukas, 1966; Raukas, 1997). At the present seacoast only low foredune ridges occur, for example those at Kloogarand, Narva-Jõesuu and Valgerand. Dunes with specific morphology, called 'basket-trap' dunes by Orviku (1933), are located on the northern coast of Lake Peipsi. Some small dunes occur also around Lake Võrtsjärv (Tavast et al., 1983).

Dry coastal ecosystems are influenced by different environmental factors. Due to the deficiency of sand, concentration of heavy storms to autumn and winter seasons and high precipitation rate, aeolian landforms in the con-

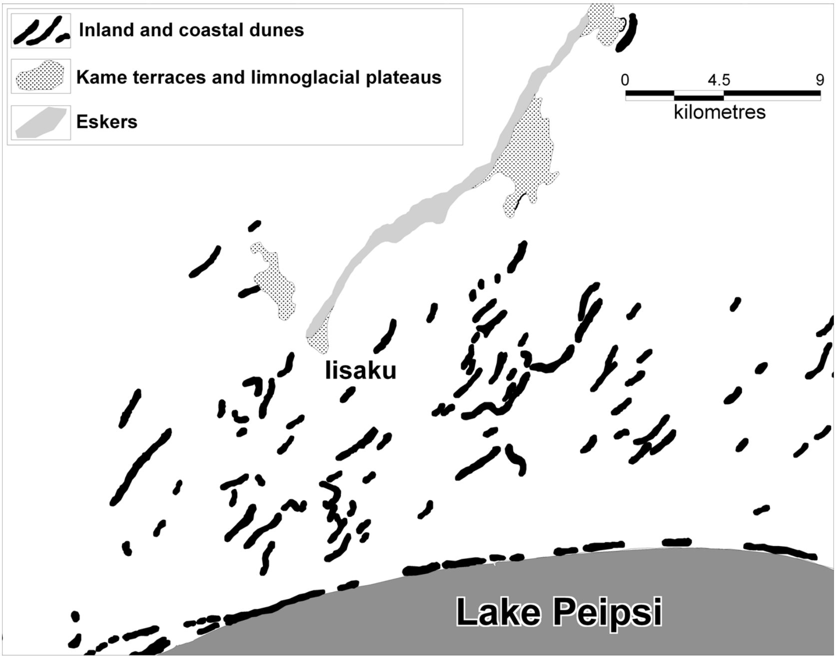


Fig. 2. Glacial topography and aeolian landforms in the Iisaku area.

temporary coastal zone are relatively low and rendered stationary by vegetation. In coastal areas the vegetation varies from shore plant communities to forests.

Influence of the climate

Dune formation is episodic. In the past all over Europe the best conditions for aeolian processes were in the dry and cool Younger Dryas (Koster, 1988 a.o.). In North-East Estonia inland dunes formed at that time. Aeolian processes started when glaciolacustrine dry sands and silts were exposed after the drainage of ice-dammed lakes and the groundwater level lowered (partly due to land uplift). Morphologically well-developed Younger Dryas continental dunes are located in the Iisaku area (Rähni, 1959) north of Lake Peipsi at both sides of Iisaku–Illuka ice-marginal formations of the Pandivere stadial (Fig. 2). As dated by different methods and based on the data available on the study area and its neighbourhood, the physical age of the Pandivere belt is ca 12 300 radiocarbon (^{14}C) years (Raukas, 2009).

The zone boundary between the Alleröd and Younger Dryas is placed at the strong and rapid increase of the content of herb pollen (particularly *Artemisia*, in North Estonia usually over 70%) and *Betula nana* L. (Pirrus & Raukas, 1996). Tundra plants (*Dryas octopetala* L., *Selaginella selaginoides* (L.) Link, *Ledum palustre* L., *Rubus chamaemorus* L., *Botrychium boreale* (Fr.) Milde, *Lycopodium pungens* La Pyl., *Lyc. alpinum* L.) are found in considerably increased amounts. In North-East Estonia in the Iisaku area (Fig. 2) inland dunes are described on the territory of about 50 km^2. Parabolic and transversal dunes here indicate a westerly–north-westerly palaeowind direction (Zeeberg, 1993).

Dunes are 0.8–2.7 km long and up to 15–20 m high. Their west and north-west windward slopes are slanting (3–18°), while the opposite leeward slopes are much steeper (18–24°). On the top and slopes of dunes there are small coversand hillocks. It is possible that in some places aeolian sands cover limnoglacial kames and the morphology and orientation of dunes depend on the glacial topography (Fig. 3).

These dunes and drift sands originate from the time when in the Alutaguse Lowland a significant regression of ice-dammed lakes took place and the so-called Small Peipsi was formed (Raukas & Rähni, 1969). Aeolian sand and

Fig. 3. Inland dunes east of Iisaku. Their orientation reflects the glacial topography. Photo by A. Miidel.

silt have been derived here from local source material, for example from glaciofluvial and glaciolacustrine deposits reworked by ancient Lake Peipsi. Dunes began to form here immediately after source deposits became available, and the process stopped when they became overgrown with vegetation. Nowadays the inland dunes are surrounded by peat bogs and covered by pine forests. OSL datings of aeolian deposits between 4000 and 7100 years BP (Raukas & Hütt, 1988) show the multiple redepositions of initial Younger Dryas glaciolacustrine and aeolian deposits here.

At the beginning of the Holocene considerable warming took place and at the beginning of the Boreal (about 9000 ^{14}C years ago) the mean annual temperature could be compared with that at present; however, at the end of the Boreal period it was higher. The Holocene climate optimum about 5500 to 6500 ^{14}C years ago was characterised by the culmination of thermophilous vegetation. Summer temperatures in the Baltic Sea area exceeded the present values by about 3 °C. Together with the warming and rise of humidity eustatic rise of water level took place. During the Litorina Sea transgression (about 7000 ^{14}C years, ca 7800 calibrated years ago) a lot of sand accumulated in the coastal zone and the dune formation was intense. The optimum was soon followed by cooling (Punning, 1995). For the last thousand years more reliable data about the climate conditions are available, which enable distinguishing a short warm interval about 1000 years ago and a severe cooling (the so-called Little Ice Age) in the 17th to the 19th centuries. Today's moist and cold Sub-Atlantic climate is not favourable for the movement of aeolian sands.

Land uplift and retreat of shorelines

The shore displacement in the Baltic Sea has been controlled by two factors: the eustatic sea-level change and the land uplift. While the former ought to be uniform all over the Baltic, the latter varies by regions, resulting in different patterns of shore displacement in different areas. So north-western Estonia is subject to uplift, but south-eastern Estonia to sinking. The recent crustal movements are probably glacioisostatic in origin. For example, in north-western Estonia it was 13 mm per year in the Pre-Boreal, 4.5 mm in the second half of the Atlantic, and at the present time, it is only up to 3 mm per year (Kessel & Miidel, 1973). Glacioisostatic movements are likely to have taken place against the background of inherited but rather low-intensity epeirogenetic movements.

The influence of land uplift is well observable in a 2.5 km^2 area at the northern coast of Lake Peipsi in the Järvevälja (Rannapungerja) Dune Field west of the Rannapungerja River mouth, where we can see 10–14 successively formed parallel dune ridges (Martin, 1984). The tilt of the windward slopes is generally 4–9° and of leeward slopes 6–17°. The dunes are mostly 1–2, seldom 3 m high; the width ranges from 20 to 30 m. Most probably these dunes were formed during the regression of the lake, which occurred more or less evenly, without long-term halts. Originally, the ridges could have been small sandbars, reblown into foredunes after the regression of lake waters. As the offshore zone was flat and shallow, water erosion was weak, and therefore the morphology of the ridges was not deformed (Raukas, 1999).

Low beach bars are common also on the seacoast. So in North Estonia we can see in many places not only high Ancylus Lake and Litorina Sea transgressional formations but also lower formations some metres high and 20–25 m wide. They constitute several joined to one another or located closely nearby former beach ridges, whose topmost parts are reblown to small dunes (Linkrus, 1998).

The coastal dunes of the Baltic Sea are scattered all over Low Estonia where sandy–silty sediments vital for their formation were available. As a result of the neotectonic uplift they are nowadays situated at different distances from the contemporary shore and at different absolute heights (Fig. 1). The size of a dune is a function of many factors, of which the most important are the length of the period of consistent wind regime under which it grew and the amount of available material. The largest dunes, up to 20–25 m in height, formed during the transgressive phases of the Baltic Ice Lake, Ancylus Lake and Litorina Sea, where during the rather stable shoreline beach deposits with great thickness accumulated for a long time. In the course of regressive phases, the shoreline retreated rapidly and beach erosion was less intensive, as a result of which less material was produced for the growth of dunes. The most prominent dunes in the vicinity of the Baltic Ice Lake's transgressive shoreline are located in Lahemaa National Park and on the Kõpu Peninsula. The dunes originating from the Ancylus stage occur on the West-Saaremaa Upland, on the Tõstamaa and Kõpu peninsulas and near Häädemeeste. Those related to the Litorina Sea transgressive shoreline are found at Sininõmme, Rannametsa and Tõstamaa.

A lot of aeolian landforms formed on the regressive sea in different phases of the Limnea Sea during the Sub-Boreal and Sub-Atlantic climatic periods (Hyvärinen et al., 1988), but they are not clearly delineated and their distribution is fragmentary. The thicknesses of these deposits are inconsiderable and there was not enough material for aeolian resedimentation. These coasts had a deficiency of sediment drift and the ridge-like dunes formed here are lower and often difficult to distinguish from sandy beach ridges (Keränen, 1986). At the present coast, where the beach is wide, only low foredune ridges have formed.

In some areas, for example at the Luidja and Tareste coasts on Hiiumaa Island, sandy spits are described. The development of the spits here was rapid and the shoreline changes in the last hundred years are clearly visible (Raukas et al., 1994; Rivis, 2005). These sandy spits elongated about

20–30 m per year (Rivis, 2005; Rivis et al., 2009). The seaward sides of the spits formed as a result of longshore transport of sediments. At the same time the spits on the neighbouring beach sections eroded intensively and the shoreline retreated about 1–3 m per year (Ratas et al., 2008; Rivis et al., 2009).

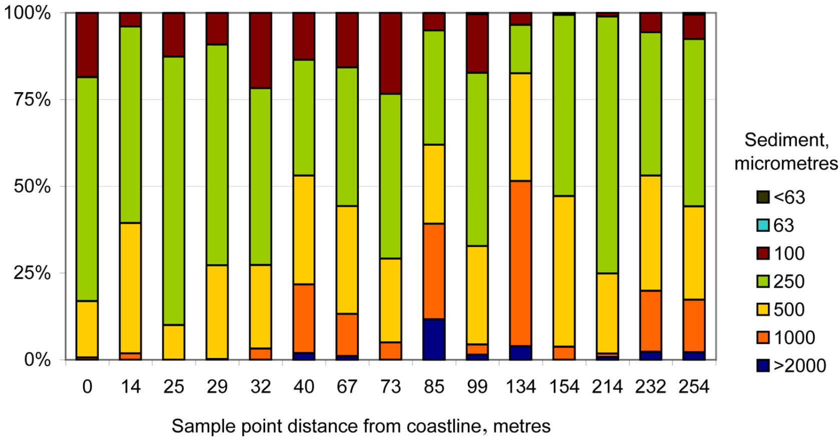
Also short-term fluctuations in the relative sea level, considered to be local in origin, have been registered. On the contemporary seashores of Estonia, where no tides occur, differences between high and low water level are about 1–1.5 m; however, in the event of exceptionally fierce storms the water level may reach 2–3 m and destroy older beach ridges and aeolian forms. One of the strongest storms in the last 40 years took place in January 2005, when the height of the sea level reached 275 cm and gusts were up to 38 m/s. This storm caused large changes in the depositional shores (Tõnisson et al., 2008). The previous highest sea level (253 cm) in Estonia was registered in October 1967.

Influence of the initial deposits

The motions of waves and currents cause coastal sediment transport in near-shore environments. These are extremely dynamic environments where sand, water and air are always in motion. The grain size of sandy beaches varies from very fine sand to pebble and cobble material. Differences occur also between beach and aeolian sediments: where beach sands are fine grained, aeolian transport is not selective and there are no significant differences in the mean size, sorting and skewness between the beach and adjacent dune sands. On the areas where beach sands are coarse and poorly sorted, adjacent dune sands are usually finer and better sorted (Bigarella et al., 1969).

Coastal dunes and aeolian processes cannot be considered in isolation from beach morphology and marine processes. Sedimentological analyses indicate that Estonian dunes developed as a result of short-distance transport of sand and silt from the adjacent beach or older deposits. This means that the grain size of aeolian deposits highly depends on the grain size of the initial material. At the same time the sediments are much better sorted than the initial material and show a reduced content of both coarse and fine fractions (Raukas, 1968). So on the outcrops of silty glaciolacustrine sediments the aeolian deposits are also silty, on the outcrops of glaciofluvial deposits they can be even medium-grained or coarse sand. In most cases in Estonian dunes fine-grained sand prevails. There are also differences in sand texture by region, which is explained by differences in the original material. For example in the western part of the Tahkuna Peninsula glaciofluvial sediments are less sorted and coarser (500 μm) than in the northern and eastern parts, where they are dominated by sands (100 and 250 μm) (Fig. 4).

(a)



(b)

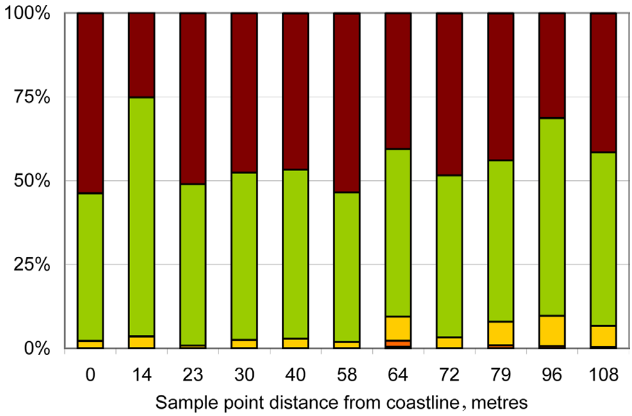


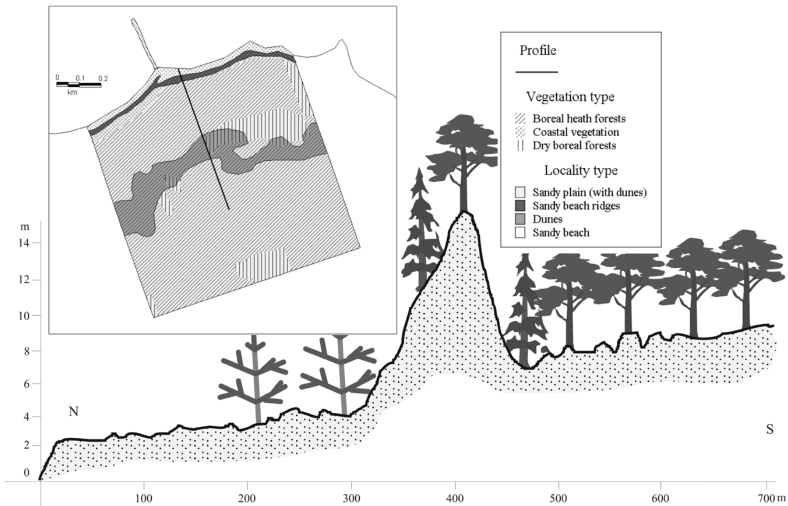
Fig. 4. Sand texture on the western (a) and northern (b) coasts of the Tahkuna Peninsula.

On the northern coast of Lake Peipsi between Kauksi and Vasknarva the sediments are predominantly sands of 250 µm. On the western coast at Meerapalu they are finer (100–250 µm), but at Mehikoorma much coarser (100–1000 µm). Coastal dunes in the northern part of Peipsi consist mainly of medium-grained sand (315–500 µm).

Soil and vegetation

Being located on the boundaries between terrestrial and marine systems, the coastal landscapes have a specific structure. Marine coastal aeolian landscapes can be divided into narrow ridges and areal zones, both are influenced by seawater (Ratas & Rivis, 2003). Landscapes are distinguished on the basis of variation in the soil–vegetation complexes along the topographic gradient (Fig. 5). The present distribution of vegetation and soils is a result of natural processes and human influence.

Soils are formed on noncalcareous sandy deposits and characterised by acid reaction. Only in sand shores and seaward beach ridges that have been directly influenced by wave action and water spray, the pH_{KCl} is usually 6.2–6.7. Wind action plays a significant role in the development of sandy soils, forming buried humus layers in the soil profile. The initial soil development was controlled by an increase of the organic matter content, and soil acidity generally increases landward across dune ecosystems (Isermann, 2005).



Azimuth°	170				
Landform	Beach	Sandy plain with dunes		Dune	Sandy plain with dunes
Deposits	Sand				
Soil type	—	Primitive sandy soil		Podsol	
Vegetation type	Coastal veget.	White dune	Boreal heath forest (*Cladina* site type)		Boreal heath forest (*Calluna* site type)

Fig. 5. Landscape map and profile at Ohami on the Kõpu Peninsula (after Ratas & Rivis, 2003).

Sandy beaches and coastal dunes have specific vegetation, depending on their age and distance from the sea. The coastal aeolian ecosystems of Estonia are well represented in the list of European Union Habitats (Natura 2000), which are mainly listed under sea dunes of the Atlantic, North Sea and Baltic coasts. Wooded dunes (2180) are the predominant habitat. The habitats on coastal sandy plains are Western taiga (9010) and Fennoscandian deciduous swamp woods (9080).

Different habitats are situated parallel to the waterline. The condition of sandy beach ecosystems generally depends on shoreline stability, which in turn depends on the balance of shore processes and shoreline dynamics. The area from the shoreline to the foredunes is mostly unstable and flooded numerous times during vegetation periods. These communities have a low species diversity.

The foredunes and yellow dunes are also highly dynamic areas. The vegetation of sandy beaches depends mainly on openness to prevailing winds and waves. There is no overall soil cover. An essential source of organic substances on sandy beaches is drift litter, which mainly consists of seaweeds. The plant cover of the lower belt of the shore is comprised of nitrophilous and halophilous species (*Atriplex littoralis, A. hastata, Matricaria perforata* etc.), which alternate from year to year. The *Honkenyo–Leymetum* association usually occupies the upper belt of sandy beaches and plays a great role in preventing sand movement. The vegetation on the foredunes is composed mainly of the grasses *Calamagrostis epigeios*, *Leymus arenarius* and *Ammophila arenaria*. These plants have long roots that reach down to the lower, more humid sand layers and their stems can survive bending by the wind; therefore, they hinder deflation (Hellemaa, 1998). In North Estonia *Rosa rugosa* occurs numerously on beach ridges and foredunes, stabilising aeolian sand. On the other hand, *R. rugosa* bushes restrict colonisation by natural dune vegetation (for example *Lathyrus maritimus*).

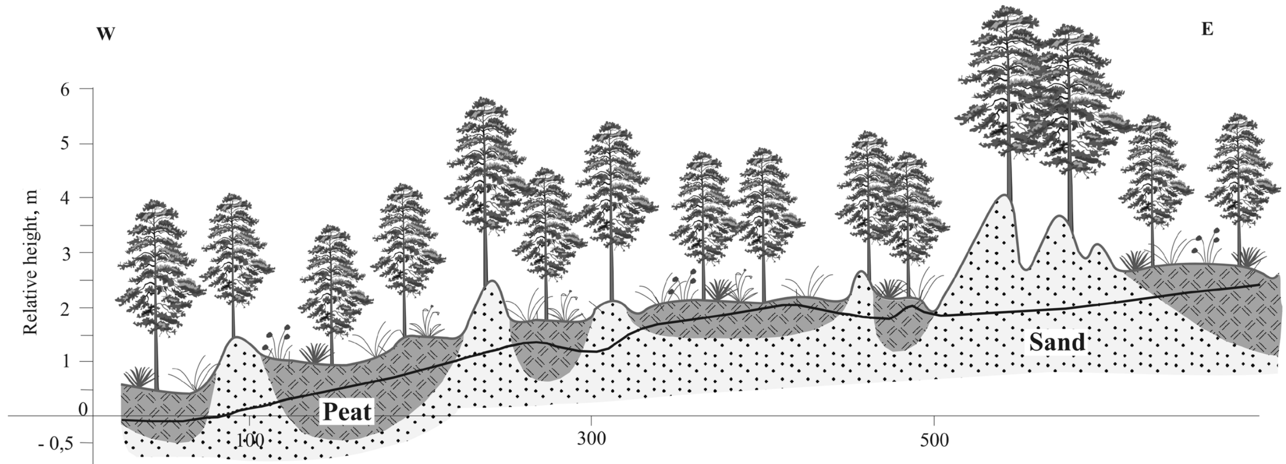
Vegetation is a most important factor in ancient coastal landform stability. Farther from the shoreline the aeolian landforms are stabilised by dry grassland, which usually has abundant carpets of lichens and mosses (grey dunes) where soil has begun to develop. Aeolian grassland is dominated by *Galio very–Thymetum* and *Koelerio–Festucetum polesicae* communities. Grey dunes are generally located near young white dunes. The most remarkable vegetation type is oligotrophic heath (brown dunes) with *Empetrum nigrum* and *E. hermaphroditium* on North Estonian islands, the southern boundary of its basic holarctic distribution area. Dunes are covered mainly with *Cladina* and *Calluna* forests, which play a great role in the protection of Arenosols and Podsols from erosion. Pines have often been planted on dune landscapes to stabilise sand.

The vegetation composition of sand dunes is closely associated with soil development. The soils are mainly formed on noncalcareous sandy deposits characterised by good water filtration ability. The soils are acidic, poor in humus and the content of K and P in the topsoil is low. The parallel long and narrow sandy landforms with boreal heath forests on Podsols and the paludified hollows between them are very characteristic of the Estonian coastal area. In the hollows, where the sand overlies varved clay and the groundwater level is high, Histosols occur. According to Loopmann (1988), these are the areas where the best paludification conditions are developing. The morphology of relief forms influences the soil conditions and the development of the peat layer. Because of the flowing water in overgrown bog stream areas located adjacent to beach ridges the *Sphagnum* peat layers are very thin there. Fen peat makes up only a small part of the peat layer. The wood peat in the study sites contains charcoal layers, which tell about previous forest fires and their influence on the subsequent bog development.

A characteristic feature of these sites is distribution of *Sphagnum* on the slopes of beach ridges (Fig. 6). Therefore it can be assumed that in the course of time the lower beach ridges will become covered with peat, which will lead to a general surface levelling and will also reduce the diversity of landscapes where paludified pine forests dominate. The peat depth in such hollows is usually up to 2 m (Rivis et al., 2009).

Human impact

The aeolian coastal areas in Estonia are mainly covered with pine forests. The forests in the coastal zone have many extremely important environmental functions including protection against erosion. Socio-economic conditions, political developments and differences in the forms of land ownership have all played a great role in the use and changes of Estonia's coastal aeolian areas. Afforestation is one of the most serious threats to open landscapes in the coastal area because it decreases the diversity of coastal ecosystems. In earlier times wooded areas were also used for grazing. For centuries the character of coastal forests has also been affected by heavy storms and forest fires. Logging and fires often triggered the movement of surface sand and moving sands used to be rather dangerous. Kõpu lighthouse in Hiiumaa which became a functional lighthouse in 1649 used about 800–1000 cords (1 cord = 3.62 m^3) of firewood per year. The cutting of trees nearby in sandy soils caused serious aeolian erosion. In 1653 local peasants had to provide 400 cords of firewood and 250 bulk barrels (1 bulk barrel = ca 115–140 litres) of wood ash to the Hüti glass factory (Roosma, 1966). In the 19th century, a large number of farmsteads were buried under wandering dunes. So a shifting dune at Kärla on the Island of Saaremaa threatened to destroy the church, pastor's mansion and



Azimuth⁰	85										
Landform	Accumulative plain with beach ridges										
Deposits	Peat	Sand	Peat	Sand	Peat	Sand	Peat	Sand	Peat	Sand	Peat
Soil type	R”	LIg	R”’	LI	R”’	Lg	R”	Lg	R” (S”’)	LI - LIg	R” (S”’)
Vegetation type	Rb	Kn	Rb	Kn	Rb	Kn	Rb	Sn	Rb	Kn	Rb (Ss)

Soils:
LI Haplic Podsols
Lg - LIg Gleyic Podsols
S”’ Eutric-Dystric Histosols
R” - R”’ Dystric Histosols

Vegetation type:
Kn Boreal heath forest (*Calluna* site type)
Sn Poor paludified forest (*Vaccinium uliginosum* site type)
SS Mixotrophic bog forest
Rn Ombrotrophic bog forest

Water table

Fig. 6. Landscape profile at Suurkõrve, North Estonia.

farmsteads in the vicinity. According to Tiismann (1924), the advance of the dune was stopped by young pines. The same author described the movement of sand in the area of Ristna lighthouse on the Island of Hiiumaa. The strong southwesterlies blew along a mass of sand, which piled up behind the doors and closed the entrances to the buildings. After each such storm islanders had to work for days to cart the sand off.

The moving sands at Lutepää near Värska in South-East Estonia were well known before the Second World War. There, in the location of a cavalry training field of the Estonian Army, the residual soil had been seriously destroyed under the hoofs of horses. This Lutepää sandfield some 3 km^2 in area used to be called the Estonian Sahara.

In the course of the years following Estonia's incorporation into the Soviet Union military activities were conducted in sandy areas in various parts of the country. Bombing, artillery shooting and infantry exercises were practised and moving sands occupied vast areas, as for example in the Kaibaldi loose sandfield in the central part of Hiiumaa Island (Fig. 7).

Fig. 7. Kaibaldi sandfield in the central part of Hiiumaa Island in 1974. Photo by R. Karukäpp.

Huge fields with a steppe-like appearance, which came into being in the 1950s–1960s as a result of the intensification of agriculture and land improvement in the then Soviet Union, promoted deflation of sandy and peat soils. For instance, during 9 April–11 May 1974, 16.2 tonnes of dry soil per hectare was carried away from the Apometsa fields of the Ranna State Farm, Harju County. On 1–7 May of the same year, clouds of dust extended upwards for dozens of metres from the fields of Paluküla and Tubala villages on the Island of Hiiumaa, posing danger to traffic. A layer of sand up to 30 cm in thickness deposited on the road, and an even thicker (up to 75 cm) layer fell on the roadside.

The velocity of wind may reach 40 m/s with gusts at a height of 10–20 m above the ground in Estonia. More persistent winds blowing with a speed of 35 m/s during several minutes cause great damage to agriculture. Up to 200 000 hectares of land is in danger of deflation in Estonia. In the Island of Hiiumaa such fields make up two-thirds of the whole arable land. When the danger was understood, fields larger than 50–60 hectares on lowlands and 20–30 hectares on elevations were prohibited. To reduce deflation, protective strips of trees have been planted, and long-term use of fragile peat soils as grasslands has been planned. With the liquidation of large-scale agriculture in Estonia, the area of fields endangered by wind erosion has essentially decreased.

Analysis of landscape changes during the last centuries is based on land cover changes (Fig. 8). The changes in forest landscapes are mainly caused by alternation of forest generations accompanied by the change of the species composition of trees.

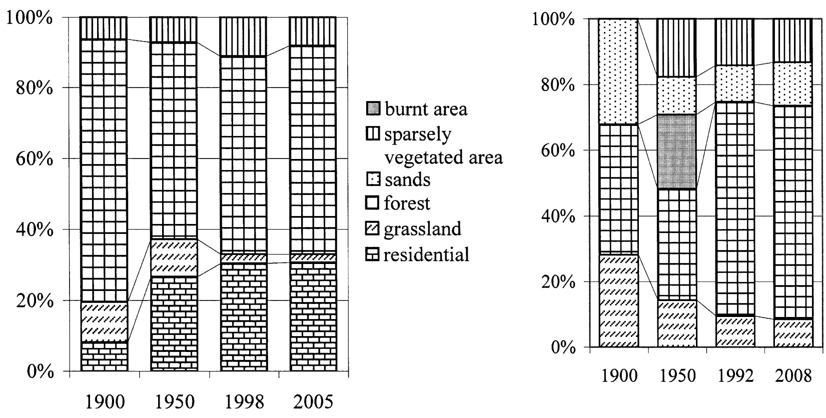


Fig. 8. Land cover changes in the Võsu and Keibu study areas during the last hundred years.

During the last decades private residences and summerhouses have replaced coastal forests in the vicinity of towns (mainly in the surroundings of Tallinn). The forests in the coastal zone have important environmental functions, among them prevention of erosion. Tourism and recreation are also users of forest resources. In the last decades recreational pressure has particularly increased in the forests of protected nature areas. Also nature-based tourism has raised questions about the tolerance of ecosystems experiencing a growing number of visitors (Törn, 2007). Heavy trampling of holidaymakers and driving of cars on the beach are frequent in many coastal areas, as for example on the aeolian landforms on the northern coast of Lake Peipsi. In very dry periods plant communities with a high proportion of lichens and mosses may seriously suffer due to human impacts.

Conclusions

The aeolian landscapes in Estonia are highly controlled by land uplift, human activity, re-advance of water bodies, initial deposits and palaeo-climatic factors (wind direction and activity, soil moisture). First dunes started to develop here immediately after deglaciation and re-advance of ice-dammed lakes. Dune formation was stopped after the stabilisation of the sand movement by vegetation, in several areas with the help of people. At the present seashore only low foredune ridges occur. Some active dunes are found on the northern coast of Lake Peipsi, where short-term and annual fluctuations of the water level are significant. The coastal landscapes of Estonia are of a high nature conservation value, expressed in the diversity of ecosystems and specific habitats. The condition of sandy beach ecosystems generally depends on shoreline stability, which in turn depends on the balance of shore processes and shoreline dynamics. The main problem of the landward areas of coastal aeolian landscapes is the decrease of natural habitats due to afforestation, recreational activities and construction. Several aeolian landscapes belong to national parks and landscape reserves. The aim of the protected areas is to preserve unique coastal landscapes and safeguard local rare plant and animal species as well as natural forest communities. Integrated coastal management plans should attempt to take into consideration the carrying capacity of the coastal and marine environment.

Acknowledgements

Our study was supported by the Estonian Ministry of Education and Research (target-financed projects SF0280016s07, 0280009s07 and 0320080s07) and the Estonian Science Foundation (grants 7392, 7564 and 9191).

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THERMAL RESOURCES OF ESTONIAN SOILS

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Introduction

Year on year, interrelations between man and nature are becoming ever more intertwined and intricate, stretching the nature's capacity for endurance to the breaking point. Pressure is put on the environment by the natural global change factors, and the technological empowerment of man is ever increasing. Consequently, the issues concerning the state of the ambient environment and the need to give an objective assessment to its quality are of increasing poignancy. Both the environment as an integral entity and its components are subject to change. In this connection much research into the regime of meteorological elements has been conducted and published; however, temperature conditions of soils have been tackled far less. Data on soil temperatures have nevertheless been comprehensively used in describing environmental conditions of agricultural lands, melioration and land reclamation work, building and solving other tasks. Therefore, surface and soil temperatures should be viewed as especially important, because soil regimes hide a lot of information on the impacts of human activities on nature and climate.

Soil temperatures have hitherto attracted attention primarily in works dealing with agricultural meteorology. Those researches have brought to the fore the necessity to take soil temperatures into account when planning and carrying out agricultural and melioration projects. Indicators of agro-climate for growing crops have been calculated and regional schemes of agro-climate in different geographical zones have been elaborated.

In eco-climatology, analysis of soil temperatures provides knowledge on natural resources, enabling to better than heretofore assess specific regional features of global climate change. For agriculture climate change is of special importance. Judging by the presently available data, the thermal resources that agriculture can take advantage of may grow in the northernmost areas of the globe, but changes in soils and their properties may call for a lengthier time period.

Thermal resources of soils and their change are an integral indicator of global and regional climate change. As thermal resources of soils depend on the mechanical composition and thermal-physical properties of soils, they may undergo a change against a relatively uniform general climatic background and thermal balance.

Material and methods

Measurements of soil temperatures have been carried out in Estonia for a long time; however, the conclusions derived from those observations are clearly lacking plausibility. Presently, transition to automatic observation stations is underway and consequently the measurement apparatus as well as the technology of performing measurements are changing.

A number of reference books and various regional descriptions based on the observations made in earlier years have been published (Eesti NSV agrokliima…, 1962; Справочник по климату ..., 1965; Eesti NSV agrokliima…, 1976; Научно-прикладной справочник ..., 1990). Climate reference books provide information on temperatures on the surface, in the upper soil layers and in the deeper soil layers measured with depth thermometers in the observation sites of the meteorology stations. For the areas between measurement points the conditions for the formation of soil temperatures can be found on maps in the Estonian climate atlas (Eesti NSV kliimaatlas, 1969). These materials provide a comprehensive overview of climates in various districts of the country and they characterise also the temperature regime of their surface and soils.

To get an extended picture of soil temperatures of a given time interval, this work uses an approach that enables to highlight the changes in climate systems of various levels, that is macro-, meso- and micro-climatic changes in meteorological elements and their complexes (Karing, 1995, 2009, 2011).

The following equation was used in calculations for describing these climate systems:

$$X_i = X_{fi} + \Delta X_{\text{mes}} + \Delta X_{\text{mic}} , \qquad (1)$$

where X_i – value of climate element X in the location of the observation point i,

X_{fi} – value of the zonal background indicator of climate element X,

ΔX_{mes} – value of the indicator of meso-climatic variability of climate element X,

ΔX_{mic} – value of the indicator of micro-climatic variability of climate element X.

The climatological data were processed using the spreadsheet system EXCEL. For analysis of the maps of surface temperatures and their comparison, the maps were transposed to a common address network (Karing, 1992, 1995). The values of the studied indicators were determined for each reference point, and territorial averages were calculated on the basis of the indicators of the reference points.

Results and discussion

Analysis of soil temperatures should be carried out separately for the surface and different soil layers. Changes of temperatures on the soil surface and air temperatures display many similar features (Fig. 1).

Because of the climatic conditions prevailing in Estonia, a country located in the northern part of the European continent, the temperatures on the soil surface and in the air layer close to the land fall into two major periods: summer warm period and winter cold period. In summer the surface temperatures are by 3–5 °C higher than air temperatures, in winter months they are lower by approximately 1 °C. In transitional months, surface and air temperatures are more or less the same.

The surface temperatures are often also called 'temperatures in the sunlight' because observations are carried out on an open area under the impact of the whole complex of meteorological factors.

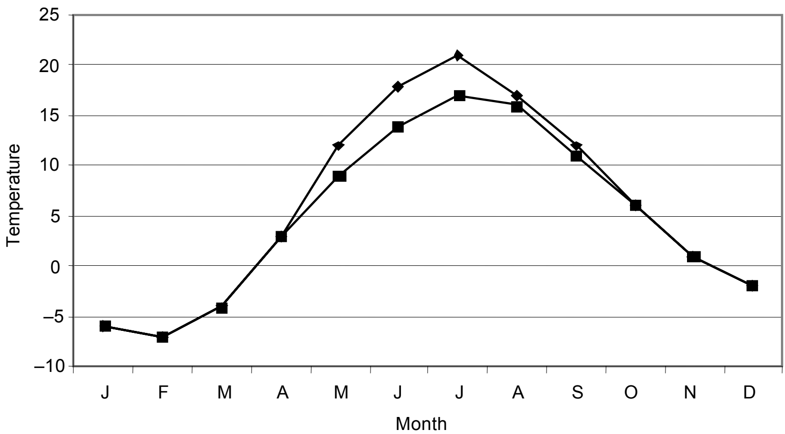

Fig. 1. Annual course of average surface and air temperatures, °C, in Estonia. ◆, surface temperature; ■, air temperature.

General regularities of the distribution of thermal resources in soils are well known. However, in every landscape and at a concrete depth, specificities of soil temperatures manifest themselves.

Data on temperatures of the ploughing-depth layer (0–20 cm) are presented in respective climate reference books, published in various years. Initial data have been reduced to a long series (Eesti NSV kliimaatlas, 1969).

In meteorology stations soil temperature is measured in soil cleared of plant cover at depths of 5, 10, 15 and 20 cm with flexible thermometers. These mercury thermometers can only be used when the temperature is above zero. In Estonia, such observations have been carried out from May to October. In other months, night frosts may occur and ruin thermometers of this kind.

Table 1 presents as an example soil temperatures in the plough layer at 10 cm depth from climate reference books (Справочник по климату ..., 1965; Научно-прикладной справочник ..., 1990). The monthly average temperatures of the plough layer usually do not differ by more than 1 ^{o}C over years. Therefore the summaries of observations made in different time phases can be taken as the basis when describing the general nature of soil temperatures of the ploughing-depth layer. Evidently no significantly new information can be obtained by lengthening the observation series.

Solar radiation transformation takes place on the surface, and specificities of thermal and moisture exchange develop in soil. Besides natural processes, also man's economic activity in transforming the environment significantly influences the character of soil. Human impact is especially important in agricultural lands in which environmental impacts are intensive and systematic depending on crop rotation and machinery used.

Table 2 features the course of territorial average temperatures at different depths in the upper 0–20 cm soil layer in the meteorology stations in Estonia. The average indicators were found by calculating the average values of the results of measurements made in different meteorology stations.

In the upper 0–20 cm part of soil the temperature is above 10 ^{o}C in Estonia from May to September. The lower layers of soil are about 1 ^{o}C

Table 1

Monthly average temperatures (^{o}C) of soil at a depth of 10 cm in Tallinn meteorology station according to climate reference books published in different years

Reference book	May	June	July	August	September	October
1965	11	16	19	17	12	6
1990	11	17	19	17	12	6

Table 2

Average temperatures (^oC) of upper soil layers in Estonia, May–October

Month	Depth			
	5 cm	10 cm	15 cm	20 cm
May	12.6	12.1	11.5	11.2
June	16.4	15.9	15.4	14.9
July	19.3	18.8	18.4	18
August	16.8	16.6	16.5	16.3
September	11.5	11.7	11.8	11.9
October	5.3	5.6	5.8	6

cooler than the upper 5 cm layer in May, June and July. In August the temperatures of the upper layers start falling and by September the temperatures of deeper layers are everywhere higher than in the upper layers.

The soil temperature variations at different depths depicted in Table 2 are caused by the varying general climatic background. The soil temperatures were measured in an open level area where the surface had been cleared of grass cover. Applying equation (1) and using territorial amplitudes of soil temperatures, the extent of impacts on soils in the area between observation sites can be approximately estimated. The factors causing variation are largely of micro-climatic nature.

The variations in the temperatures presented in Table 3 were calculated for Estonian meteorology stations situated on mineral soils. It is evident that characteristics of soils have a rather significant impact on the formation of their thermal regime.

Territorial variation of soil temperatures is expressed by temperature amplitude Tampl (Tampl = Tmax – Tmin). From May to July the variation in temperatures is 2.8–3.0 ^oC. With the approach of autumn the differences decrease, being in August 2.3–2.4, but in September and in October 1.8–2.0 ^oC. In spring, particularly on agricultural lands, the plant cover is weakly developed or totally absent before sowing. Together with the development of the plant cover, its impact on the formation of soil temperatures increases. The impact may vary widely depending on the biomass, density and height of vegetation as well as many other factors. The results of measurements made on fields with perennial hay plants were the closest to the measurements made on meteorology stations. Long-term surveys in the vicinity of observation sites and on fields with hay plants have shown that at a depth of 10 cm the temperature differences in soils are around 1 ^oC. Therefore, in the first approximation, we can consider 1 ^oC as the range of difference between soil temperatures in areas with grass plants and meteorology stations with similar soils.

Table 3

Temperatures (°C) of the upper 5–20 cm layer of mineral soils in Estonia, May–October

Month	Depth				
		5 cm	10 cm	15 cm	20 cm
May	Max	12.6	12.1	11.5	11.2
	Min	9.7	9.2	8.7	8.3
	Tampl	2.9	2.9	2.8	2.9
June	Max	18.2	17.7	17.2	16.7
	Min	15.2	14.8	14.3	13.8
	Tampl	3	2.9	2.9	2.9
July	Max	18.2	17.7	17.2	16.7
	Min	15.2	14.8	14.3	13.8
	Tampl	3	2.9	2.9	2.9
August	Max	18.1	18	17.9	17.8
	Min	15.8	15.7	15.6	15.4
	Tampl	2.3	2.3	2.3	2.4
September	Max	12.4	12.7	12.9	13
	Min	10.6	10.8	10.9	11
	Tampl	1.8	1.9	2	2
October	Max	6.5	6.7	7	7.1
	Min	4.5	4.7	5	5.3
	Tampl	2	2	2	1.8

Mapping of soil temperature is a sophisticated and complex task. The general climatic background, properties of soil, plant cover, relief and impacts of other factors have to be taken into consideration. The Estonian climate atlas includes maps of temperatures of upper layers of soils at depths of 5, 10 and 20 cm, composed applying the traditional isocline method. Analysis of the maps shows that variation in soil temperatures follows landscape differences practically at all depths in keeping with an identical logic. The most important differences can be observed in the size of quantitative indicators. Therefore in this work the author has confined himself to the description of territorial distribution of temperatures according to maps composed on the basis of measurements made at a depth of 10 cm.

In **May** coastal zone impacts have become clearly established: soil temperatures are higher than 12 °C on coasts open to the sea. In the inland areas temperatures are lower. On a large part of Estonia they vary around 11 °C. On the western coast of Lake Peipsi the temperatures are even lower, constituting one closed contour with the temperature below 10 °C. On the uplands in the extreme south-eastern part of the country the temperatures are as high as 12 ^{o}C and even higher in a small area.

In **June** the soil temperature rises higher than 17 ^{o}C on the coast of Pärnu Bay, but inland it stays below 10 ^{o}C. In the coastal zone temperatures are everywhere higher than 16 ^{o}C, and the location of the isocline separating the coastal areas from the inland areas is during the whole summer close to the position of the line that separates continental and maritime climates in Estonia as determined by Raik (1967). On the south-eastern uplands soil temperatures are above 16 ^{o}C.

In **July** soil temperatures rise even more, being over 19 ^{o}C on the coasts open to the sea, alongside Lake Peipsi and in the south-eastern part of the country. The area of the impact of the Pandivere Upland and as a separate contour the surroundings of Lake Võrtsjärv with the temperature level below 19 ^{o}C have become more distinct than earlier.

In **August** the temperature drop sets in. In the coastal zone and in a small area near Värska in south-east Estonia temperatures stay 17 ^{o}C and higher, being in inland areas predominantly from 16 to 17 ^{o}C. In the southern part of the Pandivere Upland and southwards and westwards thereof as well as in the surroundings of Lake Võrtsjärv soil temperatures drop below 16 ^{o}C.

In **September** the temperatures continue falling and the pattern becomes simpler. In the coastal zone and in the south-eastern part of the country the temperatures are 12 ^{o}C and above, in inland areas 11–12 ^{o}C. The contours of the lowest soil temperatures in the area surrounding the Pandivere Upland and Lake Võrtsjärv have merged into a larger contour with temperatures of 11 ^{o}C and below.

In **October** the decline of temperatures continues. In the coastal zone temperatures are 6 ^{o}C and higher, in the inland areas mostly within 5–6 ^{o}C. The contour of the lowest temperatures in the central part of the country has decreased and moved northwards. The temperatures stay equal to 5 ^{o}C or below.

On the basis of medium-scale maps, presented as a summary of the territorial distribution of soil temperatures, it can be said that in the coastal zone the temperatures are everywhere higher than inland. The main actors that cause differences in soil temperatures are the Baltic Sea, large lakes and, partially, the uplands.

As far as agriculture is concerned, it is important to focus in the research of soils on factors directly affecting agricultural production. The properties of soils, including soil temperatures, play a pivotal role in this connection.

Taking into consideration the conditions important for agriculture Int (1969) composed maps of temperatures of soils of different granulometric composition at a depth of 10 cm for the period from May to October. These maps are based on the schematic map of soils showing the dominating granulometric composition and moisture conditions. Three regions are distinguished on the map:

(1) cold and excessively moist mineral and marshland soils;

(2) moderately warm and often low in moisture thin and medium-thick loams;

(3) warm and basically well-moisturised clay soils and sandy soils.

The average soil temperatures for these three regions were determined on the basis of the temperatures at the meteorology stations where the soil granulometric composition was analogous to that of the region under consideration. To complement the data of the third region, data collected at expeditions were used in addition to the materials of the meteorology stations.

Later, applying the same method, Golzberg (1972) composed an Estonian agroclimatic regional map. This map in turn was updated by Kivi (1998).

Soil temperatures at 20 cm depth in black earth differ from temperatures in mineral soil at the same level. In May, June and July, the soil temperatures in black earth are higher by approximately 1–2 ^{o}C. In August the differences decrease, in September the temperatures are largely equal and in October the areas covered with turf are already warmer than the soil under bare surface. Such variations in soil temperatures are caused by the fact that for the observations the earth is cleared of plant cover in spring and it is kept in the state close to black fallow during the whole measurement period. So surface is here under a direct impact of the sun and the specific features of the radiation regime are also manifested more strongly at a depth of 20 cm. The temperature level is also affected by soil properties. The most important among these are mechanical and chemical composition of soils, soil moisture, evaporation and the state of the surface layer.

The formation of the temperature regime of the deeper layers is governed by the same regularities that apply in the upper layers. Basing on observation results presented in Fig. 2, the annual course of Estonian territorially average soil temperatures was calculated starting from the depth of 20 cm.

Figure 2 shows that in April the soil temperatures at different depths are more or less similar. Towards summer the temperatures rise, and in July the highest temperatures are observed at 20 cm depth. In deeper layers temperatures reach the maximum with a delay. The greater the depth, the longer is the delay. In the second half of summer, the soil temperatures fall. At the end of September–beginning of October an impressive change occurs in the temperature regime. At that time the temperatures at different depths are close, but when winter arrives, lower soil layers are warmer than the upper ones. In wintertime when the surface is covered with snow the differences in temperatures depend on the thickness of the snow cover.

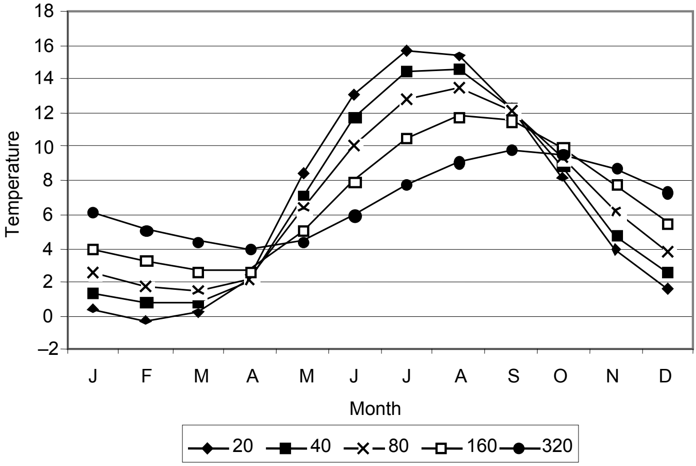

Fig. 2. Average annual course of soil temperature (^{o}C) at different depths (cm) in Estonia.

Conclusions

- Soil temperatures are an important support material in eco-climatological research for regional assessment of global changes.
- Climate reference books contain various data on soil temperatures in Estonia. Soil temperatures are of rather stable nature in those issues. If the observation series are longer than 10–15 years, the average monthly indicators calculated on their basis can be used to highlight the general eco-climatological regularities.
- The observation series of soil temperatures in Estonia should be analysed separately on three levels: surface, upper (0–20 cm) and lower (21–320 cm) layers of soil. On the surface area void of plant cover the fluctuations of soil temperatures are closely related to changes in air temperatures.
- The upper layers show the major human-induced impacts on soil, especially those caused by agricultural production. Territorial differences of temperatures are largely due to the mechanical composition and the water regime of soil.
- The lower layers of soil are characterised by decreasing temperature fluctuations and impacts of local factors with increasing depth.

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CALCAREOUS SPRING FENS IN SOUTH ESTONIA

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Introduction

Earlier widely distributed calcareous tufa-forming fens are critically endangered in Europe (Grootjans et al., 2005). A peculiar feature of calcareous spring fens is the formation of tufa or travertine (calcite), at least in patches, on the surface (Hájek et al., 2006). The calcium-rich cold ground-water discharges to the surface, and mainly because of loss of carbon dioxide to the atmosphere calcium carbonate precipitates on the surface, around vascular plant roots and moss stems (Pentecost, 1987), and prokaryote–microphyte biofilms control the conditions and products of calcite deposition (Pedley et al., 2009). Phosphorus may co-precipitate with calcium (Boyer & Wheeler, 1989; Souza-Egipsy et al., 2006) and phosphorus limitation makes the habitat unfavourable for many wetland plant species. Therefore the species composition of calcareous spring fens is rather peculiar and consists of many rare species (Grootjans et al., 2005). In Estonia the distribution of *Juncus subnodulosus* (on Saaremaa Island), *Selaginella selaginoides* (in northern and north-western Estonia) and *Saxifraga hirculus* (eastern Estonia) is mostly associated with spring fens. Of orchids *Dactylorhiza incarnata, D. baltica, D. russowii* and *Epipactis palustris* are strongly associated with calcareous spring fens.

In Estonia tufa deposits are known to be more widely distributed on uplands in southern Estonia. Hallik (1948, 1957) investigated lake marl and tufa deposits for the use of Ca-rich brackish-water sediments as a neutralising agent of sandy and acidic agricultural soils in South Estonia. He described 118 sites of which 64 were defined as tufa deposits. Later Lõokene found several more sites, counting 92 tufa deposits in South Estonia, of which 43 were on the Sakala Upland, 35 on the Otepää Heights, 7 on the Haanja

Heights, 6 on the Vooremaa Drumlin Area and 1 in the Pärnu Lowland (Lõokene, 1960, 1961, 1968a, 1968b). She concluded that the distribution of tufa deposits in South Estonia is well associated with slopes of ancient river valleys deeply cut into Devonian bedrock and covered with a thin layer of calcareous Quaternary sediments. Slopes of valleys are rather gentle and the flow rate of discharging groundwater is slow enough to favour deposition of tufa and even the formation of pseudo-terraces with thick (up to 6–7 m) tufa deposits (Lõokene, 1961). Very few calcareous spring fens are known in northern Estonia.

Our knowledge on the plant cover, habitat conditions and state of calcareous spring fens in Estonia is scarce. Laasimer (Ingerpuu), who wrote her diploma thesis about the vegetation and plant cover of spring fens, did not treat tufa-forming spring fens (Laasimer, 1977). Recently we presented some preliminary results about plant communities on one of the best preserved tufa-forming spring fens in North Estonia, the Paraspõllu Fen (Ilomets et al., 2010).

We investigated over 60 calcareous spring fen sites on South Estonian uplands, mostly described earlier by Hallik (1948) and Lõokene (1960) as tufa deposits. Our objectives were to ascertain the state of calcareous spring fens in South Estonia and to characterise their vegetation, hydrology and landscape setting. We made plant cover analyses and sampled fen surface water for pH and specific conductivity measurements. Analysis of the collected data enriches our understanding of the relationships between the plant cover structure and habitat conditions of calcareous spring fens in South Estonia.

Material and methods

Geological setting

The Haanja and Otepää heights are accumulative hilly formations in south-eastern Estonia. The Haanja Heights evolved on an Upper Devonian limestone bedrock plateau into which several primeval valleys are cut (Tavast, 1992). The tufa deposits are formed from Ca-rich groundwater of the Upper Devonian aquifer system (Lõokene, 1968a). A peculiar feature of this region is strong cementation of tufa and its accumulation as travertine. On the Otepää Heights the Middle Devonian sandstone bedrock is overlain by up to 180 m thick Quaternary cover represented by till and glaciofluvial and glaciolacustrine deposits (Raukas et al., 1988; Tavast, 1992). The Middle Devonian aquifer system outcrops in deeper river valleys (Lõokene, 1968b).

The Middle Devonian sandstone bedrock of the Sakala Upland is topographically a wavy plateau jointed by primeval valleys (Arold, 2005). The sedimentary cover is mainly formed by tills and glaciofluvial and glaciolacustrine sediments. On the slopes of primeval valleys (especially on the Halliste primeval valley) the Quaternary cover is thin or even absent. The spring waters originating from the Devonian aquifer can be rich in calcium, fostering tufa formation (Lõokene, 1961).

Vegetation sampling

In July and August 2010 we surveyed 63 sites of which 7 were located on the Haanja Heights, 33 on the Otepää Heights and 23 on the Sakala Upland. We made two types of vegetation descriptions on each site. On the sites subjectively assessed as in good or satisfactory state (still with fen plant species) at least one plant cover analysis was made on a 2 m × 2 m plot divided into four subplots of 1 m × 1 m. A list of field and surface plant species was compiled, and species coverage (in %) was estimated. The mean and maximum height of hummocks and percentage cover of hummocks were found. Around the plots within a radius of about 10 m the tree layer was described: species composition, proportion of different species, coverage and mean and maximum height were recorded.

If a site was damaged (deeply drained, tufa deposit excavated, with non-wetland secondary plant cover, etc.), its short characterisation was given (dominant plant species and status of the site).

Water and deposit sampling

On every site plant cover analyses were made. Before the plant cover analyses a water sample was taken from perforated PVC tubes inserted into the deposit to a depth of some 40 cm in the centre of the plot. The depth to water level was measured when the plant cover analyses were completed (ca 30 min). The water samples taken into 100 ml PVC tubes were kept at 4–6 ^{o}C until pH and electric conductivity (EC) analyses. The samples were held at room temperature (ca 21 ^{o}C) for about 12 hours before pH (Handylab pH11/SET, SCHOTT Instruments GmbH) and EC (Conductivity Meter Micrometer 900) measurements. The thickness of the deposit was found with a Belarusian-type peat corer (diameter 2.5 cm) and a brief description of sediments was given.

Data analyses

We used PC-ORD software (McCune & Grace, 2002) for two-way-cluster analysis to separate plots into vascular plant species assemblages. Rare species, that is those found in one or two plots, were excluded from the analyses. General relativisation was applied before clustering. STATISTICA 5 software was used in one-way ANOVA to evaluate possible differences in habitat conditions between vascular plant assemblages, and Tukey’s post hoc test was applied to differentiate between significantly different habitat parameters.

Results

Characterisation of sites

Short characterisations of the sites with tufa formation, at least in patches, and some calcareous fen sites without tufa precipitation but valuable because of their vegetation and habitat conditions are presented (Fig. 1, Table 1).

Haanja Heights

On the Haanja Heights we studied seven sites, of which in three tufa is forming on the surface. On the Loosi site (1.6 ha), situated on both sides of the valley of the Loosi Stream close to Loosi manor, calcite (in patches) is actively forming on the surface. Several springs are upwelling with calcium- and iron-rich waters. On the slopes of the Rõuge primeval valley, where Upper Devonian limestone bedrock outcrops on the surface, we examined two well-preserved sites. In the Rõuge Liinjärve site (0.6 ha) some tufa is forming on the surface. According to Lõokene (1968a), the thickness of the tufa deposit in the Rõuge sites is up to 6 m and a pseudo-terrace has formed on the valley slope. The Rõuge Tindiorg site (0.8 ha) is a reed-dominated sloping fen. Earlier at least four tufa-forming fen sites were located on the Tuhkavitsa Valley close to Tobrovo village. In the 1950s and 1960s the main part of tufa deposits was excavated. The remnant of the calcite deposit is mainly porous travertine.

Otepää Heights

On the Otepää Heights we investigated 33 sites, of which 6 are still in quite a good state, whereas on 11 sites tufa is precipitating, in patches at least, or Fe-rich sediment is formed (4 sites).

Two sites near Piigaste village are located on the north-eastern slope of the elevation. The Piigaste site (ca 1.1 ha) on the right side of the Piigaste Stream is an open tufa-forming spring fen with sedges, ferns and herbs dominating in the field layer (Fig. 2). The dense (coverage ca 70%) moss carpet is composed mainly of *Campylium* spp. and *Plagiomnium elatum*. The uppermost part, some 0.3 m, of the deposit is a mixture of tufa and moss with sedge remnants, followed by moss–sedge peat.

The Uue-Rooba site (0.4 ha) is situated close to the Piigaste site on the right slope of the Koosa Stream valley (Fig. 3). It is an open tufa-forming spring fen with sedges and herbs dominating in the field layer. Among the mosses *Plagiomnium elatum* and *Campylium* spp. dominate. The deposit with a thickness over 1 m consists of brown moss–sedge peat with tufa interlayers.

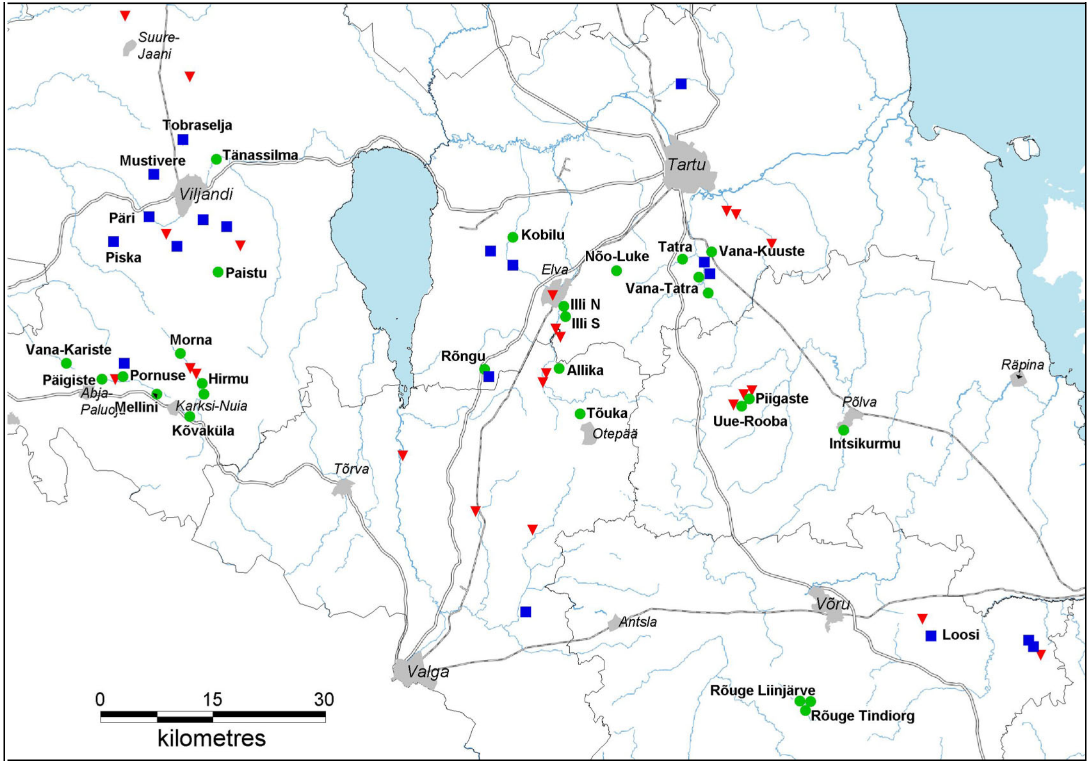


Fig. 1. Location of the studied spring fens in South Estonia. Symbols: green dots, calcareous spring fens in good state; blue squares, drained sites; red triangles, abandoned tufa deposits or damaged sites.

Table 1

Area of the sites, depth of the deposit, presence of tufa in the deposit and actual tufa formation (Y = yes, N = no), iron precipitation (Fe), pH and electric conductivity (EC) of the studied calcareous spring fens in southern Estonia. Asterisks (*) denote sites not used in the analyses; the number after the site name corresponds to the plot number on the site

No.	Name of the site	Area, ha	Depth, m	Tufa layers in the deposit	Tufa formation	pH	EC, $\mu S\ cm^{-1}$
			Haanja Heights				
1	Loosi *	1.6	>1.0	Y	Y	8.06	522
2	Rõuge Tindiorg	0.8	0.5	Y	N	7.26	765
3	Rõuge Liinjärve	0.6	>1.0	Y	Y	7.94	519
			Otepää Heights				
4	Allika	2.5	>2.0	Y	Y	7.73	530
5	Illi S	2.5	>1.0	Y	Y	7.76	568
6	Illi N	1.2	>2.0	Y	Y	7.95	558
7	Intsikurmu	0.9	2.0	Y	Y	7.15	551
8	Kobilu	1.7	>2.0	Y	N	7.05	631
9	Nõo-Luke	1.3	>2.0	Y	Y, Fe	7.39	647
10	Piigaste*	1.1	>1.0	Y	Y	7.28	358
11	Rõngu	1.4	0.9	Y	N, Fe	7.61	528
12	Tatra	9.6	>2.0	Y	Y	6.99	714
13	Tõuka	1.8	>2.0	Y	Y, Fe	7.82	691
14	Uderna-Laguja	6.8	>2.0	N	N	8.02	605
15	Uue-Rooba	0.4	>1.0	Y	Y, Fe	7.84	223
16	Vana-Kuuste	1.7	>2.0	Y	Y	7.20	361
17	Vana-Tatra	1.4	>1.0	Y	Y	7.85	252
			Sakala Upland				
18	Hirmu 1	2.0	> 2.5	Y	Y	6.97	903
19	Hirmu 2	2.2	2.2	N	N, Fe	7.40	302
20	Kõvaküla 1	5.8	4.5	Y	N	6.85	451
21	Kõvaküla 2	5.8	3.8	Y	N	6.90	423
22	Mellini 1	2.4	> 2.5	Y	Y	6.98	648
23	Mellini 2	2.4	> 2.5	Y	Y	7.08	595
24	Morna*	5.4	> 2.5	Y	Y, Fe	6.94	598
25	Mustivere*	4.0	1.8	Y	N	8.09	628
26	Paistu	8.1	>2.0	Y	Y	6.82	572
27	Piska	1.2	1.25	Y	N	7.73	471
28	Pornuse	1.0	0.8	Y	Y	6.95	752
29	Päigiste	2.6	>2.5	Y	Y	7.04	690
30	Päri 1*	2.9	0	Y	Y	7.84	717
31	Päri 2*	3.9	0	Y	Y	7.96	648
32	Tobraselja	5.7	>2.5	N	N	6.56	307
33	Tänassilma*	44.3	>2.5	Y	N	7.07	669
34	Vana-Kariste	4.5	>2.5	N	N	6.97	529

Fig. 2. Spring fen cupola at Piigaste, right slope of the valley of the Piigaste Stream, north-eastern slope of the Otepää Heights.

Fig. 3. Uue-Rooba Fe-rich tufa-forming spring fen on the right slope of the Koosa Stream, north-eastern slope of the Otepää Heights.

The Intsikurmu site (0.93 ha) in the town of Põlva is located under the eastern slope of the heights. It is an open species-rich tufa-forming fen with several orchid species and a dense (coverage up to 90%) moss carpet. The deposit with a thickness over 2 m consists of moderately decomposed brown moss and sedge peat mixed with tufa.

The Tõuka site (1.8 ha) is located in the central part of the heights, some 2.5 km north-west of the town of Otepää on the slope of the Kaarnaoja Stream (Fig. 4). The upper part of the fen is covered by sparse fen forest with *Betula pubescens* and *Picea abies*. The over 2 m thick deposit consists mainly of tufa. The lower part of the slope is an almost open, rich in vascular and moss species spring fen precipitating Fe-rich sediment on the surface in small depressions between tussocks. The upper part of the deposit (depth interval of 0.6–1 m) is formed of sedge–brown moss peat rich in tufa followed by over 1 m thick sedge–brown moss peat without tufa.

The Kobilu site (1.7 ha) is an attractive tufa-forming spring fen located on the slope of the Kavilda Valley on the north-western slope of the Otepää Heights. The upper part of the fen is forested with spruce, on the lower part close to the Kavilda River small groups of spruce, pine and birch are growing.

Fig. 4. Tõuka tufa-forming spring fen forested with *Betula pubescens* and *Picea abies* on the slope of the Kaarnaoja Stream on the Otepää Heights.

The Uderna-Laguja floodplain fen (6.7 ha) with Ca-rich springs is situated in the valley of the Elva River some 0.8 km east of Uderna village.

Two sites are located in the neighbourhood of Illi village. The Illi S site is a Fe-rich tufa-forming open spring fen (2.5 ha) spreading about 1 km southwards from the village on both sides of the Illi Stream on the north-western slope of the heights. The other site, Illi N, is located about 0.5 km north of Illi village on the slope of the Elva River valley.

The Nõo-Luke site (1.3 ha) is an open Fe-rich calcareous fen with a few spruce trees located on the upper part of the Tatra Valley on the northern slope of the heights.

The Tatra site (9.6 ha) is located in the lower part of the northern slope of the Tatra Valley. It is an open fen affected weakly by drainage with patches of pine. In the field layer *Carex lasiocarpa*, *Schoenus ferrugineus* and *Phragmites australis* dominate. *Cladium mariscus* is sparsely distributed. Tufa is actively precipitating in some depressions between tussocks. The deposit with a thickness over 2.5 m consists of sedge–brown moss peat with tufa interlayers.

On the Vana-Kuuste site (1.7 ha), which has a sparse tree layer consisting mainly of pine (up to 10 m in height and of different age), tufa is actively forming in patches. The deposit with a thickness of about 1.8 m consists of tufa rich in sedge and brown moss remnants. The site is close to Vana-Kuuste village.

The Rõngu site (0.5 ha) on the western slope of the heights is an abandoned tufa excavation site with some open-water pits. A sedge peat layer some 0.5 m in thickness has remained on the site. On the open part of the site *Carex rostrata* dominates.

The Vana-Tatra site (1.4 ha) is a *Molinia* dominated (coverage ca 25%) tufa-forming spring fen with a sparse tree layer (birch, max height ca 13 m, age ca 30–40 years). Among shrubs *Salix* species (density ca 20%) dominate.

The Allika site (2.5 ha) is on the western slope of the heights some 2 km east of Hellenurme village. *Phragmites australis* and *Menyanthes trifoliata* dominate with *Carex flava* as a codominant in the field layer. In the moss layer *Campylium*, *Philonotis* and *Drepanocladus* species dominate with an about 40–60% coverage. Tufa is precipitating in depressions between low tussocks. The thickness of the deposit is over 2 m and it consists of brown moss peat with wood and reed remnants. Tufa interlayers are frequent.

Sakala Upland

On the Sakala Upland we investigated 23 sites. Tufa is forming, at least in patches, on seven of these sites.

In the southern part of the upland, on the valley of the Hirmu Stream about 1 km north-east of Karksi village, we found two calcareous spring fen sites. The sites were named Hirmu 1 (2 ha) and Hirmu 2 (2.2 ha). The Hirmu 1 site is an open tufa-forming and sedge-dominated spring fen with a few birches and spruces located on both sides of the Hirmu River valley some 0.4 km south-west of Hirmu village. Close to the river the tree layer is denser. The deposit with a thickness over 2.5 m consists of sedge peat (uppermost ca 1 m), followed by tufa.

The other site, Hirmu 2, is about 1.5 km north-east of Karksi village, south of the first site. This reed-dominated Fe-rich calcareous fen (no tufa formed) is sparsely covered with short (2–5 m) birch trees. The sedge and wood peat layer (thickness some 1.8 m) lies on silty fine sand (5 cm) followed by grey till.

The Morna (5.4 ha) site is located on the right slope of the Kõpu River valley about 1 km north-west of Morna village. In the tree layer (coverage some 10%) birch with some spruces, height about 2–7 m and 2–4 m, respectively, dominates. Close to the river reed is growing, and in the central part of the site *Carex davalliana, C. lasiocarpa* and *Equisetum fluviatile* occur. The higher part of the valley is more forested. We found on this site two active spring cupolas (relative height about 1–1.5 m) formed mainly of tufa with some sedge peat interlayers with an overall thickness of more than 2.5 m.

Several spring fens spread on the slopes of the Halliste River valley. The Mellini (2.4 ha) tufa-precipitating *Schoenus ferrugineus–Carex davalliana* fen with a sparse (coverage ca 10%) tree layer (height of pines and spruces up to 12 m, commonly 0.5–3 m) is located in the lower part of the right slope of the Halliste River some 3 km north-west of the town of Karksi-Nuia. The topmost 1.8-m-thick section of the deposit consists of sedge–brown moss peat followed by a tufa layer (the total thickness of the deposit is over 2.5 m).

The Kõvaküla (5.8 ha) spring fen is near Kõvaküla village and spreads on the upper part of the Halliste River valley on its both sides. At present tufa is not forming but tufa layers can be found in the deposit (thickness up to 4.5 m).

The Pornuse (1 ha) site is a self-restored tufa-forming spring fen where tufa was excavated some 50 years ago, in the 1960s. The lowermost about 20–80-cm-thick layer of the tufa sediment was not extracted. On it a *Carex davalliana*-dominated plant community has formed. Small (height ca 3–4 m) spruces, birches and junipers form the tree layer with the coverage of around 20%.

The Päigiste (2.6 ha) site is a well-preserved tufa-forming *Carex davalliana–Sesleria caerulea–Shoenus ferrugineus* spring fen. Among the tree species (coverage some 2–10%) birches and pines dominate with a few spruces (height of 0.5–8 m). The topmost about 60-cm layer of the deposit consists of tufa-rich sedge, brown moss and reed peat followed by an about 110-cm-thick peat layer with snail shells, and an over 80-cm-thick tufa layer with moss, sedge and reed remnants.

One more spring fen in the Halliste River valley is the Vana-Kariste (4.5 ha) site. It is a species-rich spring fen (no calcium carbonate precipitating) on the right side of the Halliste River valley about 1 km south-east of Vana-Kariste village. The tree layer, where pine and birch are dominating with some spruces, is not dense (coverage some 20%). The height of the tree layer is up to 12 m. In the field layer *Carex lasiocarpa* and *Molinia caerulae* dominate. The sedge–brown moss and sedge–wood peat deposit is over 2.5 m thick.

The Paistu (8.1 ha) site is located about 1 km south-east of Paistu village and forms the beginning of the Varstu River on the south-eastern slope of the upland. Many small springs flow down to the river and nearby springs from the slopes. Tufa is formed in patches. Birches and spruces 0.5–6 m in height form the sparse tree layer. In the field layer several sedge species dominate. In the dense moss layer (coverage some 90%) *Campylium* and *Drepanocladus* species dominate. We found a small (relative height ca 1 m, diameter some 10 m) spring cupola. The deposit (over 2 m thick) consists of woody sedge–brown moss fen peats.

Two other sites worth mentioning are Mustivere and Päri. The Mustivere (ca 4 ha) site, which is located on the slope of the northern part of the Sakala Upland, is the largest spring cupola in the region but it is affected by amelioration. The diameter of the cupola is about 300 m and relative height up to 6–7 m. At the very top of the cupola a funnel-like depression with a diameter of some 20 m and depth of 0.5 m is formed. Spring water is upwelling during the time snow is melting in the early spring. Several other springs are recharging on the lower southern section of the cupola.

The Päri (3.9 ha) site is in the western part of the Sakala Upland on the right side of the Raudna River valley. This tufa excavation area was abandoned in the 1960s. Several springs are recharging in the upper part of the valley and flowing down to the valley bottom. On the excavated site the water flow slows down and tufa is forming on the bare surface and around stems of herbs, sedges and mosses.

Water characteristics and tufa formation

The surface water pH ranged from 6.56 to 8.09 and EC was from 223 to 903 $\mu S\ cm^{-1}$ on the sites studied. The pH and EC were nonsignificantly related ($r = -0.19$). In spring fens on the Sakala Upland the water pH values were over 7 only in four sites out of seventeen sites whereas on the Otepää Heights the water pH was over 7 in almost all sites (Table 1). The EC values in sites from the Otepää Heights were predominantly over 520 $\mu S\ cm^{-1}$, with the maximum value of 714 $\mu S\ cm^{-1}$. In the studied spring fens on the Sakala Upland the EC values were in about half of the cases less than 470, the rest had values over 530 $\mu S\ cm^{-1}$. The maximum value was as high as about 900 $\mu S\ cm^{-1}$.

Tufa, at least in patches, was forming in 21 sites (Table 1) of which 16 were classified as calcareous spring fens. Commonly tufa formation occurred on sites where the mire water EC was over 530 µS cm^{-1}. In some exceptional cases on the Otepää Heights, namely on the sites of Uue-Rooba, Vana-Tatra, Vana-Kuuste and Piigaste, tufa patches were observed at the peat water EC values between 220 and 360 µS cm^{-1}. Depth to water level was statistically not a significant determinant for calcite precipitation in our sites.

Vegetation

On the 27 spring fens in South Estonia selected for further analyses we registered 86 vascular plant species but in cluster analysis we used 45 species (present in more than 2 plots). The mosses were not taken into account in this particular case. The clusters were distinguished on the 20% level of information remaining. Almost all sites for which vegetation description was performed were open or covered with a scattered (coverage below 20%) tree layer. With the help of two-way cluster analysis the 27 plots were separated into two main groups, cut on the 10% information remaining level, both containing two vascular plant assemblages (assemblages (1), (2) and (3), (4), respectively) (Table 2, Appendix).

Assemblage (1) – *Molinia caerulea* + *Carex lasiocarpa* + *C. davalliana* – was present on sites located on the Sakala and Otepää elevations where water was above the surface. *Caltha palustris*, *Carex flava*, *C. panicea*, *Equisetum fluviatile* and *Succisa pratensis* as well as *Dactylorhiza incarnata, D. baltica* and *Epipactis palustris* were commonly represented by a few individuals. In the moss cover *Campylium* spp. and *Scorpidium scorpioides* dominated. Compared to the other assemblages the number of species per plot was significantly higher in these sites. Also the mean depth to water level was very close to the surface.

Assemblage (2) – *Schoenus ferrugineus* + *Carex lasiocarpa* – was more characteristic of sites on the Sakala Upland than of the Otepää Heights but absent on sites studied on the Haanja Heights. The water level was close to the surface. Species such as *Carex flava*, *C. panicea*, *Galium uliginosum*, *G. palustre, Parnassia palustris, Phragmites australis, Potentilla erecta* and *Primula farinosa* were registered almost on every plot. Some 50% of the surface was occupied by low hummocks; this is a significantly higher proportion than in the case of the other three assemblages. Among mosses *Drepanocladus* spp. and *Plagiomnium elatum* were the most common taxa.

Table 2

Some characteristics of vascular plant assemblages in calcareous spring fens in South Estonia. Elevation symbols: H, Haanja Heights; O, Otepää Heights; S, Sakala Upland. The numbers in the column 'Sites on the elevation' correspond to site numbers in Table 1. The superscript letters $^{a, b}$ indicate significant differences ($p < 0.05$) between assemblages for the variable

No.	Vascular plant assemblage	Dominant moss groups	Sites on the elevation	Depth to water level, mean±SD, cm	Number of sites with tufa formation	Mean number±SD of vascular plant species per plot	Mean coverage ±SD of vascular plants , %	Mean coverage ±SD of mosses, %	Mean litter coverage±SD, %	pH, mean±SD	EC, mean±SD, $\mu S\ cm^{-1}$	Tussocks, mean coverage±SD, %
1	*Molinia caerulea* + *Carex lasiocarpa* + *C. davalliana* + *Phragmites australis*	*Campylium, Pleurozium, Scorpidium*	O – 4, 17 S – 18, 19, 28, 32, 34	$+2±3^{a}$	6	$16±8^{a}$	40±19	60±25	15±8	$7.2±0.5^{ab}$	495±190	$30±15^{b}$
2	*Schoenus ferrugineus* + *Carex lasiocarpa*	*Drepanocladus*	O – 8, 16 S – 21, 22, 23, 29	$–1±5^{ab}$	4	$13±6^{ab}$	40±15	55±22	25±19	$7.0±0.1^{a}$	560±135	$50±10^{a}$
3	*Cirsium oleraceum* + *Menyanthes trifoliate* + *Phragmites australis*	*Plagiomnium*	H – 2, 3 O – 11, 12, 14 S – 20, 27	$–7±9^{b}$	2	$9±3^{ab}$	60±18	60±30	25±12	$7.5±0.5^{ab}$	605±170	$30±20^{b}$
4	*Carex rostrata*	*Plagiomnium, Paludella, Calliergonella*	O – 5, 6 , 7 , 9, 13, 15	$–8±6^{b}$	6	$7±6^{b}$	35±18	75±17	15±6	$7.7±0.3^{b}$	540±165	$45±7^{ab}$

Assemblage (3) – *Cirsium oleraceum* + *Menyanthes trifoliata* + *Phragmites australis* – can be characterised as having water level below the surface and an insignifacant presence of *Carex* species. The common species on the plots were *Equisetum palustre*, *Geranium palustre*, *Filipendula ulmaria* and *Lysimachia vulgaris* with *Plagiomnium elatum* common in the moss layer. This assemblage occurs on all the three elevations studied here, but tufa formation was observed only on two.

Assemblage (4) – *Carex rostrata* – with a characteristic tufa formation was found only in spring fens on the Otepää Heights. Among other vascular plant species *Agrostis canina*, *Equisetum palustre*, *Epilobium palustris*, *Epipactis palustris*, *Galium uliginosum* and *Rumex aquaticus* were present most frequently but with low coverage. In the moss layer *Plagiomnium elatum*, *Calliergonella cuspidate* and *Paludella squarrosa* dominated.

The number of vascular plant species per plot varied between 3 and 26. Assemblage (1) was the richest in species with its average 16 vascular plant species per plot (Table 2), differing significantly from assemblages (3) and (4). The mean species richness of tufa-forming and not tufa-forming sites was almost the same: 12 and 11 species per plot, respectively.

The coverage of *Carex rostrata* was significantly higher ($p < 0.015$) on sites where Fe-rich tufa was forming than on sites on which iron precipitation was not evident (coverage around 30% and 2%, respectively). The coverage of the other sedge species, *C. lasiocarpa*, and the total coverage of the field layer were significantly higher ($p < 0.03$) on tufa-forming sites than on sites where calcite was not precipitating (on average 8% and 1% for the sedge species and 55% and 40% for the total coverage in the field layer ($p < 0.05$), respectively). Certain differences in the coverage of spring fen vascular plant species were distinguished between the south-eastern (Haanja and Otepää) elevations and the Sakala Upland. Some sedge species such as *Carex cespitosa*, *C. davalliana* and *C. lasiocarpa* but also *Cirsium oleraceum* and *Menyanthes trifoliata* were found to be more abundant on spring fen sites of the Sakala Upland than in the south-eastern Estonian spring fens.

Also, the pH values of fen waters may differ between assemblages. The groundwater discharging to the surface was significantly more alkaline in sites where *C. rostrata* dominated than in *Schoenus ferrugineus* + *C. lasiocarpa* assemblage with pH values of 7.7 ± 0.3 and 7.0 ± 0.1, respectively. Collectively, the pH values in plots belonging to the first group (assemblages (1) and (2)) were nonsignificantly lower than in plots of the second group (assemblages (3) and (4)), 7.1 ± 0.3 and 7.6 ± 0.4, respectively. The differences between the assemblages for EC were not significant.

Discussion

Area of sites

Hájek et al. (2006) distinguished calcareous fens as spring-seepage fen habitat type with distinctive rare calciphilic species with peculiar calcium carbonate (tufa) precipitation on the surface. Commonly these groundwater-dependent tufa-forming calcareous fens are small and highly vulnerable in relation to changes in the local scale hydrology (Grootjans et al., 2005). Our data indicate that the total area of tufa-forming spring fens in South Estonia can be some 50 ha at least. Among the calcareous fen sites investigated more thoroughly in South Estonia about three quarters had an area smaller than 2.5 ha and for about a half the area was not over 2 ha. Hallik (1948, 1957) found the largest tufa deposits in South Estonia to have areas over 15–20 ha although the overwhelming majority of the tufa deposits had an area of around 1–2 ha.

Water characteristics and tufa formation

Degassing of calcium-rich emerging groundwater causes calcium carbonate precipitation on the surface but evaporation and, to some extent, photosynthesis may also play a part (Pentecost, 1988). Pedley et al. (2009) argued that, at least in alkaline riverine freshwater settings, microbial biofilms dominated by cyanobacteria, heterotrophic bacteria and diatoms in general and extracellular polymeric substances in particular are fundamental for precipitation. Therefore tufa sedimentation is controlled by both physico-chemical and biological processes (Vázques-Urbez et al., 2010).

Tufa precipitation could be affected by a critical level of the water table relative to the peat surface. The water table should be close enough to the peat surface for carbon dioxide to degas, thus raising the pore-water pH and consequently decreasing the solubility of carbonates. The corresponding maximum depth of the water table may be indicated by the thickness of the carbonate-bearing surface peat (Almendinger & Leete, 1998). The critical water table level above which precipitation dominates can vary depending on temperature, water chemistry and direction of water table movement. If the water level drops below the critical level, calcite precipitation will stop as the CO_2 partial pressure of the unsaturated zone will increase because CO_2 production exceeds loss, CO_2 can dissolve in the shallow water and cause dissolution of carbonates (forming a carbonate-depleted zone). Among other reasons the reduction of the hydraulic heads in the aquifer (pumping) and land-use changes in the groundwater recharge area are responsible for the cessation of tufa formation.

Karise (1997) characterised the groundwater in the active water exchange zone in Estonia, regardless of the lithological composition, as HCO_3–Ca–Mg type with the content of dissolved mineral salts 100–600 mg l^{-1}. Groundwater has high Ca^{2+} and Mg^{2+} concentration, 40–95 and 11–30 mg l^{-1}, respectively; the pH is about 7.2–7.6 and the concentration of balanced HCO_3^- is 200–400 mg l^{-1}, the content of free CO_2 in the upper part of the active water exchange zone is on average 20–30 mg l^{-1}, occasionally up to 100 mg l^{-1}.

Our data demonstrate that the electric conductivity was in spring fens with precipitating tufa over 530 µS cm^{-1} in most cases. Most likely it is not a threshold value for tufa formation as in several cases tufa patches were occasionally observed in sites where the EC values were much lower, around 200–400 µS cm^{-1}. In some other sites no tufa formation was registered even at EC values of about 600 µS cm^{-1}.

Hájek et al. (2002) found that in the Central Carpathian mountains the minimum calcium concentration at which calcite starts to precipitate is about 90 mg l^{-1}, but sometimes Ca concentrations of about 160 mg l^{-1} do not result in calcite precipitation. In the Kõvaküla site, located on a sharp slope, where no calcite precipitation was observed, the Ca concentration of the spring water was 120 mg l^{-1} (our unpublished data). However, on a site in North Estonia, on the even Paraspõllu Fen, the Ca concentration of the upwelling groundwater was as low as 60 mg l^{-1} on the part of the fen where calcite is formed in small depressions between tussocks (Ilomets et al., 2010). Almendinger & Leete (1998) suggested that rainfall in combination with slope inclination may affect carbonate solubility.

Vascular plant species assemblages

At landscape scale the pH and calcium content probably control the poor fen–extremely rich fen gradient. On calcareous tufa-forming fens as in the range of a fen type, certain other conditions like hydrology or biogeography may control the species composition (Hájek et al., 2006). Our data from 27 spring fen sites characterised by high conductivity and circum-neutral groundwater conditions allowed distinguishing between two groups with importantly different vascular plant species composition. The two assemblages (*Molinia caerulea* + *Carex lasiocarpa* + *C. davalliana* and *Schoenus ferrugineus* + *Carex lasiocarpa*) that form the first group are characterised by high, above or close to the surface water level and pH values around 7.1. The other two assemblages (*Cirsium oleraceum* + *Menyanthes trifoliate* + *Phragmites australis* and *Carex rostrata)* are related with deeper water levels and pH values around 7.6. The species-rich assemblages (1) and (2) with near or above surface water level resemble the spring fen communities *Caricetum davallianae* and *Scorpidio–Schoenetum ferruginei* (Paal, 2007). Several species such as *Eriophorum latifolium*, *Sesleria caerulea*, *Schoenus ferrugineus* and *Primula farinose* did not occur in the plots belonging to the two last assemblages. On West Estonian spring fens

Trass (1958) distinguished three main vegetation groups: *Carex*, *Juncus* and *Schoenus.* Laasimer (1965) concluded that *Carex hostiana–Carex davalliana* and *Schoenus ferrugineus–Scorpidium scorpioides* associations are distributed on Estonian alkaline spring fens. The last association is more characteristic of Ca-richer spring fens than the *Carex hostiana–Carex davalliana* association.

Most likely the precipitation of tufa does not affect species richness. Three assemblages (1, 2 and 3) could be found on plots located on sites with tufa formation as well as on sites where tufa formation was not observed. All sites of the *Carex rostrata* assemblage had tufa formation although in sites where *C. rostrata* dominated the depth of the water table was below the surface.

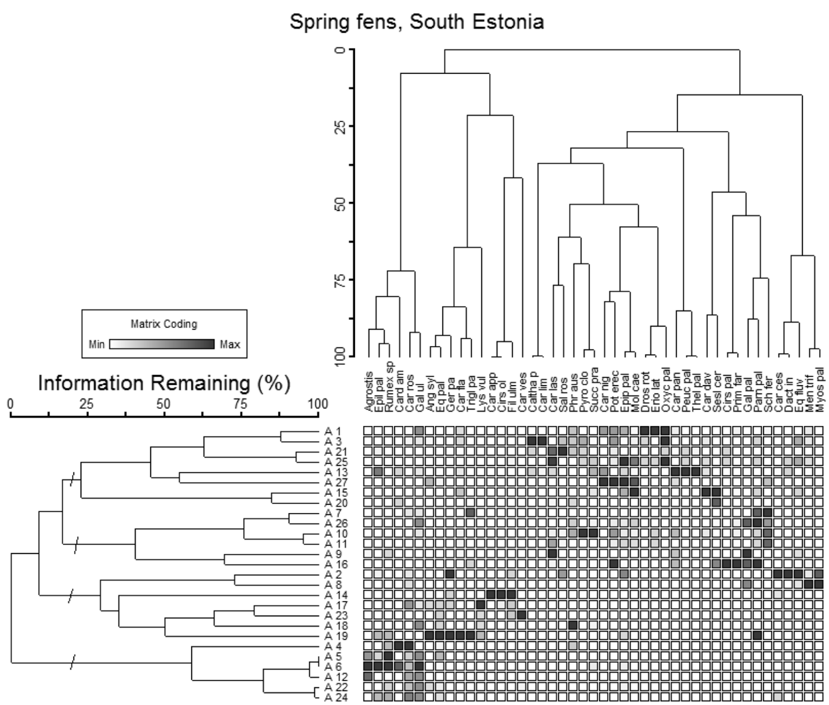
CONCLUDING REMARKS

As very few spring fens still occur on the lowland part of Europe it is very important to keep the still existing ones in a good state. Earlier, in the 1950s and 1960s, about 100 tufa deposits were known in the southern part of Estonia (Hallik, 1957; Lõokene, 1961). We found some 20 sites where tufa was forming, among others 17 calcareous tufa-forming spring fen sites. This is a considerable number at European scale. Besides, the diversity of plant communities is high. Restoration of damaged spring fens is a topical issue but costly and not very effective (Grootjans et al., 2005). The self-restored site found in South Estonia is a good example that re-establishment of the calcareous spring fen plant cover with corresponding tufa precipitation may in certain circumstances take place.

ACKNOWLEDGEMENTS

The research was supported by the Estonian Environmental Fund through project No. 12 'Petrifying springs and tufa-forming spring fens in Estonia – inventory and state. Part I', and grant No. 0280009s07 of the Estonian Science Foundation. Our thanks are also due to two anonymous reviewers for critical comments on the manuscript.

Two-way hierarchical agglomerative cluster analysis (using Sørensen distance measure and flexible beta-group linkage, $\beta = -0.25$) dendrogram of the 27 plots with calcareous spring fen vascular plant species from South Estonia



Symbols indicate plant groups formed by pruning the dendrogram (see „/" marks), A1...A27 – plot numbers. Vascular plant species: Agrostis – *Agrostis canina*, Epil pal – *Epilobium palustre*, Rumex sp – *Rumex sp*., Card am – *Cardamine amara*, Car ros – *Carex rostrata*, Gal ul – *Galium uliginosum*, Ang syl – *Angelica sylvestris*, Eq pal – *Equisetum palustre*, Ger pa – *Geranium palustre*, Car fla – *Carex flava*, Trigl pa – *Triglochin palustre*, Lys vul – *Lysimachia vulgaris*, Car app – *Carex appropinquata*, Cirs ol – *Cirsium oleraceum*, Fil ulm – *Filipendula ulmaria*, Car ves – *Carex vesicaria*, Caltha p – *Caltha palustris*, Car lim – *Carex limosa*, Car las – *Carex lasiocarpa*, Sal ros – *Salix rosmarinifolia*, Phr aus – *Phragmites australis*, Pyro clo – *Pyrola clorantha*, Succ pra – *Succisa pratensis*, Car nig – *Carex nigra*, Pot erec – *Potentilla erecta*, Epip pal – *Epipactis palustris*, Mol cae – *Molinia caerulea*, Dros rot – *Drosera rotundifolia*, Erio lat – *Eriophorum latifolium*, Oxyc pal – *Oxycoccus palustris*, Car pan – *Carex panicea*, Peuc pal – *Peucedanum palustre*, Thel pal – *Thelypteris palustris*, Car dav – *Carex davalliana*, Sesl cer – *Sesleria caerulea*, Cirs pal – *Cirsium palustre*, Prim far – *Primula farinosa*, Gal pal – *Galim palustre*, Parn pal – *Parnassia palustris*, Sch fer – *Schoenus ferrugineus*, Car ces – *Carex cespitosa*, Dact in – *Dactylorhiza incarnata*, Eq fluv – *Equisetum fluviatile*, Men trif – *Menyanthes trifoliata*, Myos pal – *Myosotis palustris.*

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BASIN DELINEATION OF SMALL WETLANDS OF ESTONIA: A LiDAR-BASED CASE STUDY FOR THE SELISOO MIRE AND LAKES OF THE KURTNA KAME FIELD

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Introduction

In geomorphology a *drainage basin* is an extent or area of land where surface water from rain and melting snow or ice converges to a single point, usually the exit of the basin, where the waters join another water body (i.e. a river, lake, reservoir, estuary, wetland, sea or ocean). In closed drainage basins the water converges to a single point inside the basin, known as a *sink*, which may be a lake or a point where surface water is lost underground (Pidwirny, 2006). The most used synonyms for *drainage basin* are *catchment basin* or *watershed* (EnDic, 2004).

According to the American Planning Association (APA, 2006), hydrological management units (hereafter HMUnits) for drainage basins can be ranked on the following hierarchy: *catchment – sub-watershed – watershed – sub-basin – basin*; the smallest unit in that hierarchy is the *catchment* with the size between 0.05 and 0.50 sq. miles (equals 0.13–1.29 km^2) and the largest unit is the *basin* with the size between 1000 and 10 000 sq. miles (2590–25 900 km^2). In that sense a *catchment* is defined as the area that drains an individual development site to its first intersection with a stream and a *basin* drains to a major receiving water body such as a large river, estuary or lake (APA, 2006).

Topographically each HMUnit is separated from an adjacent unit by a geographical barrier such as a ridge, hill or mountain known as *drainage divide* or *water divide*. Often a water divide is visualised as the line separating neighbouring drainage basins. In hilly landscape, the divide lies along topographical peaks and ridges, and may be in the form of a single range of hills or mountains (known as a *dividing range*), but in a flat landscape (especially where the ground is marshy) the divide may be invisible – just a more or less notional line on the ground on either side of which falling raindrops will start a journey to different rivers, and even to different sides of a region or continent (Pidwirny, 2006).

Drainage divides are important geographical and often also political boundaries. Roads (such as ridge-ways) and rail tracks often follow divides to minimise grades (gradients) and to avoid marshes and rivers. Drainage divides are used in water availability studies, water quality projects, flood forecasting programmes, as well as in many other engineering and public policy applications. Watershed managers and planners are interested in different types of environmental conditions within distinct segments of watersheds (e.g. hill slopes, terraces, floodplains, etc.), while hydrologists and geomorphologists are interested in the spatial variability of processes throughout a certain type of HMUnits.

Obtaining this information requires *delineation* of the drainage system, which includes the stream channel network and smaller catchments within the basin (Environmental GIS, 2005). In addition, every HMUnit can be characterised by geometric properties related to its linear, areal and relief properties. These properties are related to the position of a stream within the unit, and they can be used to compare the units.

The delineation of any kind of HMUnits can be done manually using topographic information. The widespread availability of elevation data in digital format has enabled to develop automated tools that can be used to delineate those units and their associated stream networks.

Most of the hydrologic modelling tools work with elevation data in raster format (i.e. digital elevation models or DEMs). In *ArcGIS* the *Basin* tool analyses the flow direction of each DEM cell to find the pour points and then creates *basins* for all of them (ESRI, 2007). *Watershed* tool hereby is creating the basins *only for user defined pour point* found on the DEM, for instance drainage area behind a proposed dam (ESRI, 2007).

The *ArcGis Hydrologic flow* tool uses an *eight direction pour point model*. This model considers that runoff from a given cell in a DEM will flow towards one of its eight neighbours, i.e. towards the greatest slope between adjacent cells. Using the calculations of the flow directions and the number of the cells draining to every cell in the DEM, the *basin boundaries* and the associated stream network can be modelled in a relatively straightforward way (Anon. 1). A visualised *flow accumulation* in that connection is a by-product of modelling stream network as a line layer for *predicted* and *unmapped*, sometimes also *ephemeral* streams of surface or subsurface drainage. The *flow accumulation* line features mimic mapped stream paths and extends beyond the mapped endpoints to include *unmapped* channels (Anon. 2).

Accurate drainage boundaries are essential for accurate modelling studies. Through the *ArcGIS Hydro Data Model* and associated *ArcInfo* functionality, boundaries may be determined accurately and repeatedly in an automated fashion (Anon. 1). Due to spatial and temporal variations of the characteristics of a basin, it is often necessary to delineate a basin into smaller-sized modelled areas where variables can be considered homogeneous. The size of a modelled area is based on the degree of the study details and the assumption that the basin characteristics can be considered homogeneous by the modellers. The smallest area to which a hydrologic model can be applied might be defined as *Representative Elementary Watershed* (REW) (Reggiani et al., 1998) or *specific catchment area* (Chirico et al., 2005). In Chen et al. (2011) it is stressed that the process of catchment delineation is an important step that impacts the hydrologic model development. Catchment delineation can be very tedious without automatic methods if very detailed catchments (more than hundreds catchments) are delineated in a watershed and hundreds of watersheds are defined in an entire study area.

The accurate digital surface data, visualised via DEM, are the primary advance of LiDAR (Laser Imaging Detection And Ranging) data, which is less subject to inherent horizontal error in comparison with contour lines derived from ordinary contour maps (Haile, 2005).

There are many factors that affect the accuracy of DEMs, i.e. the accuracy, density and distribution of the source data, the algorithms used for data interpolation and the DEM resolution (Liu et al., 2007; Liu & Zhang, 2008). Anderson et al. (2006) indicated that the horizontal resolution of a DEM significantly influences the level of reduction that LiDAR data sets can withstand, although the accurate soil–landscape models could be developed by the DEMs with 2, 10 and 30 m cell resolutions (Gessler et al., 2000; Thompson et al., 2001). Results of the LiDAR DEM modelled flow network in Murphy et al. (2008) show that the most accurate representation of the actual field-mapped network is even more accurate than the aerial photo-interpreted hydrographical data.

On the other hand, the results of LiDAR-derived DEM modelling of the most important hydrological features, such as drainage network and boundaries of the basin, show high sensitivity to both DEM accuracy and the resolution used (Liu et al., 2005). However, it was demonstrated that the LiDAR-derived DEMs with high accuracy and high resolution offer the capability to improve the quality of hydrological features derived from the DEMs (Liu et al., 2005).

The aim of this paper is to generate three-dimensional terrains using for the first time LiDAR data and to model a *basin* delineation of two types of small wetlands of the Alutaguse Lowland: the Selisoo Mire and three lakes of the Kurtna Kame Field (Estonia). The Selisoo Mire is influenced by intensive forestry and presumably by underground oil shale mining; Lake Ahnejärv, Lake Kuradijärv and Lake Martiska by intensive groundwater abstraction, and presumably also by oil shale mining and earlier sand and peat extraction. Therefore under the ongoing water balance studies the basin delineation of LiDAR-derived DEMs, carried out in this study, is necessary and there is a need for basic hydro-topographical characteristics for the surface water HMUnits.

Short characterisation of the study areas

Geological background

The Selisoo Mire and the Kurtna Kame Field are located in the north-eastern part of Estonia, on the Alutaguse Lowland (3345 km^2). The lowland is rich in mires and lakes and is densely covered with forests (77.9%). The region has sparsely distributed human settlements (0.5%) and low (8.4%) agricultural land cover (Arold, 2005) (Fig. 1).

The Alutaguse Lowland lies on the transitional zone between the Viru-Harju limestone plateau in the north and the Peipsi–Pihkva depression in the south. The upper part of the Earth's crust of the lowland is divided into a crystalline basement overlain by Vendian and Cambrian terrigenous rocks and Ordovician and Silurian carbonate rocks (Raukas et al., 1971; Erg, 1994). The bedrock inclines gently towards Lake Peipsi in the south.

Because of the low topographical position (30–40 m a.s.l.) the Alutaguse region was flooded by the water of the melting glaciers at the end of the last glaciation. The contemporary landscape consists of gently undulating sand and varved clay plains, which are often covered with peat. Esker ridges, kame fields, end moraines and drumlins, formed by heaped glacial deposits on the area, are contrasting to Estonian most paludified plains in lowland.

About 37% of the Alutaguse Lowland is mires. The Muraka Mire complex (12 793 ha), one of the largest mire complexes in Estonia, is located on the lowland. It consists of several mire massifs, of which Muraka, Ratva, Selisoo and Virunurme massifs are the best known (Orru, 1995). The **Selisoo Mire**, part of the Muraka Mire complex, is located to the east of the 15-m high Mäetaguse esker (62 m a.s.l.) in the north-western part of the lowland (Fig. 1). According to Kalm (2009), the surface of the Selisoo Mire is about 10 m lower close to Mäetaguse esker and it elevates about 1–2 m over the ridge (50–51 m a.s.l.) close to the south-eastern border line of the mire. In the surroundings of the Selisoo Mire the average thickness of Quaternary deposits is about 5 m, except for Mäetaguse esker, where it reaches 15 m (Kalm, 2009).

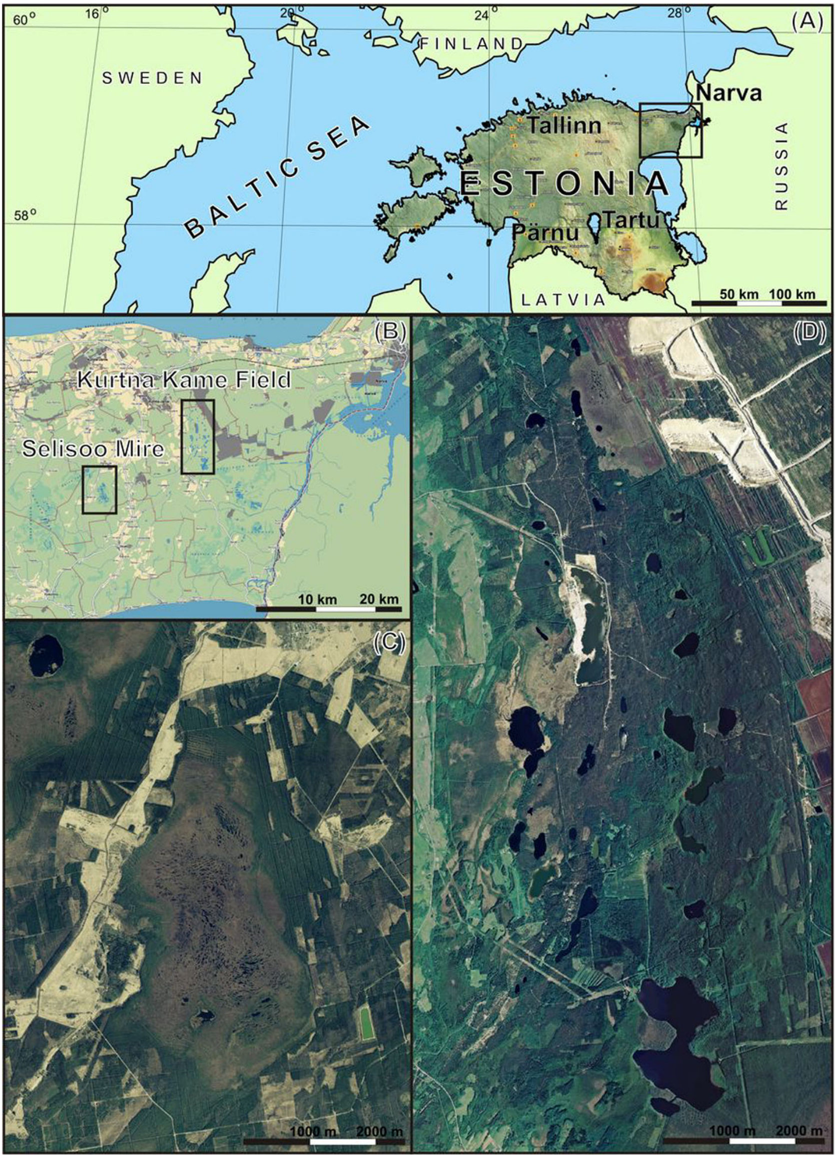

Fig. 1. (A), location of the study region in Estonia; (B), location of the Selisoo Mire and the Kurtna Kame Field on the Alutaguse Lowland; (C) and (D), orthophotos over the Selisoo Mire and the Kurtna Kame Field, respectively. The maps and orthophotos are from the Estonian Land Board. Colours on map (B): green indicates forested land, yellow agricultural land and grey human settlements and mining areas.

At the current stage, more than half of the mire (i.e. 65%) is drained for forests. Wooded tree coverage constitutes 15% of the mire extension, mainly at the bog part of the mire, and about 15% of the mire is open (Lode et al., 2011). About 2% (48.5 ha) of the mire is covered with a rather large number of pools, wet hollows and mire lakes (in total 1700 surface water bodies) (Lode et al., 2011).

The **Kurtna Kame Field** is located about 20 km to the north-east of the Selisoo Mire (Fig. 1). The kame field belongs to the north-easternmost complex of the marginal landform of the Late-Weichselian glaciation, i.e. Pandivere stage (Ilomets & Kont, 1994). It overlies the deep ancient Vasavere Valley, buried under a thick Quaternary cover (Raukas et al., 2007). The main deposit of the kame field is fine quartz-rich sand forming hillocks and small ridges of bedded sand and gravel.

There are 40 lakes of different shape and size on the Kurtna Kame Field, formed in glaciokarstic hollows of the field during the Pre-Boreal period, ca 10 000–9500 ^{14}C years ago. Lakes of the kame field differ also in the extent of their drainage area, hydrological regime and trophic status. Pine forests together with some birch and alder are the dominant land cover of the poor sandy soils of the kame field (Punning et al., 2007).

Hydrological background

Most of the rivers in the Alutaguse Lowland that flow into the northern or north-eastern directions start either from the mires of the Alutaguse Lowland or from the upwelling karstic springs (Kalm, 2009). The springs in Mäetaguse park are the most watery (407 l/s) and feed the Mäetaguse River, which is running in the west of the Selisoo Mire (Kalm, 2009). The Mäetaguse River is also the recipient of forest drainage water discharging into the river from the western part of the Selisoo Mire. The recipient of the drained surface water from the eastern part of the **Selisoo Mire** is the Milloja River, a tributary of the Roostoja River. Due to intensive forest drainage and earlier peat cutting, the natural hydrological conditions of the mire are significantly disturbed. During the last 50 years the open water area of the mire lake, located in the southern part of the bog massif, has been overgrown by about 67% (Lode et al., 2011).

The lakes of the **Kurtna Kame Field** form the greatest lake system in Estonia, consisting of 40 lakes. The largest standing water body of the lake system is Lake Konsu (136 ha), followed by lakes Kurtna Suurjärv, Jaala, Räätsma (the only iron-rich lake in Estonia), Suur Kirjakjärv, Väike Kirjakjärv and Valgejärv.

The hydrological regime of the Kurtna lake system is very diverse. There are drainage, seepage and flow-through lakes with both natural and human-induced origin, of which the latter prevails for the flow-through lakes. Lakes

Ahnejärv (5.7 ha), Kuradijärv (1.7 ha) and Martiska (3.1 ha) are small seepage lakes.

Human disturbances

The majority of the human disturbances of the **Selisoo Mire** are due to extensive forest drainage, mainly on the fen part of the mire landscape. Almost 90% (i.e. 100 km) of the ditches and 100% (8 km) of the roads were located on the fen drained for forestry and the transitional fen extension, where the mean density of the *line objects* was about 100 m/ha (Lode et al., 2011).

Intensive mire drainage during the last 50 years is reflected in overgrown water bodies of the mire, especially in the southern part of the bog massif, and tree expansion to the earlier open part of the bog massif from the east (Lode et al., 2011). The steep, up to 3-m high eastern bog marginal slope may also have formed due to intensive forest drainage after the Second World War (Kalm, 2009). The increase in the radial growth of the trees since the 1970s presumably indicates the high level of alkaline air pollution transported from the oil shale industry (Liblik et al., 2003) and also stabilised lower groundwater level on the mire. The major reason for the overgrowing of the mire lake might be the lowered lake water level at the end of the 19^{th} century (Kalm, 2009).

There are three areas with terminated and self-recovering peat cuttings, one located in the northern and two in the eastern part of the Selisoo Mire bog area (Lode et al., 2011). The role of the lowered mineral groundwater levels close to the eastern edge of the Selisoo Mire, which is caused by oil shale mining, is still not clear (Kalm, 2009).

The **Kurtna Kame Field** lies in a transitional zone between densely populated and heavily industrialised oil shale mining and processing region and a sparsely inhabited territory with vast forests and mires. The area is severely affected by the oil shale mining processes, for example by pumping out the groundwater and alkaline air emissions (Punning, 1994).

The hydrology of the Kurtna lake system has been suffering heavily from anthropogenic disturbances for the last 50 years. Many lakes in the southern part of the system were connected to each other via ditches in the 1950s to compensate for the water-level changes in Lake Konsu caused by the oil shale industry. In the 1960s peat extraction started at the north-eastern border of the lake system and the excavation of sand in the Pannjärve quarry in the centre of the kame field. In 1972 groundwater abstraction started from the central part of the kame field via Vasavere wells. In addition, there is an open-pit oil shale mine to the east of the lake system and two underground oil shale mines (one is active) to the west of the lake system (Ilomets et al., 1987; Savitski & Savva, 2005).

All these disturbances are reflected in considerable water-level changes of the lakes, where the downfall between 1946 and 1987 was estimated at up to 3.8 m (Erg & Ilomets, 1989). During the last decades the water level has risen again, partly because of the mitigation of human disturbances. The main human-induced disturbances of lakes Ahnejärv, Kuradijärv and Martiska were caused by groundwater abstraction from the Vasavere wells.

Material and methods

Creation of DEMs

LiDAR data from the Estonian Land Board were used for different generated DEMs of the Selisoo Mire and the Kurtna Kame Field. The data used were collected with a Leica ALS50-II scanner device during a flight survey in 2009. The average flying height during the survey was 2400 m, the *First Echo point* density at nadir was expected to be 0.45 points/m^2 with maximum distance between points up to 2.6 m, and the vertical accuracy of the laser data points was determined to be between 7 and 12 cm (Estonian Land Board, 2011).

The illuminated footprint diameter on the ground was 54 cm and the amount of laser scanned points on 1 km^2 could reach up to 1.4 million points. All laser-scanned points are presented in L-EST97 geographical system and in BK77 vertical system (Estonian Land Board, 2011). The data were distributed in ASCII text files, with the file data coverage of 1 km^2 and the data structured into *class*, *easting and northing coordinates*, *elevation*, *intensity* and *echo type* (Estonian Land Board, 2011).

The automatically driven *classification* procedure of the raw scanning data over land surface resulted in the following classes: 1. *Unclassified* (could be flora, buildings etc.), 2. *Terrain*, 6. *Buildings* (applicable only for major towns), 7. *Noise* and 14. *Sea.* The *Terrain data* were used for the generation of different DEMs of the Selisoo Mire and three small lakes of the Kurtna Kame Field.

The *Local Binning Algorithm* of *GEON Points2Grid Utility* with a *Standard radius* $r = 0.707 \times$ *cell resolution* (Kim et al., 2006) was used for the creation of 2, 5 and 10 m cell resolution DEMs for the Selisoo Mire project area (Fig. 2). The DEMs of the Kurtna Kame Field with pixel resolutions of 0.5 m and 2 m were generated by using the *Topo to Raster* algorithm (Hutchinson, 1989) in *ArcMap vers. 9.3* software (Fig. 3).

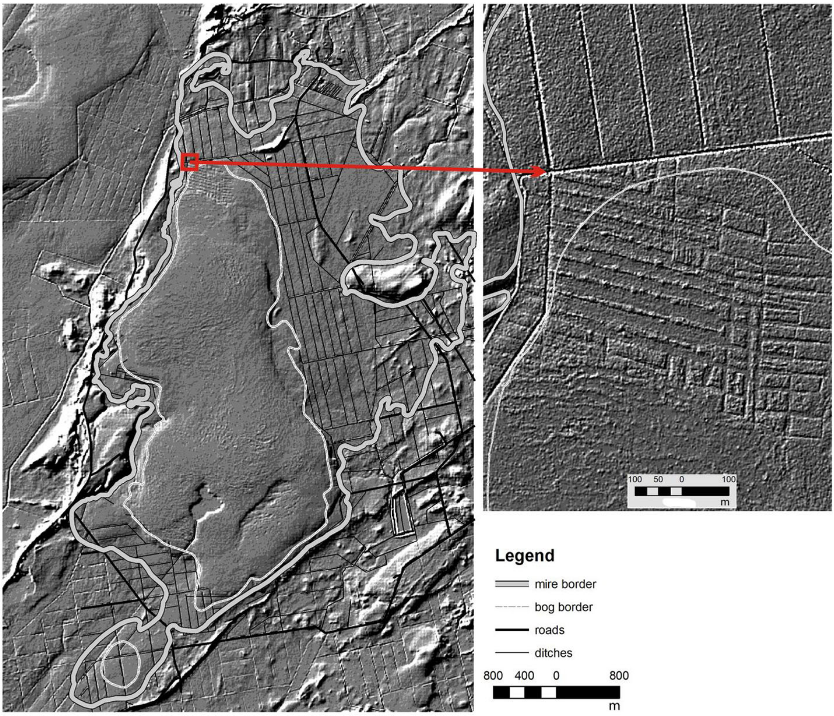

Fig. 2. *HillShade* image (left) of the Selisoo Mire inside the contour line of the zero peat deposit (*mire border* line in the figure) and the corresponding extraction from enlargement (right). The modelled cell resolution was 10 m for the left image and 2 m for the right image. Both images were generated from LiDAR-based MIN DEMs with 2 m cell resolution. The LiDAR scanning was made by the Estonian Land Board in 2009. The *mire* and the *bog border* lines were identified from a digital Estonian soil map. The *linear* tracks inside the *mire border* line were overlaid with the *ditches* and *roads* identified from an Estonian base map. Here the term 'mire' is used in the sense of peatland including both the minerotrophic (i.e. fen and transitional fen) and ombrotrophic (i.e. bog) peat-covered areas.

Analysis and modelling

Basin and *Flow accumulation* or the drainage system network modelling was carried out by using the *Spatial Analyst* extension of the *ArcMap*. The *ArcHydro Tools vers. 1.3 Final* was used to evaluate the *Sink*s of the DEMs and to model the *Drainage Points* (i.e. the most downstream point within the drainage area) for the obtained *Basin*s. The *Watershed* modelling, according to the user defined *pour points,* was carried out by using the relevant *ArcMap* extensions, where the locations of the *pour points* were defined by the users on the bog border line for the Selisoo Mire and on the line for the Kurtna lakes.

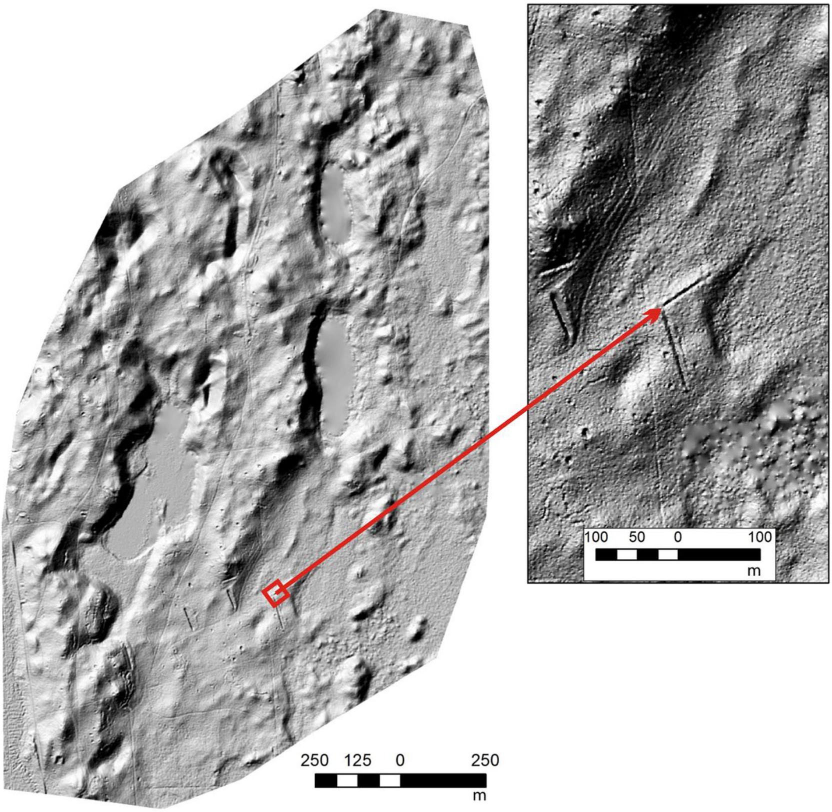

Fig. 3. *Hillshade* image with 2 m cell resolution over the studied lakes in the Kurtna Kame Field (left) and the corresponding extraction from enlargement with 0.5 m cell resolution of the central part of the kame field. Both images were generated from LiDAR-based DEMs of the same cell resolutions (i.e. 2 m for the left and 0.5 m for the right image). The LiDAR scanning was made by the Estonian Land Board in 2009.

Because they provide a better quality of the visualised mire surface pattern, the MIN DEMs of 2, 5 and 10 m cell resolutions were the main modelling layers used for the **Selisoo Mire** (see Fig. 2). *Basin* modelling for the project area over the mire extension was carried out by the default *ArcMap Filling* parameter (i.e. fills all existing *sinks* in the modelling area) since the sink depths for the mire area inside the mire border line varied between 0.9 and 0.099 m. The *Watershed* modelling was applied to the bog part of the Selisoo Mire according to the results of the main *flow accumula-*

tion pattern, obtained from corresponding modelling results over the whole mire project area.

Due to a relatively level mire surface the used classification rate for the *flow accumulation* was 30 *Classes* of the *Natural Breaks (Jenks)* method. In this way the maximum number of flow accumulation features was obtained for the visualisation of the MIN DEMs with the 2, 5 and 10 m cell resolutions.

The DEMs with cell resolutions of 2 and 0.5 m were the main modelling layers for the **Kurtna Kame Field** project area. To obtain a visibly meaningful *Basin* pattern over the modelling area, the *ArcHydro* defined *Sink*s deeper than 1 m were *fill*ed. The *threshold* of *flow accumulation* routes for the Kurtna Kame Field was set to 20 000 pixels (equals 5000 m^2). The kettle-holes deeper than 1 m, i.e. deeper than the *sink filling* limit in *basin delineation*, were delineated separately from the modelled lake basins.

The *Basin* pattern of the three modelled lakes together with the location of the *Drainage points* within the basins, and the corresponding *flow accumulation* routes were verified in the field. After that the necessary changes in the modelling scheme were applied. The *Watershed* modelling was carried out according to the user-defined *pour point* inputs, entered into the modelling scheme on the locations where the major *flow accumulation* routes intersected with the shore lines of the lakes.

Topography

The extent of LiDAR-based project area over the whole **Selisoo Mire** was 5341 ha, from which 38.4% was mire area. The contour line of the zero peat deposit bordered the area. The internal extent of transitional fen and fen peat was 1102 ha and of bog peat 949 ha (Table 1; Fig. 4).

Surface analysis of LiDAR-based MIN DEM with 2 m cell resolution showed that the highest parts of the studied project area were located outside the mire border area to the north-east and to the west. In the north-east the area had the maximum height of 71.78 m a.s.l. and in the west 70.64 m a.s.l. The bog part of the project area ranged over 949 ha and had the mean surface height of 56.51 m a.s.l.; the surface height obtained for the transitional fen and fen part was about 3 m lower and the area was about 150 ha larger (Table 1; Fig. 4). The lowest part of the project area with the minimum height of 45.24 m a.s.l. was located behind the south-eastern part of the mire area.

The obtained mean height of the bog surface was about 1.6 m lower in comparison with the mean height of the north-eastern part outside the mire and about 7.7 m higher than the south-eastern part outside the mire.

The highest part (60.94 m a.s.l.) over the whole mire extent was a small hill located in the north-eastern corner of the mire landscape, and the second highest part (59.09 m a.s.l.) was in the north-western edge of the bog extent, adjacent to Mäetaguse esker (Fig. 4).

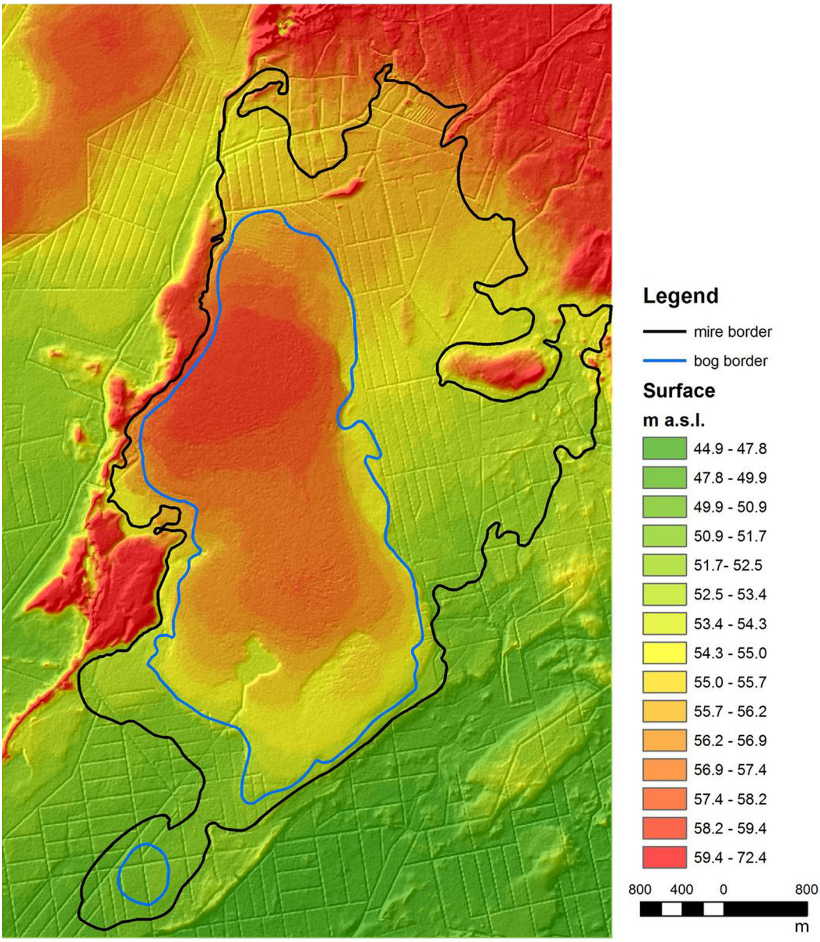

Fig. 4. Visualised topography of the Selisoo Mire project area generated from the LiDAR-based MIN DEM with 2 m cell resolution, where the 15 classes were obtained by the *Quantile* classification method. The MIN DEM image overlies the 10 m cell resolution *Hillshade* image, generated from the LiDAR data.

The obtained mean height of the project area of the **Kurtna Kame Field** was 31.37 m a.s.l. with the maximum of 68.91 m a.s.l and minimum of 43.78 m a.s.l. (Table 2; Fig. 5). The mean height of the studied lake levels was 44.9 m a.s.l for Lake Ahnejärv and 44.7 m a.s.l. for both Lake Kuradi-järv and Lake Martiska.

Table 1

Topographical characteristics of the LiDAR-based DEM over the Selisoo Mire project area (see also Fig. 4)

Characteristic	Landscape				
	Bog	Transitional fen & fen	Outside the mire		
			NE	SE	W*
Area, ha	949	1102	658	1061	1571
Mean, m a.s.l.	56.51	53.85	58.16	49.44	54.25
Min, m a.s.l.	51.75	48.61	52.81	45.24	48.18
Max, m a.s.l.	59.09	60.94	71.78	59.35	70.64
$SD_{topography}$	1.43	1.89	2.06	2.12	3.01

*Including Mäetaguse esker.

Table 2

Topographical surface characteristics of the LiDAR-based DEM of the Kurtna Kame Field project area (see also Fig. 5)

Characteristic	Project area	Lakes		
		Ahnejärv	Kuradijärv	Martiska
Area, ha	254	5.7	1.7	3.1
Mean, m a.s.l.	51.37	44.9	44.7	44.7
Min, m a.s.l.	43.78			
Max, m a.s.l.	68.91			
$SD_{topography}$	5.36			

The highest part of the kame field study area was its western edge, where the landscape is dominated by numerous kames up to 69 m a.s.l. The lowest part of the project area was at its south-eastern edge (Fig. 5).

Basin and sub-basin delineation

The **Selisoo Mire** included nine main basins (Fig. 6; Table 3). The largest 1863 ha basin (Basin 2 in Fig. 6) is located in a densely covered ditch area in the eastern part of the Selisoo Mire. Next in size are a 1390 ha basin (Basin 1) located in a relatively densely ditched north-western corner of the project area, and a 694 ha basin (Basin 4), which covers the central bog part of the mire area. The locations of almost all obtained downstream drainage points of basins were concentrated on the southern edge of the modelling area.

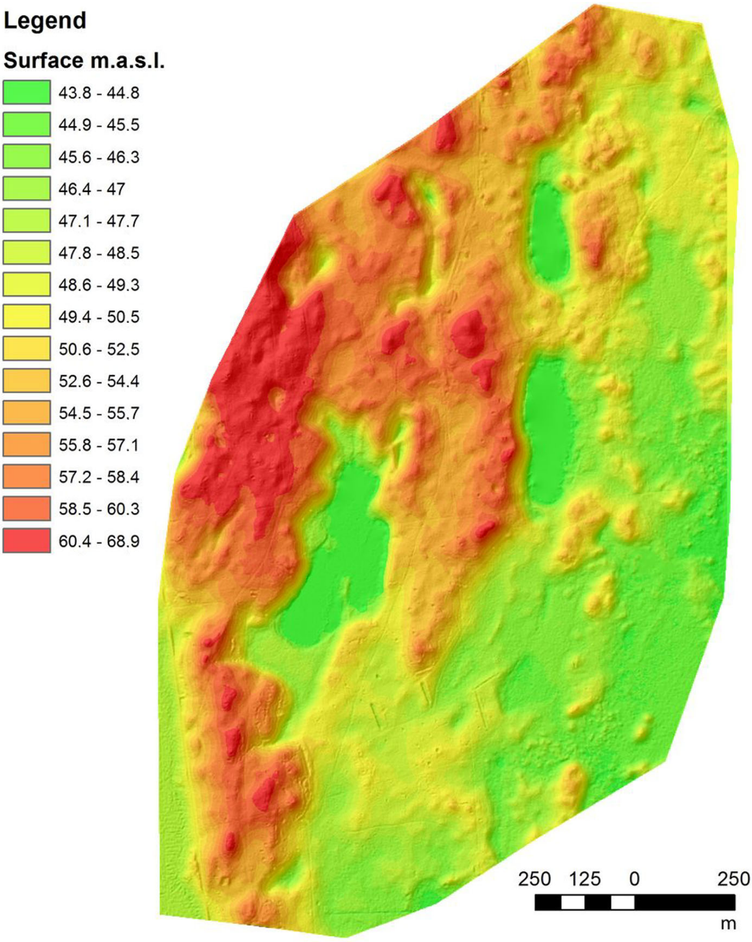

Fig. 5. Visualised surface of the central part of the Kurtna Kame Field, generated from the LiDAR-based DEM with 2 m cell resolution, where the 15 classes were obtained with the *Quantile* classification method. The DEM image overlies the 2 m cell resolution *Hillshade* image, generated from the LiDAR data.

From the mire point of view *Basins 2*, *4* and *1* with areal coverage of 48.5%, 26.6% and 18.4%, respectively, are the main basins that have topographical prerequisites for discharging surface water out from the mire area (Table 3). The same sequence of basin delineation is valid for the bog part of the mire extent, with only slightly changed surface coverage percentages: 46.2% for *Basin 2*, 37.8% for *Basin 4* and 15.0% for *Basin 1* (Fig. 6).

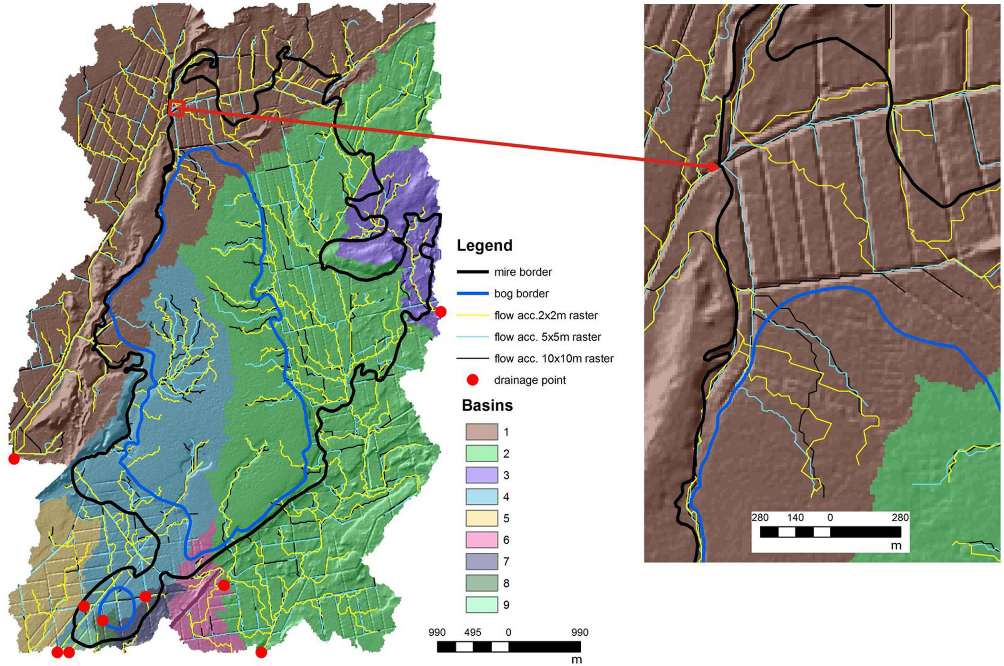

Fig. 6. *Basin* distribution of the Selisoo Mire and modelled surface flow accumulation features. *Basin* layer with the cell resolution of 10 m was generated from LiDAR-based 2 m cell resolution MIN DEM. Visualised flow accumulation features with cell size resolution of 2, 5 and 10 m were generated from LiDAR-based MIN DEMs with corresponding cell resolutions. Visualised *drainage points* represent the most downstream location within a *Basin* drainage area (see also Table 3).

Table 3

Distribution of modelled *basins* on the Selisoo Mire (see also Fig. 6)

No.	Project area				
	Basins, ha	incl. mire area		incl. bog area	
		ha	%	ha	%
1	1390	377	18.4	143	15.0
2	1863	995	48.5	438	46.2
3	213	79	3.9		
4	694	545	26.6	358	37.8
5	159	1	0.0		
6	100	19	0.9	10	1.0
7	42	17	0.8		
8	14	12	0.6		
9	10	6	0.3		
Total	4485	2051	100	949	100

The modelling of the surface *flow accumulation* routes showed cell size sensitivity in the results (Fig. 6). In the case of the Selisoo Mire the *flow accumulation* routes from 5 and 10 m cell resolution MIN DEMs more or less followed the 'tracks' of the scanned ditch system in the densely drained areas, whereas the used 2 m cell resolution DEM gave in some locations the 'crossing' *flow accumulation* routes stretching over the ditched area. In the case of undisturbed mire surface topography, as the bog part could be assumed to be, the *flow accumulation* routes from different DEMs with different cell resolution almost coincided with the surface and downstream concentration lines on the central western bog border. The *flow accumulation* routes of the largest *Basin 2* indicate several cross-bordering flow tracks over the eastern bog border. In the case of *Basin 4* there was a very clear *flow accumulation* cluster bunch on the north-western border of the bog line.

Modelling of the watersheds according to user defined modelling points on ten prevailing *flow accumulation* routes on the bog part showed that the obtained 184.6 ha *Watershed 1* was the largest watershed on the bog area. Next in size were *Watershed 10* (87.4 ha) of the drained bog forest and *Watershed 4* (78.6 ha) of the drained marginal area, following the bog border line adjacent to the self-recovering peat-cut area. The last noteworthy watershed was *Watershed 2* (66.5 ha), discharging the mire lake basin via the lake ditch to the south (Fig. 7; Table 4).

Basin delineation of the **Kurtna Kame Field** study area resulted in a large number of closed small basins with their drainage points in the deepest part of the basins. There are many small kettle-holes in the Kurtna Kame Field and for all of them their own basins were delineated from the 0.5 m cell resolution DEM, demonstrating the varying surface pattern in the glacial landscape.

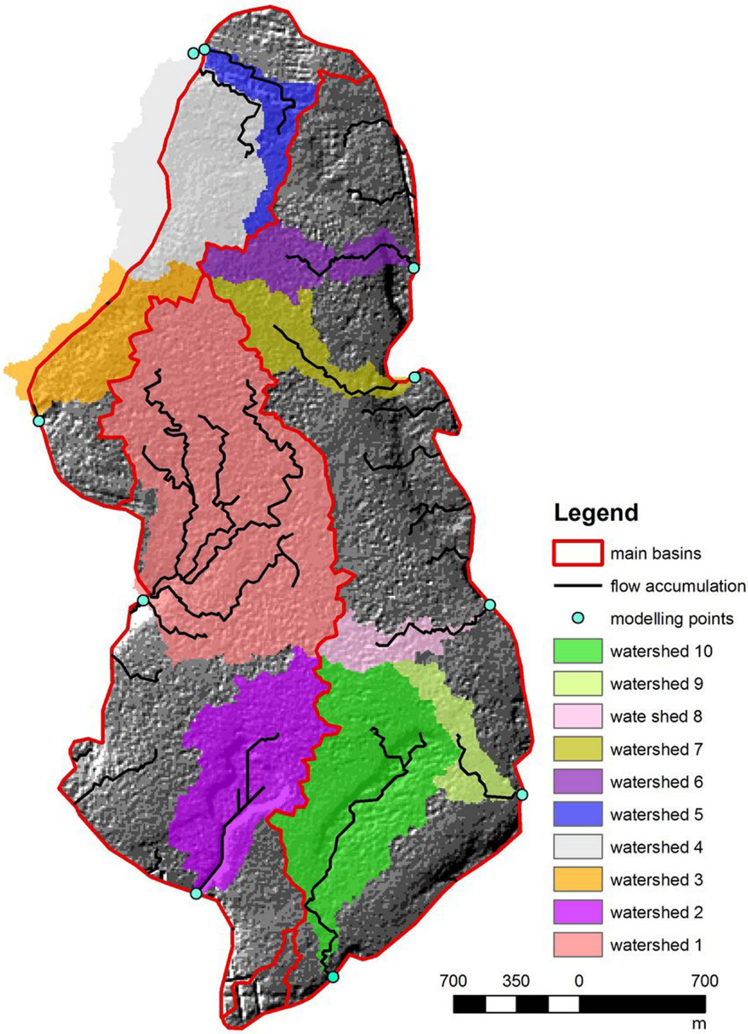

Fig. 7. Modelled *watersheds* of ten main *flow accumulation* routes on the Selisoo Mire according to the user defined *modelling point* location on the routes. Eight routes cross the bog border line and two (*watershed 3* and *watershed 4* routes in the figure) run parallel to the bog border, i.e. overlie the bog marginal drainage ditch (see also Table 5).

Table 4

Description of the main modelled *watershed*s of the Selisoo Mire by user defined *modelling points* on *flow accumulation* routes (see also Fig. 8)

No.	Watershed description	Area, ha
1	Hollow–ridge mire complex with converging flow accumulation	184.6
2	Mire lake with discharging ditch	66.5
3	Drained marginal bog area, following the bog border line	38.3
4	Drained marginal bog area, following the bog border line and self-recovering peat-cut area	78.6
5	Self-recovering peat-cut pits with functioning drainage system	19.9
6	Hollow and pool–ridge mire complex with flow accumulation perpendicular to the bog border line	26.2
7	Hollow and lawn–ridge mire complex with flow accumulation perpendicular to the bog border line	26.8
8	Lawn–ridge and ridge–hollow mire complex with flow accumulation perpendicular to the bog border line	15.3
9	Bog forest with flow accumulation perpendicular to the bog border	18.2
10	Drained bog forest with flow accumulation perpendicular to the bog border	87.4

The basin delineation of lakes Ahnejärv, Kuradijärv and Martiska resulted in *closed* basins around the lakes with the lowest drainage points located on the polygons of the lake surfaces (Fig. 8). The extents of the obtained lake basins, including the lake surfaces, were 45, 16 and 14 ha, with the largest *relative basin* of Lake Kuradijärv (9.4) and the smallest (4.5) of Lake Martiska (Table 5).

Two kettle-holes were situated adjacent to the delineated Lake Ahnejärv basin, less than 50 m to the north-east of the lake. Since the kettle-holes were deeper than 1 m, that is deeper than the *sink filling* limit in *basin delineation*, the basins for kettle-holes were delineated separately from the Lake Ahnejärv basin. The shape of the obtained Lake Ahnejärv basin itself was relatively elongated and it had several gullies stretching towards the lake; the most distinct ones were in the northern and southern parts of the basin (Fig. 8).

Several autonomous kettle-hole basins were obtained also from the Lake Kuradijärv basin delineation. The general shape of the Lake Kuradijärv basin was more rounded in comparison with the delineated Lake Ahnejärv basin. The obtained basin of Lake Ahnejärv was wider in shape in the northern part and narrower in the southern part of the area.

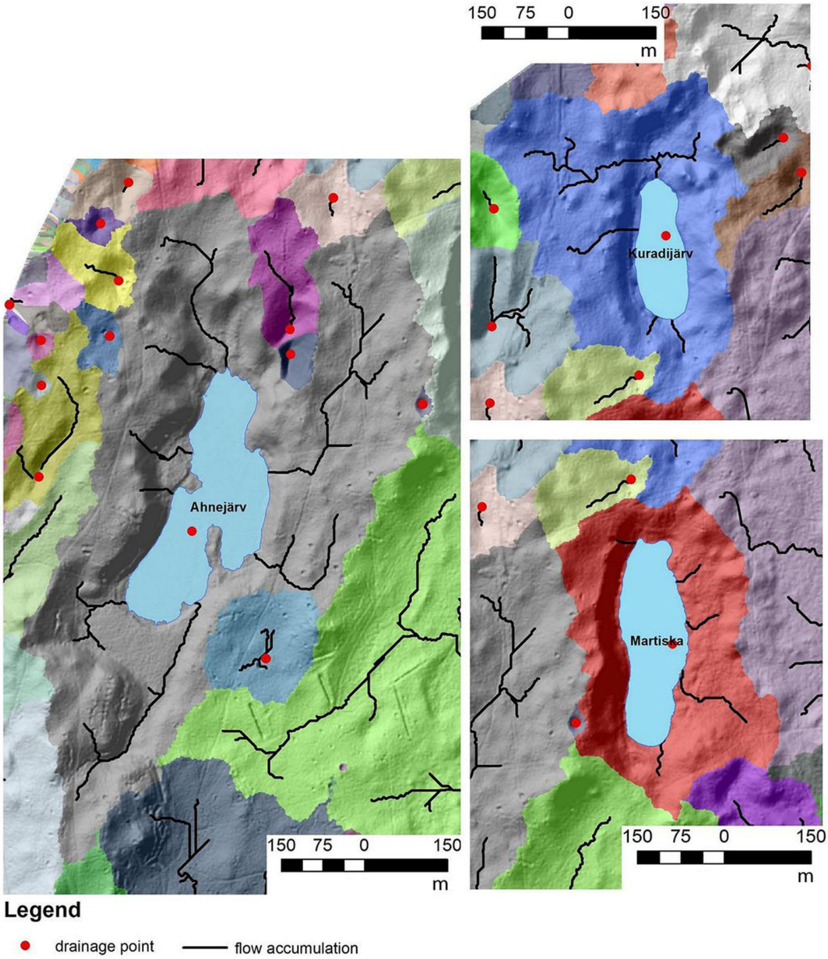

Fig. 8. *Basin* distribution of the lakes and surrounding kettle-holes (closed basins around the drainage point in images) in the Kurtna Kame Field project area and the modelled major routes of the surface *flow accumulation*. Both the *Basin* and the *flow accumulation* layers were generated from the LiDAR-based DEM with 0.5 m cell resolution. Visualised *drainage points* represent the most downstream location within a *Basin* drainage area (see also Table 5).

The simplest configuration of watershed border was obtained for the Lake Martiska basin, running at a considerably equal distance from the lake, and there were also fewer kettle-holes adjacent to the basin border line (Fig. 8).

Table 5

Relative size of basins (F_{rel}) modelled for the Kurtna Kame Field study lakes. $F_{rel} = F_{Ba}/F_{La}$, F_{Ba} denotes basin area and F_{La} is lake surface area (see also Fig. 7)

Lake	$F_{Ba,}$, ha	F_{La}, ha	F_{rel}
Ahnejärv	45	5.7	7.9
Kuradijärv	16	1.7	9.4
Martiska	14	3.1	4.5

The results of *flow accumulation* routes for the Kurtna lakes mimic the network of topography-based surface water flow (Fig. 9). The longest and most distinct surface flow routes were obtained for the Lake Ahnejärv basin and the smallest and shortest for the Lake Martiska basin. One major *flow accumulation* route was obtained for the Lake Kuradijärv basin in the wider northern part and shorter ones in other parts of the basin.

The largest obtained *watershed* for the Kurtna lakes was *Watershed A7* (8.57 ha), located in the north-western part of the Lake Ahnejärv basin (Table 6). All the three largest *watersheds* of Lake Ahnejärv (i.e. *Watersheds A3, A5* and *A7*) are located in the distant 'outcrops' of the basin, while the smaller watersheds cover the 'bulk' area. One large *watershed* prevailed in the northern part of the basin of Lake Kuradijärv (*Watershed K3*, area 7.07 ha) where the topography is gradually sloping towards the lake. Other important Lake Kuradijärv *watersheds* were relatively small (less than 1.3 ha) and steep. All major Lake Martiska watersheds were located in the most level eastern part of the lake basin. The steeper western part of the basin did not result in almost any major flow accumulation routes and therefore no significant watersheds either. All the obtained watersheds had a relatively small areal extent with the maximum coverage of *Watershed M1* being only 2.31 ha (Table 6).

Synthesis and conclusions

LiDAR data-based study results of two types of small Estonian wetlands – mire and kettle-hole lake landscapes – furnished the areas with high quality three-dimensional terrains. The used cell resolution influenced significantly the visualisation quality of the finer micro-topographical properties. This knowledge was important for following hydro-topographical modelling procedures. Comprehensive and high-quality outcomes make the use of LiDAR data attractive, although highly qualified experts and desktop facilities, often quite expensive, are needed.

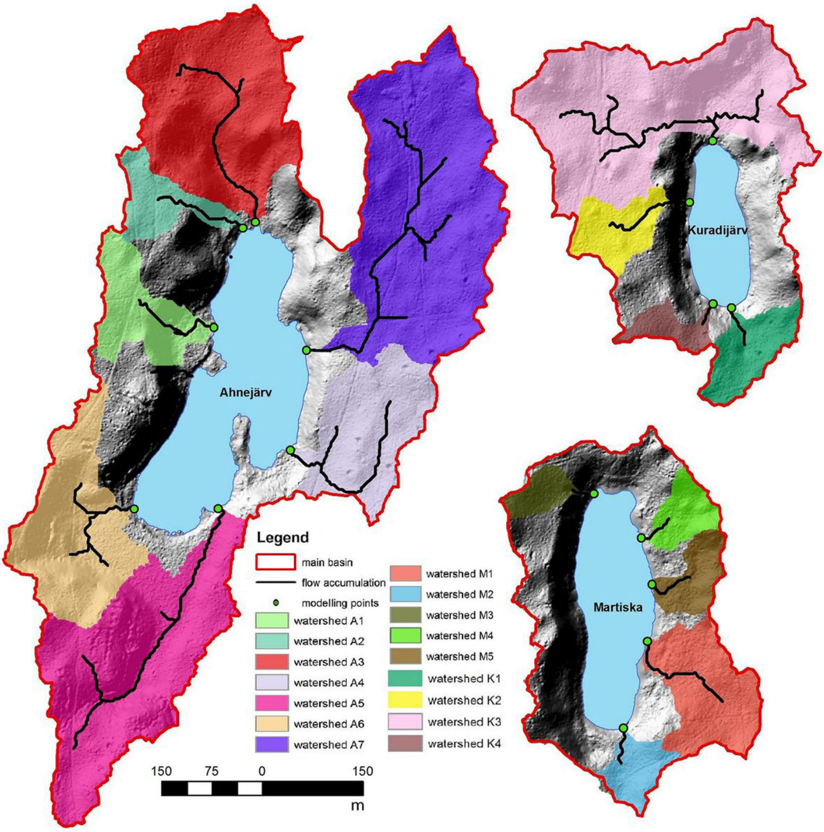

Fig. 9. Major *watersheds* of the Kurtna study lakes. The *watersheds* were modelled for major *flow accumulation* routes according to the user-defined *modelling point* locations at the route intersections with the lake surface border lines (see also Table 6).

To save computing time and to obtain more 'meaningful' results, modelling scale options are important. On the basis of visualised *HillShade* layers optimal raster resolutions were derived for hydro-topological modelling areas of different extent: 10 m cell resolution for a modelling area ≥ 1000 ha; 5 or 2 m cell resolution for a modelling area between 100 and 1000 ha; 1 or 0.5 m cell resolution for a modelling area < 100 ha. Otherwise the obtained modelling outcomes from the input DEMs with the finer pixel resolution were too fine, indicating an unnecessarily high cell resolution used.

Table 6

Description of modelled *watershed*s of the Kurtna study lakes by user defined *modelling points* on *flow accumulation* routes (see also Fig. 9)

No.	Watershed description	Area, ha
A1	Forested, with relatively steep lake shore	1.78
A2	Forested, with relatively steep lake shore	1.14
A3	Forested, with moderately sloping lake shore	5.57
A4	Forested, with relatively level lake shore	3.12
A5	Forested, with moderately sloping lake shore	6.58
A6	Forested, with moderately sloping lake shore	3.81
A7	Forested, with relatively level lake shore	8.57
M1	Forested, with moderately sloping lake shore	2.31
M2	Forested, with moderately sloping lake shore	0.75
M3	Forested, with moderately sloping lake shore	0.59
M4	Forested, with moderately sloping lake shore	0.75
M5	Forested, with relatively steep lake shore	0.83
K1	Forested, with moderately sloping lake shore	1.21
K2	Forested, with relatively steep lake shore	1.13
K3	Forested, with relatively level lake shore	7.07
K4	Forested, with relatively steep lake shore	0.56

The basin delineation of the Selisoo Mire resulted mainly in an *open* pattern. In the case of the Kurtna lakes the basin pattern was *closed*.

The location of modelled *drainage points* on the border of the modelling area of the Selisoo Mire could be taken as an evidence for a too small project area for mire basin delineation. On the other hand, the *closed* basins pattern for the Kurtna lakes was obtained by decreasing the *filling* parameter, which was not applied during the mire basin delineation runs.

However, the delineated mire basins in the frame of the mire or bog border are satisfactorily trustable due to the obtained 5 and 10 m cell resolution flow accumulation routes. The location of downstream *drainage points* could be taken also as an indicator of the main direction of the surface water flow towards the southern edge of the mire area. This also fits well to the obtained topographical results, where the whole mire had a radial type of surface lowering trend from the north-western mire edge in the eastern, south-eastern and southern directions.

The overall topography of the Kurtna Kame Field study area followed a lowering trend from the western edge of the area to its south-eastern edge. The studied lakes were formed on the transitional zone between the kame field and the lowland.

Since the use of the *default filling* parameter for the Kurtna lakes resulted in delineating *open* basins, discharging surface water *out* from the lakes, it was an evidence for decreasing the *filling* parameter value and the gained results were approved in the field.

The earlier study showed lowered groundwater levels for several ecotopes of the mire bog part (Lode et al., 2011). Therefore the current results about the general structure of the basin of the Selisoo Mire have a great meaning for the continuing mire water balance study. Changing the *filling* parameter, as in the kame field basin delineation, could result in *closed* basins around the pool complexes or inside the modelling project area also in the case of the Selisoo Mire.

Using the *threshold* classification algorithm gives a possibility of building up a surface water network for visualisation of the obtained *flow accumulation* routes. To keep the flow network as simple as possible in the visualised layer, a lower boundary (20 000 pixels = 5000 m^2) was set to the threshold of *flow accumulation* routes for the Kurtna Kame Field. In the case of the Selisoo Mire the threshold classification was performed close to the maximum possible *class* amount with the aim to get as many *flow accumulation* routes visible as possible.

As the fen and transitional fen part of the Selisoo Mire are heavily drained, the *flow accumulation* routes ought to follow the connected ditch network pathways. Therefore the pathways from the higher cell resolutions needed reconsideration. However, in general the *flow accumulation* routes both on the mire's bog part and in the lake basins of the Kurtna Kame Field mimicked well the topographical features of the ground surface, while the longer *flow accumulation* routes for the Kurtna lakes followed the larger, more level and lower basin regions.

Results of *Watershed* modelling delineated in the study areas 9 main watersheds for the bog part of the Selisoo Mire and 16 for the Kurtna Kame Field lakes. The obtained watershed modelling results are valuable inputs for *integrated* or *summarised* layer modelling for the quantification of surface water discharges either out from the mire area or into the lakes or pools.

The obtained visualisation and hydro-topographical features were the first LiDAR-based results for the studied areas. The generated terrains have a high value for the continuing water balance studies of the Selisoo Mire and the lakes of the Kurtna Kame Field. Visualised terrains with higher cell resolution demonstrated a highly satisfactory micro-topographical surface pattern over the scanned areas, for example ridges, hollows, pools and the forest drainage network for the Selisoo Mire and kettle-holes, trenches and roads for the Kurtna Kame Field.

The field verification of the *delineated* Kurtna lake basins confirmed the high accuracy of the reflected surface pattern in the generated three-dimensional terrains. This was achieved even under quite dense forest.

Similar field verification is also needed for the Selisoo Mire. The visualised *flow accumulation* raster routes indicated that not all ditches in the network were reflected as linearly continuous in the scanned database. Probably because of the dense forest, which influenced the terrain quality of the higher 2 m cell resolution DEMs, the generated *flow accumulation* routes of the same resolution did not follow the general ditch network pattern on drained mire areas. Some fieldwork and manual processing of drainage network are needed to correct the input data for further, more correct basin delineation for the DEMs with higher cell resolution.

Acknowledgements

The study was supported by Estonian target financed projects SF0280016s07 and SF0280009s07, and Estonian Science Foundation grant 7392. The authors would like to express their gratitude to the Estonian Land Board for LiDAR data, to the anonymous reviewers, the language reviser and the editors of the issue.

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