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Radon in Estonian dwellings

Results from a National Radon Survey

Statens strålskyddsinstitut
Swedish Radiation Protection Authority

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TITLE/ TITEL: Radon in Estonian dwellings - Results from a National Radon Survey/ Radon i estniska bostäder. Resultat från en landsomfattande undersökning.

SUMMARY: A countrywide survey of radon concentrations in Estonian dwellings was carried out during the period 1998-2001. The survey formed a part of the cooperation program on radiation protection between the Estonian Radiation Protection (Kiirguskeskus) Centre and the Swedish Radiation Protection Authority (SSI). The Estonian Environmental Foundation and the Swedish Ministry for Foreign Affairs have given financial support for the survey.

The survey included measurements in a number of dwellings representative for Estonia in detached houses and multifamily buildings (only dwellings on the bottom floor were included in the survey). Altogether, radon concentrations were measured in 515 dwellings, a number large enough to be statistically significant.

All measurements were made with alphatrack film detectors of the same type that SSI uses in Sweden. The measurements were made during a 2-3 month period during the winter halfyear. Two detectors were used in each dwelling. In Estonia there are 0.17 dwellings in detached houses and 0.45 million in multiapartment buildings. Of the 1.26 million inhabitants in Estonia. 0.36 million live in detached houses and 0.90 million in multiapartment buildings. Most of the latter were built during the Soviet occupation. Of the dwellings in multifamily buildings 30 % are assumed to be situated on the first floor. The mean radon concentration in dwellings in detached hoses, according to the survey results, is 103 Bq/m^3, in dwellings on the bottom floor in multiapartment buildings it is 78 Bq/m^3. In 1% of the dwellings the radon concentration exceeded 400 Bq/m^3. The highest radon concentration found in the study was 1040 Bq/m^3.

Approximately 70% of the Estonian population lives in apartments in multiapartment buildings. Based on the assumption that the average radon concentration in the dwellings in multi-apartment buildings that are not situated on the bottom floor is 30 Bqm^3, and that these dwellings constitute 70% of all dwellings in multiapartment buildings, the mean radon concentration in dwellings in multiapartment buildings is calculated to be 44 Bq/m^3. The mean value for all Estonia dwellings is calculated to be 60 Bqm^3.

Using the detriment factor given by ICRP, annually about 90 Estonians are expected to develop lung cancer due to exposure to radon in their homes. Most of them, about 75, are smokers, which are affected by the synergetic effect of the two carcinogens, smoking and radon. In Estonia the source of indoor radon is radoncontaining soil air that is transported into the buildings from the ground. Building materials with enhanced radium concentrations are not known in Estonia. In this survey, the highest indoor radon concentrations have been found in the northern part of Estonia where uraniumrich Dictyonema shale and uraniumcontaining phosphorous Glauconite sandstone exist in the bedrock and as fragments in the soils. Radon concentrations higher than 400 Bqm^3 have also been measured in buildings situated in areas with karst formations. Areas with Dictyonema shale, Glauconite sandstone and karst are areas with a special risk for radon.

SAMMANFATTNING: En landsomfattande studie av radonhalter i estniska bostäder utfördes under åren 1998-2001. Studien utfördes inom ett samarbetsprojekt mellan Esti Kiirguskeskus (Estoninan Radiation Protection Centre, RPC) och Statens strålskyddsinstitut (SSI). Den finansierades via anslag från Estlands Miljöfond och Sveriges Utrikesdepartement. Studien omfattade mätningar av radonhalten i ett för Estland representativt urval av slumpvis utvalda bostäder, såväl i småhus som i flerbostadshus (endast lägenheter på bottenvåningen) fördelade över hela Estland. Antalet bostäder tillräckligt stort för att resultatet skall vara statistiskt relevant.

Totalt mättes radonhalten i 515 bostäder. Mätningarna utfördes med samma typ av spårfilm i dosa som SSI använder och vidareutvecklat. I varje bostad mättes med två spårfilmsdosor.

I Estland finns ca 0,17 miljoner bostäder i småhus och ca 0,45 miljoner bostäder flerbostadshus. Av Estlands 1,26 miljoner invånare bor 0,36 miljoner i småhus och 0,90 i flerbostadshus, flertalet av de senare i stora bostadskomplex byggda under sovjetoccupationen. Uppskattningsvis bor 70% av befolkningen i lägenheter på bottenplanet om dessa lägenheterna på bottenplanet antas utgöra 30% av alla lägenheter i flerbostadshusen. Den uppmätta genomsnittliga radonhalten i estniska småhus är enligt studien 103 Bqm-3 och i bottenvåningarna på flerbostadshusen 78 Bq/m^3. I 1% av de mätta lägenheterna översteg radonhalten 400 Bq/m^3. I denna studie var den högsta uppmätta halten 1040 Bq/m^3.

Baserat på antagandet att de lägenheter som inte ligger på bottenplanet har en genomsnittlig radon halt på 30 Bq/m^3 och att dessa utgör 70% av alla lägenheter i flerbostadshusen skulle den genomsnittliga radonhalten i estniska bostäder i flerfamiljshus vara 44 Bq/m^3. Den genomsnittliga radonhalten för alla estniska bostäder beräknas till 60 Bq/m^3. Baserat på ICRP:s riksfaktor för lungcancer och exponering för radon beräknas att ca 90 fall av lungcancer per år orsakas av radon i hemmen. Av dessa fall antas att de flesta är rökare, ca 75 fall, vilka drabbas av den synergetiska effekten av exponering för både rökning och radon. Källa till radonet i husen är radon som transporteras med jordluft från marken.

Byggnadsmaterial med förhöjda radiumhalter har inte påträffats i Estland. I denna och tidigare undersökningar har de högsta radonhalterna inomhus uppmätts i den norra delen av Estland där uranrik Dictyonemaskiffer och uranförande fosforitsandsten förekommer i berggrunden och som fragment i jordlagret. Halter över 400 Bq/m^3 har också uppmätts i hus belägna inom områden med karstformationer. Områdena med Dictyonemaskiffer, uranförande fosforitsandsten och karst utgör områden medsärkskild risk för radon.

Statens strålskyddsinstitut
Swedish Radiation Protection Authority
KIIRGUSKESKUS

Radon in Estonian dwellings - Results from a National Radon Survey

INTRODUCTION

Background and objectives

In this report, the results of the National Radon Survey of radon concentrations in Estonia dwellings are given. This survey was performed during the period 1998-2001 and it included radon measurements in 515 randomly chosen dwellings. The Estoninan Radiation Protection Centre (ERPC) carried out the survey with the help of local and regional health authorities. The survey forms part of the cooperation program between Estoninan Radiation Protection Centre (Kiirguskeskus) and the Swedish Radiation Protection Authority (SSI). The Estonian Environmental Foundation and the Swedish Ministry for Foreign Affairs have given financial support to the survey.

The studies of indoor radon in Estonia started at the end of the 1980s, when it was recognized that elevated indoor radon concentration could be a risk factor for human health. At that time information about radon problems was mostly acquired through Swedish and Finnish publications. The first radon survey in Estonia was carried out by The Department of Building Physics at the Estonian Building Research Institute (EBRI) during the years 1989-1991 [1]. In that survey, radon levels in dwellings were measured as well as concentrations of natural radioactive elements in the soils and in the building materials produced in the country. Radon concentrations were measured in more than 400 houses using grab-sampling techniques with Lucas cells. Ninety percent of the measurements were made in dwellings and 10% in kindergartens, schools and hospitals. The highest measured radon level was 6,700 Bqm^{-3}; in 72% of the houses the radon concentration was below 100 Bqm^{-3}, and in 4% it exceeded 800 Bqm^{-3}. These results showed that the main source of indoor radon is the soil under the buildings. In Estonia no building materials with elevated radium concentrations have been found so far.

The first Estonian-Swedish Radon Project (EST 6-01), a part of the Swedish East European cooperation program in the field of radiation protection, made it possible to start a radon-monitoring program within the Estonian Environmental Monitoring Program in 1994. The main objectives of this program were to investigate the radon levels in dwellings, to identify the country's radon risk areas, and the housing construction types that tend to be associated with high indoor radon levels.

The first part of the Estonian-Swedish Radon Project (EST 6-01) was completed in 1996 and it included measurements from randomly selected dwellings in areas considered to be radon risk areas [2]. During the five years of the radon-monitoring program (1994-1998), the indoor radon concentrations were measured in 700 dwellings located in areas expected to be radon-prone areas. The measurements were made with passive alpha-track detectors; the measuring period was three months during the heating season.

The highest radon concentration found indoors was 12,000 Bqm^{-3}. The arithmetic mean of these measurements was 102 Bqm^{-3}. Approximately 65% of the measured dwellings had radon levels below 100 Bqm^{-3}. In 3% of the houses the radon concentration exceeded 800 Bqm^{-3} [3]. In all areas the average radon levels were higher in single-family houses than in apartment buildings. A summary of these measurements is given in Appendix 1 (Table 1).

The results of the radon measurements showed that the type of building which has the greatest risk for high indoor radon concentration is a special type of two-storey apartment house with crawl spaces. These buildings were built in the 1950s. The crawl spaces of these buildings lack external ventilation outlets. However, the floors on the first storey have indoor ventilation outlets that lead to the crawl spaces, creating excellent conditions for the influx of radon-containing soil air (Figure 1). The highest indoor radon level, 12,000 Bqm^{-3}, had a flat in one of these two-story apartment houses. Wherever such types of dwellings were measured they had the highest radon levels of the dwellings that were measured in that area.

In 1997, the **National Survey of Radon in Estonia** started. This survey constitut a second part of the Estonian-Swedish Radon Project (ES605A).

In this survey, radon has been measured in 550 randomly selected dwellings among the 617,400 dwellings in Estonia. The survey includes dwellings across the entire country (i.e. not only in radon risk areas).

The main aims of the survey were:

1. To estimate the countrywide radon situation for calculation of the public health risk due to indoor radon;
2. To provide a basis for work on protective measures against radon.

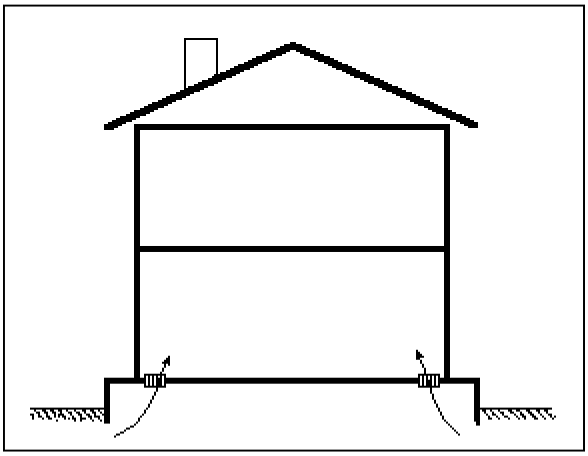


Figure 1. Two-story apartment house with crawl space ventilated via openings in the lowest floor. As built in Estonia in the 1950s.

The Estonian dwelling stock

In Estonia, 70% of the population live in apartment houses, but about 80% of the dwellings are single-family houses. The population distribution by counties and types of houses is shown in Table 1. The locations of the different counties are shown in Figure 5.

The present-day dwelling stock consists of three major types of houses: concrete panel buildings, brick-built and wooden. The use of concrete panel buildings became common in the early 1960s. Most of the urban residents live in apartment houses built after 1950, 50% were built even after 1970. These are typically two- or three-room flats including a kitchen, a hall, a bathroom and a toilet. The average floor space per capita is about 21 m^2. The houses are mostly provided with district central heating, a water supply, and natural draft ventilation. The estimated average ventilation rate in the heating season is about 0.8 - 1.2 air changes per hour. A ventilation rate of 1.0 change per hour was established in the construction rules (SNiP) for dwellings in the former Soviet Union.

In rural areas and small towns, single-family houses are the most common type. Most of them are one or two-storied wooden or brick houses, with 3 or 4 rooms, a kitchen, a hall and a toilet. The average floor space is about 31 m_ per capita. In towns there is public tap water and drainage. They have stove heating or their own heating system and natural draught ventilation; saunas are more common in single-family houses in rural areas. Private houses built in 1950-1990 are often “owner-built” – i.e. built by the people living in them. The insulation standard of these houses is often a lot better than in the standard houses, but the ventilation rates may be lower.

Table 1. Distribution of the Estonian population shown by counties and types of houses (from the 2000 Population and Housing Census)[1].

Counties	All dwellings		Apartments				Single-family houses			
	No. of dwellings	Residents	No. of flats	%	Residents	%	No. of houses	%	Residents	%
All Estonia	617,400	1,335,000	450,600	73	903600	68	166,800	27	354,600	27
HARJUMAA	224,800	512,000	195,000	87	414,200	81	29,800	13	74,000	14
HIIUMAA	5,000	10,000	2,000	40	3,700	36	3,000	60	5,800	56
IDA-VIRUMAA	86,000	176,000	75,400	88	155,000	88	10,500	12	17,400	10
JÕGEVAMAA	17,900	37,000	8,800	49	15,800	43	9,100	51	18,800	51
JÄRVAMAA	18,600	38,000	10,900	58	19,700	53	7,800	42	15,500	41
LÄÄNEMAA	15,100	28,000	8,700	57	15,300	55	6,500	43	10,600	38
LÄÄNE-VIRUMAA	33,300	66,000	20,500	62	36,000	54	12,800	38	25,800	39
PÕLVAMAA	15,700	32,000	6,800	43	13,000	41	8,900	57	17,000	53
PÄRNUMAA	40,100	90,000	24,800	62	46,400	52	15,100	38	35,700	40
RAPLAMAA	17,600	37,000	9,000	51	17,000	47	8,600	49	17,200	47
SAAREMAA	16,400	35,000	6,900	42	13,900	40	9,500	58	18,800	54
TARTUMAA	64,700	144,000	47,600	73	92,800	65	17,700	27	38,100	27
VALGA MAA	17,400	35,000	9,800	56	17,100	49	7.600	44	15,600	45
VILJANDIMAA	26,000	56,000	14,700	57	25,800	46	11,300	43	25,700	46
VÕRUMAA	18,900	39,000	9,700	51	18,000	46	9,200	49	18,600	48

[1)] The number of residents in apartments and single-family homes (1,258,200) does not correspond with the number of residents in all Estonia (1,335,000), because about 77,000 persons are not registered at any address.

THE SOURCE OF THE RADON - THE GROUND

Radon transported by soil air is the main source of indoor radon in Estonia. As far as is known, no building materials with elevated radium concentrations have been used in the construction of Estonian dwellings. Water used in households generally has a low radon concentration [4].

The bedrock in Estonia consists of sediments of Cambrian to Devonian ages, underlain by the Precambrian basement, which consists of crystalline rocks belonging to the Baltic shield [5]. The basement rocks are not exposed anywhere in Estonia. Figure 2 shows a simplified map of the bedrock of Estonia and Figure 3 shows a profile of the bedrock from north to south. The sediment rock sequence has been investigated by drilling numerous boreholes, which penetrate the sediments down to the basement. The sedimentary rocks mainly consist of sandstones, shales, limestones, siltstones and clays. These sediments dip gently southward. Thus, the oldest sediments (of Precambrian age, 590 m.y.) are exposed on the north coast of Estonia. The thickness of the sediment rock sequence is 100-600 m. The sediments are often unconsolidated, and layers of clay and sand exist.

The sedimentary rocks have low to normal uranium concentrations, usually less than 2.5 ppm uranium (30 Bq U-238 kg^{-1}), with the exceptions of the Ordovician Dictyonema black shale and phosphorous-rich Glauconite sandstone in northern Estonia. The Dictyonema shale is 2-6 m thick and is from the Lower Ordovician period (490 m.y.). It is a kerogen-rich shale with enhanced uranium contents; on average, the uranium concentration is 30 ppm (about 400 Bq U-238 kg^{-1}), but the concentration in the most uranium-rich layers is 100-300 ppm (1200-3600 Bq U-238 kg^{-1}). The Dictyonema shale is similar to the Upper Cambrian black uranium-rich alum shale found in Sweden and Norway. Directly above the Dictyonema shale lays the phosphorous-rich Glauconite sandstone that forms a layer of varying thickness, from just a few centimetres to more than 5 meters. The Glauconite sandstone also has an enhanced uranium concentration, but this is much lower than in the Dictyonema shale. The Glauconite sandstone has been extensively mined for its phosphorous, especially east of Tallinn where there are large excavations. The Dictyonema shale and the Glauconite sandstone are only exposed in the klint (a steep cliff along the northern coast of Estonia) and in a few other areas along the north coast of Estonia, e.g. in the eastern districts of Tallinn and the towns of Toila, Kunda and Sillamäe, where many houses have been built on the Dictyonema shale.

Glacial ice covered Estonia during the last glacial period. Thus, the soil in large parts of the country consists of moraine and glacial deposits of gravel, sand, silt and clay. The glacial soils consist mainly of material from the underlying rock units but also, to a large extent, of Precambrian rocks transported by the glacial ice from the bottom of the Baltic Sea and from Finland. Some of this rock material contains stones and fragments of uranium-rich granites. In some parts of northern Estonia, the glacial soils contain fragments of Dictyonema shale and Glauconite sandstone.

As a complement to the radon measurement in houses, reconnaissance surveys were made in the northern regions of Estonia to study the geology and to locate areas with special geological features which may promote the risk of radon in buildings. In these surveys, measurements were made with portable gamma-ray spectrometers and emanometers to determine the concentration of radium-226, thorium-232 and potassium-40 in soils, as well as the radon concentration in the soil air. These measurements were made at depths of 70-100 cm. A compilation of the results is given in Table 2.

Table 2. Range of activity concentrations of ^{226}Ra, ^{232}Th, ^{40}K in soil and ^{222}Rn in soil air in Northern Estonia.

	^{226}Ra, $Bqkg^{-1}$	**^{232}Th, $Bqkg^{-1}$**	**^{40}K, $Bqkg^{-1}$**	**^{222}Rn, $kBqm^{-3}$**
Northern Estonia				
Sand	9 –13	17-32	360-800	4-13
Thin layer of till above karst				49-149
Till in phosphorous-rich area	175	40	440	270-283
Till with Dictyonema fragments shale	130-820	40-80	600-16,000	380-2,500

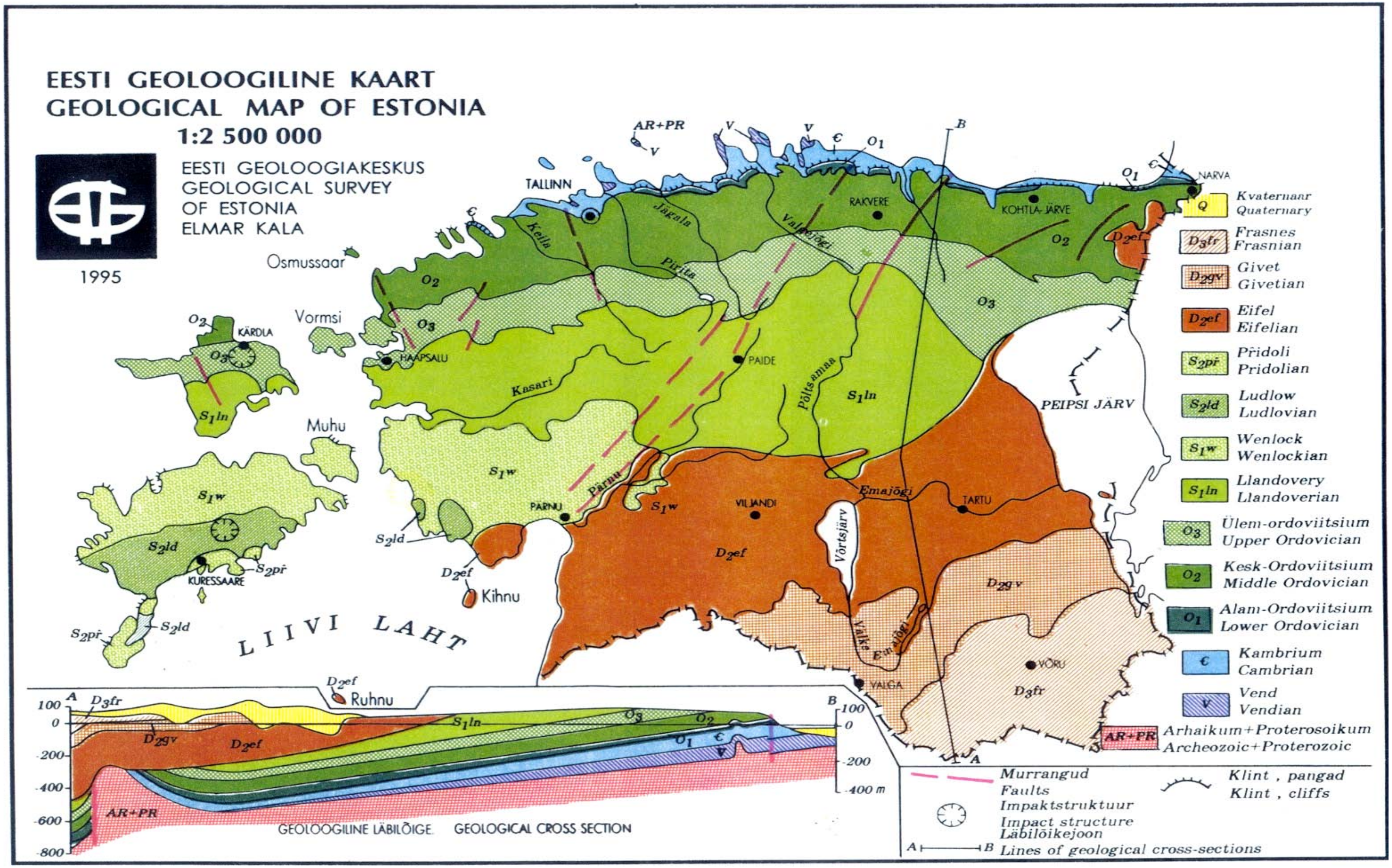
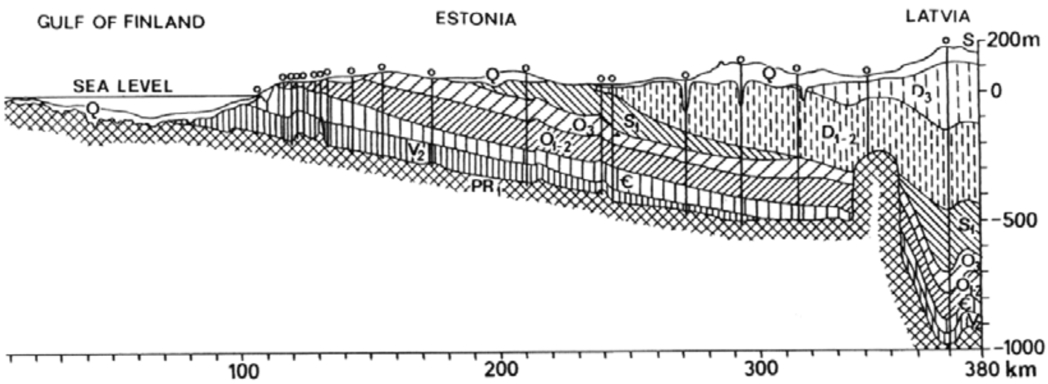


Figure 2. Geological map of the Estonian bedrock. (Eesti Geoloogiakeskus, Tallin. 1999)

Radon risk areas in Estonia, where indoor radon could create a health detriment, are found predominantly along northern coast, and are connected to soils containing fragments of Dictyonema shale and Glauconite sandstone.

Within the parts of Estonian where the bedrock consists of limestone, there exist several regions where karst formation has developed. In these regions there are frequent fractures in the limestone bedrock, and underground streams and caves formed by the weathering of the limestone. When atmospheric pressure changes occur, air is forced in and out of these underground cavities. Although the radon concentration in the air in the cavities is not more than 1,000-10,000 Bqm^{-3}, the large volumes of air that can be transported into buildings from these cavities can result in high indoor radon concentrations. The relatively high radon concentrations found in Raplamaa County may be connected with the karst in this county.



Figur 3. N-S cross-section from the Gulf of Finland through Estonia to north Latvia along a profile of boreholes. PR_1, Paleoproterozoic crystalline basement, V_3, Upper Vendian, _, Cambrian, O_{1-2}, Lower and Middle Ordovician, O_3, Upper Ordovician, S_1, Silurian, D_{1-2}, Lower and Middle Devonian, D_3, Upper Devonian, Q, Quaternary [5].

THE DESIGN OF THE NATIONAL SURVEY

In the National Survey, it was planned to carry out measurements in 550 dwellings randomly selected from the 617,400 dwellings in the whole of the Estonian housing stock. Since the survey was focused on the geographical distribution of indoor radon, only 2 or 3 houses were measured in the larger towns (Tallinn, where 1/3 of the Estonian population lives, Tartu, Narva etc.). The State Housing Register was used for selecting how many dwellings should be measured in each of the counties and in the municipalities in these counties. Lists were made giving the numbers of single-family houses and multi-apartment buildings to be investigated in each municipality. The number of the dwellings to be measured in each municipality was usually 1-3. From these lists the local public-health authorities randomly selected the houses to be measured.

The local public-health authorities visited each of the selected dwellings to put in the radon detectors. During the visit a questionnaire containing data on address, housing type, year of construction, building materials etc. was filled in by the householders. Results were obtained from 515 dwellings. For 45 dwellings, results were not received for various reasons (the detectors were lost, the measurement instructions was misunderstood etc.).

RADON MEASUREMENTS

All indoor radon measurements in the Estonian-Swedish Radon Projects were made with passive alpha-track film detectors (Figure 4). The measurements were made using CR-39 (polyallyl diglycol carbonate) alpha-track film detector material from TASL Ltd, Bristol, UK. For the measurements, the film is placed in a closed cup holder of electrically conductive plastic. These detectors were originally designed by the National Radiological Protection Board (NRPB), UK and they have been further developed by the Swedish Radiation Protection Institute (SSI) [6]. After chemical etching in a 20% NaOH solution (17 hours, etching temperature 68°C), the films were evaluated by an image analysis system using the GIPSRAD software developed by Image House a/s in Denmark. Etching and analysis of the films was done at the Estonian Radiation Protection Centre. Sensitivity calibration of the detectors was performed at SSI. The uncertainty in this method ranges from 5–10 %, the detection limit is 10 Bqm^{-}_.

The detectors were exposed during two or three month in the winter heating season. Two detectors were placed in each dwelling, usually, one in a bedroom and one in the living room. In two-storey single-family houses, one detector was placed on each level. In multi-apartment buildings the measurements were made in flats on the ground floor.

Figure 4. The alpha-track film detector used in the Estonian National Radon Survey. The detector holder on the right is open to show the plastic film used. The detector holder is closed during the measurement. Radon gas seeps into the detector through a thin slot between the lid and the bottom of the detector holder.

RESULTS

The indoor radon measurements made within the **National Radon Survey** were carried out during the heating-seasons 1998-1999; 1999-2000 and 2000-2001. A survey form was used to collect data on each dwelling measured and to form the database. Summaries of the measurements and results are presented in Tables 3 and 4.

In this survey, results were obtained from 515 randomly selected dwellings. In 67% of them, the radon level was below 100 Bqm^{-3} and in 1% of the dwellings it they exceeded 400 Bqm^{-3}. The arithmetic mean of all measurements was 95 Bqm^{-3}.

The geographical distribution of measured indoor radon levels by county and municipality is given in Figures 5, 6 and 7.

Three types of influencing factors for indoor radon levels can be seen: **geogenic**, **house-type** and **life-style related** factors. As mentioned above, geogenic factors dominate in Estonia, the main source of indoor radon being radon transported by soil air from the ground under the buildings. In the northern part of the country, some houses are built on ground containing Dictyonema shale or phosphorous-rich Glauconite sandstone, either in the bedrock or as fragments in the soil. As the previous investigations have shown, there are high-radon areas in northern Estonia – thus the higher-than-average radon levels in **Lääne-Virumaa** and **Harjumaa** were expected. In the National Radon Survey, the maximum value found in Lääne-Virumaa was 1,044 Bqm^{-3}. For this county the arithmetic mean level was 130 Bqm^{-3}. In Harjumaa, the maximum value was 475 Bqm^{-3} and the mean for the county was 115 Bqm^{-3}.

In **Raplamaa,** the maximum value found was 558 Bqm^{-3} and the arithmetic mean for the county was 203 Bqm^{-3}. These results indicate that there exist radon-prone areas in this county. The enhanced indoor radon concentrations may be due to the karst formations.

Table 3. Indoor radon concentrations in the dwellings measured in the National Radon Survey, 1998-2001. Arithmetic mean (Am), Maximum values (Max) of radon levels indoor and distribution of the indoor radon activity concentrations (%) are shown. The distributions of data in five activity concentration intervals are shown (%).

COUNTY	No. of dwellings	Indoor radon-222 concentration, Bqm^{-3}		Distribution of indoor radon-222 concentrations (Bqm^{-3}), %				
		Am.	Max.	<100	101-200	201-400	401-800	>800
Harjumaa	41	115	475	57	27	15	1	-
Hiiumaa	10	80	127	87	13	-	-	-
Ida-Virumaa	66	68	317	82	13	5	-	-
Jõgevamaa	31	76	255	74	22	4	-	-
Järvamaa	26	63	137	81	19	-	-	-
Läänemaa	30	86	174	75	25	-	-	-
Lääne-Virumaa	73	130	1,044	64	18	16	-	2
Põlvamaa	22	72	290	89	7	4	-	-
Pärnumaa	35	103	197	56	44	-	-	-
Raplamaa	33	203	558	12	52	25	10	-
Saaremaa	24	66	321	82	10	8	-	-
Tartumaa	39	100	260	61	35	4	-	-
Valgamaa	17	115	272	56	35	9	-	-
Viljandimaa	39	93	220	66	30	4	-	-
Võrumaa	29	66	227	86	11	3	-	-

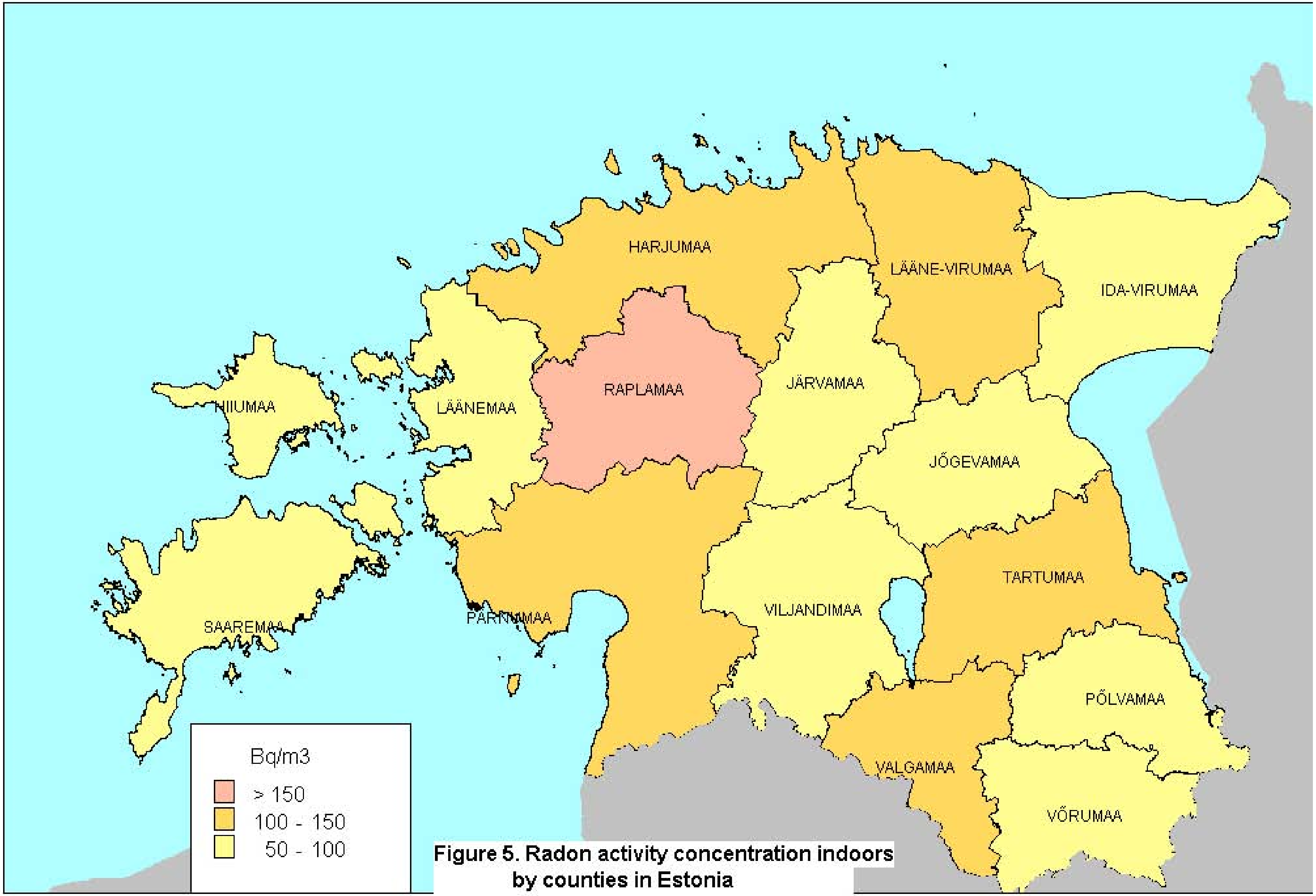


Figure 5. Radon activity concentration indoors by counties in Estonia

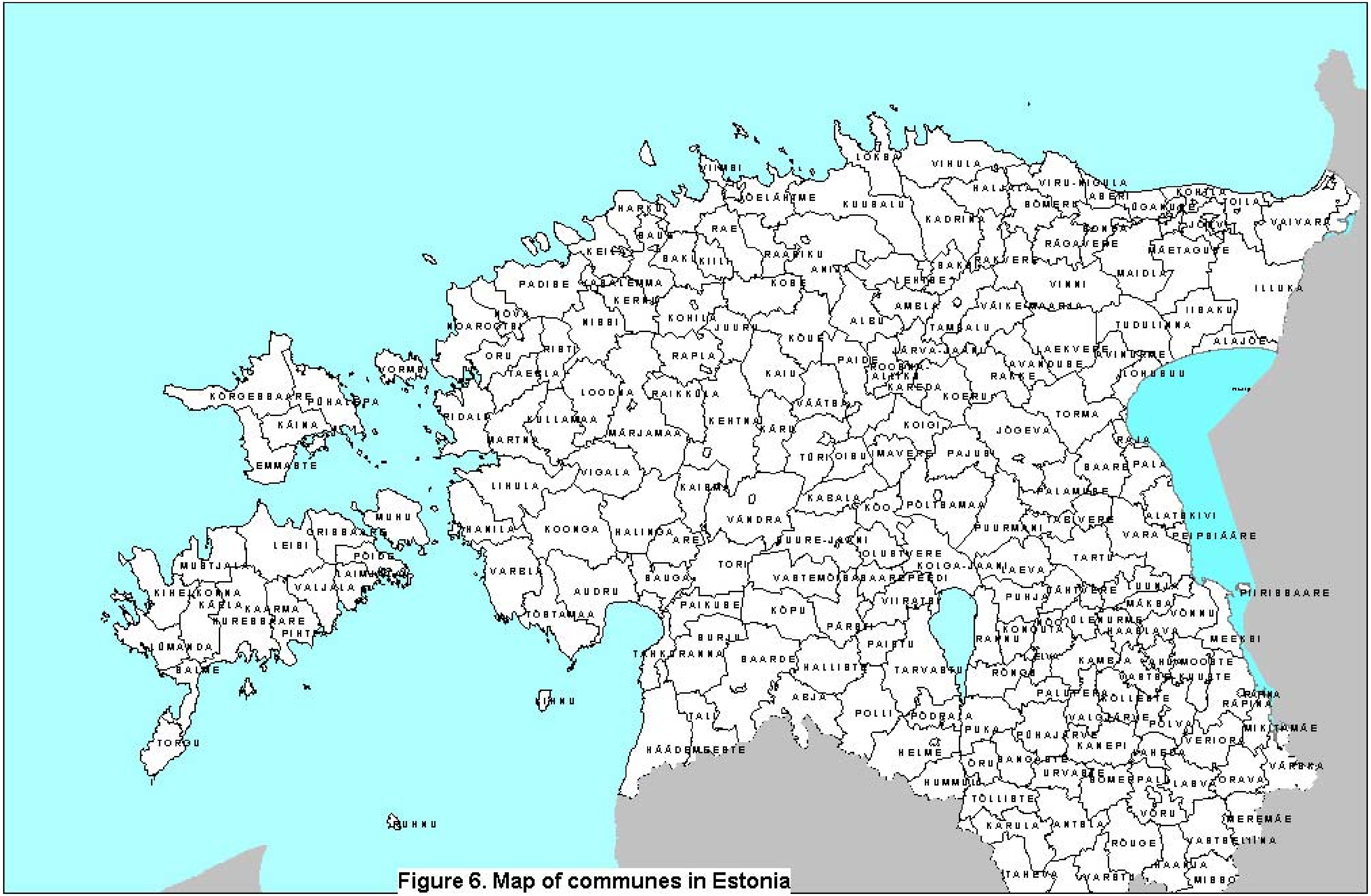


Figure 6. Map of communes in Estonia

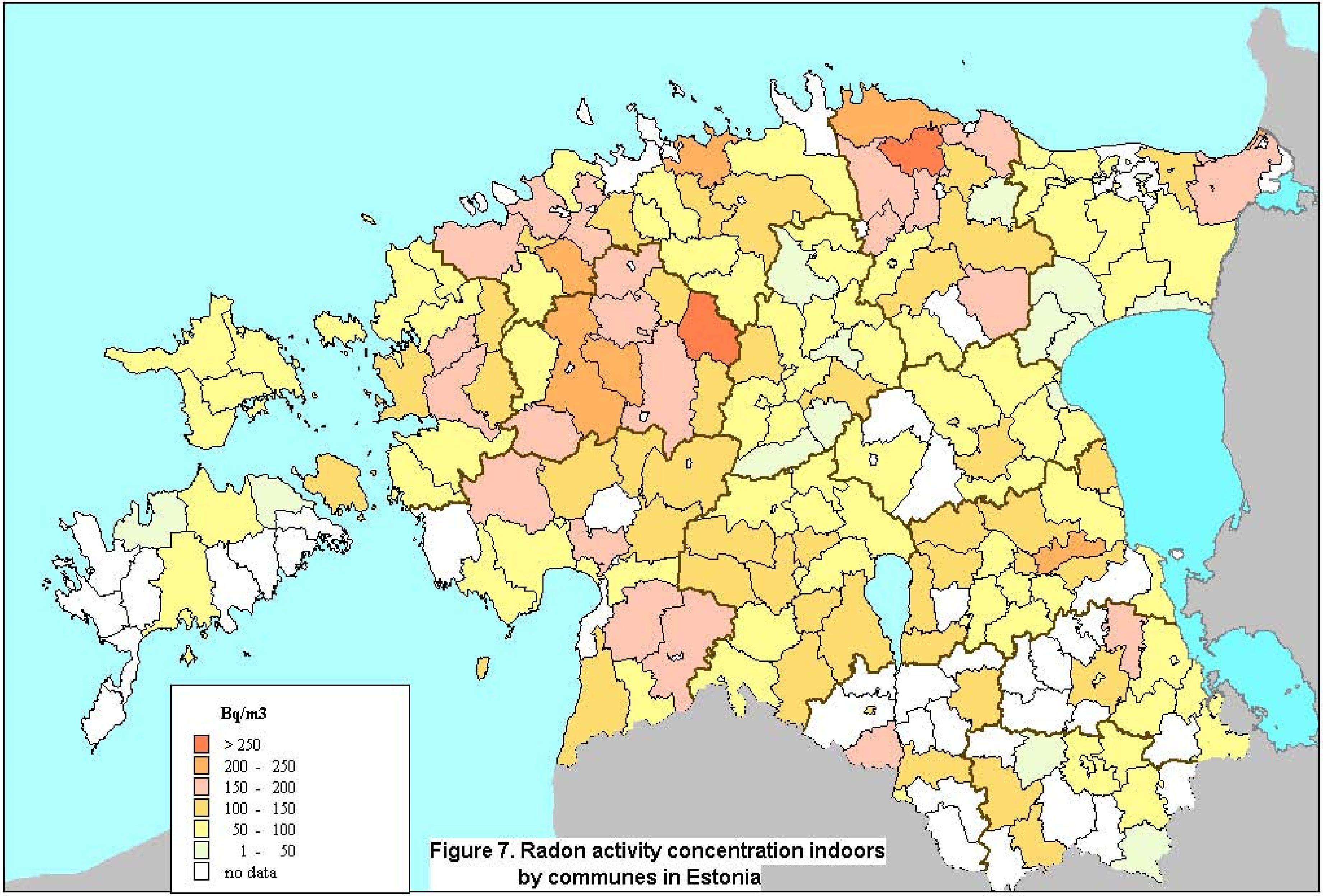


Figure 7. Radon activity concentration indoors by communes in Estonia

From the results of this survey, the conclusion can be drawn that **Hiiumaa, Läänemaa** and **Pärnumaa** counties are low-radon-risk areas, since all values found were below 200 Bqm^{-3}. These counties are situated on the west coast of Estonia where the sedimentary bedrock is covered with deposits of clay, silt and loam formed during the Baltic Glacial Lake stage. The thickness of these sediments varies from several meters to 27 meters.

Two counties: **Saaremaa**, the largest Estonian island in the Baltic Sea (2671 km^2), and **Järvamaa,** a rural area located in the central part of the country, are not considered as radon risk areas since Dictyonema shale and phosphorous-rich Glauconite sandstone are absent or occur very deep in the bedrock. The soils in these counties consist of moraine and glacial deposits of gravel, sand and clay. The thickness of the Quaternary deposits is usually 5-10 meters. However, a moderate radon risk cannot be excluded, as karst formations exist in these counties. The mean indoor radon level found in these counties were 66 respectively 63 Bqm^{-3}; the maximum value measured in Järvamaa was 137 Bqm^{-3}, and in Saaremaa 321 Bqm^{-3}.

Jõgevamaa, **Põlvamaa**, **Tartumaa**, **Valgamaa**, **Viljandimaa** and **Võrumaa** counties may, from their geological situations, be classified as normal radon risk areas.

According to previous investigations **Ida-Virumaa** county, especially the northern part, has been classified as a radon risk region. In the measurements made by EBRI in 1990, a radon gas activity concentration of 6,700 Bqm^{-3} was found in a house in Sillamäe [1], and in the first joint indoor survey (1994-1998) high levels were found in Toila (see Appendix 1). Measurements of radon in soil air were carried out in connection with the indoor radon survey in these towns. In Toila, radon concentrations as high as 140 $kBqm^{-3}$ and in Sillamäe 2,500 $kBqm^{-3}$ were measured in soils containing fragments of Dictyonema shale.

There are several geogenic factors, which can lead to an enhanced radon risk in the **Ida-Virumaa** county:

- Dictyonema shale in bedrock and fragments of this shale in soil. Just in this region the Dictyonema shale layers are more uranium-rich than elsewhere in Estonia. The mean uranium concentration in the most uranium-rich layers of the shale layers is 300 g/t (3.7 kBq $^{238}U\ kg^{-1}$), and the maximum concentration is 1,038 g/t (12.8 kBq $^{238}U\ kg^{-1}$) [7];
- Phosphate-containing glauconitic sandstone with enhanced uranium concentrations in bedrock and in soil;
- Karst in some areas;
- Deep-seated fault zones in sedimentary rocks;

As is shown in Table 3, the new measurements made in the **Ida-Virumaa** county in the frame of the National Radon Survey gave comparatively low radon values. Too low for any region to be classified as a radon risk area. These measurements were made in 66 dwellings selected randomly over the entire county, not only in the northern part, and this may have influenced the results. The results may also be connected with the types of building in which the measurements were made. Ida-Virumaa is an industrial area where 88% of the population lives in multi-apartment buildings.

The influence of the house type on the indoor radon level is shown in Table 4, where dwellings in two different house types are compared: single-family houses and multi-apartment buildings. The type of building, which is most affected by radon in all the counties, is the single-family house. The lowest levels were found in dwellings in blocks of flats.

Factors related to the life-style were not specifically studied in this survey. However, in one case in Raplamaa, in a flat in a multi-apartment building, 540 Bqm^{-3} was found in the living room and 230 Bqm^{-3} in the bedroom. This difference was due to the life-style of the single resident – the living room was not in use.

Table 4. Indoor radon concentrations in single-family houses and in flats on the ground floor in multi-apartment buildings shown by county. Results from the Estonian National Radon Survey 1998-2001 (Am = arithmetic mean, Max = maximum value).

Type of dwelling	No. of residents	No. of dwellings measured	Am, Bq/m^{-3}	Max, Bq/m^{-3}
All of Estonia				
Single-family houses	354,600	343	103	1,044
Flats on ground floor	903,600	172	78	538
Harjumaa				
Single-family houses	74,000	30	120	475
Flats on ground floor	414,200	11	100	249
Hiiumaa				
Single-family houses	5,800	8	70	127
Flats on ground floor	3,700	2	70	57
Ida-Virumaa				
Single-family houses	17,400	31	83	320
Flats on ground floor	155,000	35	58	200
Jõgevamaa				
Single-family houses	18,800	10	110	255
Flats on ground floor	15,800	21	60	126
Järvamaa				
Single-family houses	15,500	16	71	137
Flats on ground floor	19,700	10	50	115
Läänemaa				
Single-family houses	10,600	27	87	174
Flats on ground floor	15,300	3	73	89
Lääne-Virumaa				
Single-family houses	25,800	58	130	1,044
Flats on ground floor	36,000	15	80	284
Põlvamaa				
Single-family houses	17,000	8	93	290
Flats on ground floor	13,000	14	60	103
Pärnumaa				
Single-family houses	35,700	26	105	197
Flats on ground floor	46,400	9	98	170
Raplamaa				
Single-family houses	17,200	24	210	558
Flats on ground floor	17,000	9	183	538
Saaremaa				
Single-family houses	18,800	19	72	321
Flats on ground floor	13,900	5	40	129
Tartumaa				
Single-family houses	38,100	22	108	260
Flats on ground floor	92,800	17	90	218
Valgamaa				
Single-family houses	15,600	12	130	272
Flats on ground floor	17,100	5	80	124
Viljandimaa				
Single-family houses	25,700	26	100	215
Flats on ground floor	25,800	13	80	145
Võrumaa				
Single-family houses	18,000	26	63	227
Flats on ground floor	18,000	3	90	102

DISCUSSION

About 80% of Estonian dwelling houses are single-family houses, but only 30% of the population live in single-family houses. Since the State Housing Register, which was used for the random choice of dwellings to be measured, reflects the number of houses in the different counties (not the number of people living there), more measurements were made in single-family houses (66%) than in multi-apartment buildings. If the dwellings had been selected on the basis of the population distribution, most of the measurements would have been carried out in large towns and few in rural areas. However, one of the aims of the survey was to obtain data across the entire country. Thus the selection of the houses was made randomly among the dwelling houses in the different counties. It should be emphasized that the measured houses in each county were completely randomly distributed, and that the measurements were not especially directed to known radon risk areas.

In all, radon measurements were made in 515 dwellings. 172 of these dwellings were flats on the ground floor in multi-apartment buildings.

The exposure to the Estonian population due to indoor radon

The indoor radon concentrations (arithmetic mean and maximum values shown by county, type of dwelling and number of residents living in these dwellings) are given in Table 4. This Table has been compiled using the results from the 515 radon measurements that were made during the National Radon Survey.

For radon gas the arithmetic mean in single-family houses was 103 Bqm^{-3}. The activity concentration distribution is shown in Figure 8. All measurements in multi-apartment buildings in this survey were made in flats on the ground floor. Thus, the radon concentrations in multi-apartment buildings are only representative for the flats on the ground floor. In those dwellings, the average arithmetic mean value was 78 Bqm^{-3}. Figure 9 shows the activity concentration distribution in these dwellings. In flats above the ground floor, radon concentrations are much lower, normally less than 30 Bqm^{-3}. Assuming that, on average, the Estonian apartment houses have 3 storeys, 20 - 30% of the population living in multi-apartment buildings live in flats on the first floor. On this assumption, the arithmetic mean for the radon concentration in dwellings in multi-apartment buildings would be 44 Bqm^{-3}. The mean radon activity concentration for all Estonian dwellings (in single family houses and in flats in multi-apartment buildings) will be 60 Bqm^{-3}, given that the assumptions above are correct.

Using the results of the measurements performed within the National Radon Survey the radiation dose to the Estonian population due to exposure to radon was calculated. The number of residents in dwellings in single-family houses is 354,600 and in multi-apartment buildings 903,600. Assuming that the average time spent indoors is 7,000 hours per year and applying the conversion factor given by the International Commission on Radiation Protection in ICRP publication 65 [8], 0.021 millisievert (mSv) per year per Bqm^{-3} (average over 8.760 hours, equilibrium factor 0.4) the mean annual effective dose for the residents living in single-family houses is 1.7 mSv.

The mean annual effective dose due to radon for the residents in dwellings on the ground floor in multi-apartment buildings is 1.3 mSv. If we assume that the mean radon level for all flats in multi-apartment buildings is 44 Bqm^{-3}, the mean annual effective dose for persons living in multi-apartment buildings will be 0.7 mSv.

The mean annual effective dose to the whole of the Estonian population would be 1.0 mSv.

Annually, 700 new lung cancer cases are recorded in the Estonian Cancer Registry. Of all the cancer cases in the country, the majority, 21 %, are lung cancers. The health statistics show that 32% of Estonians are smokers. Smokers who are exposed to enhanced concentrations of radon have a larger risk of developing lung cancer than non-smokers.

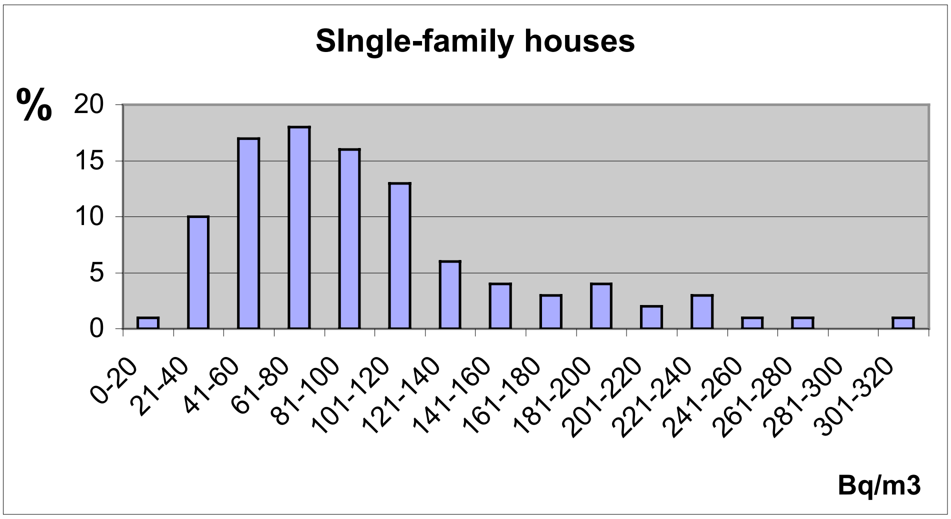


Figure 8. Distribution of radon activity concentration in single-family houses in Estonia. (The percentage of values indicated in the interval 301-320 reflects the total number of values exceeding $300 Bqm^{-3}$.)

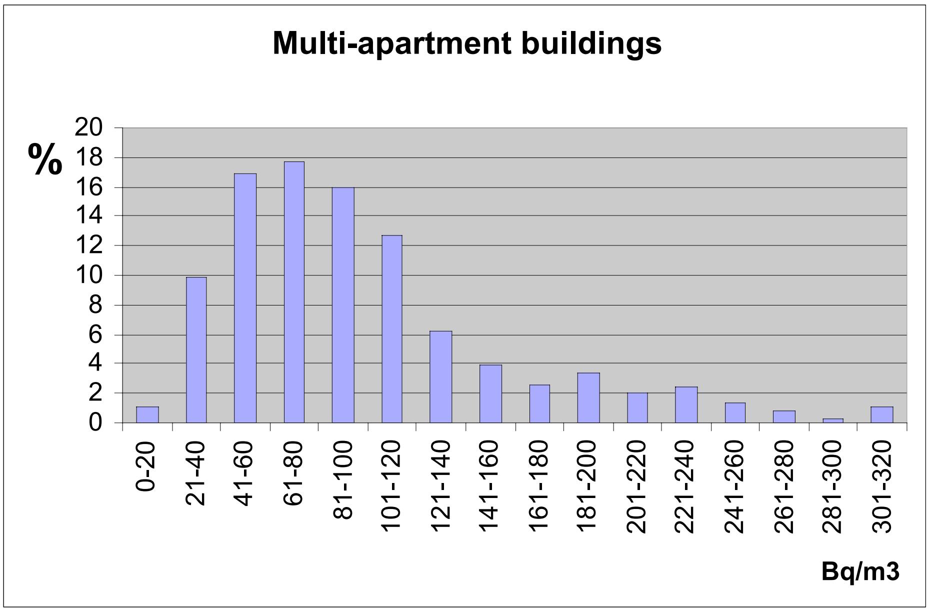


Figure 9. Distribution of radon activity concentration in ground floor flats in Estonian multi-apartment buildings. (The percentage of values indicated in the interval 301-320 reflects the total number of values exceeding $300 Bqm^{-3}$.)

Using the detriment factor $7.3 \cdot 10^{-5}$ per mSv given by the ICRP [8], our calculations indicate that about 90 Estonians (smokers and non-smokers) can be expected to develop lung cancer annually due to radon in their homes. Radon-related lung cancer cases thus would represent 13% of the total number of lung cancer cases, 700 cases, recorded annually in the Estonian Cancer

Registry. Of these radon-related lung cancer cases about 50% would live in single-family houses and 50% in multi-apartment buildings.

The ICRP based its risk assessment on studies on miners. Data from the miner studies indicate a higher excess relative risk from radon exposure for smokers than for non-smokers, but the assessment of risk for non-smoking miners is based on too small a number of cases for reliable conclusions to be drawn.

In Sweden, two large residential case-control studies have been made: *The Swedish national epidemiological radon study* presented in 1993 [9] and *Residential radon and lung cancer among never-smokers in Sweden* [10] presented in 2000. The increase of the relative risk in both studies is 0.16 per 100 Bq/m^{-3}. The studies also demonstrate a synergistic effect between tobacco smoking and radon.

In the Swedish studies the lifetime risk for radon-related lung cancer for persons who have never smoked (never-smokers) is 0.007 and for smokers 0.1 [11]. Based on these results and using the statistical distribution of indoor radon concentrations in dwellings found in the Estonian National Survey, we have calculated the number of radon-related lung cancer cases for smokers and non-smokers.

Using the Swedish results the total annual number of the radon-related lung cancers would be about 90, of which about 10 cases would be never smokers. Thus, although the health statistics give the percentage of smokers in Estonia as 32%, almost 90% of the radon-related lung cancer cases will be smokers.

Due to uncertainties in the underlying data and in the assumptions, the uncertainty in the estimated annual number of radon-related lung cancer cases is judged to be about ± 30%.

CONCLUSIONS

"Exposure to radon poses not only an important individual health risk for people exposed to elevated levels of radon, but also an important collective risk for the population. Radon exposure in dwellings is an important collective risk in comparison with many other collective risks in society, and the national radon policy should also include general recommendations to reduce the average level and thereby the collective risk of radon exposure to the population." (ICRP Publication 65) [8].

To reduce the present and future exposure to radon gas in dwellings and at workplaces, and thus the number of radon-related lung cancers, the following two actions are needed:

1) Dwellings and workplaces with radon levels in excess of the action level are to be located and remedial action against in-leakage of radon containing soil air from the ground taken.

2) In new buildings radon problems should be avoided by applying building techniques that prevent in-leakage of radon containing soil air from the ground.

Usually, intervention measures for existing dwellings are much more expensive than preventive measures taken during the construction of new dwellings. Estonian recommendations for radon in houses were issued in 1999 in the Estonian Building Code (EPN 12.2) [12], with the aim of achieving indoor radon concentrations below 200 Bqm^{-3} in all buildings (dwellings and workplaces). Estonian recommendations exist for the planning and building of radon-safe houses (EPN 12.3) [13]. However, so far the investigation and action levels have not been adopted for remedial actions in existing dwellings.

The aim of the present national survey was to provide information about indoor radon levels from the whole of Estonia using measurements in randomly chosen dwellings. The results show that there are radon problems in several parts of the country. Thus, there is a need for more information on radon-risk areas. Further surveys should be directed to the location of radon-affected dwellings. The first and most important task is to carry out radon measurements in radon-risk areas.

Radon risk mapping, or classification of radon-prone areas, based on measurements in a representative sample of the building stock combined with the use of information on geology and building construction, has been made in many countries. The results of this mapping are used in the planning of preventive action for new buildings and in the radon surveys in existing buildings to search for radon-affected houses for remedial action.

A new Estonian-Swedish Radon Project (ES605B) was started in 2002. The aim of this project is to continue the radon program in Estonia and to provide information on indoor radon for radon risk mapping. It is important for the prevention of radon-related lung cancers and for the future work on limitation of radon exposure to have more data on indoor radon levels in karst areas, in mining areas and in other regions expected be radon-prone on the basis of geological information.

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APPENDIX 1

Table 1. Indoor radon concentrations in the dwellings measured 1994-1997.

Arithmetic mean (Am), geometric mean (Gm) and maximum values (Max) of indoor radon concentrations, and the distribution (%) of indoor radon activity concentrations (Bqm^{-3}) are shown.

Area	No. of flats	Indoor ^{222}Rn, Bqm^{-3}			Distribution of indoor ^{222}Rn concentrations (Bqm^{-3}), %				
		Am	Gm	Max	<100	101-200	201-400	401-800	>801
Tallinn	161	63	30	630	90	7	2	1	-
Kunda-94	50	151	91	1,223	54	28	8	8	2
Kunda-95*	28	234	142	1,392	43	21	14	18	4
Kunda-96*	12	3,983	1,364	12,421	12	13	-	8	67
Kunda-97*	10	973	474	3,500	20	5	15	15	45
Aseri	42	91	57	526	62	31	2	5	-
Rakvere	78	68	47	499	69	21	9	1	-
Toila	46	361	260	878	11	17	35	35	2
Paldiski	14	163	85	769	43	29	14	14	-
Vooremaa	28	97	80	263	57	41	3	-	-
Raasiku	29	106	76	471	64	21	12	3	-
Narva	51	95	68	466	73	13	12	2	-
Kuusalu	10	46	44	69	100	-	-	-	-

*These houses were not selected randomly.

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