Abstract. The first large-scale survey of radon concentrations in Norwegian dwellings was undertaken in the period 1984-86. This survey was the beginning of the Norwegian radon mapping and remediation program. In the period between 1986 and 2002 several large-scale surveys (approximately 70,000 measurements) were undertaken. In 1999 a state subsidize was established which covers up to 75% of the mitigation costs if the annual mean radon concentration in living room or bedroom exceeds 200 Bq/m$^3$. In the range between 200 and 400 Bq/m$^3$ it is recommended that simple and low cost measures are considered, only. The upper level for new dwellings is 200 Bq/m$^3$. So far, approximately 1500 existing houses have been mitigated. For radon in household water the recommended action level for private wells is 500 Bq/l, while it is 100 Bq/l for waterworks (more than 20 households), as stated in the Norwegian Drinking Water Regulations. The radon mapping strategy for existing dwellings is divided into two phases. The objectives of the initial survey (phase I) is to get an overview of the problem and to identify radon prone areas. The measurements are made by CR-39 etched track detectors and the sample size varies between 10% of the housing stock in rural areas to 2% in the most densely populated areas. The follow-up strategy (phase II) is based on the results of the initial survey. In areas where more than 20% of the measurements exceeds 200 Bq/m$^3$ it is recommended that all dwellings are measured; between 5 and 20%, follow-up measurements are based on information from the questionnaires; and no further surveys are recommended if less than 5% exceeds 200 Bq/m$^3$ and no results are above 400 Bq/m$^3$.

1. Introduction

In Norway, indoor radon concentrations are among the highest in the world. This is partly be explained by the geology due to the large occurrences of radium rich soil and bedrock (e.g. alum shale and uranium rich granites), and highly permeable unconsolidated sediments (e.g. moraines and eskers) and the construction of buildings due to the cold climate. An additional factor is that most single family houses have a living area in the basement which is partly below the ground level and the extensive use of highly permeable light expanded clay aggregates in the foundation construction. Studies have revealed that the entry of radon from the building ground is the dominant source of indoor radon in Norwegian dwellings. Norwegian dwellings are primarily made from wooden materials, and concrete and brick manufactured in Norway have low levels of radium. Therefore, building materials is not an important source of indoor radon. Since nearly 80% of the population is supplied by water from surface water sources, the average contribution to indoor air from household water is very low. However, in households with their water supply from deep drilled wells in uranium rich granites the household water is sometimes the important source of elevated radon levels in indoor air.

Indoor exposure to radon and its progenies is assumed to be the second most important risk of lung cancer, representing 5-15% of the total annual number of approximately 2000 lung cancers in the Norwegian population [1]. When high radon levels occur in dwellings, the individual risk of lung cancer is sometimes higher than most other risk factors in society. The first step in controlling radiation exposures, including radon, is to determine the extent of the problem by performing surveys. It is then possible to develop optimum strategies to limit exposures. This involves setting action levels for domestic and/or occupational radon exposure. According to the Norwegian definition, the investigation level is the concentration of radon above which assessments of remedial costs should be made and remedial measures to be considered. The action level is the concentration of radon above which remedial measures should be undertaken [2].

NRPA has carried out several municipal radon mappings in cooperation with the Municipal Health Services. These surveys have been based on a recommended strategy for municipal surveys developed by NRPA [3]. The results of theses surveys have been published in the NRPA Report Series [4,5,6,7]. The municipal reports are available on the NRPA Radon Website: http://radon.nrpa.no.
2. Recommendations and regulations

The recommended investigation level and action level for radon in existing dwellings are 200 and 400 Bq/m$^3$, respectively [1]. Remedial measures in dwellings should be considered when the annual mean radon concentration in the living area exceeds 200 Bq/m$^3$. Simple and low cost measures are recommended in houses where the mean radon concentration ranges from 200 to 400 Bq/m$^3$. If the radon levels exceed 400 Bq/m$^3$, remedial measures should be undertaken with the aim of bringing the radon concentration below 200 Bq/m$^3$. Remedial measures should be cost-effective, but measures are highly justified at levels above 400 Bq/m$^3$, even if they are both extensive and expensive.

Radon is not only a problem in dwellings, but also in workplaces. Remedial measures at aboveground workplaces should be considered when the annual mean radon concentration during working hours exceeds 400 Bq/m$^3$, the same action level as for existing dwellings [2]. Aboveground workplaces include office buildings, factories, schools, kindergartens, etc. The action level for radon in underground workplaces is 1000 Bq/m$^3$ averaged over 2000 hours per year. The level can be increased if the occupancy is shorter but the total exposure should not exceed 2 MBq h/m$^3$ [8]. Underground workplaces where radon concentrations may require supervision include mines, tunnels, underground hydroelectric power stations, underground defense installations, subways, show caves and tourist mines, and underground water treatment works and stores.

Preventive measures in new buildings are less complicated and cheaper than remedial measures in existing buildings, and for this reason a lower reference level is justified based on cost-effect analysis. The general recommendation is that preventive measures should be introduced with the aim of bringing the levels in new buildings as low as reasonably achievable and with the overall goal that the average concentration in the future housing stock should become significantly below the annual average of 88 Bq/m$^3$ in the present Norwegian housing stock. New buildings include dwellings and above ground workplaces and other buildings utilized more than temporarily. The Norwegian Building Regulations says that the planning and construction of new buildings shall be carried out in such a way that the indoor exposure to radon does not represent an enhanced health risk. The upper level for radon in new buildings is 200 Bq/m$^3$ [1].

According to the Norwegian Drinking Water Regulations the level of radon in household water from waterworks (more than 20 households) shall not exceed 100 Bq/l. For private wells the recommended action level is 500 Bq/l [9].

According to the Municipal Health Services Act, the municipalities are responsible for obtaining an overview of factors which directly or indirectly represents a health risk. Radon is covered by this Act and its regulations. The responsibility of the Municipality Council is to identify radon prone areas and to consider potential radon problems in developing new areas.

3. Radon measurements

In accordance with the Norwegian guidelines for radon measurements [13], assessment of indoor radon concentrations should be based on direct integrated measurements, only. Indirect measurements (geological samples, soil gas measurements, external gamma-radiation, etc.) and results of indoor measurements in the neighbourhood are not suitable for making decisions on the need for remedial measures.

Owing to short-term variations in the indoor radon concentration it is recommended that the integration time should be at least two months and that measurements should be restricted to the heating season [10]. Action levels refer to an annual mean concentration of radon. Indoor concentrations are generally higher in the winter than in the summer, and it is therefore necessary to apply some correction factors in order to convert the result of each measurement to an annual mean concentration. Based on an earlier nation-wide survey in approximately 7500 randomly selected
dwellings distributed over a period of two years, it was found that the mean concentration during the winter is very close to twice the mean level in the summer [11]. It was therefore recommended that measurements during the heating season should be multiplied by a factor of 0.75 for the assessment of annual average. It is further recommended that measurements should be undertaken in at least two different rooms with an average occupancy of more than six hours per day. Rooms in this category are living room and bedroom. However, only one measurement was made in each dwelling in the large-scale municipal surveys undertaken by NRPA between 2000 and 2003. The main objectives of these surveys was to identify radon prone areas and to develop radon risk maps for each municipality, and one measurement in each dwellings was considered to be a better strategy than two measurements in half as many dwellings. If only one measurement is made in the dwelling it is strongly recommended that at least two follow-up measurements are made before extensive and expensive remedial measures are carried out.

Generally, Norwegian dwellings have a higher radon concentration on the floor which is in direct contact with the ground than on higher floors. If dwellings have rooms with occupancy of more than six hours on the ground floor or basement floor, it is recommended that one of the detectors should be placed there. In order to reflect the mean radon level under normal circumstances, the house should be inhabited and the ventilation conditions should be as normal as possible during the measurement period.

Most of the measurements in dwellings in Norway have been made by CR-39 etched track detectors provided by the Radon Laboratory at NRPA. The detector holder is of the NRPB/SSI design and consists of antistatic material. The etching takes place in 20% NaOH at a temperature of 90º C for 2 hours and 45 minutes. The track counting is automatic and the equipment and software are of same type as developed by Gammadata Mätteknik AB in Sweden. NRPA has been one of the top listed laboratories in the last annual NRPB intercomparisons [12]

The etched track detectors are distributed to the house owner by mail in a sealed aluminium coated envelope and are returned back to NRPA in a pre-stamped envelope after two month. The house owner is asked to fill in a questionnaire which should be returned together with the detectors. In addition to personal data, the date when the exposure started and ended, type of room, floor, ventilation system and airing of the rooms where the detectors were placed, the house owner is asked to answer some key questions about the type of building, year of construction, ventilation system, heating system, building materials, basement construction, earlier radon measurements, water supply, etc. The data in the questionnaire are recorded in the Radon Database at NRPA, which today includes data on nearly 60,000 buildings.

The measurements of radon in drinking water are performed by liquid scintillation counting. The water samples are prepared at the site by drawing 10 ml of water from the tap into a glass syringe and then transferred to a standard 20 ml glass vial pre-filled with 10 ml of scintillation liquid. The vials are then immediately sealed. In order to get fresh water from the well, the tap should be turned on for at least five minutes or until the water pump starts, before the samples are taken. The samples are collected by the local health authorities and counted at NRPA. In the period from 1996 to 2003 approximately 4000 water samples have been analyzed at NRPA by this method.

4. The radon information and remediation program

Several extensive publicity campaigns on radon have been carried out in the period 1998-2003. The objectives of the campaigns have been to improve radon awareness amongst the general population and encourage house owners to carry out radon measurements in their own dwelling, and to remediate high radon levels. As part of these campaigns, a short information video on radon was produced in 2001. This video was sent several times during commercial breaks on Norwegian television in the autumn of 2001 and the spring of 2002. In 2003, an offensive directed towards homeowners with radon measurements above the action level was carried out. Based on data in the NRPA database, information material was sent to approximately 5000 house owners. The objective was to encourage them to carry out remedial measures.
Some of the campaigns have been directed towards municipal personnel and contractors, including printed material and training courses. In cooperation with the National Office of Building Technology and Administration, Norwegian Building Research Institute and NRPA a training course on radon mitigation methods for existing and new buildings was developed. The course has been directed towards contractors, consultants and technical municipal personnel to be involved in remedial measures. The course give a detailed description of radon sources, measurement techniques, radon mitigation methods for existing buildings and preventive measures for new buildings, and do also include general information about radon, health risk, and Regulations.

The information material includes some booklets in the NRPA Radiation Protection Series:

- *Methods for measuring radon in indoor air and construction sites* (no. 3) [13]
- *Action levels for radon in indoor air and underground workplace* (no. 5) [9]
- *Health risk, measurements and mitigation* (no. 9) [1]
- *Municipal indoor radon survey projects, design and accomplishment* (no. 17) [3]
- *Fact sheets - Radon* (no. 18) [14]
- *Radon in underground workplaces* (no. 23) [8]

The booklets are displayed at the NRPA radon web site together with general information on radon and results of radon surveys. Two booklets are in preparation: 1) *Radon in household water* – with general information on radon in household water, results of surveys and technical mitigation techniques, and 2) *Radon in kindergartens and schools* – with results of surveys and remedial measures.

In 1999 a state subsidize for remedial measures in existing dwellings was introduced as part of the National Action Plan against Cancer in Norway. At the beginning, the state subsidize covered 50 % of the mitigation costs if the annual mean radon concentration exceeded 400 Bq/m³, with a maximum contribution of 15,000 NOK (~1800 EUR). In the autumn 2002 the criteria for subsidize was changed to cover up to 75 % of the costs if the level exceeds 200 Bq/m³. The maximum contribution was increased to 40,000 NOK (~4800EUR). The changes of the criteria have, in combination with the publicity campaigns, led to a considerable increase in the number of remedial measures. By January 2004, approximately 1500 houses have been mitigated as part of this state subsidize. The total costs have been 23 mill NOK (~2.8 mill EUR), which correspond to an average contribution per households of 16.000 NOK (~1900 EUR).

5. The radon mapping strategy

With the exception of some of the valleys and the lower areas in the eastern of the country, Norway is sparsely populated (15 persons per km² [15]). Owing to the low population density, it is sometimes almost impossible to identify radon prone areas in the most rural areas based on measurements in a small sample of the housing stock. In developing an optimized sampling strategy, it is therefore necessary to increase the sample density in the rural areas on behalf of the most densely populated municipalities.

There are nearly 2 millions dwellings in Norway. According to data from Statistics Norway [16], about 57 % of the housing stock is single family houses; 21 % is undetached houses (13 % vertically and 8 % horizontally separated dwellings), and 18 % and 4 % of the dwellings are in blocks of flats and other types of buildings, respectively. In Oslo nearly 70 % of the population are living in blocks of flats. The radon level in flats on the second floor or higher is generally very low and should not be included in a municipal survey sample.

Several municipal radon mappings have been undertaken in cooperation with NRPA involving measurements by etched track detectors in a sample of the housing stock. The main objectives of these mappings have been to obtain an overview of the distribution of indoor radon concentrations, and to identify radon prone areas. The mapping strategy is described in more detail in NRPA Radiation Protection series no. 17 [3]. In the initial survey (phase I), the sample size varies between 2 % of the
housing stock in the most densely populated areas to more than 10% in the rural areas. Classification of the results is shown in Table 1.

In Norway, every building is identified with a unique set of three numbers; one number for the geographic area, one for property, and one for building. An example: 55, 12 and 140336424 are numbers for area, property and building, respectively. Based on these numbers, a set of GIS coordinates is given. X- and Y-coordinates are connected to the measured radon concentration in each dwelling, and a point map is worked out based on the data. Two examples of point maps are shown in Figure 1 and 3. In the most sparsely populated areas it is sometimes possible based on these maps to visually identify the exact location of the houses. According to an agreement with home owners such information should not be published officially.

Different methods for preparing radon risk maps based on the Phase I indoor measurements have been evaluated. Methods used in other countries, e.g. in Finland and Ireland [17,18], have been studied. The method, by using a National Grid System and making measurements in a sample of randomly selected dwellings in each fixed square, is not suitable for the most sparsely populated areas of Norway.

Radon risk maps for each municipality are made by using a simplified method. The size of grid squares varies from 0.5 to 5 km depending on the density of houses. This is a compromise between the need for a sufficient number of results within each area and the problem of characterizing the risk in the most rural areas where there are very few or no measurements at all. The minimum number of measured dwellings required for characterizing an area varies between 5 and 20 for the High-risk and Moderate-risk/Low-risk areas, respectively. Areas where more than 20% of the measurements exceed 200 Bq/m³, are defined as High-risk areas. In these areas it is recommended that all dwellings are measured. No further surveys are recommended if less than 5% exceed 200 Bq/m³. In areas where 5 to 20% of the measurements are higher than 200 Bq/m³, follow-up surveys are recommended based on additional information from the questionnaires – e.g. type of dwelling, year of construction, use of light expanded clay aggregate blocks in the foundation wall, etc. Based on this approach, simplified radon risk maps have been prepared for several municipalities. These maps and reports are available on Internet http://radon.nrpa.no.

<table>
<thead>
<tr>
<th>Table 1: Classification of areas based on the results of Phase I</th>
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<tbody>
<tr>
<td>Category</td>
</tr>
<tr>
<td>High-risk area</td>
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<tr>
<td>Moderate-risk area</td>
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<tr>
<td>Low-risk area</td>
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The need for and the size of follow-up measurements and surveys (Phase II) depend on the analysis of the results of the Phase I survey, including both the results of the measurements and information from the questionnaires. Results of earlier surveys show that the most important information is the type of dwelling, year of construction, and the type and construction of the basement. Example: 10% of the dwellings in an area have radon concentration exceeding 200 Bq/m³ and the area is characterized as Moderate-risk area. 25% of single family houses built between 1975 and 1995 have radon concentrations above 200 Bq/m³. The follow-up strategy could then be to carry out measurements in all single family houses built between 1975 and 1995, while general information is recommended in the remainder of the municipality. In other areas, the analysis of the data and follow-up measurements could be based additional information on geology.
In Figure 1, a point map for a municipality in one of the densely populated areas is shown. The circles indicate measured dwellings and the triangles all dwellings in the municipality. The municipality has a population of approximately 50,000 and an area of 100 km$^2$ and the sample consisted of nearly 3% of the housing stock. In this municipality, it is possible to characterize risk areas covering most of the municipality, see Figure 2. In Figure 3, a point map in a rural area is shown where the sample consisted of 10% of the housing stock. In this municipality, it is more difficult to work out a risk map based on the results of the Phase I survey.
6. Large scale radon surveys in Norway

Several large scale radon surveys in dwellings have been undertaken in the period from 1984 – 2003. Table 2 gives an overview of the number of dwellings, the mean concentration and the percentage above 200 Bq/m³.

Table 2: Surveys of radon in indoor air

<table>
<thead>
<tr>
<th>Period</th>
<th>Number of dwellings</th>
<th>Numbers of municipalities</th>
<th>Organized by</th>
<th>Mean annual radon concentration (Bq/m³)</th>
<th>Percentage above 200 Bq/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>1984-1986</td>
<td>1,600</td>
<td>79</td>
<td>NRPA</td>
<td>80-100</td>
<td>10</td>
</tr>
<tr>
<td>1987-1989</td>
<td>7,530</td>
<td>All</td>
<td>NRPA</td>
<td>55-65</td>
<td>5</td>
</tr>
<tr>
<td>1990-1998</td>
<td>5,000</td>
<td>31</td>
<td>NRPA</td>
<td>115</td>
<td>&gt;10</td>
</tr>
<tr>
<td>2000-2001</td>
<td>29,000</td>
<td>114</td>
<td>NRPA</td>
<td>89</td>
<td>9</td>
</tr>
<tr>
<td>2002-2003</td>
<td>8,400</td>
<td>44</td>
<td>NRPA</td>
<td>150</td>
<td>18</td>
</tr>
<tr>
<td>1988-2003</td>
<td>20,000</td>
<td>-</td>
<td>Others 1)</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

1) Measured by private companies on commercial basis.

The first large scale survey of radon concentrations in Norwegian dwellings was undertaken in the period 1984-86. The survey involved 1600 dwellings in 79 municipalities from different parts of the country. In each municipality 20 dwellings were selected. Two measurements were made in each dwelling, in living room and bedroom. The measurements were performed by a method based on termoluminescence detectors in charcoal and the integration time was between 5 and 7 days. The annual mean radon concentration in these municipalities was calculated to 100 Bq/m³ [4].

A nationwide survey was undertaken in the period 1987-89. Measurements of radon by using CR-39 etched track detectors were made in a total of 7,500 dwellings. The dwellings were randomly selected and the number of dwellings in each municipality was proportional to its population. Only dwellings build before 1980 were involved in the survey. One detector was placed in the main bedroom in each dwelling for six months and the detectors were spread evenly over all seasons of the year for each
municipality. Based on this study the mean radon concentration in Norwegian dwellings was estimated to be in the interval from 55 to 65 Bq/m$^3$ [5, 19].

In the period 1991-1998 municipal surveys of radon were undertaken in 31 municipalities which cover about 6% of the population. The measurements were made by CR-39 etched track detectors and one or two detectors were placed in bedroom and/or living room in each of the approximately 5,000 dwellings for a period of two to three months in the heating season. The population weighted annual average radon concentration in these municipalities was 115 Bq/m$^3$ [20].

In the heating season 2000/2001 29,000 measurements were undertaken in the project Radon 2000-2001. In this survey 114 out of 435 municipalities in Norway participated. In each municipality measurements were performed in between 2% and 10% of the housing stock. The measurements were made by etched track detectors (Cr-39), one in each dwelling. The population weighted annual mean radon concentration was calculated to 89 Bq/m$^3$. 9% and 3% of the dwellings had higher levels than 200 and 400 Bq/m$^3$, respectively [6]. By comparing these results with the results for the same municipalities in the nationwide survey 1987-89, it was concluded that the average concentration in the present housing stock is 75% higher than twenty years ago. This could be explained by three factors; 1) due to a campaign for saving energy which started after the energy crises in the seventies, a large proportion of homes have been retrofitted and new homes have been made more energy efficient by reducing air exchange rate, 2) an extended use of highly permeable light expanded clay aggregate blocks in the foundation wall has which has increased the influx of radon soil gas, and 3) more homes have living room and bedroom on the ground floor or the basement and thereby increased to occupancy in rooms with higher radon concentrations.

In the heating season 2002/2003 radon measurements were made in additional 8,400 dwellings in the project RaMap. 44 municipalities were selected from the approximately 270 municipalities which at that time had not performed municipal surveys of radon. The selection was based on available data from earlier measurements of radon in dwellings, kindergartens, schools and groundwater, combined with information on geology. An individual sampling strategy was developed for each of the municipalities; the number of measurements in the most densely populated areas was reduced in favor of the most rural areas and moraines/eskers, and the primary objective was to identify radon prone areas. The measurements were performed using CR-39 etched track detectors, one detector in the living room or bedroom in each dwelling. The integration time was two months during the heating season. Annual mean values were calculated for each municipality. The results are not strictly comparable to the results from Radon 2000-2001 owing to different sampling strategy. In 10 municipalities the mean value of the measurements exceeds 200 Bq/m$^3$ [7]. The highest concentrations were measured in dwellings on eskers. In some of these areas more than 50% of the results exceed the action level of 200 Bq/m$^3$. The highest single value was 18,000 Bq/m$^3$, and this house was located on an esker in the south-western part of southern Norway. 18% and 7% of the results were found to be above 200 Bq/m$^3$ and 400 Bq/m$^3$, respectively, compared to 9% and 3% for the whole country. This demonstrates that the mapping strategy was successful. A more detailed presentation and discussion of the results of Radon 2000-2001 and RaMap will be published later.

It is estimated that approximately 20,000 measurements have been performed on commercial basis by private companies in the period between 1988 and 2003. Most of these data are not included in the NRPA radon database.

During heating seasons from end of 1996 to 1998 a large-scale radon survey in Norwegian kindergartens was undertaken. 3660 kindergartens were measured, corresponding to about 2/3 of the kindergartens in the country. In addition about 1500 school buildings have been measured. The results show radon concentrations at the same level as in homes [21]. Most of the kindergartens and schools have mechanical ventilation systems. Usually, the systems are turned off during the night and during weekends, and this has to be taken into consideration in the assessments of exposure and need for remedial measures [21,22]. Most of the kindergartens and schools with radon concentrations exceeding the action level have been mitigated. [23]
Surveys of radon in underground workplaces in Norway have been undertaken, and exposure in different underground environments has been estimated [24].

About 20% of Norwegian households have their water supply from groundwater sources, and nearly half of these are drilled wells in bedrock. 15% of these households are exceeding 500 Bq/l [25, 27]. The maximum value of 33,000 Bq/l and the highest proportion exceeding the action level of 500 Bq/l was measured on samples from deep drilled wells in radium rich granites located in the south eastern part of the country. Samples from the 33 largest waterworks based on groundwater show a mean level of 88 Bq/l, and no single results exceeding the action level for waterworks of 100 Bq/l [26].

7. Conclusions

Based on the results of several large-scale surveys in Norway it is estimated that 9% of the present housing stock (175,000 dwellings) has an annual mean radon concentrations exceeding 200 Bq/m$^3$ [6]. So far, only 8000 of these dwellings have been identified by making indoor measurements in approximately 70,000 dwellings, corresponding to 3.6% of the total Norwegian housing stock, and approximately 1500 houses have been mitigated. Nearly 200 of the 435 municipalities have carried out phase I radon surveys in accordance with the NRPA recommendations. The results of these surveys show that there are significant geographical variations, both between municipalities and within each municipality. However, it is sometimes difficult or almost meaningless to prepare radon risk maps in some of the most sparsely populated areas. In some of the most affected area more than 50% of the results exceed the recommended investigation level of 200 Bq/m$^3$, and some very high values (above 2000 Bq/m$^3$) have been measured in a significant number houses on highly permeable moraines and alum shale. The highest single measurement so far corresponds to annual mean radon concentration of nearly 30,000 Bq/m$^3$. In other areas less than a few percent of the results exceed the investigation level and no values were higher than the action level of 400 Bq/m$^3$. In these municipalities, no further surveys are recommended.

Future surveys will focus on the municipalities which not yet have carried out phase I surveys and on follow-up surveys (phase II) in the most affected areas. The governmental subsidize for remedial measures ended in 2003 and an extension of this arrangement will depend on the results of an ongoing evaluation of the remediation work undertaken in the five year period 1999-2003.

References