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Factors influencing microbiological quality of groundwater from potable water supply wells in Norwegian crystalline bedrock aquifers

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Abstract

Gaut, S., 2005: Factors influencing microbiological quality of groundwater from potable water supply wells in Norwegian crystalline bedrock aquifers. Doktor Ingeniør thesis 2005:99. Department of Geology and Mineral Resources Engineering, NTNU, 153 pp and appendices.

Microbiological analyses from 195 Norwegian waterworks based on groundwater in bedrock have been examined to study the vulnerability of bedrock wells to microbiological contamination. Inspections have been carried out at 49 of the 195 waterworks to identify possible causes to the recorded microbiological contamination. It is found that groundwater derived from bedrock wells is susceptible to microbiological contamination and needs better protection. Seasonal variations in the water quality occur. Coliforms are mostly detected from June to September. *Cryptosporidium*, but not *Giardia*, is detected in the groundwater from three of twenty waterworks. The microbiological water quality is correlated to (i) wellhead completion (including the well casing), (ii) type and thickness of superficial deposits, (iii) land use and contamination sources and (iv) distance from wells to running water. Recommended wellhead completion includes a well-house and a casing of at least 5.5 m, rising 40-50 cm above ground. The gap between casing and bedrock should be sealed. Wells are least vulnerable to microbiological contamination when the superficial deposits are > 2.5 m thick and the wells are located > 100 m from farmland and not within 75-125 m of running water. Variations in parameters, such as colour, turbidity, and iron, and high levels of total organic carbon can indicate that the aquifer or the well is vulnerable to microbiological contamination. Vulnerability mapping combined with a hygienic evaluation of the well area and delineation of protection zones based on simple analytical methods is suggested as a method to protect Norwegian bedrock wells.

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Summary

Previous to and parallel with Norwegian membership in the European Economic Agreement (EEA) investigations of the water quality at Norwegian waterworks showed that about 1000 of the 1587 waterworks registered in the National Waterworks Register (VREG) in 1994 did not supply water with a satisfactory quality. To improve the water quality the Program for Improved Water Supply (PROVA) was initiated in January 1995.

One of the main objectives of PROVA has been to initiate increased use of groundwater, as it is generally regarded that groundwater is better protected against contamination than surface water. Today groundwater only contributes to about 15 % of the drinking water in Norway.

Many of the small waterworks and private houses in Norway use groundwater derived from bedrock where there is little emphasise on water quality. Information from the Norwegian Institute of Public Health (NIPH) and various departments of the former Norwegian Food Control Authority (SNT) indicate bacterial contamination in many of these groundwater wells. As a consequence NIPH considers requiring obligatory disinfection of drinking water from all waterworks supplying water from bedrock wells.

VREG has until 2004, constituted the only regular collection of microbiological data from waterworks in Norway. Key statistics are presented in annual reports from VREG. The reports state the number of waterworks based on groundwater from bedrock, but water quality is not presented separately for these waterworks. The microbiological water quality for these waterworks has therefore not been evaluated earlier.

The aim of this thesis is to study the vulnerability of groundwater wells in bedrock to microbiological contamination with the following objectives:

a) Assess factors influencing the microbiological quality and how they influence on each other. Evaluate specifically how the well design affects the microbiological water quality
b) Assess the use of protection zones in Norway and their significance for the microbiological water quality

Based on these assessments advice on well construction and location is given and improvements of the method for designing protection zones in Norway are suggested.

Microbiological analyses were collected from local departments of the former SNT for 195 waterworks in Norway. This dataset is used to get an overview of the extent of microbiological contamination and to examine seasonal variations in microbiological water quality in Norwegian groundwater wells in bedrock in the period 1996-98. To be able to evaluate improvements of microbiological water quality at the 195 waterworks in this study, additional microbiological data were collected from VREG, laboratories of the former SNT or from the waterworks for the period 1999-2003.

Cryptosporidium and *Giardia* are considered a problem in groundwater in both the USA and UK, however little is known about the existence of these parasites in Norwegian groundwater. To investigate the occurrence of these parasites in water from bedrock wells, raw-water was sampled from 20 waterworks. Wells close to risk areas like farming and septic tanks were chosen due to the fact that animal and human fecal matter are sources of the parasites.

Field inspections were carried out at 49 of the 195 waterworks during the summer/ autumn 2000 and 2001 to identify possible causes of the reported microbiological contamination. Factors influencing the microbiological water quality were evaluated and their mutual relationship was examined. The main factors evaluated are:

- Design and protection of the well
- Thickness and extension of superficial deposits in the well area and location relative to the occurrence of marine sediments
- Land-use around the well
- Possible sources of contamination
- Distance from surface water

Correlation between microbiological and physio-chemical water quality were examined for 63 wells. The physio-chemical parameters evaluated are electrical conductivity, pH, turbidity, colour, alkalinity, chloride, nitrate, manganese, iron and total organic carbon.

The main findings from this study can be summarised as follow:

1. Groundwater derived from bedrock wells is susceptible to microbiological contamination and needs better protection. However, improvements in the microbiological water quality have occurred at a few waterworks from the period 1996-98 to 2003.
2. Seasonal variations in the microbiological water quality occur. Coliforms are mostly detected from June to September, which correlates with the time period of manure spreading on farmlands in Norway.
3. There are waterworks supplying untreated water derived from bedrock meeting the requirements in the Norwegian Standard for Drinking Water quality (NSDW). Consequently disinfection for everyday use does not need to be obligatory at all such waterworks.
4. *Cryptosporidium*, but not *Giardia*, is detected in the groundwater.
5. It is shown that the microbiological water quality is correlated to:
    - Wellhead completion (including the well casing)
    - Type and thickness of superficial deposits
    - Land use and contamination sources
    - Distance from wells to rivers or streams
6. It is very important to avoid contamination sources, such as farming and septic tanks in the catchment area.
7. Recommended wellhead completion includes installation of a well-house with concrete floor and watertight sealing between floor and the casing. The casing length should be at least 5.5 m and protrude 40-50 cm above ground level. The

gap between casing and bedrock should be sealed. Groundwater inflow should not occur at shallower depth than 10 m. Installation of an inner casing to seal off this water should be considered if the water quality is unsatisfactory.

8. It is shown that changes in parameters like colour, turbidity and iron can indicate microbiological contamination for single wells. Therefore, changes in these parameters and high levels of total organic carbon can be used as a symptom that the aquifer or the well is vulnerable to microbiological contamination.
9. Statistics from VREG show that few Norwegian waterworks based on groundwater from bedrock have established protection zones. It is not possible to give an evaluation of the significance of the protection zones reported in this thesis.
10. Vulnerability mapping combined with a hygienic evaluation of the well area and delineation of protection zones based on simple analytical methods is suggested as a method to establish source protection for Norwegian bedrock wells.

Definitions and abbreviations

Microorganisms:

Bacteriophage – A virus that infects prokaryotic cells. Most prokaryotes are bacteria (Madigan et al. 2003).

Clostridium perfringens is a bacteria that is widely distributed in the environment and frequently occurs in the intestines of humans and many domestic and feral animals. Spores of the organism persist in soil, sediments and areas exposed to human or animal fecal pollution (U.S. Food & Drug Administration 1992). The bacteria are used as an indicator for pathogen microorganisms, for example *Cryptosporidium*, in Norwegian groundwater. http://www.cfsan.fda.gov/~mow/chap11.html

Coliforms are used in this thesis as a collective term for total coliforms (TC) and fecal coliforms (FC), to describe the content of these bacteria in the water samples analysed. Used in figures and tables **Coliforms** mean TC and/or FC.

Cryptosporidium* and *Giardia are parasites (protozoa) that infect humans and animals. The parasites form oocysts/cysts that persist for a long time in the environment. Especially the oocysts from *Cryptosporidium* are resistant to most chemical disinfectants but are susceptible to drying and the ultraviolet portion of sunlight (Folkehelseinstituttet 2003).

Cryptosporidium parvum is a species of *Cryptosporidium* that are pathogenic to humans (Robertson & Gjerde 2000).

Fecal coliforms (FC) and *Escherichia coli* (*E. coli)* are bacteria whose presence indicates that the water may be contaminated with human or animal wastes (Østensvik 2002).

Heterotrophic microorganisms are microorganisms that require organic carbon to sustain life and reproduce (WHO/SDE/WSH 2002).

Heterotrophic Plate Count (HPC) includes heterotrophic microorganisms that are part of the natural (typically non-hazardous) microbiota of water. HPC measurements are used to indicate (Folkehelsa 1999):

- The effectiveness of water treatment processes
- Problems with biofilm in the distribution line

HPC at 22°C – the water samples have been incubated at 22°C
HPC at 37°C – the water samples have been incubated at 37°C

Intestinal Enterococci is a subgroup of the fecal streptococcus group. The bacteria are present in humans and other warm-blooded animals and are used as a bacterial indicator for determining the extent of fecal contamination (Østensvik 2002).

Total coliforms (TC) are lactose-fermenting bacteria that commonly inhabit the intestinal tract of humans and animals in large numbers (Madigan et al. 2003). They are used as indicators for the presence of pathogenic (disease-causing) microorganisms.

Water samples:

Clean-water is water sampled directly before it is distributed to the consumers. The water does not have to be treated.

Raw-water is untreated water collected either directly from the well or in the vicinity of the treatment plant, pressure tank or water reservoir.

Tapwater is water collected from a tap in a household or institution. Tapwater can be treated or untreated.

Treated water is in this thesis, disinfected water. The most widely used disinfection methods in Norway are UV or chlorine (Einan et al. 2004).

Other definitions:

Boxplots (box-and-whisker plots) are a useful presentation technique for comparison of different data subsets (Figure I). The box itself contains the mid 50 % of all data where the median value is marked with a line that divides the box. The brackets above and below this line denote a robust 95 % confidence interval on the median. The upper and lower ends of the box (called "hinges") represent the 75 % quartile and the 25 % quartile, respectively. Lines (called "whiskers") are drawn from the ends of the box towards the maximum and minimum values, respectively, each containing about 25 % of all data. The whiskers extend up to 1.5 times the length of the box and outlying data points are plotted as crosses (near outliers) and squares (far outliers) (Tukey 1977, Morland 1997, Frengstad 2002).

Hygienic barrier is defined as a natural or manmade physical or chemical obstacle. The barrier can be (Folkehelseinstituttet In prep):

- Source protection that prevents infective agents and other harmful components reaching the drinking water source
- Water treatment (e.g. disinfection, filtration and removal of chemical components like fluoride, radon or iron)

Superficial deposits are classified in two categories 1) medium to thick and 2) thin or discontinuous. The categories are taken from Norwegian Quaternary geology maps (1:50 000). Category 1 has normally thickness of at least 0.5 m with no bedrock exposed. In category 2, bedrock is exposed, although the thickness of superficial deposits locally can be more than 0.5 m.

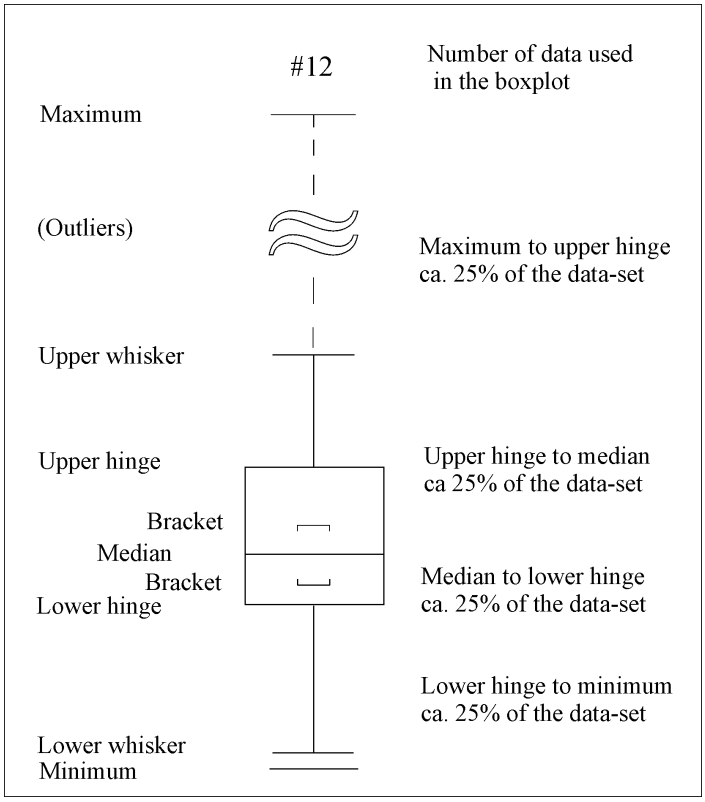

Figure I Boxplot modified after Morland (1997). Outliers in this thesis are plotted as crosses or squares.

Norwegian institutions and ministries:

Folkehelsa (present Folkehelseinstituttet) – Norwegian Institute of Public Health

Folkehelseinstituttet or Nasjonalt folkehelseinstitutt - Norwegian Institute of Public Health

Helse- og omsorgsdepartementet – Ministry of Health and Care Services

Landbruks- og matdepartementet – Ministry of Agriculture and Food

Mattilsynet – Norwegian Food Safety Authority **–** established on 1st January 2004. It is a governmental body and represents a merger of the Norwegian Animal Health Authority, the Norwegian Agricultural Inspection Service, the Norwegian Food Control Authority, the Directorate of Fisheries' seafood inspectorate, and local government food control authorities.

Meteorologisk institutt – Norwegian Meteorological Institute

Miljøverndepartementet – Ministry of the Environment

Sosial- og helsedepartementet (present Helse-og omsorgsdepartementet) – Ministry of Health and Care Services

Statens institutt for folkehelse (present Folkehelseinstituttet) – Norwegian Institute of Public Health

Abbreviations:

BUVA – Buskerud Vann- og Avløpssenter AS

DoELG – Department of the Environment and Local Government

EPA –Environment Protection Agency

FC – Fecal coliforms

GSI – Geological Survey of Ireland

HPC – Heterotrophic plate count

ISO – International Organization for Standardization

New Hampshire DES – New Hampshire Department of Environmental Services

NGU – (Norges geologiske undersøkelse) Geological Survey of Norway

NIPH – Norwegian Institute of Public Health (former National Institute of Public Health)

NS – Norwegian Standard

NS-EN –European Standard certified as Norwegian Standard

NSDW – Norwegian Standard for Drinking Water quality

PROVA – The Program for Improved Water Supply

SDE – Sustainable Development and Healthy Environments

SEPA – Scottish Environment Protection Agency

SNT – (Statens næringsmiddeltilsyn) Norwegian Food Control Authority

TC – Total coliforms

UNEP – United Nations Environment Programme

UNICEF – The United Nations Children's Fund

USEPA – United States Environment Protection Agency

VREG – (Vannverksregisteret) National Waterworks Register

WFD – Water Framework Directive

WHO – World Health Organization

WSH – Water, Sanitation and Health

ZOC – Zone of Contribution

1 Introduction

An important principle is that drinking water shall have a good hygienic standard. To prevent diseases, possibly unhealthy microorganisms (e.g. protozoa, bacteria, or viruses) or chemical compounds shall be rendered harmless or removed. In Norway drinking water has preferably been based on surface water (lakes or rivers) and groundwater only contributes to about 15 % of the drinking water (NGU 2002). Groundwater wells in bedrock are private wells supplying single households, holiday cottages or minor waterworks resulting in little emphasise on water quality. However, revision of the Norwegian drinking water regulations, combined with Norwegian membership in the European Economic Agreement (EEA), put focus on groundwater through the Program for Improved Water Supply (PROVA) showing clear evidence of water quality problems in bedrock wells. This made it necessary to increase knowledge about groundwater from bedrock wells to improve the water quality in both existing and future wells. Regional investigations of the hydrogeochemistry of the groundwater have been done by Englund & Myrstad (1980), Bjorvatn et al. (1992, 1994), Hongve et al. (1994), Banks et al. (1995a, 1995b) Reimann et al. (1996), Morland (1997), Morland et al. (1997) and Frengstad (2002), whereas this thesis examines the vulnerability of bedrock wells to microbiological contamination.

1.1 Background and problem

In Norway the general opinion has been, and still is to some degree, that Norwegian drinking water is clean and healthy, regardless whether the source is surface water, spring water or groundwater from wells. The Norwegian Institute of Public Health (NIPH) did the first reviews of drinking water quality from Norwegian waterworks in the periods 1986-1993 and 1994/95 (Myrstad 1997). In 1994 1587 waterworks, each supporting more than 100 persons, were registered in the National Waterworks Register (VREG) at NIPH. Based on data of water quality and the hygienic security (mainly information on disinfection and contamination sources) about 1000 (63 %) of these waterworks, supplying 30 % of the population (1.3 million people), did not have a satisfactory water supply (Myrstad 1997). This was caused by one or more factors: too high colour, microbiological contamination, lack of disinfection and a contamination potential in the catchment area, that were not compensated for by a treatment plant. These disappointing results came to light previous to and parallel with Norwegian membership in EEA.

To be able to both fulfil the Norwegian Standard for Drinking Water quality (NSDW) of 1995 (Sosial- og helsedepartementet 1995) and to meet the obligations set by the EEA, such as the European Union's (EU's) drinking water regulations, improvements of the drinking water quality were necessary. Thus PROVA was started 1st January 1995. The program includes information, guidance, subsidies, coordination of and grants to drinking water research and grants to waterworks for preliminary investigation of groundwater sources (Aasland et al. 2001). An evaluation of PROVA in 2000 stated that

improvements in water quality had been achieved, but that still 750 (49 %) of the 1521 waterworks reporting water quality in January 1999 (analyses from 1998) did not satisfy the drinking water regulations (Aasland et al. 2001). For 2003 797 waterworks (supplying about 3.17 million people) reported results from analyses of five parameters (turbidity, colour, pH, *E.coli* and Intestinal Enterococci) to VREG, and 343 (43 %) of these waterworks (1.1 million people) did not satisfy the drinking water regulations for one or more of the parameters (NIPH unpublished).

One of the main objectives of PROVA has been to initiate increased use of groundwater as it is regarded that groundwater in general is better protected against contamination than surface water. The national groundwater surveillance project, "Groundwater in Norway (GiN)", executed by the Geological Survey of Norway (NGU) from 1989-1992, stated that the total number of persons supplied from groundwater (waterworks and private supply) could be increased from 13 % in 1994 to 20-30 % in the future. In 1994 345 waterworks in VREG reported groundwater as the drinking water source (Ormerod 1998). This number increased to 551 in 2001 (Einan et al. 2003) and 566 in 2002 (Einan et al. 2004). Nevertheless, the reports show that the number of people supplied by groundwater from waterworks has not increased, but is still 10 %. This is probably due to:

- Waterworks that use groundwater are shut down in favour of bigger waterworks that often use surface water
- New water treatment methods favour surface water
- Few large waterworks use groundwater (population supplied is low)
- The increase in population has mainly occurred in the cities using surface water

Altogether about 15 % of the population in Norway is assumed to use groundwater as their drinking water supply (NGU 2002), 2/3 of these are connected to waterworks and 1/3 have a private drinking water source. Compared to other European countries the use of groundwater in Norway is low. In Belgium, Denmark, Netherlands, France and Germany groundwater supplies 60 % - 99 % of the drinking water (Daly et al. 1993, Harris 1998). Comparison with these and other countries is shown in Figure 1.1.1.

In Norway groundwater is mostly used by small and medium sized (<1000 people) waterworks, single households or holiday cottages. Groundwater wells are also retained as reserve water supply. Many of the small waterworks and private houses in Norway use groundwater derived from bedrock. The majority of these bedrock wells are located in rural areas where municipal waterworks cannot offer an alternative water supply (Morland 1996). It was estimated that about 100,000 bedrock wells existed in Norway in 1997 supplying 3.4-6.8 % of the population with drinking water (Morland 1997). In 1996-97 between 3000 and 4000 new wells were constructed each year. Today the drilling companies' trade organisations assume that the number of wells drilled in bedrock is approximately the same, but about 60 % are energy wells.

During the past few years the focus has been on both the physio-chemical and micro-biological quality of groundwater from bedrock wells. Information from NIPH and various departments of the former Norwegian Food Control Authority (SNT) indicate bacterial contamination in many of these groundwater wells. As a consequence NIPH

consider requiring disinfection of drinking water from all waterworks supplying water from bedrock wells.

Prevention of contamination has been practised in Norway for many years and disinfection is often the only water treatment conducted (Folkehelseinstituttet 2004). Chlorine, ultraviolet (UV) radiation and membrane filtration are mostly used (Einan et al. 2004). Doses of chlorine used are small, compared to other countries because Norwegians are very sensitive of water tasting "chlorine". Waterworks supplied by well-protected groundwater in Norway are not obliged to disinfect the drinking water (Folkehelseinstituttet 2004). Groundwater is used at 574 waterworks supplying more than 50 persons or 20 households, as registered in VREG for 2003 (NIPH unpublished). Of these waterworks only 166 disinfect the drinking water, using either UV or chlorine. It is not known how many of the 166 waterworks that use groundwater from bedrock, but a total of 185 such waterworks was registered in VREG for 2003. Usual problems with water quality in Norwegian groundwater are too high hardness, low oxygen and too high concentrations of iron and/or manganese, thus water treatment registered for 179 of the 574 waterworks in VREG is mainly aeration, alkalinisation and removal of iron and/or manganese.

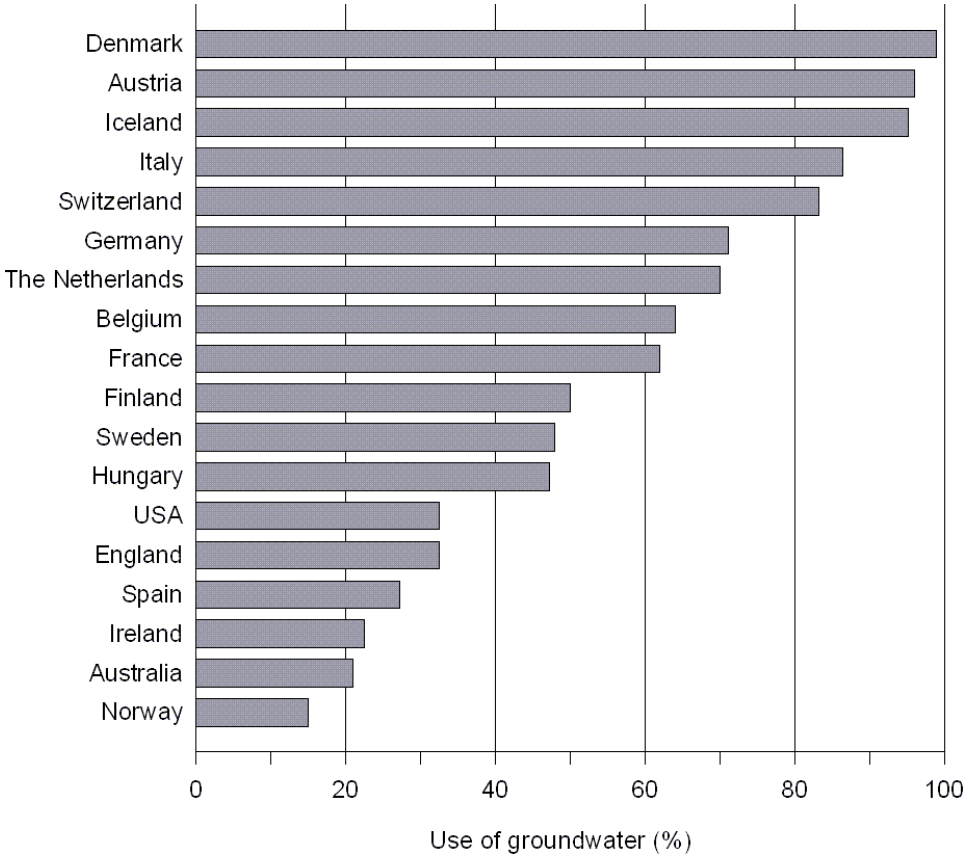

Figure 1.1.1 Use of groundwater (%) in Norway compared with other European countries, USA and Australia. The figure is based on numbers from Daly et al. (1993), Harris (1998) and Department of the Environment and Heritage (2003) and Figure 4 in Ellingsen (1992).

From January 2004 the Norwegian Food Safety Authority has collected information about water quality from Norwegian waterworks. Before that, VREG has since 1994 constituted the only systematic collection of microbiological data from waterworks in Norway. However, only average, minimum and maximum values from previous years' analyses are reported to the register and consequently no seasonal variations in water quality are registered. Key statistics are presented in annual reports from VREG. The reports state the number of waterworks based on groundwater from bedrock, but water quality is not presented separately for these waterworks. Thus, except for an under-graduate study regarding microbiological water quality from such waterworks in Nord-Trøndelag (Hanssen 1998) the microbiological water quality from waterworks based on groundwater form bedrock has not been evaluated earlier.

1.2 Aim and hypotheses

The aim of this thesis is to study the vulnerability of groundwater wells in bedrock to microbiological contamination with the following objectives:

a) Assess factors influencing the microbiological quality and how they influence on each other. Evaluate specifically how the well design affects the microbiological water quality
b) Assess the use of protection zones in Norway and their significance for the microbiological water quality

Based on these assessments advice on well construction and location is given and improvements of the method for designing protection zones in Norway are suggested.

Six hypotheses have been formulated:

1. Norwegian groundwater derived from wells in bedrock is satisfactorily protected against microbiological contamination.
2. When microbiological contamination is detected in groundwater from bedrock, it is related to snowmelt or autumn precipitation and manure spreading.
3. *Cryptosporidium* and *Giardia* do not exist in Norwegian groundwater wells in bedrock.
4. There is a correlation between groundwater wells in bedrock exposed to microbiological contamination and the following factors:
    - Design and protection of the well
    - Well capacity and depth to water inflow
    - The superficial deposits (type, thickness and extent)
    - Land use and contamination sources
    - Distance from surface water (lake/pool, river or ditch)
5. There is a correlation between physio-chemical parameters of the water, such as electrical conductivity, pH, colour, nitrate and total organic carbon, and the presence of coliforms or HPC exceeding the NSDW in the water.
6. Private waterworks supply more often water contaminated by coliforms or high HPC than public waterworks.

1.3 Organisation of the thesis

The thesis has the following content:

- Introduction (Chapter 1)
- Literature study (Chapter 2) and description of groundwater sampling, analyses and field inspections of the groundwater wells (Chapter 3).
- Description of the different datasets with selection criteria (Chapter 4) and results (Chapter 5).
- Discussion (Chapter 6) and conclusions (Chapter 7).
- References (Chapter 8)

When the work on this thesis started in 1998 only average, minimum and maximum values of microbiological quality for 1994 and 1996 were reported in VREG. Due to lack of seasonal water quality data in VREG, results from monthly microbiological analyses were collected from local departments of the former SNT for 195 waterworks in Norway. This dataset was used to get an overview of the extent of microbiological contamination and to examine seasonal variations in the microbiological water quality in Norwegian groundwater wells in bedrock in the period 1996-98 (Chapter 5.1). The microbiological quality is related to the 1995 NSDW. Improvements of drinking water quality have been in focus in Norway since the PhD study started. To be able to evaluate improvements of microbiological water quality at the 195 waterworks in this study, additional microbiological data were collected from VREG, laboratories of the former SNT or from the waterworks for the period 1999-2003 (Chapter 5.1).

Little is known about the existence of the parasites *Cryptosporidium* and *Giardia* in Norwegian groundwater, though it is considered a problem in both USA and UK (Craun et al. 1998). To investigate the occurrence of these parasites in water from bedrock wells, water has been sampled from 20 waterworks (Chapter 5.2).

A selection of 49 of the 195 waterworks was more closely examined by field inspection during the summer/autumn 2000 and 2001 to identify possible causes of the reported microbiological contamination (Chapter 5.3). Factors influencing the microbiological water quality are evaluated and their mutual relationship is examined.

Correlation between microbiological contamination and physio-chemical water quality has been examined. Water samples were taken from 41 of the 49 visited waterworks and analysed for microbiological and physio-chemical parameters. In addition 11 of the 49 waterworks (23 wells) were selected for a further study of the connection between microbiological contamination and physio-chemical water quality (Chapter 5.4).

The results are discussed related to the different hypothesis given in Chapter 1, and recommendations for well design and location are given (Chapter 6).

Different parts of the PhD study have been presented at national and international conferences (Appendices E, F and G).

2 Literature study

Microorganisms exist in soil, rock, water and air. Although, some are pathogenic to humans, most of them are harmless. Various microorganisms are used beneficially in food production, agriculture, energy and biotechnology (Madigan et al. 2003), and microbiology has played a major role in human health and welfare.

Microorganisms have been known to exist in water from groundwater wells since they first were documented by van Leeuwenhoek in 1677 (Ekendahl 1996, Madigan et al. 2003), and in 1854 John Snow demonstrated that cholera was spread by contaminated drinking water in London (Summers 1989). Since then, knowledge about different microorganisms has increased, helped by better microscopes and the possibility to grow pure cultures in the laboratory. Different techniques to collect uncontaminated deep cores, analyses of biomarkers and collaboration between hydrogeologists, geochemists and microbiologists have also contributed to knowledge about the subsurface biosphere (Bekins 2000).

2.1 Occurrence of pathogens in groundwater

In spite of increased knowledge about microorganisms and the diseases they may cause, people still get infectious diseases from food or water. Human pathogens transmitted by water include bacteria (e.g. *Escherichia coli, Salmonella spp.* and *Legionella*), viruses (e.g. Norwalk and Hepatitis A & E) and protozoa (e.g. *Cryptosporidium*) (Macler & Merkle 2000). Contamination of groundwater by these organisms is responsible for large outbreaks of waterborne diseases. Most illnesses are acute gastrointestinal illnesses mostly lasting one or two days, but they can be lethal for those who are ill, elderly, children, and immuno-suppressed and immuno-compromised (Gerba et al. 1996, Ball 1997). Estimated mortality from waterborne diseases in USA is 1400-9400 people each year (Macler & Merkle 2000). In developing countries nearly 2 million children under 14 years of age die of diarrhoeal diseases related to lack of safe water and sanitation every year (UNEP/UNICEF/WHO 2002).

2.1.1 Investigations of groundwater quality

Several investigations of groundwater quality show occurrence of pathogens or their indicators. Conboy & Goss (1999) sampled over 300 rural drinking water wells in Ontario, Canada and 148 wells in rural Zimbabwe in 1997, involving both wells in unconsolidated sediments and bedrock. In Canada 50 % of the wells and in Zimbabwe more than 90 % of the wells contained bacteria exceeding the Ontario drinking water objectives.

In the USA several studies report occurrence of pathogens in wells. Abbaszadegan et al. (2003) sampled groundwater from 448 wells (122 in bedrock) in 35 states and tested for

infective viruses, viral nucleic acid, bacteriophages, and bacteria and found that one or more of the microorganisms were present in 26 % of the samples from the bedrock wells and 64 % of the wells in unconsolidated sediments. Microbiological contamination of groundwater wells in the Boone-St. Joe limestone in Arkansas is reported by Cox et al. (1980) and an investigation of private well water in Montana showed that about 40 % of the samples tested positive for coliforms (Bauder et al. 1991). In the period 1995-2000 incidences of coliforms exceeding the maximum contaminant level (MCL) set by the US Environmental Agency occurred at 44 000 out of 156 000 public water supplies (Macler & Merkle 2000).

A Finnish study of dug wells, captured springs and wells in bedrock (Korkka-Niemi 2001) showed that about 60 % of the wells investigated were contaminated by total coliforms. In Norway, Johansen et al. (1998), Gaut (2003) and Gaut & Tranum (2003), among others, have investigated microbiological water quality in private bedrock wells supplying single households. Total coliforms (TC), fecal coliforms (FC) and *Escherichia coli* (*E. coli*) were detected in several wells, but these authors also found that heterotrophic plate count (HPC) higher than 100/ml was common. Hanssen (1998) examined analyses of TC and FC from 26 waterworks supplied by groundwater from bedrock in Nord-Trøndelag. The results showed that TC were found at 11 waterworks and FC at 8 waterworks.

2.1.2 Protozoa

It has been thought that protozoa, due to their large size, are filtrated in the soil and are unlikely to reach the groundwater (Gerba & Keswick 1981) and that presence of these organisms in groundwater indicates influence from contaminated surface water (Robertson & Edberg 1997). However, recent reports from USA and UK (Ball 1997, Craun et al. 1998, Hancock et al. 1998) show an increasing problem with outbreaks of waterborne diseases caused especially by *Cryptosporidium parvum* and *Giardia* also in groundwater. In Norway little is known about the existence of these protozoa in drinking water and groundwater is regarded as well protected against these parasites. Robertson & Gjerde (2000) analysed 408 water samples of raw-water from 147 drinking water sources in Norway, and one or both of these protozoa were detected in water samples from 47 of the localities. Two of the samples were not surface water, but were taken from a groundwater well in unconsolidated sediments. *Cryptosporidium* was detected in one of these samples.

2.1.3 Sources of microbial pathogens

Bitton & Gerba (1984), Daly (1985) and Macler & Merkle (2000), among others, describe sources of pathogenic microorganisms in groundwater. Infiltration of sewage by failed septic tank systems, land treatment sites and leaking sewer lines are the main sources together with agricultural activities like irrigation of sewage effluent, manure spreading and leakage from manure heaps or pits. Other sources are waste disposal sites (landfills), wild animals or contaminated surface water. In the USA larger, urban groundwater systems and smaller, rural groundwater systems are found to have different contamination sources (Macler & Merkle 2000). Coliforms at urban groundwater

systems are more often related to the distribution systems and may be caused by biofilm growth or cross contamination. However, in small rural systems contamination is mainly at the wellhead, indicating contamination of the well or source water. Source water contamination, either in the recharge area or by surface runoff entering the well, is also described by others (Wright 1995, Macler 1996, Robertson & Edberg 1997, Conboy & Goss 1999, Korkka-Niemi 2001, Lilly et al. 2003).

2.1.4 Outbreaks of waterborne diseases

Outbreaks of waterborne diseases caused by contaminated drinking water supplied from springs and surface water are reported for several countries. The probably best known single incidence happened in 1993 where an estimated 403,000 residents of the greater Milwaukee, Wisconsin area became ill and approximately 70 people, most of them immuno-compromised, died because of water treatment failure (Corso et al. 2003).

Groundwater, especially from wells in bedrock, is less frequently stated as the source and often the type of groundwater (spring, unconsolidated sediments or bedrock) is not specified. In the USA 650 outbreaks of waterborne diseases were reported from 1971 to 1994 (Craun & Calderon 1996, Abbaszadegan et al. 2003) of which 377 were associated with groundwater and mostly source water contamination. A more resent incidence connected to groundwater contamination in bedrock wells occurred in Walkerton, Ontario in 2000 where 2300 people became seriously ill and 7 died (Howard 2003). In 1999 and 2000 drinking water caused 39 waterborne disease outbreaks in USA and 26 of these were related to groundwater from a well (Lee et al. 2002).

Said et al. (2003) report 25 outbreaks of infectious diseases associated with private drinking water supplies in England and Wales in the period 1970-2000, but only 7 cases were caused by water from wells of which 3 were boreholes. Groundwater from bedrock (2 wells) and unconsolidated sediments (2 wells) has also caused outbreaks of cryptosporidiosis in England in the period 1988-1998 as reported by Bouchier (1998).

About 50 % of the outbreaks of waterborne diseases registered in the Nordic countries between 1975 and 1991 were related to contaminated groundwater. Most outbreaks were registered in Finland, Sweden and Norway and fewest in Iceland and Denmark (Stenström et al. 1994, Folkehelsa 1998). Type of groundwater source is not specified in these investigations. In the periods 1975-1994 (Folkehelsa 1998) and 1988-2002 (Nygård et al. 2003) 63 and 72 outbreaks respectively of waterborne diseases were registered in Norway. However, it is assumed that the number of unregistered outbreaks is several times higher. Between 1988-2002, 24 outbreaks were related to groundwater.

2.2 Transport of microorganisms in groundwater

To be able to prevent contamination of groundwater and drinking water wells, from pathogens, it is necessary to understand the mechanisms of transport, growth and survival of the microorganisms in the subsurface. Transport of microorganisms through soil and water is described in various publications (Gerba & Keswick 1981, Bitton & Gerba 1984, Matthess et al. 1985, Pekdeger et al. 1985, Lynch & Hobbie 1988, Gerba et al. 1991, Gammack et al. 1992, Lindqvist 1993) and it depends largely on:

- The nature of the soil, i.e. particle size, surface charges, organic matter
- Temperature, precipitation, soil water content and water flux
- The nature of the microorganisms i.e. size, shape and surface properties

These factors will again influence advection, dispersion, sorption, filtration and die-off rate of the various microorganisms both in soil and fractured media. However, in the latter the nature of the rock and fractures, i.e. matrix porosity and fracture density, aperture and surfaces, will substitute for the nature of the soil (Robertson & Edberg 1997). Scholl et al. (1990) correlated bacterial attachment to mineral surfaces with the ionic strength of the solution and the surface charge of bacteria and mineral. Abu-Ashour et al. (1994) summarise studies describing fast microbial transport, especially in the presence of preferential flow paths like continuous macropores, fractures, cracks, worm holes and channels formed by plant roots or animals. Both Abu-Ashour et al. (1994) and Tim et al. (1988) divide microbial movement through soil into three process groups; physical (convection, advection and hydrodynamic dispersion), geochemical (filtration, sorption and sedimentation) and biological (growth and death or survival). Bolster et al. (2000) studied the biological heterogeneity and the role it plays in bacterial transport. Their study showed the importance of understanding the intra-population variability (e.g. differences in age and mobility) in estimating transport distances and dispersal of bacteria.

Microorganisms are known to persist in the subsurface for a long time. Laboratory studies report survival of bacteria (including *E. coli* and *Salmonella typhimurium)* and viruses for as long as 77-400 days (Gerba & Keswick 1981, Pekdeger et al. 1985, Filip et al. 1988, Kott 1988, Adams & Foster 1992). The die-off rate is higher in experiments where sand is used compared to only water (Kott 1988) and when the temperatures are higher (Gerba & Keswick 1981, Blanc & Nasser 1996). The study by Blanc & Nasser (1996) showed no die-off of viruses (hepatitis A virus and poliovirus 1) at low temperatures (10°C) after 20 days. Gerba & Keswick's (1981) experimental data showed that, despite a 99.9998 % reduction of *E.coli* after 20 days, a saprophytic strain of *E.coli* survived 5.5 months in natural subsurface water held in the dark in the laboratory. The authors also give examples of an in-situ study where coliforms were detected in water from an observation well 5 months after injection in a well 5 m away.

To gain information about hydrology of complex groundwater environments, transport behaviour and dispersal of specific microorganisms are examined (Harvey 1997). Poliovirus, *E.coli*, and the bacteriophages T4, MS2 and ΦX174 are often studied, especially the phages as they are frequently used as tracers (Herbold-Paschke et al. 1991, Bales et

al. 1993, McKay et al. 1993, Blanc & Nasser 1996, Woessner et al. 2001). The historical use of microorganisms as tracers, such as indicators of fecal coliforms and bacteriophages, are summarised by Keswick et al. (1981) and Harvey (1997). More recently, investigations have shifted from study of groundwater environments to the transport behaviour of the microorganisms themselves. Most studies, such as those mentioned above, describe transport in porous media. Studies of transport by microbial tracers in fractured rocks are, among others, described by Champ & Schroter (1988), Kennedy (2000) and Becker et al. (2003). Champ & Schroter (1988) and Kennedy (2000) compared transport of microorganisms with conservative chemical tracers (^{82}Br, Nitrate, ^{3}H and different fluorescent solutes) experiencing an earlier breakthrough for the microorganisms. Becker et al. (2003) injected different types of bacteria to compare transport behaviour related to physio-chemical characteristics and motility. They found that minor differences in morphology, cell size, Gram type and motility could lead to major differences in transport behaviour. Malard et al. (1994, 1997) described bacterial contamination of wells in a fractured limestone aquifer infiltrated by sewage-polluted river water. The water infiltrated rapidly through large fractures, but water also circulated into small-sized fissures that eventually got clogged by the bacteria. During rain these bacteria were flushed out contaminating the wells.

2.3 Microbiological parameters in drinking water regulations

Since water is one of the main paths transmitting human pathogens, it is important to ensure safe drinking water by controlling the water quality. There are numerous pathogenic microorganisms, and it is not practical and too expensive to, in general, analyse the water to detect each type of pathogens that may be present. Instead, indicator organisms are used (Madigan et al. 2003). Indicators of fecal contamination are bacteria that are normal inhabitants of the gastrointestinal tract of humans and warm-blooded animals, but some can additionally originate from soil and plant material (Østensvik 2002). In general, the indicator bacteria themselves do not cause any harm to humans. The World Health Organization (WHO) recommends using *E. coli* as indicator bacteria for fecal contamination. *E. coli* originates only from the gastrointestinal tract and is therefore a positive indicator for fecal contamination of the water. Other indicators for fecal contamination are fecal coliforms, *Intestinal Enterococci* and total coliforms, though none of these groups are uniquely related to fecal contamination.

Heterotrophic plate count (HPC) gives a quantitative measure of heterotrophic microorganisms that can use organic matter as nutrient (Østensvik 2002). HPC is analysed at two temperatures:

1. 20°C /22°C; detecting microorganisms normal in soil and water. The bacteria do not indicate fecal contamination, but can cause biofilm and spoil food.
2. 36°C/37°C; detecting microorganisms, whose normal habitat are humans and warm-blooded animals, consequently indicating fecal contamination.

Bacteria adhere to the surfaces in the delivery systems. In doing so, they cover themselves with a biofilm, which is a slimy layer of protective molecules (Flemming

1993). Biofilms can, in addition to microorganisms, consist of corrosion products harming for example the pipeline and some of the bacteria like iron bacteria, cause aesthetic reduction of water quality due to smell, taste and colouring of the water (Lund 1998). Examination of biofilms shows that HPC bacteria are the dominant microorganisms present (Bartram et al. 2003), but also pathogenic bacteria (LeChevallier et al. 1987), opportunistic microorganisms (Leclerc 2003) and amoebae are found (Bartram et al. 2003). The WHO publication on HPC in drinking water (Bartram et al. 2003) concludes that, even though HPC is not an indicator for health risk, abnormal changes in HPC may indicate a problem in the treatment process and high HPC can cause regrowth of pathogens in the delivery systems. The cause for high HPC should therefore be investigated.

The protozoa *Giardia* and *Cryptosporidium parvum* are pathogens forming cysts/ oocysts that can survive for a long time in the environment (Robertson & Gjerde 2000). The cysts/oocysts are resistant to chlorination but are rendered harmless by UV or can be removed by membrane filtration.

In USA all public water supplies have to analyse on total coliforms (TC) and fecal coliforms (FC) according to the Total Coliform Rule (TCR) (U.S. Environmental Protection Agency 1989, Macler & Merkle 2000). Water samples positive for TC will be tested for the presence of FC or *E. coli* (Table 2.3.1).

Table 2.3.1 Minimum microbiological drinking water regulations in USA, EU, EEA, Norway and recommendations from the World Health Organization (WHO). The table shows parameters analysed and maximum allowable concentration.

Drinking water regulations in:	Parameter	Maximum allowable concentration	Comments
USA	Total coliforms (mg/l)	See footnote[2]	
	FC[1]/*Escherichia coli* (mg/l)	0	
EU/EEA[3]	*Escherichia coli* /100 ml	0	
	Enterococci /100 ml	0	
Norway	*Clostridium perfringens* /100 ml	0	Used as indicator for *Cryptosporidium parvum*
	Total coliforms /100 ml	0	
	Heterotrophic plate count (22ºC) /ml	-	Values exceeding 100 have to be investigated
WHO	FC[1]/*Escherichia coli* /100 ml	0	Analysis of *Escherichia coli* is preferred

1 FC = Fecal coliforms
2 For water systems analysing at least 40 samples per month, no more than 5.0 percent of the monthly samples may be positive for total coliforms. For systems analysing fewer than 40 samples per month, no more than one sample per month may be positive for total coliforms.
3 As a member of EEA, Norway also analyses for these bacteria.

Member states of EU and EEA follow EU's drinking water regulations, Council directive 98/83/EC (The Council of the European Union 1998), though each country may introduce more strict regulations like lower limits for certain parameters or additional parameters. Through the drinking water regulations member states have to ensure that water intended for human consumption by Article 4(1)(a) in the directive "is free from any micro-organisms and parasites and from any substances which, in number or concentrations, constitute a potential danger to human health". Minimum requirements are set for microbiological and physio-chemical parameters. Microbiological parameters are *E. coli* and Enterococci (Table 2.3.1). Risk assessment and monitoring for *Cryptosporidium* is part of the water supply regulations for Scotland, Northern Ireland and England and Wales.

The Norwegian drinking water regulations (Helse- og omsorgsdepartementet 2001) are founded on different Norwegian laws, and, since Norway is a member of EEA, the same standards for drinking water quality are followed as in EU, with some additional micro-biological parameters. These are *Clostridium perfringens* (including oocysts), TC and Heterotrophic plate count (HPC) at 22ºC. Quality limits are shown in Table 2.3.1. The bacteria *Clostridium perfringens* is used as a specific indicator for the protozoa because it forms cysts, though the correlation between *Clostridium perfringens* and oocysts/cysts of parasites is not clear (Østensvik 2002).

2.4 Groundwater protection

The International Association of Hydrogeologists (IAH) has since the 1970s raised the issue of groundwater protection at numerous congresses. The topic is presented in two volumes of International Contributions to Hydrogeology (Matthess et al. 1985, Verba & Zaporozec 1994) describing vulnerability mapping combined with delineation of protection zones. This combination is used in both USA and several European countries (Verba & Zaporozec 1994, U.S. Environmental Protection Agency 1997, DoELG/EPA/ GSI 1999, U.S. Environmental Protection Agency 1999).

Vulnerability mapping is based on the assumption that the surroundings may give a natural protection of the groundwater and that some areas are more susceptible to contamination than others (Verba & Zaporozec 1994). The vulnerability of each homogeneous entity in an area is evaluated and the result is presented on a vulnerability map. Only relative vulnerability is estimated and the vulnerability should be related to specific contamination sources.

Different methods are used, separately or in combination, to delineate protection zones for wells (Bradbury et al. 1991, Muldoon & Payton 1993, DoELG/EPA/GSI 1999, Robinson & Barker 2000):

- Fixed radius (arbitrary or calculated) – The zone of contribution (ZOC) is either set as an arbitrary fixed radius or calculated by using well pumping rate. When calculating, the aquifer is assumed to approximate a uniform porous medium. A simple equation containing pumping rate (Q) and residence time (time of travel)

of the water in the ground (t) is used together with for example aquifer porosity (n) and length of well (H) to estimate a ZOC with radius (r) around the well:

$$r = \sqrt{\frac{Qt}{\pi n H}}$$

- Analytical methods – The protection zone is delineated by calculations using time of travel or the uniform flow equation (Todd 1980). The aquifer is assumed to approximate a uniform porous medium.
- Hydrogeological mapping or mapping of flow-systems – Information about groundwater level and physical boundaries to groundwater flow is used to construct groundwater level maps and draw groundwater flow lines to delineate the ZOC, which need to be protected. Groundwater divides are used as boundaries for the ZOC and protection zones can be delineated based on time of travel or the uniform flow equation.
- Residence time approach – Water chemistry and isotopes are used to identify travel paths and flow rates and the minimum age of the water produced by the well can be estimated. The method does not provide any protection zones but can be used in combination with the other methods.
- Semi-analytical methods
- Numerical modelling

An evaluation of the different methods utilized on wells in fractured aquifers, was done by Robinson et al. (2000). Protection zones were delineated using the simple methods assuming the fractured aquifers approximated uniform porous media. The results where compared with each other and with protection zones delineated by a numerical model. The calculated fixed radius gave least resemblance to the numerical modelling and none of the simple methods delineated a protection zone fully including the zone delineated by the numerical model. Nevertheless, the authors concluded that methods based on porous media assumptions can be used if the fracture aquifer has numerous vertical and horizontal fractures and the fracture network has a much smaller scale than the ZOC.

2.4.1 USA

In USA the Safe Drinking Water Act (SDWA) is aimed to protect drinking water sources. SDWA does not regulate private wells that serve less than 25 individuals, but applies to all other public water supplies. Amendments in the SDWA from 1986 and 1996 established the Wellhead Protection Program (WHPP) and Source Water Assessment Program (SWAP) respectively. Through these programs all states have to delineate wellhead protection areas, register potential sources of contamination and determine the vulnerability of the public water supply to these contaminations (U.S. Environmental Protection Agency 1997, U.S. Environmental Protection Agency 1999). The US Environmental Protection Agency (USEPA) has approved SWAPs for all states. The States had flexibility in how they designed their program, resulting in different state programs or policy. Hydrogeological information like pumping tests, travel time and tracer tests are used to delineate wellhead protection areas (Macler & Merkle 2000). Risk assessment tools can be used to determine the vulnerability of

public water supply wells to microbial contamination (Jorgenson et al. 1998). Different tools for delineation and susceptibility assessments are found at the USEPA websites. In the following the states of Wisconsin and New Hampshire are used as examples of state-solutions.

Muldoon & Payton (1993) give a summary of methods used to delineate wellhead protection areas in Wisconsin.

- Fixed radius
- Mapping of vulnerability
- Mapping of flow-systems
- Residence time approach
- Semi analytical flow or particle-tracking models
- Numerical flow or transport models

For fractured bedrock aquifers numerical models (MODFLOW) combined with particle tracking (MODPATH) have been used with special attention paid to bedding-plane fractures (Rayne et al. 2001).

The New Hampshire Groundwater Protection Act: RSA 485-C protects groundwater in New Hampshire (New Hampshire DES 1997). Under this Act all groundwater is classified in four classes, GB, GA2, GA1 and GAA by increasing grade of protection. Groundwater sources in the classes GA1 and GAA include flow to public wells and potential sources that the local entity or the State wants to protect, and an active management of possible contamination sources take place. As a part of the state SWAP, vulnerability maps are created for each public water supply source. For transient systems (e.g., restaurants and hotels) Source Water Protection Areas (SWPAs) are defined as a circle centred on the supply well with a 150 m (500 ft) radius. For all other systems the SWPA depend on the volume of water pumped and geological information about the aquifer (New Hampshire DES 2000a).

2.4.2 South-Africa

The "White Paper on a National Water Policy for South Africa" (Department of Water Affairs and Forestry 1997) outlines the direction to be given to the development of water law and water management systems in South Africa. A proposed national water resource strategy was published in September 2004 (Department of Water Affairs and Forestry 2004), where groundwater protection is briefly mentioned. At present, groundwater protection zones are normally delineated based on the experience and knowledge of the hydrogeologist. Many boreholes in South Africa are located in fractured dykes and for these wells the linesink concept can be used (Xu & van Tonder 2002). The method regards the fractured dyke as an extension of the borehole and the capture zone is elliptical. The authors propose that based on this, a semi-analytical model could be constructed for conceptual modelling of the capture zone.

2.4.3 European member states

Use of protection zones in Europe is summarized by (Lallemand-Barrès & Roux 1989). Most countries use three protection zones:

1. The immediate protection zone, normally from 10-50 m
2. Protection area defined by a 50-400 days residence time for the groundwater before it reaches the well, mostly 50-60 days are used.
3. Outer protection zone. This zone is defined differently in different countries and is either equivalent to the catchment area, a maximum distance of 1-2 km or it is time dependent (400 days to10 years).

A couple of countries have additionally a fourth zone defined as the catchment area or the far recharge area.

In the EU the Water Framework Directive (WFD) was agreed by the European Parliament and Council in September 2000 and came into force on 22 December 2000 (European Parliament and Council 2000). The aim of the Directive is to ensure "good status" of all waters in the Member States by protecting and, if necessary, enhancing the water quality. By 2004 all groundwater sources were to be characterised and monitoring has to be established by 2006. The requirement of "good status" in relation to waters is to be achieved by 2015. Groundwater protection against pollution under the WFD is to be tackled in a separate Daughter Directive (COM(2003)550), which was adopted on 19 September 2003 (Commission of the European Communities 2003). As in the USA, the different Member States in EU have their own legislations related to groundwater protection and, as long as they fulfil the requirements in the WFD, they have flexibility in how to reach the goals set in the WFD. Ireland, England & Wales and Scotland are described in more detail below.

The Geological Survey of Ireland (GIS) has in cooperation with the Department of Environment and Local Government (DoELG) and the Environmental Protection Agency (EPA) developed a Groundwater Protection Scheme (GWPS) that provides guidelines for the planning and licensing authorities on how to protect groundwater and prevent pollution (DoELG/EPA/GSI 1999, Daly 2000). The GWPS consists of two main components: (i) land surface zoning and (ii) groundwater protection responses for potentially polluting activities. Land surface zoning is presented on a Groundwater Protection Map that is composed by combining an Aquifer Map and a Groundwater Vulnerability Map. As part of the land surface zoning Source Protection Areas (SPAs) are delineated for each groundwater source to regulate the activities within the ZOC. SPAs consist of an Inner and Outer protection area, which are defined by a 100-day time of travel (300 m for fixed radius) and the catchment area (1000 m recommended for fixed radius) respectively. Methods used by the GSI to determine the Inner and Outer areas are: (i) calculated fixed radius, (ii) analytical methods, (iii) hydrogeological mapping and (iv) numerical modelling. Groundwater protection responses indicate according to DoELG/EPA/GSI (1999) "the acceptability of a particular activity with respect to the potential hazard, aquifer category of source protection area and groundwater vulnerability".

The Environment Agency in England and Wales is responsible for the protection of "controlled waters" from pollution under the Water Resources Act 1991 (Environment Agency 1999a). Classification of groundwater vulnerability and groundwater source protection zones are widely used by the Agency to protect groundwater from contamination (Burgess & Fletcher 1998). The delineation of zones is based on travel time of groundwater, and for each groundwater source three zones (I-III) are defined. Zones I and II are defined by 50-days and 400-days travel time respectively, whereas Zone III defines the total catchment area of the abstraction. Conceptual hydrogeological models, often supported by numerical models like MODFLOW, are used to construct the zones. One problem is that most major aquifers in the UK are fractured to some extent and the models used are based on the assumption of flow in a relatively homogeneous medium. This problem is discussed in Robinson & Barker (2000) who assessed existing methods worldwide, to develop a rigorous and defensible methodology for deriving GPZs in fractured/fissured aquifers for England and Wales. They conclude that protection zones delineated with methods assuming approximation of a porous medium have large uncertainties and ideally, 3-D modelling should be used to delineate protection zones for wells in fractured aquifers. However, the latter is in most cases too expensive.

The groundwater protection policy for Scotland is presented by the Scottish Environment Protection Agency (SEPA 2003). SEPA has not yet designated source protection zones in Scotland (Pritchard, A. pers. com.) and primarily a 250 m ellipse forms the protection zone around wells in fractured bedrock aquifers (Lilly, A. pers com.). A microbiological risk assessment (MRA) for private water supplies is developed by Lamb et al. (1998) and a validation study of the MRA methodology is carried out that concludes that MRA can be used as a "checklist" of potential action points (Lilly et al. 2003). Through the "checklist", which is a questionnaire, information about the groundwater source and well area (general site survey) is collected to identify and characterise microbiological hazards and to estimate the risk (high, medium, low) for the water supply. Different questions are answered depending on the type of groundwater source.

2.4.4 Norway

As a member of EEA, Norway follows the European WFD to ensure that "good status" of water is reached by 2015. In Norway the Norwegian drinking water regulations require protection of water by at least two separate hygienic barriers (Helse- og omsorgsdepartementet 2001). The regulation requires one of the barriers to provide for disinfection or equivalent treatment of the water to remove, inactivate or kill possible harmful infective agents. When a groundwater source is documented to be well protected against contaminations, this treatment requirement can exist as a standby. Most public groundwater sources in Norway are located in unconsolidated sediments. To reduce the potential of contamination of the drinking water source, the following scheme is used to establish protection zones around supply wells (Folkehelsa 1987, Eckholdt & Snilsberg 1992):

- **Zone 0**: The inner area comprising all supply wells. This area is surrounded by a fence positioned at least 10 m removed from all wells, and supplied with a

locked gate. The only activities allowed inside this area are those necessary for operation of the waterwork.

- **Zone 1**: The inner recharge area. Water being recharged at the outer edge of this area must have a minimum travel time of 60 days in the saturated zone to the nearest supply well while pumping at full capacity.
- **Zone 2**: The outer recharge area. The outer edge of this zone defines the total area where all recharged water reaches the supply wells.
- **Zone 3**: The outer protection area. This zone includes areas of uncertainty as well as possible surface catchment areas, which may potentially affect the groundwater quality.

The extension of zones 1 and 2 is estimated by analytical methods (e.g. calculated fixed radius) or occasionally by numerical modelling. Within each area restrictions related to land use are given (Folkehelsa 1987). Due to lack of investigation data, like inaccurate information about aquifer parameters, security demands the zones to be large enough but presupposes that possible later investigations may provide data indicating that zones may be altered and still be secure. Eckholdt & Snilsberg (1992) recommend that similar protection zones should be delineated around groundwater wells in bedrock. However, lack of information about the aquifer often renders estimation of travel time (zone 1) difficult, and a modified guideline with three protection zones is suggested (Eckholdt & Snilsberg 1992):

- **Zone 0**: The inner area comprising the supply well(s). A fence positioned at least 10 m removed from all wells, and supplied with a locked gate surrounds this area.
- **Zone 1**: The vulnerable recharge area. Especially areas with poor natural protection like exposed bedrock.
- **Zone 2**: The outer protection area. This zone includes less vulnerable areas, which may potentially affect the groundwater quality.

2.5 Well construction and abandonment

In USA well design and abandonment is regulated by the different states. As an example New Hampshire Department of Environmental Services (New Hampshire DES) has published different fact sheets on the subject. New wells in New Hampshire have the casing set 3-6 m into bedrock (New Hampshire DES 2003). Grouting between bedrock and casing is not the normal practice, though the fact sheet informs that some experts recommend cement grouting. The top of the casing extends above ground level and a well cap is installed, but no manhole is recommended. Abandoned wells are by New Hampshire law, required to be sealed in an appropriate manner (New Hampshire DES 2000a). Drilled wells are normally filled with Portland cement, cement-bentonite grout or bentonite chips. Cement-bentonite grout is recommended for contaminated wells because the cement does not shrink and crack because of the bentonite content.

In Wisconsin the Administrative Code give regulations for well construction and abandonment (Wisconsin Department of Natural Resources 2002). Wells drilled in bedrock have a minimum casing diameter of 152 mm. Casing length for potable wells depends on the well capacity. Low capacity wells have at least 12 m of casing and high capacity wells have at least 18 m of casing. If depth to bedrock is less than 12 m or 18 m, for low- and high capacity wells respectively, the casing is drilled at least 6 m into solid rock. The annulus of the casing is normally grouted with cement. Wellhead completion for private wells can be either above or below ground level, whereas domestic wells always have the wellhead completion above ground (Wisconsin Department of Natural Resources 2003). Below ground, a watertight, concrete pit with a manhole cover is used. Above ground, domestic wells require a well-house. Private wells may do with a well cap and the casing protruding 30 cm above ground. The Administrative Code NR812 requires proper sealing of all abandoned wells. The wells are sealed with bentonite chips, neat cement grout, concrete or sand-cement grout (Wisconsin Department of Natural Resources 2001).

In Ireland GSI published in 1979 (GSI 1979) a guide to the development of groundwater for small residential and farm supplies. It contains sketches on how to design drilled and dug wells and information about location, cleaning and development, well testing and inspection. It is recommended to drain the water away from the well and to use cement grout or puddled clay to seal between the well casing and the superficial deposits and bedrock. Wright (1995) discusses the importance of guidelines for well construction and sealing of abandoned wells in Ireland, although, still in 2000, private wells were not covered by any regulations or standards (Daly 2000). A method for grouting in the casing is presented by Briody (1995). He also recommends constructing a manhole with concrete floor around the well and to let the casing protrude 10 cm above the floor.

The Environment Agency in England and Wales has written a guide to good practice for construction of water supply boreholes (Environment Agency 2000) and the SEPA has made a Scottish version of the pamphlet containing the same main information (SEPA 2004a). It is recommended to grout along the total annulus of the well casing and to drill the casing at least 3 m into solid rock. Wellhead completion should be above ground to prevent surface water entering the well. Examples show a manhole with concrete floor and the well casing with a well cap, protruding 30 cm above the concrete floor. It is recommended both by the Environment Agency (1999b) in England and Wales and the SEPA (2004b) that redundant boreholes and wells are backfilled to prevent contamination of the groundwater. Permeable material may be used as backfilling to mimic the aquifer material, or bentonite, cement grout or concrete can be used. In both cases the top of the borehole or well has to be filled with an impermeable material, like concrete. If permeable infilling is used it is important to hinder groundwater flow between aquifer units, if more than one unit is present.

Members of GEOTEC, a trade organisation for drilling companies in Sweden, use Normbrunn-97 [standard well-97] (Risberg 1997) worked out by the Geological Survey of Sweden, as a basis for their type approved groundwater well in bedrock. According to the standard the casing should be drilled minimum 2 m into bedrock and the total

length of the casing has to be at least 6 m. Sealing is required between bedrock and casing at the bottom of the casing. No information about wellhead completion is given.

In Norway the Norwegian Standard NS 3420 contains information about well drilling both in bedrock and unconsolidated sediments. Additionally guidelines are presented in two booklets published by NGU (Eckholdt & Snilsberg 1992) and NIPH (Folkehelsa 1987). It has been recommended to seal between bedrock and casing and the revised edition of NS 3420 (September 2004) has implemented this as a requirement. However, sealing material is not specified nor is it required to follow the Norwegian Standard. When sealing is done it is normal to seal only at the bottom part of the casing. In Norway bentonite chips are mostly used as sealing material. The chips are swelled in water and emptied into the well after installation of the casing. The casing is then hammered down and the bentonite is pressed in between casing and bedrock. Swelling of the bentonite is required before drilling of the main borehole starts. It is suspected that this is not always done. Other materials used are cement-based suspensions like rapid-hardening cement with bentonite or other swelling material.

NS 3420 states that the casing should be drilled at least 1 m into solid rock. When the superficial deposits are thin (< 2m) Eckholdt & Snilsberg (1992) recommend the casing to be drilled at least 4 m into bedrock. No recommendations exist for wellhead completion except for a well cap and possible packing of low permeability sediments around the well to ensure surface runoff away from the well. Under Norwegian law, all wells are to be properly secured (Miljøverndepartementet 2004a) and contamination of groundwater is illegal under the "Pollution law" (Miljøverndepartementet 2004b). Nevertheless, no regulations exist on how to take care of redundant boreholes.

3 Methods

Six main Datasets (A-F) are used in this thesis. Analyses of water samples are the basis for Datasets A-D and field inspections are the basis for Datasets E-F. Overview of the datasets is given in Textbox 3.1 and notes on the contribution to the datasets are given in Textbox 3.2.

Textbox 3.1 – Overview of the datasets

Dataset A
- 195 waterworks based on groundwater from bedrock.
- Number of wells unknown
- Microbiological and physio-chemical analyses (1996-98)

Dataset A_{mod}
- 169 of the 195 waterworks in dataset A. Number of wells unknown
- Waterworks discarded are either not based on groundwater from bedrock or they have collected less than 4 water samples each year

Dataset B
- B_1: 41 waterworks (96 wells) from dataset E sampled once (2000/2001)
- B_2: 11 waterworks (23 wells) from dataset E sampled monthly or every other month for one year (2001-2002)
- Microbiological and physio-chemical analyses

Dataset C
- 123 of the 169 waterworks in dataset A_{mod}. Number of wells unknown.
- Microbiological and physio-chemical analyses (1999-2003)

Dataset D
- 20 waterworks
- Analyses of Cryptosporidium and Giardia (20 waterworks in 2004)
- Analyses of *Clostridium perfringens* (10 waterworks in 2004)

Dataset E
- 49 of the 195 waterworks (135 wells) in dataset A
- Field inspections (2000 and 2001)

Dataset E_{mod}
- 63 of the 135 wells in dataset E
- Microbiological and physio-chemical analyses (1996-2003)

Dataset F
- 41 of the wells in dataset E of which 24 are part of dataset E_{mod}
- 3 of the wells in dataset D
- Inspection of wells with a downhole video camera (2004)

Textbox 3.2 – Note on the contribution to the datasets

Dataset A and A_{mod}

– Water samples collected by waterwork or SNT staff
– Microbiological parameters analysed by SNT
– Most physio-chemical parameters analysed by SNT. However, other laboratories used are:
  - Planteforsk
  - NGU-Lab
  - BUVA (Buskerud Vann- og Avløpssenter AS)

Dataset B (both B_1 and B_2)

– Water samples collected by personnel at the waterworks
– Microbiological parameters analysed by SNT
– Physio-chemical parameters, except TOC, analysed by NGU-Lab
– TOC analysed by SNT in Trondheim

Dataset C

– Water samples collected by waterwork or SNT staff
– Microbiological and physio-chemical parameters analysed by SNT and Hardanger Miljøsenter (Alex Stewart environmental services AS)

Dataset D

– Water samples collected by personnel at the waterworks or Frank Sivertsvik or Erik Rohr-Torp, NGU
– *Cryptosporidium, Giardia* and turbidity analysed at the Norwegian School of Veterinary Science.
– *Clostridium perfringens* analysed at local laboratories

Dataset E and E_{mod}

– Field inspections carried out by the author

Dataset F

– Inspection of the wells with downhole video camera done by Frank Sivertsvik and Gaute Storrø, NGU

Administration, data processing and interpretation

I have selected the waterworks and wells for each dataset and administrated all collection of data. The data processing is also done by me, although Frank Sivertsvik has helped interpreting the logging done by the downhole video camera in dataset F.

3.1 Collection of water samples

Analyses of water samples are the basis for Datasets A-D (Textbox 3.1, Chapter 4.1). This chapter describes the different sampling methods used. The water samples have been collected by different people, consequently modifications of the methods described in this chapter may have occurred. This is not expected to influence the microbiological or physio-chemical water quality.

3.1.1 Microbiological analyses

Personnel from each waterwork or from the SNT have collected water samples analysed for microbiological parameters in Datasets A, B and C. The water is sampled on sterile plastic bottles specially designed for water to be analysed on microbiological parameters. Sampling volume is normally 0.5 litre. If the drinking water is treated with chlorine prior to sampling, the sampling bottle contains 1 ml of 5 % sodium thiosulphate to adsorb any excess of chlorine.

Procedure when sampling from a tap is by first burning the tap opening with a lighter and then letting the water flow for about 3 minutes before sampling. The opening of the bottle is held into the water flow and the bottle is filled almost to the top. Contamination is avoided by never touching the bottle opening with anything except the sampling water. The bottle is kept cool and brought to the laboratory for analyses within 24 hours of the sampling.

Personnel from NGU or at the different waterworks collected the water samples for *Cryptosporidium* and *Giardia* analyses (Dataset D). Each sample consists of 10 litres of water sampled in an ordinary plastic carboy from the sampling tap at the well or inside a house supplied by the well. One of the samples had to be taken from the water reservoir by dipping the carboy into the water to get it filled. All samples in this dataset are taken of untreated groundwater. Transport to the laboratory was undertaken as soon as possible after sampling, either by post, courier service or delivered directly to the laboratory by personnel from NGU. Due to the wide geographic distribution it was not possible to standardise the collection and delivery of water samples.

Water from 10 of the waterworks in Dataset D was also analysed for *Clostridium perfringens*. Separate water samples were collected to perform these analyses. Sampling procedures are the same as for Datasets A-C.

3.1.2 Physio-chemical analyses

Datasets A-C also consist of water samples analysed on physio-chemical parameters. As for the microbiological analyses, personnel from the waterworks or from the local SNT have collected the samples in Datasets A and C. Water is sampled in plastic bottles and the volume varied between 0.5 and 1.0 litre depending on the number of parameters analysed. The water samples are split into several fractions in the laboratory depending on the type of analyses carried out. Normally only one or two physio-chemical parameters are analysed in addition to microbiological analyses. When the drinking water

sampled for microbiological analyses is untreated, and only a few physio-chemical parameters are analysed, a separate water sample for physio-chemical analyses is often not collected.

Personnel from the waterworks collected the samples for physio-chemical analyses in Dataset B. Plastic bottles (0.5 litre) are used for analyses carried out at NGU-Lab, whereas 250 ml acid-washed (1M HCl) plastic bottles are used for analyses of total organic carbon (TOC). Bottles are sent to NGU as soon as possible after sampling. For TOC analyses 1 % 4M H_2SO_4 is added to the water samples on arrival at NGU. The bottles were often stored a few days at NGU before they were delivered to the laboratory. All samples arriving at NGU are stored in a refrigerator. The water samples analysed at NGU are split and two samples of 50 ml are filtered at 0.45 µm using Millipore filter capsules and polypropen syringes. The bottles are rinsed twice with filtered water before they are filled. One of the 50 ml samples is used for IC analyses whereas the other is added 0.5 ml of 65 % concentrated ultrapure HNO_3 for ICP-AES analyses. The remaining non-filtered water is used for determination of colour, pH, alkalinity, conductivity and turbidity.

3.2 Laboratory analyses

The microbiological analyses in Dataset A-C, analyses of *Clostridium perfringens* in Dataset D and the physio-chemical parameters in Dataset A and C were mostly carried out at different laboratories of the SNT (Textbox 3.2). Local variations from the methods described in this chapter and Appendix A may have occurred. However, the analyses for each individual waterwork have been analysed at the same laboratory. It is assumed that all laboratories follow the reference methods set for the different parameters used in this study. All physio-chemical parameters in Dataset B, except TOC, are analysed at NGU-Lab. All methods and equipment are thoroughly described in NGU laboratory's quality handbook (NGU-Lab 1997). TOC (Dataset B) is analysed at the former SNT in Trondheim and *Cryptosporidium* and *Giardia* in Dataset D are analysed at the Norwegian School of Veterinary Science.

3.2.1 Microbiological analyses

Water samples were analysed on HPC, TC, FC, *E. coli*, *Clostridium perfringens*, *Cryptosporidium* and *Giardia*, and the results are part of one or more of the Datasets A-D (Table 3.2.1). Analytical techniques and reference methods are shortly described below and summarised in Table 3.2.2. A more detailed description of the methods is given in Appendix A.

Heterotrophic plate count (HPC) is analysed at two incubation temperatures. For Datasets A and B most laboratories have used HPC at 22°C and 37°C following Norwegian Standard (NS) 4791. For Dataset C both NS 4791 and NS-EN ISO 6222 are followed. The same method is used for all temperatures. Lower detection limit is 1 CPU (colonies per unit).

Table 3.2.1 Microbiological parameters in the Datasets A-D.

Parameter	Dataset
Heterotrophic plate count (HPC) 22ºC and 37ºC/36ºC	A, B and C
Total coliforms (TC)	A, B and C
Fecal coliforms (FC)	A, B and C
Escherichia coli	C
Clostridium perfringens (incl. oocysts)	D
Cryptosporidium and *Giardia*	D

Table 3.2.2 Analytical techniques and reference methods used for different microbiological parameters. NS = Norwegian Standard, NS-EN = European Standard certified as Norwegian Standard, ISO = International Organization for Standardisation, and US EPA = US Environmental Protection Agency.

Parameter	Technique	Reference method	Comments
Heterotrophic plate count 22°C and 36°C	Colony count by inoculation in a nutrient agar culture medium	NS-EN ISO 6222	
Heterotrophic plate count 22°C and 37°C		NS 4791	Method followed until 1st January 2001
Total coliforms and *Escherichia coli*	Membrane filtration	NS-EN ISO 9308-1	
	Enzyme substrate method	Colilert-18/Quantitray	
Total coliforms	Membrane filtration (mEndo agar)	NS 4788	Valid through 1st November 2003
Fecal coliforms	Membrane filtration (mFC agar)	NS 4792	Valid through 1st November 2003
Total coliforms and Fecal coliforms	MPN-method (most probable number)	NS 4714	Used instead of NS 4788 and NS 4792 if the sample contains lots of particles
Clostridium perfringens	Membrane filtration (mCP agar)	mCP-agar	
	Membrane filtration (SFP agar)	NS-ISO 6461-2 with verification	
Cryptosporidium and *Giardia*	Membrane filtration (IMS and IFA)*	US EPA Method 1623	

*IMS = immunomagnetic separation and IFA = immunofluorescence assay

Total coliforms (TC) are analysed by different methods.

1. NS 4788 is mostly followed describing a membrane filtration method after NS 4790. From 2002 mostly membrane filtration by NS-EN-ISO 9308-1 is used instead of NS 4788. Lower detection limit is 1 coliform per test volume.
2. If the water samples contain lots of particles the multiple fermentation tube technique or MPN-method (most probable number) is used (NS 4714) instead of the membrane filtration.
3. Some laboratories use the enzyme substrate method (Colilert-18/Quantitray) instead of NS-EN ISO 9308-1. Lower detection limit is 1 coliform per test volume.

Fecal coliforms (FC) are analysed by the same methods (membrane filtration or MPN-method) as TC, with some adjustments. Membrane filtration follows NS 4792 and the MPN-method NS 4714.

Escherichia coli (E. coli) is either analysed by the enzyme substrate method Coliert-18/Quantitry or by membrane filtration following NS-EN ISO 9308-1. Lower detection limit for both methods is 1 *E. coli* per test volume.

Clostridium perfringens is analysed by the membrane filtration methods described in the European Council Directive 98/83/EC or in NS-ISO 6461-2. Lower detection limit is 1 *Clostridium perfringens* per test volume.

Cryptosporidium and *Giardia* are analysed by the US EPA Method 1623. The method makes it possible to simultaneously isolate both *Cryptosporidium* oocysts and *Giardia* cysts from water samples. Lower detection limit is 1 oocyst/cyst per test volume.

3.2.2 Physio-chemical analyses

Water samples are analysed on colour, turbidity, electrical conductivity, pH, alkalinity, TOC, iron (Fe), manganese (Mn), nitrate (NO_3^-) and chloride (Cl^-) and the results are part of the Datasets A-C except for TOC that is only part of Datasets A and B. Analytical techniques, reference methods (Norwegian Standard) and units are summarised in Table 3.2.3. A more detailed description of the methods is given in Appendix A.

3.3 Fieldwork - examination of wells and well fields

Field inspections have been carried out at 49 waterworks examining a total of 135 wells (Dataset E) with regard to the following parameters:

- Capacity
- Water level
- Depth to pump inlet
- Well design (total well depth, depth to bedrock, drilling direction, diameter, length of casing)

- Wellhead protection (length of casing above ground level, sealing between bedrock and casing, existence of concrete well-protection or well-house, fencing)
- Existence of protection zones
- Existence of superficial deposits (depth, type and distribution) and location relative to marine sediments
- Land use
- Possible sources of contamination
- Comments (by the owner), if any, to the microbiological or physio-chemical water quality (e.g. seasonal changes, changes related to precipitation)
- Water treatment
- Pipeline leakages
- Distance from surface water sources (lake, river, ditch)

During field inspection a questionnaire (Appendix B) was used to ensure that all parameters were investigated. Technical data about the wells are collected from the well owner, drilling companies and from the groundwater database at NGU. Borehole logs and geological maps (scale 1:50 000) are used to help determine type, thickness and extension of superficial deposits. GPS or maps (scale 1:5 000) are used to determine well co-ordinates.

Table 3.2.3 Analytical techniques, reference methods and units for the different physio-chemical parameters in Datasets A-C.

Parameter	Unit	Analytical technique	Reference method
Colour	mg/l Pt	Spectrophotometer	NS-EN ISO 7887 (former NS 4787)
Turbidity	FTU	Nephelometry	NS 4723 or NS-ISO 7027
Electrical conductivity	mS/m	"Dip-type" measuring cell	NS-ISO 7888 or former NS 4721
pH	–	Titration	NS 4720
Alkalinity	mmol/l	Titration with HCl	NS 4754
Total organic carbon (TOC)	mg C/l	Infrared spectrometry	NS-EN 1484 (former NS 8245)
Iron (Fe)	mg Fe/l	ICP-AES or atomic absorption spectrometry	NS 4773
Manganese (Mn)	mg Mn/l	ICP-AES or atomic absorption spectrometry	NS 4773
Nitrate (NO_3^-)	mg NO_3/l	Ion chromatography (IC) or molecular absorption spectrometric method	NS-ISO 6777
Chloride (Cl^-)	mg Cl/l	Ion chromatography (IC) or Photometry	NS 4769

3.4 Video inspection of wells

Video inspection has been carried out at 44 wells (Dataset F). All but one well, which was inspected by the company Miljøgeologi as (Forbord 1997, 2002), was logged by personnel from NGU in the following manner: Inspection of the internal appearance of the wells is done by a downhole video camera (Tiny CS 3002 S from Rico EAB), which is lowered into the wells. During the inspection casing length is measured, existence or lack of sealing between bedrock and casing is noticed and water inflows are localized. If possible the well is logged down to 15-20 m. Data is recorded on an Archos video AV380.

3.5 Data processing

The software program Microsoft Excel has been used to compile collected data into databases. Part of the data are handled statistically and presented graphically using the data analysis program DAS. DAS is developed at the Institute for Technical Statistics, University of Vienna (Dutter et al. 1992) on the basis of the exploratory data analysis (EDA) method (Tukey 1977).

A 95 % confidence interval is used when estimating statistical significance of the data. For boxplots the brackets above and below the median value denote a robust 95 % confidence interval on the median, and when the brackets of two boxes do not overlap the difference is statistically significant. When boxplots cannot be used, the statistical significance is estimated by the t-test (Swan et al. 1995).

Some errors are likely to have occurred during water sampling, analyses, collection of well information or data processing. Possible errors concerning the datasets are:

- Errors occurring during water sampling. Numerous water samples in Datasets A-C are collected and a few of these samples may have been contaminated during sampling. However, it is expected that in total it will not influence the results. Contamination during sampling of water for Dataset D is possible but not likely.
- Contamination during preparation of samples and analytical errors.
- Determination of height of marine limit and lithology (Dataset E_{mod}). The information received from geological maps is sometimes inaccurate, but will seldom influence on the results because the wells are normally not located close to the height limit.
- Determination of extent and thickness of the superficial deposits due to inaccuracy of geological maps (Dataset E_{mod}). Field inspections are carried out at all wells and errors (if any) are most likely related to thickness of the deposits.
- Collection of well information and assigning well specific parameters (Dataset E_{mod}), e.g. depth, depth to bedrock, casing length and water inflow. Due to missing and only partly filled in drilling logs information received about casing length, well yield and well depth sometimes depends on the memory of the well

owner. Drilling logs received from drilling companies at a later time have revealed a few errors, and others may therefore exist.

- All kinds of errors occurring during data handling and processing, e.g. registration of information in the databases from different sources (laboratories, field inspection, well owners and drilling companies). It is expected that most of these errors are found, but some may still exist.

4 Description of the datasets

Microbiological and/or physio-chemical analyses have been performed on water samples presented in four Datasets (A-D). In addition field inspections were carried out at 49 waterworks (Dataset E) and video inspection was done in 44 wells (Dataset F). Selection criteria and composition of the Datasets A-D are presented in Chapter 4.1 and for Datasets E and F in Chapter 4.2.

4.1 Microbiological and physio-chemical data

4.1.1 Introductory comments

When this PhD study started in 1998 the 1995 NSDW was used (Sosial- og helsedepartementet 1995). In 2002 the standard was changed (Helse- og omsorgs-departementet 2001) to fulfil the requirements in EU's drinking water regulations (Council directive 98/83/EC). This revision resulted in several changes in parameters analysed. Table 4.1.1 presents the NSDWs of 1995 and 2002 and which microbiological parameters that are part of the Datasets A-C. The important changes related to this study are that *E. coli* are analysed instead of FC, HPC at 37°C is no longer measured and, instead of a guidance level (100/ml) an action level (100/ml), is set for HPC at 22°C. In practice the former guidance level and the new action level are equal because in both cases investigations have to be initiated to find the cause of the high HPC content if the count exceeds 100/ml. Maximum allowable concentration of coliforms are the same in the revised and former NSDW. The 1995 NSDW is referred to with the year 1995 given or as the former NSDW.

The NSDW contains both physio-chemical and microbiological parameters. When stating for example "water samples exceed the NSDW" in this thesis it refers to microbiological parameters.

In this study laboratories of the different departments of the former SNT have carried out most of the microbiological analyses in Datasets A-C (Textbox 3.2). To simplify the writing, this name is used even though SNT has been a part of the Norwegian Food Safety Authority from 1 January 2004 and the laboratories are privatised.

Datasets A-C also contain physio-chemical data. Table 4.1.2 gives a summary of the parameters analysed and the different laboratories used.

Table 4.1.1 Type of microbiological analyses collected for the Datasets (A-C) and NSDWs of 1995 and 2002. Guidance level is removed in the new regulations of 2002. The analyses are carried out at different laboratories of the former Norwegian Food Control Authority and Hardanger Miljøsenter (Textbox 3.2).

Norwegian standard for drinking water quality	Type of analysis	Dataset	Guidance level	Maximum allowable concentration
1995	HPC[1] (22ºC) /ml	A, B and C	100	-
	HPC (37ºC) /ml	A, B and C	10	-
	TC[2] (37ºC) /100ml	A, B and C	0	0
	FC[3] (44ºC) /100ml	A, B and C	0	0
1 January 2002	HPC (22ºC) /ml	C	-	-
	TC (37ºC) /100ml	C	-	0
	E. coli[4] /100ml	C	-	0
	Enterococci /100ml	-	-	0
	Clostridium perfringens (incl. oocysts) /100ml	C	-	0

[1]HPC = Heterotrophic plate counts, [2]TC = Total coliforms
[3]FC = Fecal coliforms, [4]*E. coli* = *Escherichia coli*

4.1.2 Dataset A – Microbiological and physio-chemical parameters, 1996-1998

Dataset A is used to get an overview of the extent of microbiological contamination in Norwegian groundwater wells in bedrock, and to select waterworks for further field inspection in an attempt to identify possible causes to the recorded microbiological contamination. The first part of the study included collection of microbiological data from waterworks using groundwater derived from bedrock. A list of such waterworks was put together based on information from databases at NIPH and NGU and reports from a former NIPH project; "Investigation of and assistance to operation of water-works in Norway" [In Norwegian: Driftsoppfølgingsprosjektet (DOP)]. The list was regarded to contain most existing waterworks based on groundwater from bedrock supplying more than 100 persons.

Microbiological analyses were at that time done by the laboratories connected to the departments of SNT and they were in 1998 contacted and requested to provide micro-biological analyses for the waterworks. To include waterworks not registered in any of the databases or reports, all departments were asked to supply data from any other waterworks supplied by groundwater from bedrock. In total SNT contributed with microbiological water analyses from 195 waterworks in Norway (Figure 4.1.1, Appe-ndix H), each primarily supporting more than 100 persons or 20 households. However, some waterworks supply water to cafés, schools and public institutions. The request for microbiological analyses included data from the years 1996 and 1997. Data from these years are received from those departments of the SNT that replied quickly. However, some of the departments did not respond until the end of 1999 and from some of them microbiological analyses from 1998 and 1999 are received instead of or in addition to

data from 1996 and 1997. Additional data from the period 1991-1995 are received for some waterworks.

Table 4.1.2 Different physio-chemical parameters analysed in Datasets A, B and C. Dataset B consists of two Datasets B_1 and B_2. The laboratories used are listed.

Laboratory	Physio-chemical parameter	Dataset
Mostly local laboratories of the Norwegian Food Control Authority, but also: Hardanger Miljøsenter, NGU-Lab, Planteforsk and BUVA	- electrical conductivity - pH - turbidity - colour - alkalinity - nitrate - Fe and Mn - TOC	A and C
Norwegian Food Control Authority in Trondheim	- TOC	B_1
NGU-lab	- electrical conductivity - pH - turbidity - colour - alkalinity - chloride (Cl^-) - nitrate (NO_3^-) - manganese (Mn) - iron (Fe)	B_1 and B_2

In accordance with the 1995 NSDW (Sosial- og helsedepartementet 1995), waterworks are to sample water for microbiological analyses at least once a month (12 samples a year). However, this is only done by approximately 50 % of the waterworks in this study. The other waterworks have sample frequencies between 1 and 9 samples per year, with the majority taking at least 4 samples a year.

A first evaluation of Dataset A, using the whole dataset, is presented in Appendix E (Gaut et al. 2000). This thesis presents results that are slightly different because selection of waterworks for field inspection (Chapter 4.2) and collection of Dataset C (Chapter 4.1.4) revealed that microbiological data from 10 waterworks represented other water sources than groundwater from bedrock. These waterworks were therefore discarded before a more thorough data processing took place. To make the dataset more homogeneous, only data from the period 1996-1998 has been used, leaving out one waterwork with data only from 1993. Furthermore, 16 waterworks with water samples

taken less than four times a year are discarded. The changes leave a modified Dataset A_{mod} that consists of 169 waterworks (Figure 4.1.1).

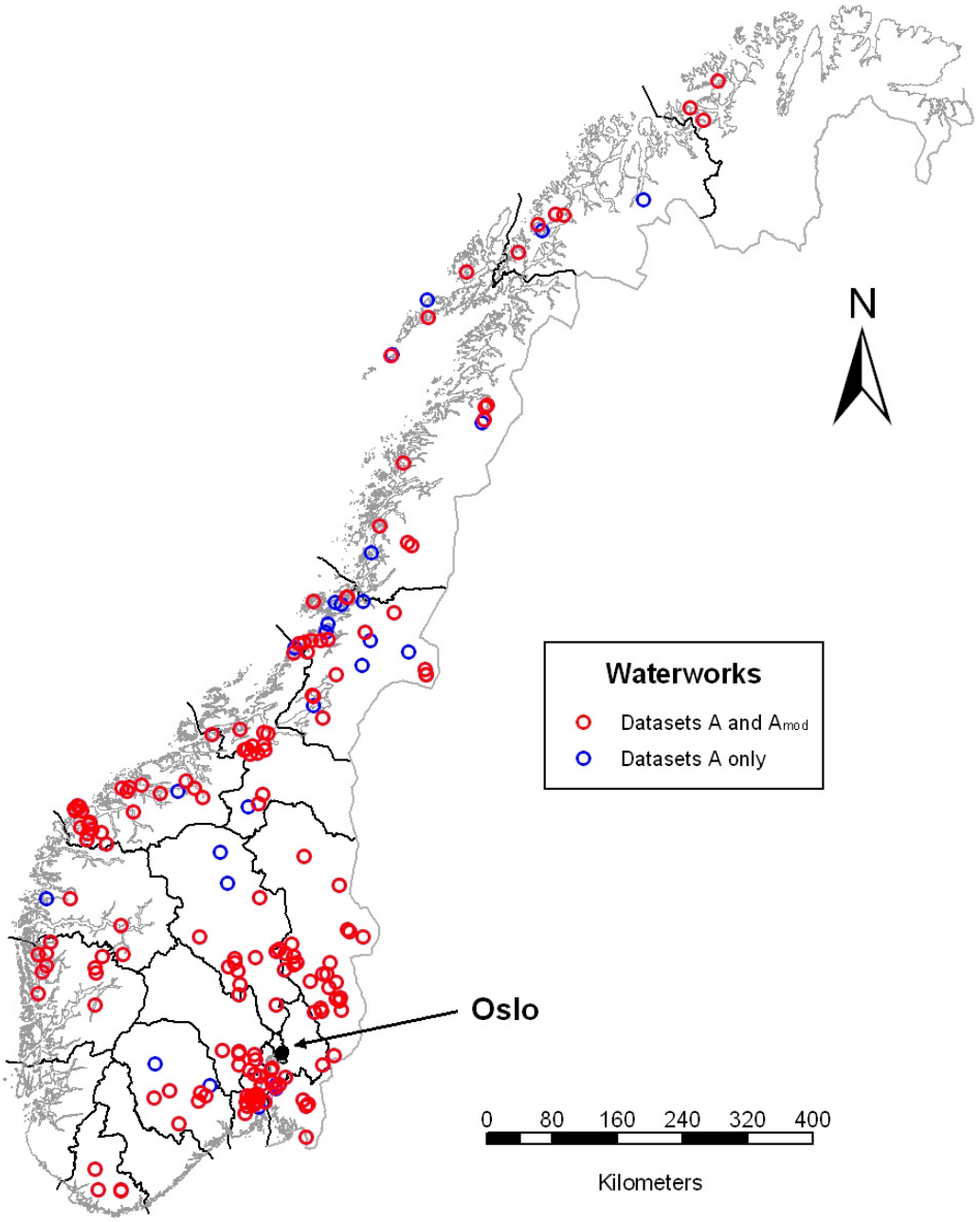

Figure 4.1.1 Geographical distribution of the 195 waterworks in Dataset A (red and blue) and the 169 waterworks in dataset A_{mod} (red). The waterworks are supplied by groundwater from bedrock.

The minimum sampling frequency is set to 4 water samples for the waterworks included in Dataset A_{mod}, because:

- About 30 waterworks take only 4 samples. Setting the limit at 5 or 6 samples a year would make the dataset unnecessarily small.
- For the waterworks sampling 4 times a year the samples are approximately evenly distributed throughout the year (e.g. February, May, August and November)
- With a lower frequency than 4 samples a year; waterworks reporting violations of the drinking water regulations have a high uncertainty in frequency and magnitude of this contamination. However, waterworks not reporting violations of the drinking water regulations have a high uncertainty in whether this applies for the whole year or not.

Dataset A_{mod} has some limitations:

- At least 3 waterworks use both groundwater from bedrock and surface water. When using water analyses from these waterworks, it is assumed that data labelled groundwater in laboratory reports represents only groundwater.
- Water samples from most of the 169 waterworks are not collected directly from the supply well. Instead raw-water is collected in the vicinity of the treatment plant or pressure tank or the water sample is tapwater from a household or a public institution. Thus, the reported water quality in these cases represents an integrated value where the waterworks is supplied from more than one well. To avoid this problem when evaluating factors influencing on the microbiological water quality (Chapter 5.3) only microbiological quality from single wells is used. When the water samples are tapwater the pipeline may have affected the water quality.

In addition to the microbiological analyses, the drinking water is regularly analysed for pH and conductivity. Turbidity and the content of nitrate, nitrite and ammonium are also measured a few times a year. Most of the waterworks in this study supply less than 1000 persons. In accordance to the 1995 NSDW these additional measurements are to be done four times a year. Some waterworks also analyse on Fe, Mn, colour, alkalinity or hardness. These data is part of Dataset A and several of the parameters are used together with Datasets B and C, to find possible correlations between microbiological and physio-chemical parameters in the water.

4.1.3 Dataset B – Microbiological and physio-chemical parameters, 2000-2002

This dataset consist of two sets, B_1 and B_2 (Appendix I), which are collected to compare microbiological quality with physio-chemical parameters in order to examine correlations between the two types of data for groundwater derived from bedrock. Field inspections were carried out at 49 of the 195 waterworks in Dataset A during the summer/autumn 2000 (44) and 2001 (5). Dataset B_1 consists of groundwater samples from 41 of these 49 waterworks (Figure 4.1.2a). The samples were collected in the period November 2000 to January 2001 (36) and in September 2001 (5). Personnel at the waterworks were responsible for the sampling. Tables 4.1.1 and 4.1.2 show the

parameters analysed and the laboratories used. Unfortunately Dataset B_1 cannot be used as originally planned because of two problems:

1. It was requested that water samples for both physio-chemical and microbiological parameters were to be sampled at the same time. Nevertheless, this is only done for 15 waterworks. Since laboratory reports for the microbiological analyses were received after the physio-chemical and TOC analyses were done, it was not possible to correct for this error.
2. Waterworks with more than one well often sampled raw-water for microbiological analyses from the water reservoir or tapwater at a household or public institution, whilst one sample of raw-water was taken from each well for physio-chemical parameters and TOC.

Dataset B_2 consists of water samples from 11 of the waterworks (23 wells) visited in 2000 (Figure 4.1.2b). The water samples were analysed for microbiological parameters at the local laboratories of the SNT and physio-chemical parameters at NGU. The aim was to get a dataset where samples for both microbiological and physio-chemical analyses were collected simultaneously. The waterworks were selected due to microbiological problems indicated from Dataset A, except one, which had changed water source to a newly drilled well with unknown water quality. Nine waterworks consist of one well, one waterwork sampled two wells and the last waterwork consists of 12 wells. The first 11 wells were sampled once a month for 12 months. From the last waterwork (Sørlandet at Værøy), water was sampled from all 12 wells. The intention was to sample each well every other month during one year, but due to operating problems at the waterwork this was only done for 8 wells. Three wells were sampled 4-6 times but not every other month. The last well was sampled only once and was therefore discarded from the dataset.

4.1.4 Dataset C – Microbiological and physio-chemical parameters, 1999-2003

Improvement of drinking water quality has been focused in Norway since this PhD study started in 1998. In order to evaluate changes in the microbiological water quality over time at the 169 waterworks from Dataset A_{mod}, additional microbiological analyses were collected for the period 1999-2003 for the same waterworks (Dataset C). Analyses in Dataset C were collected from waterworks' owners, former laboratories of SNT, the Norwegian Food Safety Authority and from VREG at NIPH. It has been possible to collect data from 123 out of the original 169 waterworks (Appendix J). In accordance with the 2002 NSDW, the microbiological parameters analysed changed in 2002 (Table 4.1.1) and consequently *E. coli* is analysed instead of fecal coliforms (FC). Regarding the changes, TC and HPC at 22°C are used for comparison of the Datasets A_{mod} and C since these parameters have been analysed during the whole period 1996-2003. Additionally, *E. coli* and FC are set as equal and used as one parameter because *E. coli* is regarded as the most common member of the fecal coliform group detected in groundwater (Hellesnes 1979, Østensvik 1998).

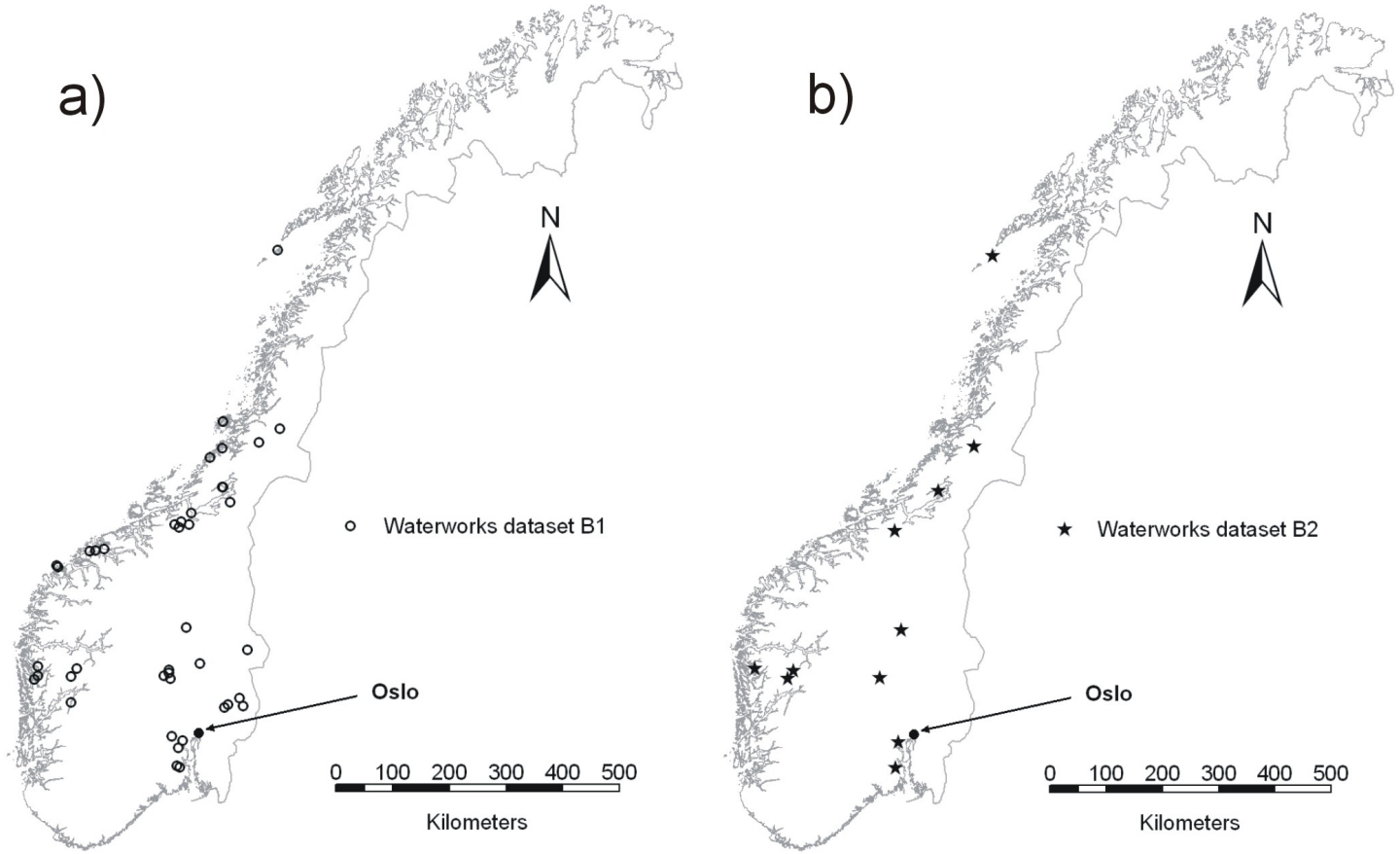

Figure 4.1.2 a) Geographical distribution of the waterworks in Dataset B_1 representing 41 waterworks with both microbiological and physio-chemical analyses. b) Geographical distribution of the waterworks in Dataset B_2 representing 11 waterworks with monthly microbiological and physio-chemical analyses. All waterworks are based on groundwater from bedrock.

Dataset C consists of analyses of both disinfected (treated) and not disinfected (untreated) water samples. The disinfected samples are treated with chlorine or ultraviolet (UV) radiation. In many of the reported analysis water treatment prior to sampling is unknown. Water samples are collected either from the well, a water reservoir or from a tap in the distribution line. Like Dataset A, some waterworks have more than one well and the reported water quality represents therefore an integrated value.

Collection of Dataset C resulted also in some physio-chemical data. These are used together with similar data from Datasets A and B to find possible correlations between microbiological and physio-chemical parameters.

4.1.5 Dataset D – *Cryptosporidium, Giardia* and *Clostridium perfringens*

The existence of *Cryptosporidium* and *Giardia* in Norwegian groundwater is unknown. To investigate a possible occurrence of these parasites in water from bedrock wells, 20 samples of raw-water were collected from 20 waterworks (Figure 4.1.3a) and analysed at the Norwegian School of Veterinary Science. Wells close to risk areas like farming and septic tanks were chosen due to the fact that animal and human fecal matter are sources of the parasites. Only 15 suitable wells were found among the 49 waterworks inspected (Dataset E, Chapter 4.2.1) and five of the 20 wells were therefore selected:

- In contact with local offices of the Norwegian Food Safety Authority
- From waterworks registered in VREG that have detected coliforms.

In each case the waterworks' owners were contacted to verify suitable location.

Water samples were collected from 28 April to 27 May 2004. At 10 of the waterworks an additional water sample was collected for analyses of *Clostridium perfringens* at the nearest laboratory (Figure 4.1.3b).

4.2 Field inspections

4.2.1 Dataset E – Field inspections

Field inspections were carried out at 49 waterworks (Dataset E) during the summer/ autumn 2000 (44) and 2001 (5) in order to identify possible causes to the recorded microbiological contamination (Figure 4.2.1). The waterworks were chosen from the 195 waterworks in Dataset A. Based on recorded microbiological quality, the waterworks are given a colour and a symbol that is plotted on a map. The map is used as a help to pick the 49 waterworks in Dataset E. Because Dataset E is collected to find plausible causes to microbiological contamination, most of the waterworks selected (38 out of 49) had recorded problems with the microbiological quality in the period 1996-98 and did not fulfil the 1995 NSDW. Other selection criteria are:

- High frequency of water sampling for microbiological analyses.
- Different geographical sites (e.g. at the coast, inland, mountain area, lowland).
- Location in clusters to minimise travel expenses.

- Ongoing investigations. Sørlandet waterwork at Værøy is selected because NGU already had a project to enhance the microbiological quality and to assess the vulnerability of the waterwork. As a consequence of this work, Nordland waterwork (Værøy) is chosen as well.

A total of 135 wells have been examined during the field inspections (Dataset E) and collected data (Chapter 3.3) are compiled into a database (Appendix K).

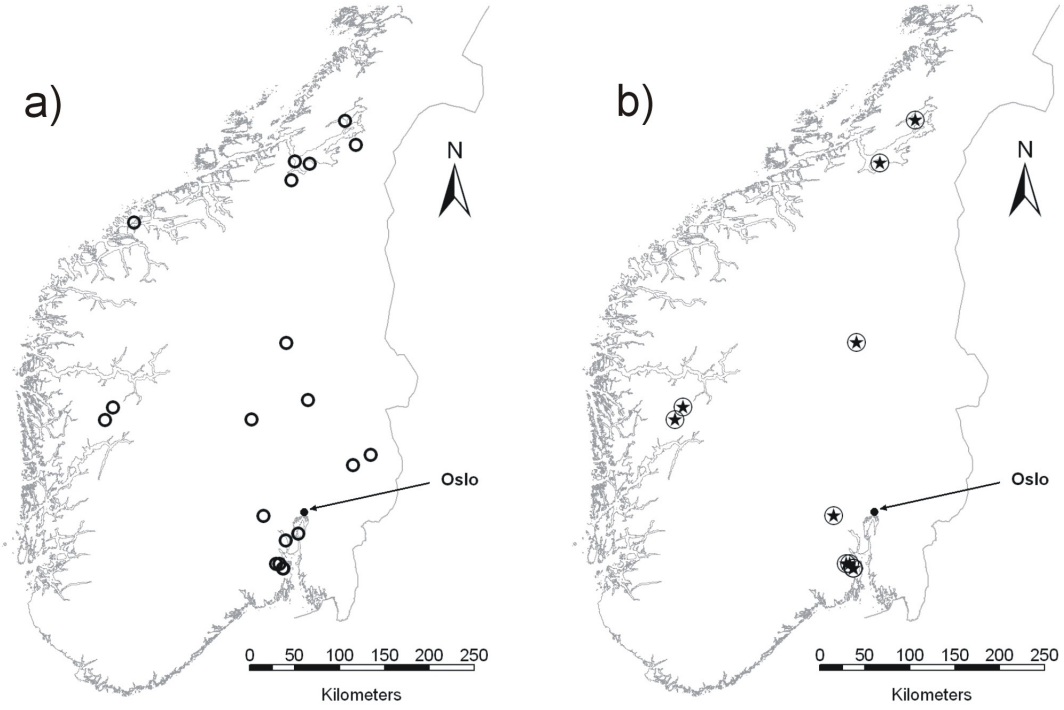

Figure 4.1.3 a) Geographical distribution of 20 waterworks where water is sampled for analyses on *Cryptosporidium* and *Giardia*. b) Geographical distribution of 10 of the waterworks in a) that additionally are sampled for analyses of *Clostridium perfringens.* All waterworks are based on groundwater from bedrock.

To verify possible causes of microbiological contamination, data from Dataset E and the video inspections (Dataset F, Chapter 4.2.2) are compared with reported microbiological quality. Unfortunately, microbiological quality of groundwater exists for only 63 of the 135 wells, because several of the waterworks do not collect water samples directly from the well (Chapter 4.1.2). Therefore a modified dataset (Dataset E_{mod}, Appendix L) is created using the 63 wells in Dataset E and corresponding microbiological quality for each well. A limitation is poor or non-existing drilling logs that have caused lack of data, such as well depth, thickness of superficial deposits at the well point or length of casing, for some wells. Due to this, the number of wells is less than 63 for part of the interpretation.

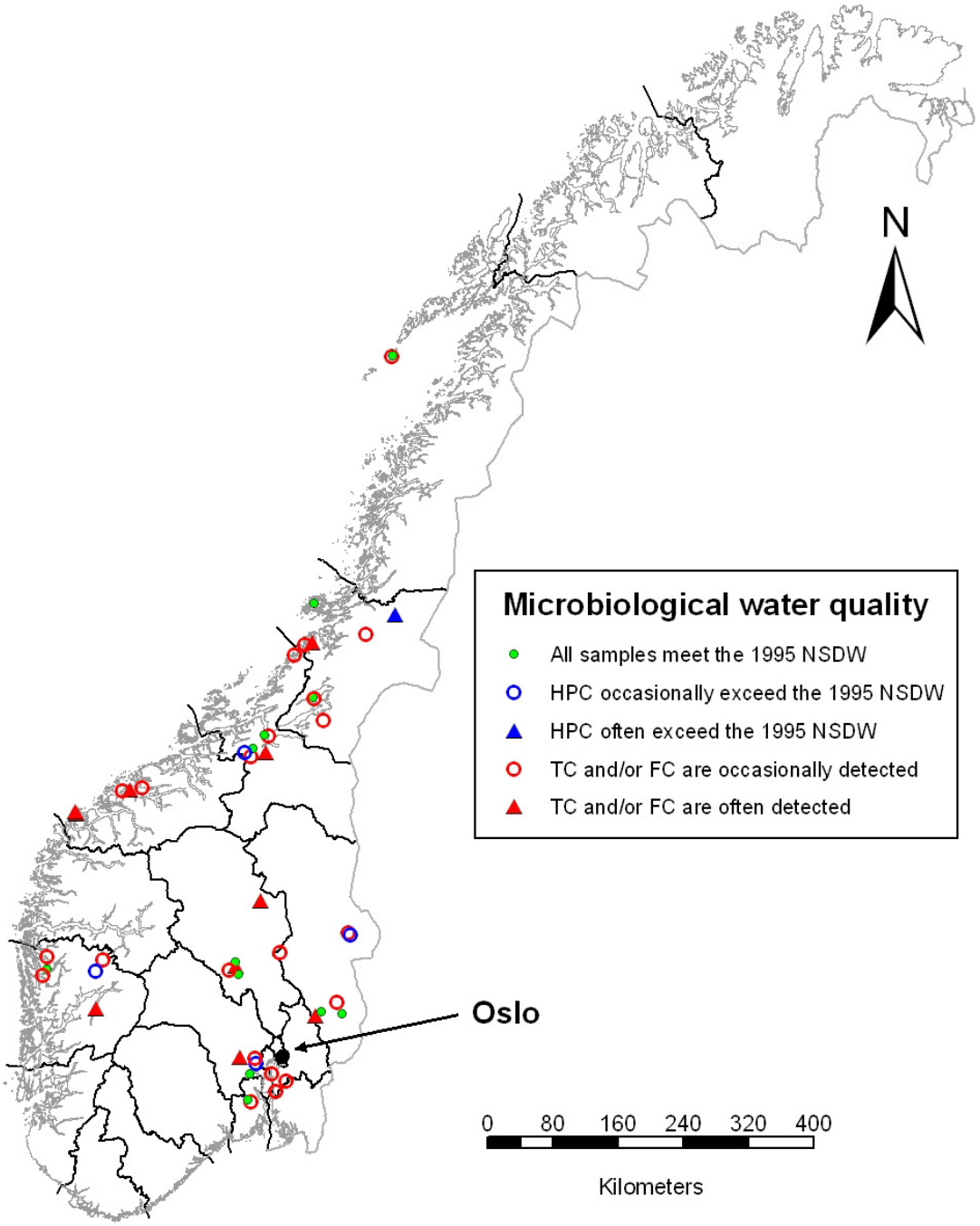

Figure 4.2.1 Geographical distribution and recorded microbiological water quality of 49 (Dataset E) of the 195 waterworks in Dataset A. All waterworks are based on groundwater from bedrock. Field inspection was carried out at these waterworks during summer/autumn 2000 (44) and 2001 (5).

4.2.2 Dataset F – Video inspections of wells

A downhole camera was used to inspect 41 wells included in Dataset E and 3 wells in Dataset D (Appendix M). Dataset E_{mod} contains 24 of the 41 wells in Dataset E and results from these wells are used to verify possible causes to microbiological contamination of the drinking water (Appendix L). Due to the small diameter of the well, large raising-main and pump-cable, additional inner casing, abandonment of the wells and lack of cooperation from well owners, inspection was intended but not carried out in additional 29 wells included in Dataset E and 2 wells in Dataset D.

5 Results

This chapter presents results based on the Datasets A-D and field inspections (Datasets E and F) introduced in Chapters 3 and 4. An overview of the microbiological quality in Norwegian bedrock wells, seasonal variations and changes in the quality from 1996-2003 (Chapter 5.1) are based on Dataset A_{mod} (169 waterworks) and Dataset C (123 waterworks). The existence of *Cryptosporidium* and *Giardia* in the groundwater is presented in Chapter 5.2 based on Dataset D. Data from the field inspections (Datasets E and F) and physio-chemical parameters in Datasets A-C are compared with the microbiological quality for 63 wells in Chapter 5.3 and 5.4 to illustrate factors influencing the microbiological quality.

5.1 Microbiological quality in Norwegian bedrock wells

5.1.1 Microbiological quality reported in the period 1996-1998

Microbiological analyses of groundwater from wells in bedrock are collected from 195 waterworks in Norway for the period 1996-98. Quality control of the dataset lowered the number of waterworks to 169 (Dataset A_{mod}, Chapter 4.1.2), which is presented in this chapter. Most of the waterworks supply primarily more than 100 persons or 20 households. The rest of the data relates to groundwater wells supplying cafés, schools or public institutions.

Revision of the Norwegian drinking water regulations from 1 January 2002 (Helse- og omsorgsdepartementet 2001) to meet the EU standard, set some new standards for the microbiological drinking water quality as described in Chapter 4.1.1 and Table 4.1.1. When discussing the microbiological quality of water supplied by waterworks in the period 1996-98 in Chapter 5.1, it is decided to use data on HPC at 22°C and HPC at 37°C because both parameters were part of the current regulations. The 1995 NSDW is therefore used. However, a brief evaluation of the microbiological quality related to the 2002 NSDW is also presented.

It is examined how many of the 169 waterworks that supply water where the number of coliforms (TC and/or FC) or HPC (at 22°C and 37°C) exceeds the former NSDW. Approximately 50 % of the waterworks sample water only at one location through the whole period 1996-98, whereas the other waterworks report to sample water from several locations. Water collected is one or more of the following: raw-water, tapwater, clean-water or unspecified samples. The water is either treated (disinfected with chlorine or UV) or untreated. If more than one water sample is collected at a specific date the water sample assumed to best represent the water reaching the consumers is used when evaluating the water quality for each waterwork. For example, tapwater is used instead of raw-water and treated water is preferred to untreated water.

Based on the reported microbiological quality, the waterworks are classified in five groups (Table 5.1.1). Waterworks that meet the requirements in the 1995 NSDW are

classified in group 1, waterworks with water quality that only exceed the 1995 NSDW on HPC are classified in groups 2 and 3 and waterworks with reported coliforms in the groundwater are classified in groups 4 and 5. Some waterworks in groups 4 and 5 neither meet the 1995 NSDW on coliforms nor HPC. Figure 5.1.1 shows the geographical location and microbiological quality of each waterwork in Dataset A_{mod}. No waterworks in this survey are located in the counties Oslo and Rogaland.

It is in Table 5.1.1 differentiated between waterworks supplying water exceeding the 1995 NSDW "often" and "occasionally". For TC and FC, indicating the presence of potentially pathogenic bacteria of fecal origin, detection of TC and/or FC in ≥ ¼ of the samples is equal to "often". HPC is both used as an indicator of the presence of biofilm in the distribution line and to measure the efficiency of disinfection (Folkehelsa 1999). The analyses give a quantitative measurement of heterotrophic microorganisms that can use organic matter as nutrient, and these are mostly harmless. Therefore, HPC has to exceed the levels set in the 1995 NSDW in ≥ 1/3 of the samples to be regarded as "often".

Table 5.1.1 Classification of waterworks in five groups, related to the number of water samples a year that does not meet the 1995 NSDW for HPC, TC and/or FC. Total number of waterworks is 169.

Group	Exceeding the 1995 NSDW	Definition	Number of waterworks
1	None	No samples a year	40
2	Occasionally HPC at 22°C > 100/ml and/or 37°C > 10/ml	< 1/3 of the samples a year	24
3	Often HPC at 22°C > 100/ml and/or 37°C > 10/ml	≥ 1/3 of the samples a year	23
4*	Occasionally detection of TC and/or FC.	< 1/4 of the samples a year	49
5*	Often detection of TC and/or FC	≥ 1/4 of the samples a year	33

* For some waterworks the groundwater also exceeds the NSDW regarding HPC

A first evaluation of the microbiological data from the original 195 waterworks showed that only 26 % of the waterworks met the 1995 NSDW with respect to microbiological parameters (Gaut et al. 2000). Quality control and a more thorough data processing (Chapter 4.1.2) lowered this number to 24 %, showing that as many as 76 % of the waterworks had problems to meet the 1995 NSDW (Figure 5.1.2). Of the 76 %, about 1/3 (47) of the waterworks only exceeded the guidance level for either HPC at 22°C or both 22°C and 37°C (HPC_{only}) (Table 5.1.1). The rest (82) had problems with the presence of coliforms or both coliforms and HPC exceeding the 1995 NSDW. About 40 % (33) of the latter group detected coliforms often.

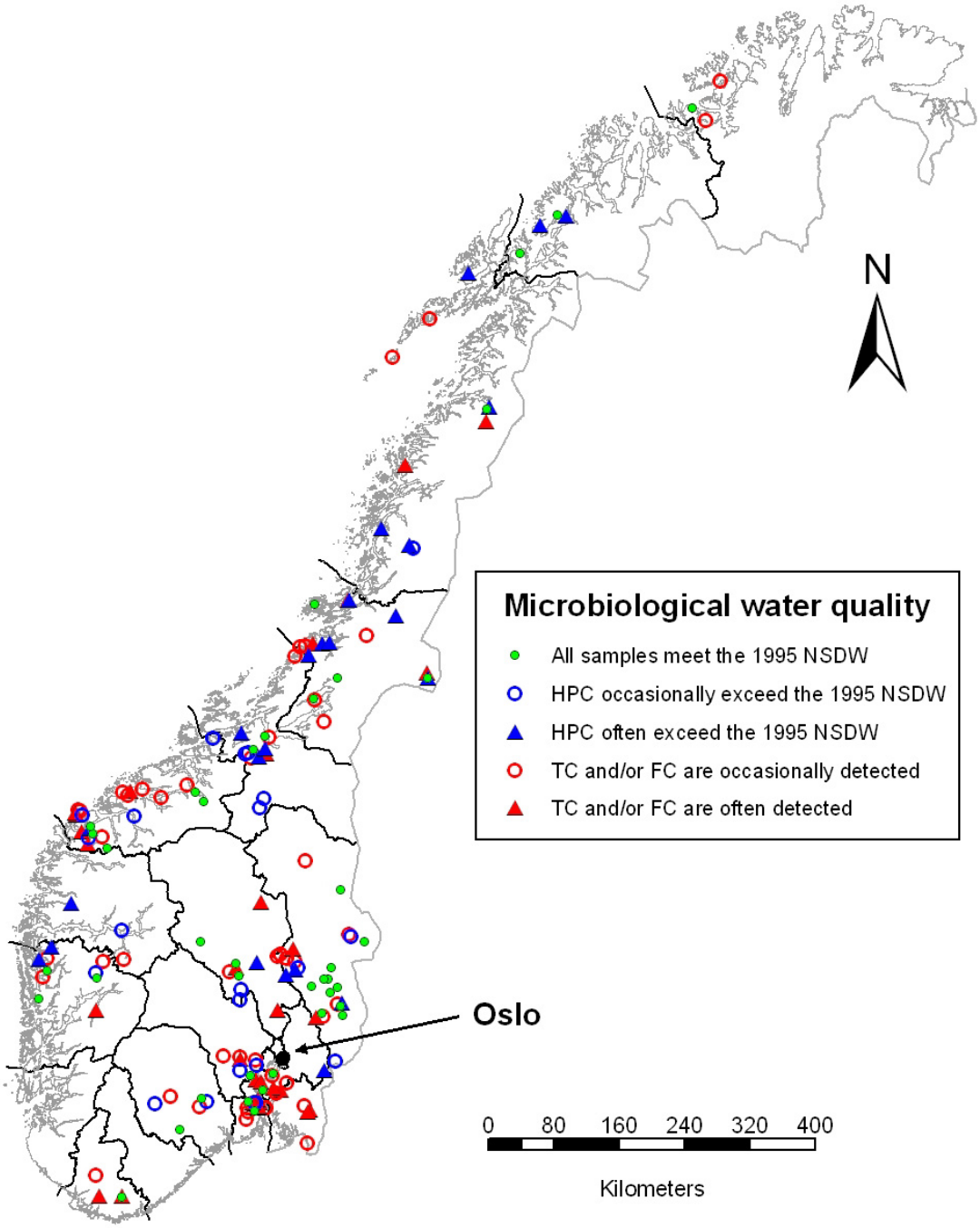

Figure 5.1.1 Reported microbiological quality of groundwater from 169 waterworks in Norway (Dataset A_{mod}). Data are mainly from the two-year period 1996 and 1997, but also from 1998.

a)

	Exceeding the 1995 NSDW		
	None	HPC_{only}	Coliforms
Group	1	2 and 3	4 and 5
Per cent (%)	24	28	48
Fraction	1/5	4/5	

b)

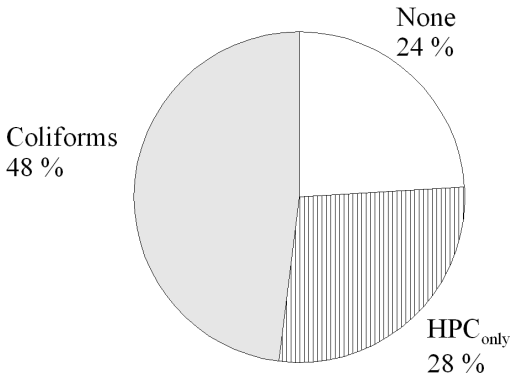

Figure 5.1.2 Norwegian waterworks using groundwater from bedrock, exceeding the 1995 NSDW with respect to microbiological water quality. Total number of waterworks is 169. The results are expressed in a) percentages and fraction and b) pie chart. Data represent the period 1996-98.

The number of coliforms and HPC in the water samples exceeding the 1995 NSDW varies. Median and arithmetic mean for the measurements are calculated for 729 water samples from 158 of the 169 waterworks in Dataset A_{mod}. The results are presented in Table 5.1.2. Most waterworks detect only 1 or 2 coliforms in the water samples, the median values are 2 for both TC and FC and 51 % and 65 % of the samples have TC and/or FC ≤ 2 respectively. The median value for HPC at 37°C is 30 and for HPC at 22°C is 300 and 52 % and 60 % of the water samples have HPC equal to or below these values respectively. All waterworks exceeding the 1995 NSDW on HPC at 37°C also exceed the former NSDW on HPC at 22°C in the period 1996-98, though not necessarily in the same water samples.

The number of water samples exceeding the 1995 NSDW in Dataset A_{mod} varies between the waterworks. Of group 2 (occasionally HPC) as many as 16 waterworks had only one incidence of HPC exceeding the 1995 NSDW in the period (Table 5.1.3). The corresponding number of group 4 (occasionally TC and/or FC) is 25, but 17 of these waterworks (not presented in Table 5.1.3) also had samples with too high HPC. Of all waterworks reporting detection of TC and/or FC (groups 4 and 5) in the drinking water, 58 (approximately 70 %) had also incidences where HPC in the water samples exceeded the 1995 NSDW (Table 5.1.3).

Table 5.1.2 Number of water samples with coliforms and HPC exceeding the 1995 NSDW. Water samples from 158 of the 169 waterworks in Dataset A_{mod} were investigated and total number of samples exceeding the 1995 NSDW regarding one or more of the parameters, is 729.

	Total coliforms	**Fecal coliforms**	**HPC at 22°C**	**HPC at 37°C**
Total samples exceeding the 1995 NSDW	237	130	507	103
Arithmetic mean	14.02	7.43	492	102.7
Median	2	2	300	30
Max	348	120	5300	1340
Min	1	1	101	11
Number of samples ≤ arithmetic mean	199 (84 %)	106 (82 %)	369 (74 %)	78 (76 %)
Number of samples ≤ median	122 (51 %)	85 (65 %)	302 (60 %)	53 (52 %)
Number of samples ≤ 5	157 (66 %)	103 (79 %)	-	-

Table 5.1.3 Number of waterworks (groups 2-5) exceeding the 1995 NSDW. Several waterworks in groups 4 and 5 also exceed the 1995 NSDW regarding HPC. The total number of these waterworks (Total), and those where HPC "often" exceeds the 1995 NSDW (Often) are given.

Group	**Exceeding the 1995 NSDW**	**Total number of waterworks**	**Waterworks where also HPC exceeds the 1995 NSDW (Total/Often)**	**Waterworks where the 1995 NSDW is exceeded only once**
2	Occasionally HPC at 22°C > 100/ml and/or 37°C > 10/ml	24	-	16
3	Often HPC at 22°C > 100/ml and/or 37°C > 10/ml	23	-	-
4	Occasionally detection of TC and/or FC.	49	36 / 7	25
5	Often detection of TC and/or FC	33	23 / 14	-

The majority of water samples analysed is of untreated water both for waterworks supplying water exceeding and not exceeding the 1995 NSDW (Table 5.1.4). In all groups the existence of treatment is unknown for 3-12 waterworks. 1-4 waterworks in each group are reported to sample both untreated water and treated water or water where the existence of treatment is unknown.

Table 5.1.4 Number of waterworks in the different classification groups 1-5 (Table 5.1.1) sampling treated or untreated water. *"Treated water"* is disinfected with chlorine or UV. "*Untreated water"* covers untreated water and raw-water samples (in the reports received) and samples from waterworks not disinfecting the water. *"Existence of treatment unknown"* means; unspecified samples, tapwater and clean-water from waterworks where the existence of treatment is unknown.

Group	Total number of waterworks	Treated water	Untreated water	Existence of treatment unknown	Type of water sampled varies between untreated and treated/unknown treatment
1	40	4	27	8	1
2	24	1	15	6	2
3	23	4	13	5	1
4	49	4	38	3	4
5	33	0	20	12	1

The reported microbiological quality for the waterworks in Dataset A_{mod} is also compared with the present NSDW from 2002 (Table 4.1.1). All samples where only HPC at 37°C exceeded the 1995 NSDW are left out and the guidance level for HPC at 22°C is treated as an action level. As seen in Table 5.1.5, the difference in water quality when relating to the 2002 NSDW instead of the 1995 NSDW is minimal. Only three waterworks change group number; from 3 to 2 (two waterworks) and from 2 to 1 (one waterwork). Additionally two more waterworks, going from 16 (Table 5.1.3) to 18, of group 2 have only one incidence of HPC exceeding 100/ml. No difference can be seen for the waterworks in groups 4 and 5 that also report HPC exceeding the NSDW when comparing with Table 5.1.3.

Table 5.1.5 Differences in microbiological water quality at the 169 waterworks in Dataset A_{mod} when comparing the number of water samples a year that does not meet the 1995 NSDW and the 2002 NSDW regarding HPC and TC and/or FC.

Group	Exceeding the 1995/2002 NSDW	Number of waterworks compared with the 1995 NSDW	Number of waterworks compared with the 2002 NSDW
1	None	40	41
2	Occasionally HPC	24	25
3	Often HPC	23	21
4*	Occasionally detection of TC and/or FC	49	49
5*	Often detection of TC and/or FC	33	33

* For some waterworks the groundwater also exceeds the NSDW regarding HPC

5.1.2 Seasonal variations in the microbiological quality reported 1996-1998

Dataset A_{mod} is examined for seasonal changes in microbiological quality using data from the 131 waterworks with water samples exceeding the 1995 NSDW. For 6 of the 131 waterworks the sampling date is not known and the waterworks cannot be used in this evaluation. Samples of disinfected water are not used, consequently excluding 8 waterworks where all water samples are disinfected. In total, data from 117 waterworks with water samples exceeding the 1995 NSDW in the period 1996-98 are examined. Distribution of waterworks between the different counties is shown in Table 5.1.6. The numbers of reported contamination episodes each month are registered separately for each county for the different parameters (Appendix N). It is not differentiated between the years 1996, 1997 and 1998. Due to similar geographical area and/or few waterworks or few contamination episodes in one or more of the counties, some counties are plotted together. These are:

- Akershus, Buskerud and Vestfold
- Telemark and Vest-Agder
- Hordaland and Sogn & Fjordane
- Sør-Trøndelag and Nord-Trøndelag
- Nordland, Troms and Finmark

Table 5.1.6 Number of waterworks with water samples exceeding the 1995 NSDW in the Norwegian counties in the period 1996-98. Total number of waterworks is 117. Total number of samples represents all water samples analysed; both exceeding and not exceeding the 1995 NSDW.

County	Total number of waterworks	Total number of samples	County	Total number of waterworks	Total number of samples
Østfold	0	0	Rogaland	0	0
Akershus	6	87	Hordaland	7	123
Oslo	0	0	Sogn & Fjordane	3	42
Hedmark	14	393	Møre & Romsdal	18	309
Oppland	7	166	Sør-Trøndelag	11	138
Buskerud	6	114	Nord-Trøndelag	14	233
Vestfold	14	124	Nordland	6	89
Telemark	4	79	Troms	2	31
Aust-Agder	0	0	Finmark	2	83
Vest-Agder	3	41			

Total number of water samples exceeding the 1995 NSDW is summarised in Figure 5.1.3. In Figure 5.1.3a), the blue curve shows total samples with both coliforms and/or HPC exceeding the 1995 NSDW. Fewest samples are found from January to April, an increase occurs through summer with a peak in September before the number of samples decreases towards December. It is shown that the increase from March to June is caused by an increase in samples with HPC exceeding the 1995 NSDW, whereas the pronounced peak in September is mainly caused by coliforms. In Figure 5.1.3b) the

curves for TC and FC have a nearly identical shape though FC occur in fewer samples than TC. During winter and spring few water samples exceed the 1995 NSDW. Most coliforms detected during winter are TC, whereas a small increase in FC detected occurs during spring. A pronounced increase in water samples exceeding the 1995 NSDW starts in July with a major peak in September, followed by a rapid decrease. Figure 5.1.3a) shows that samples with HPC exceeding the guidance level follow a more undulating curve and high HPC is more common throughout the year compared to coliforms. Peaks appear in February, June and October with a steady increase from March to October. Separation of HPC at 22°C and HPC at 37°C (Figure 5.1.3c) shows that the latter exceeds the guidance level in fewer water samples than HPC at 22°C, though the curve shape resembles that of HPC at 22°C.

Seasonal changes in water samples exceeding the 1995 NSDW regarding HPC or coliforms for the counties in Table 5.1.6 are presented in Figures 5.1.4 and 5.1.5 respectively. Figure 5.1.4 shows that the distribution of samples with too high HPC differs between the counties, though similarities exist:

- In Oppland (a), Telemark and Vest-Agder (b), Hordaland and Sogn & Fjordane (c), Møre & Romsdal (c) and Nordland, Troms and Finmark (d) the amount of water samples exceeding the 1995 NSDW is approximately the same throughout the year. It is not possible to locate the peaks in February, June and October from Figure 5.1.3(a), except for Hordaland and Sogn & Fjordane (Figure 5.1.4c) that has a peak in February. However other small peaks are located, such as Hordaland and Sogn & Fjordane in August and Telemark and Vest-Agder in November.
- The counties contributing most to the peaks found in Figure 5.1.3(c) are Hedmark (Figure 5.1.4a), Akershus, Buskerud and Vestfold (b) and Trøndelag (d). Hedmark has maximum peaks in May and October with several water samples exceeding the 1995 NSDW also in June. Vestfold, Akershus and Buskerud have three peaks; February, June and September, whereas Trøndelag has many samples exceeding the 1995 NSDW from June to December with a peak in September.

Seasonal changes in coliforms are shown in Figure 5.1.5.

- For most counties a wide peak is shown, which extends from July to October with the maximum normally in September. Exceptions are Telemark and Vest-Agder (b) and Møre & Romsdal (c), which have a decrease in samples exceeding the 1995 NSDW in August. Consequently peaks occur both in July and September.
- Trøndelag (d) and Nordland, Troms and Finmark (d), are interpreted to only have a peak in the autumn.
- Hedmark (a), Oppland (a), Akershus, Buskerud and Vestfold (b) and Hordaland and Sogn & Fjordane (c) have an additional peak in spring occurring from February to May depending on the county.
- In Møre & Romsdal (c) no month has zero samples with coliforms.

It is investigated if the seasonal changes are related to sampling frequency. Correlations are indicated for all counties, but no direct relationship is found. In Figures 5.1.6 and 5.1.7 examples from 6 counties are shown. Diagrams a-c) show HPC and diagrams d-f) show coliforms in both figures. Total number of water samples analysed (black), number of samples not exceeding the 1995 NSDW (green) and number of samples exceeding the 1995 NSDW (red) are plotted in Figure 5.1.6. In Figure 5.1.7 only total number of water samples analysed (black) and percent of total samples exceeding the 1995 NSDW (blue) are plotted.

Simultaneous increases and decreases occur comparing the red, green and black curves both for HPC and coliforms (Figure 5.1.6). Examples are Hedmark (a) in January-March and November-December, Hordaland and Sogn & Fjordane (b) in November-December and Akershus, Buskerud and Vestfold (e) in July-August.

However in periods the number of samples exceeding the 1995 NSDW increases or remains the same, even though the total number of samples collected decreases. Examples are Hedmark in May (a) and Hordaland, Sogn & Fjordane (b) in July, Telemark and Vest-Agder (c) in April, Akershus, Buskerud and Vestfold (e) in July and Nordland, Troms and Finmark (f) in November. In these examples the red and green curves are simultaneously converging (Figures 5.1.6) and the curve showing the percent of the total samples exceeding the 1995 NSDW are increased (Figure 5.1.7). This further confirms that the increase in number of samples exceeding the 1995 NSDW is not entirely related to sampling frequency, but also to increases in microbiological contamination of the water. Divergence of the green and red curves and decrease in the percent of total samples exceeding the 1995 NSDW will likewise confirm that the seasonal changes in samples exceeding the 1995 NSDW are not only related to sample frequency. Examples are Hedmark (Figures 5.1.6a and 5.17a) in June, Telemark and Vest-Agder (c) in February, Oppland (d) in December and Nordland, Troms and Finmark (f) in October.

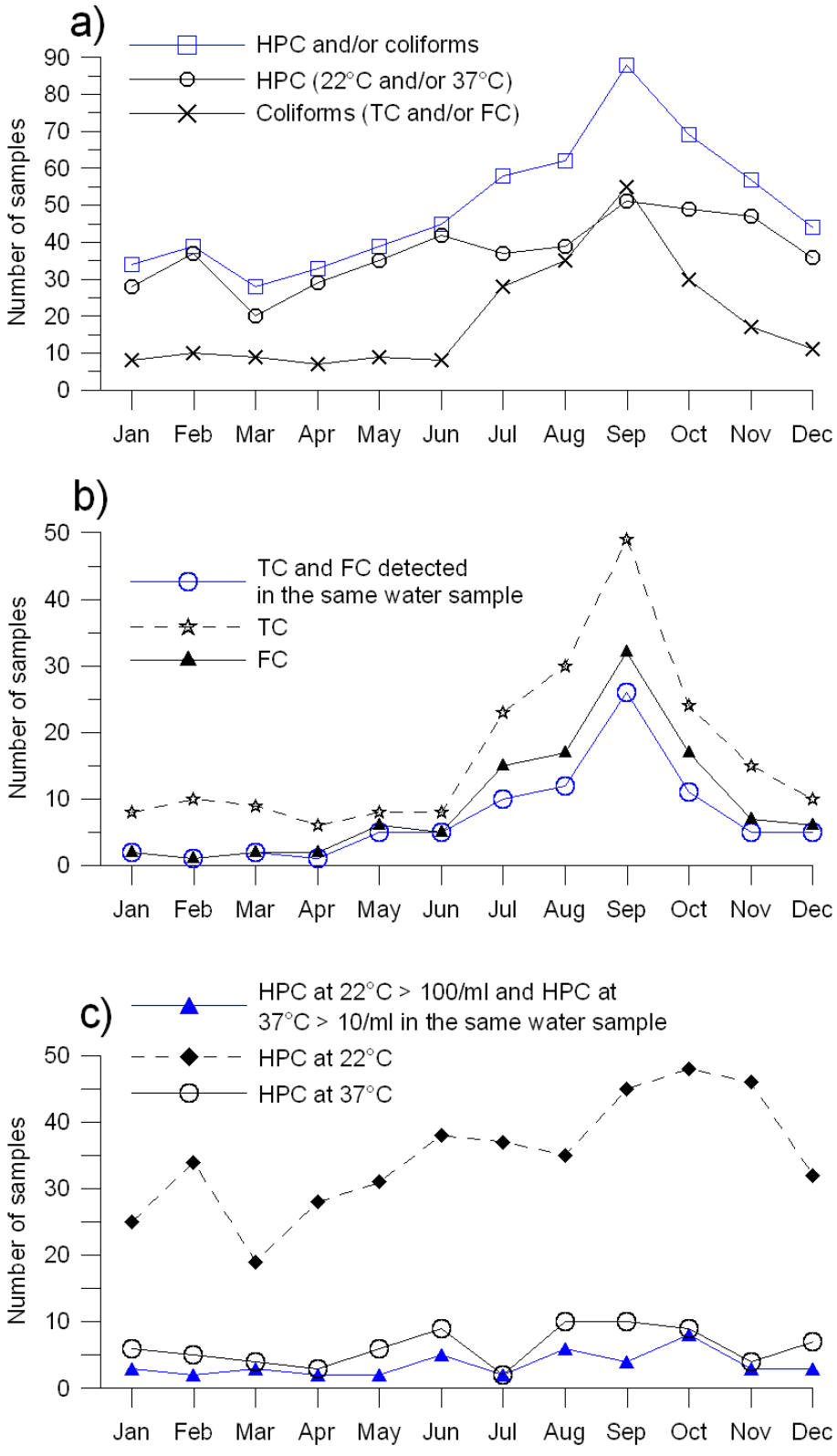

Figure 5.1.3 Seasonal changes in number of water samples that exceeds the 1995 NSDW regarding HPC and coliforms in the period 1996-98. Number of waterworks is 117. a) Total samples with HPC and/or coliforms, b) TC and FC and c) HPC.

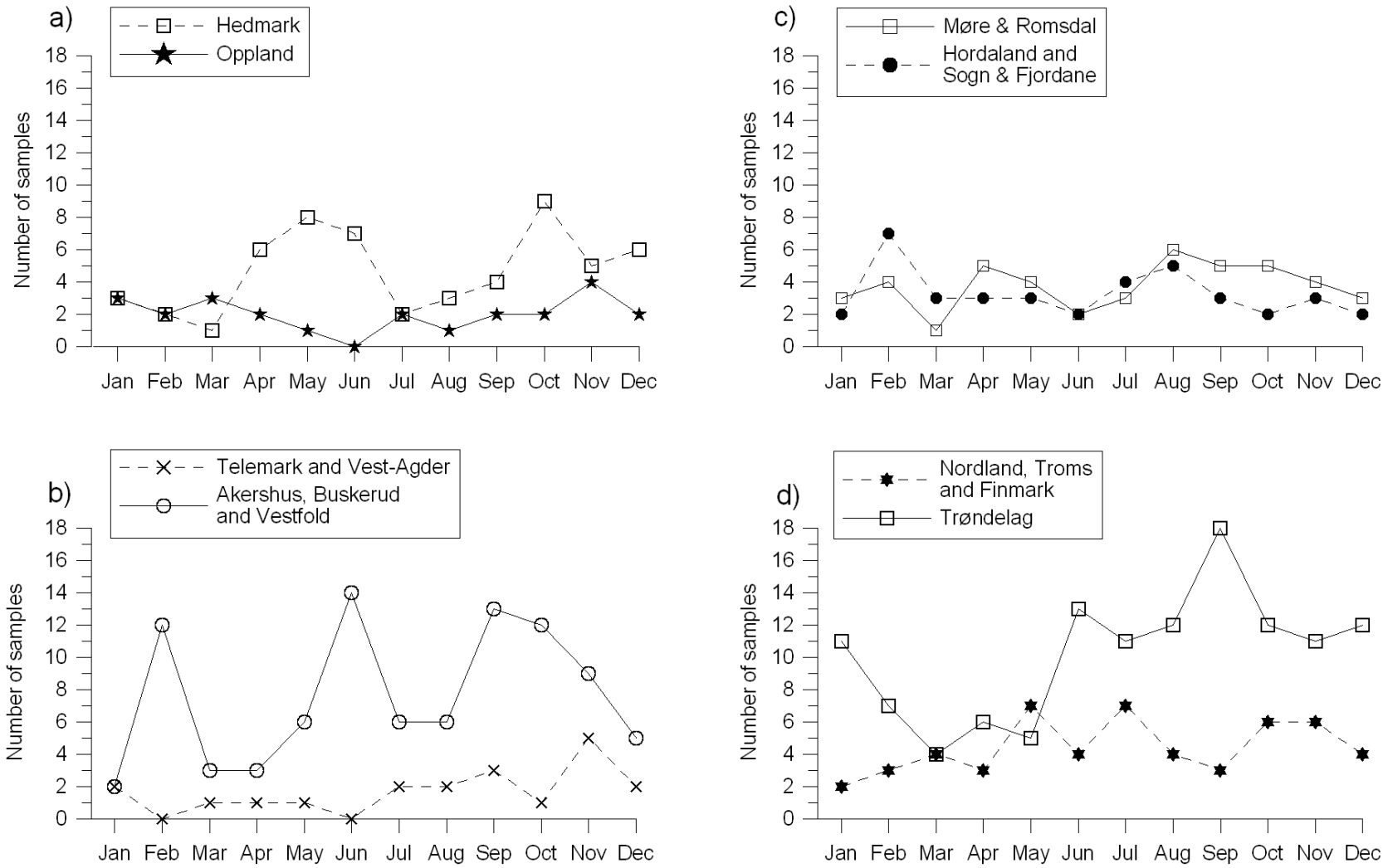

Figure 5.1.4 Seasonal changes in number of water samples with HPC at 22°C and/or 37°C exceeding the guidance level in the 1995 NSDW in the period 1996-98. Number of waterworks in the different counties is presented in Table 5.1.6.

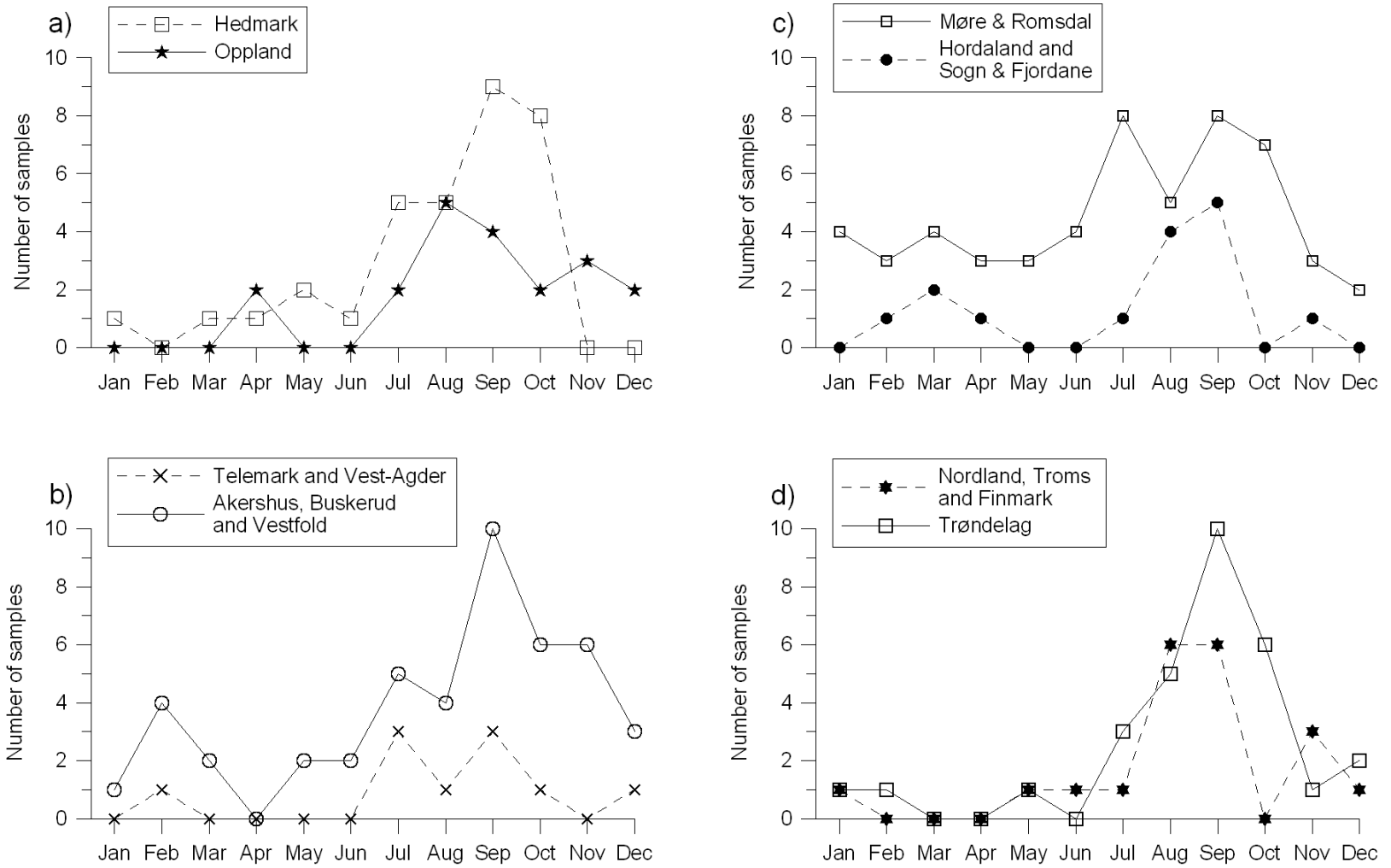

Figure 5.1.5 Seasonal changes in number of samples with total coliforms and/or fecal coliforms exceeding the 1995 NSDW in the period 1996-98. Number of waterworks in the different counties is presented in Table 5.1.6.

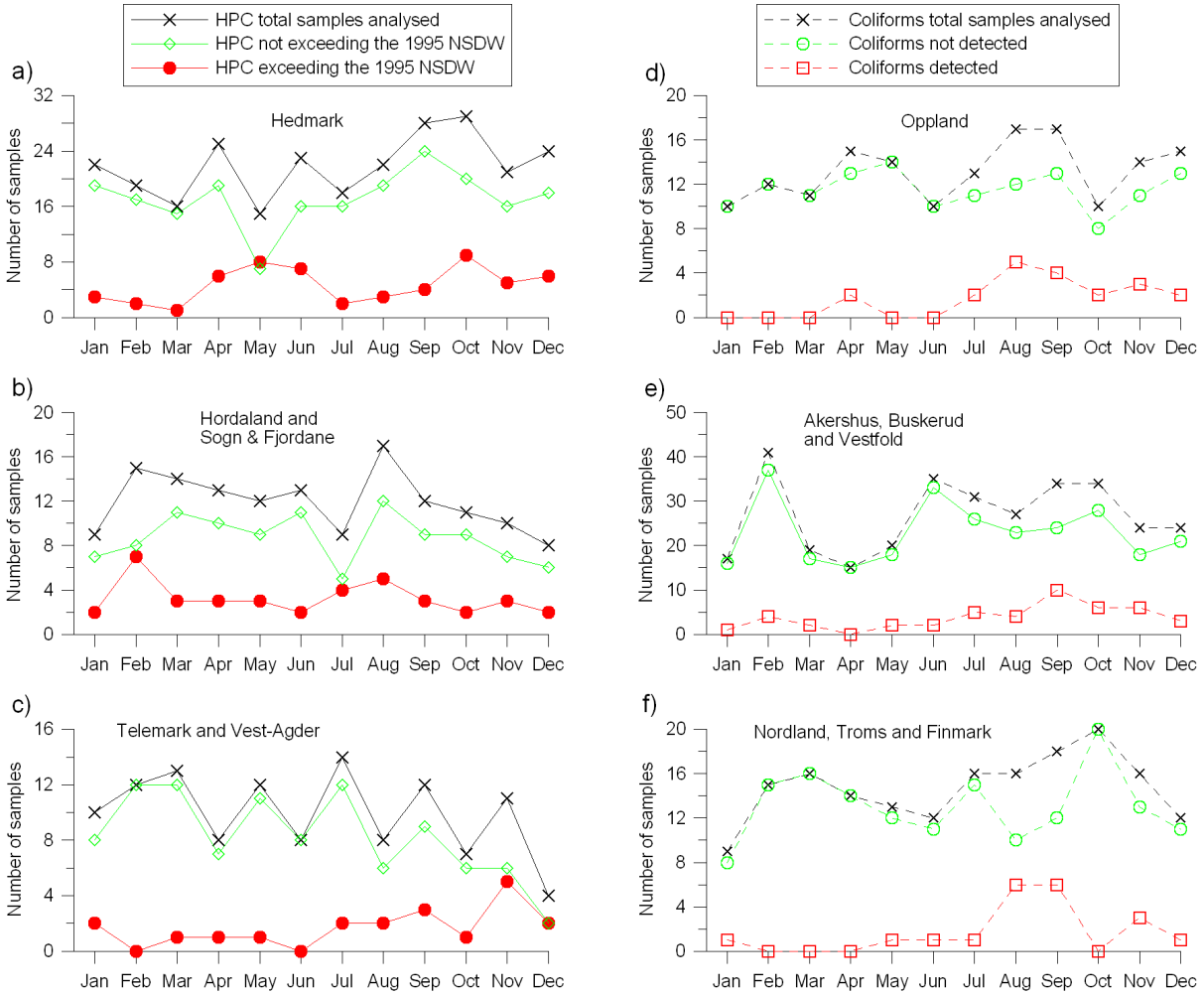

Figure 5.1.6 Seasonal changes in number of water samples analysed. Diagrams a-c show HPC at 22°C and/or 37°C and d-f show coliforms (TC and/or FC). Black; all samples analysed, green; samples where HPC or coliforms do not exceed the 1995 NSDW and red; samples where HPC or coliforms exceeds the 1995 NSDW.

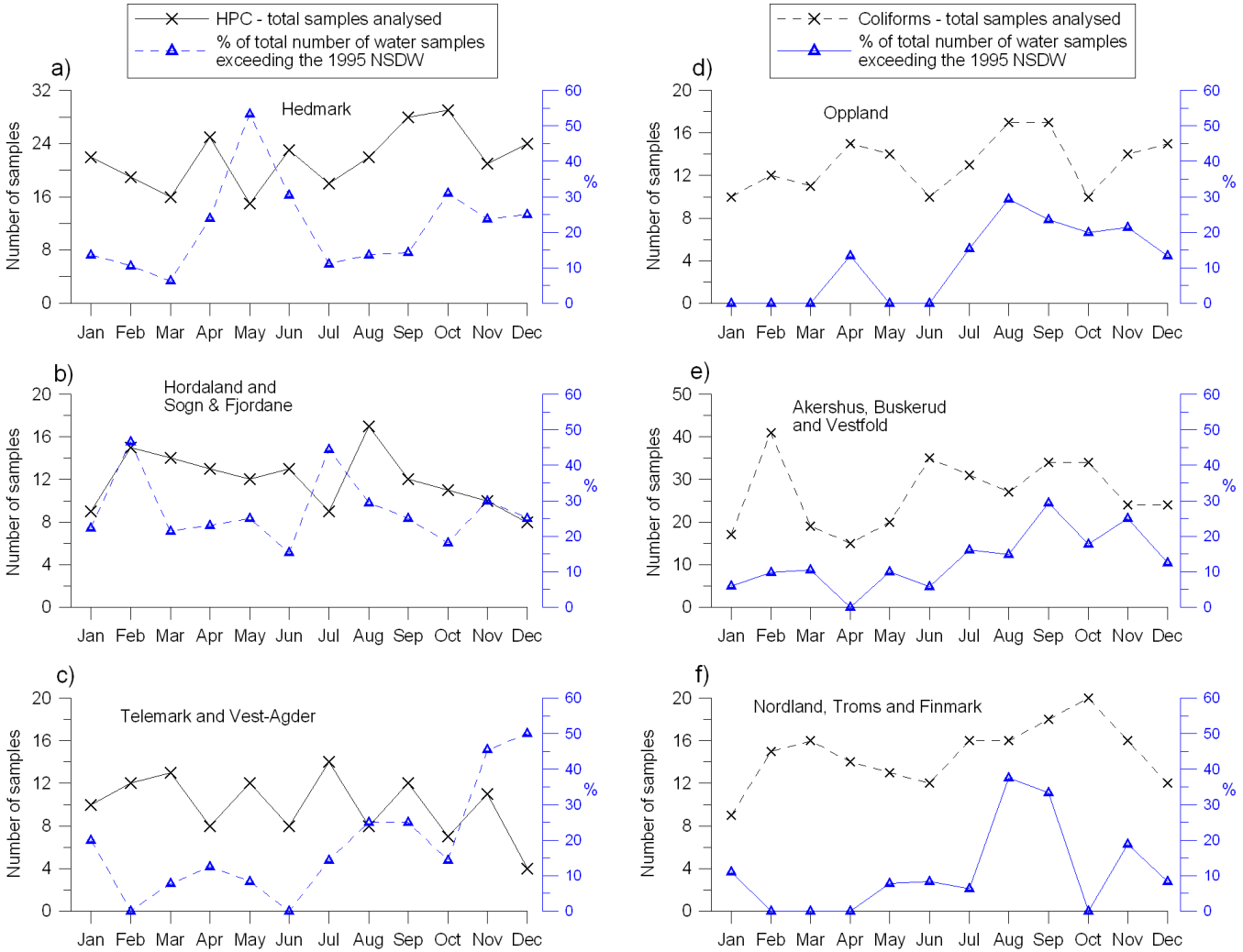

Figure 5.1.7 Percent (%) of the total water samples analysed exceeding the 1995 NSDW (blue) and total water samples analysed (black). Diagrams a-c show HPC and d-f show coliforms (TC and/or FC).

5.1.3 Changes in microbiological quality in the period 1996 to 2003

This study started in 1998 and since then there has been an increased focus on drinking water quality in Norway related to the NSDW, PROVA and Norwegian membership in EEA (Chapter 1.1). In order to investigate any positive effect of this increased focus, additional microbiological analyses of water samples from 123 of the 169 waterworks in Dataset A_{mod} have been collected for the period 1999-2003 (Dataset C). For comparison only coliforms (TC and FC/*E. coli*) and HPC at 22°C are used as in the 2002 NSDW. Collection of the dataset is described in Chapters 3.1 and 4.1.4. Like Dataset A, water quality from water samples assumed to best represent the water reaching the consumers is used if water quality is received for more than one type of water. The microbiological quality per year for each waterwork is presented in Appendix C and the results are summarised in Figure 5.1.8a).

Water quality data from waterworks in Dataset C is compared with respective waterworks in Dataset A_{mod} to detect changes in water quality over time. The microbiological water quality is not always the same each year for individual waterworks. Thus, the pronounced improvement registered for 1999 compared to the period 1996-98 (Figure 5.1.8a) is only apparent, caused by comparing a three year period with a single year. This is demonstrated by Figure 5.1.8b) where the results from the two year period 1996-97 are compared with the results from each of the years 1996 and 1997.

The microbiological water quality is known for only 104 of the123 waterworks for each of the years 1996-2003 (Figure 5.1.8b). A small improvement in water quality has occurred from 1997 to 1999 when comparing the single years. This improvement is caused by a decrease in number of waterworks with reported coliforms from 37 to 23. Except for 2000, the number of waterworks with good quality remains more or less constant during the subsequent period 1999-2003. Thus, in general, the number of waterworks with good water quality shows a small increase after 1997.

The changes of the microbiological quality at individual waterworks, from one year to another are presented in more detail in Table 5.1.7. The table shows how many of the 123 waterworks that have no water samples exceeding requirements in the NSDW (good quality) at different time intervals compared to the water quality reported in 1996-98. Of the 27 waterworks with good microbiological water quality in 1996-98 only 9 maintain this status through the whole period 1999-2003. In total, only 18 waterworks have good microbiological water quality throughout the entire period 1999-2003. Of the 96 waterworks with reported HPC > 100/ml (33) or detected coliforms (63) in 1996-98, 9 waterworks have good microbiological quality in the entire period 1999-2003, whereas 20 waterworks, not presented in Table 5.1.7, have microbiological problems every year.

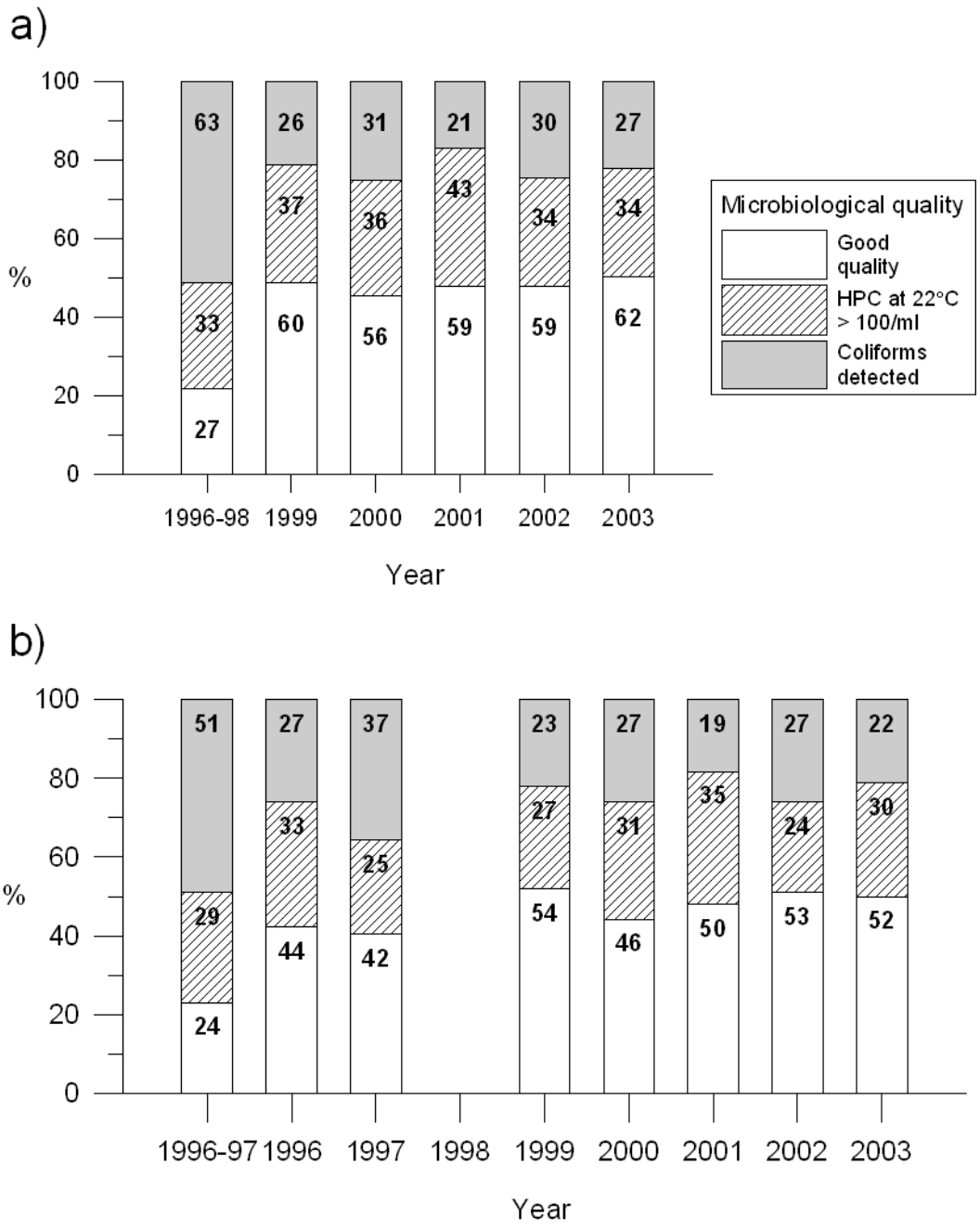

Figure 5.1.8 Changes in microbiological quality in the period 1996 to 2003. a) All 123 waterworks in Dataset C. b) 104 of the 123 waterworks in Dataset C. Waterworks are shown in percent with actual number of waterworks labelled on bars. Good quality = no water samples exceed the 2002 NSDW and Coliforms = TC and FC/*E. coli*.

Table 5.1.7 Number of waterworks with good microbiological water quality in different time periods from 1999 to 2003. Good = no water samples exceed requirements in the 2002 NSDW, HPC_{only} = HPC at 22°C exceed > 100/ml and coliforms = total coliforms and/or fecal coliforms/*Escherichia coli* are detected.

Microbiological quality reported in 1996-1998		**Number of waterworks reporting <u>good</u> microbiological water quality throughout the entire time period compared to the water quality reported in 1996-98, listed to the left.**				
		1999-2003	**2000-2003**	**2001-2003**	**2002-2003**	**2003**
Good	27	9	9	12	13	19
HPC_{only}	33	3	4	7	11	18
Coliforms	63	6	9	10	16	25
Total	123	18	22	29	40	62

5.1.4 Existence of protection zones – waterworks in Dataset C

Of the 123 waterworks in Dataset C, 22 have delineated protection zones (NIPH unpublished). With exception of six waterworks included in Dataset E, the number and extent of the zones are unknown. The land use and wellhead completion are also unknown for all but eight waterworks in Dataset E. Table 5.1.8 shows that of the 22 waterworks with established protection zones only 36 % (8) of the waterworks reported good microbiological water quality and 32 % (7) still reported coliforms in 2003. The corresponding numbers for the 101 waterworks assumed not to have delineated protection zones, are 53 % (54) and 20 % (20) respectively.

Table 5.1.8 Number of waterworks supplying groundwater periodically exceeding the 2002 NSDW in relation to reported existence of protection zones. Data are from VREG for 2003 (NIPH unpublished). Total number of waterworks is 123.

	Total number of waterworks	**Exceeding the NSDW (%)**		
		None	HPC_{only}	Coliforms
Waterworks with protection zones	22	36	32	32
Waterworks without protection zones	101	53	27	20

5.1.5 Private and public waterworks – Dataset A_{mod}

Throughout the world private water supplies, generally, more often have problems with the microbiological water quality than public water supplies (Dawson & Sartory 2000). In Norway waterworks are owned and operated on a private bases or by the municipality. Of the 169 waterworks in this survey (Dataset A_{mod}) 72 are private and 97 are public. The ratio of waterworks with different microbiological water quality within the two groups in the period 1996-98 is plotted on an x-y-plot in Figure 5.1.9. Which shows no significant difference in microbiological water quality between private and public waterworks.

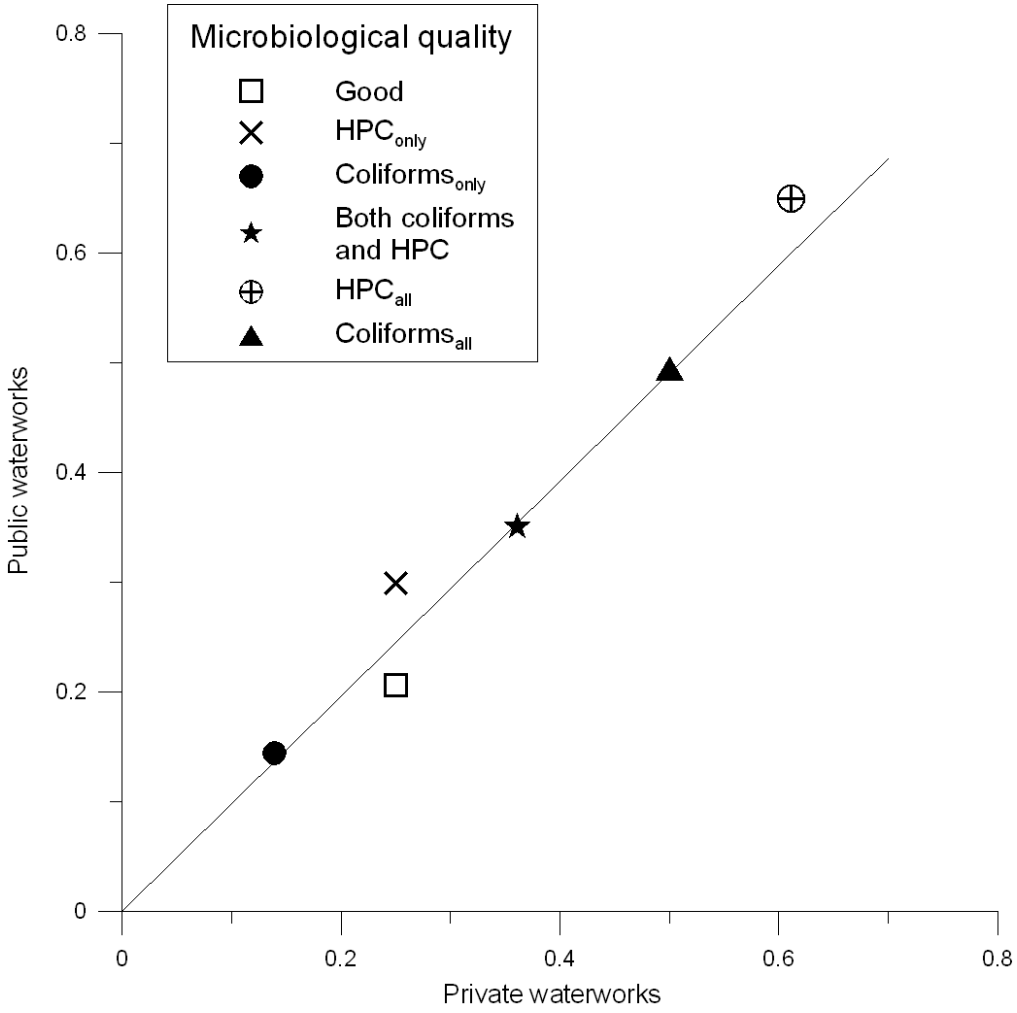

Figure 5.1.9 x-y-Plot showing the differences in microbiological water quality between 72 private waterworks and 97 public waterworks in Dataset A_{mod} in the period 1996-98. The ratio of waterworks with different microbiological water quality within the two groups is plotted. Good = no water samples exceed requirements in the 1995 NSDW. HPC_{all} and $coliforms_{all}$ represent all waterworks reporting these parameters exceeding the 1995 NSDW, whereas HPC_{only} and $coliforms_{only}$ represent waterworks only reporting one of these parameters exceeding the 1995 NSDW.

5.2 *Cryptosporidium* and *Giardia* in groundwater

Groundwater was sampled from 20 waterworks (Dataset D) and analysed for *Cryptosporidium* and *Giardia* (Figure 5.2.1a). The samples were also analysed for turbidity. For 10 of the waterworks water samples were simultaneously collected and analysed for *Clostridium perfringens* (Figure 5.2.1b).

Cryptosporidium is found in three of the 20 samples (Table 5.2.1, Figure 5.2.1a), whereas *Giardia* and *Clostridium perfringens* are not found (Tables 5.2.1 and 5.2.2). Unfortunately analyses of *Clostridium perfringens* were not performed on any of the water samples from waterworks where *Cryptosporidium* are found.

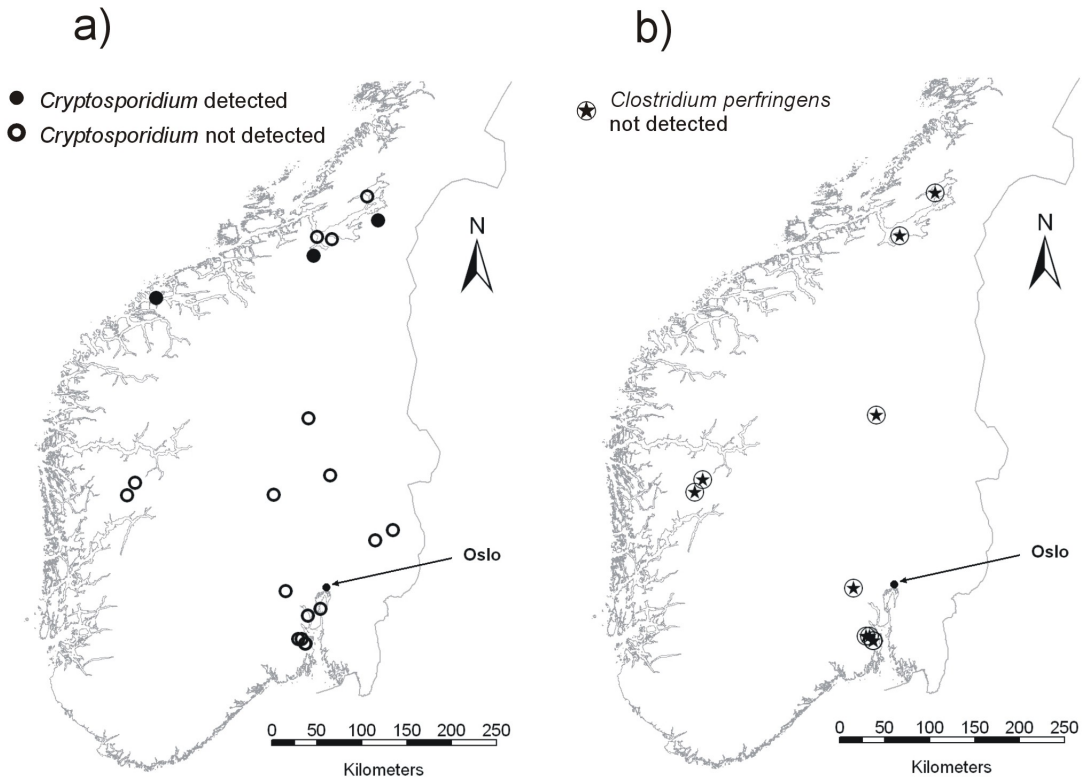

Figure 5.2.1 a) Geographical distribution of the 20 waterworks where water was sampled for analyses for *Cryptosporidium* and *Giardia*. Filled circles mark waterworks where *Cryptosporidium* was detected. *Giardia* was not detected. b) Geographical distribution of the 10 waterworks where water was also analysed for *Clostridium perfringens*. This bacteria was not detected at any of the waterworks.

Table 5.2.1 Analyses of *Cryptosporidium* (*Crypto*), *Giardia* and turbidity at 20 waterworks based on groundwater from bedrock. The samples were collected in 2004 and analysed at the Norwegian School of Veterinary science. nd = not detected.

Waterwork	Date collected	Date analysed	Turbidity (FTU)	Volume (litre)	*Crypto*	*Crypto*/l	*Giardia*
Lavollen, Trondheim	28/04/04		0.4	10	nd	–	nd
Lisbetsæter Gjestehus	28/04/04		0.4	10	1	0.1	nd
Vika Camping	28/04/04		1.0	10	nd	–	nd
Buskerud vgs. (BH1)	04/05/04		0.5	10	nd	–	nd
Fagerstrand sameie I and II (BH1)	07/05/04		0.5	10	nd	–	nd
Markabygda (water reservoir)	04/05/04	07/05/04	0.7	10	1	0.1	nd
Vennes	05/05/04	07/05/04	0.3	10	nd	–	nd
Brekkeåsen (Bh ved vannverk)	12/05/04	14/05/04	0.3	9.5	nd	–	nd
Gretteåsen	13/05/04	14/05/04	0.5	9.75	nd	–	nd
Krakken 1	13/05/04	14/05/04	0.4	10	nd	–	nd
Solby	13/05/04	14/05/04	0.65	9.5	nd	–	nd
Hella (Well at Svolvik)	18/05/04		0.3	9.5	nd	–	nd
Søre-Midøy	24/05/04	28/05/04	0.9	10	1	0.1	nd
Kyte	25/05/04	28/05/04	0.3	10	nd	–	nd
Haugsvik*[1]	25/05/04	14/05/04	0.4	10	nd	–	nd
Reinli (fra stavkirke)	27/05/04	03/06/04	0.4	9.5	nd	–	nd
Morterud	26/05/04	03/06/04	0.3	9	nd	–	nd
Venabygdsfjellet (Well 1-3)	24/05/04	03/06/04	0.6	10	nd	–	nd
Kvisler (BH1)	26/05/04	03/06/04	1.4	8	nd	–	nd
Lismarka (BH2)	25/05/04	03/06/04	0.4	9.75	nd	–	nd

*[1] Many ferric(?) particles in sample, interfering with immunomagnetic separation (IMS)

Table 5.2.2 Analyses of *Clostridium perfringens* from 10 waterworks based on groundwater from bedrock. All samples were analysed within 24 h of sampling. Volume analysed is 100 ml. Because two techniques/reference methods are used, the results are given both as 0 (mCP agar) and < 1 (SFP agar), thus the results are equivalent (Table 3.2.2).

Waterwork	Date collected	*Clostridium perfringens*	Comments
Lavollen, Trondheim	28. April 2004	0	
Buskerud vgs. (BH1)	05. May 2004	0	Sample collected the day after the sample analysed for *Cryptosporidium*
Vennes	05. May 2004	<1	
Brekkeåsen (Bh ved vannverk)	13. May 2004	<1	
Gretteåsen	13. May 2004	<1	
Krakken 1	13. May 2004	<1	
Solby	13. May 2004	<1	
Kyte	25. May 2004	0	
Haugsvik	25. May 2004	0	
Venabygdsfjellet (Well 1-3)	24. May 2004	0	

5.3 Factors influencing the microbiological quality of the groundwater

As described in Chapters 3.3 and 4.2, a total of 135 wells from 49 waterworks (Dataset E) in Dataset A are examined with regard to the following parameters:

- Design and protection of the well
- Thickness and extension of superficial deposits in the well area and location relative to the occurrence of marine sediments.
- Land-use around the well
- Possible sources of contamination
- Distance from surface water

Microbiological quality of the groundwater is known for 63 of the 135 wells examined (Chapter 4.2). The 63 wells (Dataset E_{mod}) represent 34 waterworks. 14 private waterworks contribute with one well each and the remaining 49 wells are from 20 public waterworks. To identify possible causes for microbiological contamination data are compiled into a database (Appendix L) and for each parameter listed above; the wells are grouped according to reported microbiological water quality:

- Good microbiological quality (all reported water samples meet the revised NSDW of 2002). In tables and figures these wells are classified as "None".

- HPC at 22°C is periodically reported to exceed 100/ml. Coliforms are not detected in these wells. In tables and figures these wells are classified as "HPC_{only}".
- Coliforms (TC and/or FC) are periodically detected. In table and figures these wells are classified as "Coliforms". In some of the wells, HPC at 22°C is also reported to exceed 100/ml.

Microbiological analyses used are both from Dataset A (1996-1999), Dataset B (2000-2002) and Dataset C (1999-2003). Waterworks with only one well have been included in the interpretation, even though the waterworks do not collect water directly from the well.

To evaluate statistical significance (95 % confidence interval) boxplot (Tukey 1977) or student t-test (Swan et al. 1995) is used. Statistical significant differences found by the t-test are presented in Appendix D.

In Chapter 5.3.1 improvements of 13 wells are described and improvements in microbiological water quality are listed in Table 5.3.2. Except for Chapter 5.3.1, it is in Chapter 5.3 chosen to use microbiological water quality recorded after completing the well improvements. This will reduce the influence from improper wellhead constructions on the reported microbiological water quality when evaluating the other parameters.

Comments on abandoned wells are presented in Chapter 5.3.6

5.3.1 Well construction and protection

Improper well design and wellhead protection is a well-known cause to microbiological contamination of the groundwater (Wheaton & Bohman 1999, Daly 2000, Korkka-Niemi 2001). In this chapter protection zones, wellhead completion and design of the casing are described for the 63 wells in Dataset E_{mod} to identify possible correlations with microbiological water quality. In addition well depth, capacity, water inflow, water level and use of yield enhancement are correlated with reported microbiological water quality.

Protection zones:

Only 5 of the 34 waterworks in Dataset E_{mod} (10 wells) had established protection zones around the wells at the time of field inspection, and 2 waterworks (14 wells) had started the process. Mainly three protection zones (zones 0-2) are used for the 10 wells, based on guidelines given by Eckholdt & Snilsberg (1992) (Chapter 2.4.4). The external boundary of the outer protection area (zone 2) is equal to the surface catchment area.

A fence, surrounding zone 0 exists for 3 of the 5 waterworks with established protection zones. 3 other waterworks with no formally established protection zones have also enclosed the area around the well. Totally in Dataset E_{mod}, fencing is put up around 10 wells, though only 2 fences are satisfactory maintained. The rest have access

possibilities for animals or people through holes. The fenced in areas are from 1.5 m^2 to 350 m^2, but mostly about 20-30 m^2. Figure 5.3.1 shows one of the two satisfactory maintained fences.

Of the two wells with a properly maintained fence one supply water meeting the requirements in the NSDW, whereas the other contain water with HPC exceeding 100/ml. Since only two wells out of 63 have a proper fence, no comparison can be done between microbiological water quality and fencing. Of the 10 wells with protection zones only one has reported a water quality that meets the NSDW. This well also has a proper fencing. The remaining nine wells have recorded problems with coliforms (5) or HPC (4).

Figure 5.3.1 Example of fencing (approximately 20 m^2) around a groundwater well in bedrock. The size and design of the fences varies between the waterworks in Dataset E_{mod}.

Wellhead completion:

Visiting the well sites revealed a multitude of wellhead completions (Figure 5.3.2). Wells are protected by well-houses, concrete well-protections (manhole) or a combination of both. There are also wells with no protection except a solid cap on the casing.

A well-house with a concrete floor is constructed for 12 of the wells in Dataset E_{mod} (Figure 5.3.2a). Satisfactory water quality is reported for 42 % (5) of these wells (Table 5.3.1). The corresponding number is 23 % (8) for the 30 wells designed with only a concrete well-protection (Figure 5.3.2b). When a well-cover (Figure 5.3.2c) or a proper well-house is combined with the concrete well-protection instead of using a concrete lid, the amount of wells that meets the requirements in the NSDW increases from 23 % to 50 %, and only 1 well (6 %) is contaminated with coliforms. However, this difference is only statistically significant when using a 90 % confidence interval instead of 95 % (Appendix D).

Figure 5.3.2 Examples of wellhead completions. a) Well-house, b) concrete well-protection, c) concrete well-protection with well-cover (small "house") instead of a concrete lid and d) no protection except a proper cap on top of the casing.

Table 5.3.1 Number of wells with water samples reported to exceed the NSDW in relation to existence of well-house and/or concrete well-protection. Examples of the wellhead completions are shown in Figure 5.3.2.

	Total number of wells	**Exceeding the NSDW (%)**		
		None	HPC_{only}	Coliforms
Well-house with concrete floor	12	42	25	33
Concrete well-protection, no well-house or well-cover	30	23	27	50
Concrete well-protection in combination with well-cover (12) or well-house (4)	16	50	44	6
Well-house with concrete floor and concrete well-protection in combination with well-cover or well-house	28	46	36	18

Wellhead completion and improvements:
The condition of the concrete well-protections in Dataset E_{mod} is highly variable. Some are properly installed and maintained (Figure 5.3.2b), whereas others have an insufficient completion or maintenance (Figure 5.3.3a and b). In the latter group repairs are often required (Figure 5.3.3b) or the concrete lid needs placement correction (Figure 5.3.3c), which sometimes is caused by improper completion of the delivery pipe through the concrete well-protection. Other wells lack even the simplest cap on the casing (Figure 5.3.3d) leaving the well extremely exposed to contamination.

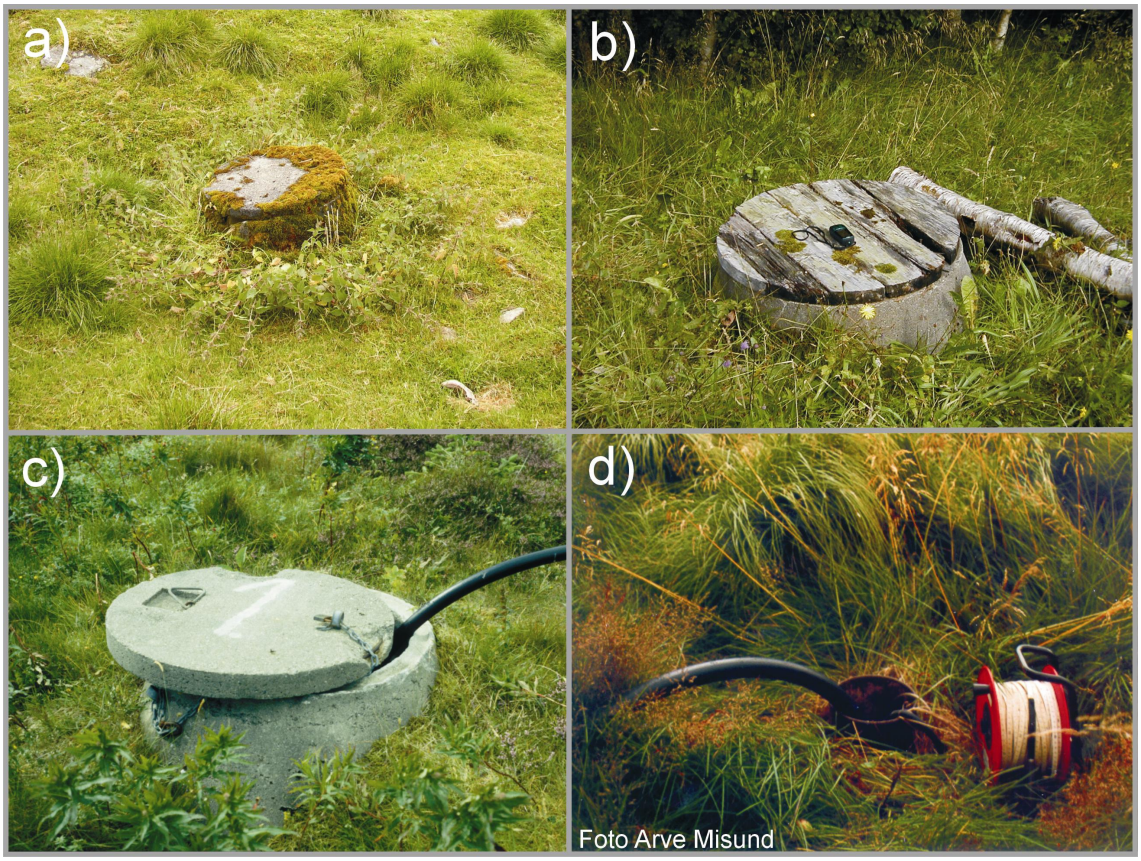

Figure 5.3.3 Examples of improper wellhead completion of wells in Dataset E_{mod}. a) Neglected concrete well-protection, b) the lid on the concrete well protection is damaged or c) not properly enclosed and d) well without any wellhead protection.

At 13 wells improvements of the wellhead completion (including sealing against bedrock) were initiated by the waterworks (Table 5.3.2) between 1998 and 2002. Evaluation of wellhead improvements was not originally a part of this study, but the 13 wells made it possible to comment on the improvements conducted and their effect on the microbiological water quality. Well-house or concrete well-protection with well-cover are installed where these were non-existing, and existing concrete well-protections are repaired or changed and often the concrete lid is replaced by a well-cover. In connection with these measures, occasionally the top of the well casing is elevated to protrude above ground level. At two waterworks sealing between the casing and bedrock has

been carried out. The improvements in microbiological quality from these efforts are mostly seen as a removal of coliforms, whilst the concentration of HPC often remains unchanged. Cement-based grout was used as sealing between the casing and bedrock at one well. Unfortunately this was not successful and coliforms reappeared in the well water.

Table 5.3.2 Type of wellhead improvements (incl. sealing/grouting against bedrock) and changes in microbiological quality. Number of waterworks is given in parenthesis.

Type of improvement	Changes in microbiological quality (Number of waterworks)
Established concrete well-protection with well-cover. Top of casing elevated to protrude ground level if necessary.	HPC removed causes good quality (2) Maintenance of good quality (2)
Concrete well-protection changed and well-cover installed. Top of casing elevated to protrude ground level if necessary.	Maintenance of good quality (2) Still HPC (2)
Concrete well-protection changed. Fine grained sediments used to improve surface runoff away from well.	Still coliforms and HPC (2) Coliforms removed while HPC remains (1)
Sealing carried out between casing and bedrock and well-house established	Coliforms removed, HPC remains (1)
Cement-based grouting between casing and bedrock	Coliforms removed, HPC remains. Coliforms reappeared when the grout broke after short time (1)

Well casing:

Figure 5.3.4 shows that wells with detected coliforms have a statistical significant shorter casing length than wells where no microbiological problems are reported. Of the 23 wells with casing lengths of > 5 m 43.5 % (10) have not reported water samples exceeding the NSDW compared to 20 % (5) of the 25 wells with casing lengths ≤ 5 m (Table 5.3.3). Applying the t-test on Table 5.3.3 and dividing the microbiological water quality in two groups; good or exceeding the NSDW, the quality is only statistically significant better in wells where the casing length is > 5 m when using a confidence interval of 90 % (Appendix D). All wells with casing length ≤ 2.5 m contain water exceeding the NSDW and 78 % of these wells have reported detection of coliforms. The amount of wells with good microbiological water quality is the same (approximately 45 %) when comparing the selection of wells from the three groups in Table 5.3.3 where the casing length is more than 5 m (> 5 m, > 5-10 m and >10m). In this dataset, the results indicate that where the casing length exceeds 5 m the microbiological water quality is less influenced by the casing length than other factors, such as the thickness of superficial deposits or the sealing between bedrock and casing.

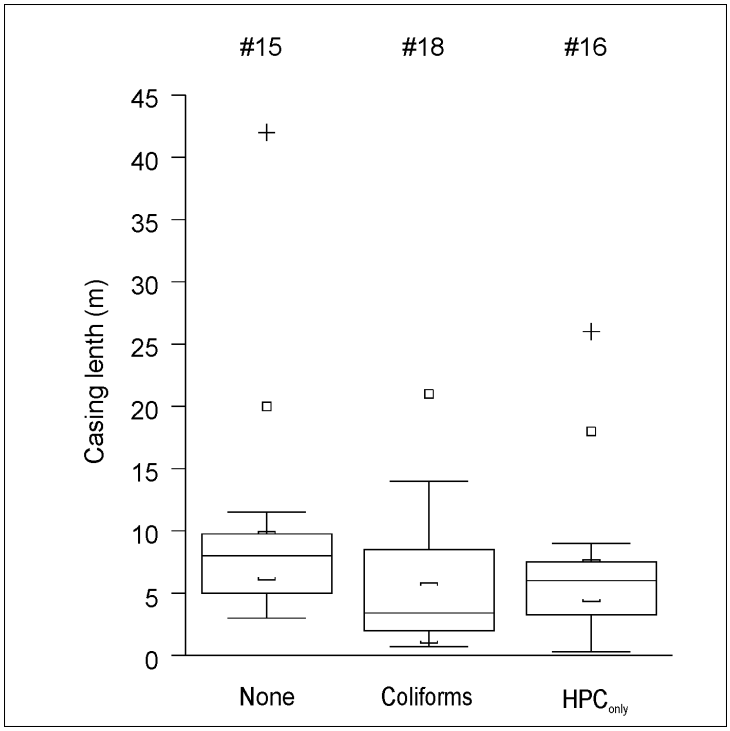

Figure 5.3.4 Boxplots presenting number of wells with groundwater exceeding the 1995 NSDW compared to the length of the well casing for the 49 wells where casing length are reported.

Of the 63 wells examined, 42 have the top of the casing above ground level and for the remaining 21 the top of the casing is below ground level. More wells supply groundwater periodically exceeding the NSDW in the latter group compared with the first group (Table 5.3.3). A cap on top of the well casing is registered for 23 of the wells, whereas 31 wells have no cap. In the first group 70 % of the wells report the microbiological water quality periodically to exceed the NSDW compared to 61% in the latter group. Existence of both well cap and location of wellhead (top of casing) are simultaneously related to microbiological water quality (Table 5.3.3). The largest amount of wells meeting the NSDW is then found when the wellhead is protruding above ground level for both wells with and without a well cap. All 6 wells (100 %) with cap and wellhead below ground level have reported coliforms or HPC exceeding 100/ml, whereas the corresponding amount is 67 % of the wells with no cap that are located below ground level. Using the t-test this difference is statistically significant (Appendix D). There is also a similar statistically significant difference between the microbiological quality of the 6 wells with well cap located below ground level and the 17 wells with cap and the well casing protruding above ground level.

A downhole video camera is used to investigate the presence or status of sealing or water leakage between casing and bedrock at the bottom of the well casing (Chapters 3.4 and 4.2). Of the 24 inspected wells in Dataset E_{mod}, 8 wells had water leakage at the bottom of the casing, whereas 10 wells had neither visible leakage at the day of inspection nor any indications of previous leakages. It was not possible to locate leakages for the remaining 6 wells due to high water level or the existence of an additional inner

casing (with slots) extending to the bottom of the well. Table 5.3.4 shows that 60 % of the wells with no identified leakages at the bottom of the casing have reported coliforms compared to 25 % of the wells with confirmed leakage, but no statistically significant difference (t-test) exists in microbiological water quality. It is noticed that wells in both groups generally have water inflow less than 10 m below surface. Additionally, wells with leakages have mostly casing length > 5 m, whereas wells without leakages have casing length ≤5 m.

Table 5.3.3 Number of wells exceeding the NSDW regarding microbiological parameters. The table presents length of well casing, existence of well cap and location of top of casing above or below ground level.

	Total number of wells	**Exceeding the NSDW (%)**		
		None	HPC_{only}	Coliforms
Length of well casing >5 m	23	43.5	39	17.5
Length of well casing > 10 m	9	45	22	33
Length of well casing > 5 but ≤ 10 m	14	43	50	7
Length of well casing > 0 but ≤ 5 m	25	20	32	48
Length of well casing > 2.5 but ≤ 5 m	16	31	31	38
Length of well casing > 0 but ≤ 2.5 m	9	0	22	78
Top of well casing is above ground level	42	40	29	31
Top of well casing is below ground level	21	24	33	43
Cap exists on top of well casing	23	30.5	30.5	39
No cap exists on top of well casing	31	39	35	26
Cap exists and top of well casing is above ground level	17	41	24	35
Cap exists and top of well casing is below ground level	6	0	50	50
No cap exists and top of well casing is above ground level	22	41	36	23
No cap exists and top of well casing is below ground level	9	33.3	33.3	33.3

Cement-based suspensions, bentonite or polyurethane are reported for use as sealing between bedrock and casing for 19 wells in Dataset E_{mod} and 11 of these are inspected by the downhole video camera. Inspection revealed visible sealing only in two of the 11 wells. In one of these cases the sealing has leakages, whereas the other well is artesian and the water level too high to verify if the sealing is watertight. In the other 9 wells possible sealing is hidden behind an inner casing (with slots) for 2 wells and leakage is detected in 5 wells. No leakage is detected in the remaining 2 wells. Leakages between bedrock and casing are thus verified for 6 of the 19 wells. Of the remaining 13 wells 46 % (6) have no reported water samples exceeding the NSDW and only 8 % (1) have reported coliforms (Table 5.3.4). No sealing between bedrock and casing is reported for

42 wells in Dataset E_{mod}. Of these 42 wells 31 % (13) have no reported samples exceeding the NSDW and 43 % (18) have reported coliforms. In the group of wells with possible sealing, statistically significant fewer wells are contaminated with coliforms (Appendix D).

Table 5.3.4 Number of wells with microbiological water quality exceeding the NSDW in relation to observed leakages during inspection with downhole video camera and reported sealing between casing and bedrock at the bottom of the casing.

	Total number of wells	**Exceeding the NSDW (%)**		
		None	HPC_{only}	Coliforms
Observed leakage between bottom of well casing and bedrock	8	37.5	37.5	25
No visible leakage between bottom of well casing and bedrock	10	10	30	60
Wells with reported sealing between bedrock and bottom of well casing	13	46	46	8
Wells with reported sealing between bedrock and bottom of well casing, leakage observed	6	50	17	33
Wells with no reported sealing between bedrock and bottom of well casing	42	31	26	43

Different well parameters:

The existence of bacteria in the groundwater is compared to well depth, well capacity and depth to water inflow and groundwater level (Figure 5.3.5). Based on the median values in the boxplots it is indicated that wells with reported coliforms have greater well depth and lower capacity than wells without coliforms. However, no statistically significant correlation with microbiological water quality exists for any of the four parameters in the figure.

Well yield enhancement by hydraulic fracturing or use of explosives:

Groundwater wells in crystalline bedrock may often have insufficient yield to meet the required need. Hydraulic fracturing or explosives are therefore used to enhance the well yield. Information about packer depth or depth of explosions is not recorded in the well logs and for 26 wells in Dataset E_{mod} it is not known if any attempt to increase the yield has taken place. Table 5.3.5 shows comparison of water quality between wells where hydraulic fracturing or explosives are used and wells where no yield enhancement techniques are utilized. It is indicated that wells in the latter group have a better microbiological water quality because more wells report to meet the NSDW and less wells report coliforms. However, when applying the t-test, the difference is not statistically significant.

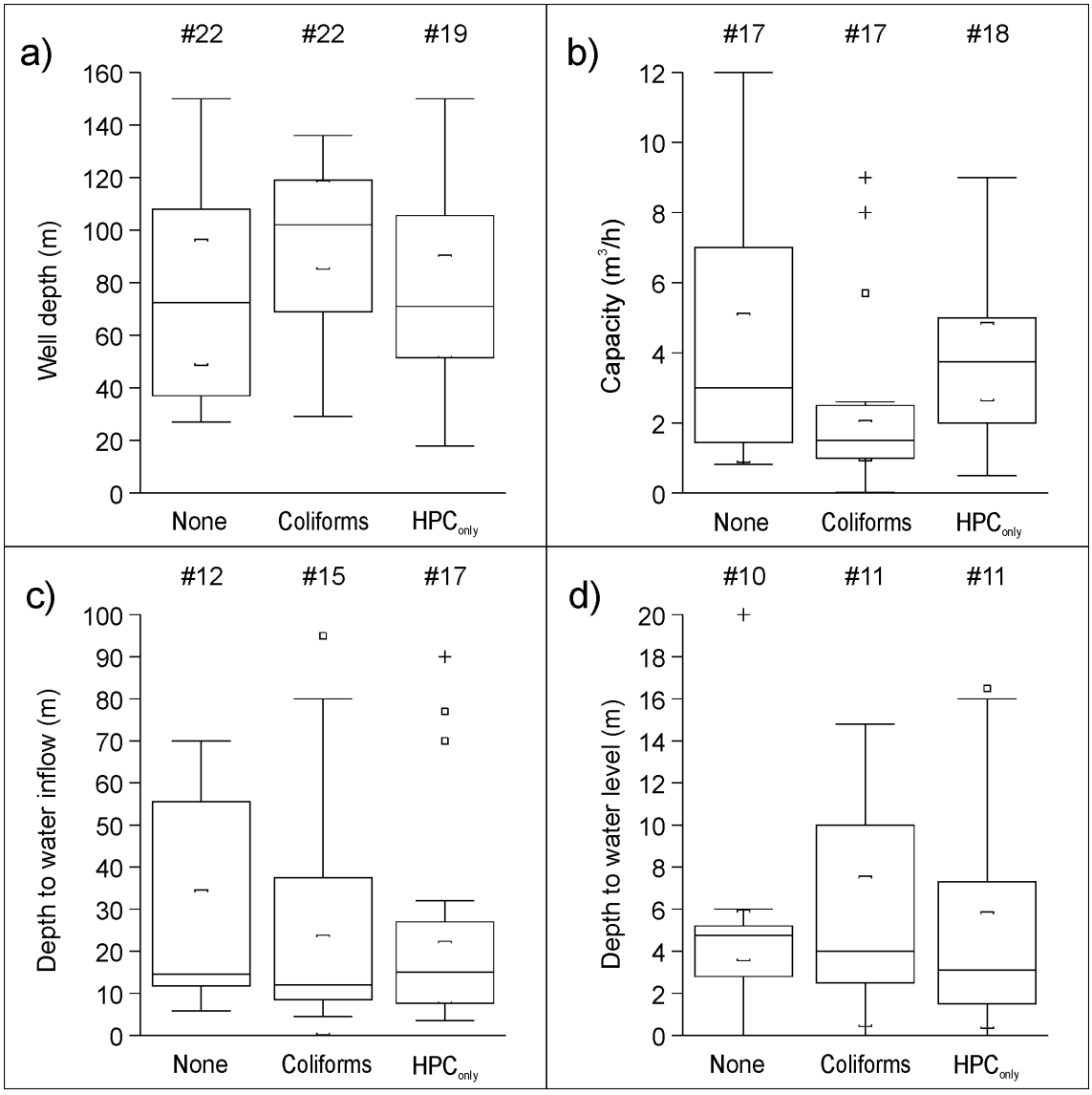

Figure 5.3.5 Boxplots showing number of wells with groundwater exceeding the NSDW compared to a) well depth, b) well capacity, c) depth to water inflow (closest to surface) and d) depth to water level. Total number of wells is the sum of the three groups in each diagram.

Table 5.3.5 Number of wells where use of explosives or hydraulic fracturing is performed to enhance the yield compared to number of wells where no enhancement techniques are used. Number of wells in both groups is related to water samples exceeding the NSDW.

	Total number of wells	**Exceeding the NSDW (%)**		
		None	HPC_{only}	Coliforms
No hydraulic fracturing or use of explosives	22	41	36	23
Hydraulic fracturing or use of explosives	15	33	20	47

5.3.2 Thickness and extent of superficial deposits

In this chapter extent, thickness and type of superficial deposits are described together with well location related to marine limit to find possible correlations with microbiological water quality. The thickness and extent of the superficial deposits are evaluated for a radius of 20 m around each well using field observations in combination with geological maps. The superficial deposits are then classified in two categories; 1) medium to thick, or 2) thin or discontinuous. Examples of the categories are shown in Figure 5.3.6. Of the 40 wells situated in areas with medium to thick superficial deposits, 25 % (10) have reported coliforms in the groundwater compared to 43 % (10) of the 23 wells in category 2 (Table 5.3.6). A trend exists that wells in category 1 are less susceptible to microbiological contamination, though it is not statistically significant using a 95 % confidence interval (t-test).

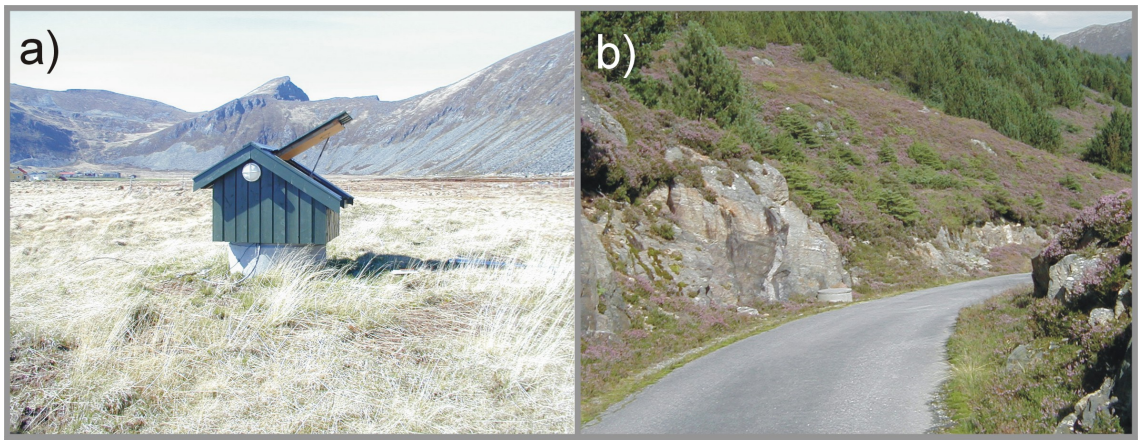

Figure 5.3.6 Thickness and extent of superficial deposits. a) Category 1, medium to thick and b) category 2, thin or discontinuous.

The thickness of the superficial deposits at the well site is recorded in the well log for 48 wells in Dataset E_{mod}. The statistical presentation in Figure 5.3.7 based on these wells indicates that wells reporting only incidences of HPC exceeding 100/ml or good microbiological water quality ("None") are situated in areas where the superficial deposits are thicker than where the wells reporting coliforms are located.

In Table 5.3.6 wells with more or less than 5 m, 2.5 m and 1 m of superficial deposits are differentiated. No statistically significant difference in microbiological water quality can be seen for the wells whether depth to bedrock is more or less than 5 m or more or less than 1 m. When comparing wells with thickness of deposits > 2.5 m and ≤ 2.5 m, less wells have good microbiological water quality (15 % compared to 45 %), and more wells have recorded coliforms (42.5 % compared to 23 %), and HPC exceeding 100/ml (42.5 % compared to 32 %) in the latter group. When applying the t-test this difference in microbiological water quality between the two groups is statistically significant (Appendix D).

Table 5.3.6 Number of wells with water exceeding the NSDW in relation to extent and thickness of superficial deposits, depth to bedrock at the well point, and well location above or below the marine limit.

	Total number of wells	**Exceeding the NSDW (%)**		
		None	HPC_{only}	Coliforms
Medium to thick superficial deposits (category 1)	40	40	35	25
Thin or discontinues superficial deposits (category 2)	23	26	31	43
Depth to bedrock from surface in the well point > 5 m	14	43	36	21
Depth to bedrock from surface in the well point ≤ 5 m	34	24	38	38
Depth to bedrock from surface in the well point > 2.5 m	22	45	32	23
Depth to bedrock from surface in the well point ≤ 2.5	26	15	42.5	42.5
Depth to bedrock from surface in the well point > 1 m	35	31.5	31.5	37
Depth to bedrock from surface in the well point ≤ 1 m	13	23	23	54
Well location above marine limit (a.m.l.)	21	19	48	33
Well location below marine limit (b.m.l.)	42	43	21	36
Well location a.m.l. with medium to thick superficial deposits	12	8	50	42
Well location a.m.l. with thin or discontinues superficial deposits	9	33	45	22
Well location b.m.l. with medium to thick superficial deposits	28	54	21	25
Well location b.m.l. with thin or discontinues superficial deposits	14	21.5	21.5	57

Marine sediments are currently found in Norway at elevations up to about 200 m above current sea level ("marine limit") due to post-glacial isostatic uplift after the last glaciation. Geological maps are examined to evaluate if the 63 wells in Dataset E_{mod} are situated above or below marine limit. It is shown that 57 % of the 42 wells located below the marine limit have either reported coliforms or HPC exceeding 100/ml compared to 81 % of the 21 wells located above the marine limit (Table 5.3.6). This difference is statistically significant (Appendix D). Location related to marine limit is further compared with the extent and thickness of the superficial deposits (categories 1 – medium to thick and 2 – thin or discontinuous) in the well areas. Below the marine limit 2/3 (28) of the wells are grouped in category 1 and 54 % (15) of these wells have a water quality meeting the NSDW. The equivalent number for wells grouped in category 2 is only 21.5 % (3). Above the marine limit, the well locations are about equally distributed between the two categories; 12 in category 1 and 9 in category 2. However, in this

case, the amount of wells with good microbiological water quality is highest and the amount of wells with recorded coliforms is fewest in category 2. Only for the wells below the marine limit is the difference in microbiological quality between wells in categories 1 and 2 statistically significant according to the t-test (Appendix D).

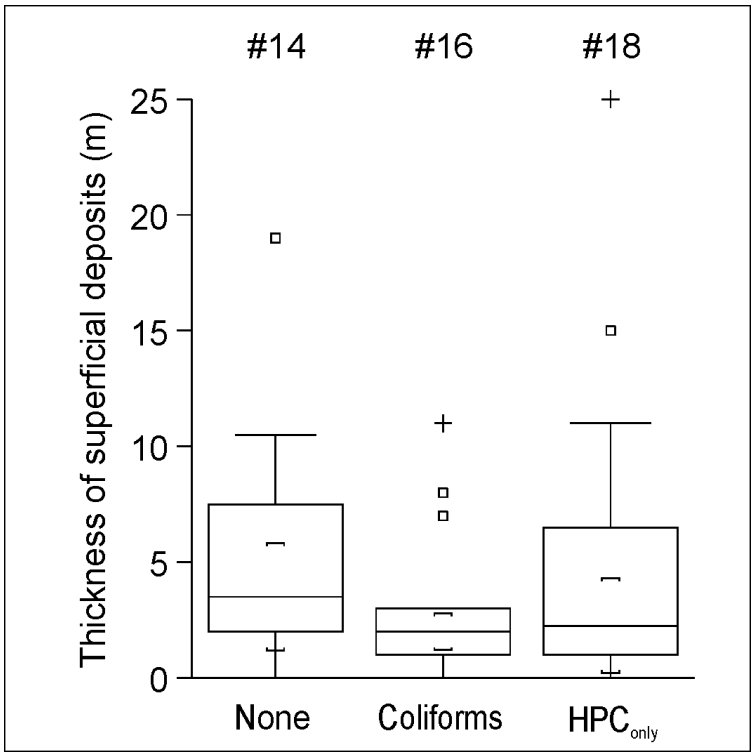

Figure 5.3.7 Boxplots showing number of wells exceeding the NSDW compared with thickness of superficial deposits at the well sites for wells in Dataset E_{mod}. Total number of wells is 48.

Geological maps, mostly in scale 1:50 000, are used to give a rough estimate of type of superficial deposits in the well areas. Most wells in the dataset are located in areas with till and marine deposits. Other sediment types represented in the dataset (9 wells) are weathered material, talus and glaciofluvial deposits. The number of wells in each of these latter groups is too few to make any comparison. Only three wells, based on the geological maps, are located in areas with no sediment cover. However, field inspections at these well sites showed a thin cover of moss, humus and peat on bedrock. Groundwater from these three wells is reported to periodically exceed the NSDW (Table 5.3.7). Of the 23 wells located in areas with till, 35 % (8) have reported coliforms and 39 % (9) have reported HPC exceeding 100/ml. 14 of the 23 wells are located in areas where the till cover is medium to thick. Approximately no difference in microbiological water quality can be seen between wells where the till is medium to thick or thin or discontinuous. In both groups about 35 % of the wells have reported coliforms and 25 % have reported good microbiological water quality. For the 28 wells located in areas with marine deposits, 29 % (8) have reported coliforms and 25 % (7) have reported HPC exceeding the NSDW. Neither for these 28 wells can any statistically

significant difference be found in microbiological water quality related to the thickness of the marine deposits (t-test).

Table 5.3.7 Number of wells exceeding requirements in the NSDW in relation to type of superficial deposits. Geological maps (1:50 000) are used for type evaluation. Marine deposits are including shore deposits. Number of wells with observed medium to thick sediment cover is listed in parentheses.

Type of superficial deposits (Thickness observed in the field)	**Total number of wells**	**Exceeding the NSDW (%)**		
		None	HPC_{only}	Coliforms
Till (14 of 23 medium to thick)	23	26	39	35
Marine deposits (20 of 28 medium to thick)	28	46	25	29
Exposed bedrock (thin cover of moss, humus and peat)	3	0	33	67

5.3.3 Land use

The land use around the wells in Dataset E_{mod} is divided in three main groups; Farmland, outlying fields and built-up areas or scattered houses. Examples of the different types of land use are presented in Figure 5.3.8. Farmland includes arable land (Figure 5.3.8a), pasture (Figure 5.3.8b) or production of grass (Figure 5.3.8c). Table 5.3.8 shows that for 11 wells farmland is the only land use within 100 m. The groundwater from 91 % (10) of these wells is reported to periodically contain either coliforms (64 %) or HPC exceeding 100/ml (27 %). This number decreases to 60 % (6) when farmland is > 100 m away, but the difference is not statistically significant (t-test). However, wells located in areas were no farmland exists have a statistically significant better microbiological water quality than the 11 wells located less than 100 m away from farmland (Appendix D).

It has been difficult to find out whether manure or fertilizers are used. Manure is probably used on arable land or for grass production in the vicinity of 8 wells and pasture is found in the vicinity of 8 wells. Of these 16 wells 56 % (9) have reported coliforms and 25 % (4) have reported HPC exceeding the NSDW. The corresponding number for the 8 wells where it is unlikely that manure is used is 25 % (2) both for wells reporting coliforms and HPC exceeding the NSDW.

In the dataset built-up areas (Figures 5.3.8e and f) or scattered houses (including cottage development areas) are the only land use close to 10 wells, whereas for an additional 8 wells farmland exists >100 m away (Table 5.3.8). 16 wells are located close to main roads or parking areas. In all three cases groundwater from about 30-38 % of the wells periodically contain coliforms, and about 70 % of the wells in the above mentioned groups supply water exceeding the NSDW.

As many as 24 wells are situated in outlying fields (Figure 5.3.8d) where no buildings or farmland exists. Coliforms are periodically detected in the water from 25 % (6) of

these wells and additional 33 % (8) of the wells have reported HPC exceeding the NSDW. In Norway sheep and cattle graze in outlying fields and during the field inspections sheep were observed at the well site for five of the 24 wells. Of these wells 2 have reported coliforms and 3 have reported HPC exceeding 100/ml.

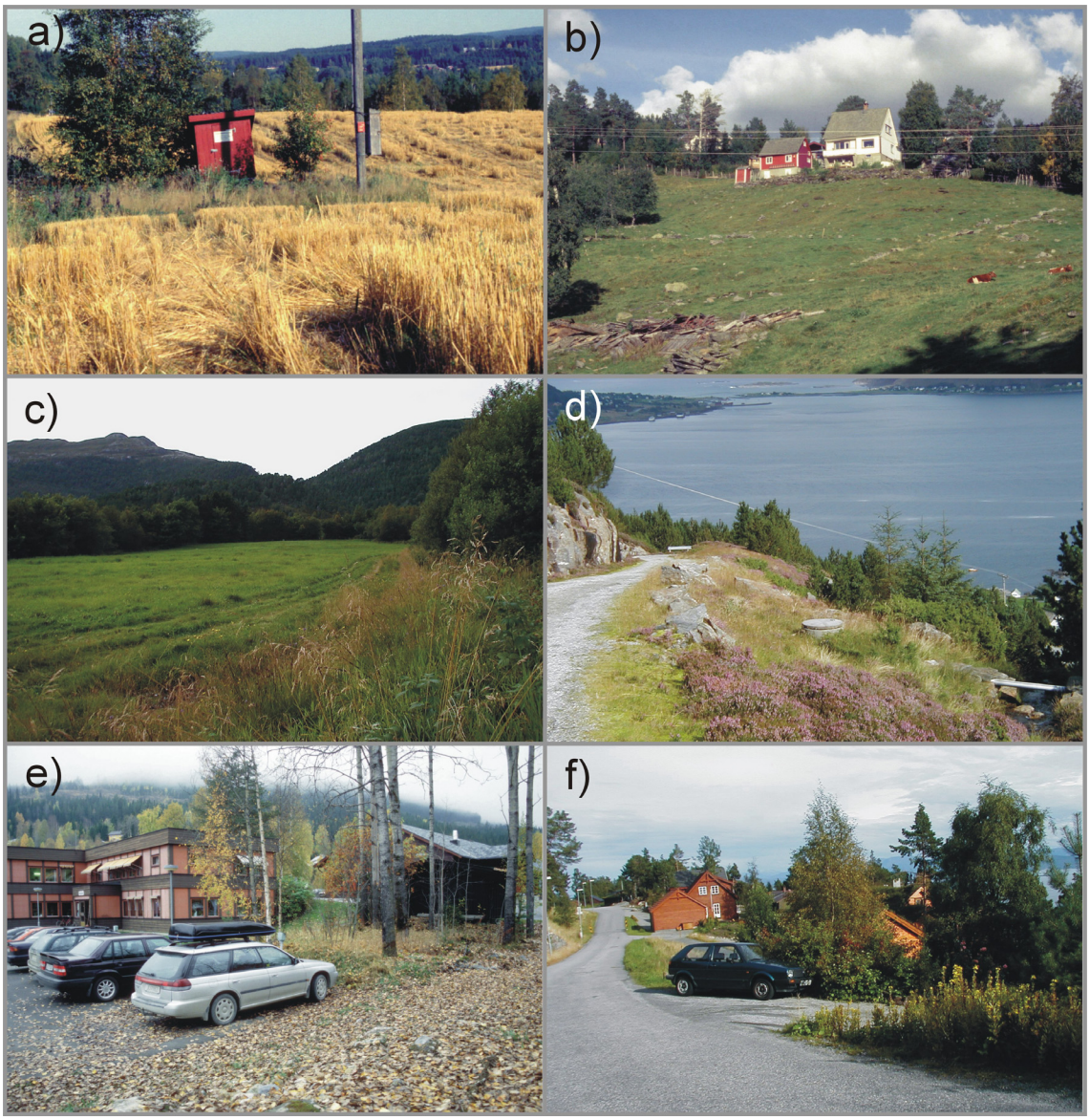

Figure 5.3.8 Examples of land use around the wells. a) Arable land, b) pasture, c) production of grass, d) outlying field, e and f) built-up area or scattered houses.

Examination of wells reporting coliforms related to land use shows that the amount of wells with groundwater periodically containing coliforms is highest for the 11 wells situated < 100 m from farmland (64 %, 7 wells). In the vicinity of built-up areas or scattered houses (10 wells) this amount decreases to close to 30 % (4), whereas in outlying fields where no sheep are observed (19 wells) the amount is 21 % (4). When

comparing microbiological water quality between the three groups with only one type of land use in the well area, a statistically significant difference is found between wells located less than 100 m from farmland and those located in outlying fields (Appendix D).

Table 5.3.8 Number of wells with microbiological quality exceeding the NSDW related to type of land use in the catchment area.

	Total number of wells	**Exceeding the NSDW (%)**		
		None	HPC_{only}	Coliforms
Farmland only (<100 m from the well)	11	9	27	64
Farmland (<100 m from the well)	19	26.5	26.5	47
Farmland (>100 m from the well)	10	40	20	40
No farmland	34	38	36	26
Manure or domestic animals	16	19	25	56
No manure or domestic animals	8	50	25	25
Outlying fields only	24	42	33	25
Outlying fields only – no grazing sheep	19	53	26	21
Built-up areas or scattered houses only	10	30	40	30
Built-up areas or scattered houses incl. wells >100 m from farmland	18	33.3	33.3	33.3
Roads or parking area	16	31	31	38

5.3.4 Sources of microbiological contamination

During field inspection of the wells in Dataset E_{mod} possible microbiological contamination sources were registered. The most common sources registered are:

- Farming < 100 m from the well (incl. grazing sheep in outlying fields)
- Septic tanks, sewage infiltration systems and sewer leakages
- Wildlife (moose and deer) in the well area
- Surface runoff towards the well and accumulation of surface water (pools/ponds) close to or in contact with the wellhead

Number of wells in Dataset E_{mod} reporting water samples exceeding the NSDW related to contamination sources in the catchment area is presented in Table 5.3.9. Farming < 100 m from the well and grazing sheep present a contamination source for 24 wells. Coliforms are found to be a problem in the groundwater from 46 % (11) of the wells, whereas 21 % (5) do not exceed the NSDW.

Septic tanks and sewage infiltration systems are situated less than 50 m from 5 wells and one waterwork (3 wells) has reported possible leakages in the sewer. Of these 8 wells, 5 (62 %) have reported coliforms in the groundwater and only 2 wells (25 %) have neither reported coliforms nor HPC exceeding 100/ml.

Table 5.3.9 Number of wells with microbiological water quality exceeding the NSDW in relation to registered potential sources of contamination in the catchment area. 12 wells are registered with two potential contamination sources and 2 wells with three potential contamination sources.

	Total number of wells	**Exceeding the NSDW (%)**		
		None	HPC_{only}	Coliforms
Farming < 100 m from the well incl. grazing sheep in outlying fields	24	21	33	46
Septic tanks, sewage infiltration systems and reported possible sewer leakages	8	25	12.5	62.5
Wildlife (e.g. moose and deer) in the well area	10	40	10	50
Wells with surface water accumulated close to or in contact with the wellhead or bacterial contamination reported to occur during heavy rain	20[a)]	25	25	50
	20[b)]	35	20	45
Possible contamination from surface water or heavy rain. No other contamination source is registered	10[a)]	40	50	10
Possible contamination from surface water or heavy rain. Other possible contamination sources are also registered	10[a)]	10	0	90
Wells with no obvious contamination source	16[b)]	63	31	6

a) Microbiological quality before wellhead improvements

b) Microbiological quality after wellhead improvements

Droppings from wildlife like moose and deer can be a source of contamination. This is possible for all wells, however 10 wells are situated in areas where this type of wildlife is reported to be more extensive. Coliforms are detected in 50 % of the wells, whereas 40 % have no reported water samples exceeding the NSDW.

Surface runoff towards the well with accumulation of water in small ponds/pools close to or in contact with the wellhead is observed or reported for 14 wells in the dataset. Furthermore, problems with the microbiological water quality are reported to occur during heavy rain for 6 wells. The wellhead completions are improved for 8 of these 20 wells. Improvements in the microbiological water quality are registered in 3 wells; 2 wells have reduced HPC to less than 100/ml resulting in good water quality, and in 1 well coliforms are removed but HPC remains more than 100/ml. Microbiological water quality for the 20 wells is presented in Table 5.3.9 and quality both before and after improvements of the wellhead completions are given. After improvements, 65 % (13) of the 20 wells have reported HPC exceeding 100/ml or coliforms. 10 of the 20 wells also have other possible sources of contamination (e.g. farming) in the vicinity of the well area. A comparison is made between these 10 wells and the 10 wells with no other possible contamination source. Table 5.3.9 shows that 9 (90 %) of the 10 wells with an additional source of contamination have reported coliforms. The equivalent number for the 10 wells with no other potential contamination sources is 1 (10 %), whereas 5 (50 %) have reported HPC exceeding the NSDW.

No contamination sources are observed or reported for 10 wells and, after improvements of the wellhead completion of 6 wells, neither these have any obvious source of contamination. Of the 16 wells only 1 (6 %) has reported coliforms and 5 (31 %) have reported HPC exceeding 100/ml.

One additional source of microbiological contamination can be the pipeline because several waterworks do not collect water samples directly from the supply well (Chapter 4.1). To evaluate the influence from the delivery pipe, it is necessary to sample both water from the pipeline and raw-water directly from the well to compare the water quality. Most waterworks in this study collect only 1 water sample at the time to be analysed for microbiological parameters and consequently it is generally not possible to evaluate the influence of the pipeline. However, three waterworks in Dataset E collected both tapwater and raw-water at the same date. Bacteriological analyses from two of these waterworks indicate that the high HPC level in the tapwater came from the delivery pipe.

5.3.5 Well location related to distance from surface water

The distance between wells and surface water (lakes/pools, rivers/streams and drainage ditches) for the wells in Dataset E_{mod} is measured and the correlation between distance to surface water and microbiological water quality is presented in Figure 5.3.9. The surface water sources are subdivided into river/stream, lake/pool and drainage ditch in Figure 5.3.9b-d). It is shown that only distance from river/stream gives a statistically significant correlation with microbiological water quality (Figure 5.3.9b). Wells with no water samples exceeding the NSDW are located further from the river/stream than wells where the water quality exceeds the NSDW. Wells in the latter group are generally situated less than 75 m from the surface water. It is also indicated that wells reporting coliforms are located closer to the river/stream than wells reporting HPC > 100/ml. Too few wells are located in the vicinity of a drainage ditch to be plotted in a boxplot (Figure 5.3.9d).

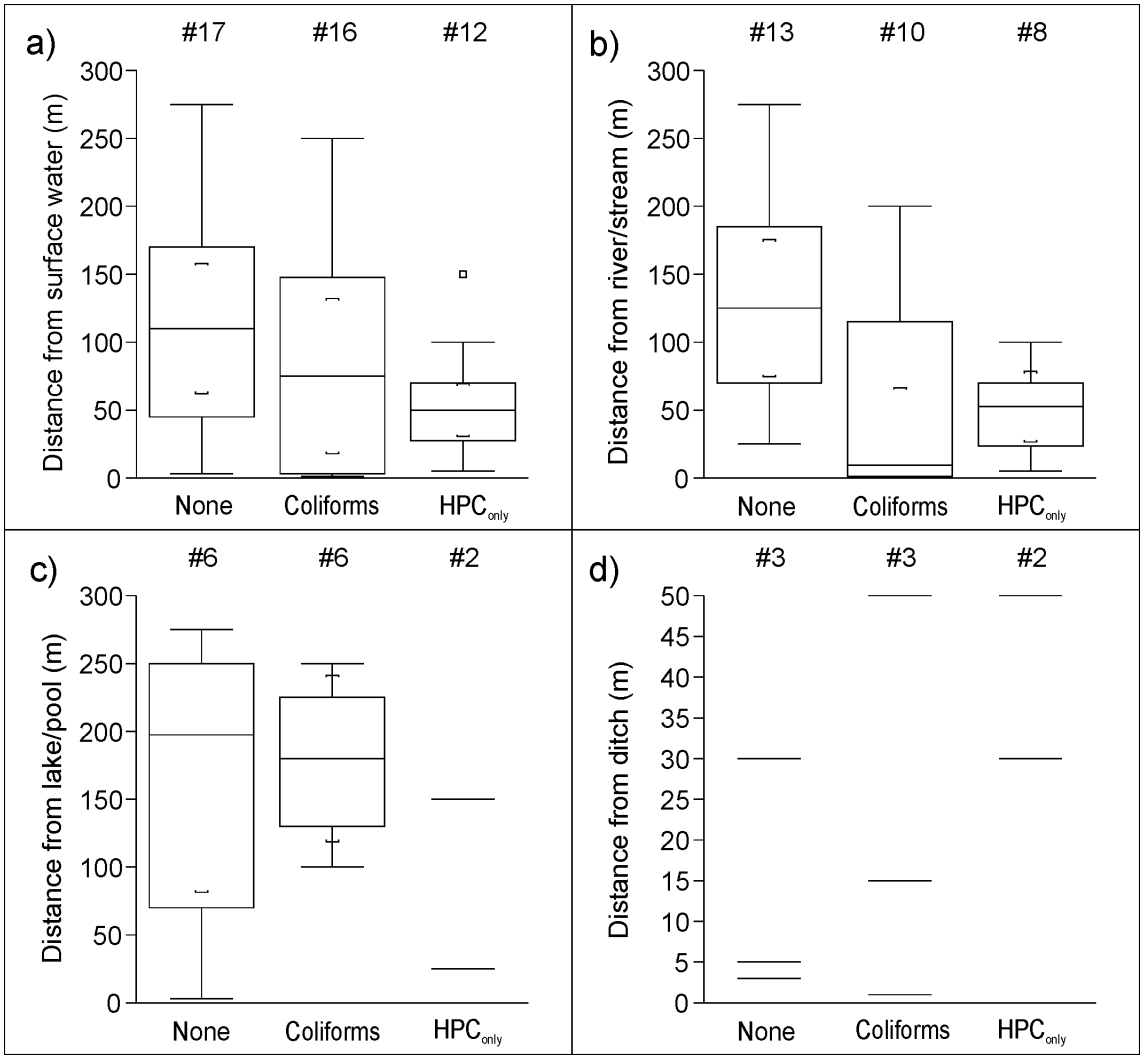

Figure 5.3.9 Boxplots presenting correlation between wells with groundwater exceeding the NSDW and distance from surface water. Number of wells is the sum of the three groups in each diagram. a) Both river/stream, lake/pool and ditch, b) river/stream, c) lake/pool and d) drainage ditch. It is not possible to plot a boxplot when the number of wells is < 5. This is the case for one subgroup (HPC_{only}) in c) and all subgroups in d).

5.3.6 Abandoned wells

During field inspections several wells not in use were observed. These wells were used as backup, not yet in use or abandoned. Especially wells in the two latter groups are easy pathways for contaminants to enter the groundwater because they have little or no protection (Figure 5.3.10). The dataset is too small to evaluate the effect of these wells on the microbiological water quality of the nearby supply wells.

Figure 5.3.10 Typical examples of abandoned wells (Pictures a and b) and wells not yet in use as supply wells (Pictures c and d).

5.4 Correlation between physio-chemical and microbiological parameters

Microbiological analyses of the groundwater exist for 63 single wells (Dataset E_{mod}, Chapter 4.2). For these wells physio-chemical analyses from Datasets A-C are used to determine median values for each parameter presented in Table 5.4.1. When the measurements of one of the parameters are given as < the detection limit, half of the detection limit is used to calculate the median value. The results are compiled in a database (Appendix L). Wells where no water samples are reported to exceed the requirements in the NSDW (good microbiological quality) have median value M, whereas wells that periodically report detection of coliforms and/or HPC exceeding requirements in the NSDW have two different median values:

- BM – median value for the samples exceeding the requirements in the NSDW
- Mb – median value for the samples not exceeding the requirements in the NSDW

The intention was also to discuss microbiological quality in relation to hardness, chemical oxygen demand, nitrite and ammonia, but too few analyses of these parameters exist to perform any reliable statistical correlations.

Table 5.4.1 Physio-chemical parameters presented in Chapter 5.4.

Physio-chemical parameters	Physio-chemical parameters
Electrical conductivity	Chloride (Cl^-)
pH	Nitrate (NO_3^-)
Turbidity	Manganese (Mn)
Colour	Iron (Fe)
Alkalinity	Total organic carbon (TOC)

Boxplots are used to compare differences in median values for the physio-chemical parameters listed in Table 5.4.1. The median value M for the wells where no reported water samples exceed the NSDW regarding coliforms or HPC is compared to the median values BM and Mb for the wells with water that periodically exceeds the NSDW (Figures 5.4.1, 5.4.2, 5.4.3), additionally the median values BM and Mb are compared. Total organic carbon (TOC) is an exception because none of the water samples analysed for TOC exceeded the NSDW regarding microbiological parameters. Therefore former reported microbiological water quality is used to group the wells (Figure 5.4.4). For the wells not meeting requirements in the NSDW it is differentiated between:

- Coliforms – wells periodically detecting TC and/or FC. Some wells also report incidences of HPC exceeding 100/ml.
- HPC_{only} – wells only reporting incidences of HPC exceeding 100/ml and never coliforms

No statistically significant differences exist for any of the physio-chemical parameters when comparing M with BM and Mb (Figures 5.4.1-5.4.3). When comparing BM and Mb a statistically significant difference is found for colour and almost for chloride (Figure 5.4.2). For the wells only reporting HPC exceeding the NSDW the colour and chloride content is higher in the water samples where HPC exceeds 100/ml than for the water samples where HPC is less than 100/ml. Although no other statistically significant differences are found, some trends exist. Wells reporting good microbiological quality or only HPC exceeding the NSDW supply water with turbidity generally < 0.5 FTU (Figure 5.4.1), whereas wells periodically reporting coliforms have often higher turbidity in the water samples exceeding the NSDW. Measurements of Fe show that the median values are equal to 0.005 mg Fe/l (half of the detection limit) for all groups in Figure 5.4.3, except for the water samples exceeding the NSDW from the wells periodically reporting coliforms. These samples have a greater scattering of the measurements than the rest of the groups and a median value of 0.16 mg Fe/l. Manganese has a higher median value for all water samples exceeding the NSDW (Figure 5.4.3), both for wells periodically reporting coliforms and HPC_{only}, comparing BM and Mb. The detection limit for manganese is less than for iron (0.001 mg Mn/l) and the measurements are more scattered. This is probably why the differences between water samples exceeding and not exceeding the NSDW are not as pronounced as for iron. Wells periodically reporting detection of coliforms have generally higher TOC measurements than wells with good microbiological water quality or those reporting only HPC exceeding the NSDW (Figure 5.4.4), although neither is this difference statistically significant.

Median values for water samples not meeting the NSDW (BM) and water samples meeting the NSDW (Mb) from the same well are correlated in x-y-plots (Figures 5.4.5, 5.4.6 and 5.4.7) to examine changes in physio-chemical parameters in single wells. It is differentiated between wells reporting coliforms and those only reporting HPC exceeding the NSDW. Small or no differences between BM and Mb are found for pH, electrical conductivity (Figure 5.4.5), alkalinity, chloride (Figure 5.4.6) and nitrate (Figure 5.4.7), although one well has a much lower electrical conductivity when coliforms are detected. Differences between BM and Mb are found for iron and manganese in water from some wells and iron content > 0.02 mg Fe/l indicates that the water does not meet the NSDW (Figure 5.4.7). The most pronounced differences between BM and Mb are found for turbidity (Figure 5.4.5) and colour (Figure 5.4.6). Wells only exceeding the NSDW regarding HPC have small differences between BM and Mb for turbidity, and all wells except one, have median values of turbidity < 0.5 FTU. In the wells periodically reporting coliforms turbidity > 0.5 FTU are found for the contaminated water samples. When colour measurements are < 2 mg Pt/l, no differences can be seen between Mb and BM neither for wells reporting coliforms nor HPC exceeding the NSDW (Figure 5.4.6). When the colour of the water exceeds 2 mg Pt/l both increases and decreases in the measurements may indicate the presence of coliforms or HPC > 100/ml.

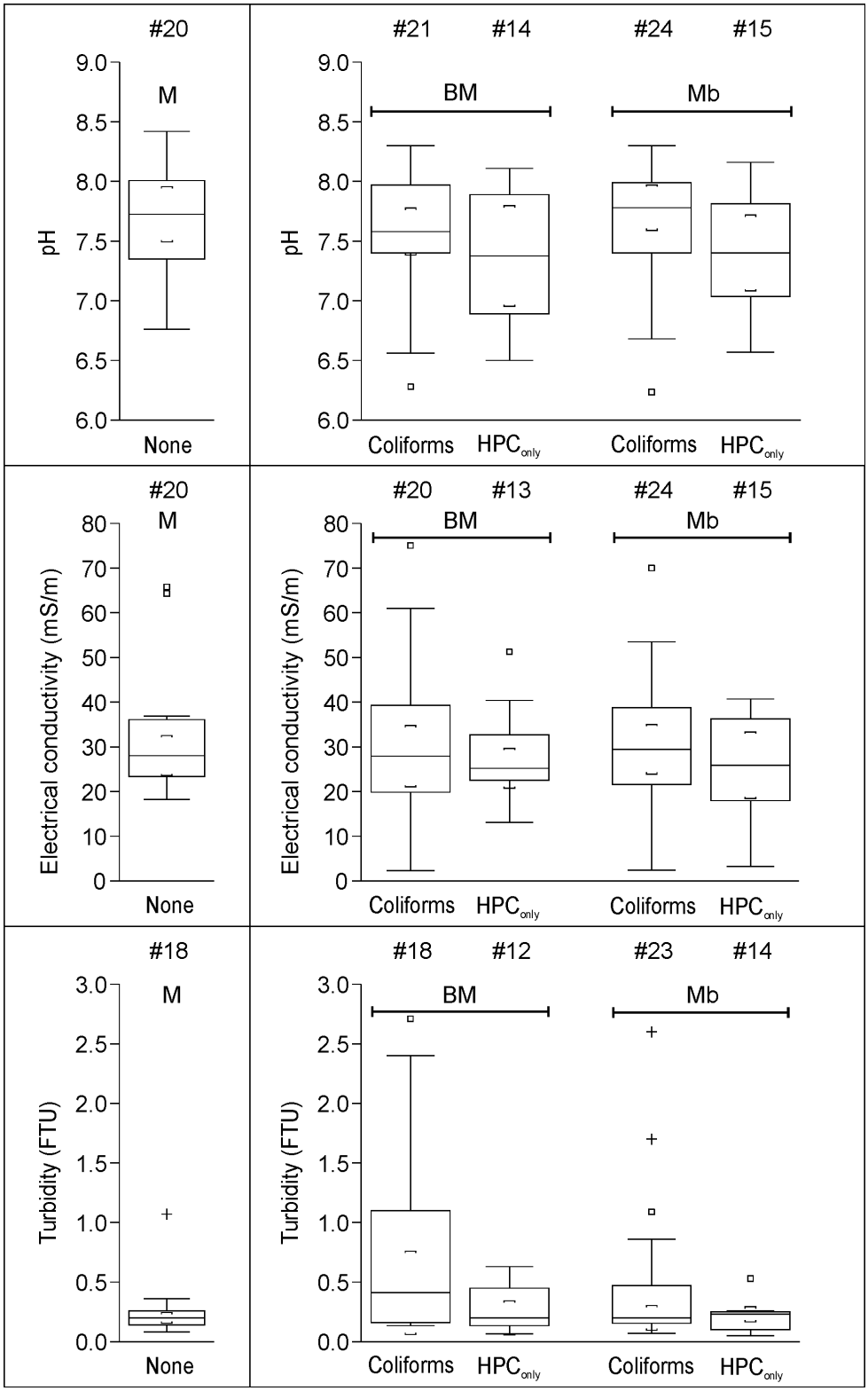

Figure 5.4.1 Boxplots showing differences in median values for water samples collected at wells reporting good microbiological water quality (left column) and wells periodically reporting coliforms or HPC exceeding the NSDW (right column). Total number of wells in the latter column is the sum of coliforms and HPC_{only} for BM (exceeding the NSDW) and Mb (not exceeding the NSDW) respectively.

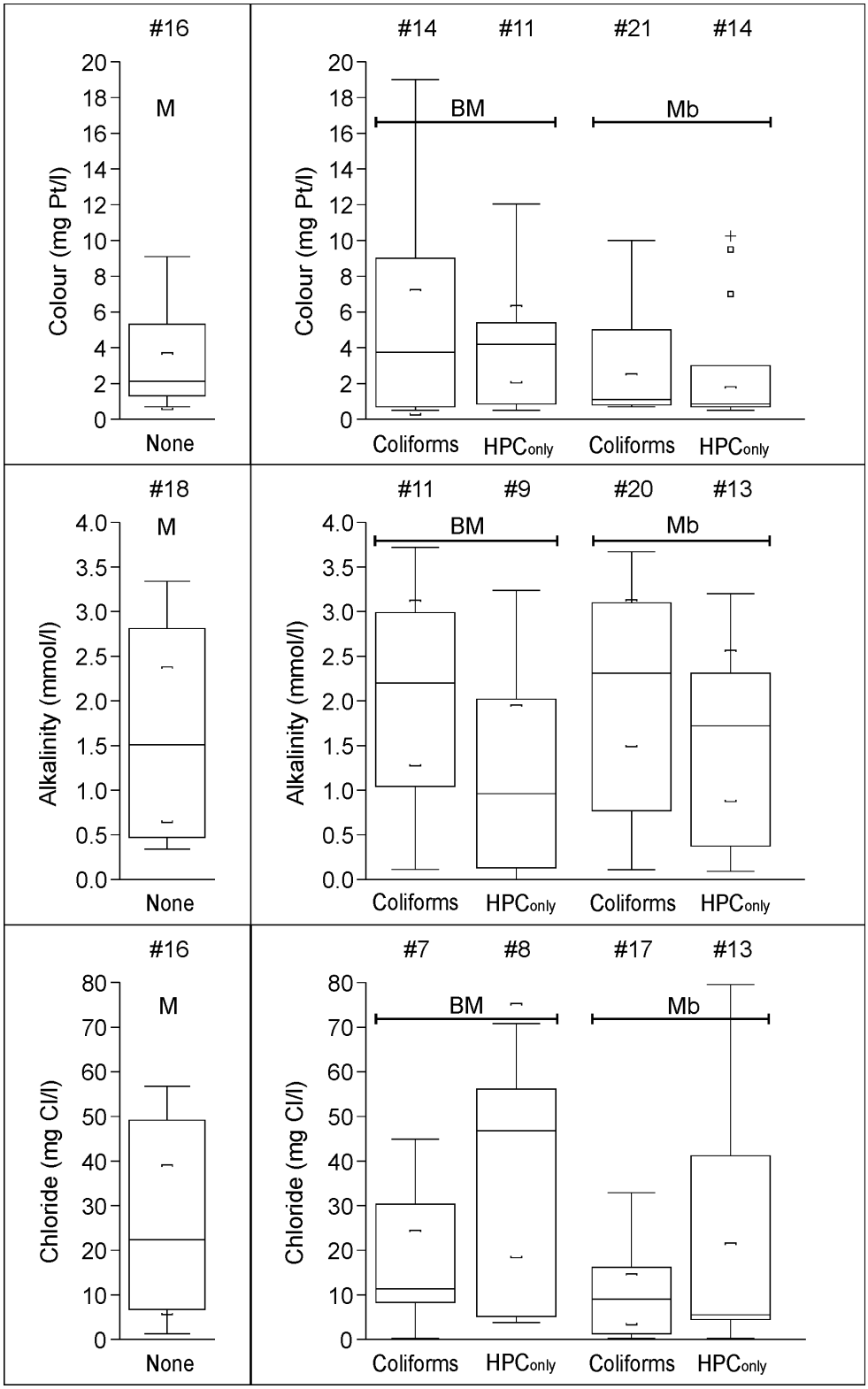

Figure 5.4.2 Boxplots showing differences in median values for water samples collected at wells reporting good microbiological water quality (left column) and wells periodically reporting coliforms or HPC exceeding the NSDW (right column). Total number of wells in the latter column is the sum of coliforms and HPC_{only} for BM (exceeding the NSDW) and Mb (not exceeding the NSDW) respectively.

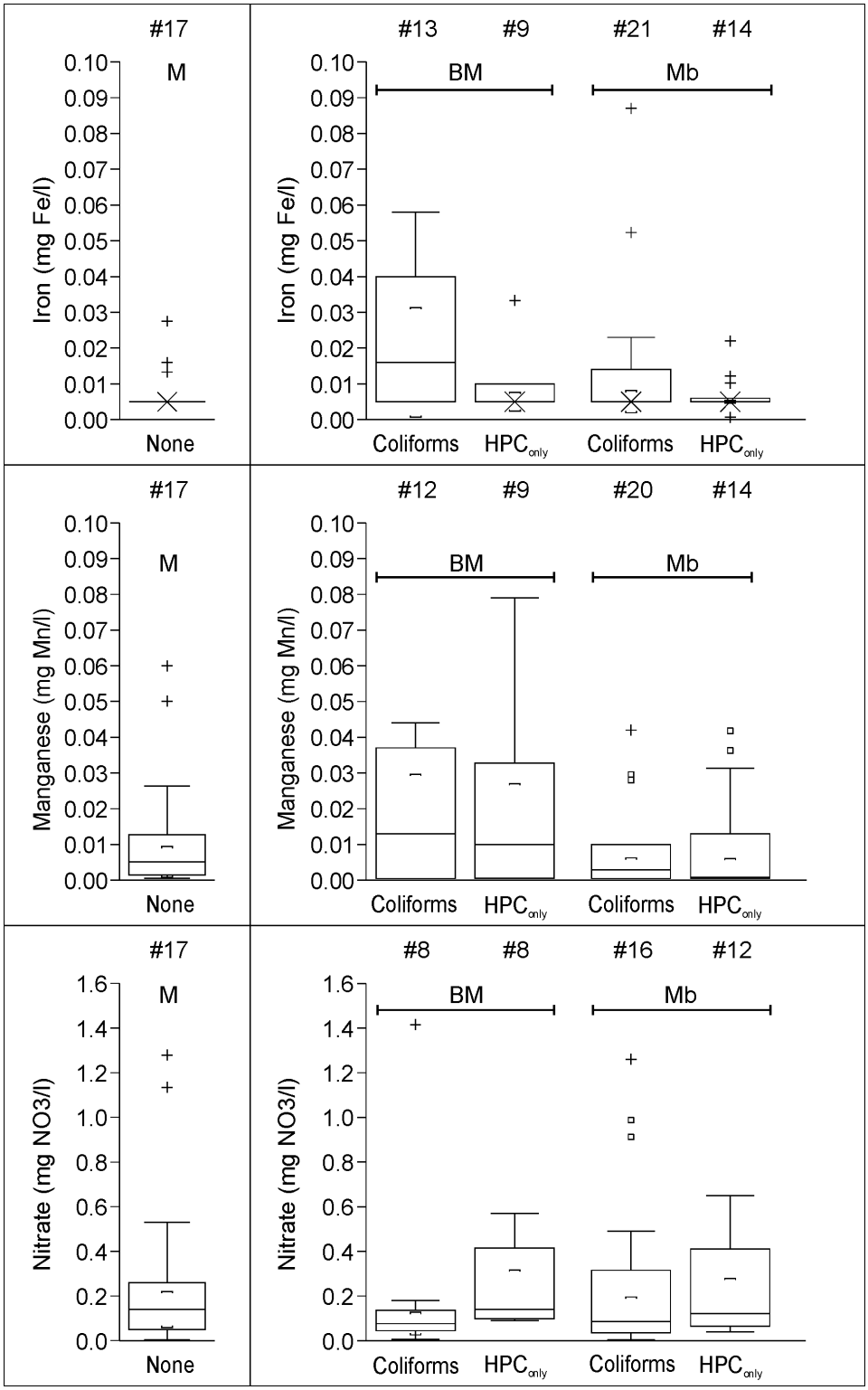

Figure 5.4.3 Boxplots showing differences in median values for water samples collected at wells reporting good microbiological water quality (left column) and wells periodically reporting coliforms or HPC exceeding the NSDW (right column). Total number of wells in the latter column is the sum of coliforms and HPC_{only} for BM (exceeding the NSDW) and Mb (not exceeding the NSDW) respectively.

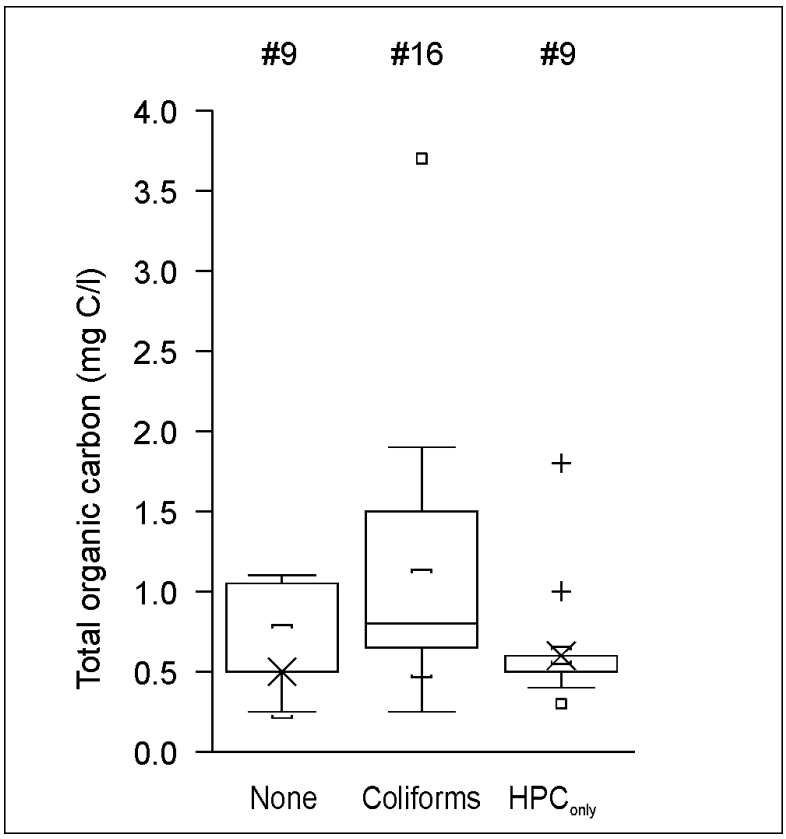

Figure 5.4.4 Boxplots showing TOC for water samples collected at wells reporting good microbiological water quality (none) and wells periodically reporting coliforms or HPC exceeding the NSDW. For most wells TOC was analysed only once and none of these water samples simultaneously exceeded the NSDW regarding microbiological parameters. Total number of wells is 34.

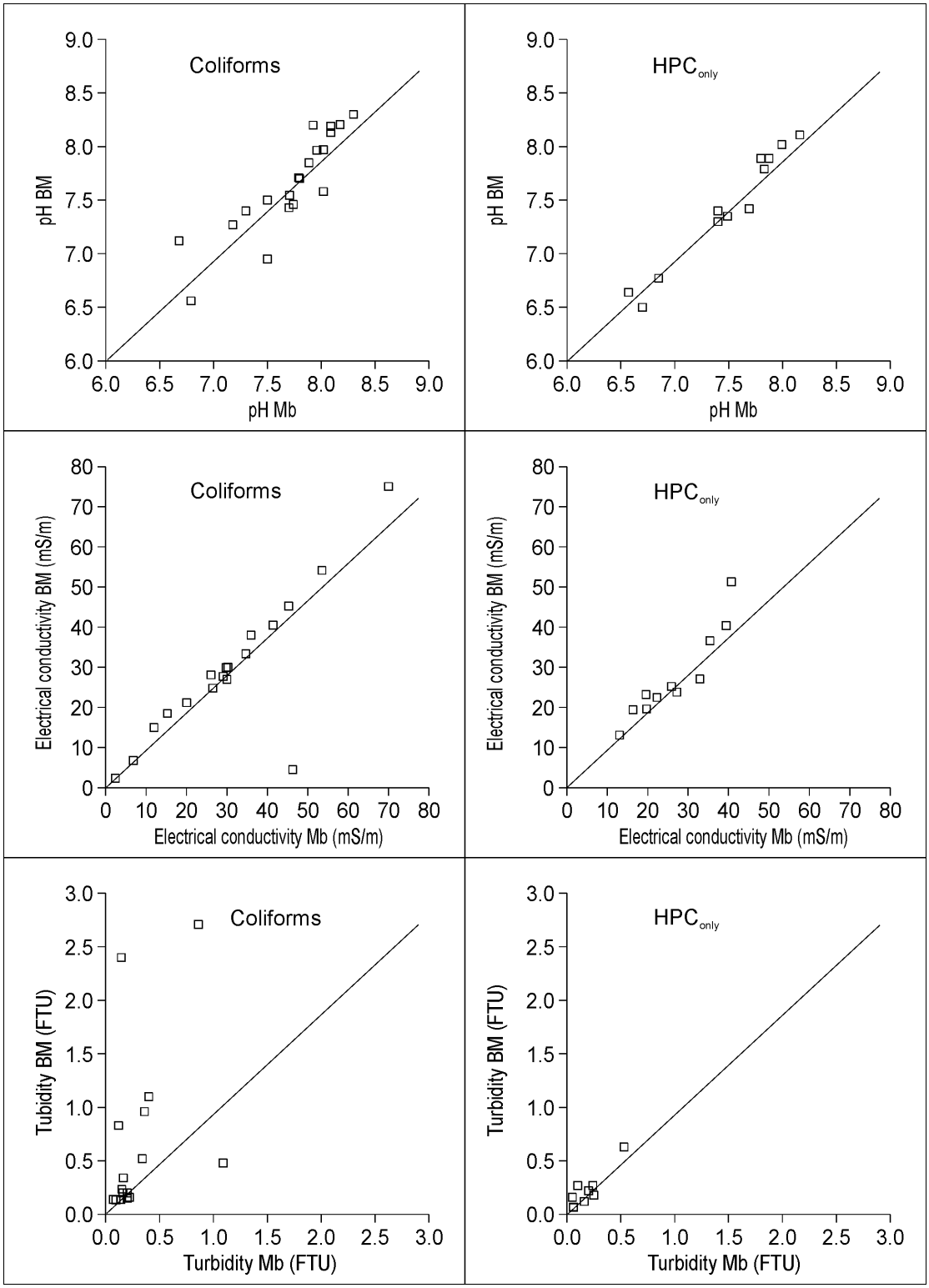

Figure 5.4.5 x-y-Plots of median values of water samples from single wells periodically reporting coliforms (left column) and HPC_{only} exceeding the NSDW (right column). BM (y-axis) median values of water samples exceeding the NSDW and Mb (x-axis) median value of water samples not exceeding the NSDW.

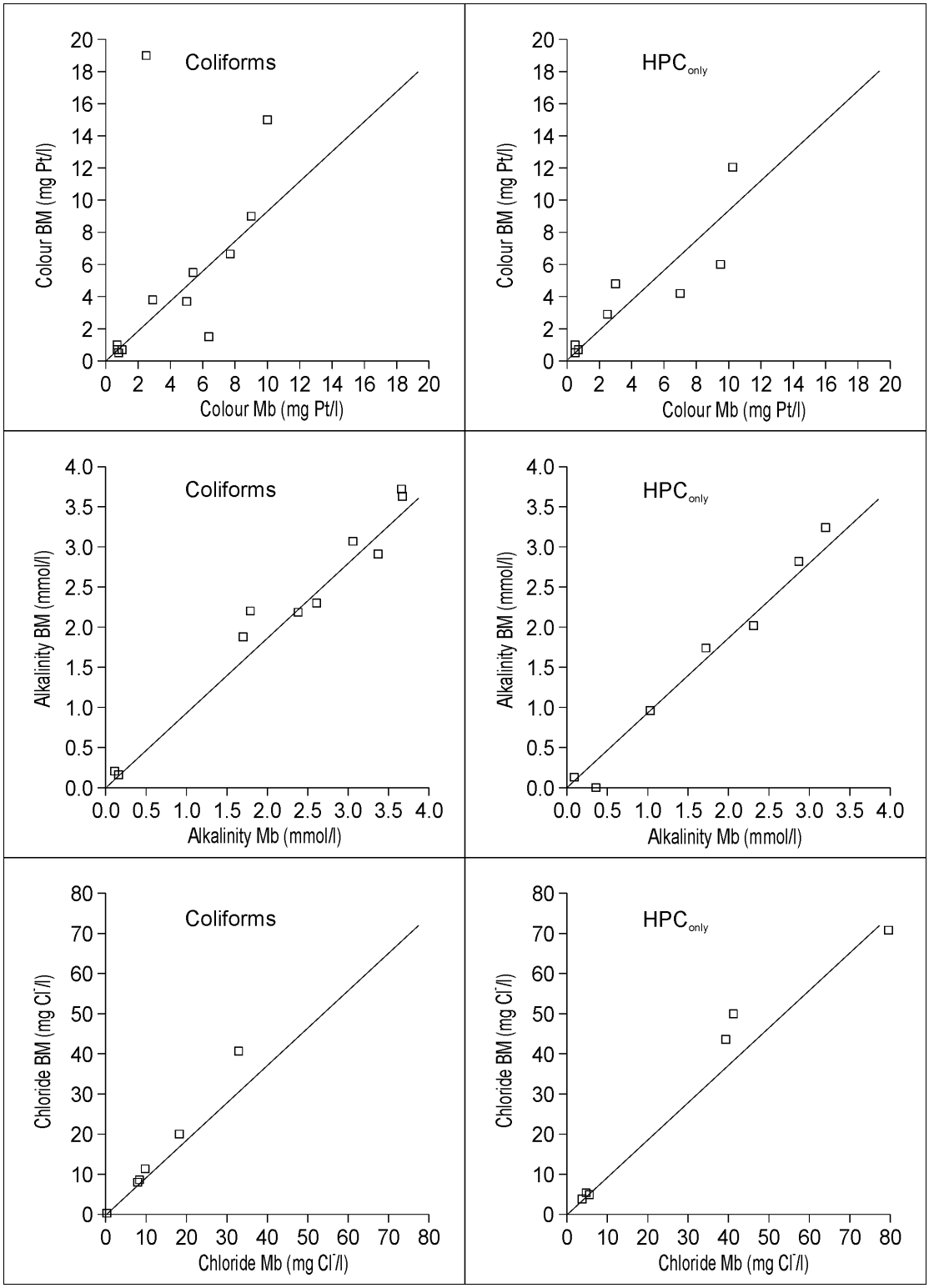

Figure 5.4.6 x-y-Plots of median values of water samples from single wells periodically reporting coliforms (left column) and HPC_{only} exceeding the NSDW (right column). BM (y-axis) median values of water samples exceeding the NSDW and Mb (x-axis) median value of water samples not exceeding the NSDW.

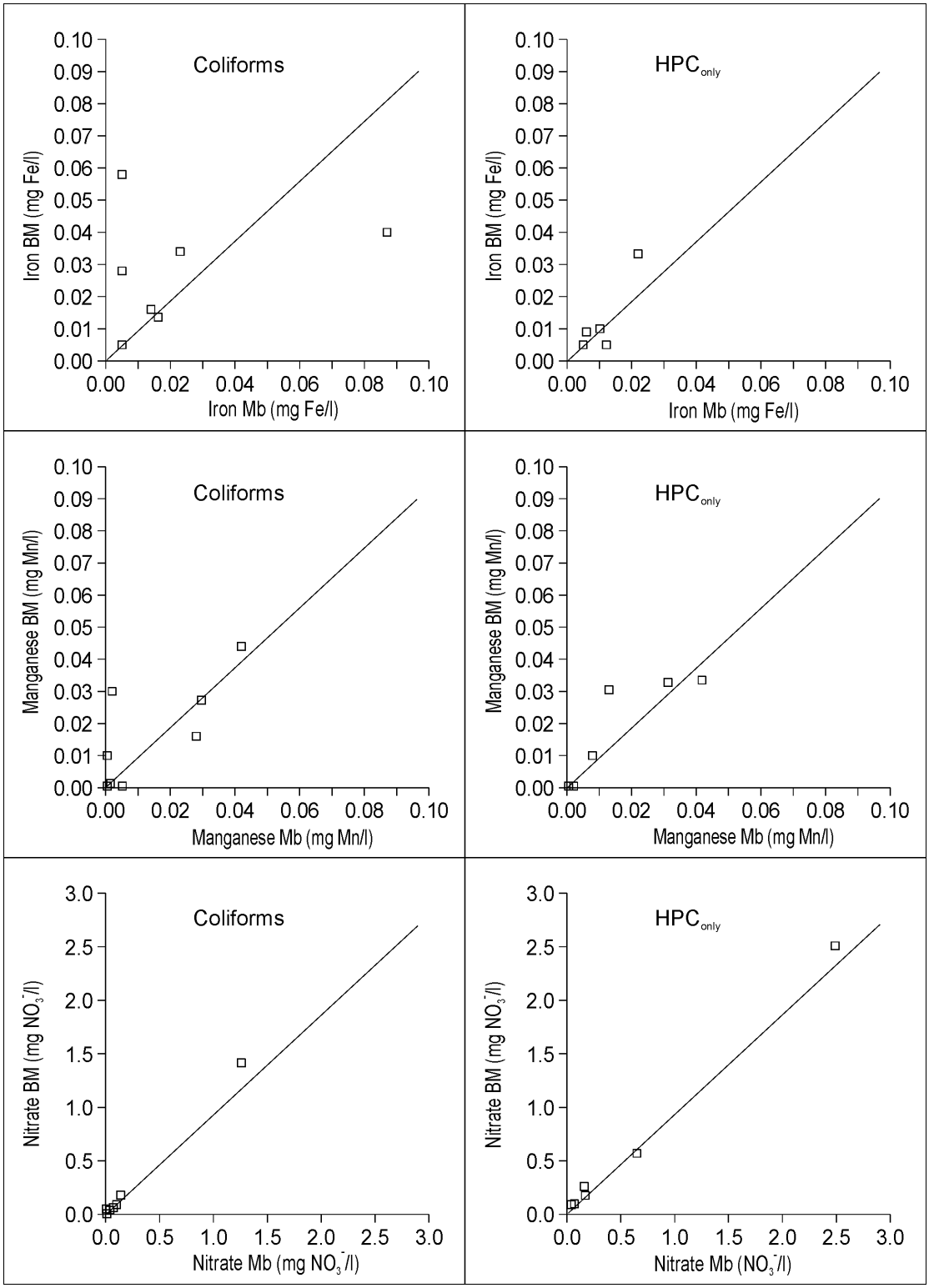

Figure 5.4.7 x-y-Plots of median values of water samples from single wells periodically reporting coliforms (left column) and HPC_{only} exceeding the NSDW (right column). BM (y-axis) median values of water samples exceeding the NSDW and Mb (x-axis) median value of water samples not exceeding the NSDW.

6 Discussion

The hypotheses presented in Chapter 1.2 are discussed and recommendations of wellhead completion are suggested based on the results presented in Chapter 5.

6.1 Microbiological quality in Norwegian bedrock wells

Hypothesis 1: Norwegian groundwater derived from wells in bedrock is satisfactorily protected against microbiological contamination.

6.1.1 Discussion of the dataset

As described in Chapter 5.1, the waterworks in Dataset A_{mod} have sampled different types of water (raw-water, tapwater, clean-water or unspecified samples) and only approximately 50 % have reported to collect the same type of water for all samples. Idealistically, both raw-water and tapwater should have been collected and analysed each month, but to administrate this during the PhD study would not have been possible within the time limits and economy. Working with the dataset has shown the importance of collecting water samples at the same location each time and to sample both raw-water and tapwater. This would have made it possible to evaluate the effectiveness of disinfection (if applied) and to identify if the source of contamination was in the delivery system or related to the aquifer or groundwater well. Even though Dataset A_{mod} is not ideal, it consists of water samples collected at 169 waterworks based on groundwater from bedrock. It represents the type of water samples collected at Norwegian waterworks showing the type and amount of samples collected to evaluate the microbiological quality of the drinking water.

Those waterworks in Table 5.1.4, that collect both treated and untreated water samples, either had a treatment plant installed during the period 1996-98, or they sample at different localities and collect different types of water each sampling date.

As described in Chapter 4.1.2, water samples represent the period 1996-98, but microbiological analyses for all three years are only received for 40 of the waterworks. The microbiological quality reported for the 169 waterworks in Chapter 5.1.1 may therefore have been different if data had been received for all three years from all waterworks. A probable consequence is a reduction in the number of waterworks meeting the 1995 NSDW and an increase in the number of waterworks reporting coliforms. In Figure 5.1.8b) this is evident from the comparison of the microbiological quality for each of the years 1996 and 1997 with the results from the combined period 1996-97.

6.1.2 HPC and coliforms as indicators for microbiological contamination

HPC and coliforms are indicators of microbiological and hygienic quality of the water. As described in Chapter 2.3 only *E. coli*, and consequently 80-90 % of FC, is a positive indicator of fecal contamination. In Chapter 5, occurrence of TC and FC is mostly presented as one group. In most water samples both TC and FC are analysed, but Figure 5.1.3b) shows that TC are constantly detected in more water samples than FC throughout the period 1996-98. It is therefore possible that TC do not always originate from fecal contamination. Table 5.1.2 shows that both the numbers of TC and FC detected in a 100 ml water sample are generally < 5 and the median value is 2. Because the number of coliforms detected is low, it is possible that only TC or FC are detected in the water sample even though both are present in the groundwater. Figure 5.1.3b) shows that the two parameters have the same seasonal variations and although, TC are often detected without FC, there are examples where only FC are detected. Consequently TC may indicate fecal contamination without the presence of FC. It is therefore important that both TC and FC are analysed.

HPC gives a quantitative measure of heterotrophic microorganisms living in soil and water. HPC at 22°C represents the natural microbiota, whereas HPC at 37°C may indicate fecal contamination because these microorganisms are adapted to humans and warm-blooded animals (Østensvik 2002). The 1995 NSDW mandatory program for sampling and analyses included both HPC at 22°C and 37°C, but Dataset A_{mod} demonstrates that HPC at 22°C is analysed more often than HPC at 37°C. Individual water samples exceeding the 1995 NSDW regarding HPC at 37°C do not always contain HPC at 22°C > 100/ml. This is explained from the fact that the two parameters represent separate microbial populations in the water. However, an evaluation of the dataset shows that all waterworks, except one, exceeding the guidance level for HPC at 37°C of 10/ml in the period 1996-98, also exceed the 1995 NSDW regarding HPC at 22°C.

The revised NSDW of 2002 does not require piped drinking water to be analysed on HPC at 37°C. However, HPC at 37°C, as opposed to HPC at 22°C indicates contamination from humans and animals, which may be of fecal origin (Østensvik 2002). Removing this parameter could therefore result in fewer indications for this type of contamination. Supposing this, it would be expected that HPC at 37°C is detected in the same samples as coliforms at least as often as HPC at 22°C. To evaluate the importance of HPC at 37°C as an indicator of fecal contamination, the 195 waterworks in Dataset A are examined. A total of 23 waterworks have reported water samples were HPC at 22°C and/or HPC at 37°C are exceeding the 1995 NSDW at the same time as coliforms are detected. HPC at 37°C alone is exceeding the 1995 NSDW in only two water samples where coliforms are detected. The equivalent number for HPC at 22°C alone and both HPC at 22°C and 37°C is 19 and 11 samples respectively. At the same 23 waterworks, 34 water samples contain only coliforms without HPC exceeding the 1995 NSDW, and 4 samples where only HPC and not coliforms, exceeds the 1995 NSDW. The results show that HPC at 22°C is detected more often than HPC at 37°C and that HPC at 37°C has no unique correlation with the bacteria indicating fecal contamination. This is probably because HPC at 22°C is part of the natural microbiota of the surface water.

Groundwater fed by surface water contaminated with coliforms will therefore also often contain large amounts of microorganisms growing at 22°C.

HPC originating from the aquifer or groundwater well may indicate that the well is vulnerable to microbiological contamination. Especially when the high values are connected to periods with rain or snowmelt is it likely that the water has too short residence time in the subsoil to remove unwanted microorganisms. Thus, if fecal contamination become available it is likely to reach the well. The high HPC level may also be caused by biofilm growth in the groundwater well or the delivery system. This is likely for the waterworks in this study, because only a few of them specify that they collect raw-water.

The distribution line contributes to outbreaks of waterborne diseases (Stenström et al. 1994, Macler 1995, Nygård et al. 2003, Payment & Robertson 2004). In the USA this issue occurs mainly at large public waterworks, whereas smaller private waterworks have instead problems with source contamination (Macler 1995). Waterworks in this study (Dataset A) are small and supply mostly < 500 people. Based on Dataset A_{mod}, the influence on the microbiological water quality from the pipeline cannot be investigated in general, but the pipeline is found to contribute to high HPC levels at two waterworks. At two other waterworks coliforms and HPC are detected in the raw-water, but not in the disinfected water. This is consistent with the field inspections of waterworks in Dataset E showing that microbiological contamination at the well site or aquifer is a major problem. Coliforms are more likely caused by source contamination rather than from biofilm or leakages in the pipeline. HPC originating from the aquifer or groundwater well can therefore be regarded as a more serious problem compared with HPC originating from the delivery system.

6.1.3 Microbiological water quality in the period 1996-2003

Based on the results in Chapter 5.1 and the discussion in Chapter 6.1.1 at least 76 % of the 169 waterworks in Dataset A_{mod} did not meet the requirements in the 1995 NSDW (Sosial- og helsedepartementet 1995) regarding coliforms or HPC in the period 1996-98. Detection of coliforms was only reported once for 25 waterworks (Table 5.1.3) and single incidences of HPC exceeding the 1995 NSDW are reported for 16 waterworks. There is a possibility that these 41 single incidences are caused by contamination during sampling or analyses. Though, for 17 of the 25 waterworks detecting coliforms, HPC exceeds the requirements in the 1995 NSDW in more than one water sample. This indicates that these 17 waterworks are vulnerable to microbiological contamination of the water and that the water originally contained the coliforms.

It was expected that all waterworks sampling treated water had good microbiological water quality but, as shown in Table 5.1.4, this is not the case for 9 of the 13 waterworks. Since raw-water is not sampled, it is impossible to evaluate whether the disinfection is not working or the microorganisms originate from the delivery system. However, based on the discussion in Chapter 6.1.2, it can be speculated that pipeline biofilm is the main contributor to HPC for the 5 waterworks only exceeding the 1995

NSDW regarding this parameter. Coliforms in the water from the remaining 4 waterworks are more likely caused by source contamination.

Consistent with the 2002 NSDW HPC at 37°C is no longer analysed in piped drinking water and an action level at 100/ml has replaced the former guidance level of 100/ml for HPC at 22°C (Table 4.1.1). Compared to the former NSDW, the new action level appears to have the same purpose as the old guidance level. In both cases the waterworks are to take initiatives to detect the cause of the high HPC level. According to the new NSDW this should take place after the first time, whereas exceeding of the former guidance level could occur several times. The new action level is interpreted to be equivalent to the old guidance level. Comparing Dataset A_{mod} with the 2002 NSDW only results in minor changes in microbiological quality and only 3 waterworks change "microbiological group" (Table 5.1.5).

Possible improvements of the water quality from the period 1996-98 to 2003 are investigated for 123 of the waterworks in Dataset A_{mod}. The microbiological water quality for each individual waterwork often changes from one year to another, but Table 5.1.7 shows that some of the waterworks reporting water samples exceeding the 1995 NSDW in 1996-98 have improved the water quality. Still 27 of the 123 waterworks reported coliforms by the end of 2003 and, additionally, 34 waterworks reported HPC exceeding the NSDW (Figure 5.1.8a). Some of the improvements are caused by installation of disinfection plants based on chlorination or UV. Nevertheless, still 17 of the 33 waterworks known to disinfect the water by the end of 2003 (NIPH unpublished) report coliforms (7) or HPC > 100/ml (10) at least once a year. This indicates that the disinfection is not sufficient, not used or the bacteria originate from the delivery system. The remaining 44 waterworks with microbiological problems in 2003 are assumed not to have a disinfection plant operating and should have this installed for regular use.

6.1.4 Concluding remarks hypothesis 1

Through an examination of the data it has not been possible to verify hypothesis H1. Instead it is clear that groundwater from bedrock wells are vulnerable to microbiological contamination. Based on the Dataset A_{mod}, it is not possible to locate the source of the contamination for each waterwork. Microbiological analyses and field inspections indicate that the microorganisms both are due to source contamination (aquifer or well) and originate from biofilm in the delivery system. It is most likely that coliforms are caused by source contamination, whereas the delivery pipe is also a likely cause for HPC.

6.2 Seasonal variations of microbiological quality

Hypothesis 2: When microbiological contamination is detected in groundwater from bedrock, it is related to snowmelt or autumn precipitation and manure spreading.

6.2.1 Discussion of the dataset

A total of 117 waterworks from Dataset A_{mod} is used to examine seasonal variations in the microbiological water quality. As described in Chapter 5.1.1, waterworks sample water at different locations and sometimes both treated and untreated water. To describe seasonal variations of source contamination, the dataset includes only untreated water samples and those where it is unknown if treatment is used. Ideally, only analyses of raw-water should be used. This is not possible but, when more than one locality is sampled at a specific date, analyses of the samples best representing raw-water are used to minimise the influence of the distribution system.

No direct relationship is found between total number of samples analysed and number of samples exceeding the 1995 NSDW regarding HPC or coliforms (Figures 5.1.6 and 5.1.7). However, some correlations occur. One factor is additional sampling when coliforms are detected because most waterworks take a new sample within a week to see if the bacteria remain in the water. Consequently, in periods with high detection of coliforms the total samples collected are increased.

6.2.2 Seasonal variations

Most groundwater recharge in Norway occurs during snowmelt (spring) and autumn precipitation (Pedersen et al. 2003). A higher occurrence of bacteria in the wells during these seasons may indicate infiltration of surface water with short residence time in the ground or access to surface runoff towards the well. It is expected that most contaminated water samples will be detected during spring and autumn presented by two distinct peaks, in an x-y-plot where number of samples exceeding the 1995 NSDW is plotted for each month. Figures 5.1.3 shows that peaks occur in the autumn, but not necessarily during snowmelt.

The number of water samples exceeding the requirements in the 1995 NSDW regarding HPC or coliforms is not the same. This is most likely caused by variations in availability of the different bacteria throughout the year. Coliforms are related to sewage, manure spreading and droppings from grazing livestock or wildlife. Manure spreading in Norway is not allowed between 1 November and 15 February and never on snow or frozen land (Landbruks- og matdepartementet et al. 2003). Most manure spreading is also finished by 1 September. As a result, most infiltration caused by snowmelt in spring occurs before the manure spreading start during spring farming. This is consistent with the increase in water samples containing coliforms from early summer (June) with a peak in the autumn (September) related to autumn precipitation (Figure 5.1.3a). FC are more fecal-specific in origin than total coliforms, and the elevated amount of water samples with FC in spring is probably caused by infiltration of melting water

(Figure 5.1.3b). FC are in this case assumed mostly to be caused by grazing livestock or wildlife because manure spreading occurs after the melting period. Similar seasonal variations are also reported from Finland by Korkka-Niemi (2001) and from Ontario by Goss et al. (1998).

Water samples more often exceed the requirements in the 1995 NSDW regarding HPC at 22°C than HPC at 37°C (Figure 5.1.3c). This is both related to fewer analyses of HPC at 37°C and less occurrence of HPC at 37°C in the groundwater than HPC at 22°C. The latter is because the normal habitat for most HPC microorganisms detected after incubation at 37°C is warm-blooded animals and humans, whereas most microorganisms detected at 22°C have their natural habitat in soil and water. Consequently HPC at 22°C is likely to be related to all episodes where surface water rich in these microorganisms reach the well without sufficient filtration through the subsoil. This will cause the curve in Figure 5.1.3c) to have more than one peak. HPC at 22°C can also originate from biofilm growing in the well or delivery system. This might contribute to the high level of HPC at 22°C throughout the year.

Water samples with too high HPC and coliforms are plotted separately for groups of counties in Figures 5.1.4 and 5.1.5 respectively. It is shown that the maximum number of water samples exceeding the 1995 NSDW does not occur at the same time for all parts of Norway though similar trends, like an autumn peak, exist. This is probably caused by variations in precipitation and temperature between parts of Norway, in addition to site specific factors like contamination sources, well design and wellhead protection, land use and existence of superficial deposits (See also Chapt. 6.4). In Norway the inland regions normally have cold winters with temperatures below 0°C and normally very low infiltration rate (Meteorologisk institutt 2003). Along the coast from the south and along the west coast, except in the far north, the winter temperatures are above 0°C for long periods and precipitation is mostly rain and consequently more infiltration of water occurs during the winter.

Waterworks in Hedmark (Figures 5.1.4a and 5.1.5a) and Møre & Romsdal (Figures 5.1.4c and 5.1.5c) can be used to exemplify differences in microbiological quality related to geographical variations in temperature and precipitation. Most waterworks in Møre & Romsdal are situated along the coast where winter temperature is mainly above 0°C and coliforms are detected throughout the whole year because the supply wells are constantly influenced by infiltration of contaminated water. In Hedmark the waterworks are located inland and the median temperature during winter is below 0°C leading to low infiltration of water during winter and infiltration during snowmelt and autumn precipitation. Low infiltration combined with low access of fecal contamination when infiltration occurs in spring leads to detection of coliforms mostly during summer and autumn.

6.2.3 Concluding remarks hypothesis 2

Examination of the data shows that microbiological contamination can be related to high infiltration during snowmelt and autumn precipitation, whilst, low infiltration caused by snow and frost in winter causes less contamination. Coliforms are mostly detected from July to September, which correlate with the time period of manure spreading in Norway. Based on the dataset hypothesis 2 is not confirmed, but the results are consistent with the hypothesis.

6.3 *Cryptosporidium* and *Giardia* in groundwater

Hypotheses 3: *Cryptosporidium* and *Giardia* do not exist in Norwegian groundwater wells in bedrock.

In the last few years there has been focus on pathogenic organisms like *Cryptosporidium* and *Giardia*, which were assumed to not exist in Norwegian drinking water. Until an epidemic caused by Giardia in 2004 (Søbstad 2004), no registrations existed of waterborne illnesses caused by these parasites in Norway (Folkehelseinstituttet 2003). Despite of this, investigations demonstrate that both parasites exist in low concentrations in Norwegian surface water used as drinking water sources (Robertson & Gjerde 2000).

For the first time the occurrence of *Cryptosporidium* and *Giardia* in groundwater from bedrock wells in Norway is investigated. All samples are taken from waterworks with possible contamination sources like farming or septic tanks (Chapter 4.1.5). *Giardia* is not found but, like in surface water, *Cryptosporidium* is found in low concentrations, though only at 3 of 20 waterworks (Table 5.2.1). The low number of positive samples can be related to sampling taking place in April and May. Since coliforms are mostly detected in autumn and *Cryptosporidium* and *Giardia* are related to fecal contamination, it is possible that sampling in August/September would have revealed a larger occurrence of the parasites.

One of the contaminated water samples was taken from a tap in a public house (an inn) and the water sample represents 2 wells. Both pigs and horses were observed grazing 50-100 m away from the wells and an old septic tank is located only few meters from one of the wells. An overflow of the septic tank occurred November 2003 approximately 5 months before sampling for *Cryptosporidium* and *Giardia* analyses. At the time of sampling the septic tank was still in use. Even though the overflow occurred several months in advance, it is the most likely cause of contamination because:

- In November 2003 microbiological analyses (TC and FC) were done at separate water samples from both wells and bacteria were only detected in the well closest to the septic tank.
- Contamination may have remained in small fractures and slowly been washed out during episodes of snowmelt or precipitation. The *Cryptosporidium* oocysts known to survive for months (Craun et al. 1998) can thereby be detected in the well several months later.

- Downhole inspection of the well with video camera shows multitudes of inflow of water from 4.7-7.9 m below surface (Appendix M).

At one contaminated waterwork the water sample was taken from the water reservoir by dipping the carboy into the water. The waterwork is supplied by 4 wells, where only one (W4) is close to farming. During sampling, water from this well was not pumped into the water reservoir, but it was not possible to collect water directly from the well. The water reservoir is covered and bird droppings, and other types of contamination sources, common to open water reservoirs, should be avoided. *Cryptosporidium* oocyst detected in the water sample might therefore be caused by:

- Remaining oocysts from W4 from the time this water was pumped into the water reservoir.
- *Cryptosporidium* from wild animals such as moose or deer.
- Contamination during sampling or analyses.

The third contaminated water sample is taken from one well situated in the vicinity of a farm with domestic animals. Manure spreading or droppings from grazing livestock are the most likely contamination sources.

In this study 10 of the waterworks sampled for analyses on *Cryptosporidium* and *Giardia* were also sampled for analyses on *Clostridium perfringens*. Of these, 5 waterworks did the analyses regularly. *Clostridium perfringens* was not found in any of the analysed samples. None of the waterworks with water samples where *Cryptosporidium* is detected had ever analysed for *Clostridium perfringens.* Therefore, it is not possible to verify if *Clostridium perfringens* and *Cryptosporidium* occur simultaneously.

The bacteria *Clostridium perfringens* is used as an indicator for *Cryptosporidium* in Norwegian drinking water, and waterworks based on surface water are required to analyse for *Clostridium perfringens.* Waterworks using groundwater are though only required to analyse for this bacteria if the groundwater is influenced by surface water. Water leakages between bedrock and casing and water inflow < 10 m below surface are observed in several wells. These wells are likely to be influenced by surface water or groundwater with short residence time in the subsoil, and some of them are part of waterworks supplying water not analysed for *Clostridium perfringens*. Additionally, oocysts from *Cryptosporidium* are detected in the groundwater from two of these waterworks. Based on this, all groundwater should be analysed for *Clostridium perfringens*.

Robertson & Gjerde (2000) found a significantly higher probability that samples with turbidity ≥ 2 FTU contained one or both of the parasites. In Dataset D all samples have turbidity < 2 FTU (Table 5.2.1) and too few data exists to do any comparison between turbidity and presence of *Cryptosporidium.*

In this study 20 wells are sampled, which is a small number. Nevertheless, it is proved that *Cryptosporidium* can be found in groundwater derived from bedrock wells. The supposed contamination sources identified are similar to those found by Ball (1997) and Robertson & Edberg (1997) who describe manure and sewage effluent to have contami-

nated the groundwater with *Cryptosporidium*. Oocysts exist in low concentrations below the infectious dose (10-100) to get Cryptosporidiosis (Leclerc 2003). Although it cannot be ignored that individuals with poor immune systems can be ill, it is possible that the *Cryptosporidium* oocysts found are not pathogenic to humans. Several species of *Cryptosporidium* exist, but primarily *Cryptosporidium parvum* is known to infect humans (Craun et al. 1998). The species of *Cryptosporidium* is not determined during the analyses, which means that the oocysts found can be a different specie than *Cryptosporidium parvum*. Neither was the viability of the oocysts examined, and a possibility is that they are only dead shells and thereby not infectious.

Concluding remarks hypothesis 3

The given hypothesis that "*Cryptosporidium* and *Giardia* do not exist in Norwegian groundwater wells in bedrock" is partly rejected. *Cryptosporidium* is found, whereas *Giardia* is not detected. Too few samples are analysed to verify the hypothesis according to *Giardia* and further studies are recommended to give a more reliable verification.

6.4 Factors correlating with the microbiological quality of the groundwater

Hypotheses 4: There is a correlation between groundwater wells in bedrock exposed to microbiological contamination and the following factors:

- Design and protection of the well
- Well capacity and depth to water inflow
- The superficial deposits (type, thickness and extent)
- Land use and contamination sources
- Distance from surface water (lake/pool, river or ditch)

6.4.1 Design and protection of the well

Improper design or protection of the groundwater well may cause microbiological contamination as described by Conboy & Goss (1999) and Korkka-Niemi (2001).

Casing:

An important part of a groundwater well in bedrock is the casing. To simplify the discussion, three factors are considered: (i) the top of the casing, (ii) the total length of the casing and (iii) the presence of sealing between bedrock and casing at the bottom. About 2/3 of the wells examined in Dataset E_{mod} have the well casing protruding above ground level and Table 5.3.3 indicates that these wells are less likely to have microbiological contamination than the remaining 1/3 of the wells. This is the case whether a well cap is installed or not, indicating that it is more important to locate the top of the casing above ground level than using a well cap. However, when the top of the casing is below ground level the 6 wells with a cap are more likely to report a water quality

exceeding the NSDW. This result is the opposite of what would be expected since the well cap is constructed to protect the well from contamination. It is therefore assumed that for these 6 wells other factors have a stronger influence on the microbiological quality of the water, thereby concealing any influence of the cap.

The possibility to avoid microbiological contamination increases with increasing casing length (Figure 5.3.4). Indications are that the casing length should be at least 2.5 m because when the casing length is less than 2.5 m no wells are reported to have good microbiological water quality (Table 5.3.3). It is expected that the casing is drilled into bedrock and that the thickness of the superficial deposits at the well site determines the length of the casing, which is documented in Figure 6.4.1. Therefore, the casing length cannot be discussed without evaluating the influence from the unconsolidated sediments.

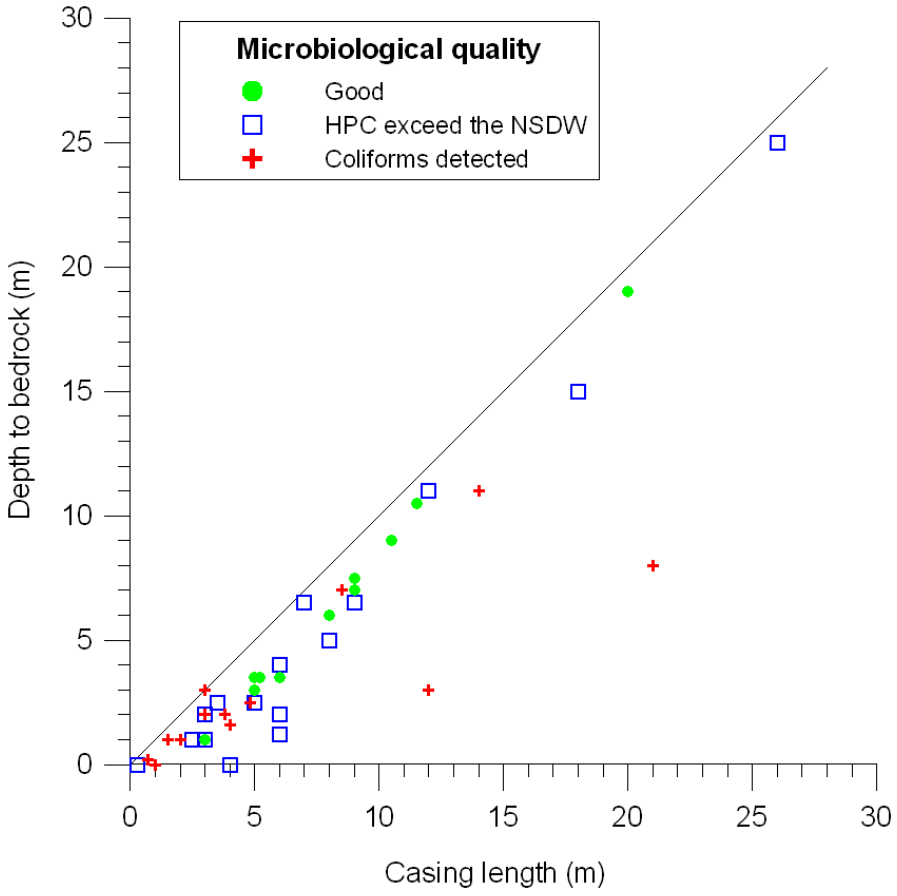

Figure 6.4.1 Correlation between casing length and depth to bedrock. Coliforms are TC and/or FC and HPC is HPC at 22°C. Total number of wells is 40.

Wells with less than 2.5 m of superficial deposits at the well point are statistically more susceptible to microbiological contamination than wells with more than 2.5 m of sediments (Table 5.3.6, Appendix D). Additionally, Figure 6.4.1 shows that most of the wells with depth to bedrock < 2.5 m and casing length < 5 m periodically supply water with either coliforms or HPC exceeding the NSDW. When the casing length is > 5 m there is also a statistically significant better chance to avoid coliforms in the water (Figure 5.3.4). It can therefore be suggested that the casing length of a well in bedrock should be at least 5 m and that the superficial deposits should be at least 2.5 m thick. Based on Dataset E_{mod} (Figure 6.4.1), it may be concluded that thickness of superficial deposits is more important than casing length because increasing the casing length when the depth to bedrock is < 2.5 m does not improve the microbiological water quality. Nevertheless, the results in Figure 6.4.1 also show that long casing and thick superficial deposits do not necessarily imply good microbiological quality. The microbiological water quality can in both cases be caused by leakage between casing and bedrock as discussed below.

Bentonite or cement-based suspensions are normally used as sealing material in Norway and sealing is performed at the bottom of the casing. It is important that the sealing is performed properly. Leakage is observed at 5 wells that have reported that sealing is performed with bentonite or cement-based suspensions. There are reasons to believe that the drillers do not always let the sealing material harden sufficiently before drilling is continued.

Wellhead protection

Based on the results presented in Chapter 5.3.1, a well-house or a concrete well-protection (manhole), in combination with a well-cover or a well-house (Figure 5.3.2), appears to be more efficient than a plain concrete well-protection in preventing bacterial contamination (Table 5.3.1). However, the data also show that other factors may affect the water quality, because as many as 15 of the 28 wells with a well-house or well-cover have unsatisfactory water quality.

Of the 12 wells protected by a well-house, the 5 wells with good microbiological water quality (Table 5.3.1) are generally situated in areas with no observed contamination sources and have thicker superficial deposits at the well site than the remaining 7 wells.

The superficial deposits are generally medium to thick around the 16 wells protected by a concrete well-protection in combination with a well-cover or a well-house, and no differences exist in sediment thickness related to microbiological water quality. The wells are located in outlying fields and they generally supply water with either good microbiological quality or too high measurements of HPC (Table 5.3.1). Nevertheless, two wells are located in an area with grazing sheep and one is located 10 m from a main road. All these three wells have HPC exceeding the requirements in the NSDW but no detection of coliforms. There are flaws in the wellhead completion for the 16 wells, including incomplete sealing between the concrete floor and the casing and a general lack of well cap that may contribute to poorer microbiological water quality. The above information indicates that it is more important with thick superficial deposits and well location away from possible contamination sources than a perfect wellhead completion.

Though, as shown below, thick superficial deposits and no obvious contamination sources cannot compensate for a faulty wellhead completion.

In Dataset E_{mod} 30 wells are protected by a plain concrete well-protection and at least 12 of them have flaws in the construction (e.g. lack of concrete floor, leaky walls and lid) and surface water may enter. Figure 6.4.2 gives an example of several similar constructed wells belonging to one waterwork. The wells are located in outlying fields with 2-11 m thick superficial deposits and no obvious contamination source like septic tanks or large mammals exist. Birds or possibly small mammals like mice are therefore the most likely contamination source of the fecal bacteria detected. Due to a faulty concrete wellhead-protection surface water has accumulated inside the manhole. This is mainly due to leakage between the concrete-ring and the concrete floor and between the well casing and the concrete floor. The water level inside the manhole depends on the water level in the sediments. Periodically the water level raises and exceeds the height of the casing that does not protrude ground level, and water may flow into the well casing.

Figure 6.4.2 An example of a well where surface water flows into a leaky concrete wellhead-protection (manhole). In the example the water level periodically exceeds the height of the casing and surface water flows into the well.

Figure 6.4.2 illustrates also the importance of multiple barriers against pollution. In this case, the accumulation of water inside the concrete well-protection would not have been that critical if the well casing had protruded above ground level and a watertight well cap existed to prevent water from entering the well casing.

Well depth, capacity and depth to water inflow:

Results from Chapter 5.3.1 (Figure 5.3.5) indicate that wells with reported coliforms have greater well depth and lower capacity than wells with good microbiological quality or reported HPC exceeding the NSDW. Increased residence time of the groundwater in the underground increases the die-off rate of the microorganisms and the ability of the underground to remove unwanted microorganisms from the groundwater (Matthess et al. 1985). Based on this, deep wells presumably pumping water from a great depth with high residence time should have a better microbiological quality than shallow wells, which is the opposite of what is indicated in Figure 5.3.5.

Generally fracture permeability decreases with increasing cover, depending on type of bedrock, fracture roughness and degree of normal stress (Barton et al. 1985). In Norway, median groundwater yield decreases with increasing well depth for almost every rock type (Morland 1997). Similar results are shown in Finland (Rönkä 1993) where median yield for wells more than 80 m in depth is approximately half of the median yield for wells up to 40 m depth.

In Norway the drilling companies guarantee water when drilling a well or the customer does not have to pay. It can therefore be hypothesized that low capacity wells are drilled deeper in an effort to increase the yield instead of abandoning the well.

There has not been any attempt to seal off the water inlet in the uppermost 10 m of the wells in Dataset E_{mod}. Thus, for low capacity wells, inflow of microbiological contaminated water may cause a greater problem because of less dilution of the contamination than in high capacity wells. Figure 6.4.3a) confirms that low capacity wells (< 2000 l/h) in Dataset E_{mod}, regardless of well depth, often report microbiological quality exceeding the NSDW. It is also shown that wells deeper than 100 m, regardless capacity, often have microbiological problems. The contaminated water can be a result of water inflow through fractures close to ground level or at the bottom of the casing as described earlier. It is vaguely indicated in Figure 5.3.5 that groundwater wells reporting coliforms have water inflow closer to surface than both wells reporting HPC exceeding NSDW and wells with good microbiological water quality.

Figure 6.4.3b) shows that wells with low capacity (<2000 l/h) and water inflow in the upper 12 m of the well, supply water with either coliforms or HPC exceeding the NSDW and 4 of these have both low capacity and well depth > 100 m. Additionally, only one well with no microbiological problem and high capacity (> 2000 l/h) has water inflow ≤ 10 m from ground level.

The correlations summarised above indicate that leakage either at the bottom of the well casing or water inlet < 10 m below surface is a likely cause of the coliforms detected in the deep wells.

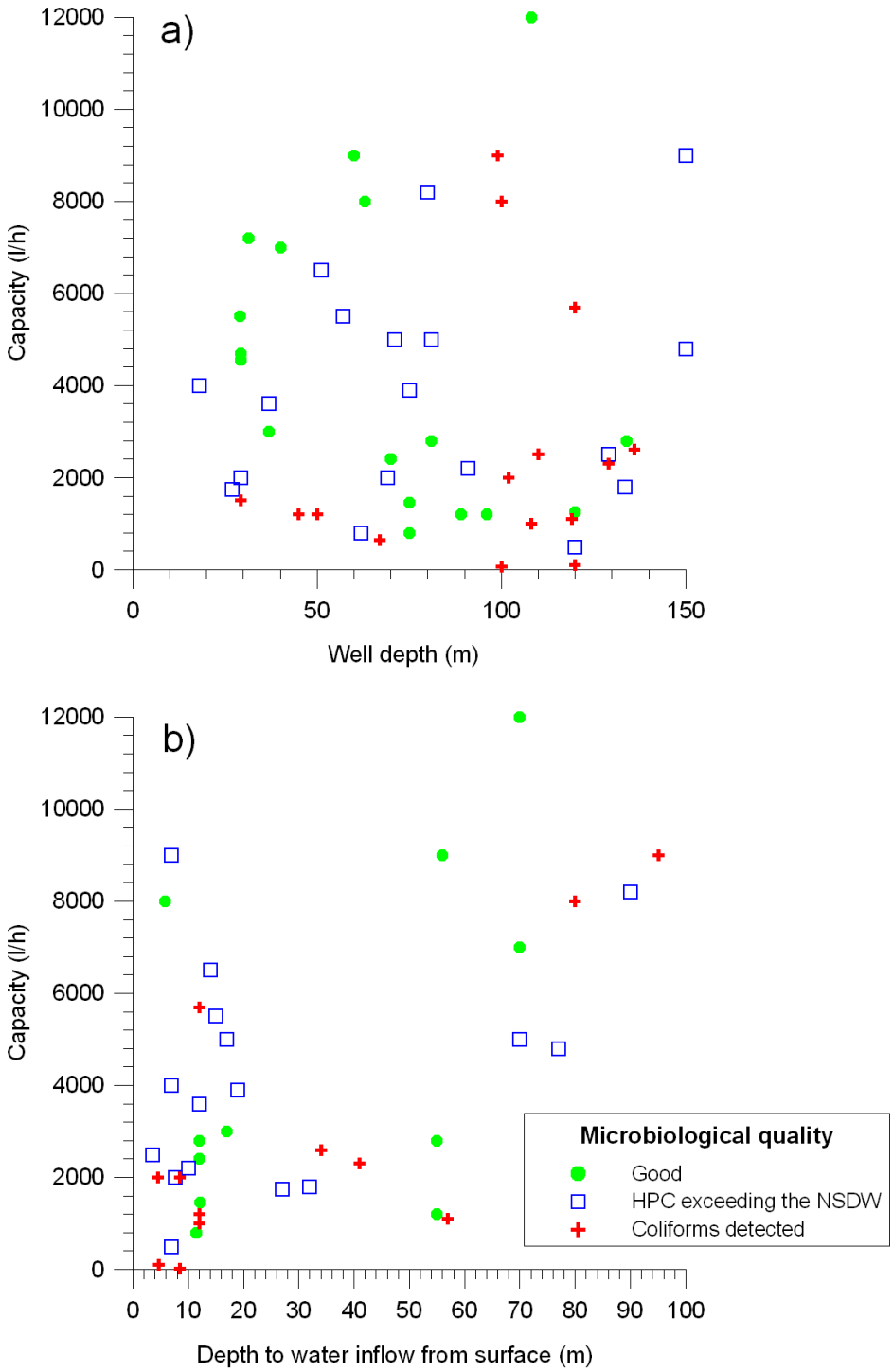

Figure 6.4.3 x-y-Plots showing wells from Dataset E_{mod}. a) Microbiological quality related to well depth and capacity. Deep (> 100 m) wells and low capacity wells (< 2000 l/t) often report coliforms. Total number of wells is 52. b) Microbiological quality related to depth to water inflow closest to ground level and well capacity. Only one well with good microbiological quality has water inflow less than 10 m below ground level. Total number of wells is 39.

6.4.2 Thickness and origin of the superficial deposits

Verba & Zaporozec (1994) pointed out the importance of superficial deposits related to groundwater vulnerability mapping. Sediment type, i.e. grain and pore size, is regarded as an important factor controlling migration of water and microorganisms in soil (Gerba & Keswick 1981, Robertson & Edberg 1997). Marine sediments are currently found in Norway at elevations up to about 200 m above sea level ("marine limit"). Statistically less wells situated below the marine limit supply water exceeding the NSDW (Appendix D). Below the marine limit most sediments are marine deposits, though till, weathered material, talus and glaciofluvial deposits are also found. Till in Norway contains mostly sand and silt and little clay material (Jørgensen 1977), though exceptions are found. Marine deposits containing clay may therefore be less permeable and give better protection against microorganisms. Data presented in Chapter 5.3.2 (Table 5.3.6) suggest that wells located in areas with medium to thick superficial deposits are less susceptible to microbiological contamination, which is also found by Conboy & Goss (2000). The result is supported by the fact that wells with superficial deposits > 2.5 m at the well site have a statistically significant better microbiological quality than when the thickness is ≤ 2.5 m (Table 5.3.6, Appendix D). This result is further compared with well location above and below marine limit. It is found that, when the superficial deposits fall into the category medium to thick, wells below marine limit are least susceptible to microbiological contamination. As expected, wells below marine limit are least susceptible when the superficial deposits are medium to thick compared to thin or discontinuous.

6.4.3 Land use and contamination sources

Pollution can reach the well in two ways: (i) surface water having direct access to the well, and (ii) through the unconsolidated sediments and/or fractures in the bedrock (Daly 2000). Surface runoff towards the well with accumulation of water in ponds/pools close to or in contact with the wellhead is exemplified in Chapter 6.4.1 in connection with improper wellhead-protections. For the wells to be microbiologically contaminated from this accumulated water or infiltrated water with short residence time in the subsoil, a source for the microorganisms needs to be present (Chapter 5.3.4). Farming, different types of septic tanks, sewage and infiltration systems and large mammals (moose and deer) are observed or reported contamination sources for coliforms in this thesis (Table 5.3.9). 10 wells, where none of these contamination sources are registered, are compared with 10 wells where contamination sources are present. It can be seen that, by removing sources for coliforms, these bacteria are less frequently detected, whereas some wells still have HPC exceeding the NSDW. This is because HPC at 22°C is part of the microbiota in soil and water and will grow in the stagnant water. It is therefore important to hinder surface water to accumulate too close to wells even though no obvious source of coliforms exists.

Malard et al. (1994) showed that infiltration of river water into an aquifer can cause microbiological pollution. Distance from surface water sources (lake/pool, river/stream and ditch) is investigated in Chapter 5.3.5 and a statistical significant correlation is found between distance to river/stream and well site (Figure 5.3.9b). Most contaminated wells are within 75 m of the river/stream, but based on the results a safety distance should be set at 125 m. No correlation is found between distance from well site to

lake/pool or ditch. Nevertheless, ditches exist in the vicinity of 8 wells in Dataset E_{mod}, all within 50 m of the well, and 5 of these wells have reported coliforms or HPC exceeding the NSDW in the groundwater. In Dataset E one waterwork has reported correlation between incidences of microbiological contamination and stagnant water in a ditch < 50 m from the wells. According to information from the waterwork, removal of the water by tidying and draining the ditch solved the problem. This indicates that drainage ditches should be avoided too close to the well, especially if they contain stagnant water.

Mainly three types of land use are described in this study; farmland, outlying fields, and built-up areas or scattered houses (Chapter 5.3.3). Compared to outlying fields, wells situated in the vicinity of farmland or built-up areas are more often contaminated with coliforms. However, wells in outlying fields are vulnerable to microbiological contamination if sheep or other large mammals are allowed to wander too close to the well. The 29 wells situated in the vicinity of farmland are most susceptible to contamination, especially wells within 100 m of a farming area (Table 5.3.8). Manure can have contaminated 16 of the 29 wells either from manure spreading or from grazing cattle. It is indicated that more of these wells are contaminated by coliforms than wells where no manure is present. Further examination of Dataset E_{mod} indicates that wells furthest from the grazing land are less contaminated, but exceptions are found. Similar results were found by Goss et al. (1998) who discovered that the number of wells with microbiological contamination decreased with increasing distance from feedlot or exercise yards. The correlation was more pronounced for dug or bored wells than drilled wells.

Wells situated close to built-up areas or scattered houses may be contaminated from sewage systems, septic tanks or pit latrines (Daly 1985, Daly et al. 1993, Macler & Merkle 2000). This is also found in this study. Leakage or overflow from septic tanks < 50 m from the wells are confirmed to be the contamination source for 2 wells and leakage from a sewage pipeline is expected to be the cause of contamination for one well. Improper sewage treatment by infiltration is stated as the reason for microbiological contamination at one waterwork. Gaut & Tranum (2003) report the same as one of the reasons of poor microbiological quality for several wells in a small community outside Oslo (Norway).

As expected, most wells have good microbiological quality when no potential contamination source is present (Table 5.3.9).

6.4.4 Concluding remarks hypothesis 4

The microbiological quality is correlated with some of the factors presented in hypothesis 4 and it can be concluded that the hypothesis is partly verified. A ranking of importance of the different factors that may influence the microbiological water quality is done based on the results in Chapter 5 and the discussion above.

1. It is most important to locate the groundwater well apart from any known contamination source; especially septic tank systems and farming with manure

spreading or grazing animals. Recommended minimum distance is 100 m. The best location is in outlying fields with no grazing livestock.

Groundwater wells in bedrock should not be located within 75-125 m of a river or stream in order to achieve sufficient residence time for water infiltrated from this watercourse. It is also important to avoid stagnant water in drainage ditches.

2. Thickness and extent of the superficial deposits are important factors in reducing microbiological contamination of the groundwater. Based on the dataset the thickness of the deposits should be at least 2.5 m to ensure attenuation of possible pathogenic microorganisms. Wells located below the marine limit are better protected than those situated above the marine limit especially when the extent and thickness of the sediments are medium to thick.

3. The casing should protrude above ground level and have a total length of at least 5.5 m to ensure that minimum 5 m extend below surface. No improvements in the microbiological quality are detected when casing length is increased for the wells where depth to bedrock is < 2.5 m. Thus, it can be concluded that thickness of superficial deposits is more important than the length of the casing.

   Proper wellhead completion (including the well casing) hinders contamination of the groundwater through the wellhead and inflow (leakage) of unfiltered and possibly microbiologically contaminated water at the bottom of the casing. Groundwater inflow should not occur at shallower depth than 10 m. Installation of an inner casing to seal off this water should be considered if the water quality is unsatisfactory.

4. No statistically significant correlation is found between microbiological water quality and use of hydraulic fracturing or explosives. Nevertheless, it is important that yield enhancement is done properly and that packers for hydraulic fracturing are placed no closer than 30 m from the surface (Banks & Robins 2002) to avoid propagation of fractures to ground level that can easily be contaminated.

5. Groundwater level, capacity and well depth are not directly related to microbiological quality.

6.5 Physio-chemical parameters

Hypothesis 5: There is a correlation between physio-chemical parameters of the water, such as electrical conductivity, pH, colour, nitrate and total organic carbon, and the presence of coliforms or HPC exceeding the NSDW in the water.

The physio-chemical water quality (Dataset A-C) of the wells in Dataset E_{mod} is compared with the microbiological water quality to detect possible correlations. Parameters studied are electrical conductivity, pH, turbidity, colour, alkalinity, chloride (Cl^-), nitrate (NO_3^-), manganese (Mn), iron (Fe) and total organic carbon (TOC). The median value for each parameter is calculated. Median value, M, for the water samples from the wells reporting good microbiological quality is compared with the median values for the water samples from the wells periodically exceeding the NSDW. Two different median values are calculated for the water from the wells in the latter group:

- BM – median value for the water samples exceeding the requirements in the NSDW
- Mb – median value for the water samples meeting the requirements in the NSDW

No statistically significant correlation is found between any of the physio-chemical parameters and the microbiological water quality when comparing wells with good microbiological quality with wells exceeding the NSDW. However, the results indicate that turbidity, Fe and Mn are higher in wells reporting microbiological problems. This is also found when comparing BM and Mb both generally (Figures 5.41-5.4.3) and for single wells (Figures 5.4.5-5.4.7). In Chapter 5.3.4 it is shown that wells with possible contamination from surface runoff towards the well is less contaminated by coliforms when no other contamination source is observed in the well area. Based on this result, a possibility is that wells with periodically microbiological contamination in periods are supplied by non-contaminated surface water or shallow groundwater causing a lack of statistically significant correlation between microbiological contamination and most physio-chemical parameters studied.

Microorganisms use organic carbon as nutrient (Madigan et al. 2003) and high levels of TOC enhance the ability for survival and growth. This is consistent with higher TOC level in some of the wells with water periodically exceeding the NSDW (Figure 5.4.4). The measurements of colour also tend to be higher in water samples not meeting the NSDW when comparing BM and Mb. A statistically significant difference exists for wells periodically reporting HPC_{only} exceeding the NSDW (Figure 5.4.2). Measurements of colour and TOC will increase when organic matter is dissolved in water and also high turbidity can be caused by supply of muddy surface water or infiltrated water with too short residence time in the subsoil to be filtrated. The particles in the water will contain organic material enhancing the ability of the microorganisms to attach to the particles (Robertson & Edberg 1997) causing turbidity, colour and TOC to be connected with high content of microorganisms.

High levels of iron may be caused by supply of water with chemistry different from more mature groundwater; for example, leakage between casing and bedrock supplying water with short residence time. This water can have high content of organic matter and low oxygen content and iron can be dissolved in the water. The iron can also be connected to particles in the water because high turbidity is measured in the wells with high iron content.

Wells periodically reporting high levels of HPC_{only} have higher chlorine content when HPC exceeds the NSDW. These wells are situated < 1 km from the coast. The results may therefore indicate infiltration of surface water with short residence time and that the surface water is influenced by precipitation with high chlorine content.

Concluding remarks hypothesis 5

No unique correlation is found between the physio-chemical parameters investigated and the microbiological water quality and hypothesis 5 is not verified. However, it is shown that changes in parameters like colour, turbidity and iron can indicate microbiological contamination for single wells. Therefore, changes in these parameters and high levels of TOC can be used as a symptom that the aquifer or the well is vulnerable to microbiological contamination.

6.6 Ownership - Private and public waterworks

Hypothesis 6: Private waterworks supply more often water contaminated by coliforms or high HPC than public waterworks.

Dawson & Sartory (2000) states that throughout the world private water supplies tend to be more often contaminated by bacteria than public water supplies. Comparison of microbiological water quality from private and public waterworks in this thesis (Dataset A_{mod}, Figure 5.1.9) shows no differences in microbiological quality between the two groups. The inconsistency with the statement by Dawson & Sartory (2000) can be caused by the comparison of only waterworks based on groundwater from wells in bedrock in this thesis. Dawson & Sartory (2000) does not specify the drinking water sources for the private water supplies. However, studies from both UK (Reid et al. 2003, Said et al. 2003) and Norway (Johansen et al. 1998) show that surface water and shallow wells are more often used as drinking water sources for private water supplies. The Norwegian study also shows that fewer boreholes were contaminated with coliforms or HPC exceeding the NSDW than surface water sources and shallow wells. Based on the field inspections from 1/3 (49 waterworks, Dataset E) of the waterworks in Dataset A_{mod}, waterworks have often the possibility to locate the supply wells apart from contamination sources. This cannot be expected for private wells supplying a single household located on a small property, which makes private wells more vulnerable to contamination. Another safety mechanism for waterworks are the requirements in the Norwegian drinking water regulations. Consequently, the waterworks will have to

improve the water quality if it is unsatisfactory. This is not the case for private households.

Concluding remarks hypothesis 6

Based on Dataset A_{mod} private waterworks are not supplying water more often exceeding the NSDW than public waterworks. However, it is feasible that, if water supply sources for single households were part of the dataset in this thesis, private water supplies could be more vulnerable to microbiological contamination than public water supplies in Norway.

6.7 Recommended construction and location of bedrock wells

6.7.1 Recommended wellhead completion

The results discussed in Chapter 6.4 show the importance of not only protection of the groundwater sources, but also the need of proper wellhead completion including design of the well casing, and the establishment of multiple barriers against contamination. Figure 6.7.1 shows recommended wellhead completion of a groundwater well in bedrock based on the results presented in Chapter 5.3 and discussions in Chapter 6.4. The design is discussed in this chapter.

Inspection of wells in Dataset E_{mod} with downhole video camera displayed high frequency of cavities in the well wall and highly fractured rock in the uppermost part of the borehole. These fractures will function as preferential flow paths for water. Water leakages occurred between casing and bedrock in 1/3 of the wells inspected and sealing to prevent water inflow was only occasionally observed (Chapter 5.3.1). It is concluded in Chapter 6.4.4 that the total length of the well casing extending below surface should be at least 5 m and that the superficial deposits should be at least 2.5 m. When this is the case, the well casing is drilled 2.5 m into bedrock. When the thickness of the superficial deposits decreases the length of casing drilled into bedrock increases. Since the bedrock is highly fractured close to surface, the increased length of casing in bedrock will seal out fractures in the upper part of the borehole. This will compensate partly for the thin superficial deposits that do not provide sufficient residence time for the water in the subsoil for possibly harmful microorganisms to be removed or killed.

Examining Figure 6.4.1, it is seen that, when depth to bedrock is more than 3 m, most of the wells with good microbiological water quality have the casing drilled 1.5-2 m into bedrock. However, coliforms and HPC exceeding the NSDW are also reported for wells where the casing is drilled > 2 m into bedrock. Based on the video and field inspections this is probably caused by leakages between bedrock and casing, water inflow in the upper 10 m of the well and existence of contamination sources. No information from the dataset indicates that the casing length should be drilled more than 2.0 m into bedrock if the thickness of the superficial deposits is > 3 m, but 2 m should be a minimum to ensure that the casing is finished in solid rock. The casing should also be drilled further

into bedrock if it is assumed that the thickness of the superficial deposits decreases away from the well site or bedrock is exposed within 25 m of the well.

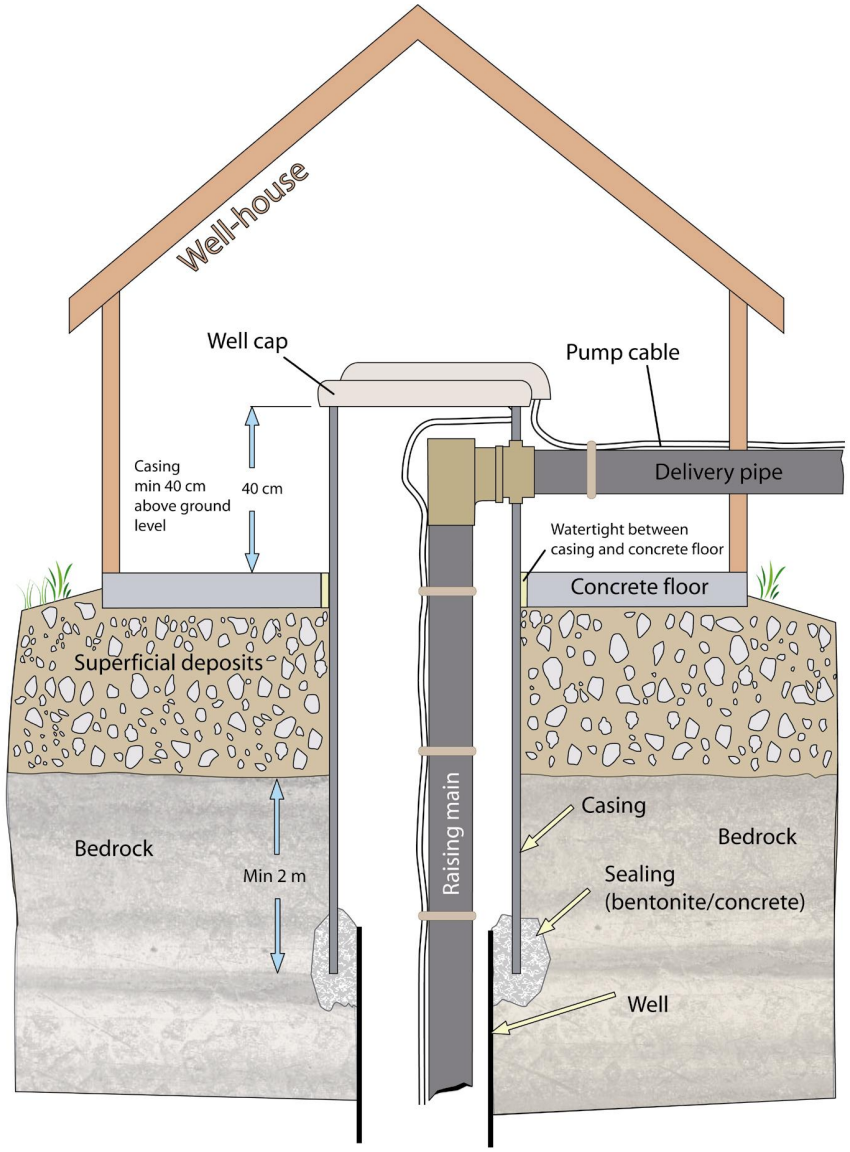

Figure 6.7.1 Recommended wellhead completion with concrete well protection. Total length of the well casing should be minimum 5.5 m to ensure that at least 5 m extend below surface.

Sealing is necessary between bedrock and casing to prevent leakages and should always be carried out. However, it can be discussed whether sealing is important when the superficial deposits are thick and continuous. Results from the video inspections show that leakage also occurs when the superficial deposits are 11 m, but it is not known at which depth the water reached the casing. If water from the unconsolidated sediments or water accumulated between these sediments and bedrock are to be utilized, this should

be evaluated by hydrogeological expertise and the well should be constructed differently to ensure sufficient residence time of the water from the unconsolidated sediments.

The Norwegian Standard (NS) 3420 recommend to drill at least 1 m of casing into bedrock and the revised edition (September 2004) has implemented sealing requirements. The sealing requirements are similar, whereas the recommended casing length is too short compared to results presented in this thesis. Compared to other countries, the results from this study are similar to the type-approved groundwater well in Sweden (Risberg 1997). In Great Britain (Environment Agency 2000, SEPA 2004a) it is recommended to drill the casing minimum 3 m into bedrock and to grout-in the casing instead of sealing only at the bottom. This type of sealing is less vulnerable to cracks in part of the sealing, but is also time consuming and will be more expensive.

A minimum total casing length of 5 m extended below surface, with at least 2 m of casing drilled into solid rock, with proper sealing between bedrock and casing, will be sufficient for most wells, but not all. Water inflow is observed from shallow fractures (< 10 m below surface) and this water may be contaminated due to short residence time in the subsoil. In these cases it is possible to seal off the water inflow with an additional inner casing equipped with packers in both ends, preventing water from entering the well (Figure 6.7.2). If the well wall is too irregular at the location of the bottom packer, it will not be watertight. Consequently it is important to locate a smooth part of the well wall. If a proper drilling log is lacking, a downhole camera can be used to locate a suitable spot.

Steel casings are generally used in Norway. Video inspection revealed that the casing rusts, but this should normally not influence on the water quality. However, in two cases the well owners report particles in the drinking water that can be associated with water raising and falling inside the casing. The problem could also be related to biofilm observed at the bottom of the casing. In both cases a possible solution to the problem could be to install an inner plastic casing to seal off the steel casing. A similar solution could be used as in Figure 6.7.2, except that the top of the inner casing is elevated to the same level as the top of the outer casing.

Figure 6.4.2 illustrates the importance of the well casing protruding above ground level. This will not only prevent inflow of surface water, but also hinders small animals like mice and frogs from falling into the well, especially if no other protection exists. The height above ground level should be 40-50 cm. Thus, the total casing length should be at least 5.5 m.

As described in Chapters 5.3 and 6.4, it is not demonstrated that a well cap will improve the water quality. However, it is an additional insurance to keep surface water and small animals away from the well and, when it is securely locked, it will prevent people from dropping objects into the well. It is therefore recommended to install a well cap. In addition to be locked or securely tightened the cap should be constructed with a junction box for the pump cable. A well cap is recommended by most guidelines (e.g. Indre Sogn Interkommunale Servicekontor 1990, Risberg 1997, Environment Agency 2000),

whereas a specific height of the casing above ground level of 30 cm is given in UK (Environment Agency 2000, SEPA 2004a).

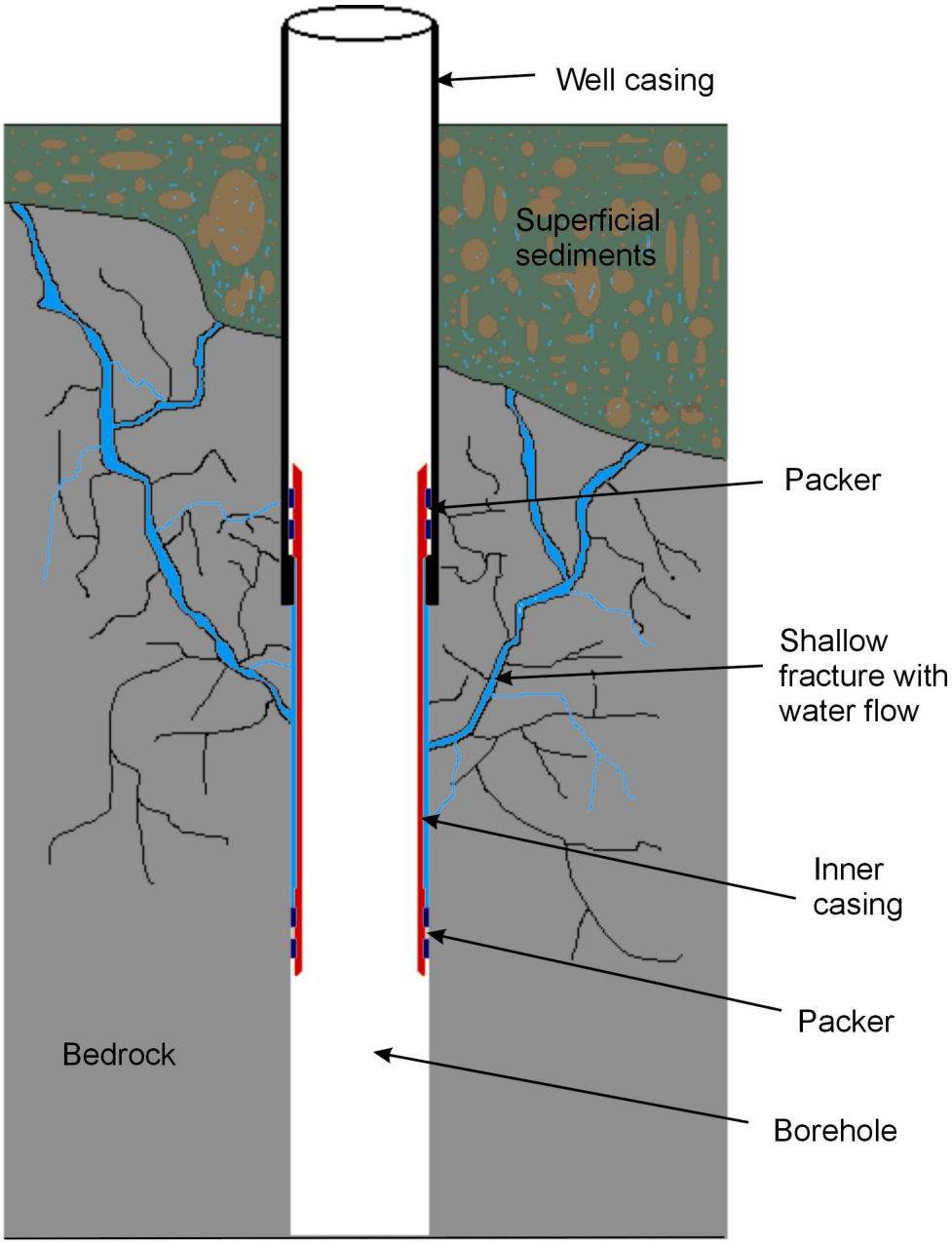

Figure 6.7.2 Installation of an inner casing (red), equipped with packers at both ends, prevents water from the shallow fractures to flow into the well. Figure by Frank Sivertsvik, NGU.

As stated above, it is recommended to let the casing protrude above ground level to avoid contamination of the well from surface water or other types of contamination. A well-house (Figure 6.7.1) or a concrete well-protection (Figure 6.7.3) should be constructed around the well casing. To avoid raw air inside the well-house, a bleeder valve with a vermin cover should be installed. Based on the results given in Chapter 5.3.1, and discussion in Chapter 6.4.1, it is recommended to use a well-house, primarily because it is:

- Above ground level
- Most likely to be constructed properly
- Less likely to be destroyed or neglected.

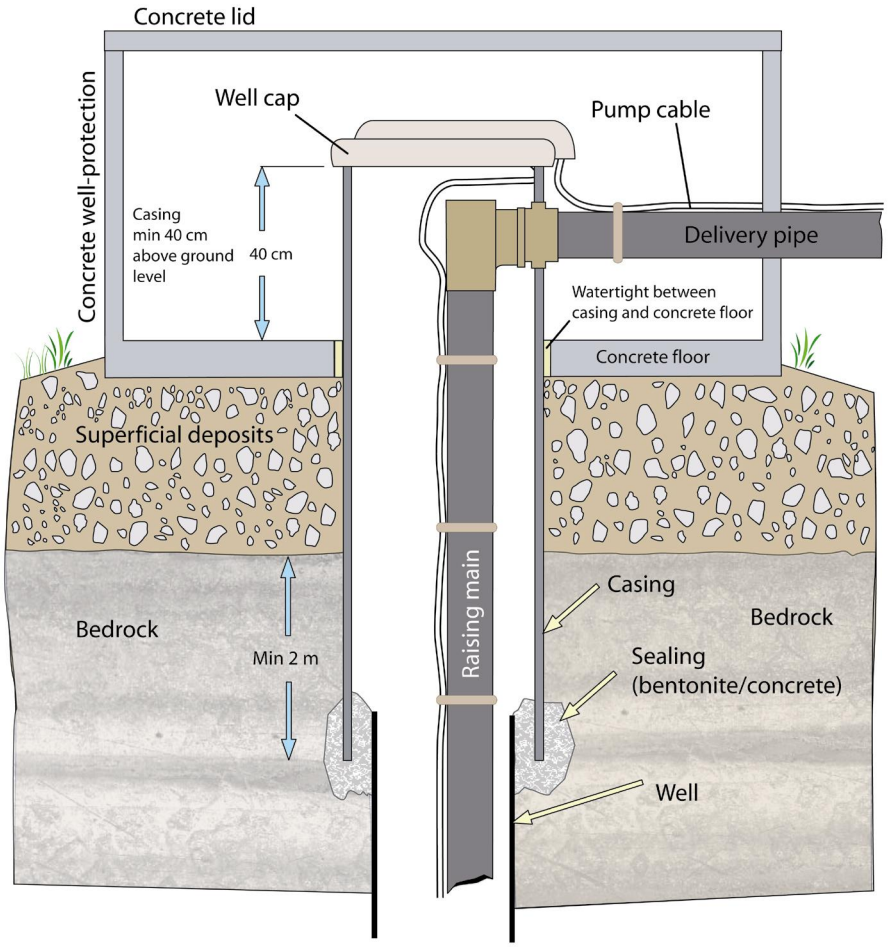

Figure 6.7.3 Proposed wellhead completion with concrete well-protection. Total length of the well casing should be minimum 5.5 m to ensure that at least 5 m extend below surface.

The base of both the well-house and the concrete well-protection should be a concrete floor that is properly sealed around the casing. Applicable systems exist for the delivery pipe to be installed through the upper part of the casing, avoiding penetrating the well cap. A watertight sealing is also needed where the delivery pipe and pump cable are

passing through the chamber wall. When a concrete well-protection is used, it is likewise important that the space between the concrete rings (if more than one is needed) is sealed and that the cover is watertight. An option for the latter is to use a fibre glass cover sloping outwards on top of the manhole cover (Figure 6.7.4a) or use a well-cover (Figure 6.7.4b).

Even though the well-house or concrete well-protection are properly constructed, water may accumulate on the concrete floor. A drain with a vermin cover to prevent small animals entering through the drain should therefore be installed. Consideration has to be made that no surface water accumulating outside the wellhead protection can enter through the drain.

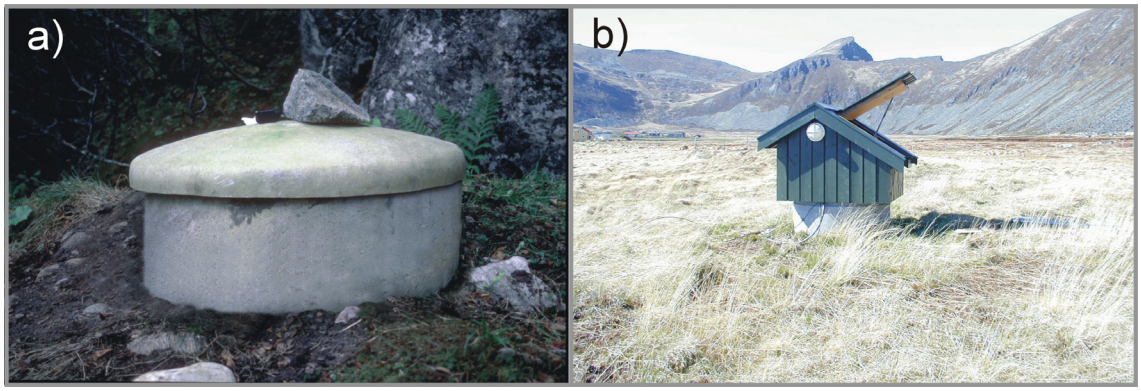

Figure 6.7.4 a) Fibre glass cover sloping outwards on top of the concrete well-protection to ensure that the manhole cover is watertight. b) Well-cover on top of a concrete well-protection.

6.7.2 Recommended protection in the immediate vicinity of the well

It is essential to drain surface water away from the vicinity of the wellhead as demonstrated in Chapter 6.4.3. Drainage ditches can be used but caution has to be taken to avoid stagnant water in the ditch too close to the well. New wells should be located where surface water naturally flows away from the borehole. To increase this ability, low permeability sediments may be packed around the well-protection to ensure sloping away from the well (Eckholdt & Snilsberg 1992). If the terrain at the well point is suppressed or is susceptible to flooding, it should be elevated.

Based on the results and discussions the optimal location for drinking water wells is in outlying fields with no domestic animals grazing in the vicinity of the well. This is not always possible, especially for private wells supplying single households. Nevertheless, waterworks should be able to locate wells at least 100 m, and preferably further, away from human activities like farming or built-up areas. If farming cannot be avoided, manure spreading and pasture should be forbidden within at least 100 m of the well. In this study, some wells were within 50 m of septic tanks and sewage infiltration systems, which was too close. The distance will depend on depth and type of overburden. For sewage infiltration systems Daly et al. (1993) recommends at least 60 m between the percolation area and the groundwater well when there is only 1 m of a high permeability

sediment between the percolation pipes and bedrock. In Norway sewage infiltration systems cannot be located within 100 m from drinking water wells and depth to bedrock or groundwater should be no less than 0.5 m (Miljøverndepartementet 1992). For groundwater this is the minimum depth throughout the year. When protection zones are delineated it is recommended that sewage infiltration systems and manure spreading should be avoided within zone 1. Ideally this gives a residence time in the subsoil of at least 60 days before the groundwater reaches the groundwater well.

Results described in Chapter 5.3.2 show that groundwater wells should be located in areas with continuous superficial deposits and, preferably, with a thickness of at least 2.5 m. When this is not possible, it is important to place the well at a location where at least some sediments exist.

The usefulness of a fence compared to other types of protection cannot be investigated based on Dataset E_{mod}. A fence will not protect the well from surface water runoff towards the well. Neither will the residence time in the subsoil of infiltrated water in a particular spot be increased if a fence is put up. Therefore, proper wellhead completion, drainage and existence of superficial deposits in the well area are more important.

However, a fence protects the immediate vicinity of the well from human and animal activities and gives the well extra protection from vandalism or contamination at the well site. Fencing is especially important when livestock are present. Sheep enjoy resting at manholes or with their back to house walls and examples from this study indicate that sheep droppings are the source of contamination for at least three wells. According to Norwegian guidelines the fence should be positioned at a distance 10-30 m from the well (Folkehelsa 1987). Daly (2000) recommends 10 m, and remarks that the barrier should rather be a high wall than a fence because fences tend to attract farm animals. Based on results in Chapter 5.3 the enclosed area will depend on land use and thickness of the superficial deposits. When the superficial deposits are continuous and at least 2.5 m thick, the fence can be positioned 10 m from the well, whereas the presence of livestock and thin or discontinuous superficial deposits require a larger enclosed area.

6.7.3 Abandoned wells

The aim of this thesis is not to discuss how to secure abandoned wells, but it is important to point out the risk they represent to the groundwater and that regulations should be made. Poor water quality is often combined with low yield and/or unfavourable well location. Therefore new wells are drilled or the waterworks change supply source to surface water. The old wells are then either abandoned or kept as a reserve supply source for the waterwork. During field inspections (Dataset E_{mod}) several abandoned or unused wells were found. The condition of these wells varied, but often they are neglected and have poor wellhead protection (Figure 5.3.10). As a consequence, the wells stand as open holes into the aquifer, representing pathways for contaminants. Since no specific regulations exist in Norway on how to take care of abandoned drilled wells, at least guidelines should be made on how to seal them properly. Examples of backfilling are given both in USA, Great Britain and Ireland (Wright 1995, Environment Agency

1999b, New Hampshire DES 2000b, Wisconsin Department of Natural Resources 2001) (Chapter 2.5), and these could also be used in Norway.

6.8 Protection zones and groundwater wells in bedrock

Matthess et al. (1985) emphasise the importance of protection of groundwater because:

1. Clean-up is difficult and expensive
2. There is a time lag between introduction of the contamination and the first traces of the contamination in the groundwater and consequently people regard the groundwater as protected.

It is therefore important to develop guidelines to protect groundwater sources.

6.8.1 Evaluation of the use of protection zones in Norway and their significance for the microbiological water quality

One of the aims in this study is to assess the use of protection zones in Norway and their significance for the bacteriological water quality.

Present practice in Norway (Ellingsen 2002) is to use the protection zones recommended by Eckholdt & Snilsberg (1992) (Chapter 2.4.4), with four zones for unconsolidated sediments and three zones for bedrock wells. No guidelines exist to ensure a uniform determination of the outer boundary of zones 1 and 2 for groundwater wells in bedrock. According to Banks & Robins (2002), this is done by "common sense", which means that the boundaries in each case depend on the knowledge and experience of the hydrogeologist. The outer boundary of zone 1 (the vulnerable recharge area) is delineated based on an evaluation of possible contamination sources, detection of vulnerable areas (mostly exposed bedrock) and surface runoff towards the well. Outer boundary of zone 2 is normally set equal to the surface catchment area.

In 2003 a total of 574 waterworks, each supplying more than 50 persons or 20 households were based on groundwater in Norway (NIPH unpublished). Groundwater wells in bedrock supplied 185 of these waterworks and protection zones are established for 25 % of them. About 50 % of the remaining 389 waterworks, most of which are based on groundwater from springs or wells in superficial deposits, have also delineated protection zones. Based on these numbers, the use of protection zones for Norwegian waterworks supplying groundwater is not optimal, especially not for those supplying groundwater from bedrock.

A total of 22 of the 123 waterworks in Dataset C have delineated protection zones (Table 5.1.8). However, a larger part of the waterworks without established protection zones have good microbiological quality than the ones with defined protection zones in 2003. Consequently, it seems that the existing zones do not improve the water quality.

Except for 6 waterworks included in Dataset E, no information exists on the size of the protected area and number of zones delineated for each waterwork.

The presence of unwanted microorganisms in the groundwater indicates too short residence time of the water in the subsurface before reaching the well. This can be caused by a too small extension of the protection zones in one or more directions.

Field inspections at the 6 waterworks in Dataset E implies that contamination can also be due to lack of land use restrictions within the protection zones or that they are not followed. For example, the owners of 2 of the 6 waterworks do not wish to enclose the wells. As a result sheep are grazing at the immediate vicinity of the wells of one of the waterworks. In these cases it can be suggested that zone 0 does not exist because it is impossible to fulfil the restrictions without a fence.

Improper well construction and/or wellhead completion are also assumed to cause water quality problems. Video inspections of wells in Dataset E have revealed leakages at the annulus of the well casing. The leakage imply that a shortcut exists for surface water or infiltration water into the well, which will lead to shorter residence time than expected, of the water in the subsurface.

Concluding remarks

The statistics from VREG show that few waterworks in Norway based on groundwater have established protection zones. This is especially the case for those based on groundwater from bedrock. It is not possible to give an evaluation of the significance of the reported protection zones in this thesis. Information about local factors, such as extension of the protection zones, existing land use restrictions, present land use, well construction and wellhead completion, that may influence the microbiological water quality is not sufficiently known.

6.8.2 Suggestions of improvements for delineation of source protection zones in Norway

It is necessary to get a simple, robust and uniform method to establish protection zones around wells in fractured bedrock in Norway. This is highlighted by the implementation of the WFD, which requires protection of all existing and possible groundwater sources.

Both investigations performed on behalf of the Environment Agency in UK (Robinson & Barker 2000) and the USEPA (Bradbury et al. 1991) state that numerical modelling gives the best results when delineating protection zones for groundwater wells in bedrock. According to these authors, delineation of protection zones in Norway may follow the existing guidelines (Folkehelsa 1987, Eckholdt & Snilsberg 1992) with the exception that delineation of the boundaries should be set by numerical modelling. A problem is that groundwater from bedrock in Norway is mostly used by small and medium sized (<1000 people) waterworks, single households and holiday cottages, which have small resources to pay for extensive hydrogeological investigations. Besides, information from monitoring wells often gives uncertain and conflicting results and prediction of flow paths and particle transport in fractured media is difficult due to

complicated fracture networks. Even with large datasets from surface, boreholes and tunnel investigations, modelling results are hampered by uncertainties of the subsurface fluid flow (Voss & Tirén 2003), thereby reducing the quality of geological predictions. This is also recognised by Bradbury et al. (1991) and Robinson & Barker (2000).

In addition to numerical models, tracers have for many years been used to characterize groundwater flow and transport (Sanford et al. 1996). In connection with small water-works tracer tests will often be too expensive and/or not useful because too few wells exist to establish a picture of the groundwater flow in the aquifer. Instead of using tracers to characterize the groundwater flow, tracers can be injected to confirm (but not disprove) contamination from a possible contamination source like a septic tank.

A possible tracer can be NaCl because it is cheap, and electrical conductivity can be measured in the well. A disadvantage using NaCl as a tracer is that the dilution of the tracer plume in the aquifer can be too high to get reliable measurements. Additionally, high and variable background levels of Cl can render this ion useless as a tracer. The latter is pointed out by Henry et al. (1991) who assessed the usefulness of different tracers for monitoring the movement of septic tank effluent through the unsaturated zone. A possible tracer not discussed by the authors is synthetic DNA, which has a low detection limit and is not harmful to the environment. The synthetic DNA tracer has proven useful to identify sources of pollution and is successfully used in tracer studies in fractured aquifers (Sabir et al. 2000, Gaut et al. In prep.). DNA can also be used to trace the source of contamination by analysing the DNA of the pathogenic microorganisms detected in the drinking water. This DNA is compared with DNA from microorganisms sampled from potential contamination sources to do a verification of the source (Howard 2003). However, the synthetic DNA and the DNA analyses are expensive.

From an economical view, vulnerability mapping combined with hygienic evaluation of the well area is probably a better solution in Norway than groundwater modelling to protect groundwater wells in bedrock. This is based on the results presented in Chapter 5 and the literature study. A guidebook on mapping groundwater vulnerability is written by Verba & Zaporozec (1994). The method will especially be useful when establishing new wells or well fields. Waterworks based on groundwater in bedrock are normally located in areas with scattered houses and often have large areas where the well(s) can be located. Thus, it should be possible to locate areas with at least some superficial deposits and at the same time avoid typical contamination sources such as farmland and septic tanks.

By means of Geographical Information Systems (GIS) it should be possible to put together data from different databases and maps to create a basis for the vulnerability mapping. The composed database should contain information from quaternary geology and bedrock maps and different databases, such as the Raw Minerals and Stones database and the Groundwater database at NGU. Necessary information includes:

- Groundwater level
- Location of wells and springs

- Superficial deposits; extension, thickness, lithology and vertical permeability of both saturated and unsaturated zones
- Rock type
- Fractures and faults

Ideally, groundwater flow maps should be created. However, there are few places where groundwater level in bedrock can be measured and reliable maps showing flow directions will mostly not be possible to create. Instead basic maps containing information about physical boundaries to groundwater flow, such as dikes and faults, and location of wells and springs, and measured groundwater levels should be crated. This will be a useful tool when evaluating vulnerability and creating protection zones for specific areas.

The suggested database mentioned above, created as a basis for the vulnerability mapping, will mostly be based on data mapped in the scale 1:50 000. Consequently further vulnerability mapping is necessary when delineating protection zones for individual groundwater sources because the scale 1:50 000 is too rough. For the more detailed mapping air photos can be a tool to identify the more vulnerable areas and possible contamination sources. Based on this thesis, especially important features are exposed bedrock, thin (< 2.5 m) and discontinuous superficial deposits and farmland. The well should be located minimum 100 m from farmland, septic tanks, sewage infiltration areas and surface water sources, especially rivers or streams.

Being aware that assessment of flow direction will be inaccurate, because of the applied assumption that the fractured bedrock approximates a uniform porous media, combining calculations of time of travel with flow system mapping can be used to delineate protection zones. The latter is partly used today because the outer boundary of zone 2 is normally set equal to the surface catchment area. Pumping tests should always be carried out to estimate aquifer parameters like transmissivity and hydraulic conductivity needed in the calculations. Each pumping test will most likely, give a different value of the aquifer parameters, and more than one pumping test should be carried out. Protection zones can then be delineated using an average value or each value can be used to delineate a zone. The different zones can then be compared and the area common for all the estimates will at least have to be protected. This method is a variant of the method used by Evers & Lerner (1998) who used different calibrations of a numerical model to delineate different catchment areas for the same well. The authors defined the area falling within all the reasonable estimates as a Zone of Confidence and the outer boundary of all the estimates were defined as a Zone of Uncertainty. Flow-system-mapping can help to reduce the size of the protection zone if groundwater divides are close to the well, which in the study by Bradbury et al. (1991) is 0.3-2.4 km.

The vulnerability map and the protection zones are used together to assess the activity restrictions that are necessary within each protection zone. Areas with exposed bedrock are especially vulnerable to contamination and need stricter regulations than areas with thick and extensive superficial deposits. The vulnerability map can also be used to expand or decrease the area of the different protection zones. In Ireland the vulnerability in different areas are rated according to type and thickness of the superficial deposits

and thickness of the unsaturated zone (DoELG/EPA/GSI 1999). This may also be a possibility in Norway.
In addition to be used in combination with delineating of protection zones, vulnerability maps can be used by regulators when making plans for land use and protection of groundwater sources. As mentioned this is highlighted by the implementation of the WFD.

Concluding remarks
Numerical modeling will probably give the best results when establishing protection zones, but it will be too expensive for most Norwegian waterworks based on ground-water from bedrock. For these waterworks vulnerability mapping combined with hygienic evaluation of the well area and delineation of protection zones based on simple analytical methods is probably a better solution. Tracer tests can be used to evaluate the influence from possible contamination sources.

Small scale vulnerability maps (1:50 000) containing information about the superficial deposits, bedrock, groundwater and possible contamination sources should be compiled as a basis for a more detailed vulnerability mapping at each individual groundwater source.

6.9 Disinfection of drinking water supplied from groundwater in bedrock

All drinking water has to be disinfected. However, when the drinking water source is groundwater this treatment is accepted as a standby if the source is otherwise well protected against contamination (Folkehelseinstituttet In prep).

Based on reported microbiological water quality from this study, there are waterworks supplying untreated water meeting the requirements in the NSDW. This shows that disinfection for everyday use does not need to be obligatory at all waterworks based on groundwater from bedrock. Nevertheless, examination of microbiological quality for 123 waterworks in the period 1996-2003 shows that the water quality can change from one year to another. Therefore systematic and at least monthly groundwater sampling and analyses are required each year if disinfection is to be avoided. Other requirements should be:

- A proper wellhead completion including design of the well casing as described in Chapter 6.7
- Fencing (zone 0) to keep humans and animals away from the well
- Establishing of protection zones with restrictions on the land use

Similar criteria are considered to avoid disinfection in the USA (Wireman & Job 1997, Wireman & Job 1998, U.S. Environmental Protection Agency 2000).

The waterworks should document good microbiological water quality during one year before exemption of disinfection can be granted. Based on the discussion in Chapter 6.2,

it is important to ensure proper sampling during autumn to detect possible coliforms. HPC in the raw-water should not exceed the NSDW because this implies that the well is vulnerable to microbiological contamination. If the water at a later time exceeds the NSDW disinfection should be required until the cause is detected and faults improved.

6.10 Further work

Implementation of WFD requires protection of water, and towards 2006 and 2015 protection of existing and possible drinking water sources will be focused. This PhD study identifies some of the problems related to groundwater in bedrock, but also points out further work.

This study revealed that 60 % of 104 examined waterworks based on groundwater from bedrock had problems with the microbiological water quality in 1997. In 2003, 50 % of them still exceeded requirements in the NSDW. Field inspections at 49 waterworks showed that a major problem is contamination of the aquifer or at the well site due to improper well construction or wellhead completion. Based on the datasets it has not been possible to evaluate the contribution of microbiological contamination due to conditions of the delivery system. A project with systematic sampling of both raw-water and tapwater should be initiated to reveal the extent of microbiological contamination due to the delivery system in relation to source contamination.

NIPH each year publishes a report on the water quality of Norwegian waterworks required to report data to VREG. The report presents the water quality for all waterworks collectively and for waterworks based on surface water in particular. This thesis has revealed a need for separate data on water quality for waterworks based on groundwater in superficial sediments and bedrock. It should therefore be evaluated if this type of data also were to be presented separately in the reports.

An enlarged, coherent and well-planned study of the occurrence of both *Cryptosporidium* and *Giardia* in a representative selection of Norwegian groundwater wells in superficial deposits and bedrock should be carried out. Robertson et al. (2000) investigated the occurrence of these parasites in Norwegian surface water and found that the probability to detect the parasites increased with number of samples collected. Furthermore, studies should therefore include multiple sampling at each groundwater well or waterworks throughout the year to increase the probability to detect possible cysts/oocysts. Seasonal changes in the occurrence of the parasites should also be investigated, though no significant difference between the seasons was found in surface water. To set possible seasonal changes in a climatic context, precipitation, temperature and snow cover need to be documented at the sampling localities. Both single, private wells and waterworks should be sampled to look at differences. The water samples should also be analysed for *Clostridium perfringens* to verify if this is a suitable indicator for the protozoa.

Downhole camera inspections conducted in this thesis are part of a project where the aim is to investigate 200-250 wells registered in the Groundwater database at NGU, to evaluate the construction of the upper part of the borehole. Inspections of the wells in Dataset E have raised different questions that would be interesting to investigate further:

- Leakage between casing and bedrock is observed in wells where bentonite is reported as sealing material. Wells where bentonite is used should be examined, preferably in co-operation with the drilling companies, to reveal if leakages are a problem in these wells. If so, the project should investigate if leakages are related to, for example, short setting time for the bentonite before further drilling or injection of too small amounts of bentonite.
- It is in this study assumed that leakage between bedrock and casing and water inflow from fractures < 10 m from the surface are likely to be microbiologically contaminated. Sampling of this water should be done to analyse the microbiological and physio-chemical water quality to evaluate this assumption.

Results show that improper wellhead completion, including design of the well casing, is often the cause of microbiological contamination. Following this study a guideline recommending proper construction should be made available to the public through printed and digital pamphlets. Based on the results from this study, well construction should be discussed with the trade organisations for the drilling companies. Additionally, the chapter about well construction in the Norwegian Standard NS 3420 should be changed in accordance with Chapter 6.7.

Hydraulic fracturing or explosives are used as yield enhancement techniques for groundwater wells in bedrock. Results from this thesis indicate that wells where stimulation of the yield has taken place more often detect coliforms than wells where no hydraulic fracturing or explosives are used. A project should investigate this relationship further because yield enhancement is frequently used and it would be useful to know whether it influences the water quality or not. The project should be conducted in co-operation with one or more drilling companies to more easily locate wells where yield enhancement is performed. Knowledge about packer depth and fractures in the well is important to evaluate whether fractures have propagated to ground level.

To better protect Norwegian groundwater wells in crystalline bedrock, investigations should be initiated to evaluate why waterworks with established protection zones do not have a microbiological water quality meeting the NSDW. It will be necessary to receive detailed maps showing the extent of the different protection zones and information about restrictions within each zone. The microbiological water quality should be evaluated to reveal if the contamination is caused by errors during sampling, analyses or originate in the delivery system. Field inspections are essential to confirm that the land use complies with the restrictions within each zone and especially that the well construction and wellhead completion are satisfactory. A downhole video camera is preferred to check the upper part of the well, especially sealing between bedrock and casing and to discover possible water inflow in the upper 10-15 m of the borehole.

7 Conclusion

This chapter summarises the discussion and the concluding remarks in Chapter 6 to give an overview of the main findings from this study.

1. Groundwater from bedrock wells is susceptible to microbiological contamination and needs better protection.
2. Improvements in the microbiological water quality have occurred at a few waterworks from the period 1996-98 to 2003.
3. The distribution line influences the quality of the tapwater due to biofilm in the pipeline. It is important to analyse both raw-water and tapwater to be able to evaluate this influence.
4. Examination of the data shows that microbiological contamination can be related to snowmelt and autumn precipitation. Coliforms are mostly detected from July to September, which correlates with the time period of manure spreading on farmlands in Norway.
5. Wells belonging to private and public waterworks based on groundwater from bedrock in Norway are equally susceptible to microbiological contamination.
6. There are waterworks supplying untreated water derived from bedrock meeting the requirements in the NSDW. Consequently disinfection for everyday use does not need to be obligatory at all such waterworks. However, monthly sampling and analyses of water should be required to ensure good microbiological quality.
7. *Cryptosporidium*, but not *Giardia*, is detected in the groundwater. Too few samples are analysed to verify if *Giardia* is absent and further studies are recommended to give a more reliable verification.
8. Based on the discussion, it is shown that the microbiological water quality is correlated to:
    - Wellhead completion (including the well casing)
    - Type and thickness of superficial deposits
    - Land use and contamination sources
    - Distance from wells to river or streams

    It is most important to locate the groundwater well apart from any known contamination source, preferably at least 100 m. The best location is in outlying fields with no grazing livestock.

    Groundwater wells in bedrock should not be located within 75-125 m of a river or stream and stagnant water should be avoided in drainage ditches.

    Based on the dataset, the thickness of the superficial deposits should be at least 2.5 m to ensure attenuation of possible pathogenic microorganisms. Wells located below the marine limit are better protected than those situated above the marine limit.

Recommended wellhead completion includes a well-house and a casing of at least 5.5 m, rising 40-50 cm above ground (Figure 6.7.1). The gap between casing and bedrock should be sealed. This will hinder contamination of the groundwater through the wellhead and inflow (leakage) of unfiltered, and possibly microbiologically contaminated, water at the bottom of the casing. Groundwater inflow should not occur at shallower depth than 10 m. Installation of an inner casing to seal off this water should be considered if the water quality is unsatisfactory.

9. Groundwater level, capacity and well depth are not directly related to microbiological quality. Neither is any statistically significant correlation found between microbiological water quality and use of hydraulic fracturing or explosives.
10. It is shown that changes in parameters like colour, turbidity and iron can indicate microbiological contamination for single wells. Therefore, changes in these parameters and high levels of TOC can be used as a symptom that the aquifer or the well is vulnerable to microbiological contamination.
11. Statistics from VREG show that few Norwegian waterworks based on groundwater from bedrock have established protection zones. It is not possible to give an evaluation of the significance of the protection zones reported in this thesis.
12. Suggestions of improvements for designing source protection zones for Norwegian bedrock wells are given. From an economical view, vulnerability mapping combined with hygienic evaluation of the well area and delineation of protection zones based on simple analytical methods is suggested.

8 References

Abbaszadegan, M., LeChevallier, M.W. & Gerba, C.P., 2003: Occurrence of viruses in US groundwater. *Journal AWWA*, 95(9), 107-120.

Abu-Ashour, J., Joy, D.M., Lee, H., Whitley, H.R. & Zelin, S., 1994: Transport of Microorganisms through soil. *Water, Air and Soil Pollution*, 75, 141-158.

Adams, B. & Foster, S.S.D., 1992: Land-Surface Zoning for Groundwater Protection. *J. IWEM*, 6(June), 312-320.

Andersson, A., Andersson, O. & Gustafson, G., 1984: BRUNNAR. Undersökning - Dimensionering - Borrning - Drift. Byggforskningsrådet R42:1984, Svenskt Tryck Stockholm, 241 pp.

Bales, R.C., Li, S., Maguire, K.M., Yahya, M.T. & Gerba, C.P., 1993: MS-2 and Poliovirus Transport in Porous Media: Hydrophobic Effects and Chemical Perturbations. *Water Resources Research*, 29, 957-963.

Ball, D., 1997: Cryptosporidium and *E. coli* O157. *The GSI Groundwater Newsletter,* 32, 3-5. Available from: http://www.gsi.ie/workgsi/groundwater/groundwaterfra.htm

Banks, D., Røyset, O., Strand, T. & Skarphagen, H., 1995a: Radioelement (U, Th, Rn) concentrations in Norwegian bedrock groundwaters. *Environmental Geology*, 25, 165-180.

Banks, D., Reimann, C., Røyset, O., Skarphagen, H. & Sæther, O., 1995b: Natural concentrations of major and trace elements in some Norwegian bedrock groundwaters. *Applied Geochemistry*, 10, 1-16.

Banks, D. & Robins, N., 2002: An introduction to Groundwater in Crystalline Bedrock. Geological Survey of Norway, 63 pp.

Barton, N.R., Bandis, S. & Bakhtar, K., 1985: Joint deformation and conductivity coupling. *International Journal of Rock Mechanics and Mining Sciences*, 22, 121-140.

Bartram, J., Cotruvo, J., Exner, M., Fricker, C. & Glasmacher, A. (eds.), 2003: Heterotrophic Plate Counts and Drinking-water Safety. The Significance of HPCs for Water Quality and Human Health. World Health Organization, IWA Publishing, 256 pp.

Bauder, J.W., White, B.A. & Inskeep, W.P., 1991: Montana extension initiative focuses on private well quality. *Journal of Soil and Water Conservation*, 46(1), 69-74.

Becker, M.W., Metge, D.W., Collins, S.A., Shapiro, A.M. & Harvey, R.W., 2003: Bacterial transport experiments in fractured crystalline bedrock. *Ground Water*, 41(5), 682-689.

Bekins, B., 2000: Preface - Groundwater and microbial processes. *Hydrogeology Journal*, 8(1), 2-3.

Bitton, G. & Gerba, C.P., 1984: Microbial pollutants: Their survival and transport pattern to groundwater. Chapter 4. *In*: Bitton, G. & Gerba, C.P. (eds.), Groundwater pollution microbiology, John Wiley & Sons, p 65-88.

Bjorvatn, K., Bårdsen, A., Thorkildsen, A.H. & Sand, K., 1994: Fluorid i norsk grunnvann - en ukjent helsefaktor. *Vann*, 29, 124-128.

Bjorvatn, K., Thorkildsen, A.H., Raadal, M. & Selvig, K.A., 1992: Fluoridinnholdet i norsk drikkevann. Vann fra dype brønner kan skape helseproblemer. *Norsk Tannlægeforenings tidsskrift*, 102, 86-89.

Blanc, R. & Nasser, A., 1996: Effect of effluent quality and temperature on the persistence of viruses in soil. *Water Science and Technology*, 33(10-11), 137-242.

Bolster, C.H., Mills, A.L., Hornberger, G. & Herman, J., 2000: Effect of Intra-Population Variability on the Long-Distance Transport of Bacteria. *Ground Water*, 38(3), 370-375.

Bouchier, I., 1998: *Cryptosporidium* in water supplies. Third report of the Group of Experts. The Drinking Water Inspectorate. Available from: http://www.dwi.gov.uk/pubs/bouchier/index.htm

Bradbury, K.R., Muldoon, M.A., Zaporozec, A. & Levy, J., 1991: Delineation of wellhead protection areas in fractured rocks. U.S. EPA Technical Guidance Document, EPA 570/9-91-009, USEPA Office of Water, 144 pp.

Briody, A., 1995: Protecting private domestic boreholes. *The GSI Groundwater Newsletter,* 27, 3-4. Available from: http://www.gsi.ie/workgsi/groundwater/groundwaterfra.htm

Burgess, D.B. & Fletcher, S.W., 1998: Methods used to delineate groundwater source protection zones in England and Wales. *In*: Robins, N.S. (eds.), Groundwater Pollution, Aquifer Recharge and Vulnerability, Geological Society, p 199-210.

Champ, D.R. & Schroeter, J., 1988: Bacterial transport in fractured rock – a field-scale tracer test at the chalk river nuclear laboratories. *Water Science and Technology*, 20(11/12), 81-87.

Commission of the European Communities, 2003: Proposal for a Directive of the European parliament and of the council on the protection of groundwater against pollution. COM(2003)550. 20 pp. Available from: http://europa.eu.int/eur-lex/lex/LexUriServ/site/en/com/2003/com2003_0550en01.pdf

Conboy, M.J. & Goss, M.J., 2000: Natural protection of groundwater against bacteria of fecal origin. *Journal of Contaminant Hydrology*, 43, 1-24.

Conboy, M.J. & Goss, M.J., 1999: Contamination of rural drinking water wells by fecal origin bacteria - Survey findings. *Water Quality Research Journal of Canada*, 34(2), 281-303.

Corso, P.S., Kramer, M.H., Blair, K.A., Addiss, D.G., Davis, J.P. & Haddix, A.C., 2003: Cost of Illness in the 1993 Waterborne Cryptosporidium Outbreak, Milwaukee, Wisconsin. *Emerging Infectious Diseases*, 9(4), 426-431.

Cox, G.D., Ogden, A.E. & Slavik, G., 1980: Contamination of Boone-St. Joe limestone groundwater by septic tanks and chicken houses. *Arkansas Academy of Science Proceedings,* XXXIV, 41-44.

Craun, G.F. & Calderon, R.L., 1996: Microbial risks in groundwater systems: Epidemiology of waterborne outbreaks. Under the microscope. Examining microbes in groundwater, American Society for Microbiology, p 9-20.

Craun, G.F., Hubbs, S.A., Frost, F., Calderon, R.L. & Via, S.H., 1998: Waterborne outbreaks of cryptosporidiosis. *Journal of American Water Works Association*, 90(9), 81-91.

Daly, D., 2000: Practical Approaches to Preventing Pollution of Wells. *The GSI Groundwater Newsletter,* 38, 9-15. Available from: http://www.gsi.ie/workgsi/groundwater/groundwaterfra.htm

Daly, D., 1985: Groundwater quality and pollution. It affects you. It depends on you. Information Circular 85/1. Geological Survey of Ireland, 25 pp.

Daly, D., Thorn, R. & Henry, H., 1993: Septic tank systems and groundwater in Ireland. Report series RS 93/1 (Groundwater), Geological Survey of Ireland, Department of Transport, Energy and Communications, 30 pp.

Dawson, D.J. & Sartory, D.P., 2000: Microbiological safety of water. *British medical bulletin*, 56(1), 74-83.

Department of the Environment and Heritage, 2003: Freshwater Australia. Poster. Available from: http://www.freshwater2003.gov.au/publications/index.html Accessed November 2004.

Department of Water Affairs and Forestry, 2004: National Water Resource Strategy, First Edition. Available from: http://www.dwaf.gov.za/Documents/Policies/NWRS/Default.htm

Department of Water Affairs and Forestry, 1997: White Paper on a National Water Policy for South Africa. http://www.dwaf.gov.za/Documents/Policies/nwpwp.pdf

DoELG/EPA/GSI, 1999: Groundwater Protection Schemes. A joint publication by the Department of the Environment and Local Government, Environmental Protection Agency and Geological Survey of Ireland. Geological Survey of Ireland, 24 pp.

Dutter, R., Leitner, T., Reimann, C. & Wurzer, F., 1992: Grafische und geostatistiche Analyse am PC. Beiträge zur Umweltstatistik. *Schriftenreihe der Technischen Universität Wien*, 29, 78-88.

Eckholdt, E. & Snilsberg, P., 1992: Grunnvann. Beskyttelse av drikkevannskilder. GiN-veileder nr. 7. *NGU Skrifter*, 105, 1-24.

Einan, B., Myrstad, L. & Nordheim, C.F., 2004: Rapport fra vannverksregisteret. Drikkevann 2003. Vannrapport 109, Rapport 2004:2, Folkehelseinstituttet, 33 pp.

Einan, B., Myrstad, L. & Nordheim, C.F., 2003: Rapport fra vannverksregisteret. Drikkevann 2002. Vannrapport 108, Rapport 2003:11, Folkehelseinstituttet, 26 pp.

Ekendahl, S., 1996: Deep subsurface ecosystems - Numbers, activity and diversity of groundwater bacteria in Swedish granitic rock. Department of general and marine microbiology, Göteborg university, Sweden, 57 pp.

Ellingsen, K., 2002: Beskyttelse av grunnvannskilder, Dokka vannverk og Torpa vannverk, Nordre Land kommune. NGU rapport 2002.073, Norges geologiske undersøkelse, 14 pp.

Ellingsen, K., 1992: Grunnvann i Norge (GiN). Sluttrapport. *NGU Skrifter*, 111, 35.

Englund, J. & Myrstad, J.A., 1980: Groundwater Chemistry of Some Selected Areas in Southeastern Norway. *Nordic Hydrology*, 11, 33-54.

Environment Agency, 2000: Water supply borehole construction and headworks. Guide to good practice. Environment Agency, England & Wales, 8 pp.

Environment Agency, 1999a: Groundwater Source Protection Zones. Environment Agency, England & Wales, 15 pp.

Environment Agency, 1999b: Decommissioning redundant boreholes and wells. Environment Agency, England & Wales, 14 pp.

European Parliament and Council, 2000: Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. *Official Journal of the European Communities*, L327, 1-72.

Evers, S. & Lerner, D.N., 1998: How uncertain is our estimate of a wellhead protection zone? *Ground water*, 36(1), 49-57.

Filip, Z., Kaddu-Mulindwa, D. & Milde, G., 1988: Survival of some pathogenic and facultative pathogenic bacteria in groundwater. *Water Science and Technology*, 20(3), 227-231.

Flemming, H., 1993: Biofilms and environmental protection. *Water Science and Technology*, 27(7-8), 1-10.

Folkehelsa, 1999: Bakteriologiske drikkevannsanalyser - hva forteller de? Available from: http://www.fhi.no/publ/artikler

Folkehelsa, 1998: Årsak til smittespredning via drikkevann. Nytt fra Program for vannforsyning. *VANN*, 33(1), 151-157.

Folkehelsa, 1987: Beskyttelse av grunnvannskilder. Drikkevann A3, Statens Institutt for Folkehelse, 30 pp.

Folkehelseinstituttet, In prep: Vannforsyningens ABC - et oppslagsverk om drikkevann. Available from: http://www.fhi.no/artikler/?id=46542. Accessed November 2004.

Folkehelseinstituttet, 2004: Vannbehandling. Available from: http://www.fhi.no/artikler/?id=42117

Folkehelseinstituttet, 2003: Kan klorering fortsatt aksepteres som hygienisk barriere ved norske vannverk? Available from: http://www.fhi.no/publ/artikler

Forbord, R.E., 2002: Videoinspeksjon av borehull ved Hoston vannverk. Brev til Orkdal kommune, 2.1638-007, Miljøgeologi as, 4 pp.

Forbord, R.E., 1997: Hoston vannverk - Orkdal kommune. Forslag til sikring av borebrønn og beskyttelse av grunnvannsforekomsten. (Høringsutkast), Rapport 2.1638-004, Miljøgeologi as, 18 pp.

Frengstad, B., 2002: Groundwater quality of crystalline bedrock aquifers in Norway. Dr. ing. thesis 2002:53, Department of Geology and Mineral Resources Engineering, Norwegian University of Science and Technology, 389 pp.

Gammack, S.M., Paterson, E., Kemp, J.S., Cresser, M.S. & Killham, K., 1992: Factors Affecting the Movement of Microorganisms in Soils. Chapter 8. *In*: Stotsky, G. & Bollag, J.M. (eds.), Soil Biochemistry, Marcel Dekker, p 263-305.

Gaut, A., 2003: Vannforsyning i Hurumåsen. Rapport for KUR-prosjektet, Hole kommune. Rapport 133641-1, Statkraft Grøner, 11 pp.

Gaut, A. & Tranum, I., 2003: Sørbråten og Solemskogen. Gjennomgang av drikkevannskvalitet og vurdering av muligheten for en utvidet, tilfredsstillende vannforsyning. Rapport 132681-1, Statkraft Grøner AS, 13 pp.

Gaut, S., Storrø, G. & Brattli, B., 2000: Bacterial contamination in Norwegian groundwater wells in bedrock. *In*: Sililo, Oliver et al. (ed.). Groundwater: Past Achievenents and Future Challenges. Proceedings of the XXX IAH Congress, 26. Nov-1.Dec 2000, Cape Town, South Africa. Balkema, 751-754.
The paper is presented in Appendix E in this thesis.

Gaut, S., Allestam, G., Storrø, G., Brattli, B. & Braathen, a., In prep: Comparative analysis of tracer behaviour in a fracture aquifer; the Holmedal well field of western Norway. The paper is presented in Appendix G in this thesis.

Gerba, C.P. & Keswick, B.H., 1981: Survival and transport of enteric viruses and bacteria in groundwater. *In*: van Duijvenbooden, W. et al. (eds.). Quality of Groundwater, Proceedings of an International Symposium, 23-27 March 1981, Noordwijkerhout, The Netherlands. Studies in Environmental Science, 511-515.

Gerba, C.P., Rose, J.B. & Haas, C.N., 1996: Sensitive populations: who is at the greatest risk? *Int. J. Food Microbiol.*, 30(1-2), 113-123.

Gerba, C.P., Yates, M.V. & Yates, S.R., 1991: Quantitation of Factors Controlling Viral and Bacterial Transport in the Subsurface. *In*: Hurst, C.J. (eds.), Modelling the environmental fate of Microorganisms, American society for microbiology, p 77-88.

Goss, M.J., Barry, D.A.J. & Rudolph, D.L., 1998: Contamination in Ontario farmstead domestic wells and its association with agriculture: 1. Results from drinking water wells. *Journal of contaminant hydrology*, 32, 267-293.

GSI, 1979: Water Wells. A Guide to the Development of Groundwater for Small Residential and Farm Supplies. Information Circular 79/1, Geological Survey of Ireland, 22 pp.

Hancock, C.M., Rose, J.B. & Callahan, M., 1998: The prevalence of *Cryptosporidium* and *Giardia* in US groundwater. *Journal of American Water Works Association*, 90(3), 58-61.

Hanssen, G., 1998: Bakterier og grunnvann. Prosjektarbeid. Institutt for geologi og bergteknikk, Norges teknisk-naturvitenskaplige universitet, 45 pp.

Harris, R.C., 1998: Protection of groundwater quality in the UK: present controls and future issues. *In*: Mather, J. et al. (eds.), Groundwater Contaminants and their Migration, Geological Society, p 3-13.

Harvey, R.W., 1997: Microorganisms as tracers in groundwater injection and recovery experiments: a review. *FEMS Microbiology Reviews*, 20, 461-472.

Hellesnes, I., 1979: Indikatorer med hygienisk betydning i vann. *VANN*, 14(1B), 57-75.

Helse- og omsorgsdepartementet, 2001: Forskrift 4. desember 2001 nr 1372 om vannforsyning og drikkevann (Drikkevannsforskriften). Available from: http://www.lovdata.no/for/sf/ho/ho-20011204-1372.html. Accessed 19 November 2004.

Henry, H., Thorn, R.H. & Brady, E.M., 1991: An assessment of the suitability of a range of chemical and biological tracers to monitor the movement of septic tank effluents to groundwater. *Irish Geography*, 24(2), 91-105.

Herbold-Paschke, K., Straub, U., Hahn, T., Teutsch, G. & Botzenhart, K., 1991: Behaviour of pathogenic bacteria, phages and viruses in Groundwater during transport and adsorption. *Water Science and Technology*, 24(2), 301-304.

Hongve, D., Weideborg, M., Andruchow, E. & Hansen, R., 1994: Landsoversikt - drikkevannskvalitet. Spormetaller i vann fra norske vannverk. VANN 92, Statens Institutt for Folkehelse, Oslo, 110 pp.

Howard, K., 2003: Bacteria transmission in fissured carbonates: fatal consequences in Walkerton, Ontario. *In*: Krásný, J. et al. (eds.). Proceedings of the international conference on groundwater in fractured rocks, 15-19. Sept 2003, Prague, Czech Republic. IHP-7, Series on groundwater No. 7, 347-348.

Indre Sogn Interkommunale Servicekontor, 1990: Grunnvatn i fjell til spredd busetnad. GiN-veileder nr. 6. *NGU Skrifter*, 102, 1-15.

Johansen, T., Mathisen, A., Halvorsen, N.R. & Bjørkly, S., 1998: Oppfølging av private drikkevannskilder i Drammen. Biologiske analyser 1998. Helseavdelingen, miljørettet helsevern, Drammen kommune, 36 pp.

Jørgensen, P., 1977: Some properties of Norwegian tills. *Boreas*, 6(2), 149-157.

Jorgenson, D., Wireman, M. & Olson, D., 1998: Assessing the vulnerability of public water supply wells to microbial contamination. *Groundwater Monitoring & Remediation*, Spring, 60-66.

Kennedy, K.G., 2000: Bacteriophages as particle migration indicators in subsurface environments. *In*: Dassargues, A. (ed.). Tracers and Modelling in Hydrogeology. Proceedings of TraM'2000, International Conference on Tracers and Modelling in Hydrogeology, 23-26. May 2000, Liège, Belgium. IAHS Publication no. 262, 151-158.

Keswick, B.H., Wang, D. & Gerba, C.P., 1981: The Use of Microorganisms as Ground-Water Tracers: A Review. *Groundwater*, 20(2), 142-149.

Korkka-Niemi, K., 2001: Cumulative geological, regional and site-specific factors affecting groundwater quality in domestic wells in Finland. Monographs of the Boreal Environment Research, 20, Finnish Environment Institute, 98 pp.

Kott, Y., 1988: Movement and survival of bacteria in porous media. *Water Science and Technology*, 20(3), 61-65.

Lallemand-Barrès, A. & Roux, J., 1989: Périmètres de protection des captages d'eau souterraine destinée à la consommation humaine. Guide méthodologique et réglementaire. 2nd edition, Manuels et methods n° 33. Éditions BRGM, 222 pp.

Lamb, A.J., Reid, D.C., Lilly, A., Gauld, J.H., McGaw, B.A. & Curnow, J., 1998: Improved source protection for private water supplies: Report on the development of microbiological risk assessment approach. The Robert Gordon University, Aberdeen,

Landbruks- og matdepartementet, Miljøverndepartementet & Helsedepartementet, 2003: Forskrift 4. juli 2003 nr 951 om gjødselvarer mv. av organisk opphav. Available from: http://www.lovdata.no/for/sf/md/md-20030704-0951.html. Accessed November 2004.

LeChevallier, M.W., Babock, T.A. & Lee, R.G., 1987: Examination and Characterization of distribution system biofilm. *Appl. Environ. Microbiol.*, 53, 2714-2724.

Leclerc, H., 2003: Relationships between common water bacteria and pathogens in drinking-water. Chapter 6. *In*: Bartram, J. et al. (eds.), Heterotrophic Plate Counts and Drinking-water Safety. The Significance of HPCs for Water Quality and Human Health, World Health Organization, IWA Publishing, p 80-118.

Lee, S.H., Levy, D.A., Craun, G.F., Beach, M.J. & Calderon, R.L., 2002: Surveillance for Waterborne-Disease Outbreaks - United States, 1999-2000. *MMWR Suveillance Summaries,* 51(SS08), 1-28. Available from: http://www.cdc.gov/mmwr/preview/mmwrhtml/ss5108a1.htm

Lilly, A., pers. com.: Personal Communication from Dr. Allan Lilly at the Macaulay Institute, Scotland in January 2004.

Lilly, A., Edwards, A.C. & McMaster, M., 2003: Microbiological risk assessment source protection for private water supplies: Validation study. Macaulay Land Use Research Institute, 53 pp.

Lindqvist, R., 1993: Dispersal of bacteria in ground water: mechanisms, kinetics and consequences for facilitated transport. Department of Ecology Chemical Ecology and Ecotoxicology, Lund University, Sweden, 25 pp.

Lund, V., 1998: Begroing i ledningsnett og dets helsemessige betydning. *Norsk veterinær tidsskrift*, 110(10), 642-646.

Lynch, J.M. & Hobbie, J.E. (eds.), 1988: Microorganisms in Action: Concepts and Applications in Microbial Ecology. Blackwell Scientific Publications, 363 pp.

Macler, B.A. & Merkle, J.C., 2000: Current knowledge on groundwater microbial pathogens and their control. *Hydrogeology Journal*, 8, 29-40.

Macler, B.A., 1996: Developing the Ground Water Disinfection Rule. *Journal of American Water Works Association*, 88(3), 47-55.

Macler, B.A., 1995: Developing a National Drinking Water Regulation for Disinfection of Ground Water. *Ground Water Monitoring and Remediation*, 15(4), 77-84.

Madigan, M.T., Martinko, J.M. & Parker, J., 2003: Brock Biology of Microorganisms. 10th edition, Prentice-hall International, 1019 pp.

Malard, F., Reygrobellet, J. & Winiarski, T., 1997: Physico-Chemical and Biological Dynamics of a Sewage-Polluted Limestone Aquifer. *Int. Revue ges. Hydrobiol.*, 82(4), 507-523.

Malard, F., Reygrobellet, J. & Soulié, M., 1994: Transport and Retention of Fecal Bacteria at Sewage-Polluted Fractured Rock Sites. *J. Environ. Qual.*, 23, 1352-1363.

Matthess, G., Foster, S.S.D. & Skinner, A.C., 1985: Theoretical background, hydrogeology and practice of groundwater protection zones. International Contribution to Hydrogeology, vol. 6, Heise, 204 pp.

McKay, L.D., Cherry, J.A., Bales, R.C., Yahya, M.T. & Gerba, C.P., 1993: A Field Example of Bacteriophage as Tracers of Fracture Flow. *Environmental Science and Technology*, 27, 1075-1079.

Meteorologisk institutt, 2003: Klimatologisk hurtigoversikt. Året 2003. *Met.no info,* 13, 1-8. Available from: http://met.no/observasjoner/maned/2003/2003-aar.pdf

Miljøverndepartementet, 2004a: Lov 14. juli 1985 nr. 77: Plan og bygningslov. med endringer senest ved lov av 7. mai 2004 nr 24. Kap. XIV. Særlige bygninger og anlegg. Available from: http://www.lovdata.no/all/nl-19850614-077.html. Accessed December 2004.

Miljøverndepartementet, 2004b: Lov 13. mars 1981 nr. 6 om vern mot forurensninger og om avfall (Forurensningsloven) med endringer senest ved lov av 17. desember 2004 nr. 99. Available from: http://www.lovdata.no/all/nl-19810313-006.html. Accessed December 2004.

Miljøverndepartementet, 1992: Forskrift om utslipp fra separate avløpsanlegg. Fastsatt av Miljøverndepartementet 8. juli 1992, 67 pp.

Morland, G., Reimann, C., Strand, T., Skarphagen, H., Banks, D., Bjorvatn, K., Hall, G.E.M. & Siewers, U., 1997: The hydrogeochemistry of Norwegian bedrock groundwater - selected parameters (pH, F, Rn, U, Th, B, Na, Ca) in samples from Vestfold and Hordaland, Norway. *Norges geologiske undersøkelse Bulletin*, 432, 103-117.

Morland, G., 1997: Petrology, lithology, bedrock structures, glaciation and sea level: Important factors for groundwater yield and composition of Norwegian bedrock boreholes? NGU Report 97.122 I, Geological Survey of Norway, 274 pp.

Morland, G., 1996: Bruk av grunnvann i Norge. NGU rapport 96.082, Norges geologiske undersøkelse, 25 pp.

Muldoon, M. & Payton, J., 1993: Determining wellhead protection boundaries - An introduction. Publ WR313-92, Wisconsin Department of Natural Resources, 21 pp.

Myrstad, L., 1997: Landsrapport vannverksregisteret. Status for vannforsyning 1994. Folkehelsa vannrapport 97, Folkehelsa, 58 pp.

New Hampshire DES, 2003: Bedrock (Artesian, Drilled) Well Design. *Environmental Fact Sheet,* WD-WSEB-1-2. Available from: http://www.des.state.nh.us/factsheets/ws/ws-1-2.htm. Accessed November 2004.

New Hampshire DES, 2000a: Drinking Water Source Assessment Program. *Environmental Fact Sheet,* WD-WSEB-12-7. Available from: http://www.des.state.nh.us/factsheets/ws/ws-12-7.htm. Accessed March 2004.

New Hampshire DES, 2000b: Well abandonment and decommissioning. *Environmental Fact Sheet,* WD-WSEB-1-7. Available from: http://www.des.state.nh.us/factsheets/ws/ws-1-7.htm. Accessed March 2004.

New Hampshire DES, 1997: The N.H. Groundwater Protection Act; RSA 485-C. An Overview. *Environmental Fact Sheet,* WD-WSEB-22-1. Available from: http://www.des.state.nh.us/factsheets/ws/ws-22-1.htm. Accessed March 2004.

NGU, 2002: Geology for society: Groundwater. http://www.ngu.no/index.asp?ilangid=1. Accessed January 2005.

NGU-Lab, 1997: Gruppe 3: Vannanalyse. NGU-Labs kvalitetssystem, Faggruppe for laboratorier, Norges geologiske undersøkelse.

NIPH, unpublished: Data from the National Waterworks Register (VREG) for 2003. Data can be received from the Norwegian Institute of Public Health.

Nygård, K., Gondrosen, B. & Lund, V., 2003: Sykdomsutbrudd forårsaket av drikkevann i Norge. *Tidsskr. Nor. Lægeforen.*, 23, 3410-3413.

Ormerod, K., 1998: Norske drikkevannskilder, mikrobiologiske karakteristika. *Norsk veterinær tidsskrift*, 110(10), 624-632.

Payment, P. & Robertson, W., 2004: The microbiology of piped distribution systems and public health. Chapter 1. *In*: Ainsworth, R. (eds.), Safe piped water: Managing microbial water quality in piped distribution systems, World Health Organization, IWA Publishing, p 1-18.

Pedersen, T.S., Kikhusmo, L.A. & Kannick, H., 2003: Overvåkning av grunnvann. Landsomfattende grunnvannsnett (LGN). Rapport 1, Norges vassdrags- og energidirektorat, 165 pp.

Pekdeger, A., Matthess, G. & Schröter, J., 1985: Protection of groundwater against pathogenic bacteria and viruses. Hydrogeology in the Service of Man, Memoires of the 18th Congress of the International Association of Hydrogeologists, 1985, Cambridge. 149-158.

Pritchard, A., pers. com.: Personal Communication from Alex Pritchard at the Scottish Environment Protection Agency (SEPA) in December 2003.

Rayne, T.W., Bradbury, K.R. & Muldoon, M.A., 2001: Delineation of capture zones for municipal wells in fractured dolomite, Sturgeon Bay, Wisconsin, USA. *Hydrogeology Journal*, 5(5), 432-450.

Reid, D.C., Edwards, A.C., Cooper, D., Wilson, E. & Mcgaw, B.A., 2003: The quality of drinking water form private water supplies in Aberdeenshire, UK. *Water Research*, 37, 245-254.

Reimann, C., Hall, G.E.M., Siewers, U., Bjorvatn, K., Morland, G., Skarphagen, H. & Strand, T., 1996: Radon, fluoride and 62 elements as determined by ICP-MS in 145 Norwegian hard rock groundwater samples. *The Science of the Total Environment*, 192, 1-19.

Risberg, G., 1997: Normbrunn -97. Kriterier för utförande av energibrunn i berg. SI:6 Dnr 08-955/97, Sveriges geologiska undersökning.

Robertson, J.B. & Edberg, S.C., 1997: Natural Protection of Spring and Well Drinking Water Against Surface Microbial Contamination. I. Hydrogeological Parameters. *Critical Reviews in Microbiology*, 23(2), 143-178.

Robertson, L. & Gjerde, B., 2000: Cryptosporidium og Giardia i drikkevasskjelder i Noreg. SNT-Rapport 6, Statens næringsmiddeltilsyn, 50 pp.

Robinson, N.J. & Barker, J.A., 2000: A Fractured/Fissured Rock Apporach to GPZs. Project record W6/020/1, Environmental Agency, 312 pp.

Rönkä, E., 1993: Increased depth of drilled wells - advantage or drawback. *In*: Banks, S. and Banks, D. (eds.). Hydrogeology of hard rocks. Memoires of the XXIVth Congress International Association of Hydrogeologists, 28th June - 2nd July 1993, Ås (Oslo), Norway. Geological Survey of Norway, 772-779.

Sabir, I.H., Haldorsen, S., Torgersen, J., Alestrom, P., Gaut, S., Colleuille, H., Pedersen, T.S. & Kitterod, N.O., 2000: Synthetic DNA tracers; examples of their application in water related studies. *In*: Dassargues, A. (ed.). Tracers and modelling in hydrogeology. Proceedings of TraM'2000, International Conference on Tracers and Modelling in Hydrogeology, 23-26. May 2000, Liège, Belgium. IAHS Publication no. 262, 159-165.

Said, B., Wright, F., Nichols, G.L., Reacher, M. & Rutter, M., 2003: Outbreaks of infectious disease associated with private drinking water supplies in England and Wales 1970-2000. *Epidemiology and infection*, 130(3), 469-479.

Sanford, W.E., Shropshire, R.G. & Solomon, D.K., 1996: Dissolved gas tracers in groundwater: Simplified injection, sampling, and analysis. *Water Resources Research*, 32, 1635-1642.

Scholl, M.A., Mills, A.L., Herman, J.S. & Hornberger, G.M., 1990: The influence of mineralogy and solution chemistry on the attachment of bacteria to representative aquifer materials. *Journal of Contaminant Hydrology*, 6, 321-336.

SEPA, 2004a: Water Supply Borehole Location, Construction and Headworks. Guide To Good Practice. Available from: http://www.sepa.org.uk/pdf/groundwater/guide_to_good_practice.pdf. Accessed 15. November 2004.

SEPA, 2004b: Decommissioning Redundant Boreholes and Wells. Available from: http://www.sepa.org.uk/pdf/groundwater/guide_to_good_practice.pdf. Accessed November 2004.

SEPA, 2003: Groundwater Protection Policy for Scotland. Environmental Policy Number 19, Scottish Environment Protection Agency, 47 pp.

Søbstad, Ø, 2004: *Giardia lamblia* utbrudd i Bergen. MSIS-rapport 44, Folkehelseinstituttet. http://www.fhi.no/artikler/?id=49551

Sosial- og helsedepartementet, 1995: Forskrift om vannforsyning og drikkevann m.m. (Drikkevannsforskriften). I-9/95, Sosial- og helsedepartementet, 40 pp.

Stenström, T.A., Boisen, F., Georgsson, F., Lahti, K., Lund, V., Andersson, Y. & Ormerod, K., 1994: Vattenburna infektioner i Norden. Epidemiologiskt uppföljningsarbete och hälsoproblem relaterade till förekomst av mikroorganismer i vatten. Tema Nord 1994:585, Nordisk Ministerråd, 91 pp.

Summers, J., 1989: Soho - A History of London's Most Colourful Neighbourhood. Bloomsbury, London, pp 113-117.

Swan, A.R.H., Sandilands, M. & McCabe, P., 1995: Introduction to Geological Data Analysis. Blackwell Science Ltd, 446 pp.

The Council of the European Union, 1998: Council directive 98/83/EC of 3 November 1998 on the quality of water intended for human consumption. *Official Journal of the European Communities*, L330, 32-54.

Tim, U.S., Mostaghimi, S. & Dillaha, T.A., 1988: Modeling the Movement and Persistence of Bacteria and Viruses in Porous Media. *AZO paper*, 88, 2627.

Todd, D.K., 1980: Groundwater hydrology. 2nd edition, John Wiley & Sons, Inc., 535 pp.

Tukey, J.W., 1977: Exploratory Data Analysis. Addison-Wesley, 506 pp.

U.S. Environmental Protection Agency, 2000: 40 CFR Parts 141 and 142. National primary drinking water regulations: Ground water rule; Proposed rules. *Federal register*, 65(91), 30193-30243.

U.S. Environmental Protection Agency, 1999: Understanding the Safe Drinking Water Act. EPA 810-F-99-008, U.S. Environmental Protection Agency, 3 pp.

U.S. Environmental Protection Agency, 1997: State source water assessment and protection programs: Final guidance. EPA 816-R-97-009, Office of Water, U.S. Environmental Protection Agency, 127 pp.

U.S. Environmental Protection Agency, 1989: Drinking water; National primary drinking water regulations; Total coliforms (including fecal coliforms and E. coli); Final rule. *Federal Register*, 54, 27544-27568.

U.S. Food & Drug Administration, 1992: The "Bad Bug Book". Foodborne Pathogenic Microorganisms and Natural Toxins Handbook. Updated edition 30th January 2003. Available from: http://www.cfsan.fda.gov/~mow/preface.html. Accessed December 2004.

UNEP/UNICEF/WHO, 2002: Environmental Threats to Children. Chapter 3. *In*: Lone, R. & Dinsmore, C. (eds.), Children in the New Millennium: Environmental Impact on Health, IWA publishing, p 43-86.

Verba, J. & Zaporozec, A. (eds.), 1994: Guidebook on Mapping Groundwater Vulnerability. International Contributions to Hydrogeology, Vol 6, Heise, 131 pp.

Wheaton, J. & Bohman, B., 1999: Geophysical Investigations of Cased Well Completions. *Ground Water Monitoring & Remediation*, 143-151.

WHO/SDE/WSH, 2002: Heterotrophic Plate Count Measurement in Drinking Water Safety management. Report of an Expert Meeting, Geneva 24-25 April 2002. World Health Organization, 1-13.

Wireman, M. & Job, C., 1998: Determining the risk to public water supply wells from infective microorganisms. *Water Well Journal*, March, 63-67.

Wireman, M. & Job, C., 1997: The use of groundwater sensitivity assessments for purposes of the Groundwater Disinfection Rule. *Ground Water Monitoring & Remediation*, Fall, 63-66.

Wisconsin Department of Natural Resources, 2003: Requirements for the Operation and Design of Community Water Systems. *Wisconsin Administrative Code Register,* 570(Chapter NR 811), 73-115. Available from: http://www.legis.state.wi.us/rsb/code/nr/nr811.pdf. Accessed December 2004.

Wisconsin Department of Natural Resources, 2002: Well construction and pump installation. *Wisconsin Administrative Code Register,* 559(Chapter NR 812), 123-225. Available from: http://www.legis.state.wi.us/rsb/code/nr/nr812.pdf. Accessed December 2004.

Wisconsin Department of Natural Resources, 2001: Answers to your questions on well abandonment. Brochure, PUB DG 016 2001, Wisconsin Department of Natural Resources, 8 pp.

Woessner, W.W., Ball, P.N., DeBorde, D.C. & Troy, T.L., 2001: Viral Transport in a Sand and Gravel Aquifer Under Field Pumping Conditions. *Ground Water*, 39, 886-894.

Wright, G., 1995: Well construction standards. *The GSI Groundwater Newsletter,* 27, 2. Available from: http://www.gsi.ie/workgsi/groundwater/groundwaterfra.htm

Xu, Y. & van Tonder, G.J., 2002: Capture zone simulation for boreholes located in fractured dykes using the linesink concept. *Water SA*, 28(2), 165-169.

Østensvik, Ø, 2002: Ny drikkevannsforskrift - nye mikrobiologiske parametere og referansemetoder. *VANN*, 37(1), 61-67.

Østensvik, Ø, 1998: Fekale indikatorbakterier i drikkevann. *Norsk veterinær tidsskrift*, 110(10), 606-614.

Aasland, T., Rasmussen, I.N. & Halvorsen, H.K., 2001: Evaluering av program for vannforsyning. Sluttrapport. Asplan Viak AS 2000-058, Asplan Analyse, Asplan Viak AS, 144 pp.

Appendix A

Analytical methods

Appendix A – Analytical methods

The analytical methods used for microbiological and physio-chemical analyses together with reference methods, mostly a Norwegian Standard (NS), are described in this appendix.

A.1 Bacteriological analyses

Water samples are analysed on heterotrophic plate count (HPC), total coliforms (TC), fecal coliforms (FC), *Escherichia coli*, *Clostridium perfringens*, *Cryptosporidium* and *Giardia*. Analytical techniques and reference methods are summarised in Table A1.

Table A1 Analytical technique and reference method for different microbiological parameters. NS = Norwegian Standard, NS-EN = European Standard certified as Norwegian Standard, ISO = International Organization for Standardisation and USEPA = US Environmental Protection Agency.

Parameter	Technique	Reference method	Comments
Heterotrophic plate count (HPC) 22°C and 36°C	Colony count by inoculation in a nutrient agar culture medium	NS-EN ISO 6222	
Heterotrophic plate count (HPC) 22°C and 37°C		NS 4791	Method followed until 1st January 2001
Total coliforms and *Escherichia coli*	Membrane filtration	NS-EN ISO 9308-1	
	Enzyme substrate method	Colilert-18/Quantitray	
Total coliforms	Membrane filtration (mEndo agar)	NS 4788	Valid through 1st November 2003
Fecal coliforms	Membrane filtration (mFC agar)	NS 4792	Valid through 1st November 2003
Total coliforms and fecal coliforms	MPN-method	NS 4714	Used instead of NS 4788 and NS 4792 if sample contain lots of particles
Clostridium perfringens	Membrane filtration (mCP agar)	mCP agar	
	Membrane filtration (SFP agar)	NS-ISO 6461-2 with verification	
Cryptosporidium and *Giardia*	Membrane filtration (IMS and IFA)*	US EPA Method 1623	

*IMS = immunomagnetic separation and IFA = immunofluorescence assay

A.1.1 Heterotrophic plate count (HPC)

The incubation temperature used for analyses of HPC differs somewhat between the different laboratories. For Dataset A and B most laboratories used HPC at 22°C and 37°C following NS 4791. For Dataset C both NS 4791 and NS-EN ISO 6222 are followed. Colony count by inoculation in a nutrient agar culture medium is used for both HPC at 22°C and 37°C (36°C). The sampling bottle is shaken and if necessary the sample is diluted, before 1 ml of the sample is put on a Petri dish together with the nutrient agar culture medium. The Petri dish is incubated either at 22°C for 72 hours or 37°C (36°C) at 48 hours. After incubation colonies of bacteria are counted. Lower detection limit is 1 CPU (colonies per unit) where 1 unit is equal to 1 Petri dish.

A.1.2 Total coliforms (TC)

TC are analysed by three methods:

1. NS 4788 is mostly followed, which describes a membrane filtration method after NS 4790. 100 ml of water is filtrated through a 45 mm membrane with pore size 45μm and a fixed grid. Before filtration the sample is diluted if necessary. The membrane is then put on a Petri dish with mEndo agar and incubated for 22-24 h at 37°C. All non-transparent, dark red, colonies with metallic sheen are counted. Lower detection limit is 1 coliform per test volume. Present standard used is membrane filtration by NS-EN-ISO 9308-1 instead of NS 4788.

2. If the water samples contain lots of particles the multiple fermentation tube technique or MPN-method (most probable number) are used (NS 4714) instead of membrane filtration. With this method the results are given as a most probable number (MPN) index, which represents the number of coliform bacteria that, most likely, would give the results shown by the test. The principle of the method is described by Bartram & Pedley (1996). The most common procedure is to process five fractions of water from each of three consecutive 10-fold dilutions. Consequently 15 tubes with culture medium are inoculated and incubated at 37°C for 48 h. The tubes are examined after 24 h and tubes with positive reaction (turbidity, gas production or colour change) are counted. Re-examination is done after a total of 48 h of incubation. Inocula from the positive tubes are transferred to tubes containing a suitable confirmation medium and incubated for 48 h at 37°C. Tubes with production of gas are positive and the number of positives for each sample dilution is recorded. The pattern of positive results is compared with an MPN-table.

3. Some laboratories use the enzyme substrate method (Colilert-18/Quantitray) instead of NS-EN ISO 9308-1. 100 ml of the water sample is put into a sterile bottle and Colilert-18 is added. The sample is poured into a Quantitray or Quantitray 200 depending on expected amount of bacteria. The Quantitray is sealed and incubated at 37°C for 18-20 hours. After incubation the Quantitray is examined and the number of yellow champers counted. The number of coliforms is then found from an MPN-table. Lower detection limit is 1 coliform per test volume.

A.1.3 Fecal coliforms (FC)

Both membrane filtration and MPN-method described in chapter A.1.2 can be used to analyse for FC with adjustments for culture medium, temperature and incubation time. Membrane filtration follows NS 4792. The agar used is m-FC and the Petri dishes are incubated at 44.5°C for 18-24 h. All blue and blue-green colonies are counted.

The MPN-method (NS 4714) is similar for TC and FC except for the second incubation where a different confirmation medium, incubation time and temperature (24 h at 44°C) are used.

A.1.4 *Escherichia coli (E. coli)*

Escherichia coli (E. coli) is either analysed by the enzyme substrate method Coliert-18/Quantitry or by membrane filtration following NS-EN ISO 9308-1 described in Chapter A.1.2. After incubation at 37°C for 18-20 h, examination of the Quantitray is done with UV-light (365nm) and all yellow and fluorescent champers are counted. Lower detection limit for both methods is 1 *E. coli* per test volume.

A.1.5 *Clostridium perfringens*

The analysis follows either the method described in European Council Directive 98/83/EC (mCP agar) or NS-ISO 6461-2 with verification. Both methods use membrane filtration of a 100 ml water sample.

1. mCP agar: The membrane is incubated anaerobically on mCP agar at 44°C for 21 h. Opaque yellow colonies that turn pink or red after exposure to ammonium hydroxide vapours for 20-30 seconds are counted. Lower detection limit is 1 *Clostridium perfringens* per test volume.
2. NS-ISO 6461-2: The membrane is incubated anaerobically on SFP agar at 37°C for 21±3 h. Number of black colonies are counted and registered as presumptive *Clostridium perfringens*. Verification is done in two steps: a) anaerobic incubation of the black colonies on blood agar at 37°C through the night and b) each suspected colony is then anaerobically incubated at 37°C for 21±3 h in two tubes; one with lactose-pepton-broth the other with motility agar. Colonies that are yellow in lactose-pepton-broth and do not give cloudy growth in motility agar are *Clostridium perfringens*. Lower detection limit is 1 *Clostridium perfringens* per test volume.

A.1.6 *Cryptosporidium* and *Giardia*

Analyses of *Cryptosporidium* and *Giardia* follow the US EPA Method 1623. The method makes it possible to simultaneously isolate both C*ryptosporidium* oocysts and *Giardia* cysts from water samples.

In brief, the analytical technique can be divided into 5 stages as follows:
a) Membrane filtration of the water sample, b) elution of the material from the membrane filter, c) concentration of the eluted material by centrifugation, d) isolation of

the parasites from the concentrated eluted material by immunomagnetic separation (IMS), and e) detection and identification of the parasites by immunofluorescence assay (IFA), using light microscopy with Normaski (DIC; differential interference contrast) optics for confirmation of identity. Descriptions of these five sections are found in Robertson & Gjerde (2000).

A.2 Physio-chemical analyses

Water samples are analysed on colour, turbidity, electrical conductivity, pH, alkalinity, total organic carbon (TOC), iron (Fe), manganese (Mn), nitrate (NO_3^-) and chloride (Cl). Analytical techniques, reference methods (Norwegian Standard) and units are summarised in Table A2.

Table A2 Unit, analytical techniques and reference method for the different physio-chemical parameters comprised in datasets A-C.

Parameter	Unit	Analytical technique	Reference method
Colour	mg/l Pt	Spectrophotometer	NS-EN ISO 7887 (former NS 4787)
Turbidity	FTU	Nephelometry	NS 4723 or NS-ISO 7027
Electrical conductivity	mS/m	"Dip-type" measuring cell	NS-ISO 7888 or former NS 4721
pH		Titration	NS 4720
Alkalinity	mmol/l	Titration with HCl	NS 4754
Total organic carbon (TOC)	mg C/l	Infrared spectrometry	NS-EN 1484 (former NS 8245)
Iron (Fe)	mg Fe/l	ICP-AES or atomic absorption spectrometry	NS 4773
Manganese (Mn)	mg Mn/l	ICP-AES or atomic absorption spectrometry	NS 4773
Nitrate (NO_3^-)	mg NO_3/l	Ion chromatography (IC) or molecular absorption spectrometric method	NS-ISO 6777
Chloride (Cl^-)	mg Cl/l	Ion chromatography (IC) or Photometry	NS 4769

A.2.1 Colour

Determination of colour follows Norwegian Standard NS-EN ISO 7887 (former NS 4787). NGU-Lab uses a Shimadzu UV-1201 Spectrophotometer. The sample is filtered through a membrane with pore size 0.45 μm. Absorbance is measured at 410 nm and the result is given as the concentration of platinum (mg/l Pt) in a reference solution with a similar absorbance. Analytical uncertainty is presented in Table A3.

Table A3 Analytical uncertainty and lower most detection limit for different physio-chemical analyses at NGU-Lab. rel. = relatively

Parameter	**Lower detection limit**	**Analytical uncertainty**		
		Range	**Uncertainty**	
Colour	-	1.4	± 7.5 % rel.	
Turbidity	-	0.05-1.0 FTU	± 0.04 FTU	
		1.0-10 FTU	± 0.4 FTU	
		10-100 FTU	± 4 FTU	
		100-1000 FTU	± 40 FTU	
Electrical conductivity	0.07 mS/m	0.07-0.02 mS/m	± 3 % rel.	
		> 0.02 mS/m	± 1 % rel.	
			p-alkalinity	**t-alkalinity**
Alkalinity	0.04 mmol/l	0.04-0.2 mmol/l	± 0.02 mmol/l	± 0.04 mmol/l
			± 5.0 % rel.	± 4.0 % rel.
			± 4.3 % rel.	± 1.0 % rel.
pH	-	-	+ 0.05 pH units	

A.2.2 Turbidity

Turbidity is measured following Norwegian Standards NS 4723 or NS-ISO 7027. Both NGU-Lab and the Norwegian School of Veterinary Science use a Hach turbidimeter 2100A. Determination of turbidity is based on nefelometry (measurement of light dispersion) due to suspended material's ability to disperse light. The degree of light dispersion is compared to a standard solution and the result is given in FTU (Formazin Turbidity Unit). Analytical uncertainty is given in Table A3.

A.2.3 Electrical conductivity

Electrical conductivity is measured following Norwegian Standard NS-ISO 7888 or former NS 4721. At NGU-Lab the equipment used is a CDM210 Conductivity meter with a "dip-type", platinized measuring cell CDC641T and a built-in temperature compensator. Analytical uncertainty and lower detection limit is given in Table A3.

A.2.4 Alkalinity and pH

Alkalinity and pH values are measured according to Norwegian Standards NS 4754 and NS 4720 respectively. NGU-Lab uses a Radiometer Titralab 94 with a calibrated pH electrode of the type pHC 2701-8 "Red Rod", for both analyses. Alkalinity is determined by titration with hydrochloric acid (HCl) to pH 8.3 (p-alkalinity) and pH 4.5 (t-alkalinity). Two different concentrations of HCl are used depending on expected t-alkalinity. For t > 2 mmol/l 0.1 N HCl is used and for t < 2 mmol/l 0.02 N HCl is used. For the latter titration is continued to pH 4.2 to determine a more precise alkalinity. Analytical uncertainties are given in Table A3.

A.2.5 Total organic carbon (TOC)

Total organic carbon (TOC) is measured following NS-EN 1484 (former NS 8245). After acidification with 1% 4M H_2SO_4 the sample are burnt at 850°C in access of oxygen to let the organic carbon oxidize to CO_2. The amount of CO_2 is then measured by infrared spectrometry**.** TOC is given as C/l and analytical uncertainty is ± 15%.

A.2.6 Fe and Mn

Fe and Mn are mostly measured by two methods following NS 4773. At NGU an Inductively coupled plasma – atomic emission spectrometry (ICP-AES) is used, whereas other laboratories use atomic absorption spectrometry with atomization in flame. With the latter method special guidelines are followed for each metal.

Inductively coupled plasma – atomic emission spectrometry (ICP-AES) measures the element-specific atomic spectra of the electromagnetic waves emitted by different atoms under excitation. This implies that a wide range of elements may be determined simultaneously without being chemically separated. The principles of the equipment are described by Walsh (1997). Analytical uncertainty is ±5 % for Fe and Mn.

A.2.7 Nitrate (NO_3^-)

NO_3^- is measured with methods following NS-ISO 6777. At NGU-Lab ion chromatography (IC) is used. The method is simply based on an anion exchange process (Rowland 1997). Analytical uncertainty for the Dionex Ion Chromatograph 2120i instrument at NGU is 10 % relatively.

A.2.8 Chloride (Cl^-)

NGU-Lab analyse Cl^- by ion chromatography (IC) with the same instrument described for nitrate following NS-EN ISO 10304. Analytical uncertainty is 10% relatively. Other laboratories have measured Cl^- using a photometric method following NS 4769.

A.3 References

Bartram, J. & Pedley, S., 1996: Microbiological analyses. Chapter 10. In: Ballance, R. & Bartram, J. (eds.), Water quality Monitoring - A Practical Guide to the Design and Implementation of Freshwater Quality Studies and Monitoring Programmes, UNEP/WHO. Available from: http://www.who.int/water_sanitation_health/en/

Robertson, L. & Gjerde, B., 2000: Cryptosporidium og Giardia i drikkevasskjelder i Noreg. SNT-Rapport 6, Statens næringsmiddeltilsyn, 50 pp.

Rowland, A.P., 1997: Atomic absorption spectrometry and other solution methods. In: Gill, R. (eds.), Modern analytical Geochemistry, Addison Wesley Longman Limited, p 67-86.

Walsh, J.N., 1997: Inductively coupled plasma - atomic emission spectroscopy. In: Gill, R. (eds.), Modern analytical Geochemistry, Addison Wesley Longman Limited, p 41-66.

Appendix B

Questionnaire used during field inspection

Appendix B – Questionnaire used during field inspection

Bedrock well

Registred date:

Waterwork:	**Municipality:**		**Maps:** **Bedrock:** **Sup.deposits:** **Hydrogeology:**	
Well ID:	**County:**			
Elevation above sea level: m	**Locality, UTM**	**Zone:**	**EW coordinates:**	**NS coordinates:**
Contact person/ Well owner			**Telephone (work/home):**	
Postal address well site:			**Section nb. (of property):**	**Lot number (of property):**

Postal address of well owner (only if different from postal address for well site)

Use of well: ☐ Food production ☐ Tourist industry ☐ Waterwork **Number of persons:**
☐ Household ☐ Farming ☐ Cottage ☐ Other industry ☐ Energy ☐ Not in use **Other:**

Drilling company:	**Drilling date:**	**Well log:** ☐ Yes ☐ No
Is the well registred in the well register at NGU? ☐ Yes ☐ No	**Archive ID:**	**Well log recieved:** ☐ Yes ☐ No
Total depth of well: (measured from surface) m	**Depth to bedrock:** (measured from surface) m	**Bedrock:**

Depth from surface: (from - to)	**Water inflow, section with faster drilling [No:sleppe], mud colour, rock type, clay minerals on joints, fractures etc.**
m	
m	
m	
m	

Water flow (after completed drilling before any blasting/pressurization): l/hour	**Water flow before blastin/pressurization measured by:** ☐ Rising-head readings ☐ Blow-out ☐ Test pumping Duration:

Drilling: ☐ Horizontal ☐ Vertical ☐ Inclined	**When drilling inclined, indicate deviation from vertical (0-90°):**	**When drillling inclined, idicate direction (0-360°):**
Casing-/well casing material: ☐ Plastic ☐ Steel ☐ Sainless steel	**Length of casing-/well casing:** m	**Drill diameter (after compl. drilling):** mm
Location of filter (depth from surface) m	**Diameter of filter:** mm **Mesh size:** mm	**Type of filter:** **Filter material:** ☐ Stainless steel ☐ Plastic Other:
☐ Yield enhancement by blasting **Water flow after blasting** l/hour	☐ Yield enhancement by pressurization **Water flow after pressurization** l/hour	**Comments:**
Depth of packer m	**Maximum pressure** kp/cm² **Minimum pressure** kp/cm²	
Water flow after blasting/pressurization measured by: ☐ Rising-head readings ☐ Blow-out ☐ Test pumping Duration:		

Assumed stable water level (measured from surface):

After drilling: m	After any blasting/pressurization: m	Present: m
Date of measurement:	Date of measurement:	Date of m.:

Pump inlet (from surface): m	**Pump (type and yield):**
Present well capacity:	**Water consumption:**

Protection of well head and area (casing, sealing, fencing, protection zones)

Bacteriological water quality:

Physio-chemical water quality:

Type of watertreatment/disinfection:

Comments to water quality (yearly variations, colour, boiling regulations etc.):

Pipeline (leakages, contamination, biofouling, etc.):

Surficial deposits (depth, type, extent, etc.):

Land use:

Possible contamination sources:

Reports etc.:

Appendix C

Changes in microbiological water quality 1996-2003

Appendix C is not included due to copyright restrictions

Appendix D

Student t-test

Appendix D – Student t-test

Statistically significant differences found by the student t-test (Swan et al. 1995) are presented in Table D1.

Factors possibly influencing the microbiological water quality presented in Chapter 5.3 are compared in pairs to evaluate the statistical difference between the two. To estimate the t-value the microbiological water quality reported for each well is given values from 0-2, and for each pair of categories wells with the following microbiological water quality are part of the dataset:

- Wells reporting good microbiological quality (Good, value 0) and wells reporting water samples periodically exceeding the 2002 NSDW regarding coliforms and/or HPC (value 2)
- Good (value 0) and wells periodically reporting coliforms in the water samples (value 2)
- Good (value 0) and wells periodically reporting HPC at 22°C > 100 ml in the water samples (value 1). Coliforms are never reported

For each of the categories 1 and 2 in Table D1, the mean value ($\overline{x_1}$ and $\overline{x_2}$) and the mean standard deviation ($\overline{S_1}$ and $\overline{S_2}$) are calculated. The t-value are then found by Equation D1:

$$t = \frac{\overline{x_1} - \overline{x_2}}{\sqrt{\overline{S_1}^2 + \overline{S_2}^2}} \qquad \text{(Equation D1)}$$

Table D1 Calculated t-values based on reported microbiological water quality for wells in Dataset E_{mod}. Significant differences (95 % confidence interval) are indicated in bold type. Almost significant differences (90-95 % confidence interval) are underlined.

Categories that are compared	Microbiological water quality		
	Good and water samples exceeding the NSDW	**Good and coliforms detected**	**Good and HPC > 100/ml**
1. Concrete well-protection 2. Concrete well-protection in combination with well-cover or well-house	<u>1.76</u>	**3.79**	0.35
1. Casing length > 5 m 2. Casing length ≤ 5 m	<u>-1.76</u>	**-2.43**	-0.77
1. Cap and above 2. Cap and below	**-3.35**	**-3.74**	**-5.20**
1. Cap and below 2. No cap and below	**3.85**	**2.24**	**2.24**
1. Possible sealing between bedrock and casing 2. No sealing between bedrock and casing	-0.94	**-2.59**	0.44
1. Depth to bedrock > 2.5 m 2. Depth to bedrock ≤ 2.5 m	**-2.31**	**-2.32**	<u>-1.88</u>
1. Above marine limit (a.m.l.) 2. Below marine limit (b.m.l.)	**2.04**	1.03	**2.45**
1. b.m.l and category 1 deposits 2. b.m.l and category 2 deposits	**-2.16**	**-2.36**	-0.87
1. Only farmland < 100 m 2. No farmland	**2.35**	**2.83**	1.55
1. Only farmland < 100 m 2. Only outlying fields – no sheep are grazing	**2.93**	**4.12**	**-2.12**

References:

Swan, A.R.H., Sandilands, M. & McCabe, P., 1995: Introduction to Geological Data Analysis. Blackwell Science Ltd, 446 pp.

Appendix E

Paper

The paper "*Bacterial contamination in Norwegian groundwater wells in bedrock*" was presented at XXXth IAH Congress on Groundwater in Cape Town, South Africa 26th November – 1st December 2000.

Part of the paper was presented as a poster at "Det 11. seminar om hydrogeologi og miljøgeokjemi" at the Geological Survey of Norway, 7-8 February 2002.

The reference to the paper is:
Gaut, S., Storrø, G. & Brattli, B., 2000: Bacterial contamination in Norwegian groundwater wells in bedrock. *In*: Sililo, Oliver et al. (eds.). Groundwater: Past Achievements and Future Challenges. Proceedings of XXXth IAH Congress, 26th Nov-1st Dec 2000, Cape Town, South Africa, 751-754.

Appendix F

Extended abstract

The extended abstract "*Factors influencing the bacteriological quality of groundwater in Norwegian bedrock wells*" was presented at the International Conference on Groundwater in Fractured Rocks held in Prague 15th to 19th September 2003.

The reference to the extended abstract is:
Gaut, S., Brattli, B. & Storrø, G., 2003. Factors influencing bacteriological quality of groundwater in Norwegian bedrock wells. *In*: Krásný, J. et al. (eds.). Proceedings of the International Conference on Groundwater in Fractured Rocks, 15-19. September 2003, Prague, Czech Republic. IHP-VI, Series on groundwater No. 7, 341-342.

Appendix G

Paper (In prep.)

The paper " *Comparative analysis of tracer behaviour in a fracture aquifer; the Holmedal well field of western Norway*" is in preparation.

Parts of the paper has been presented at the TraM'2000 International Conference on Tracers and Modelling in Hydrogeology as part of a presentation of the DNA tracer tests conducted in Norway (Sabir et al. 2000). I presented both the paper and general information about the synthetic DNA tracer, such as construction and analyses.

The Holmedal study was also presented at "Det 9. seminar om hydrogeology og miljøgeokjemi" at the Geological Survey of Norway, 9-10 February 2000.

The reference to Sabir et al. 2000 is:
Sabir I.H., Torgersen J., Gaut S., Haldorsen S., Aleström P., Colleuille H., Pedersen T.S. & Kitterød N.O., 2000: Synthetic DNA tracers: examples of application in water related studies. *In*: Dassargues A. (ed.) Tracers and Modelling in Hydrogeology. Proceedings of TraM'2000, International Conference on Tracers and Modelling in Hydrogeology, IAHS Publication no. 262, 159-165.