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Groundwater sustainability indicators: testing with Finnish data

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The objective of the study was (1) to test the applicability of the groundwater indicators defined by the UNESCO/IAEA/IAH Working Group on Groundwater Indicators at different scales (national/regional/aquifer) by using the data from Finland, and (2) to assess the availability and suitability of data. The indicators allow for assessment of groundwater abundance in proportion to population and water use, as well as its quality and vulnerability. The data used include groundwater recharge estimates, water use and treatment statistics, extent of classified groundwater areas, hydrogeology and groundwater quality (background, chloride and raw water). The indicators show that Finnish groundwater is generally in good shape and of relatively good quality. The groundwater used is renewable and can theoretically be used on a larger scale and enhanced by artificial recharge. The indicators could be more useful in decision-making if focussed on a smaller area, as the relevant decisions concerning groundwater resources are commonly made locally or regionally. Spatial representativeness of samples and data source selection emerged as key considerations.

Introduction

Groundwaters play an important role in the world: they feed springs and streams, support wetlands and maintain land surface stability. Groundwater is a significant global resource, comprising 96% of the Earth's unfrozen freshwater (Shiklomanov and Rodda 2003). According to Morris (2003), groundwater systems provide 25% to 40% of the world's drinking water. In Finland the share of groundwater is more than 60% of the community water supply. Groundwater commonly meets the quality requirements for potable water, requires less chemical treatment than surface water and is better protected against pollution. All over the world, both megacities and rural communities depend on groundwater for their domestic water supply. Of total water abstraction in the EU, about 18% (OECD 1997) is taken from groundwater (12% according to EEA 1995). If the public water supply is considered, the share of groundwater is clearly higher: for example in Austria, Denmark, Iceland, Portugal and Switzerland over 75% and 50%–75% in Belgium (Flanders), Finland, France, Germany, and Luxembourg (Eurostat 1997). In agriculture groundwater is used for sprinkler irrigation in an increasing number of regions in the north and south of Europe (EEA 2003).

The development of groundwater indicators by the International Hydrological Programme (IHP) — UNESCO's intergovernmental scientific co-operative programme in hydrology and water resources — is also a contribution to the United Nations (UN) World Water Assessment Programme (WWAP) (2003). One of the goals of WWAP is to report globally on water resources in the World Water Development Report (WWDR). Through the WWDR, the UN wishes to highlight successful water policies and determine how sustainable the use of freshwater is today globally. The first WWDR published in 2003 extensively reviewed international indicator development as applied to freshwater resources (UN and WWAP 2003). Since then the "Working Group on Groundwater Indicators", led by UNESCO, consisting of experts of several organisations, including the International Atomic Energy Agency (IAEA), the International Association of Hydrogeologists (IAH) and the International Groundwater Resources Assessment Centre (IGRAC), has developed groundwater indicators. The group sought to propose indicators that although simple, are both scientific and policy-relevant, and applicable on the global, national and local levels. The proposed groundwater indicators were applied in Finland and in several other case study locations. Within the WWAP framework, globally applicable indicators have been developed for all aspects of water resources and their management, including areas such as legislation and health.

The role of groundwater is twofold from the viewpoint of the WWDR: "groundwater has to be seen within the broader context of the hydrological cycle and aquifers as a significant hydrological component of watersheds and basins" and "groundwater should be integrated within the context of broader economy and social dimension, particularly the use and related consequences". The approach used in developing the groundwater indicators combines the top-down and cause-effect approaches. The DPSIR (Driving force, Pressure, State, Impact and Response) developed from the PSR of OECD and used, for example, by EEA and UNEP, is the conceptual framework. The aim of using DPSIR is to provide information on all these elements, show the connections between them and to estimate the effectiveness of responses (EEA 1999). Due to their particular characteristics with respect to, for example, water quality, groundwater-specific indicators were considered necessary. Furthermore, in the context of Integrated Water Resources Management (IWRM), the groundwater component is commonly not treated with sufficient attention and quantitative detail although IWRM can be regarded as the vehicle that makes the general concept of sustainable development operational for the management of freshwater resources.

As stated by the Working Group on Groundwater Indicators, the proposed groundwater indicators are based on measurable and observable data and provide information about groundwater quantity and quality (contemporary state and trend) and focus on social (groundwater availability and use), economic (groundwater development, abstraction and protection) and environmental (groundwater depletion and pollution) aspects of groundwater resources policy and management. Particular attention is being paid to sustainability aspects. Groundwater indicators are used to communicate information in a descriptive and, when possible, also in a visual way, especially for decision-makers.

The indicators are tested to assess their applicability in different hydrogeological environments as well as the availability of relevant data in countries with diverse monitoring schemes and information systems. This study assesses the applicability and descriptiveness of groundwater indicators based on Finnish groundwater data. The objective was to collect experience regarding the applicability of the indicators in order to support further use and indicator development. In particular, testing the indicators at different sub-national scales contributes to refining the indicators in such a way that local characteristics can be accounted for without compromising international comparability. Due to the variable relevance of the indicators to the conditions in Finland, a selected group of the ten indicators defined by the Working Group on Groundwater Indicators were tested. Selected examples describing the groundwater situation using indicators highlighted some key challenges such as up-scaling and spatial and temporal representation. Other case studies in Spain, Brazil and the Republic of South Africa tested the IHP's groundwater indicators on different scales (Vrba and Lipponen 2007).

Context

Finland is a relatively large and sparsely populated country, located in the northern hemisphere and crossed by the Arctic Circle. Finland has been a member of the European Union (EU) since 1995, and as such the Water Framework Directive (WFD 2000/60/EC) gives direction to Finnish water policy. The overall goal of the WFD is for all groundwater bodies to have a "good chemical and quantitative status" by 2015. The characteristics of groundwater are reflected in further detail in the Groundwater Directive (2006/118/EC). The criteria set for the assessment of the chemical status of a groundwater body include groundwater quality standards (for nitrate and pesticides) and threshold values based on the protection of the body of groundwater. The criteria are established by Member States according to the guidance given. The Water Resources Strategy of Finland (MAF 1999) aims, for example, to ensure the operational security of waterworks by promoting the use of groundwater resources. Its goal is to improve the usability and status of water resources by 2010, and one key method of achieving this is through the advancement of groundwater investigations and monitoring for community water supplies.

Groundwater management, legal basis and use

Current legislation has a crucial effect on data collection (although the historical development of regulation and national monitoring also play a major role). The two ministries responsible for water related issues at the national policy level are the Ministry of the Environment and the Ministry of Agriculture and Forestry. The Regional Environment Centres follow the state and use of (ground)water in their areas as regional authorities, while the Finnish Environment Institute (SYKE) is the governmental research and development centre compiling data and carrying out analyses for national and international use. The Ministry for Social Affairs and Health is in charge of the quality of household waters, and supervision at the local level is provided by municipal health officers.

Municipalities are responsible for planning the overall development of water services while the Regional Environment Centres are the competent supervising authorities in groundwater protection, inspecting and controlling compliance as well as permitting certain activities, decisions concerning groundwater management are in practice are made at local and regional levels where information needs consequently also emerge. Environmental Permit Authorities (three) regulate large scale groundwater abstraction (more than 250 $m^3\ d^{-1}$).

Under Finnish legislation, the protection of groundwater is largely taken care of by the prohibitions on polluting and altering of the groundwater. As a rule, activities potentially harmful to groundwater are located in outside areas important or suitable for water supply, but if located within such areas relevant conditions are specified under the environmental permit. The protection of groundwater is also commonly an element cited in Environmental Impact Assessments for projects. The permit authorities may also establish a protection area around the groundwater abstraction site. There are also voluntary arrangements for protecting groundwater, including the preparation of draft protection plans by local authorities and waterworks for guidance purposes. Such protection plans have already been prepared for almost 1000 groundwater areas (Rintala *et al*. 2007).

The use of groundwater and surface water as well as water quality are monitored nationally. The share of groundwater in community water supply has grown since the 1930s reaching 61% in 2001. Based on information provided by the Regional Environment Centres for WFD reporting in 2005, settlements used approximately 94% of the groundwater abstracted (a total of about 630 000 $m^3\ d^{-1}$, equals 7.3 $m^3\ s^{-1}$) by waterworks supplying more than 100 m^3 d^{-1}. Industry used approximately 6% of the abstraction. In 1999 some 89% of the Finnish population was connected to a public water supply and 81% to a sewer system (Lapinlampi and Raassina 2002).

Groundwater formation and occurrence in Finland

In Finland average rainfall equals 660 mm a^{-1}, of which about 13% is infiltrated into groundwater, while most of the precipitation evaporates or is discharged as runoff. Areally precipitation varies from approx. 450 to 800 mm a^{-1}. Even in a climate with cold winters half of the annual rainfall evaporates (Kuusisto 1986, Hyvärinen *et al*. 1995). Water use by sectors is approximately as follows: urban 12%, agriculture 2%, industry 33%, cooling and other 53% (EEA 2000).

In general, groundwater forms in spring, when snow melts and following autumn rains. The amounts formed are low after the summer when the precipitation has evaporated and only some water infiltrates to groundwater. Another low point is in late winter before the snow starts to melt (Soveri *et al*. 2001).

The main geological formations found in Finland include the oldest Precambrian formations and the youngest glacial formations (Mälkki 1999). The most important aquifers are sand-gravel deposits in longitudinal eskers and ice marginal deposits, which cover 5% of the surface area of Finland. In gravel and sand areas groundwater is usually easily exploitable. Salpausselkä ice-marginal formations and the connecting eskers are of vital importance as they host many significant aquifers (Salonen *et al*. 2002, Mälkki 1999). In rural areas, private wells are used for tapping groundwater from moraines and also from crystalline bedrock. Usually the yield is sufficient for a single household (Korkka-Niemi and Salonen 1996, Backman *et al*. 1999, Mälkki 1999).

Classification of groundwater areas

An early mapping of groundwater areas considered as important for community water supply was carried out from 1973 onwards (National Board of Waters 1976). To improve the protection of Finnish groundwater resources, the classification of so-called “Groundwater Areas” was introduced in the 1980s. The purpose of this exercise was to identify priority areas for groundwater utilization as well as to improve the management of groundwater. The classification divides groundwater areas into three classes according to their priority: (I) groundwater areas important for water supply, (II) groundwater area suitable for water supply, and (III) other groundwater area. The classification is still being continuously revised as water supply investigations are undertaken. Aquifers, as referred to in the indicator definitions, occur mainly in classes I and II. Altogether approximately 6600 groundwater areas have been identified (Gustafsson 2006). Of the total, 2300 belong to the first class, 1500 to the second class and 2800 to the third class (Fig. 1). Classified groundwater areas have a defined inner zone of estimated groundwater formation (in unconfined aquifers), which is the most vulnerable part, and an outer marginal zone. Groundwater recharge in the classified areas was estimated by Britschgi and Gustafsson (1996) at 5.8 million m^3 d^{-1}. The estimate is based on the surface area, local precipitation and the approximate infiltration coefficient for each area in the case of unconfined aquifers. Confined aquifers have only been included within the classification only when a water supply well that providing water for more than 10 people has already been constructed in the area and therefore meeting the requirements for inclusion within Class I. For confined aquifers the yield is based on the water extractable from the well (either defined by test pumping or actual water use) (R. Britschgi pers. comm.).

Groundwater quality

Finnish groundwater is commonly slightly acidic due to the bedrock, which consists of acidic intrusive igneous and metamorphic rocks and only minor fractions of carbonate minerals. The pH is on average 6.5. The amounts of dissolved compounds are small, which leads to low hardness. Alkalinity of groundwater is mostly low, about 1.0 mmol l^{-1} and thus the buffer capacity is low. Conductivity is also low, usually less than

10 mS m^{-1} or at least under 50 mS m^{-1} (Lahermo *et al*. 1990, Korkka-Niemi and Salonen 1996).

In Finland, nitrate concentrations are very low. According to Soveri *et al*. (2001) the nitrate concentration in groundwater in its natural state is less than 0.5 mg l^{-1}. Nitrate concentrations are not a problem in Finland, since only 1.8% of the waterworks using groundwater have nitrate concentrations exceeding 25 mg l^{-1} (Lehtikangas *et al*. 1995). The maximum allowable in drinking water according to the Finnish Ministry of Social Affairs and Health (2000) is 50 mg l^{-1}. According to the assessment of groundwaters affected by agriculture 1992–2002 (Mitikka *et al*. 2005), within aquifers under cultivation, the NO_3 concentration in groundwater was usually below 10 mg l^{-1}, but at two aquifers the concentration exceeded 25 mg l^{-1}. At the observation sites in the natural state (the monitoring network of SYKE), the NO_3 concentration in groundwater lay mostly between 0–1 mg l^{-1}.

There are also natural regional differences in groundwater quality. In coastal areas electric conductivity is higher due to higher chloride concentrations caused by the late emergence from the sea and hence more limited wash-out of salt water (Mälkki 1999). On the western coast the iron and manganese concentrations are quite high because the clay formations capping the aquifers diminish recharge and cause reducing conditions. Sulfide ores cause higher sulfate concentrations in eastern Finland as well as on the southern and western coast (Lahermo *et al*. 1990, Korkka-Niemi and Salonen 1996). In certain areas, the geology and rock types in particular, cause radon, fluoride or arsenic occur in elevated concentrations in groundwater, especially in drilled wells, in which the concentrations of many naturally occurring elements are commonly higher than in dug wells (Kahelin *et al*. 1998, STUK 2000, Lahermo and Backman 2000).

The quality of household water distributed in Finland is generally good. For example, a majority of quality checks at large waterworks met the health-based requirements and usability-based recommendations. The microbiologial requirements were also met to a high degree (Zacheus 2006). Among the large waterworks, the proportion of utilities distributing surface water is bigger.

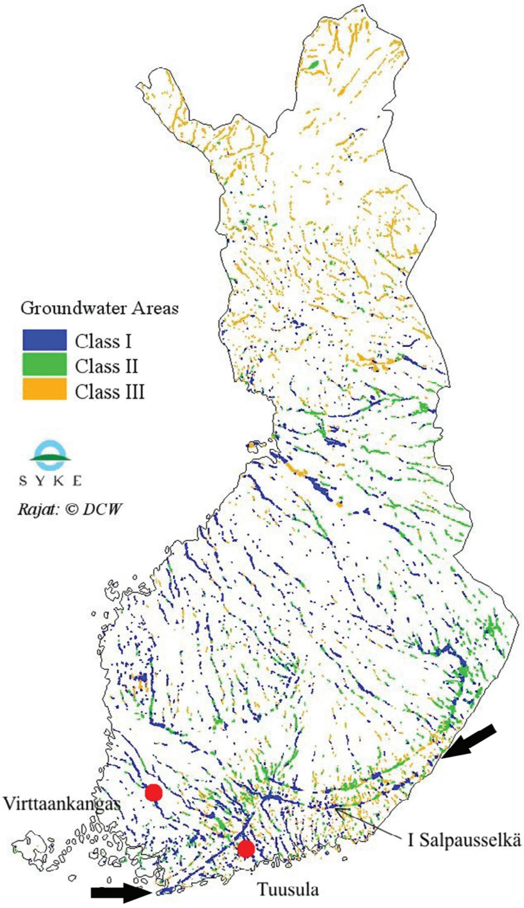

Fig. 1. The classified groundwater areas (updated 14 Jan. 2005) and the locations of the examples described in the text. Black arrows indicate the zone of the First Salpausselkä. Reproduced with permission from the Finnish Environment Institute (SYKE) (©SYKE, Regional Environment Centres, source: SYKE, groundwater database POVET).

Groundwater supplied by municipal waterworks is abstracted mainly from gravel and sand formations, where it is generally of good quality. Quality problems occur more commonly in rural areas, where private wells dug into moraine deposits or minor beach terraces or drilled into fractured bedrock are used. According to a survey made by Korkka-Niemi (2001), only 37.2% of the private wells fulfilled the requirements and recommendations for drinking water quality. Nevertheless the health-related requirements were met by 63% of the households.

One of the most studied problems regarding groundwater quality and human activity in

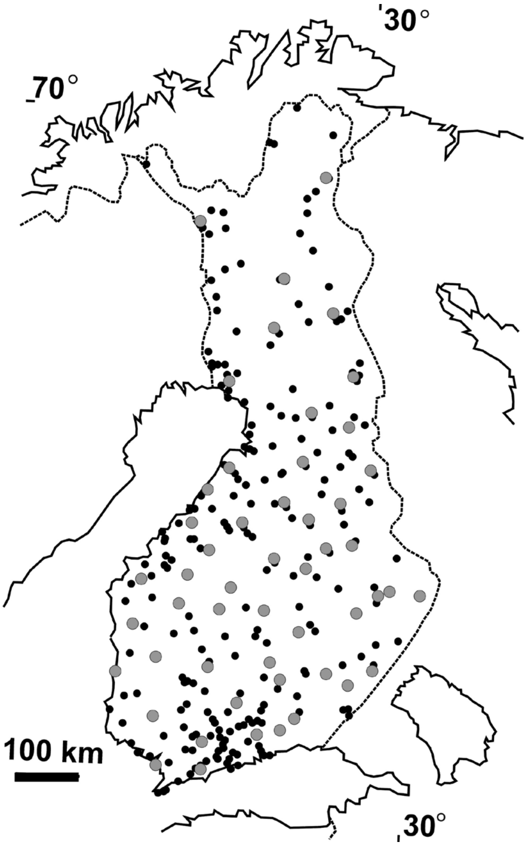

Fig. 2. Locations of Finnish groundwater observation stations of SYKE (grey dots) and the national groundwater monitoring sites for reporting according to the requirements of the Water Framework Directive (black dots).

Finland relates to the use of the sodium chloride for de-icing of slippery roads in winter time. According to Nystén *et al.* (1999), the chloride concentrations exceed the national technical-aesthetic guideline value of 25 mg l^{-1} (based on prevention of corrosion of pipes) in 34% of the observation wells in 84 groundwater areas in the First Salpausselkä zone (Fig. 1). According to Korkka-Niemi (2001), 2.7% of private wells have chloride concentrations exceeding the guideline value. Roads that are used for transporting various hazardous chemicals pose a risk to groundwater, while along the main roads there are also gas stations with fuel tanks. Groundwater is exposed to the chemicals used by industry, landfill sites and many smaller risks, but potentially harmful activities are preferably located outside groundwater areas or special protective measures are required in the permitting process.

Data and methods

Data sets of the Environmental Administration were principally used to test the indicators. Variables needed for determining the indicators are presented in Table 1. Definitions and instructions for the calculation of the indicators were provided by the Working Group on Groundwater Indicators (Vrba and Lipponen 2007).

The groundwater quality data used in this study derive from the monitoring network of SYKE consisting of 53 observation stations located in environments of variable climatological conditions and soil types in areas where human impact is minor (Fig. 2). If some abstraction occurs, it is only for individual households. The chemical sampling and measurements, including water levels, are carried out quarterly (Soveri *et al* 2001).

The European Environment Information and Observation Network (EIONET) is a partnership network of the European Environment Agency (EEA) and its member and cooperating countries. Groundwater monitoring to meet the requirements of the Water Framework Directive, which became operational in the end of 2006, consists of 282 groundwater monitoring sites in Finland, including wells, monitoring wells or springs (Fig 2). Almost all of the stations of SYKE, referred to above, are included in the agreed groundwater monitoring for WFD. Based on the data from the groundwater monitoring sites, Finland reports to the European Union on the status or groundwaters according to the requirements of the WFD. At the 180 surveillance monitoring sites, five basic water quality parameters are being monitored. There are 187 operational monitoring sites, where the monitoring is more intensive or oriented towards detection of a certain pollutant (J. Gustafsson pers. comm.). In the framework of EIONET, selected waterworks provide the Environmental Administration with data on groundwater quality.

A nation-wide groundwater database (POVET), which the Environmental Administration started using in 2002, is maintained by

Table 1. Groundwater indicators, their formula, the variables used and the results. The scale in the table refers to the scale(s) at which the indicators were applied in this study.

Indicator	Formula (unit)	Variables (value)	Result	Scale
Groundwater renewable resources per inhabitant	(Groundwater renewable resources)/ inhabitants (m^3 a^{-1} per inhabitant)	Recharge (85 mm a^{-1}), base flow (–83 mm a^{-1}), seepage (0), surface area (304 473 km^2), inflow (0), artificial recharge (0.050 km^3)	126 m^3 inhabitant^{-1}	national
Total abstraction of groundwater/ Groundwater recharge	(Total abstraction of groundwater) × 100%/ (Groundwater recharge) (%)	Groundwater use for drinking (296 000 000 m^3 a^{-1}), groundwater use in industry (10 300 000 m^3 a^{-1}) recharge (85 mm a^{-1})	1.2%	national
Total abstraction of groundwater/ Exploitable groundwater resources	(Total groundwater abstraction) × 100%/ (Exploitable groundwater resources) (%)	Groundwater use for drinking (296 000 000 m^3 a^{-1}), groundwater use in industry (10 300 000 m^3 a^{-1}), groundwater reserves in superficial deposits (70–75 m^3 s^{-1}) and bedrock (23 m^3 s^{-1})	10%	national
Groundwater as a percentage of total drinking water on a country level	(Groundwater used as drinking water) × 100%/(total use of drinking water) (%)	Groundwater used as drinking water (249 000 000 m^3 a^{-1}) Total use of drinking water (408 000 000 m^3 a^{-1})	61%	national
Groundwater vulnerability indicator	(Soil media) × 2 + (depth to water table) × 4 + (unsaturated zone lithology) × 5 + (aquifer media) × 3	Soil media, depth to water table, unsaturated zone lithology, aquifer media	Vulnerability varies from moderate to high	aquifer
Groundwater quality indicator	Σ(area of aquifers with groundwater natural quality problem) × 100% /Σ(area of studied aquifers) (%)	Σ[area of groundwater areas with exceeding parameters (EC, pH, nitrate, chloride, iron, manganese fluoride)] Σ[area of studied groundwater areas (45.07 km^2)]	74%	National/area/waterworks
Groundwater treatment requirements	Σ[volume of groundwater treated by simple (S)/demanding method (D)] × 100%/ Σ(volume of studied groundwater) (%)	Volumes of water treated by alkalization (S), iron removal (S), coagulation (D), filtration (S), disinfection (S), or no treatment required, Σ[volume of studied groundwater (110790 m^3 d^{-1})]	29% (no treatment required) 63.3% (simple methods) 7.5% (demanding methods)	Regional (3 regions)

the Regional Environment Centres and contains detailed information about aquifers; for example, general information about hydrogeology, activities and land use (settlements, forestry, cultivation, industry) and risk activities (fur-farming, pig houses, gravel extraction, petrol stations). It also contains information about monitoring and sampling of groundwater from wells, sampling tubes, ponds and springs (Mitikka *et al*. 2005).

POVET is part of a more extensive Environmental Information System, HERTTA, which is developed, maintained and administrated by the Finnish Environmental Administration. Data collected since 1970s by the Finnish Environmental Administration are stored in HERTTA which consists of subsystems containing abundant data on the state of the environment, its development and preservation. HERTTA also includes also a Map Service connected to the Geographical Information Systems (GIS) of the Environmental Administration (Niemi and Heinonen 2003).

The latest official national water supply statistics date from 1999 and are compiled in the publication of Lapinlampi and Raassina (2002). These statistics contain multifaceted information on producing drinking water and treating sewage. Since 1994, waterworks supplying water to 50 people or more have been included within the statistics. The data are collected from several databases concerning water protection, waterworks and sewerage systems and supervision.

Indicator application

The groundwater indicators examined in this study (Table 1) cover different aspects of groundwater availability in terms of quantity and quality, use and vulnerability to pollution.

Groundwater renewable resources per inhabitant

This indicator shows how much groundwater is theoretically available for each inhabitant per year. Groundwater renewable resources (Gwrr) consist of the recharge from precipitation (Recharge), surface water that infiltrates into groundwater (Seepage), groundwater which discharges into surface water (Base flow), the flow of groundwater from (and to) neighbouring countries (Inflow) and artificial recharge (Vrba and Lipponen 2007).

Recharge

In an average year, 85 mm of precipitation infiltrates into groundwater. Recharge is the average infiltration multiplied by the area of Finland (304 473 km^2) without surface waters (Kuusisto 1986, Statistics Finland 2004). Recharge can be estimated more accurately for groundwater areas where the community water supply focuses. Using the estimated distribution of mineral soil types and their infiltration properties it would also be possible to come up with different estimates.

Seepage

There are no estimations or data for seepage. It is considered likely that the impact of seepage is minor as compared with the impact of recharge or base flow. In humid areas like Finland, the direction of flow is usually from groundwater to surface water. Under special circumstances, for example, when groundwater is abstracted close to a waterbody, the flow can also be reversed.

Base flow

For the water balance, the base flow is estimated at 83 mm (Kuusisto 1986). This is multiplied by the area of Finland without surface waters to arrive at the total base flow in Finland. There are substantial uncertainties due to factors such as the occurrence of peatlands.

Inflow

The inflow from neighbouring countries has only a marginal effect on renewable groundwater resources in Finland. Based on the POVET data, Finland has approximately 15 groundwater areas shared with Russia and 20 areas in the vicinity of the border with Norway. There are no common groundwater areas with Sweden — the border follows the Tornio River. As there are altogether 3756 groundwater areas in classes I and II, these 35 areas are not very significant. These shared areas are situated in sparsely populated areas, and there is no pressure to use them for municipal water supply.

Artificial recharge

Artificially recharged groundwater makes up approximately about 12% of the water supplied by waterworks (Gustafsson *et al.* 2006). The volume of artificial recharge is hence about 0.050 km^3 a^{-1}.

Per inhabitant

At the end of the year 2003, Finland had 5 219 732 inhabitants (Statistics Finland 2004). According to the population projections, Finland's population is predicted to remain quite stable and consequently water resources are expected to suffice for the future (Table 2).

$$\text{Gwrr/Inhabitants} = [(\text{Recharge} - \text{Base flow}) \times \text{Surface area} + \text{Seepage} + \text{Inflow} + \text{Artificial recharge})]/\text{Inhabitants} = 126\ \text{m}^3\ \text{a}^{-1} \times \text{Inhabitant}$$

Notwithstanding climate changes and other features, the reserves are full or partially filled, which has an impact on base flow. During an average year in Finland, the same quantity of water infiltrates into groundwater as flows out. The outflow is due to abstraction or base flow. Abstraction, however, is considered in the indicator of Total abstraction of groundwater/groundwater recharge.

Total abstraction of groundwater/ groundwater recharge

This indicator compares the amounts of abstracted groundwater to total groundwater recharge. Hence it essentially indicates the intensity of renewable groundwater use or stress on the resource. The indicator shows whether groundwater is used in a sustainable way or if there is any indication of overexploitation. When abstraction is less than recharge, groundwater use is considered sustainable.

Irrigation loss is a minor factor in Finland as irrigation is seldom used. If it is used, it occurs only in summer, when groundwater basins are not recharged because of evaporation. Total abstraction includes groundwater use for domestic purposes, industry and agriculture.

Groundwater is not used very much for irrigation as generally the need for irrigation is small and it occurs over relatively short periods. Agriculture uses groundwater in animal husbandry. Some farms use water from public waterworks, but most of them use groundwater from their own wells. Data on groundwater volumes extracted from private wells used in agriculture are not available.

Surface water is used on a large scale by industry, but sectors like the food industry requiring high quality water also use groundwater. The industry that has groundwater intake plants of its own uses about 11 700 000 m^3 a^{-1} of groundwater. The figure derives from VAHTI, which includes information on permitted activities that make up about 75%–80% of total industry groundwater. Estimation of industries' water use is complicated by the fact that many small industries take their water from the networks of community water supply and information about their water use is not available in VAHTI.

The data on the groundwater used by waterworks (and on treatment) derives from National Water Supply Statistics (Lapinlampi and Raassina 2002). These statistics include the water used by waterworks and water leakage from the networks, estimated at approximately 13% of the water pumped into water supply networks.

A nationwide rural well water survey estimated that about 310 000 households regularly

Table 2. Population projection for Finland (source: Statistics Finland 2004).

	2010	2020	2030
Population	5 268 000	5 317 000	5 291 000

use water from private wells (Korkka-Niemi *et al*. 1993). The information on the use of wells is a rough estimation, and since 1993 the number of people using private wells has been decreasing due to urbanisation, extended coverage of water distribution networks and improved community water supply. In 1993 about 15% of Finland's inhabitants were not covered by community water supply while in 1999 this figure was about 11%. This change has not been taken into consideration when evaluating water use in rural areas (Lapinlampi and Raassina 2002). One household is estimated to use about 0.5 m^3 d^{-1} (Korkka-Niemi *et al*. 1993). These estimates were used in the calculation of the value of the indicator, 1.2%, using the formula in Table 1. This value is smaller by an order of magnitude than the groundwater use by communities, industry and power plants as percentages of the volume of groundwater forming, ranging from 12.2% to 30.6%, which was estimated for River Basin Districts a part of the preliminary characterization according to article 5 of the Water Framework Directive (Silvo *et al*. 2006).

Total abstraction of groundwater/ exploitable groundwater resources

The result belongs to one of the scenarios introduced here, which give an indication of the sustainability of abstraction (Vrba and Lipponen 2007).

Scenario 1: abstraction ≤ recharge; i.e. < 90%
Scenario 2: abstraction = recharge; i.e. = 100%
Scenario 3: abstraction > recharge; i.e. > 100%

The exploitable resources are essentially the yield of groundwater reserves in superficial deposits and bedrock. Artificially recharged groundwater, as it is used today, is included. The exploitable groundwater resources mean the volume of groundwater that can be annually abstracted under the current socio-economic constraints, political priorities and ecological conditions. It has to be feasible to make the groundwater potable.

Mälkki (1999) estimated the renewable reserves in the superficial deposits and bedrock in Finland. The reserves in bedrock were estimated on the basis of an average area (1 ha) of a fractured zone and the frequency of occurrence of fractured zones in bedrock (1 km^2). When taking into account the coverage of terrain, nearly half of the area of Finland (150 000 km^2) can be considered potential area for bedrock groundwater. Groundwater is considered exploitable down to a depth of 100 metres (cf. Rönkä 1983, Niini and Niini 1995, Mälkki 1999). In practice the depth of drilled wells in Finland reaches about 60–80 meters (J. Piekkala pers. comm.). Porosity of the bedrock is estimated at 1%. The reserves in bedrock are estimated at 1.5 km^3. When a bedrock aquifer is used as a water source, the annual recharge is about half the volume of water reserves in a fractured zone. So the flow rate potential for water supply is estimated at about 23 m^3 s^{-1} (Mälkki 1999). It should be noted that this is likely to be the case in the upper part of the bedrock.

The surface area of groundwater areas has been evaluated several times. The first estimation was made by Mälkki and Salmi (1970) and the last is from the national classification of groundwater areas (Britschgi and Gustafsson 1996). Currently the spatial analysis of the extent of groundwater areas is facilitated by the information widely available in GIS format. Based on these different results, groundwater flow rate in the groundwater deposits considered as aquifers can be estimated at 70–75 m^3 s^{-1} (Mälkki 1999). Mälkki (1999) also estimated the volume of water stored in the aquifers potential for water supply. When the total surface area of such aquifers that store groundwater abundantly can be estimated at 6000 km^2, aquifer thickness as 10 metres and porosity as 20%, the volume of water stored is 12 km^3.

The estimations of renewable reserves of groundwater by Mälkki (1999) and artificial recharge are added together resulting in resources of 2.979 km^3 a^{-1}. Total abstraction is defined within the indicator "Total abstraction groundwater/Groundwater recharge" at 0.306 km^3 a^{-1}. Using the formula in Table 1 gives the result of 10%. This indicator value being much higher than total abstraction/recharge probably results from the generally small storage of small glacial aquifers in Finland in relation to recharge.

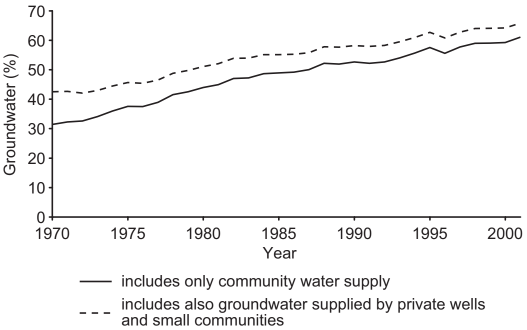

Fig. 3. The share of groundwater used for domestic purposes. The values for 2000 and 2001 are estimations (Korkka-Niemi *et al*. 1993, Lapinlampi and Raassina 2002).

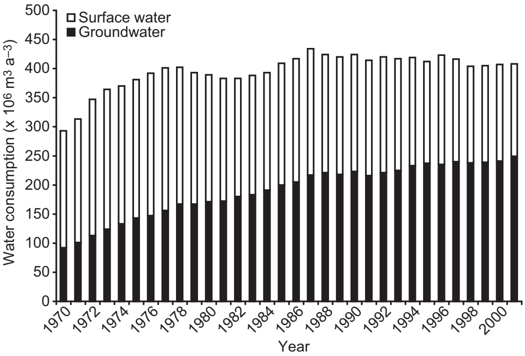

Fig. 4. Sources of the water supplied by community waterworks. The groundwater includes artificially recharged groundwater (Lapinlampi and Raassina 2002).

According to the classification of the Working Group on Groundwater Indicators, the defined indicator value falling into the first scenario shows that the groundwater resources are "underdeveloped" and use could probably be developed further. It has to be noted, however, that due to the remote location of some of these resources from population centres, many of them cannot be feasibly utilized. The current trend in Finland is for increasing use of groundwater for water supply. The increase is largest in the use of artificially recharged groundwater, which was estimated to make up 12% of the community water supply (Gustafsson *et al*. 2006). Two large artificial recharge schemes are in the process of obtaining permits.

Groundwater as a percentage of total drinking water on a country level

This indicator measures the groundwater dependency of supplying drinking water as a priority use, but it could also be applied to other uses such as industrial usage. The total supply consists of surface water, artificially recharged groundwater and groundwater, but only community water supply is considered (Fig. 3).

The share of groundwater has been increasing gradually up to the current level of 61% (including artificially recharged groundwater) while total water consumption has also increased (Fig. 4). Yet, the average volume of water used per person, specific consumption, has decreased since 1970. Specific consumption was at its highest in 1972 at 335 l d^{-1} while in 1999 it was only 243 l d^{-1} (Lapinlampi and Raassina 2002).

Groundwater vulnerability indicator

The indicator has been developed to evaluate the natural vulnerability of groundwater areas. The concept of vulnerability is reviewed in detail by Vrba and Zaporozec (1994). The indicator specifies how much the physical environment protects the groundwater basin or the groundwater-containing formation from pollution. The factors affecting vulnerability to be taken into consideration are the soil media, depth to water table, unsaturated zone lithology and aquifer media. Only the natural characteristics of aquifers are considered, the anthropogenic impacts like roads or industry are not evaluated.

The classification applied to this indicator as defined by the Working Group on Groundwater Indicators was modified by Artimo from Turku Region Water Ltd. (TSV) to better reflect the geological environment (Tables 3–7). Modifications were needed for a more precise representation of the soil materials and properties in the unsaturated zone and in the aquifer media. The modified classification was based on the results obtained from the mapping of hydrogeological units of the Virttaankangas aquifer (Artimo and Saraperä 2003, Artimo *et al*. 2003a). Depositional environments resembling those of Virt-

Table 3. The factors affecting groundwater vulnerability. (From Aller *et al*. 1987, modified by Artimo 2005).

Feature	Weight
Soil media	2
Depth to water table	4
Unsaturated zone lithology	5
Aquifer media	3

Table 4. Ratings for soil media. (From Aller *et al*. 1987, modified by Artimo 2005).

Soil media	Rating
Thin or absent	5
Gravel	4
Sand	3
Loam	2
Clay	1

taankangas, are common in the esker areas that host many major aquifers. Therefore, this division of the unconsolidated glacigenic deposits into similar hydrogeological units could also be applicable to other aquifers in Finnish eskers.

The Virttaankangas esker area (Fig. 1) has been studied in detail to evaluate the effects of producing artificially recharged groundwater. All the data required to create the vulnerability map according to the definition existed already as a result of several research and development projects of TSV. The data used here include distribution of the deposits presented as hydrogeological units (till unit, glaciofluvial coarse unit, glaciofluvial fine unit, clay and silt unit and littoral sand unit) and topography of the bedrock surface (Artimo and Saraperä 2003, Artimo *et al*. 2003a, 2003b, 2004, Saraperä and Artimo 2004a, 2004b, Tuhkanen 2004).

The mapping was conducted by first dividing the area into 160 × 200 = 32 000 cells. The total area is 8 km × 10 km = 80 km^2. For each cell the four features were defined first separately (Fig. 5) and after weighting, they were compiled into the vulnerability map (Fig. 6), which demonstrates the remarkable variation in vulnerability within the aquifer. For each cell of the Unsaturated Zone Lithology and Aquifer Media maps, the relative thickness of each medium either above or below the groundwater table has been calculated. The proportion of the section above or below the groundwater table for each medium has been multiplied by the corresponding rating or weight. The sum of these matrices has been divided by the total thickness of the layer above or below the groundwater table. The resulting cell value is gradual within the range 0–5, reflecting the summed impact of all media.

The most vulnerable part is the ridge of the esker, which has the highest depth to water table but where the soil media is the most vulnerable. An appropriate classification for this aquifer would be the following: moderately vulnerable at 35–40, vulnerable at 40–45 and highly vulnerable in parts where the indicator value is 45 or above. The parts where the indicator value is less

Table 5. Ratings for depth to water table. (From Aller *et al*. 1987, modified by Artimo 2005).

Depth to water table (m)	Rating
0–2	5
2–5	4
5–10	3
10–20	2
20+	1

Table 6. Ratings for unsaturated zone lithology. (From Aller *et al*. 1987, modified by Artimo 2005).

Unsaturated zone lithology	Rating
Glaciofluvial coarse	5
Littoral sand	4
Glaciofluvial fine	3
Till	2
Silt and clay	1

Table 7. Ratings for aquifer media. (From Aller *et al*. 1987, modified by Artimo 2005).

Aquifer media	Rating
Glaciofluvial coarse	5
Littoral sand	4
Glaciofluvial fine	3
Till	2
Silt and clay	1

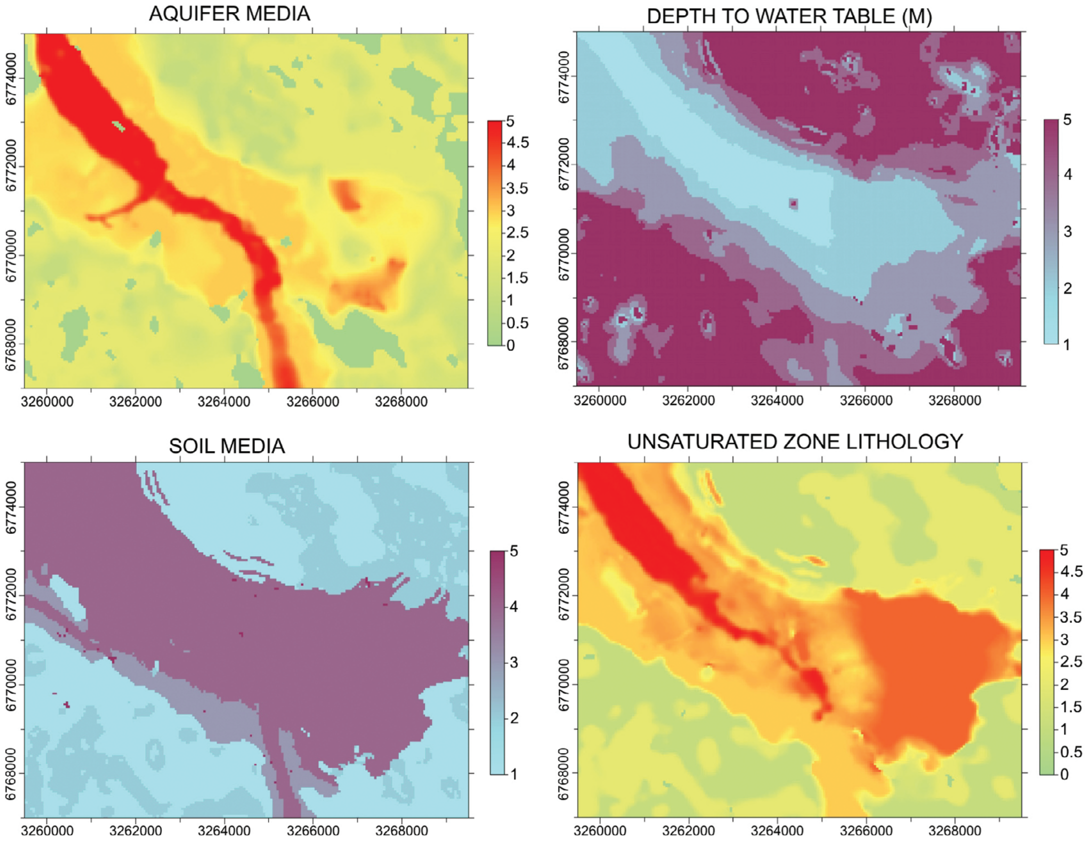

Fig. 5. The elements of natural groundwater vulnerability in the Virttaankangas esker. The maps are based on the Finnish Coordinate System (Projection Gauss-Krüger) YKJ. Reprinted with permission from UNESCO.

than 35 can be considered to have low vulnerability.

In certain parts of the area there is also a perched water table, which overlies the actual groundwater table. In this case study, the vulnerability has been determined only for the actual groundwater. The perched water table is caused by a confining layer of silt and clay with low hydraulic conductivity, which has been taken into account in the vulnerability map. The perched water table is caused by a layer of silt and clay with low hydraulic conductivity. This layer has also been taken into account in the vulnerability map of the deeper aquifer. However, the thin silt and clay deposits are easily undervalued in weighting of the presented classification, even though they act as efficient vertical flow barriers. Therefore, the vulnerability indicator values are too high in these areas. The perched water can in many cases be more vulnerable than the actual groundwater. The present data provide the possibility of defining the indicator for perched water as well.

Groundwater quality indicator

As quality requirements differ according to sector of use, the appropriate reference should be chosen accordingly. The examples and considerations related to this indicator focus on drinking water as a priority. The abundance of water quality parameters requires prioritisation. The ones considered here, as recommended by the Working Group on Groundwater Indicators, were pH, electric conductivity and concentrations of iron, manganese, fluoride, chloride and nitrate. Three examples are presented for the indicator: (1)

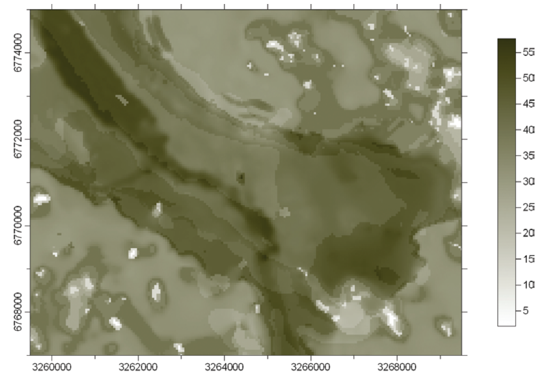

Fig. 6. A composite natural vulnerability map of Virtaankangas esker consisting of the elements shown in Fig. 5. The darker the colour, the higher the vulnerability. The saturated zone is absent in the white areas (there is no permanent groundwater table). Finnish Coordinate System (Projection Gauss-Krüger) YKJ. Reprinted with permission from UNESCO.

results of the national groundwater monitoring network, (2) elevated chloride concentrations as a consequence of de-icing, and (3) raw water quality at a water utility in Tuusula.

Example: Background quality of groundwater from the national monitoring network

Two out of 53 groundwater observation stations were eliminated because no sampling was conducted there. The median of each parameter at each sampling point was compared with the Finnish drinking water quality standards and recommendations set by the Ministry of Social Affairs and Health (2000) (Tables 8 and 9). The Finnish standard is based on the quality requirements defined at the Community level in the EU Drinking Water Directive (98/83/EY) which with a few exceptions is based on the WHO guidelines for drinking water. The standards are presented in indicator groundwater treatment requirements.

In the samples of 30 aquifers — mainly suitable for supplying rural areas — only one parameter, pH, is below the recommended value. In the samples from five aquifers two parameters exceeded the recommended value and four aquifers had three. Only samples from 12 aquifers had no parameters exceeding the recommended values.

Low pH values are typical in Finland because the Precambrian bedrock contains acidic rock types and only minor fractions of carbonate-bearing minerals. pH is raised by alkalization, which is the most common groundwater treatment method used in Finland (*see* the indicator groundwater treatment requirements). It is worth noting that the guideline value for pH is not health-based. Acidity is an important operational water quality parameter, but it does not have a direct impact on the potability of water (WHO 2004). Consequently, it would seem somewhat misleading to refer to a quality problem. Similar results can be expected from other glaciated Precambrian shield areas, for example, in Sweden (SEPA 2000), which should be considered when applying pH as a parameter in determining groundwater quality. High iron and manganese are common technical-aesthetic problems in groundwater in Finland (Hatva 1989, Korkka-Niemi 2001).

Example: Elevated chloride concentrations due to de-icing:

In most of the 84 groundwater areas studied by Nystén *et al*. (1999) in the First Salpausselkä zone (Fig. 1) for assessing impacts from de-icing, samples were taken from several points. The total number of samples in their study was 352, including, for example, waterworks, observation wells, private wells and springs. In defining the groundwater quality indicator, if the chloride concentration exceeded the guideline limit of 250 mg l^{-1} recommended by WHO (based on the estimated taste threshold) at any point within the groundwater area, it was classified as having a quality problem. As a result of the average concentration in two points (out of a sample of 352 observation points) exceeding the limit, 3.1% of the areas of groundwater formation or 3.8% of the total groundwater areas (according to the Working Group on Groundwater Indicator's classification) indicates a common quality problem (2.5%–10% of the aquifer area). If the national technical-aesthetic guideline value (25 mg l^{-1}, set by the health authority with the aim of preventing pipe corrosion) is applied instead, approximately 39% of the groundwater areas exceed the reference chloride concentration, when taking into account only the area of groundwater formation. Of the total surface area of groundwater areas in the zone of the First Salpausselkä, 49% exceed the national guideline value, in other words, the problem is frequent according to the definition of the Working Group on Groundwater Indicators (> 10%). In comparison, the guideline value was exceeded in 34% of the observation wells.

Excessive chloride concentrations increase rates of corrosion of metals in the distribution system, depending on the alkalinity of water. According to WHO (2004), successful control of iron corrosion has been achieved by adjusting the pH to the range 6.8–7.3, hardness and alkalinity to at least 40 mg l^{-1} (as calcium carbonate), oversaturation with calcium carbonate of 4–10 mg l^{-1} and a ratio of alkalinity to $Cl^- + SO_4^{2-}$ of at least 5 (when both are expressed as calcium carbonate). As groundwater in Finland on average has a pH of 6.5 and the alkalinity is commonly low, its corroding potential differs from groundwaters in many other countries.

Example: Raw water quality

Raw water quality data from waterworks would be most informative considering, for example, cost implications of groundwater actually being treated for consumption. However, these data are not collected systematically. The data collected at waterworks cover the quality of the treated water ready to be pumped to customers. An example of municipal water supply in Tuusula region (Fig. 1), where the utility supplies water to approximately 100 000 inhabitants, is presented in Table 10. The respective groundwater formation is an esker consisting partly of highly conductive gravel and sand. Values of chemical parameters in three wells tapping groundwater and in two wells tapping artificially recharged groundwater from among the production wells are shown. In this example, only the pH values of raw water differ from the recommendations.

Table 8. The number of values exceeding the limit at observation stations of the groundwater monitoring network of SYKE (out of the total of 51 stations). Reprinted with permission from UNESCO.

Parameter	Number of exceeding values
EC	0
pH	37
Nitrate	0
Chloride	0
Iron	8
Manganese	6
Fluoride	1

Groundwater treatment requirements

In Finland, groundwater is generally of good quality and no severe problems occur. Polluted groundwater bodies are not used for drinking water and thus the required groundwater treatment methods are fairly simple. It is not rare that groundwater can be used for domestic purposes without pre-treatment. The most common treatment method is alkalization. Filtration to remove iron is also commonly used. Less common treatment methods are coagulation, disinfection, filtration, dilution, biological or chemical treatment and fluorine removal with membrane filters.

In theory, the treatment methods applied at waterworks are compiled into water supply statistics (Lapinlampi and Raassina 2002). When evaluated, the data gathered by Regional Environment Centres turned out to be defective to some degree and could not be used in its entirety. Since only some of the centres could deliver

Table 9. Areas with values exceeding the limit. Reprinted with permission from UNESCO.

	All quality parameters	Without pH
Area of groundwater areas with one or more quality problems (km^2)	33.13	8.68
Area of the studied groundwater areas (km^2)	45.07	45.07
Percentage	74	19

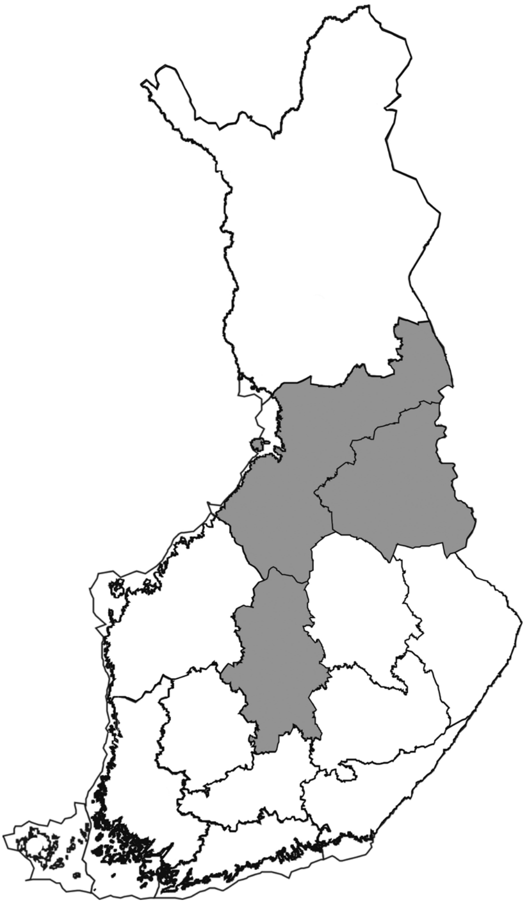

Fig. 7. The indicator groundwater treatment requirements was defined for the area of North Ostrobothnia, Kainuu and Central Finland (in grey). Reprinted with permission from UNESCO.

complete data, the areas of North Ostrobothnia, Kainuu and Central Finland Regional Environment Centres (Fig. 7 and Table 11) were selected as examples.

In this sample area, 28.9% of the water requires no treatment. Altogether 63.3% of the total water volume is treated by simple methods and 7.5% by demanding methods. The treatment method of 0.2% of water remains unknown. This gives an indication of treatment need of groundwater in aquifers that yield groundwater sufficiently to be used for community water supply (Table 11).

Yet, the classification of treatment methods into demanding and simple ones is not clear-cut: the methods can easily be used on a large scale at waterworks but private use may be complicated. A method is considered simple when adjusting the process is simple and the result is immediately seen. The demanding methods must be monitored carefully and adjusted by accurate measurements. Also, some methods could be considered simple in Finland but demanding in certain developing countries.

Discussion and conclusions

The indicators suggest that Finnish groundwater is generally in good shape. Finland abstracts only a small proportion of its estimated annual groundwater recharge and can be regarded as a low intensity user. Groundwater is renewable and theoretically groundwater could be used on a larger scale and it can be enhanced by artificial recharge.

Table 10. Raw water from well 1 and well 2 is artificially recharged and that from wells 3–5 natural groundwater; Finnish and WHO standards for drinking water quality.

	Well 1 (AR)	Well 2 (AR)	Well 3	Well 4	Well 5	Max conc. in Finland	WHO
pH	6.6	6.7	6.4	6.2	6.4	6.5–9.5	6.5–9.5
Nitrate (µgN l^{-1})	290	310	1300	790	410	25000[1,2]	50000[1]
Chloride (mg l^{-1})	6	6	25	24	23	250	250
Iron (µg l^{-1})	< 30	< 30	< 30	< 30	< 30	200	
Manganese (µg l^{-1})	0.16	0.17	0.19	0.23	21.2	50	400[1]
Fluoride (µg l^{-1})	310	120	140	< 100	120	1500[1]	1500[1]
Arsenic (µg l^{-1})	0.14	0.08	0.08	0.2	0.22	10[1]	10[1]

[1] Requirements. The other limits are recommendations.

[2] If no infants or pregnant women use the water, the maximum allowable level of nitrate is 50 000 µg l^{-1}. (Finnish Ministry of Social Affairs and Health 2000, Soveri *et al.* 2001, WHO 2004).

The ratio of total abstraction of groundwater to groundwater recharge gives some indication of the low degree of development of groundwater resources in Finland or rather, the abundance of the resource. The quantity of renewable resource cannot be directly related to the amount available sustainably on a continuous basis. The resulting average value for the country naturally does not reflect the irregular distribution of the abstraction within the country. Hence there is a scale limitation: The distribution of population (or demand) and local constraints may make further development of groundwater resources not feasible in parts of the area. To improve the sensitivity of the indicator, it could be defined for smaller areas.

Relating groundwater abstraction to exploitable groundwater resources is more complicated because there is no universally agreed upon definition for "exploitable", which has to be considered in the socio-economic context of a country, with attention to be paid also to ecological impacts. Different definitions in different countries are likely to add uncertainty to international comparisons.

In general, Finnish groundwater is of good quality and can be used as drinking water without treatment or with simple treatment like alkalization and iron removal. Low pH values are typical in Finland, and as they can be addressed by simple treatment methods and pH does not directly impact potability, this cannot be considered a major issue. If the deviations are strictly interpreted from the criteria, it is important to mention the parameters exceeding the recommendations.

The national groundwater monitoring data of the SYKE network provide information about the natural background quality of groundwater, unrelated to the actual points of use. Raw water data from waterworks is not collected systematically, but information on the applied treatment methods indicates groundwater quality indirectly. Specialized surveys on the occurrence of trace elements or ions that are not routinely analysed give an overall idea about the extent of particular quality problems in the country, but it is difficult to quantitatively estimate the degree to which different quality problems overlap. Due to the variability of groundwater quality observed in different areas resulting from different aquifer types and geology, the groundwater quality indicator information should be interpreted with a view of the hydrogeological setting to ensure comparability and the relevance of any observed divergence.

The elevated chloride concentrations in the First Salpausselkä zone demonstrate the importance of the choice of reference in the application of a groundwater quality indicator. The health authorities have set the recommended standard limit of 250 mg l^{-1} applicable to waterworks, which complies with EU regulations, and the nationally recommended guideline value of 25 mg l^{-1} for preventing corrosion. Depending on which one is applied, there is a substantial difference in the extent of the quality problem expressed by the indicator. The lower percentage resulting from only considering the estimated area of groundwater formation highlights the importance of limiting criteria. The chloride

Table 11. Treatment methods used at water treatment plants using groundwater in North Ostrobothnia, Kainuu and central Finland in 1998–2000. The classification of methods into simple and demanding follows the recommendation of the Working Group on Groundwater Indicators.

	Treatment method [simple (S)/ demanding method (D)]	Number of water intake plants	Treated water (m^3 d^{-1})	Total water treated (%)
1	Alkalization (S)	191	57568	52.0
2	No treatment required	175	32036	28.9
3	Iron removal (S)	38	10571	9.5
4	Coagulation (D)	6	8308	7.5
5	Filtration (S)	6	2042	1.8
6	Disinfection (S)	1	17	0.0
7	Treatment unknown	8	248	0.2
	Total	425	110790	100.0

example also raises the question of representation: is it appropriate to assign individual high values for wells to represent the entire groundwater area when in reality only a part of the area may be adversely affected by the quality problem? It seems possible that the aquifer area/groundwater area-based approach may exaggerate the extent of a problem and individual high values can potentially introduce a bias.

The indicators could potentially better support decision-making if focussed on smaller regions. This level of application would facilitate addressing, for example, groundwater quality problems that only occur in certain regions (for example, radon, fluorine, arsenic) and particularly in private wells. In order to focus on the priority areas for water supply, some indicators could be defined for the groundwater areas of classes I and II. As the population is strongly concentrated in southern Finland and larger-scale agriculture is also practised mostly in southern and central Finland, the stress on aquifers varies considerably. For example, knowing the distribution of treatment needs can be used in preparing regional development plans or in developing treatment methods by focusing on where the need is greatest and the level of costs lowest.

The vulnerability indicator can be a useful tool in protecting groundwater, when the classification is adjusted to the geological environment in question. In practice this can be done by modifying the weights, as was done in this study for Virttaankangas, where the vulnerability varies remarkably within the area of an aquifer – an esker in this case. The applied weighting was considered appropriate and changing it requires the insight of a hydrogeologist on a case-by-case basis. In the Virttaankangas example, Aquifer Media could have been given even a bigger weight. Data needed for a vulnerability assessment at this level of detail are available for only a few aquifers in Finland in addition to the Virttaankangas esker at the moment. The vulnerability indicator could support the preparation of groundwater protection plans, approximately 1000 of which exist, but for large scale application, a simpler approach would be needed. One suggestion for future development into that direction is made below, based on an idea originated by E. Mälkki. At the stage when groundwater protection plans are made, there is usually less data available than required with the definition of the vulnerability indicator presented earlier. It might be fruitful to relate the zones identified as naturally vulnerable using the indicator and view these in relation to the potential sources of pollution. A useful reference for such as comparison would be information available from the compliance monitoring system VAHTI containing data on the environmental licences required for activities posing a pollution risk to the environment and for emissions to water and soil.

As determining the thickness of the layer above the groundwater table and hydraulic conductivity, essentially a detailed expression of vulnerability, was not explicitly a part of the scope of groundwater area mapping and classification, this was identified in the exchanges with E. Mälkki (pers. comm.) as a potential area of development. An indicator could be developed consisting of the parameters of vertical hydraulic conductivity between the ground surface and the groundwater table and horizontal hydraulic conductivity in the saturated zone. This thinking was earlier applied by Karhula (2002). In the case of Virttaankangas, the concept could be applied in follow-up mapping of groundwater areas (classes I and II) for unconfined aquifers by combining the quality of soil media and the thickness of the unsaturated zone into one indicator. The indicator could be defined for the inner zones of the classified groundwater areas, estimated to correspond to the actual area of groundwater recharge, which could then be divided into, for example, three categories of vulnerability.

Application of the vulnerability indicator is most appropriate at a local or regional levels. Many of the key parameters of its composition are heavily dependent on geology and it is therefore appropriate to adapt them to the local circumstances. The cost of obtaining the data necessary for determining the vulnerability indicator varies: for an individual aquifer the cost is affordable, but the cost of collecting the data for a more extensive, highly-detailed regional survey would be prohibitive.

Estimation were commonly needed in order to conduct assessments of rural water supplies — in particular, those that largely rely on groundwater — due to a lack of data. The information related to groundwater areas collected and provided by the Finnish Environment Administration is commonly geo-referenced, which greatly facilitates the spatial analyses required for some groundwater indicators. In the future, groundwater bodies will be grouped and assigned to the nearest or most appropriate river basin district for monitoring and reporting to the EU according to the requirements of WFD. "Standard" methods for international comparisons with indicators are desirable, but for practical application, indicators such as vulnerability and quality seem to benefit from local or regional adjustment for optimal use. Adequate information systems on the environment and water supply are available for defining parameters or at least for reasonable approximations of the indicators. Comparable indicator data on surface water would be useful for a wider evaluation of the feasibility of groundwater-based water supply solutions with regard to, for example, treatment requirements.

In the case of Spain, groundwater indicators were tested through the assessment the situation of one aquifer, Sierra de Estepa, in the south of Spain; in the case of Brazil, aquifers in the São Paulo area in the south-east are assessed. Not all the indicators were determined in all the case study countries. Hirata *et al*. (2007) concluded, based on testing selected groundwater indicators from the same set, that the indicators are suitable for evaluating the current situation of groundwater in the State of São Paulo, and in particular, for evaluating: (1) importance, (2) abstraction and (3) natural quality of groundwater. As a result, from applying the indicator "total groundwater abstraction to groundwater resources", Hirata *et al*. (2007) identified basins showing evidence of overexploitation.

Differences may occur in the way parameters are determined, for example, in the Republic of South Africa (RSA), a GIS-based generic algorithm was applied to recharge estimation on a national scale using an iterative raster-based modeling approach (Girman 2007). The values of groundwater recharge and abstraction have been determined at the quaternary catchment level in RSA. With a population of 44.8 million, the estimated groundwater resources per inhabitant in RSA are 223 m^3 a^{-1}, substantially more than in Finland. The different geology is likely to play a role here: aquifers in Finnish glacial deposits are typically small and discontinuous. The proportion of total groundwater abstraction of groundwater recharge was estimated by Girman (2007) at 6.3% in RSA, as compared with 1.2 in Finland. This indicates that the intensity of groundwater resources use is greater in RSA.

In cases where the definition of a concept is not unanimously applied due to, for example different socio-economic conditions, there are likely to be limitations to comparisons. The general hydrological parameters applied in the calculations also have to be assumed as representative throughout the area in question. In the case of quality data, individual values have to be used as a basis for assigning values to areas, assuming that they are representative. Therefore it is crucial that the results are linked to information on the data used. From the definition of the exploitable groundwater resources it clear that as the current socio-economic constraints, political priorities and ecological conditions vary from one country to another, the volume of potentially exploitable groundwater varies. Such variation has to be acknowledged when comparing certain indicators. The presentation of results from the groundwater vulnerability indicator would need to be developed, as it is not necessarily very informative for the general public. When all case studies use different ways of assessing vulnerability, the resulting figures are not comparable (Pernía Llera and Lambán Jiménez 2007, Hirata *et al*. 2007).

The question of international comparison is challenging, because of the different availability and existence of data in different countries. To be usable at the country level, the indicators have to be specific, which simultaneously decreases their comparability. The results should be given in a defined form to make comparison possible. Locally sensitive but globally coherent groundwater indicators to accommodate international comparisons are, nevertheless, a valid aim. Those indicators that reflect purely physical abundance are least controversial and likely to be most suitable for international comparisons, but even these have to be viewed against the climatic background. As soon as socio-economic factors start having an influence, adaptation to the country's conditions and interpreting accordingly becomes more pressing. For example, the indicator relating groundwater abstraction to exploitable resources or groundwater treatment requirements indicator are such a case, the latter involving techniques that depend on the wealth and the level of development in the country. With regard to groundwater quality, it makes sense to have universal, health-based reference levels, because, as quality defects linked to geology in Finland demonstrate, the background concentration varies, and what is anomalous in one place is not necessarily anomalous in another.

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