Hydrogeology Journal (2014) 22: 1953–1967
DOI 10.1007/s10040-014-1174-5

The effect of urban heat islands on geothermal potential: examples from Quaternary aquifers in Finland

Teppo Arola · Kirsti Korkka-Niemi

Abstract The use of renewable energy can be enhanced by utilising groundwater reservoirs for heating and cooling purposes. The urbanisation effect on the peak heating and peak cooling capacity of groundwater in a cold groundwater region was investigated. Groundwater temperatures were measured and energy potentials calculated from three partly urbanised aquifers situated between the latitudes of 60° 25′N and 60° 59′N in Finland. The average groundwater temperature below the zone of seasonal temperature fluctuations was 3–4 °C higher in the city centres than in the rural areas. The study demonstrated that due to warmer groundwater, approximately 50–60 % more peak heating power could be utilized from populated areas compared with rural areas. In contrast, approximately 40–50 % less peak cooling power could be utilised. Urbanisation significantly increases the possibility of utilising local heat energy from groundwater within a wider region of naturally cold groundwater. Despite the warming in urban areas, groundwater still remains attractive as a source of cooling energy. More research is needed in order to determine the long-term energy capacity of groundwater, i.e. the design power, in urbanised areas of cold regions.

Keywords Groundwater management · Urban groundwater · Cold region · Finland

Introduction

The use of renewable energy systems (RES) is expected to increase globally, as it provides local energy that is not dependent on the international energy transport market and reduces the emission of greenhouse gasses (Andea et al. 2010). The EU is promoting the use of RES in Europe through Directive 2009-28-EN. This directive has set a target of 38 % for the share of RES in the gross overall energy consumption of Finland by 2020. In 2010, RES accounted for 32.2 % of the overall energy consumption of Finland, 3.2 % of which was produced by heat pumps (Statistics Finland 2012). Although heat pumps produced only a minor proportion of the total Finnish RES consumed in 2010, the amount of energy from heat pumps is expected to rise from approximately 4 TWh at present to 8 TWh by 2020 (Ministry of Employment and the Economy 2010). One solution to increase RES is to exploit groundwater energy by means of heat pumps or heat exchangers.

One technique used to exploit groundwater energy is called an open loop energy system or open system (Bonte et al. 2011; Haehlein et al. 2010). Open loop heating and cooling systems extract thermal energy from and/or discharge waste heat into bodies of water such as aquifers and lakes. Water is pumped from the body of water through a heat-transfer system and is returned to the environment at a lower temperature for heating applications and a higher temperature for cooling applications. In most cases, groundwater is pumped from an abstraction well and discharged into the subsurface via an injection well (Sanner 2001). If energy is exploited by a heat pump, the term groundwater heat pump (GWHP) system is also used. GWHP systems have been successfully used for energy purposes in North America and Europe since the 1920s (Banks 2012; Ferguson and Woodbury 2006). Large-scale groundwater utilisation experiments were conducted in Finland in the late 1970s and early 1980s with positive results (Iihola et al. 1988). The Finnish geological environment, where high-yielding glaciofluvial sand and gravel aquifers exist at a depth of only a few metres, provides easily exploitable energy reservoirs. Approximately 56,500 ha of aquifers in Finland, comprising 801 groundwater areas (Finnish Environment Institute 2012), are under urban or industrial land use (Finnish Environment Institute 2006). These aquifers are located around the country, and near or under all major cities. However, groundwater is not a widely used energy source in Finland.

Yearly and daily groundwater temperature variations are minimal compared with temperature variations in the

Received: 29 January 2014 / Accepted: 21 July 2014
Published online: 17 August 2014

T. Arola (✉)
Department of Geosciences and Geography c/o Golder Associates Oy, University of Helsinki, Apilakatu 13B, 20540, Turku, Finland
e-mail: teppo_arola@golder.fi
Tel.: + 358 40 7676008

K. Korkka-Niemi
Department of Geosciences and Geography, University of Helsinki, Gustaf Hällströmin katu 2a, Helsinki, 00014, Finland

air or in lake or river water (Mälkki and Soveri 1986; Silliman and Booth 1993). Groundwater temperatures to depths of approximately 10–25 m are generally equal to the mean air temperature in moderate and warm climates (Banks 2012; Budel 1982; Kasenov 2001). For example, according to the Irish Meteorological Service, mean annual air temperatures in Ireland generally range between 9 and 11 °C. By comparison, the average groundwater temperatures range between 8 and 11 °C (Allen et al. 2003). The mean air temperature in Finland was approximately 2.3 °C during the time period from 1981 to 2010 (Tietäväinen et al. 2010), while the mean groundwater temperature varied from 3.0 to 6.6 °C (Mälkki and Soveri 1986; Oikari 1981). Similar results demonstrating higher groundwater than surface temperatures have been reported from other northern areas such as Russian Siberia (Banks et al. 2004; Parnachev et al. 1999), Canada (Ferguson and Woodbury 2004; Parsons 1970) and Sweden (Rosen et al. 2001). These temperature differences are mainly due to two reasons—firstly, in winter the snow cover functions as an insulator, preventing cold air conduction into the subsurface layers; secondly, frost is formed when topsoil is cooled below the freezing point of water. This change in the state of water releases latent heat into the soil (McKenzie et al. 2007; Soveri 1985; Woo and Marsh 2005). Frost also acts as an insulator, reducing the flow of cold meltwater into deeper soil layers in early spring, when the melting of snow begins (Soveri 1985).

Urbanisation increases the air and subsurface temperature in cities (Bornstein 1968; Ferguson and Woodbury 2004; Oke 1973; Preston-Whyte 1970). This phenomenon is called the urban heat island (UHI) effect (Howard 1818 in. Landsberg 1981). The air UHI effect is dependent on numerous factors such as the size of the city and the population (Karl et al. 1988; Oke 1973); even solitary shopping centres have been found to form minor local UHIs (Suomi and Käyhkö 2011). Many studies have suggested that the main reason for the UHI effect is the replacement of natural vegetation by artificial surfaces such as concrete and tarmac (Allen et al. 2003; Cotton and Pielke 1995; Landsberg 1981). According to Ferguson and Woodbury (2004) and Leppäharju (2008), the heat loss from buildings increases the subsurface temperature by several degrees. Since air and subsurface soil temperatures significantly influence groundwater temperatures, the latter should be higher in urbanised than in rural areas. Two studies have determined groundwater in the Winnipeg area (Canada) to be 2–5 °C warmer than outside the city (Ferguson and Woodbury 2004; Zhu et al. 2010). Similar results have also reported from Germany (Kerl et al. 2012; Menberg et al. 2013a), Ireland (ERA 1991 in. Allen et al. 1999), Japan (Tanicughi et al. 2007), Turkey (Yalcin and Yetemen 2009) and the UK (Banks et al. 2009). Leppäharju (2008) detected elevated groundwater temperatures from Espoo, southern Finland, concluding that the further the measurement point was from the artificial land surface, the lower was the groundwater temperature. Heat leakage into the ground due to heat conduction from buildings was the most likely explanation for the elevated groundwater temperatures in Winnipeg (Ferguson and Woodbury 2007). Research conducted in Ireland in a glaciofluvial buried valley area with moderate groundwater temperatures (Allen et al. 2003) revealed that the heat island effect improved the economics of GWHP systems for heating.

The urbanisation effect on groundwater energy utilisation from shallow Quaternary aquifers situated in northern regions has remained undetermined. The present study investigated whether urbanisation could enable the more extensive use of groundwater for heating energy purposes in a snow-dominated, cold groundwater region. Secondly, it was aimed to measure the influence of urbanisation on the use of groundwater for cooling purposes.

Area description, material and methods

Three aquifers situated under three cities in southern Finland, Turku, Lohja and Lahti, were selected for this study (Fig. 1). The selection was made because natural groundwater temperatures are higher in southern than in northern parts of the country (Mälkki and Soveri 1986). The cities are situated north of 60° latitude, and the population density is low, especially in the Lohja area (Table 1). The climate in Turku and Lohja is a mixture of coastal and inland types, while that in Lahti is mainly of the inland type, although Lahti's climate is affected by the adjacent Lake Vesijärvi (Alalammi 1987). The winter snow cover lasts for 85–100 days in Turku, 100–115 days in Lohja and 130–145 days in Lahti. According to the Finnish Meteorological Institute, permanent snow cover occurs from the end of December until the end of March in Turku and Lohja, and from the end of November until mid-April in the Lahti region.

The site selection criteria included the availability of groundwater monitoring wells in the city centre, as well as in urban and rural areas of the aquifer, and background information on the soil structure and groundwater conditions. A city centre area denotes a downtown area including office buildings and apartments with a height of several floors that are built close together or are connected to one another (Fig. 2). An urban area denotes a planned area that is mostly in industrial use or is occupied by individual houses and is less populated than a city centre and a rural area denotes an area where no buildings exist and land use is only related to recreation.

This study aimed to identify monitoring wells that are situated in an urban area, but are separated from the city centre so that possible heat movement with groundwater flow from the city centre to urban area would not affect the groundwater temperatures in the area concerned. The monitoring wells were selected in areas where groundwater pumping would not influence the groundwater flow conditions.

Geology and hydrogeology of the research areas

The bedrock in the research areas is dominated by plutonic and metamorphic rocks, including granites, gneisses and amphibolites, and is associated with the Svecofennian (1970–1780 Ma) orogeny (Karhunen 2004;

 DOI 10.1007/s10040-014-1174-5

Fig. 1 Location map of *Turku*, *Lohja* and *Lahti*. Finland's capital, *Helsinki*, is also shown. (Basemap database © Esri, DeLorme, Navteq. With permission from Golder Associates global ESRI licence)

Lehijärvi 1964; The Geological Survey of Finland 2012). The bedrock is mainly covered by glacial and postglacial sediments deposited during the Weichselian glacial stage and the Holocene (Lahermo et al. 1990; Lunkka et al. 2004; Saarnisto and Salonen 1995). The investigated aquifers are located in glaciofluvial sand and gravel

Table 1 General information on the selected cities (Statistics of Finland 2012)

City	Population (31 Dec. 2011)	Inhabitants/km^2 land	City location	Location
Turku	178,630	726	Coastal city at the mouth of a river	60°27.1′N/22°16.2′E
Lohja	39,726	114	Inland city on the Salpausselkä ridge	60°25′N/22°083′E
Lahti	102,308	758	Inland city on the Salpausselkä ridge	60°59.1′N/25°40.4′E

 DOI 10.1007/s10040-014-1174-5

Fig. 2 Aerial photographs demonstrating different research areas—**a** city centre, **b** urban, and **c** rural. The orientation and scale is identical in every picture. The example is from Turku

deposits with a thickness from a few metres to some tens of metres.

Turku
Located beneath the city of Turku is a northwest to southeast-oriented esker. The available drilling information indicated that the depth of the sand and gravel deposits is approximately 20 m (Rantala and Arola 2004). The esker is partly covered by clay deposits to a depth of over 10 m (Niemelä et al. 1987). Large areas of sand and gravel have been exploited for building purposes, mainly in the 20th century, and have subsequently been substituted with mixed filling material (Rantala and Arola 2004). The groundwater piezometric level varies from 1 to 15 m below the ground surface (Finnish Environment Institute 2012), and the estimated volume of the aquifer in the measured area is approximately 0.046 km^3. In the research area is located the Kaarninko water intake plant, which has Water Rights Court permission to pump groundwater at a rate of 2,500 m^3/day (Rantala and Arola 2004).

Lohja
The city of Lohja and its surrounding areas are mostly located on the Salpauselkä I end moraine, which formed approximately 12,100–12,300 years ago and is mainly composed of glaciofluvial material, but moraine ridges, mainly till, also exist (Lunkka et al. 2004). Hence, the Lohja area is typified by thick sand and gravel deposits with fine-grained silt and clay deposits, as well as till, especially on the northern, proximal side of the end moraine complex. According to the available drilling information, the average depth of the sand and gravel deposits varies from 30 to 60 m (Arola et al. 2011). The groundwater piezometric level varies from 2 to 40 m below the ground surface (Finnish Environment Institute 2012), and the estimated volume of the aquifer in the measured area is approximately 0.41 km^3.

Groundwater is pumped from 12 groundwater intake plants situated on the Salpauselkä I formation in the Lohja area. According to the Water Rights Court permission for water intake plants and the volume of pumped groundwater in 2010, a total of 11,650 m^3/day of groundwater can be utilised from the aquifer (Arola et al. 2011).

Lahti
Lahti is situated on the same Salpausselkä I formation as Lohja, and hence has similar soil structures, consisting among others of sand and/or gravel deposits several tens of metres thick. The city of Lahti, especially its southern parts, is located on a large subglacial delta formation. Geographically, Salpausselkä turns from a southwest–northeast direction to a west–east direction in the Lahti city area, since Lahti is located on the confluence of two ancient ice lobes, the Baltic and the Lake Finland ice lobe (Punkari 1982). The groundwater piezometric level varies from 2 to 55 m below the ground surface (Finnish Environment Institute 2012), and the estimated volume of the aquifer in the measured area is approximately 0.38 km^3. Groundwater is pumped from 12 groundwater intake plants situated on the Salpauselkä I formation, and permits allow the pumping of 35,500 m^3/day groundwater from the aquifer (Mäyränpää 2012).

Field measurements and statistical analyses

In the first stage of this project, groundwater temperatures and piezometric levels were examined from 10 monitoring wells situated in the Turku aquifer, 14 monitoring wells situated in the Lohja aquifer and 13 monitoring wells situated in the Lahti aquifer (see Table 2). The weather, air temperature, sampling time and the land use of the area, especially the location of district heating pipes near a monitoring well, were also observed. The groundwater level was measured using an electronic water level gauge, and the groundwater temperature using a YSI-556 MPS and/or Eijelkamp Diver data logger. Groundwater temperatures were surveyed from wells in the Turku area using both the YSI and Diver instruments to make comparative measurements. Tables to describe the measured information, temperature profiles for the groundwater in the monitoring wells and groundwater temperature maps were also prepared.

 DOI 10.1007/s10040-014-1174-5

Table 2 Information on the monitoring wells, aquifer, land use and measured groundwater data. *Depth* indicates the depth of the well bottom below the ground level. *PE* denotes polyethylene pipe material; *Fe* is iron pipe material. The *seasonal fluctuation zone* is the depth range within which groundwater temperatures fluctuate due to variations in the air temperature.

Sampling point	Well construction details: Depth (m b.g.l.)	Casing type (mm)	Screen penetrating entire groundwater column	Hydrogeology: Aquifer type	Aquifer zone	Groundwater level (m b.g.l.)	Water column thickness (m)	Land use	Average groundwater temperature (°C)	Thickness of seasonal fluctuation zone (m)
Turku city										
Well 2	13.7	Fe Ø 40	No	Unconfined	Recharge	3.59	10.13	Rural	6.2	2.5
Hp 7[a]	15.3	PE Ø 40	No	Confined	Covered	5.49	8.76	City	10.2	3
Pvp 3	11.6	PE Ø 52	No	Confined	Recharge	2.25	9.50	Urban	8.1	3
Well 4	7.1	PE Ø 53	Not known	Semiconfined	Discharge	1.52	5.58	Urban	7.1	5
Hp 8	8.5	Fe Ø 30	No	Confined	Discharge	2.35	6.08	Urban	7.2	4
GA 1	20.7	PE Ø 52	Yes	Unconfined	Recharge	9.41	10.16	Urban	8.2	0.5
PVp 11[a]	12.0	Fe Ø 30	No	Confined	Covered	3.21	8.75	City	9.2	2.5
Hp 1	15.0	PE Ø 40	No	Confined	Covered	5.41	9.61	City	10.3	2
GA 6	9.0	PE Ø 52	No	Confined	Covered	2.67	7.14	City	9.4	2
Well 10	12.8	Fe Ø 40	No	Unconfined	Recharge	9.69	3.40	Rural	6.8	0
Lohja city										
LEM A	6.5	PE Ø 52	Not known	Unconfined	Recharge	3.98	2.90	Urban	7.6	2.5
L214	11.0	PE Ø 25	No	Semiconfined	Covered	2.81	7.36	City	9.9	5
GA 6	20.3	PE Ø 52	No	Unconfined	Recharge	7.49	12.65	City	7.8	0
GA 2	18.0	PE Ø 52	No	Unconfined	Recharge	8.05	6.00	Urban	8.4	0
SK 100	21.9	PE Ø 52	No	Semiconfined	Discharge	5.36	9.20	Rural	6.2	1
SK 200	27.8	PE Ø 52	No	Unconfined	Recharge	14.02	8.50	Rural	5.8	0
GA 5	15.6	PE Ø 52	No	Semiconfined	Recharge	5.79	9.76	City	9.0	1
PK 1	11.4	PE Ø 52	No	Unconfined	Recharge	7.70	4.21	City	9.4	1
Keko	11.5	PE Ø 52	Not known	Semiconfined	Recharge	2.67	10.83	Urban	7.2	1.5
GA 1/KTK	18.6	PE Ø 52	No	Confined	Discharge	10.78	7.81	Urban	6.9	1
OKS 1	18.1	PE Ø 52	Not known	Unconfined	Recharge	13.47	5.07	Urban	7.7	0.5
5.07	32.9	PE Ø 52	No	Unconfined	Recharge	22.01	8.00	Urban	8.9	0
GA 1/TB	19.6	PE Ø 52	No	Unconfined	Recharge	22.86	2.00	Urban	8.0	0
GA 1/TB Ojamo	38.0	PE Ø 52	Yes	Unconfined	Recharge	23.60	5.00	Urban	6.9	0
Lahti city										
GA 1/TB	22.2	PE Ø 52	Yes	Confined	Covered	3.40	11.45	City	9.0	4
Well 159	28.6	PE Ø 50	No	Unconfined	Recharge	26.21	3.00	Rural	5.8	0.5
GA 2	28.7	PE Ø 52	No	Unconfined	Recharge	25.48	3.10	Urban	7.6	0
GA 1	21.3	PE Ø 52	No	Unconfined	Recharge	12.45	9.80	Urban	7.3	1
Hp 5 PR	24.7	PE Ø 52	No	Semiconfined	Recharge	13.40	9.90	Urban	7.6	2
Well 126	56.8	PE Ø 50	No	Semiconfined	Covered	15.81	13.20	City	8.7	0.5
GA 1/Shell[a]	12.2	PE Ø 52	No	Semiconfined	Recharge	4.37	7.87	City	10.7	4
GA 4/Shell	14.0	PE Ø 52	No	Unconfined	Covered	3.56	11.00	City	9.6	5
Well 22[a]	23.0	PE Ø 50	No	Unconfined	Recharge	7.38	13.05	City	11.4	0.5
Well 21[a]	21.0	PE Ø 50	No	Confined	Covered	2.62	11.70	City	9.1	3
SK 1/Hp[a]	29.0	PE Ø 52	Yes	Unconfined	Recharge	11.40	10.50	Urban	7.1	0
GA 2/TB	6.0	PE Ø 52	No	Unconfined	Recharge	2.70	3.15	Urban	9.6	2.8
GA 7/TB	13.5	PE Ø 52	Yes	Unconfined	Recharge	5.10	4.25	Urban	8.0	2

[a] Indicates that a district heating pipe is located within 15 m from the well

DOI 10.1007/s10040-014-1174-5

The groundwater temperature was measured at approximately 1-m intervals from the top of the water column to the bottom of each monitoring well. The measurements were recorded in March 2012 and September 2012, representing groundwater temperatures after winter and summer. Well 10 in Turku and GA1/TB Ojamo in Lohja were covered by snow and could not be located and investigated in March.

Analysis of covariance (ANCOVA) was used to determine how important the area characteristics (land use, aquifer type or aquifer zone), well depth or water column thickness are in average water temperatures or temperature fluctuation zone. Regression tree analyses (RTA) is a tool to construct a set of decision rules on the predictor variables and it was used to determine the most effective predictors of average groundwater temperatures. In addition, Pearson correlation coefficient for numerical variables was calculated. Statistical analyses were performed by SPSS, STATISTICA and R.

Energy calculations

In the second phase, the effect of changes in groundwater temperatures for the peak heating and peak cooling energy capacity were calculated. Groundwater temperature data measured in spring and autumn were combined to calculate the average groundwater temperatures for different land use areas at the aquifer in question. Only temperatures below the zone affected by seasonal temperature fluctuations, i.e. where groundwater temperatures are constant, were used in calculations.

The peak heating power capacity (H_{peak}) producible by a groundwater heat pump (GWHP) and the peak cooling power capacity (C_{peak}) producible by a heat exchanger were calculated using the following equations:

$$\textit{Peak heating power}(W): H_{peak} = F \cdot \Delta T \cdot Svc_{wat} / 1 – (1 / COP_H) \quad (1)$$

$$\textit{Peak cooling power}(W): C_{peak} = F \cdot \Delta T \cdot Svc_{wat} / 1 + (1 / COP_C) \quad (2)$$

where F=flow of water (l s^{-1}), ΔT=difference between incoming and outgoing temperature in the heat pump/heat exchanger – temperature drop in heating mode and temperature rise in cooling mode (K), S_{VCwat}=specific heat capacity of water (J l^{-1} K^{-1}), COP_H=coefficient of performance for heating (dimensionless), and COP_C= coefficient of performance for cooling (dimensionless; Allen et al. 2003; Banks 2012).

The Water Rights Court permit values for groundwater pumping (Arola et al. 2011; Mäyränpää 2012; Rantala and Arola 2004), supplemented by the volume of pumped groundwater in 2010 in the Lohja aquifer (Arola et al. 2011), were used as water flow values (F) in energy calculations.

Groundwater can be utilised down to a temperature of +1 °C in the heating mode without freezing it. Hence, ΔT is 4.5 °C if the initial groundwater temperature is 5.5 °C. For cooling simulation, the theoretical upper limit for the groundwater temperature is the air temperature inside buildings. However, reported average groundwater return temperatures in cooling systems have ranged from 12 to 16 °C in Canada (Cruickshanks and Adsett 1994), Belgium (Bakema and van der Hengel 1994) Denmark (Sörensen et al. 1994) and Sweden (Andersson 1994). Based on previous studies and noting the Nordic location of Finland, a maximum groundwater return temperature of 12 °C was used for cooling calculations. Hence, ΔT for cooling is 6.5 °C if the initial groundwater temperature is 5.5 °C.

The specific heat capacities of water were taken from Yaws (1998). Based on the information presented by Allen et al. (2003), Bayer et al. (2011), Saner et al. (2010) and the European Heat Pump Association, EHPA (2009), a COP_H of 3.5 and COP_C of 25 was used in this analysis.

Results

Aquifer measurements

Groundwater temperature variations of 4.7–13.7 °C were observed between aquifers. The closer the monitoring well was to the centre of the city, the more elevated were the groundwater temperatures. The results of all temperature measurements in rural, urban and city centre areas are presented in box plot format in Fig. 3, which includes measurements from all three aquifers. Altogether, 189 temperature measurements were taken from monitoring wells situated in rural areas, 515 from urban areas and 969 from city centre areas. The median groundwater temperature was 6.2 °C in rural, 7.4 °C in urban and 9.4 °C in city centre areas.

A summary of the results and monitoring well details is presented in Table 2, and groundwater temperature profiles are provided in Figs. 4, 5 and 6. Table 2 presents the monitoring well construction, aquifer information, the average groundwater temperature below the zone affected by seasonal temperature fluctuations and the thickness of the fluctuation zone. It also describes the land use of monitoring well areas and provides hydrogeological information on the aquifer in question. In Table 2, the covered area is an area where the rainfall infiltration rate is extremely low, from 10^{-8} to 10^{-11} cm/s, due to the artificial land surface and/or clay deposits near the monitoring well in question. The table shows that most of the observation wells were situated in city centre or urban areas. However, a small number of observation wells for each city were located in rural areas. Approximately 75 % of the observation wells have screens penetrating only part of the aquifer. The location of district heat pipes is also marked in the tables if they occurred within 15 m from the monitoring well.

 DOI 10.1007/s10040-014-1174-5

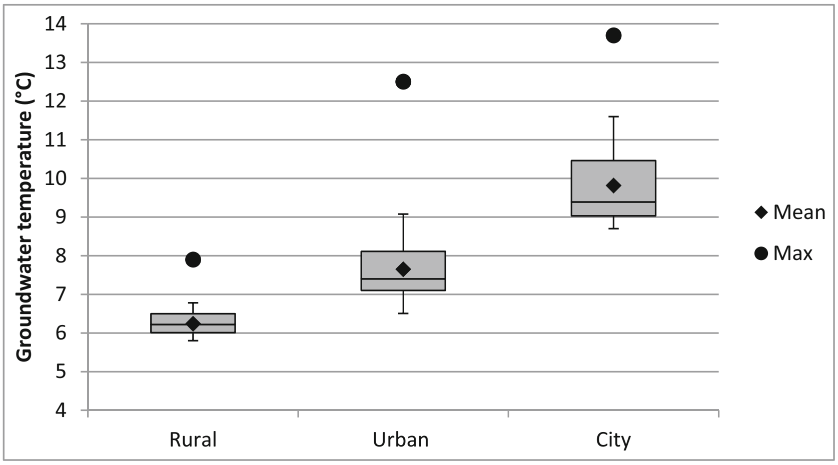

Fig .3 Distribution of the measured groundwater temperatures from all aquifers. The *boxes* indicate the 25th and 75th percentiles and median. *Whiskers* indicate the 10th percentile (*lower*) and 90th percentile (*upper*). The mean and maximum values are also presented

In the Turku aquifer, the minimum observed groundwater temperature was 4.7 °C (well 2) and the maximum 13.0 °C (Hp 7; Fig. 4). The zone affected by seasonal temperature fluctuations in Turku varied in most wells between 2 and 4 m. Exceptions include well 4, where the fluctuation zone was 5 m, and wells 10 and GA1, where no fluctuation zone was observed in the autumn and only a 1-m fluctuation zone in spring in well GA1. The data indicate no clear seasonal thermal fluctuation zone when the depth of groundwater piezometric head extended from 9 to 10 m from the ground surface.

In the Lohja aquifer, the minimum observed groundwater temperature was 5.6 °C (SK100) and the maximum 13.7 °C (L214; Fig. 5). The seasonal thermal fluctuation zone in Lohja aquifer varied between 1 and 2.5 m. The data indicate no clear seasonal thermal fluctuation zone when the depth of groundwater piezometric head extended 14 m from the ground surface. However, there was no clear trend for the existence of a fluctuation zone. For example, no fluctuation zone was observed in well GA6, even though the groundwater level was at a depth of 7.5 m below the ground surface. At the same time, a 1-m fluctuation zone was observed in well GA1/KTK at a depth of 11.5 to 12.5 m below the ground surface. At well 5.07, the groundwater temperature was constant throughout the water column, but the temperature was between 8.4 and 8.6 °C in spring and between 9.5 and 9.6 °C in autumn; hence, seasonal temperature variations could be observed in the whole water column, and not only in the thermal fluctuation zone.

In the Lahti aquifer, the minimum observed groundwater temperature was 5.8 °C (well 159) and the maximum 13.7 °C (GA4/Shell; Fig. 6). The thickness of the seasonal fluctuation zone in the Lahti aquifer varied between 1 and 5 m. The presence of the fluctuation zone followed no clear pattern. For exam-

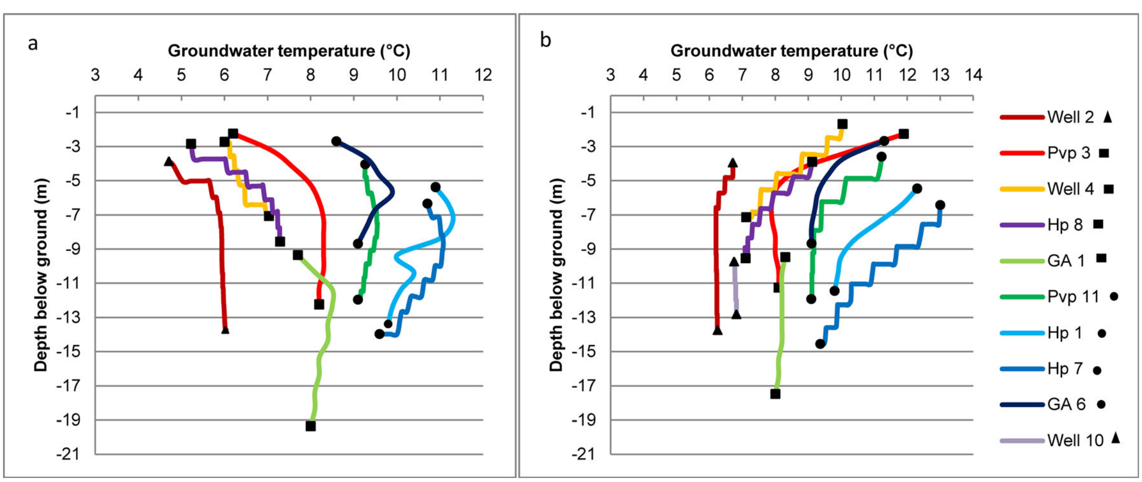

Fig. 4 Observed groundwater temperatures in the Turku aquifer in **a** March 2012 and **b** September 2012. A *triangle* indicates a monitoring well situated in a rural area, a *square* in an urban area and a *dot* in the city centre. The names of the monitored wells are also indicated

 DOI 10.1007/s10040-014-1174-5

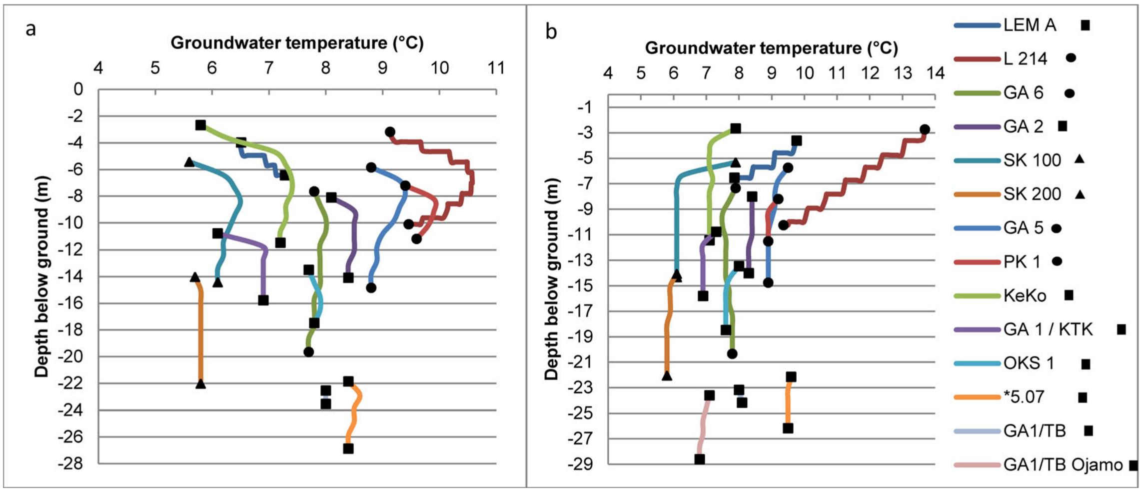

Fig. 5 Observed groundwater temperatures in Lohja aquifer in **a** March 2012 and **b** September 2012. A *triangle* indicates a monitoring well situated in a rural area, a *square* in an urban area and a *dot* in the city centre. The names of the monitored wells are also indicated

ple, no fluctuation zone was observed in well Sk1/Hp, even though the groundwater level was at a depth of 11.5 m below the ground surface. At the same time, a 1-m fluctuation zone was observed in well 159 in autumn in the depth range of 26–27 m below the ground surface.

Results of energy calculations

Table 3 summarises the parameters of groundwater flow, results of ΔT calculations and the specific heat capacity of water at the existing temperature for different land uses. The specific heat capacity is temperature dependent and, hence, fluctuates according to changes in the groundwater temperature.

Significant differences were observed in the peak heating and cooling power of groundwater from different land use areas. The peak heating power (H_{peak}) was approximately 1.5 times greater in city centres than in rural areas in all cities (Table 4). The peak cooling power (C_{peak}) was 39 % less in the city centre than in the rural area in Turku aquifer, 50 % in Lohja and 36 % in Lahti aquifer, respectively. In terms of kilowatts, over 500 kW greater peak heating power could be utilised from the city centre than from rural areas in Turku, over 2,300 kW more in Lohja and nearly 7,100 kW more in Lahti.

Discussion

Groundwater temperatures

The highest groundwater temperatures were recorded near large buildings, namely an industrial building in Turku, an apartment building complex in Lohja and between an apartment building complex and a concert hall in Lahti. District heating pipes may also have locally elevated the

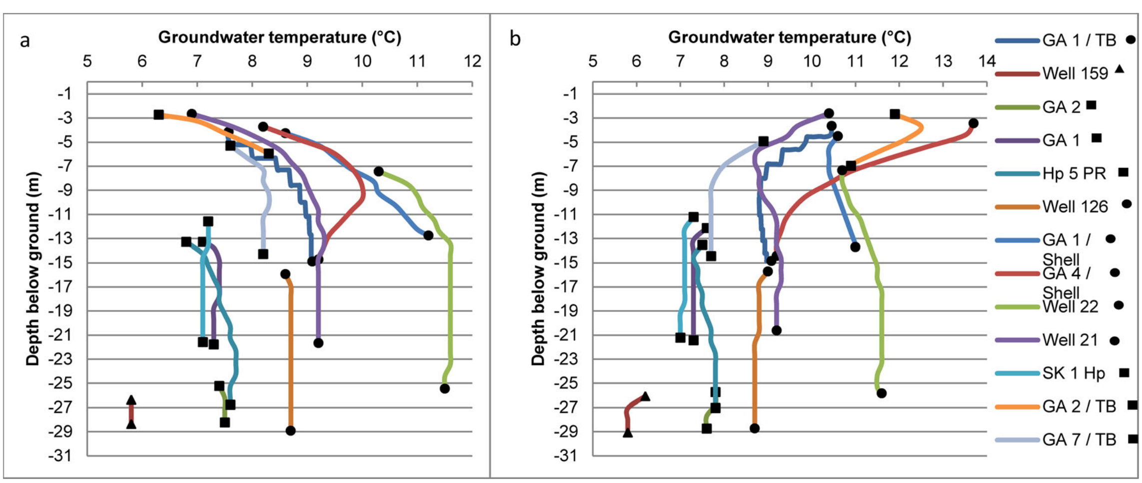

Fig. 6 Observed groundwater temperatures in the Lahti aquifer in **a** March 2012 and **b** September 2012. A *triangle* indicates a monitoring well situated in a rural area, a *square* in an urban area and a *dot* in the city centre. The names of the monitored wells are also indicated

 DOI 10.1007/s10040-014-1174-5

Table 3 Parameters of groundwater flow (F), temperature difference (ΔT) and specific heat capacity of water (S_{VCwat}) used for energy calculations in the Turku, Lohja and Lahti aquifers

	Heat			Cool			
Parameter	Turku	Lohja	Lahti	Turku	Lohja	Lahti	Units
F	28.93	134.84	410.88	28.93	134.84	410.88	L s^{-1}
ΔT rural	5.3	5.0	5.8	5.7	6.0	6.2	K
ΔT urban	6.7	6.6	6.9	4.4	4.3	4.1	K
ΔT city centre	8.8	8.0	8.8	2.2	3.0	2.3	K
S_{VCwat} rural	4,201	4,202	4,200	4,200	4,200	4,199	J L^{-1} K^{-1}
S_{VCwat} urban	4,198	4,198	4,198	4,204	4,204	4,205	J L^{-1} K^{-1}
S_{VCwat} city centre	4,194	4,196	4,194	4,210	4,208	4,210	J L^{-1} K^{-1}

groundwater temperatures, but no clear warming trend near heating pipes was observed. The warming effect of district heating pipes on the subsurface was observed in March, when the snow had melted on the ground surface above the heating pipe. In Germany, the thermal energy input to the subsurface from district heating pipes was reported to be approximately 10 % of the total energy input, and was determined to be equal to the heat leakage from buildings (Menberg et al. 2013b). This may explain why heat loss from buildings had the most significant effect on groundwater temperatures, while no clear connection between district heating pipes and elevated groundwater temperatures was detected. Even though the effects of urbanisation on groundwater temperatures were clear, there were significant differences in groundwater temperatures within areas having the same type of land use and aquifer conditions. This may indicate that local, small-scale construction can influence the groundwater temperature. No sites that use groundwater as an energy source are located near the research area.

Differences in groundwater flow velocities inside an aquifer may influence the measured temperatures at monitoring wells. Particularly for a confined aquifer with a low groundwater flow rate, the temperature recorded in a monitoring well may reflect the subsurface soil temperature more than the groundwater temperature. In most cases, the temperature remained constant below the seasonal fluctuation zone.

According to ANCOVA (Table 2) there is a statistically significant correlation between average groundwater temperature and land use of the areas ($p<0.005$, The F test $=13.7$). All comparisons between the average groundwater temperature and for the different land use classes are significant (Fig. 3). Average groundwater temperature correlates weakly, but statistically significantly ($p<0.05$) with groundwater level ($\varrho=-0.36$) and temperature seasonal fluctuation zone ($\varrho=-0.35$). The refers to Pearson correlation coefficient. ANCOVA analyses show the statistically significant correlation between temperature seasonal fluctuation zone and well depth ($p<0.005$, The Z test$=13.2$). Temperature seasonal fluctuation zone has strong, statistically significant ($p<0.001$) correlation (Pearson) between groundwater level ($\varrho=-0.68$) and well depth ($\varrho=-0.55$).

According to RTA, city centre land use predicts the warm groundwater temperature best. If the land use is rural or urban, the most effective groundwater temperature predictor is the water column thickness. The average groundwater temperature is higher in aquifers where the water column thickness is below 8.25 m.

Table 4 Results of energy calculations for Turku, Lohja and Lahti. The results are separated according to land use. In the column "Difference from rural area (*kW*)", the results from the rural area of each city serve as a reference level for comparison with the results of urban and city centre area calculations. Percentage differences in both peak heating and peak cooling in kilowatts are presented

	Heat			Cool		
Area	Peak heat power (kW)	Difference from rural area (kW)	Percentages from rural area (%)	Peak cool power (kW)	Difference from rural area (kW)	Percentages from rural area (%)
Turku city						
Rural	907	0	100	663	0	100
Urban	1,131	224	125	509	–154	77
City centre	1,490	583	164	261	–402	39
Lohja city						
Rural	3,974	0	100	3,262	0	100
Urban	5,246	1,272	132	2,333	–929	72
City centre	6,337	2,363	159	1,637	–1,625	50
Lahti city						
Rural	14,012	0	100	10,285	0	100
Urban	16,565	2,553	118	6,878	–3,407	67
City centre	21,109	7,097	151	3,747	–6,538	36

 DOI 10.1007/s10040-014-1174-5

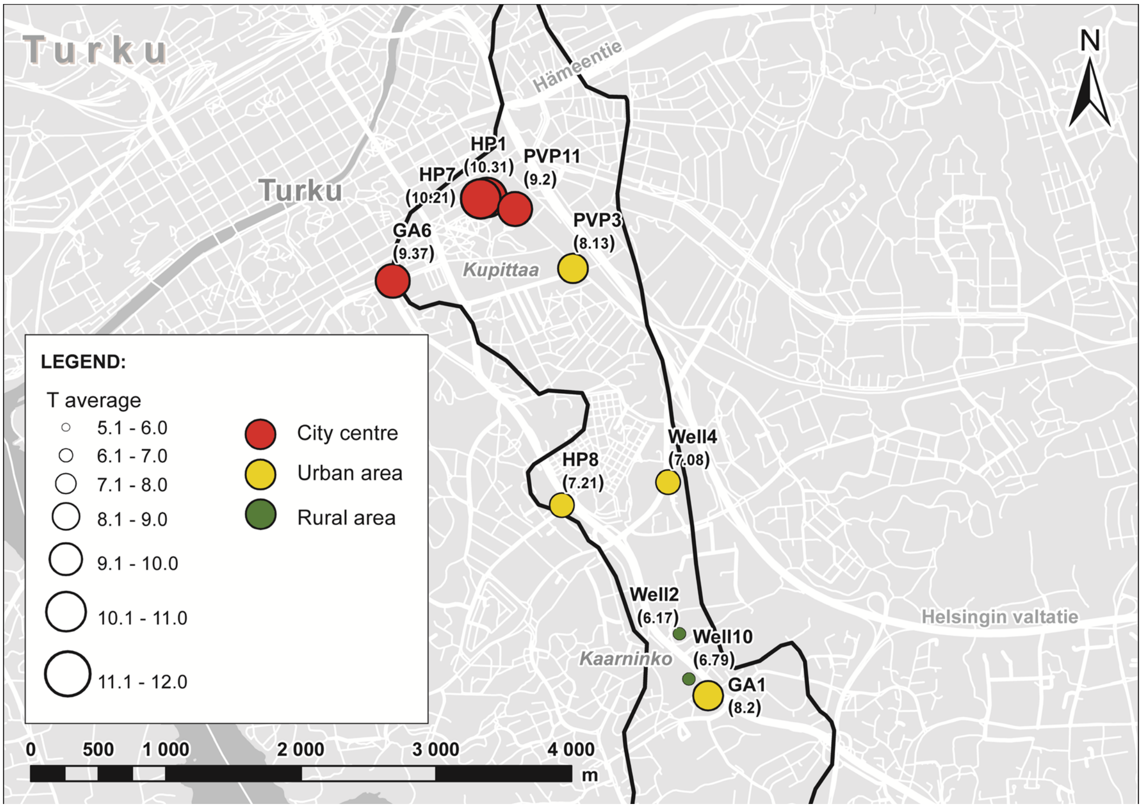

Fig. 7 Average groundwater temperatures (*T*) below the seasonal mixing zone in the Turku aquifer. The *size* of the symbol indicates the temperature category. The name of each monitoring well and the average groundwater temperature (°C) are also shown. The *colour* of the symbols indicates the land use and the *black line* indicates the estimated aquifer location. Basemap database © National Land Survey of Finland

Groundwater temperature data below the zone affected by seasonal temperature fluctuation from spring and autumn were combined and are presented on the maps in Figs. 7–9. Hence, the maps present yearly average groundwater temperatures. In the Turku aquifer (Fig. 7), the average groundwater temperatures were between 6.2 and 6.8 °C in the rural area, between 7.1 and 8.2 °C in the urban area and between 9.4 and 10.3 °C in the city centre. Groundwater temperatures decreased from the city centre to rural area, but were elevated again in the separate urban area where monitoring well GA1 is located.

Groundwater temperatures in Lohja were between 5.8 and 6.2 °C in the rural area, between 6.9 and 8.9 °C in the urban area and between 7.8 and 9.9 °C in the city centre (Fig. 8). Similar to the (separated) urban area in Turku, elevated groundwater temperatures were recorded in the industrial areas in Lohja, as can be seen at monitoring wells 5.07 and LEM A.

Figure 9 presents the groundwater temperatures below the seasonal fluctuation zone in the Lahti aquifer. The groundwater temperature recorded in the rural area (well 159) was 5.8 °C. Temperatures in urban area varied between 7.1 and 9.6 °C. The latter was the temperature in well GA2/TB, which may not be representative. The peak groundwater temperature observed in well GA2/TB is suggested to be due to street construction work that may have allowed warm surface water flow to the well. The well was situated less than 5 m from the excavation area. Excluding GA2/TB, average urban area temperatures varied between 7.1 and 8.0 °C. Temperatures in the city centre area varied between 8.7 and 11.4 °C. Similarly as in Turku and Lohja, the separate urban area had an elevated groundwater temperature, as could be seen at monitoring well SK1/Hp. However, the raised temperature of well SK1/Hp may also be a result of heat leakage from a district heating pipe, which was located 15 m from the monitoring well.

A UHI effect with an average air temperature difference of 1.9 °C has been reported in the Turku area (Suomi and Käyhkö 2011). Even though a UHI effect could also exist in Lohja and Lahti, the changes in the air temperature cannot alone explain the differences of several degrees in the observed groundwater temperatures. In geological formations in southern and western Finland, similar to those investigated in this study, the temperatures of over 1,000 springs were analysed in the late 19th century. Moberg (1890, 1889, 1888) reported that groundwater temperatures of springs in the Turku, Lohja and Lahti areas ranged from 5.5–7 °C. Despite the large number of measurements, the data are only indicative, because all the measurements were carried out in summer and

 DOI 10.1007/s10040-014-1174-5

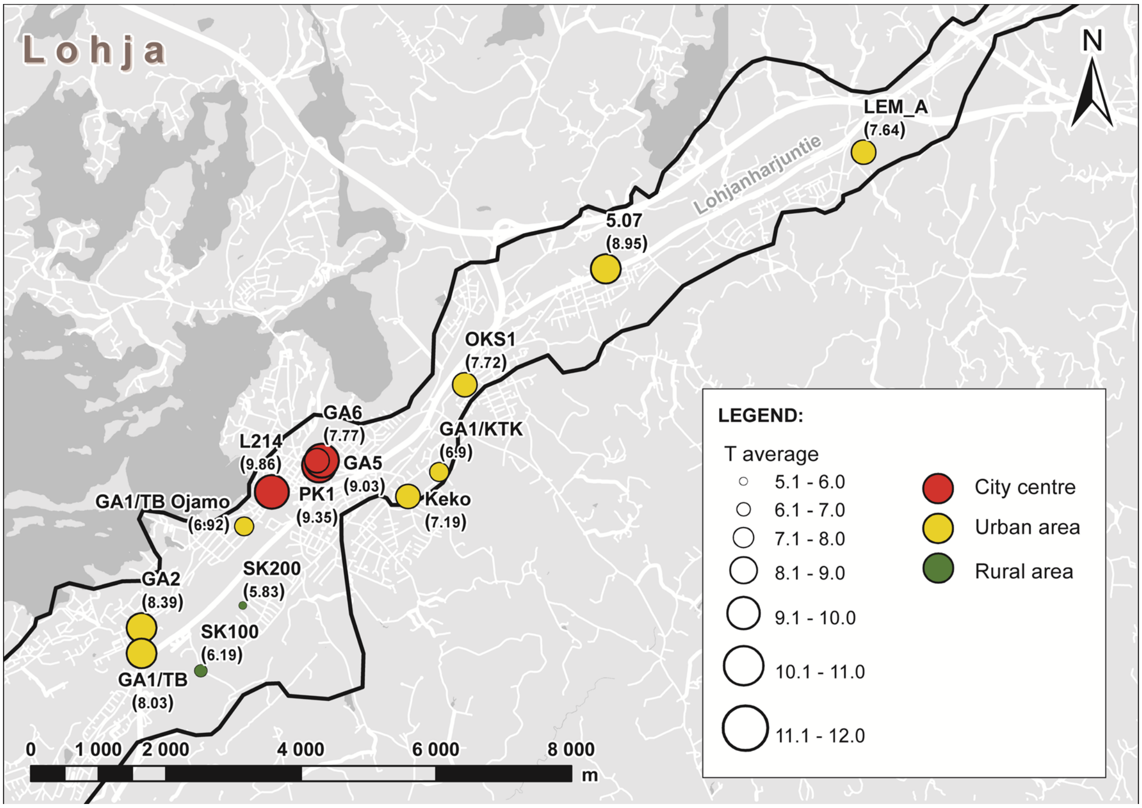

Fig. 8 Average groundwater temperatures (*T*) below the seasonal mixing zone in the Lohja aquifer. The *size* of the symbol indicates the temperature category. The name of each monitoring well and the average groundwater temperature (°C) are also shown. The *colour* of the symbols indicates the land use and the *black line* indicates the estimated aquifer location. Basemap database © National Land Survey of Finland

the influence of solar radiation on the spring water was clear, as also noted by Moberg (1888). The results for groundwater temperatures from rural areas in this study were similar to those observed over 100 years ago and, hence, groundwater temperatures from rural areas are representative as background temperatures in energy calculations.

Energy utilisation

Because groundwater temperature differences between different land use areas were largely similar in all aquifers, the ratio of utilisable energy was also similar. Thus, it is possible to estimate the changes in heating and cooling capacities by measuring the groundwater temperatures and knowing the hydrogeological environment. The peak heating and peak cooling power capacity were calculated, which can be used as an estimate when mapping the energy potential for large areas. However, in real situations, the continuously utilisable groundwater energy for heating and cooling, i.e. the design power, will most likely differ from the calculated peak power. This is due to groundwater pumping, which allows rapid groundwater flow and may reduce the local groundwater 'heat island' effect.

The increased proportional heating capacity in shallow Pleistocene aquifers is rather similar in Finland to that in Ireland and Germany. Investigations in Ireland by Allen et al. (2003) and Allen and Milenic (2003) revealed that in the area of a Pleistocene gravel aquifer, both the heating and cooling resource was approximately 1.6 times greater in an urban than in a rural area. The reason for the higher cooling capacity in urban areas was that Allen and Milenic (2003) assumed concurrent groundwater energy use for heating and cooling; cooled groundwater leaving a heat pump was transferred directly to a heat exchanger for cooling purposes. This assumption cannot be applied in cold regions, as the time period when both heating and cooling is demanded in buildings is minimal (Jylhä et al. 2011; Kalamees et al. 2011). As the groundwater temperatures in the Pleistocene gravel plain in Munich were observed to be 8–10° higher under populated than rural areas (Kerl et al. 2012), it can be estimated that the peak heat power would be at least 1.5 times higher in an urban area than in a rural area.

The assumption of using groundwater at constant temperatures, i.e. the temperatures observed below the seasonal fluctuation zone (Fig. 10), is made because most open loop systems are planned to avoid seasonal

 DOI 10.1007/s10040-014-1174-5

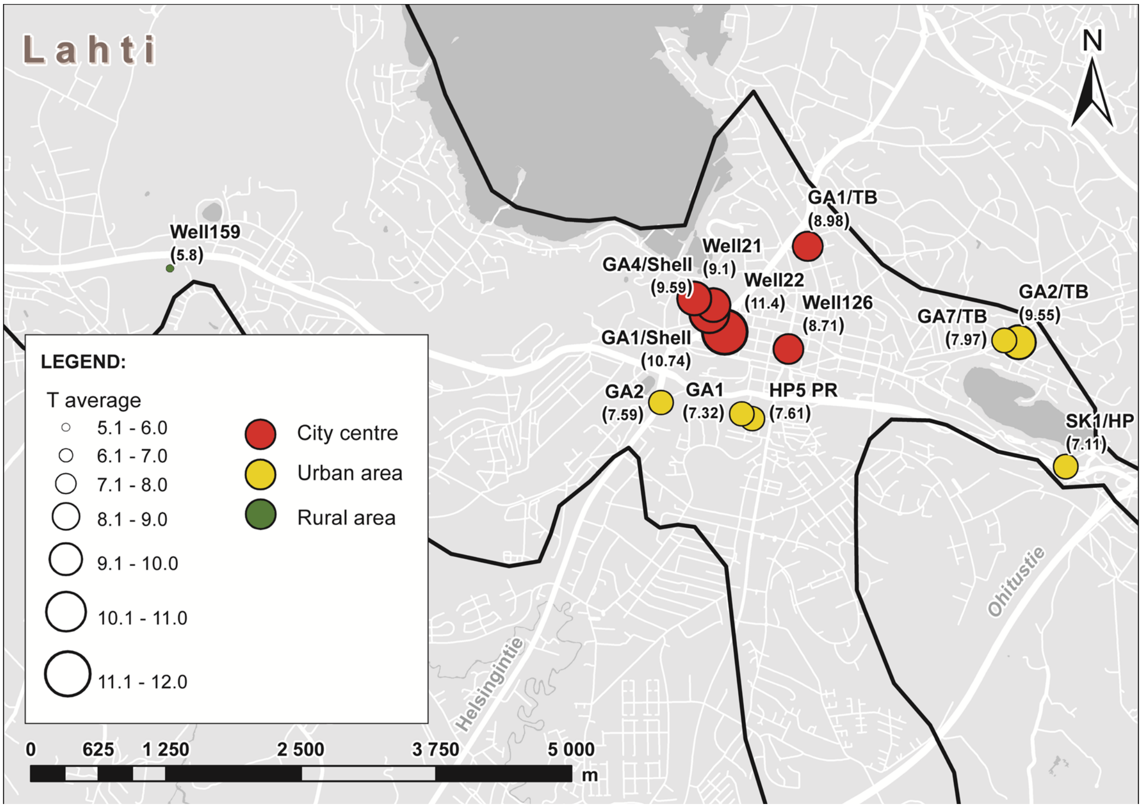

Fig. 9 Average groundwater temperatures (*T*) below the seasonal mixing zone in the Lahti aquifer. The *size* of the symbol indicates the temperature category. The name of each monitoring well and the average groundwater temperature (°C) are also shown. The *colour* of symbols indicates the land use and the *black line* indicates the estimated aquifer location. Basemap database © National Land Survey of Finland

variations in groundwater temperatures. To avoid seasonal temperature variations, a production well is not screened through the whole aquifer and/or the pump is placed near the bottom of the production well. This assumption is made even though the groundwater flow from the injection well to the abstraction well may cause groundwater with a non-constant temperature to flow to the pump.

No measurements are available for COP_H or COP_C or the seasonal performance factor (SPF) from modern Finnish open loop systems; hence, the COP_H and COP_C values available from the literature were used. Cooling was obtained through the use of heat exchangers rather than a GWHP. The COP for cooling was calculated, because a cooling system uses an electrical water pump to circulate groundwater.

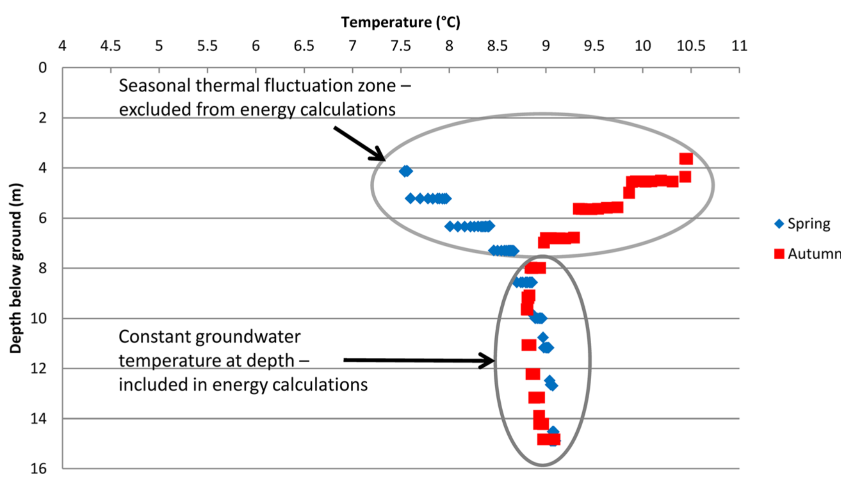

Fig. 10 The principle of the groundwater temperature data analysis used to calculate the energy potential. Each *diamond* represents a single measurement in spring and each *square* a measurement in autumn. This dataset, recorded by a data logger, is from well L214 in the Lohja aquifer

 DOI 10.1007/s10040-014-1174-5

Conclusions

Due to urbanisation, groundwater can form a significant local renewable energy source for heating in Finland. The data indicate that urbanisation, especially heat loss from buildings, has elevated groundwater temperatures in the investigated cities. The average groundwater temperatures below the seasonal fluctuation zone were 1.3–2.0 °C higher in the urban area and 3.0–4.0 °C higher in the city centre of the investigated cities than in the rural area around them. ANCOVA and RTA analyses show that average groundwater temperature in the saturated zone is strongly predicted by urbanization stage of the land use. Furthermore, the average groundwater temperature is higher in the areas where the unsaturated zone is thin. The results of ANCOVA analyses indicate that the temperature seasonal fluctuation zone is the thickest in covered areas, in shallow wells and when the unsaturated zone is thin.

Warmer groundwater enables a 50–60 % higher peak heating load utilisation from the city centre than rural areas in Turku, Lohja and Lahti. One reason for the very limited utilisation of groundwater as a source of heating energy in Finland may be that the urbanisation effect on groundwater temperatures has not previously been recognized.

Due to elevated groundwater temperatures, more heating and less cooling power can be utilised from populated than rural areas. The peak cooling loads decrease by approximately 40–50 % in populated areas compared to rural ones. However, groundwater still constitutes an effective cooling energy utilisation process in Finland, because groundwater temperatures, even in urbanised areas, remain below air temperatures during the summer and the COP for cooling is extremely high. Cooling is also only needed for a limited period in Finland, mostly from June to August.

More research is needed to evaluate the comparability of peak and design power along with heat leakage from buildings and its influence on groundwater temperatures during the continuous groundwater pumping stage. This could be conducted at a site where hydro- and thermogeological conditions are known before installing a GWHP energy system. Further research is also needed to determine the possible urbanisation effect on groundwater energy use in the area north of the Arctic Circle. Because local building types significantly affect groundwater temperatures, the peak heating and cooling power, as well as the design power, have to be carefully measured at each groundwater energy utilisation site.

Acknowledgements The authors wish to thank the following organisations who kindly allowed us to use their groundwater monitoring wells and provided help with this research: the City of Turku; Turun vesilaitos; the City of Lohja; Lohjan vesi- ja viemärilaitos; the Centre for Economic Development, Transport and the Environment for Uusimaa; Lahti Aqua; St1 Energy Oy; Neste Oil Oyj; Oy Teboil Ab; TOK and SOK. We also thank Professor Veli-Pekka Salonen and Dr Martin Preene for their support and advice, Dr Roy Siddall for language revision and Dr Sakari Salonen for helping us with regression tree analysis. Special thanks go to colleagues at the Turku office of Golder Associates. This research was funded by Golder Associates Oy, Maa- ja vesitekniikan tuki ry and the K.H. Renlund Foundation.

References

Alalammi P (1987) Atlas of Finland, folio 131: climate. National Board of Survey, Geographical Society of Finland, Helsinki

Allen A, Milenic D (2003) Low enthalpy geothermal energy resources from groundwater in fluvioglacial gravels of buried valleys. Appl Energ 74:9–19

Allen AR, McGovern C, O'Brien M, Leahy KL, Connor BP (1999) Hydrogeology and land use management. IAH, Bratislava, Slovakia, pp 655–664

Allen A, Milenic D, Sikora P (2003) Shallow gravel aquifers and the urban 'heat island' effect: a source of low enthalpy geothermal energy. Geothermics 32:569–578. doi:10.1016/S0375-6505(03)00063-4

Andea P, Mnerie D, Cristian D, Pop O, Jigoria-Oprea D (2010) Conventional vs. alternative energy sources overview: part I, energy and environment. In: Computational Cybernetics and Technical Informatics (ICCC-CONTI), 2010 International Joint Conference. Timisoara, Romania, May 2010, pp 595–600

Andersson O (1994) Aquifer thermal energy storages in Sweden: experiences so far and market potential. In: Kangas MT, Lund PT (eds) Thermal energy storage: better economy, environment, technology: proceedings, vol 2. Calorstock '94, 6th International Conference on Thermal Energy Storage, Espoo, Finland, August 1994, pp 22–25

Arola T, Rantala J, Palin A, Lehtonen M (2011) Lohjan pohjavesialueiden suojelusuunnitelma [Groundwater protection plan for Lohja]. Project report, Golder Associates Oy, Turku, Finland

Bakema G, van der Hengel P M (1994) Cooling the largest events hall in the Benelux with an ATES system. In: Kangas MT, Lund PT (eds) Thermal energy storage: better economy, environment, technology: proceedings, vol 2. Calorstock '94, 6th International Conference on Thermal Energy Storage, 22–25 August 1994, Espoo, Finland

Banks D (2012) An introduction to thermogeology: ground source heating and cooling. Wiley-Blackwell, Oxford, UK

Banks D, Parnachev VP, Frengstad B, Holden W, Karnachuk OV, Vedernikov AA (2004) The evolution of alkaline, saline ground- and surface waters in the southern Siberian steppes. Appl Geochem 19:1905–1926. doi:10.1016/j.apgeochem.2004.05.009

Banks D, Gandy CJ, Younger PL, Withers J, Underwood C (2009) Anthropogenic thermogeological 'anomaly' in Gateshead, Tyne and Wear, UK. Q J Eng Geol Hydrogeol 42:307–312. doi:10.1144/1470-9236/08-024

Bayer P, Saner D, Bolay S, Rybach L, Blum P (2011) Greenhouse gas emission savings of ground source heat pump systems in Europe: a review. Renew Sust Energ Rev 16:1256–1267. doi:10.1016/j.rser.2011.09.027

Bonte M, Stuyfzand P, Hulsmann A, van Beelen P (2011) Underground thermal energy storage: environmental risks and policy developments in the Netherlands and European Union. Ecol Soc 16(1):22

Bornstein RD (1968) Observations of the urban heat island effect in New York City. J Appl Meteorol Climatol 7:575–582

Budel J (1982) Climatic geomorphology. Princeton University, Princeton, NJ

Cotton WR, Pielke RA (1995) Human impacts on weather and climate. Cambridge University Press, Cambridge

Cruickshanks F, Adsett E (1994) Sussex health centre aquifer thermal energy storage. In: Kangas MT, Lund PT (eds) Thermal energy storage: better economy, environment, technology—proceedings, vol 1. Calorstock '94, 6th International Conference on Thermal Energy Storage, 22–25 August 1994, Espoo, Finland

EHPA (2009) European heat pump statistic: outlook 2009. European Heat Pump Association, Brussels, 65 pp
Ferguson G, Woodbury AD (2004) Subsurface heat flow in an urban environment. J Geophys Res 109, B02402. doi:10.1029/2003JB002715,2004
Ferguson G, Woodbury AD (2006) Observed thermal pollution and post-development simulations of low-temperature geothermal system in Winnipeg, Canada. Hydrogeol J 14:1206–1215. doi:10.1007/s10040-006-0047-y
Ferguson G, Woodbury AD (2007) Urban heat island in the subsurface. Geophys Res Lett 34, L23713. doi:10.1029/2007GL032324,2007
Haehlein S, Bayer P, Blum P (2010) International legal status of the use of shallow geothermal energy. Renew Sust Energ Rev 14:2611–2625. doi:10.1016/j.rser.2010.07.069
Iihola T, Ala-Peijari T, Seppänen H (1988) Aquifer thermal energy storage in Finland. Water Sci Technol 20(3):75–86
Finnish Environment Institute (2006) The Corine 2006 database. http://wwwd3.ymparisto.fi/d3/Static_rs/spesific/corinelandcover.html. Accessed 29 Dec 2012
Finnish Environment Institute (2012) The Hertta database. http://wwwp2.ymparisto.fi/scripts/hearts/welcome.asp. Accessed 10 Jul 2012
Jylhä K, Kalamees T, Tietäväinen H, Ruosteenoja K, Jokisalo J, Hyvönen R, Ilomets S, Saku S, Hutila A (2011) Rakennusten energialaskennan testivuosi 2012 ja arviot ilmastonmuutoksen vaikutuksista [Test reference year 2012 for building energy demand and impacts of climate change]. Report no. 2011, Finnish Meteorological Institute, Helsinki, 6 pp
Kalamees T, Jylhä K, Tietäväinen H, Jokisalo J, Ilomets S, Hyvönen R, Saku S (2011) Development of weighting factors for climate variables for selecting the energy reference year according to the EN ISO 15927-4 standard. Energ Build 47:53–60. doi:10.1016/j.enbuild.2011.11.031
Karhunen R (2004) Iniön ja Turun kartta-alueiden kallioperä. Suomen geologinen kartta 1:100 000. Kallioperäkarttojen selitykset, lehdet 1041 ja 1043 [Pre-Quaternary rocks of the Iniö and Turku map-sheet areas: explanation to the maps of Pre-Quaternary rocks, Sheets 1041 and 1043]. Geological Survey of Finland, Espoo, Finland
Karl TR, Diaz HF, Kukla G (1988) Urbanization: its detection and effect in the United States climate record. J Clim 1:1099–1123
Kasenov M (2001) Applied ground-water and hydrology and well hydraulics, 2nd edn. Water Resource Publications, Littleton, CO
Kerl M, Runge N, Tauchmann H, Goldscheider N (2012) Hydrogeologisches Konzeptmodell von München: Grundlage für die thermische Grundwassernutzung [Conceptual hydrogeological model of the city of Munich, Germany, as a basis for geothermal groundwater utilisation]. Grundwasser 17(3):127–135. doi:10.1007/s00767-012-0199-8
Lahermo P, Ilmasti M, Juntunen R, Taka M (1990) The hydrogeochemical mapping of Finnish aquifers. In: Geochemical atlas of Finland, part 1. Geological Survey of Finland. Espoo, Finland, 66 pp
Landsberg HE (1981) The urban climate. Int. Geophys. Ser., vol 28. Academic, New York
Lehijärvi M (1964) Kallioperäkartan selitys. Lahti. Suomen geologinen kartta 1:100 000. Lehti 3111 [Geological map of Finland, sheet 3111 Lahti: explanation to the map of rocks]. Geological Survey of Finland, Espoo, Finland
Leppäharju N (2008) Kallioenergian hyödyntämiseen vaikuttavat geofysikaaliset ja geologiset tekijät [Geophysical and geological factors of bedrock energy utilisation]. MSc Thesis, University of Oulu, Finland, 91 pp
Lunkka JP, Johansson P, Saarnisto M, Sallasmaa O (2004) Glaciation in Finland. In: Ehlers J, Gibbard PL (eds) Quaternary glaciations: extent and chronology. Elsevier, Amsterdam, pp 93–100
Mälkki E, Soveri J (1986) Pohjavesi [Groundwater]. In: Mustonen S (ed) Sovellettu hydrologia [Applied hydrology]. Vesiyhdistys ry. Mäntän kirjapaino, Mänttä, Finland
Mäyränpää R (2012) Hollola-Lahti-Nastola. Seudullinen pohjaveden suojelusuunnitelma vuosille 2012–2021 [Groundwater protection plan for Hollola-Lahti-Nastola area for 2012–2021]. Project report. Lahden seuden ympäristöpalvelut, Lahti, Finland
McKenzie JM, Voss CI, Siegel DI (2007) Groundwater flow with energy transport and water ice-phase change: numerical simulations, benchmarks, and application to freezing in peat bogs. Adv Water Resour 30:966–983. doi:10.1016/j.advwatres.2006.08.008
Menberg K, Bayer P, Zosseder K, Rumohr S, Blum P (2013a) Subsurface urban heat islands in German cities. Sci Total Environ Vol 442:123–133. doi:10.1016/j.scitotenv.2012.10.043
Menberg K, Blum P, Shaffitel A, Bayer P (2013b) Long-term evolution of anthropogenic heat fluxes into a subsurface urban heat island. Environ Sci Technol 47:9747–9755. doi:10.1021/es401546u
Ministry of Employment and the Economy (2010) Finland's national action plan for promoting energy from renewable sources pursuant to Directive 2009/28/EC. Ministry of Employment and the Economy, Energy Dept., Helsinki, Finland
Moberg K AD (1888) Kertomus karttalehteen no. 8. Lahti [Explanation to map sheet 8. Lahti]. Weilin ja Göös osakeyhtiön kirjapaino, Helsinki, Finland
Moberg K AD (1889) Kertomus karttalehteen no. 2. Lohja [Explanation to map sheet 2. Lohja] Weilin ja Göös osakeyhtiön kirjapaino, Helsinki, Finland
Moberg K AD (1890) Kertomus karttalehteen no. 10. Turku [Explanation to map sheet 10. Turku]. Suomalaisen kirjallisuuden seuran kirjapaino, Finland
Niemelä J, Sten C-G, Taka M, Winterhalter B (1987) Turun-Salon seudun maaperä. Suomen geologinen kartta 1:100 000. Maaperäkarttojen selitykset, lehdet 1043 ja 2021 [Quaternary deposits in the Turku-Salo map-sheet areas. Geological map of Finland 1:100 000. Explanation to the maps of Quaternary deposits, sheets 1043 and 2021]. Geological Survey of Finland, Espoo, Finland
Oikari H (1981) Pohjaveden lämpötila Etelä- ja Keski-Suomessa vuosina 1975–1978. Vesihallituksen lähde- ja pohjavesiputkihavaintoihin perustuva selvitys [Groundwater temperature in southern and central Finland in 1975–1978]. MSc Thesis, University of Helsinki, Finland, 65 pp
Oke TR (1973) City size and the urban heat island. Atmospheric Environ 7:769–779
Parnachev VP, Banks D, Berezovsky AY, Garbe-Schönberg D (1999) Hydrochemical evolution of Na–SO_4–Cl groundwaters in a cold, semi-arid region of southern Siberia. Hydrogeol J 7:546–560. doi:10.1007/s100400050228
Parsons ML (1970) Groundwater thermal regime in glacial complex. Water Resour Res 6:1701–1720
Preston-Whyte R A (1970) A spatial model of an urban heat island. J Appl Meteorol 9: 571–573. doi: 10.1175/1520-0450(1970)009<0571:ASMOAU>2.0.CO;2
Punkari M (1982) Glacial morphology and dynamics in the eastern part of the Baltic shield interpreted using Landsat imagery. Photogramm J Finland 9:77–93
Rantala J, Arola T (2004) Piispanristin-Skanssin alueen ympäristötekninen maaperä ja pohjavesiselvitys [Environmental soil and groundwater report for Piispanristi-Skanssi area]. Project report, Golder Associates Oy, Turku, Finland
Rosen B, Gabrielsson A, Fallsvik J, Hellström G, Nilsson G (2001) System för värme och kyla ur mark: en nulägesbeskrivning [Systems for heating and cooling from the ground: a status report]. Varia 511, Statens Geotekniska Institut, Lindköping, Sweden
Saarnisto M, Salonen V-P (1995) Glacial history of Finland. In: Ehlers J, Kozarski S, Gibbard PL (eds) Glacial deposits in north-east Europe. Balkama, Rotterdam, The Netherlands, pp 3–10
Saner D, Juraske R, Kübert M, Blum P, Helweg S, Bayer P (2010) Is it only CO_2 that matters? A life cycle perspective on shallow

geothermal system. Renew Sust Energ Rev 14:1798–1813. doi:10.1016/j.rser.2010.04.002

Sanner B (2001) Shallow geothermal energy. GHC Q Bull 22(2). geoheat.oit/bulletin/bull22-2/art4.pdf. Accessed July 2014

Silliman SE, Booth DF (1993) Analysis of time-series measurements of sediment temperature for identification of gaining vs. loosing portions of Juday Creek, Indiana. J Hydrol 146:131–148

Sörensen SN, Reffstrup J, Qvale B (1994) Groundwater used for cooling and seasonal storage in Denmark. In: Kangas MT, Lund PT (eds) Thermal energy storage: better economy, environment, technology: proceedings, vol 2. Calorstock '94, 6th International Conference on Thermal Energy Storage, 22–25 August 1994, Espoo, Finland

Soveri J (1985) Influence of meltwater on the amount and composition of groundwater in Quaternary deposits in Finland. National Board of Waters, Helsinki, Finland

Statistics Finland (2012a) Official statistics of Finland (OSF): energy supply and consumption (e-publication). 4th Quarter 2012, Statistics Finland, Helsinki, Finland. http://www.stat.fi/tup/kunnat/kuntatiedot/398.html. Accessed 7 Nov 2012

Suomi J, Käyhkö J (2011) The impact of environmental factors on urban temperature variability in the coastal city of Turku, SW Finland. Int J Climatol 32:451–463. doi:10.1002/joc.2277

The Geological Survey of Finland (2012) Lohja bedrock map. Geological Survey of Finland, Espoo, Finland. http://geomaps2.gtk.fi/activemap. Accessed 12 July 2012

Tanicughi M, Uemura T, Jago-on K (2007) Combined effects of urbanisation and global warming on subsurface temperature in four Asian cities. Vadose Zone J 6:591–6. doi:10.2136/vzj2006.0094

Tietäväinen H, Tuomenvirta H, Venäläinen A (2010) Annual and seasonal mean temperatures in Finland during the last 160 years based on gridded temperature data. Int J Climatol 30(15):2247–2256. doi:10.1002/joc.2046

Woo M-K, Marsh P (2005) Snow, frozen soils and permafrost hydrology in Canada 1999–2002. Hydrol Process 19:215–229. doi:10.1002/hyp.5772

Yalcin T, Yetemen O (2009) Local warming of groundwaters caused by the urban heat island effect in Istanbul, Turkey. Hydrogeol J 17:1247–1255. doi:10.1007/s10040-009-0474-7

Yaws C (1998) Chemical properties handbook: physical thermodynamic, environmental, transport, safety and health related properties for organic and inorganic chemicals. McGraw-Hill, New York

Zhu K, Blum P, Ferguson G, Balke K-D, Bayer P (2010) The geothermal potential of urban heat islands. Environ Res Lett 5:044002. doi:10.1088/1748-9326/5/4/044002