Combining water and energy supply

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1202270-016

Title
Combining water and energy supply

Client	Project	Reference	Pages
Programmabureau Kennis voor Klimaat	1202270-016	1202270-016-BGS-0001	79

Version	Date	Author	Initials	Review	Initials	Approval	Initials
	feb. 2013	Reinder Brolsma		Frans van de Ven		Henriëtte Otter	

State
final

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Abstract

This study explores the feasibility of a *distribution and storage* system that supplies both heat and cold based on local sources and drinking water to buildings. Water has a large heat capacity and is an effective medium for storage and extraction of thermal energy. This water derived heat can be used to acclimatize buildings or reduce the energy demand of hot tap water production. By combining thermal energy and drinking water supply in one network would save on underground distribution network. This study is conducted as part of the Dutch research programme 'Knowledge for Climate', co-financed by the Dutch ministry of Infrastructure and Environment.

A conceptual framework is provided to determine 1) the heat demand of an urban area, 2) the heat yield of the urban water system, and 3) the heat storage capacity of the urban aquifer system. This framework is applied to a 19th century mainly residential suburb of Amsterdam: the Watergraafsmeer. The results show that in the present situation, a heat demand is present of 1047 TJ/a, which is attributed to 753 TJ/a for space heating, 147 TJ/a for space cooling and 147 TJ/a for hot tap water supply. The urban water system and cycle can provide 213 TJ/a of heat in a time period when it can be used directly. A further 746 TJ/a of heat is available during periods when there is no demand. Aquifer thermal energy storage (ATES) can provide between 478 and 929 TJ/a of heat storage, depending on the applied injection temperature, and can therefore in principle provide a solution for the temporal mismatch between urban water thermal energy availability and demand.

Actual use of the heat from the urban water cycle requires heat pumps to provide a temperature level suitable for space heating and cooling and hot tap water supply. To determine the overall energy performance of using the urban water cycle for heat supply and storage, we compared the primary energy consumption (E_{pr}) of the traditional system (based mainly on natural gas) with that of the electrical heat pump, heat exchangers and pumps. The E_{pr} of the traditional system is 1032 TJ/a compared to 928 TJ/a for the urban water system (7% reduction). Key factors limiting the energy savings are the seasonal performance factor of the urban water system of heat pumps and related components (relating heat delivered to electrical energy used) and the conversion factor of electrical energy to primary energy which depends on the national electricity mix.

The urban water system can provide an effective source of heat for urban areas. However, a more detailed design is needed and more research on both the thermal and economic efficiency. Delivering both drinking water and thermal energy using the same network does not seem feasible.

The water quality in the combined distribution network can not be guaranteed to meet consumption standards. Point source purification can be used as a solution. Due to the low cost and high quality of the current drinking water system, a combined system delivering both heating, cooling and drinking water is assumed to be not feasible. The higher cost for providing drinking water and slightly increased health risk are expected to outweigh the advantage of saving on one distribution system.

Abbreviations used in text

ATES	Aquifer thermal energy storage
COP	Coefficient of performance
HE	Heat exchanger
HL (consumers)	High-level consumers
HP	Heat pump
HT (ATES)	Medium temperature ATES
LL (consumers)	Low-level consumers
MT (ATES)	Medium temperature ATES
NAP	Mean sea level
OLT (ATES)	Optimized low temperature ATES
P.O.U. filter	Point of use filter
SLT (ATES)	Standard low temperature ATES
SPF	Seasonal performance factor

Contents

Appendices

1 Introduction

An average dwelling in the Netherlands uses about 1850m^3 of natural gas per year (CBS, 2012). About 75% of this energy is used for space heating of houses by predominantly individual heating systems. A significant reduction in energy use in the built environment can be achieved by using a more effective system for space heating.

This report focuses on the potential use of the urban water system (including groundwater, surface water, drinking water and sewerage) to harvest, store and transport thermal energy for space heating and provide water for household use. Water has a large heat capacity and can therefore be used for storage and extraction of large amounts of heat, i.e. thermal energy. The extracted heat can be used for space heating in buildings. By storing heat in water, heat can be extracted from buildings, thereby cooling them.

In the urban water system heat can be stored in or extracted from groundwater, surface water, reservoirs and water distribution systems. Because water is liquid, the thermal energy within it can be transported easily. The urban water cycle has both a "natural" part (precipitation, groundwater and surface water) and an anthropogenic part (water and sewage system). Currently, water is used a heat transportation medium for central heating systems, high temperature district heating and Aquifer Thermal Energy Storage (ATES).

Using the urban water system for heat delivery has several advantages:

A large fraction of energy in the urban ‘natural’ environment remains unused. Solar energy can be used directly for heating through solar thermal collectors, or be converted to electricity using a solar photo-voltaic collector. Water from solar thermal collectors is obtained at a high temperature and can be implemented in most current systems. Solar energy that is stored in surface water and the soil in summer can also be extracted and stored for space heating in winter. The heat obtained from these sources is at a low temperature and needs a different type of network when compared to the traditional district heating networks.

The heating and cooling demand pattern of dwellings and office buildings differs in time. While in spring and autumn dwellings consume energy for heating, office buildings might use energy for cooling. Connecting both systems can close the gap in the energy balance.

Due to projected climate change, and improved building techniques a shift in the urban heat/energy balance is expected to occur. Warmer winters and improved building insulation reduces the heating demand. On the other hand, due to warmer summers the demand for cooling, i.e. discharge of heat, increases. Present day net users of heat will use less heat or may eventually become net users of cold. This may increase the chances for efficiently linking sinks and sources of heat and cold.

In the traditional Dutch situation, dwellings are connected to multiple networks for water and energy:
- Drinking water network;
- Sewer network;
- Electricity network;
- Gas distribution and/or district heating network.

Usage of excess heat, e.g. from industry, for heating of buildings increases in the Netherlands. In the current situation, this involves high temperature networks at a temperature level up to 90°C. The transition towards a green economy however implies that supply of waste heat can be expected to decrease at some point in time. This means that shifting to a heat source at moderate temperature (20-30°C) is essential for long term sustainable heating systems that are not relying in any way on fossil fuels.

In the current situation, distribution of hot water via a district heating network has always required an additional transport network on top of the drinking water network. Eliminating one of the networks might be cost efficient. By using the drinking water network for energy supply and using electricity for cooking the gas distribution network would not be necessary. Using a network from which heat can be extracted or heat can be discharged to and drinking water can be extracted saves one network. Of course, the quality of drinking water at the tap used for consumption must be guaranteed.

Temperature of the drinking water in current distribution systems is increasing, because the temperature of the surface water and the subsurface are increasing in summer. This provides additional heat to the distribution system resulting in an increase in drinking water temperature above 25°C (e.g. van der Hoek 2011, Mol et al. 2011), which causes a potential risk for Legionella and other waterborne pathogens. This provides an opportunity to harvest heat from the drinking water system, while cooling it at the same time.

Surface water is widely present in most cities in the northern and western part of the Netherlands. During the day it receives short wave radiation from the sun and longwave radiation form the air. This radiation is partly stored in the water as heat. This heat can be extracted from the water for heating of dwellings (e.g. De Graaf, 2009) or regeneration of aquifer thermal energy storage. This reduces the temperature of the surface water. Effect on chemical and ecological quality of the surface water is poorly investigated, but it is assumed that cooling has a positive effect.

Households and commercial buildings add around 65 PJ per year to the wastewater. Three quarter of this energy (49 PJ/year) comes just from households (Blom et al., 2010). About 54% of the drinking water that is used in a household is heated and leaves the house at an average temperature of 27ºC: water from bathing and shower has a temperature of approximately 38ºC to 40ºC, tap water could leave the house at a temperature of 10ºC to 55ºC depending on the use, and water from the dishwasher and washing machine has a temperature of approximately 40ºC (Hofman & Loosdrecht, 2009). This waste of thermal energy could provide a great opportunity for energy saving or reclamation.

Several choices exist to produce warm water in dwellings and public buildings. The optimal choices with respect to energy, economy and comfort for the production of heat and warm water depend on the local circumstances and will differ for each location (Braber et al., 2011). An important aspect is that heat losses should be prevented; usually individual systems are better than collective systems. Heat pumps and solar collector systems are the best option to save up energy. These are not common practice in the Netherlands and provide another opportunity to optimize the energy system.

This research is conducted as part of the Dutch research programme 'Knowledge for Climate', co-financed by the Dutch ministry of Infrastructure and Environment. In Theme 4 (Climate Proof Cities) of this research programme the impact of and adaptation measures for climate change in urban areas are investigated. This Climate Proof Cities project, CPC 3.4

Water and Energy Systems, explores the feasibility of a water system that provides heating and cooling for houses. This system can serve as a mitigation and adaptation measure.

Central question is how these combined water & energy systems can be organized and operated in the most efficient way. To this end the demand of heat and cold – and its variation over time, including its extremes – needs to be known, as well as the options to transport energy from multiple sources to multiple users.

The Watergraafsmeer, Amsterdam, has been selected as a case for this study. Waternet, responsible for the water cycle in Amsterdam, is actively studying market potential of the water and energy nexus. Their ambition and knowledge makes the Watergraafsmeer an ideal case.

1.1 Aim

The aim of this study is to explore the feasibility of a water system that provides water for consumption and at the same time serves as a sink and source, storage and transportation medium for thermal energy to provide heating and cooling to dwellings. The result of this study is a basic design and assessment of the feasibility of such a system.
Because such a system has not yet been designed, the ambition in this study was not to come up with a conceptual system design, but focus on the most important components of such a system. Based on these main components the feasibility is determined. The system is compared to the standard Dutch situation, consisting of a separate drinking water system in combination with a gas based heating system.

1.2 Outline

In Chapter 2 the approach is described to come to the basic design and assess the feasibility of the system. In Chapter 3 the district Watergraafsmeer is described focused on typology, the environmental setting and current infrastructure. In Chapter 4 the method described in Chapter 2 is applied to the Watergraafsmeer. The findings of the basic design and efficiency together with the implications for water quality are discussed in Chapter 5 and finally, the main conclusions are presented in Chapter 6.

2 Approach

Several steps have been taken to determine the basic design and feasibility of a water system that can be used for heating and cooling of houses and deliver water for consumption. These steps are outlined in Figure 2.1.
The first step is to identify and quantify the most important sources and sinks of heat in the urban water cycle and water system. In other words, the actual heating and cooling demand and supply within a district are determined. The heat demand is defined as the direct demand of households for acclimatizing houses and delivering hot sanitary water.
When both heating and cooling demand are known, these can be compared to determine whether the total balance is in equilibrium. On shorter time and spatial scale a mismatch exists between cooling and heating demand.
To overcome this imbalance in time, storage is needed. A commonly used and effective method to store heat in the urban water cycle is aquifer thermal energy storage (ATES).
Finally, a distribution network is needed to bridge the spatial gap in heat demand. In this report two options for a distribution network are assessed.

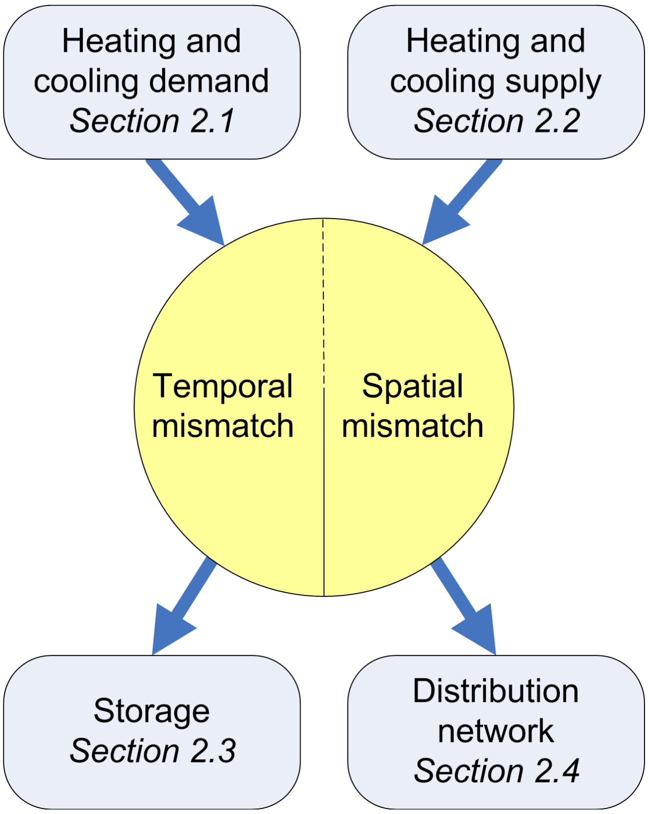

Figure 2.1 Outline of the used method and reference to the corresponding report sections.

2.1 Heating and cooling demand

To determine the level of heating and cooling demand for a district area, two approaches can be applied (Figure 2.2):

- Estimate the local demand using generally available information and local characteristic heating and cooling demand per dwelling;
- Use of existing data on current energy consumption.

The results of these two approaches should fairly match. Nevertheless, the actual energy consumption amount (method 2) will be the most reliable and representative.

Especially where detailed data about composition and characteristics of the built environment in the district are not available, calculations for a specific area will give results with a high level of uncertainty. In such cases, the second method will prevail and calculation of the share of heating and cooling from energy supply data must be carried out. A reasonable conversion factor should be applied to convert the actual energy consumption figures into actual end-users demand figures.

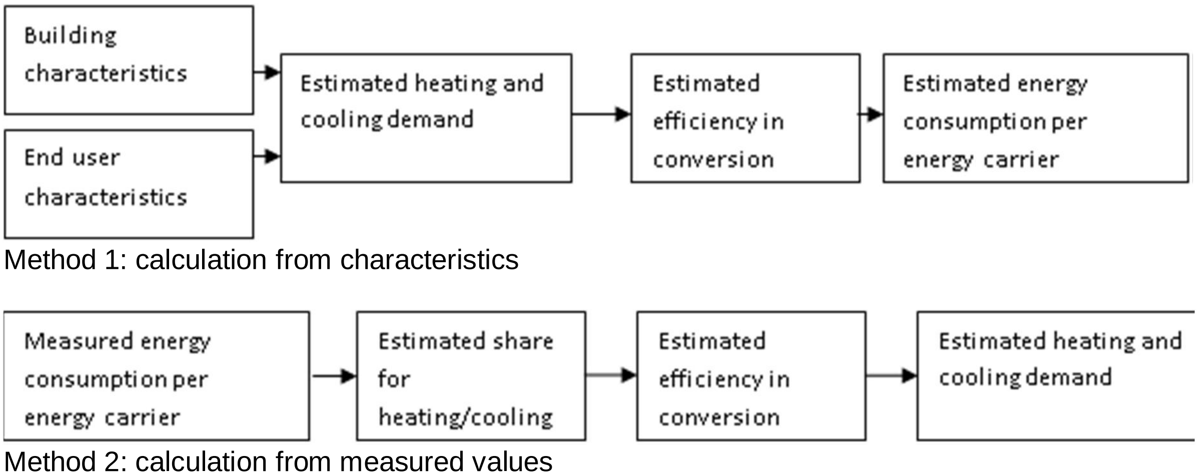

Figure 2.2 Flowcharts of two methods for determining energy demand.

Heating and cooling of buildings is a process where various parameters, like actual demand, system capacity, temperature level, place and time play a role in developing an alternative supply system.
The key factors that determine the heating and cooling demand process are represented in Figure 2.3. In this process, building and installation characteristics are assumed to be constant. Although during a year temperature levels will vary, the overall conditions are more or less constant because a system will operate under the conditions connected to the design conditions. Only renovation and new buildings will gradually modify the building stock and hence the building's thermal characteristics. This also applies to heating installations for which technological improvement also improves the average efficiency level. Such gradual process changes have to be observed over a long term period (e.g. one or two decades).
Both weather conditions and human factors can vary on an hourly basis. It should be acknowledged that there is a certain interaction between the constant and variable factors. Although "constant" factors like the actual position and quality of buildings have impact on the demand as well, this influence on time patterns can be neglected for the size of area under investigation. The variable factor "Climate" does merely determine the time-dependent (annual) patterns in heating and cooling demand. Besides, the level of heating demand for

space heating will vary from year to year. Corrections of energy demand to the long term average level can be made, using actual degree days (sum of daily temperature values over a certain period) for a specific year compared to the average degree days for a long period (e.g. a decade).

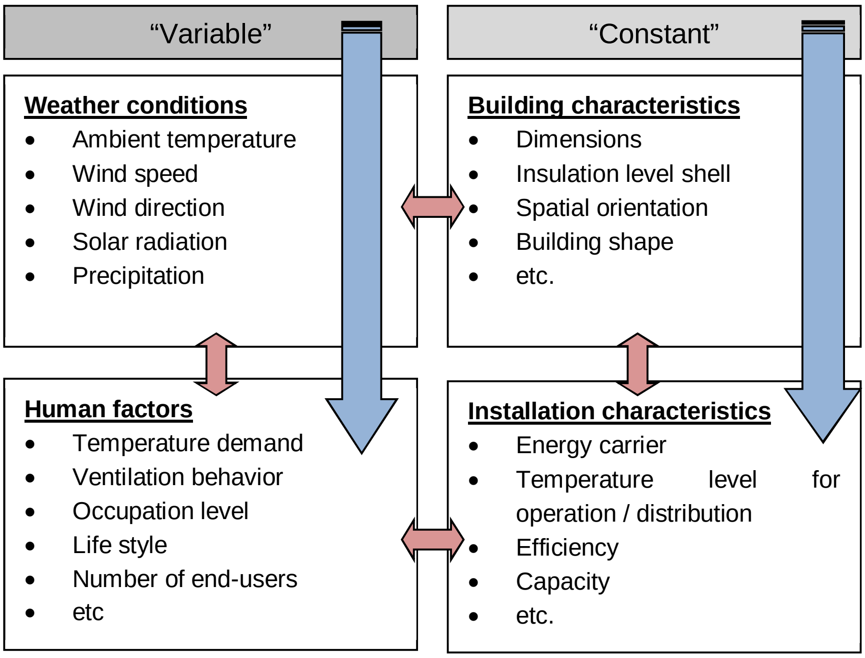

Figure 2.3 Key factors that determine the heating and cooling demand process.

In this report we apply method 2, and we base the heating demand for dwellings on actually metered gas and electricity consumption data. These data refer to the year 2009. For this specific year, no additional corrections are needed since average outdoor temperature for 2009 fairly correspond to the latest 10-years average. Details on background and the metering data are included in Appendix A. The following general assumptions were made (based on Agentschap NL 2007, Agentschap NL and NIBUD):

- For dwellings 70% of the total gas consumption is allocated for the function space heating.
- Cooling need in existing dwellings is still minimal and can be neglected. Only for future observations, a share of 5% of the electricity demand for dwellings can be used as a maximum.
- For the utility buildings mix, the space heating demand is 85% of the gas consumption.
- For the function cooling, a share of 8% of the total electricity consumption for the utility building mix is used.
- Space heating by electricity is negligible.

Based on these assumptions, the heating demand $Q_{heating}$ [MJ/y] from gas can be calculated as follows:

$$Q_{heating} = G_{supply} C_{gas} S_{function} \eta_{conversion} \quad (2.1)$$

where G_{supply}, annual gas supply [m^3/a], C_{gas}, caloric value (upper heating value) for gas [MJ/m^3] $S_{function}$, share of gas supply for a specific function, e.g. space heating [%] and $\eta_{conversion}$ is the conversion efficiency factor [%].

The cooling demand, $Q_{cooling}$ [MJ/y], from electricity can be calculated as follows:

$$Q_{cooling} = E_{supply} C_{electricity} S_{function} \eta_{conversion} \quad (2.2)$$

where E_{supply} is annual electricity supply [kWh/y], $C_{electricity}$, caloric value of supplied electricity [MJ/kWh], $S_{function}$, share of electricity supply for a specific function [%] and $\eta_{conversion}$, conversion efficiency factor [%]. Values for $S_{function}$ are derived and presented in Appendix A. Values for $\eta_{conversion}$ are dependent on the conversion system. For space heating, it is assumed that gas boilers are applied, both for dwellings and for utility buildings. The typical value for $\eta_{conversion}$ is 0.9.
For hot sanitary water production, the conversion efficiency is somewhat lower than the efficiency for space heating although the same boiler will generally be applied for both functions. For hot sanitary water production with gas, the applied value for $\eta_{conversion}$ is 0.85. For hot sanitary water production with electricity, the applied value for $\eta_{conversion}$ is 0,8.
For space heating and hot sanitary water, the calculations are based on a conservative approach by applying state-of-the-art high efficiencies. When assuming less efficient conversion technologies, the calculated energy demand will be lower. It is assumed that space cooling in dwellings is provided by single duct air conditioners heat pumps. A typical conversion efficiency factor $\eta_{conversion}$ is 2.25. For space cooling in utility buildings, the demand is based on coefficient of performance (COP)-values of 3.5.

2.1.1 Temporal distribution

Once the heating and cooling demand levels have been determined, the distribution in time and space for houses and buildings can be established in order to develop potential options for a match with other sinks and sources. Most important in this respect is the energy demand in time:

- During the year;
- Peak demand of heating during the day in winter.

To account for temporal variability the development of temporal patterns per type of demand is required. These time patterns are more or less specific for a certain built area, however a general pattern can be assumed.
For weather conditions, hourly values for a reference year can be used as a basis. The energy consumption values can then be converted into demand figures according to the following approach. Monthly values of energy demand are calculated based on allocation factors per month. The allocation factors per month are dependent on the function under investigation. Allocation of annual demand for heating is performed using degree-days and for cooling demand, cooling days are applied. For hot sanitary water, allocation is only partly performed, based on degree-days. Values and their background are described in more detailed in Appendix A.

The peak demand of heating during day in winter is basically determined by the required capacity under design conditions where the daily average lowest outdoor temperature is assumed (winter conditions). The finally required capacity for a network is the sum of all the buildings design capacities, multiplied by a simultaneity factor. This factor is dependent on the number of connections to a grid but, as a rule of thumb for network operators, a value of 0.7 is likely to apply.

2.2 Thermal energy in the urban water system

We define the urban water system as the total of drinking water and sewerage infrastructure combined with rainfall, surface water (urban drainage) and groundwater. Water conveyed in the urban water system can be used in a number of ways to extract or store heat. These sources are defined as components in the water and energy cycle that deliver water to a central distribution system that delivers water to houses and other buildings. There is no exchange of water between the different components of the water cycle except for sanitary water. To exchange thermal energy heat exchangers or heat pumps are used. Over a day or year a component can be both a sink and a source of heat. The elements of the urban water cycle considered in this study include:

- Drinking water;
- Waste water;
- Surface water.

Other sources of heat that can be combined with the urban water cycle include: heat from solar panels (solar sanitary water boilers) and waste heat from power plants and industry. We note that rainfall itself is not considered as a separate source for heat. Rainfall might provide a source for local water use or grey water, but its potential for providing heat is likely to be limited.

2.2.1 Drinking water and wastewater

Two options for generating heat from drinking water can be recognized:

- Direct use of heat from drinking water using a heat exchanger or a heat pump;
- Harvesting heat from drinking water and storing it, for example in an ATES system.

The first concept can be used when drinking water is supplied from raw groundwater which has a relatively constant temperature. This type of system is applied in Hamburg (Plath and Rottger, 2009). The second type of system is interesting for drinking water produced from surface water with a fluctuating seasonal temperature.

Operational boundary conditions applying to drinking water heat harvesting are given by both the water and energy operators (Meer et al., 2010). For aesthetic reasons, the water company requires drinking water not to be cooled below 10°C (=$T_{threshold}$) while regenerating an ATES system requires a minimum water temperature of 17°C (T(t)>17°C).

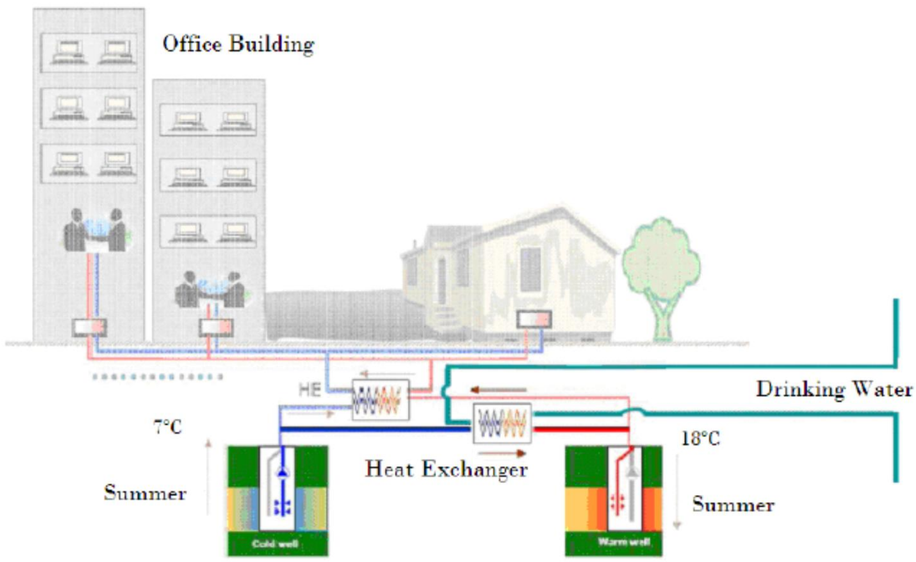

Figure 2.4 Energy recovery from drinking water to restore the balance in ATES (source: Plath and Rottger, 2009).

Extraction of heat from wastewater can be carried out in two ways:

- Using shower heat exchangers inside houses where the heat from shower wastewater is directly transferred to the cold water stream to the shower and the heater;
- By more centralized harvesting inside larger sewerage pipes.

Both systems can be applied simultaneously. Sewerage heat harvesting is constrained by a number of boundary conditions. Monsalve (2011) provides the following three boundary conditions for heat harvesting in Amsterdam:

- Distance between harvesting location and consumers should be less than 300 m;
- Flows in the sewer should be greater than 0.01 m^3/s and the sewer should have a diameter > 400 mm;
- Wastewater temperature should be over 12°C.

For both heat extraction from drinking water and heat extraction from centralized wastewater a very simple and intuitive way to quantify the heat supply was applied, that can be drawn from these sources using:

$$Q_{heating,supply} = cp\, V\, (T(t) - T_{threshold}) \tag{2.3}$$

where c_p is the heat capacity of water (4.18MJ/m^3), V is the volume of water annually available to harvest heat from [m^3/year], T(t) is the temperature during the heat harvesting period and $T_{threshold}$ is the return temperature threshold applied in the heat exchanger used to harvest the heat [°C]. The volume of water, V [m^3], is calculated using metered water volumes supplied by the local water utility company. In order to assess heat harvesting potential using shower heat exchangers indicator numbers were used.

2.2.2 Surface water

The capacity of the surface water system to supply heat depends on several factors. The main factors are:

- Area of surface water determines the amount of radiation that is captured and converted into thermal energy.
- Water depth determines the heat storage capacity. Deep water bodies have a larger heat capacity then shallow water bodies, but by vertical mixing of heat, the temperature amplitude during the year is smaller than in shallow water. Regeneration of ATES is most efficient using water near to the maximum temperature (20^{O}C at present). This means that extraction is most efficient in shallow water. However, if water is needed for cooling, deep water bodies are preferred.
- Flow rate of the surface water. The total capacity of heat extraction is not influenced by the flow rate, but the temperature effect of local heat extraction can spread faster. When a district has a large in and out flux like a river, then heat extraction can be larger than in a district only having a local water system.

A hydrodynamic numerical model that includes an energy module to simulate surface water fluxes and water temperature resulting from ambient meteorological conditions can be used (e.g. SOBEK, Rainfall Runoff coupled to Flow).
The following boundary conditions were used in the water quality model 1) local meteorological data for air temperature, global radiation, air temperature, air humidity and cloud cover, 2) water temperature for model boundaries, 3) water temperature for rainfall runoff.
The harvestable heat has been determined using two methods:

- Using a fixed end temperature of the emitted water $Q_{sw} = \max(T_{end} - T_{act,sw}, 0)\, V_{SW}\, cp$, where T_{end} is the fixed end temperature of the surface water [^{o}C], $T_{act,sw}$ is the actual temperature of the surface water and V_{SW} is the volume of the extracted water.
- Using a fixed temperature differential between extracted water and emitted water: $Q_{sw} = \Delta T_{sw}\, V_{SW}\, cp$, where ΔT_{sw} is the fixed temperature difference.

2.3 Thermal energy storage

The easiest and most common way to store heat in water bodies in the Netherlands, is storage in groundwater; ATES. Hydrogeological conditions in the Netherlands are good for ATES because the groundwater velocity is relatively low and the heat exchange with the surface environment is minimal. In order to assess the capacity of both an individual ATES and the total capacity of an area, a set of simple analytical equations has been used.
First, the capacity of an ATES well is assessed by calculating the injection velocity. This velocity has to be sufficiently low to avoid clogging of the injection well. The Dutch ATES construction guidelines recommend the following equation (IF Technology, 2001):

$$v < 1000 \frac{k}{150^{0.6}} \sqrt{\frac{v_v}{2MFI.u_{eq}}} , \qquad (2.4)$$

where v is the maximum flow velocity of water at the interface between filter and gravel pack [m/h], k is the hydraulic conductivity [m/d], v_v is the clogging velocity [m/year], *MFI* is the membrane filtration index [s/l^2] and u_{eq} is the total annual full load hours [hour] of the system.
Second, the injection pressure in the injection has to be sufficiently low to avoid rupturing of the clay plugs in the annulus of the well (Olsthoorn, 1982):

$$\Delta s < 0.22L , \qquad (2.5)$$

where Δs is the injection pressure (i.e. the additional pressure relative to the standing water level), and L is the depth of the top of the injection filter to the ground surface [m]. The additional injection pressure can be calculated with:

$$\Delta s = \frac{Q}{2\pi kD} K_0\left(\frac{r}{\lambda}\right) , \qquad (2.6)$$

where Q is the injection rate [m/day], kD is the transmissivity of the aquifer, K_0 is the zero order Bessel function, r is the distance at which pressure change occurs (for this case we assume it to be equal to the well radius) [m] and λ is defined by $\sqrt{kDc}$, where c is the combined hydraulic resistivity of over and underlying aquitards (days; $1/c = 1/c_{under} + 1/c_{above}$).
Three heat storage scenarios are assessed and quantified. We will consider three options of ATES systems:

- a *standard low temperature* ATES (SLT) system, as operated most commonly in the Netherlands, with a temperature differential of 8 to 16°C (dT = 8°C) (ambient groundwater temperature is between 10 and 12°C). A heat pump is required in this system because low temperature heating systems require circulation water at around 45-55°C. When delivering hot tap water as well, the outflowing water should be at least 60°C;
- an *optimized low temperature* ATES (OLT) system utilizing the maximum injection temperature allowed within the provincial groundwater plans, resulting in a temperature differential of 8 to 25 ^{o}C (dT = 17°C). Also in this system a heat pump is required. ;
- a *medium temperature ATES* (MT) system working at a temperature differential of 60 to 40^{O}C (dT = 20°C). In this system, no heat pump is required, and the only electrical power required is for the pumps that circulate the water through the heat exchanger.

The volume of water required to store a certain amount of heat for heating can be calculated with:

$$V = \frac{E}{c_p.\Delta T}\left(\frac{SPF-1}{SPF}\right) \text{ or}$$

$$E_{thermal} = c_p.\Delta T.V\left(\frac{SPF}{SPF-1}\right), \qquad (2.7)$$

where c_p is the specific heat of water [4.18 MJ/m^3/^{o}C], ΔT is the temperature differential [^{o}C] E is the required heat [MJ] and SPF is the seasonal performance factor [-]. The amount of electrical energy used to generate the heat can be calculated with:

$$E_{electrical} = E_{thermal} / SPF \qquad (2.8)$$

This value represents the yearly mean coefficient of performance of the combined heat pump and electrical pumps [-] and is often more representative for actual energy savings than the COP. The above equation is only valid for heating (not cooling) because the fraction electrical energy used to drive the heat pump can be added to the thermal energy delivered. The SPF is generally around 0.5 to 1 lower than COP values defined for optimum operating conditions. The COP depends on the used temperature differential, the SPF for heating increases with a higher the source temperature and a lower sink temperature. We assume the following SPFs: SPF_{SLT} = 3.0, SPF_{OLT} = 4.0, which are based on a bandwidth of COP and SPF values for heat pumps given by Tahersima *et al* (2011) and Staffell (2009) and SPF_{MT} = 28 based on Nuiten and van der Ree (2012). The SPF for hot tap water delivery is estimated to be around 2. It is noted that for heat delivery using heat pumps and ATES, the pump energy is only a small fraction of the overall electricity use (that's the reason for the large difference in SPF between a system with and without heat pump). The actual pump energy in the SLT and OLT systems can therefore safely be ignored given the large bandwidth in SPF vales for heat pumps. In order to compare the amount of electrical energy used to the conventional heating method using gas, we have to convert the electrical energy, $E_{electrical}$ [J], to primary energy, $E_{primary}$ [J]. For the Dutch energy mix, we can use (NEN 5128 – 1998):

$$E_{primary} = 2.5E_{eletrical} \qquad (2.9)$$

In order to calculate to total heat storage capacity, we have to consider the subsurface space claim of a typical system and compare it to the total available area. We can use the following equation to calculate the thermal radius of one ATES system:

$$R_{th} = \sqrt{\frac{Vc_w}{H\pi c_{bulk}}}, \qquad (2.10)$$

where V is the injected volume of water in a season [m^3], H is the filter length (often equal to the aquifer thickness)[m], and c_w and c_{bulk} is the heat capacity of water and bulk sediment, respectively [Jm^{-3}]. A generally applied design criterion in the Netherlands is that the wells of an ATES system should be located 3 x R_{th} from each other. This means that two ATES systems (consisting of two wells each), are to be placed 7 x R_{th} from each other and the total space claim of one system comprises:

$$A = \pi \times (3.5 \times R_{th})^2 .\qquad (2.11)$$

The total subsurface heat storage capacity can be calculated by multiplying the thermal capacity of one ATES system with the ration the total available area and the subsurface claim of a single system.

2.4 Combined thermal energy and drinking water network

In order to assess the options of using the urban water cycle as a source and carrier for heat, we assessed two options to distribute heat:

- A single pipe water mains network;
- A dual pipe water mains network.

In both systems, the indoor climate and sanitary water system is the same and consists of heat exchangers and heat pumps. In the single water mains network, water for space heating is discharged to the same pipe as it is extracted from. In the dual pipe system water for space heating is discharged to another pipe as it is extracted from. For both systems, the sources and sinks outside of the indoor system for thermal energy are the same, e.g. surface water.

A related type of system has been tested in an experimental setup in Hamburg, Germany (Plath and Rottger, 2009, Niehues, 2010). Germany (Plath and Rottger, 2009). Plath and Rottger (2009) report that the systems operates well and has an efficiency nearly comparable to conventional heat pump systems. The paper does not detail whether the system is compared to air source or ground coupled heat pumps (this strongly impacts the efficiency). Niehues (2010) is more critical and states that any modification in the tap water system, not primarily designed for drinking water purposes should be avoided. This includes this system. Main risks he identifies are hygienic risks (both microbiological and chemical) from due to temperature changes and operational chemicals (cooling fluids) and unwanted excessive temperature fluctuations in the water network.

2.4.1 Indoor heating and drinking water system

In both systems, the indoor system is the same. At the house level, drinking water is split into a stream for sanitary use and a stream from which heat is extracted for space heating or cooling. Space heating and cooling of the house is achieved with a reversible heat pump. In winter, thermal energy for space heating is extracted from the drinking water distribution network. Water at 16-20^{o}C is extracted from the drinking water distribution network. The reversible heat pump then extracts thermal energy from the water. Water at a temperature of 8-12^{o}C is discharged to the drinking water distribution network. The efficiency of the reversible heat pump increases with water temperature of the water in the distribution network.
In summer the building is cooled by the same reversible heat pump by storing heat from the house into the water of the distribution system.

Different options exist for upgrading the temperature from the drinking water distribution system to hot sanitary water. Hot sanitary water can be provided by a heat pump if it is designed to provide water at high temperatures (>60^{o}C). Most modern heat pumps used in the current space heating systems allow for this. However the SPF of a heat pump supplying hot tap water is far less than when used only for space heating and, a more economical option is the use of a solar thermal collector, which can be placed on the roof of a building, or using a heat pump with auxiliary gas heater for the required regular (often weekly) increase in the operating temperature for the legionella prevention. The final and common option is to use an additional electrical water heater on top of the heat pump.

When the quality of the water in the system is of lower quality than drinking water, or the quality cannot be guaranteed due e.g. higher temperatures in the system, a local system is needed to provide drinking water for consumption and for using the shower/bath. Several options exists, e.g. a point of use filter, and will be further discussed in Chapter 6. Used sanitary water is discharged to the sewer system.

2.4.2 Single pipe water mains system

Figure 2.5 presents a conceptual diagram of heat and drinking water distribution using a single pipe system. The system is explained based on the situation in summer and in winter. In summer, heat is harvested from houses (by cooling the house), surface water (not shown in Figure 2.5) and possibly from the soil surrounding the water pipes. This thermal energy is transported by water, at a temperature of 12-16°C, to ATES wells using heat exchangers. ATES wells are positioned along the water network based on heat demand. Harvesting of heat provides cooling of houses and surface water and therefore is an adaptation measure to increasingly hotter summers due to climate change. In winter, the cycle reverses and heat is recovered from the ATES wells to heat water in the supply network. The water is transferred to households where thermal energy is abstracted.

The system is not closed as water is extracted for domestic use. Water can be supplied to the distribution system from the drinking water production plant or another water source. If flow is limited to the flow caused by water consumption, the water flux will not be sufficient to supply enough thermal energy. This may cause failure of the system due to excessive cooling or heating beyond the temperature range for good heat pump functioning. In both cases the efficiency of the heat pump (expressed by its SPF) decreases. Therefore, it is expected that it will be necessary to actively circulate the water in the system. Consequently, the water is diluted by fresh water rather then refreshed or replaced. This increases the residence time of water in the drinking water distribution network and may cause limitations on the water's usability for direct consumption. This limitation puts the constraints on the theoretical capacity of this type of system when it is based on the current drinking water system. In the single pipe system, a temperature gradient is established along the flow direction of the water network implying that the household which is downstream closest to an ATES system receives water at the most suitable temperature, i.e. highest temperature in winter and the lowest temperature in summer. The heat pump of this user will have the highest COP and uses the least electricity of the users along the network. This means that metering of heat extracted from drinking water and electricity use of the heat pump should be metered combined (as GJ of energy used as is usually done in district heating).

In spring and autumn, thermal energy supply and demand can vary from dwelling to dwelling and over time. Using a single pipe system one dwelling that has an energy demand can extract heat from the system, while the next dwelling that has an energy surplus can discharge its heat to the same system. This way the energy demand and supply can partly be solved within the water mains network. The single pipe network can be based on the current distribution network if its capacity is sufficient. The power capacity, P [W] of the heat distribution network working in heating mode can be calculated as follows:

$$P = c_p \Delta T Q \left(\frac{SPF}{SPF - 1} \right), \tag{2.12}$$

where Q is the capacity of water distribution network, where both the household connection and street pipes are to be considered [m^3/s]. If the system operates in cooling mode, the term in brackets on the right hand side is not included. Only in heating mode will the electrical energy of the heat pump contribute to the thermal energy delivered. The number of household connections [n] that can be connected per attached ATES system can be calculated by dividing the heat capacity within the drinking water network with the heat demand per heat pump of a household:

$$n = \frac{E_{network,supply}}{CF \cdot E_{heatpump,demand}} = \frac{Q_{network}(T_{in} - T_{low})}{CF \cdot Q_{heatpump} dT}, \quad (2.13)$$

where $Q_{network}$ is the water flux in the water network, T_{in} is the water temperature directly after it has been supplied with heat from a certain source (ATES, directly from surface water, et cetera) [^oC], T_{low} is the lowest temperature it is allowed to have [^oC], $Q_{heatpump}$ is the water flux required by the heat pump [m^3s^{-1}] and dT is the temperature difference of water flowing in and out of the heat pump [^oC]. pump and CF is the coincidence factor [-]. For heat distribution networks in the Netherlands, applied CF range between 0.5 and 0.6. Here, we apply a value of 0.6.

2.4.3 Dual pipe water mains system

Figure 2.6 presents a conceptual diagram of heat and drinking water distribution using a dual pipe distribution network, existing of a warm water and a cold water pipe. In summer, the cold water system can be used as a sink for heat generated by a heat pump used for space cooling. Heat is discharged through the warm water pipe and can ultimately be stored in an ATES system for use in heating mode during winter or discharged to surface water. In winter, the warm water pipe is used to provide energy for heating and the cold water pipe is used to discharge the cooled water. Also, in this case heat is obtained from either surface water or ATES.

The capacity of this conceptual heat delivery system strongly depends on heat losses in the pipe system to the soil. All households extract water at approximately the same temperature. Therefore, it can be expected that the COP will be equal for all households. Metering for energy consumption is therefore easier. In transition seasons heating and cooling demand varies between dwellings and during the day. Based on their individual demand for heating and cooling, dwellings can extract from the cold water or warm water system. Local circulation cells of water can develop. This is however not considered to be a problem.

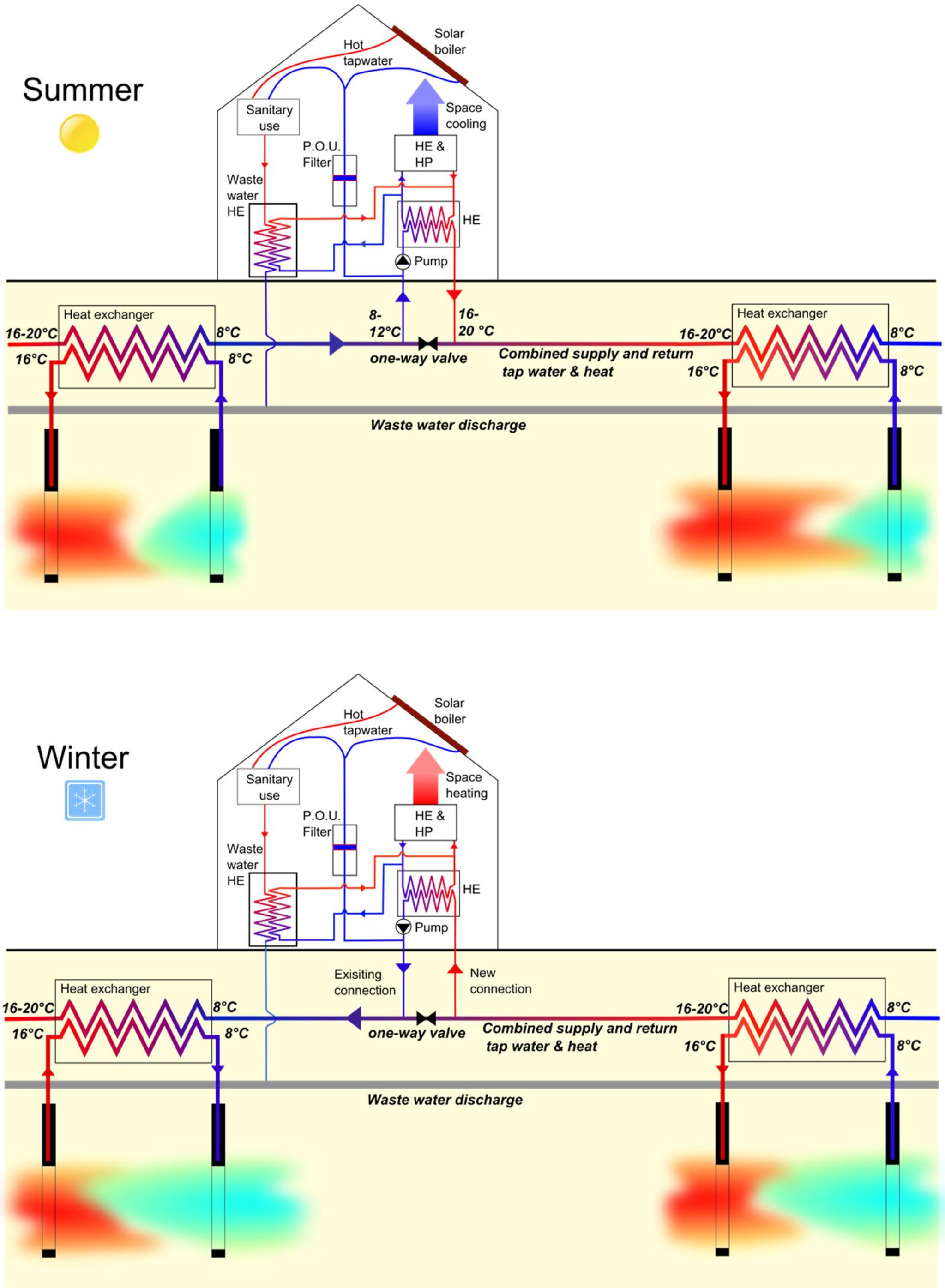

Figure 2.5 Heat distribution system option 1: Heat distribution using a single pipe system based on the existing water network. Abbreviations used: HE: heat exchanger, HP: heat pump, P.O.U. Filter.

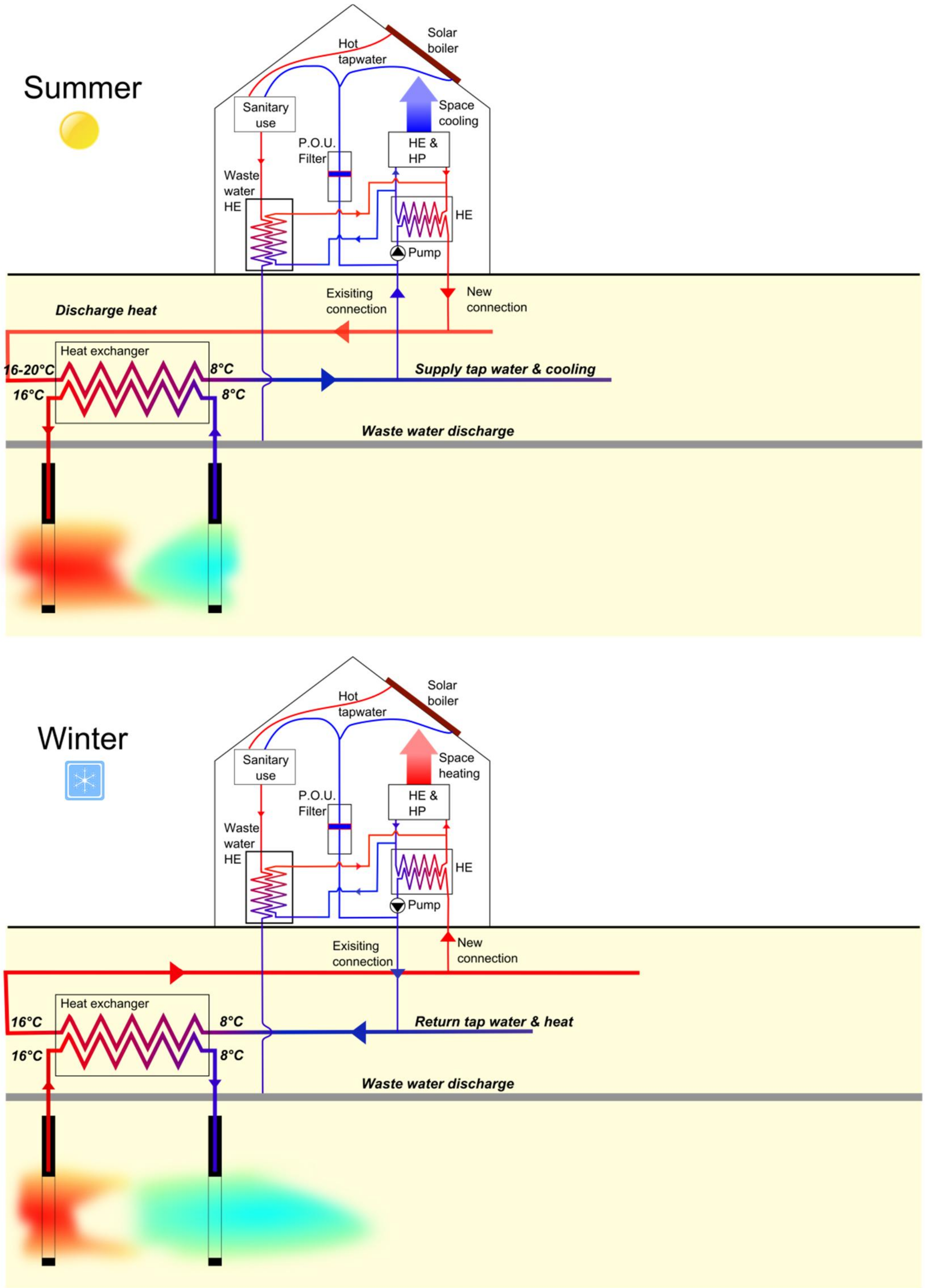

Figure 2.6 Heat distribution system option 2: Heat distribution using a double pipe system with one new water pipe. Abbreviations used: HE: heat exchanger, HP: heat pump.

3 Description – Case Watergraafsmeer

3.1 General description

The approach as described in Chapter 2 for assessing the urban water and energy balance is applied to the Watergraafsmeer district (WGM) located in Amsterdam, the Netherlands (Figure 3.1). The main roads are the Middenweg and the Kruislaan, dividing it in four nearly equal parts. Furthermore, the Watergraafsmeer is intersected by two main railway sections. The district can be characterized as a fairly green urban area, as a consequence of many sports fields, parks and a large cemetery.

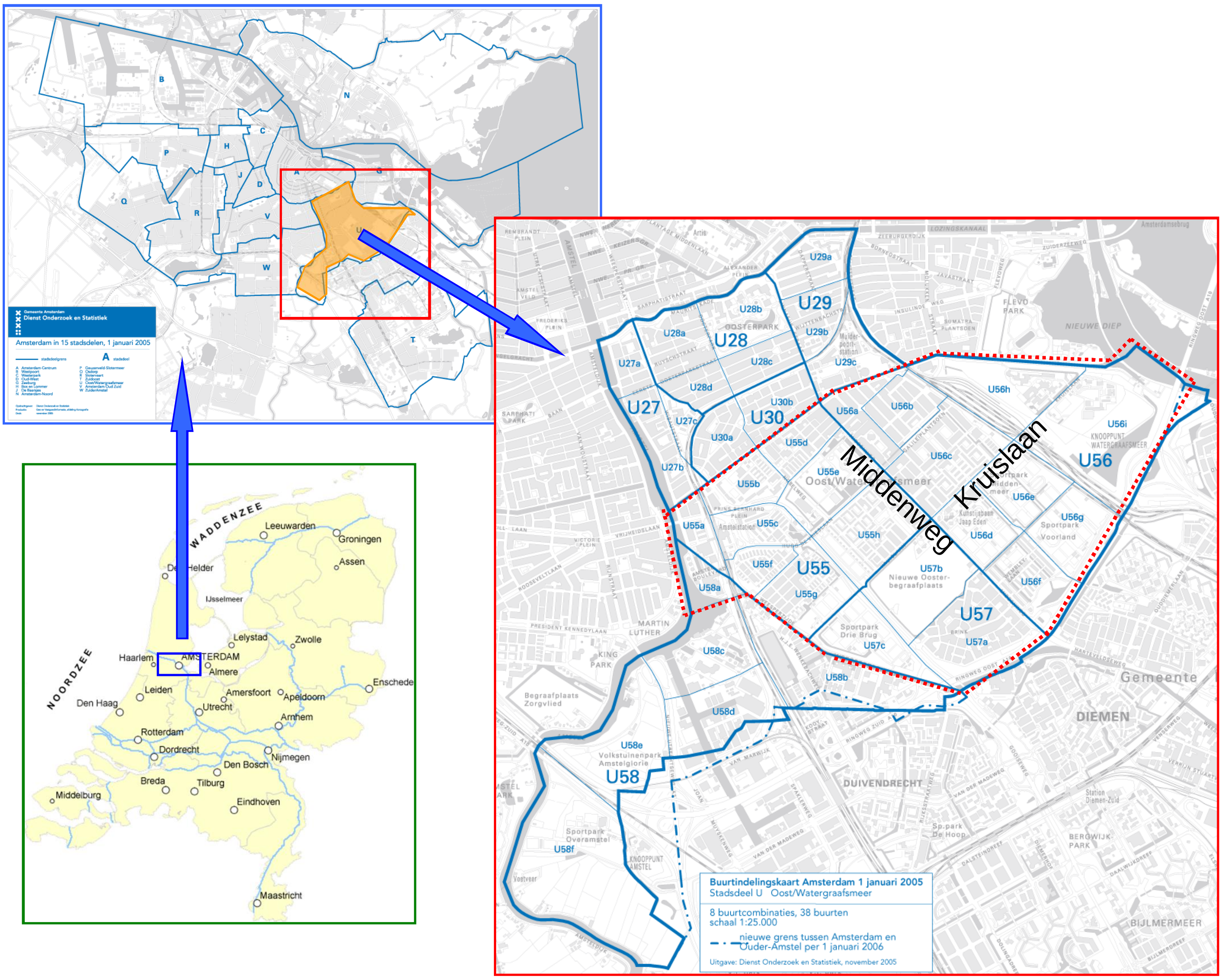

Figure 3.1 Location of Watergraafsmeer in Amsterdam, The Netherlands. For this research project the investigation has been limited to an area in Oost/Watergraafsmeer, composed from the sections U55, U56, U57 and U58a. (more specifically the area within the red dotted line).

The total area of almost 600 ha is subdivided by application according to Figure 3.2. The Watergraafsmeer is dominated by domestic housing and utility buildings. The locations of all buildings in this area are shown in Figure 3.3. Each blue dot represents a building. Most of the built environment, in numbers, is composed by approximately 15000 dwellings. The number of other large utility buildings in this area is about 150.

Large energy consumers in the district are the Jaap Eden Baan (ice rink) and the University of Amsterdam (UvA) Science Park in the eastern part of the polder and the Amstel Business Park. Detailed information on energy consumption of large consumers was only limited available due to privacy restrictions.

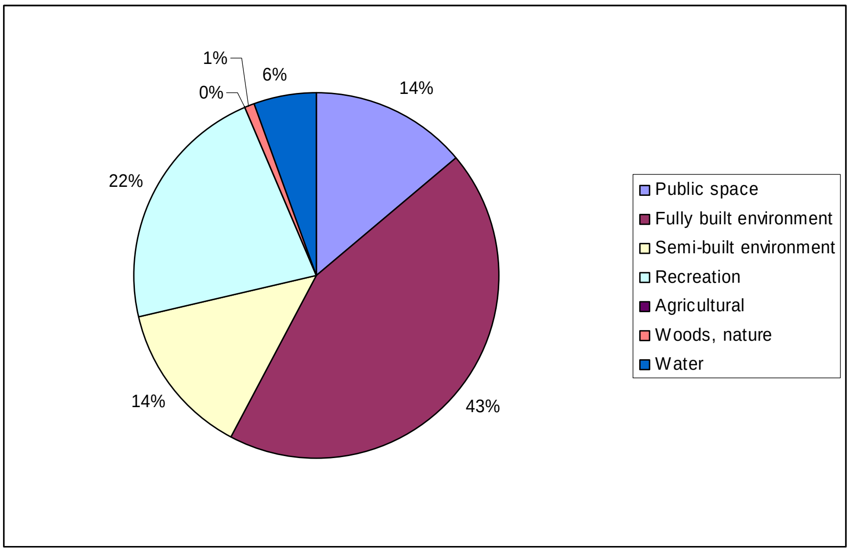

Figure 3.2 Use of space for different functions (Source: Gemeente Amsterdam Bureau Statistiek).

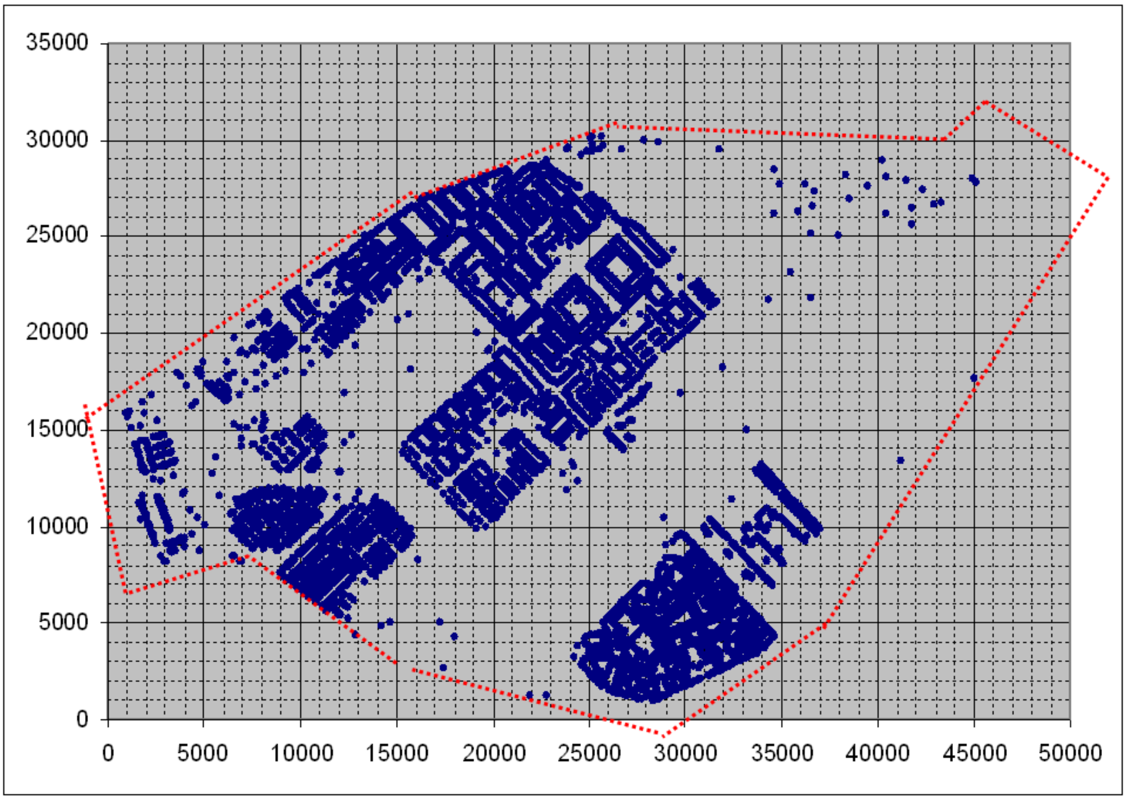

Figure 3.3 Locations of buildings indicated by blue dots (source: E-Atlas Amsterdam 2009 Liander)..

3.2 Drinking water and wastewater infrastructure

Drinking water consumed in the Watergraafsmeer is produced in two production locations: Weesperkarspel and the Leiduin Dunes (Hauser et al., 2011). Raw water at Weesperkarspel is drawn from the surface water body the Bethune polder, while the Leiduin Dunes are artificially recharged with water drawn from the Lekkanaal (which is kept at a constant stage with Rhine water). During the day water consumed in the Watergraafsmeer is drawn from Weesperkarspel while at night it is drawn from the Leiduin area. In the Watergraafsmeer area, most water pipelines are made of cast iron which was the most commonly used material in the early 20^{th} century. Main transmission pipes have a capacity of 60-90 m^3/hour which is based on fire fighting requirements. Three transport drinking water pipes (200 – 600 m^3/hr are crossing the Watergraafsmeer, supplying water to neighboring areas. Household connections generally have a capacity of 1.5 to 2.5 m^3/hour. The drinking water transmission system is a looped system (Figure 3.4).

Figure 3.4 Drinking water distribution network (Hauser et al., 2011).

The wastewater system in the Watergraafsmeer is predominantly a separated system discharging only domestic and industrial wastewater. In newer areas built in the last decades, separate storm water drains are constructed. This has the advantage that sewer overflows during intense storms are prevented. Wastewater from dwellings drains through gravity to central pits where it is further transferred to the wastewater treatment plant with booster pumps. The transport sewer system and pressurized system is shown in Figure 3.5.

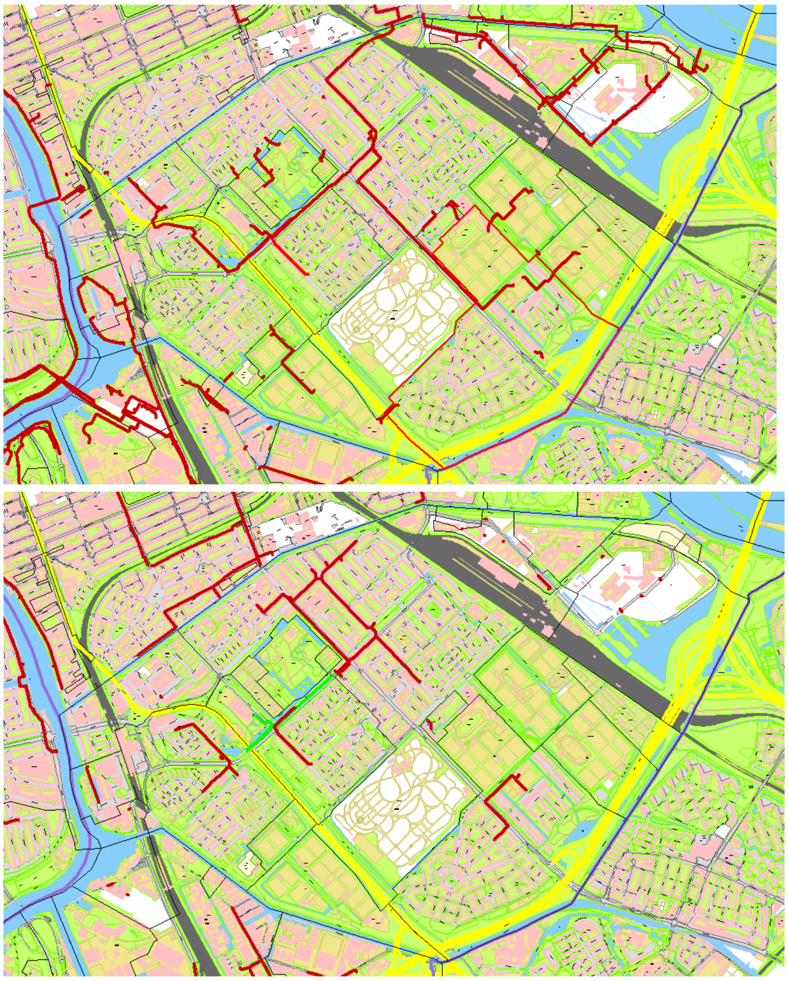

Figure 3.5 Pressurized transport sewer system and main gravity driven transport sewer system (source: data Waternet and topographical background Kadaster).

3.3 Groundwater

An inventory of the hydrogeological setting of the Watergraafsmeer was made using data of the Dinoloket (groundwater level monitoring data, the geological information of REGIS (accessible via http://dinoloket.nl) We note that REGIS information is considered to be the most accurate representation of the geological data in the Netherlands on a national scale. These data have to be used with some caution however: In the entire Watergraafsmeer, only two boreholes were used to construct the geological model (B25G0292 & B25G0929). Based on the combined hydrogeological information of the above sources, the hydrogeological units described in Table 3.1 and shown in a E-W and N-S profile in Figure 3.6 are discerned.

The hydrogeology of the Watergraafsmeer and the wider region of the east of Amsterdam is quite complex due to the glacial reworking of sediments during the Eemian. In the table below, we followed the generally used aquifer typology for the different sand layers in Amsterdam. We however joined the first and second aquifer (in Amsterdam often called sand layer) and discerned three parts in the third aquifer. This was done as the first and second aquifers are relatively thin and have a limited potential for ATES whereas the third aquifer is far more important for ATES. The Maassluis formation is often not considered as a 'true' aquifer due to its fine texture. It has however recently become an interesting formation for medium to high temperature ATES because its vertical anisotropy may prevent free convection (floating up of hot, less dense, water).

Table 3.1 Hydrogeological setting of the WGM

	Geological formation	Hydrogeology	Lithology	Top (m-MSL)	Bottom (m-MSL)	Hydrogeological parameters
1	Naaldwijk	Holocene cover	Fine sand, clay and peat	3 to -5	-12 to -15	
2	Boxtel & Krefteheije	1st +2nd Aquifer (following typical aquifer names used in Amsterdam)	Fine to coarse sand	-10 to -12	-17 to -24	kD = 100 - 300 m2/d k_h = 5 - 15 m/d
3	Eem	1st Aquitard	Loam, clay, marine clay	-17 to -24	-25 to -45	c = 300-3,000 d K_v = 0.005-0.01 m/d
4	Drente	3rd Aquifer, part A (an EW trending valley, absent or thin in north and south)	Coarse sand	-25 to -45	-40 to -50	kD = 0 - 600 m2/d k_h = 20 – 35 m/d
5	Drente (Uitdam & Gieten clays)	2nd aquitard (present in north of WGM)	Glacial till	-40 to -50	-52 to -65	C = 4,000 – 50,000d $k_v = 4x10^{-4}$ m/d
6	Urk / Sterksel	3rd Aquifer, part B	Coarse sand	-52 to -65	-70 to -85	kD = 250 – 800 m2/d k_h = 20 - 30 m/d
7	Waalre	3nd Aquitard (present in SW WGM)	Clay	-70 to -95	-90 to -100	C = 1,000-2,000 d Kv = 0.01 - 0.07 m/d
8	Waalre & Peize	3rd Aquifer, part C	Very coarse sand	-90 to -100	-140 to -150	kD = 2000 – 3,500 m2/d k_h = 40 - 60 m/d
9	Top Peize & Maasluis	4th Aquifer	Fine to coarse sand & clay	-140 to -150	-300 to -310	kD = 1,000 – 2,000 m2/d k_h = 5 - 10 m/d
	Oosterhout	Hydrogeological base	Clay	-300 to -310	n/a	

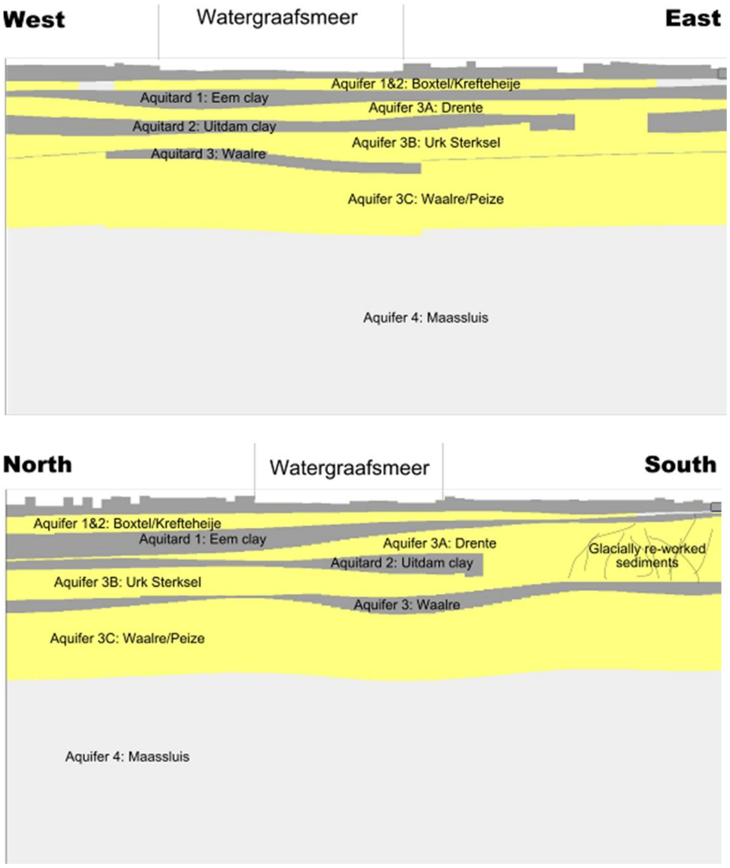

Figure 3.6 Hydrogeological cross sections over the Watergraafsmeer showing main aquifers and aquitards. Total depth shown is 300 m (source: Dinoloket.nl).

3.4 Surface water

The Watergraafsmeer is a polder and has an average surface level -4 to -5m NAP (mean sea level). The surface water level in the Watergraafsmeer is -5.5m NAP, which is lower than the surrounding areas. The average water level in the river Amstel and Amsterdam-Rijnkanaal is -0.4m NAP. Therefore, a permanent situation of upward seepage exists. The polder is drained by a network canals (Figure 3.7) and polder drains which convey the drainage water to two pumping stations. Under normal conditions water is discharged to the Amsterdam-Rijnkanaal in the east. In wet conditions water is also discharged in the west to the river Amstel. The inlet of water is limited, therefore the circulation of water in the surface water system is limited.

The area covered by surface water is about 6% of the total area of the Watergraafsmeer.

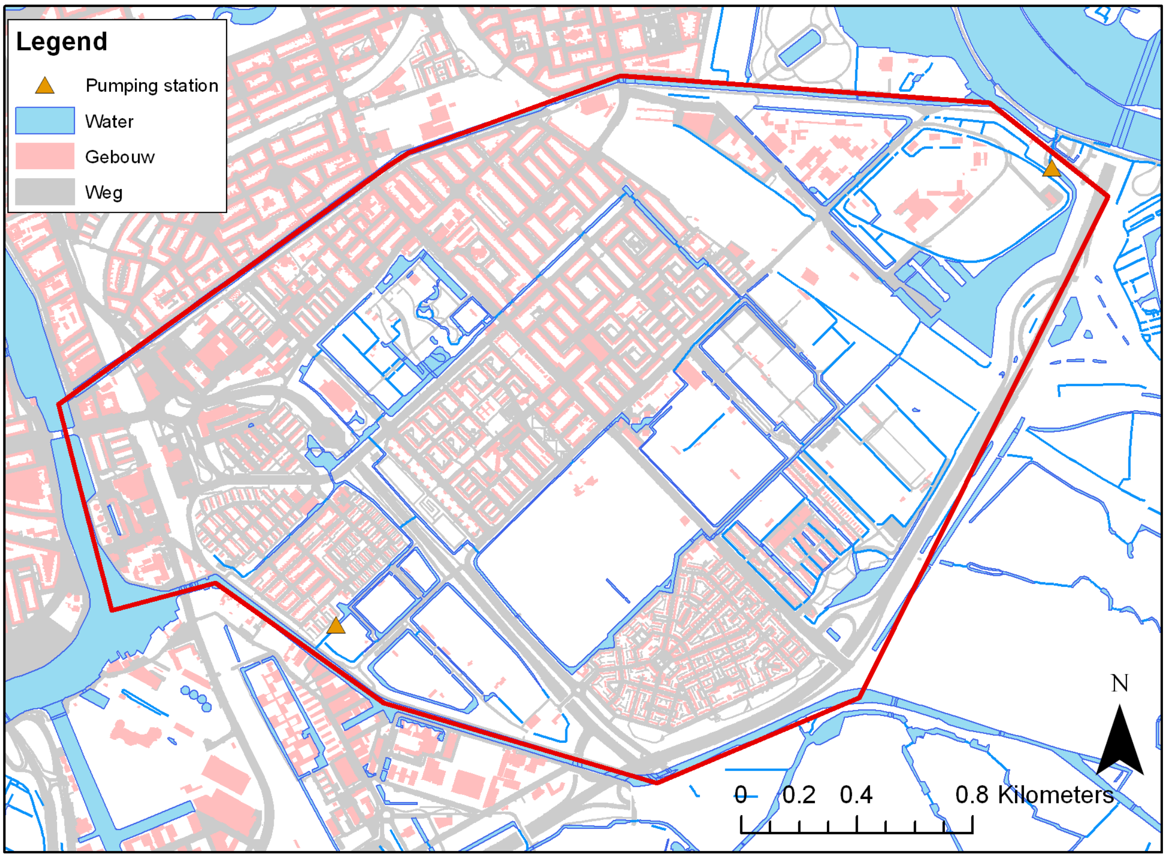

Figure 3.7 Surface water in the Watergraafsmeer. The pumping stations are located in the east and the west (source: Waternet and Top10Vector).

4 Results – Case Watergraafsmeer

The approach as described in Chapter 2 has been applied to the case Watergraafsmeer in order to assess the feasibility of a system that delivers both thermal energy and drinking water to dwellings.
The following steps have been undertaken to assess the feasibility:
- Quantify heating and cooling demand of dwellings;
- Determine and quantify available sinks and sources of thermal energy;
- Determine required storage capacity.

4.1 Heating and cooling demand

4.1.1 Analysis of totals

A data set with gas and electricity consumption figures for the year 2009 was supplied by Alliander, the energy (electricity and gas) network controller for the Amsterdam region. In this section a summary is given of the analysis that has been performed.
In Appendix A the full analysis is described.

For the district under investigation:
- Total gas consumption was 32.5 10^6 m^3, which is equivalent to 1142 TJ (primary)
- Total electricity consumption was 204 10^6 kWh, equivalent to 733TJ (primary)
- Average gas consumption for all connected consumers (utility and dwellings) in the district was approximately 2670 m^3/consumer;
- Average electricity demand for all connected consumers (utility and dwellings) in the district was approximately 11.600 kWh/consumer.

The connected consumers can be subdivided into two categories, respectively high-level (HL) and low-level (LL) consumers.
For gas:
- Low-level consumption covers all consumers with a consumption below 170.000 m^3/year. In general this applies to all dwellings and to small (utility) buildings.
- High-level consumption (over 170.000 m^3/year) stands for buildings like offices and industrial sites.

For electricity, the threshold between the two categories is formed by the available connection capacity, exceeding the level of 3 x 80A or not. In general, all dwellings belong to the LL-category. Table 4.1 shows the consumption figures split by consumer category (HL/LL).

Table 4.1 Energy consumption per consumer category.

Source	Unit	Consumer category		
		HL	LL	Total
Electricity	10^6 kWh	155.6	48.1	203.7
	% of total	76.4	23.6	100.0
	Per consumer 10^6 kWh	1.1	0.0036	
Gas	10^6 m^3	14.3	18.2	32.5
	% of total	44.0	56.0	100.0
	per consumer 10^3 m^3	19.60	1.72	

For the low-level category, the average energy consumption is according to expectations, based on the knowledge that this category is mainly covering the household energy consumption, combined with limited consuming utility buildings, e.g. shops. For high-level consumers, the monitored average values are much more difficult to judge due to lack of specific knowledge of the consumer types in this category.

4.1.2 Analysis of detailed data

Starting from the data totals above, a specification is made, based on postal codes which mark the energy supply to dwellings on the one hand and utility buildings on the other. By restricting data to the relevant postal codes, a small gap in total energy consumption compared to the values under 4.1.1 arises (approximately 5% less). Based on these monitored values and the assumptions from Section 2.1.1, the total heating and cooling demand for the Watergraafsmeer area are specified in Table 4.2 for different functions and building categories.

Table 4.2 Heating and cooling demand for the Watergraafsmeer area for different functions based on monitored values.

Category	Space heating demand [TJ]	Space cooling demand [TJ]	Hot sanitary water demand (gas) [TJ]	Hot sanitary water demand (electricity) [TJ]
Dwellings	385	9.14	118	
Utility buildings	368	138.2	20.1	9.0
Total by function	753	147.3	138.1	9.0

The temporal distribution is shown in the Figure 4.1. Actual values are available in Appendix A.

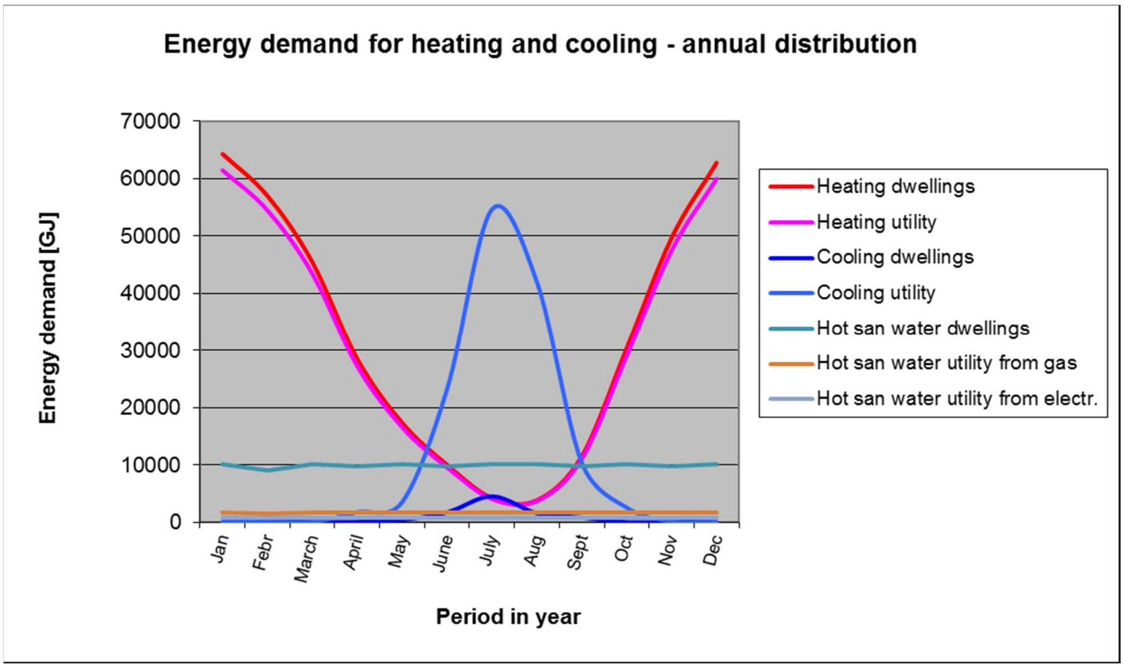

Figure 4.1 Temporal distribution of energy demand for different functions.

4.2 Thermal energy in the urban water system

Within the urban system several sources of thermal energy can be identified. Because water is used as transport medium for thermal energy, the focus is on sources within the urban water system. The sources investigated in this case study are:

- Surface water;
- Drinking water system (in current situation);
- Wastewater;
- Main sources outside the urban water system.

4.2.1 Surface water

Figure 4.2 shows the yearly averaged flow pattern in the water system. Drainage of the system takes place through two pumping stations in the southeast and northwest. The average flow rate is relatively low at about $0.05 m^3 s^{-1}$ and the maximum flow rate does not exceed $0.15 m^3 s^{-1}$.

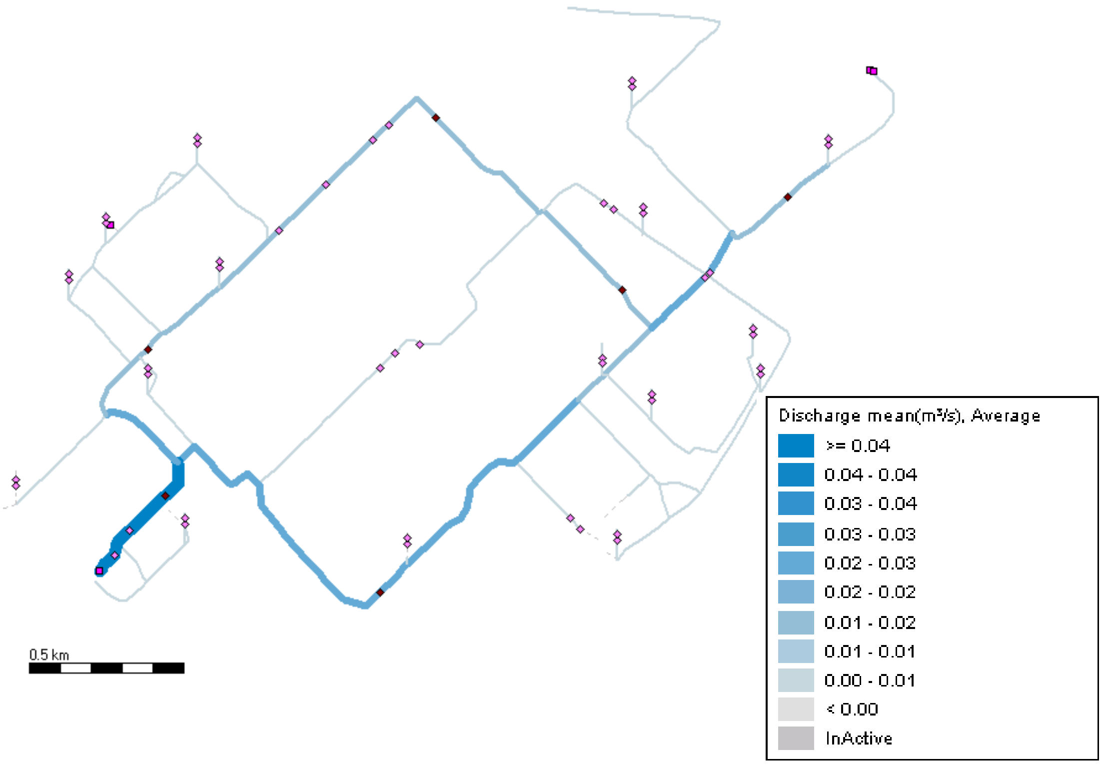

Figure 4.2 Spatial distribution of the yearly averaged circulation in the Watergraafsmeer

Thermal calculations have been made for the period 2005 to 2007. The three summers in this period are quite different. The number of days in which the water temperature exceeds 18˚C is given in Table 4.3 for reference. Compared to the average of the period 2000-2009 the summer of 2007 is cool, the summer of 2005 is average and the summer of 2006 is relatively warm.

Table 4.3 Number of days in which the water temperature in a Dutch water of 1.5m deep exceeds 18 ˚C (source Report WKO Hoog Dalem, 2010).

Year	Days water temperature > 18°C
2005	83
2006	103
2007	65
Average 2000-2009	78

Water temperature measurements for the model boundaries were not available. Therefore, simulated values were used, obtained from a separate model (Landelijk Temperatuurmodel) which simulates water temperature for an isolated water body with a depth of 1.5 m using Schiphol meteorological data. The simulated water temperature (Figure 4.3) is fed to the boundaries of the Watergraafsmeer model. In practice this implies that all boundaries of the Watergraafsmeer model have the same water temperature forcing, i.e. runoff, groundwater and inlet water. Due to lack of field data the model was calibrated nor validated. The model can be improved by applying more realistic water temperatures to these boundaries, preferably measured data.

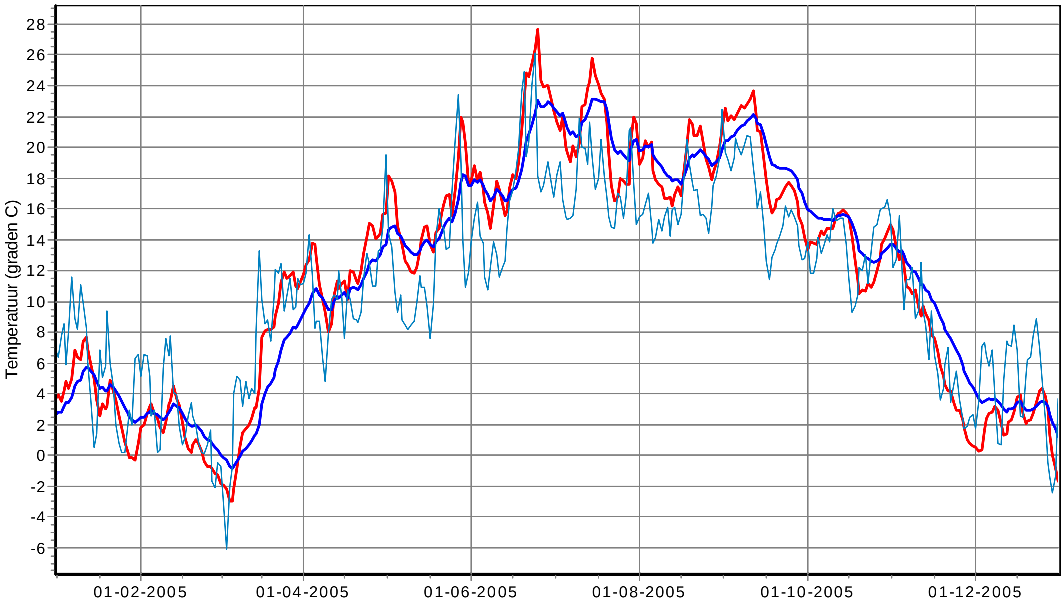

Figure 4.3 Air temperature (thin blue line) and simulated water temperature form the Landelijk temperatuurmodel for an isolated water body of 1.5m (red line) and 5.0m (blue line) for the year 2005.

Harvesting heat during warm periods / Potential heat extraction

An estimate has been made of the potential summer heat that can be abstracted from the surface water in Watergraafsmeer in favour of regeneration of ATES. The simulations were performed for the period 2005-2007 assuming all the area and volume of the Watergraafsmeer participates in the heat collection (i.e. 245.000 m^3, 295.000 m^2, average depth 0.83 m).

Next to the natural situation, we compare two methods that differ in the way the heat is extracted:

1. Heat extraction with a fixed end temperature: Regeneration takes place during May-September when the natural water temperature exceeds 16˚C. In this case we assume that after regeneration the return water temperature is always 16˚C (so available dT is high on warm days and is next to zero on cool days).

2. Heat extraction with a fixed temperature difference: Regeneration during May-September when the natural water temperature exceeds 16˚C. In this case, we assume that after regeneration the return water temperature is always 4˚C cooler than the source.

The resulting water temperature is presented in Figure 4.4. Clearly, the first method is a more realistic approach as the surface water temperature remains sufficiently high for regeneration. The second method results in water temperatures far below 16˚C, which is too low for efficient regeneration. The total heat that is gained is higher in the first method as it profits more from days when water temperature is above 20˚C.

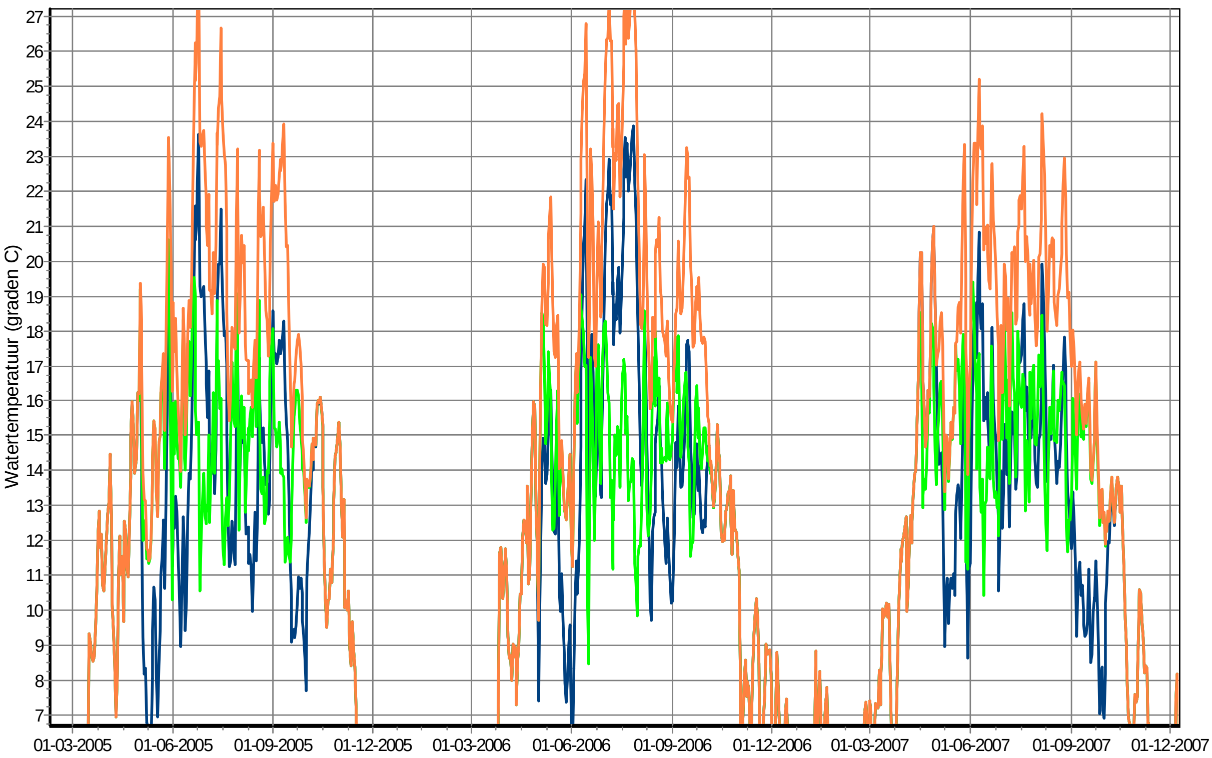

Figure 4.4: Simulated water temperature (˚C) for the natural situation (orange), heat abstraction to 16˚C (green) and heat abstraction with dT=4 (blue).

Therefore, the estimates for the potential heat abstraction are based on the first method. The gained thermal energy varies between the three investigated years between 492 and 662TJ (Table 4.4). During the year, heat can be extracted during approximately five months (Table 4.5).

Table 4.4 Yearly heat extraction capacity based on fixed end temperature.

Year	TJ/season
2005	-513
2006	-662
2007	-492

Table 4.5 Monthly heat extraction capacity based on fixed end temperature.

Month	TJ/month average 2005-2007
5	-44
6	-132
7	-190
8	-105
9	-71

4.2.2 Drinking water

The potential heat extraction from drinking water is calculated as described below. A threshold temperature of 10°C and a minimum harvesting temperature of 17°C is used. Figure 4.5 shows the measured temperature in a main water pipe line at the Muiderstraat located just outside the Watergraafsmeer.

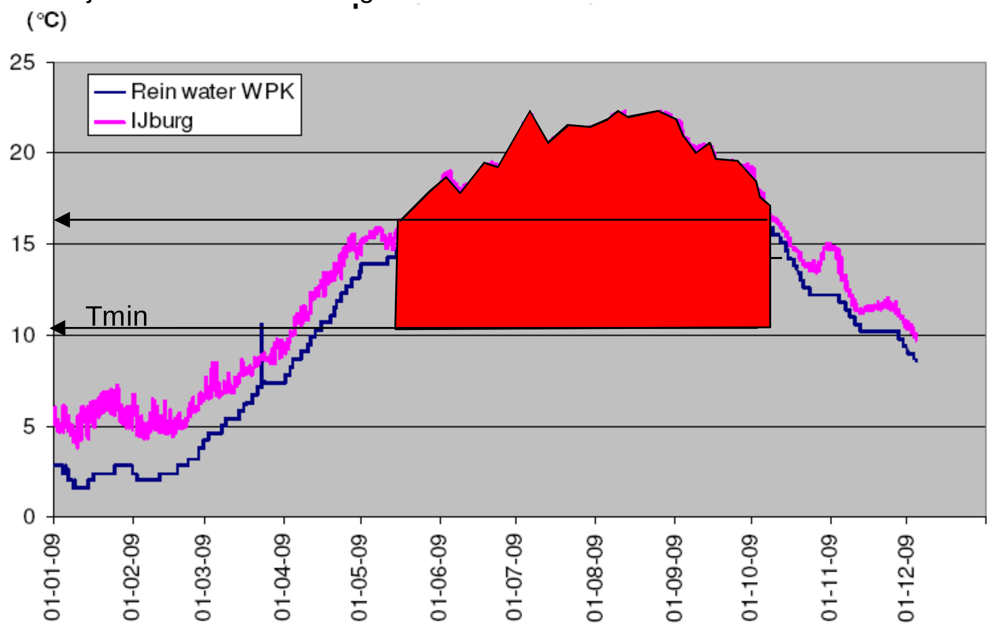

Figure 4.5 Temperature in main water transmission line at the Muiderstraat Amsterdam [4]

From this figure, it can be seen that water exceeds the required temperature of 17°C in the period between May 15th to October 1st. The average temperature in this period is around 19°C. The total harvestable heat for the Watergraafsmeer is then estimated to be equal to the total water use of 4,600m^3/day, with an average temperature differential of 9°C and a harvesting period of 139 days at 24TJ.

Next to the distributed drinking water that is used in the Watergraafsmeer, three distribution pipes cross the Watergraafsmeer to deliver drinking water for neighbouring areas. These pipes distribute each 200 – 600m^3/hour (low and peak demand) and offer a large potential of energy harvesting. Using an average of 400m^3/hour this is equivalent to 14TJ for one degree of temperature difference for one pipe. In practice this will only be extracted in summer, resulting in a total available heat amount of 22TJ.

4.2.3 Wastewater

Two options to recover heat from wastewater are described below: heat recovery from showers and heat recovery from sewer systems. Both can be done simultaneously; heat recovery from showers has a negligible effect on the heat available in the sewer system.

Heat recovery from showers

In dwellings, the shower is very suitable for heat recovery as a large volume of hot sanitary water is used and relatively hot wastewater is produced simultaneously. Several versions of heat exchangers for showers are available on the market and about 40 - 70% of the heat can be recovered (e.g. http://www.shower-save.com/index.php/gastec, visited 29-07-2011). The saving on total gas use is estimated at 8.2%, taking into account the efficiency of shower heat exchangers (50%), gas use for warm water (23.5%, See Appendix A) and the percentage of warm water used in the shower (70%, Blokker and Pieterse-Quirijns, 2010). Total gas consumption in the Watergraafsmeer is 503TJ (for dwellings, Table 4.2), resulting in a potential saving of 41TJ per year.

Heat recovery from sewer systems

The total amount of harvestable energy depends on factors such as distance from harvesting to use, wastewater flow and temperature. For each location the available heat and the feasibility of recovery has to be determined separately.

As described in Section 2.2.1 heat recovery from wastewater is in a sewer system is feasible in certain locations that have a main sewer system with a diameter of 400 mm and a minimum flow of 10 -12 L/s. A total of 14 zones in Amsterdam were studied by Monsalve (2011). Two locations were in Watergraafsmeer where a sewer system after renovation will meet the requirements of feasible heat recovery. A business case for one location (James Wattstraat) showed that for a wastewater flow of 20 L/s 391 kW of heat could be delivered, using a 50% heat pump efficiency and a COP of 4, requiring an electricity input of 98 kW. We note that the COP used by Monsalves (2011) appears quite high compared to the earlier estimates made in section 2.3. Close to the sewer system new student apartments are going to be build and with the recovered heat 195 apartments can be provided with heat (where an assumption is used of 2 kW per apartment). Assuming a total of 1250 full load hours, a thermal energy production is found of 135MWh or around 0.5 TJ. The total heat harvesting capacity a this one location was further investigated by Tissier (2011) who estimated the total harvestable heat capacity at this location to be 1734 MWh or 6 TJ for a 80 m long heat exchanger.

It is hard to translate this one location estimate to a regional estimate for heat recovery from wastewater. Monsalve (2011) shows that wastewater leaving dwellings has an average temperature of 27°C but almost all heat has dissipated within 100 m (Monsalve, 2011). For heat harvesting to be financially attractive, the flow has to be adequate. This means that harvesting close to homes is difficult because the flow of only a few households is insufficient.

A quick scan of the sewer system in Watergraafsmeer shows that there are in total five locations were the amount of wastewater is enough to extract heat from (Table 4.6). In total this is equivalent to 62TJ of potential available heat. It has to be remarked that implementation of the extraction of this heat is only feasible on the long term, e.g. when the sewer system has to be renovated.

Table 4.6 Potential heat from sewer system in Watergraafsmeer (provided by Stefan Mol, Waternet)

Area	Number of inhabitants	Heat Potential (TJ)
James Wattstraat	2300	6
Galileoplantsoen	12000	30
Hugo de Vrieslaan	2000	5
Schagerlaan	3000	8
Middenweg	5000	13
Total Watergraafsmeer		**62**

Another option is heat extraction from the pressurized sewer system leaving the Watergraafsmeer. Recently heat exchangers have been developed for this type of sewer system as well.

4.2.4 Sources outside the urban water cycle

A number of heat sources outside of the urban water cycle are available: Most notably heat supply from the Jaap Eden Ice Ring, the University Science Park and deep geothermal energy.

Jaap Eden ice skating rink and project development Jeruzalem

The Jaap Eden ice skating rink uses cooling machines to make an ice rink during winter time. The heat that is currently generated in this process is discharged and not used. The housing corporation Rochdale intends to renovate some 700 duplex houses and to use the waste heat from the Jaap Eden ice rink in combination with an ATES system (DWA, 2010a and 2010b).
The 700 houses were to be fully isolated requiring a heating power of 6kW per house, 4.2MW in total. This is considerably lower than houses, which are mostly heated with gas fired heaters, having a thermal power ranging between 20 and 40kW. Assuming an average number of 1250 full load hours per year, the total heating demand for the renovated 700 houses is 18.9 TJ (5,250 MWh). Of this 18.9 TJ, around 75% of heat could be harvested from the Jaap Eden ice rink (14.2 TJ at 20°C). Using an ice rink as a heat source is in this setting very interesting because the heat is generated during winter time (the ice rink is only active in winter) and has a very constant load. The beneficial use of heat is also expected to have a positive impact on the cooling machines of the ice rink due to the lower condenser temperature of the freezing machines.

University of Amsterdam Science Park

UvA Science Park consumes about 64 10^6kWh electricity. Part of this energy is used for lighting, computers and other office purposes. Two large consumers use electricity for data and communication centers consuming 57% of the total consumption, corresponding to 35 10^6kWh. Assuming that most of the energy is used by computer servers, more than 50% of 35 10^6KWh of energy is than discharged through cooling systems. It can be assumed that about 18 10^6kWh or 63TJ of thermal energy can be obtained from the data centers for heating.

Geothermal Energy

In 2007, the first geothermal well system was successfully commissioned which has sparked an interest in this technology. Over the last five years, some 60 exploration licenses have been published and several more geothermal wells have been drilled. The Dutch geological survey investigated which geological formation are likely suitable for extracting geothermal energy and found sandstones from the Rotliegend, Triassic and Lower Cretaceous formations to have the highest probability of producing geothermal heat. Based on various sources of information, Figure 4.11 shows the suitability for geothermal energy in the Netherlands. In the

Watergraafsmeer, Triassic sandstones are likely to be present but the potential is however uncertain. Another problem with many geothermal wells in the Netherlands, is the high chance of natural gas or oil produced along with the geothermal energy. This requires additional technical measures at the well system. Given the uncertainty on the geothermal potential, this source of heat is not included. Experience from other locations in the Netherlands however do show that if a good producing geothermal aquifer is present, it can easily supply many dwellings with heat. Compared to harvesting heat from the water cycle this heat is produced at relatively high temperature (60-80°C for geothermal instead of 15-25°C for heat from the water cycle). On the other hand, geothermal wells are not completely sustainable in the sense that they do not have an infinite life time or are renewable: once a geothermal well is exhausted, recovery takes several thousand years.

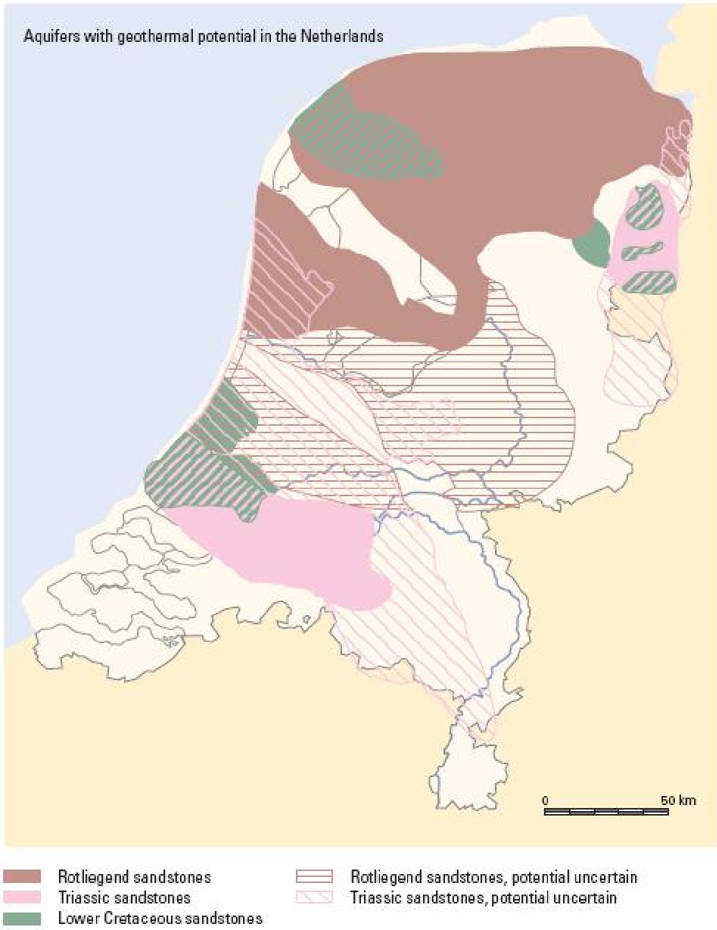

Figure 4.6 Geological formations likely suitable for geothermal energy.

4.3 Thermal energy storage

In general, the hydrogeological conditions in the lower part of the 3rd aquifer (3C) in the Watergraafsmeer and Amsterdam in general are very suitable for ATES and all existing ATES systems are realized in this aquifer. In order to assess the total capacity for thermal heat delivery and storage, we will however here consider all available aquifers. For the assessment of the potential of ATES, we will assume that sufficient heat sources are available. Connection of the different heat sources will be discussed in the next section on heat distribution. Here, we focus first on storing heat to resolve the mismatch of demand and availability of heat in time. Table 4.7 shows required water circulation volumes for the three ATES concepts.

Table 4.7 Annual water circulation.

ATES type	ΔT (°C)	Annual water circulation (million m3/year)		
		HL	LL	Total
SLT ATES	8	9.1	9.5	18.6
OLT ATES	17	4.6	4.8	9.3
MT ATES	20	4.8	5.0	9.8

Although all ATES established over the last years have been established in aquifer 3C, it is interesting to consider the more shallow aquifers for thermal energy storage in the Watergraafsmeer. The energy analysis shows that around half of the total heat requirement originates in domestic housing, while the currently installed ATES are associated with utility buildings. Domestic houses (mostly 3 or 4 floor building blocks) have a lower heat demand per m^2 built area compared to utility buildings (often with more floors). This means that shallow ATES with a lower capacity may be more appropriate here.

Equations (2.4) to (2.6) are used to calculate the maximum allowable flow velocity in the ATES boreholes assuming a membrane filtration index (MFI) = 2 s/L, v_v = 0.1 m/year and u = 1350 hours (average of band width in utilisation hours for a conventional gas heater in the Netherlands (NOVEM). For the two shallow aquifers, a relatively small filter diameter is assumed as shallow wells are often drilled with a smaller diameter while for deeper wells often a larger diameter is selected. Table 4.8 presents the hydrogeological parameters of the aquifers as used in the calculations. The results show that the capacities for ATES wells in the different aquifers ranges between ~3 to ~ 90m^3/hour. At these flow rates, the expected injection pressure, Δs, remains well under the maximum allowable injection pressure, Δs_{max}.

Table 4.8 Design flow rates for ATES wells in the different aquifers in the WGM, expected injection pressures and maximum allowable injection pressure

	L	K_h	H	$c_{combined}$	v_{max}	r_{filter}	Q_{max}	Δs	Δs_{max}
	(m)	(m/d)	(m)	(d)	(m/hour)	(m)	(m3/hour)	(m)	(m)
1st +2nd Aquifer	13	10	12	750	0.8	0.3	2.9	0.64	2.86
3rd Aquifer, part A	28	27.5	10	1395	1.6	0.3	4.4	0.47	6.16
3rd Aquifer, part B	55	25	19	1395	1.5	0.4	14.0	0.87	12.10
3rd Aquifer, part C	93	50	50	600	2.2	0.5	87.4	1.06	20.46
4th Aquifer	143	7.5	160	1000	0.7	0.5	89.6	2.23	31.46

Based on the calculated well capacities shown in Table 4.8, and the number of utilisation hours per year (u=1350 hours / year) we can calculate the total volume of water circulated per year. For this calculation we apply a safety factor of 0.8 to consider well maintenance and other factors that cause an ATES well system to be utilised less than a conventional gas heater. Using Equation (2.7) and the ΔT shown in Table 4.7, we calculate the delivered heat for the different aquifers and ATES systems (SLT, OLT and MT). The results of these calculations are shown in Table 4.9. These results show that in aquifer 3C, ATES systems can be realized that can generate 383 to 764 MWh of heat. Note that the OLT system delivers more heat than the HT ATES system. The fraction of electrical heat generated by heat pump is however much higher in the MLT system, which means that the HT has a higher fraction of renewable heat.

Table 4.9 Heat yield per ATES system for different aquifers (including heat generated by electrical energy used in heat pump) and number of systems required to meet heat demand of LL and HL shown in table 3. Based on u = 1350 hours and a safety factor on the maximum well capacity of 0.8.

Aquifer	Volume circulated per season	Standard low temperature ATES			Optimised low temperature ATES			Medium temperature ATES		
		Heat delivered per system / season		# of systems to deliver total demand	Heat delivered per system / season		# of systems to deliver total demand	Heat delivered per system / season		# of systems to deliver total demand
		MJ	MWh		MJ	MWh		per system	MWh	
Aq 1st +2nd	3900	174,304	48	4760	347,246	96	2389	338,492	94	2451
Aq 3rd part A	5900	263,691	73	3146	525,321	146	1579	512,078	142	1620
Aq 3rd part B	30880	1,380,130	383	601	2,749,478	764	302	1,640,385	456	506
Aq 3rd part C	118000	5,273,813	1,465	157	10,506,425	2,918	79	10,241,557	2,845	81
Aq 4th	121000	5,407,893	1,502	153	10,773,538	2,993	77	10,501,936	2,917	79

The total (land) area of the Watergraafsmeer is around 10 km^2, the maximum number of systems that can be placed randomly can be estimates by dividing the total area by the area per system. Table 4.11 shows the results of these calculations. Also shown are the maximum heat delivery for the three types of ATES systems in the Watergraafsmeer and the total potential heat delivery.

Table 4.10 Subsurface space claim of ATES systems in different aquifers, maximum number of systems in the Waterfgraafsmeer and total heat delivery. Note that total required heat demand is around 800,000 GJ/year.

	Thermal radius per bubble	Subsurface claim	Max systems	Potential heat delivery		
				SLT	OLT	HT
	(m)	(m^2)	(#)	(GJ/year)	(GJ/year)	(GJ/year)
1st +2nd Aquifer	23.3	20963	477	83,000	166,000	161,000
3rd Aquifer, part A	31.4	38055	263	69,000	138,000	135,000
3rd Aquifer, part B	40.8	64161	156	132,000	262,000	256,000
3rd Aquifer, part C	62.9	152220	66	346,000	690,000	673,000
4th Aquifer	35.6	48778	205	1,109,000	2,209,000	2,153,000
Total GJ				1,739,000	3,465,000	3,378,000
Total GJ/ ha				1,739	3,465	3,378

From Table 4.11, it can be seen that overall the subsurface in the Watergraafsmeer has sufficient potential to meet demand. Surprisingly however, most of the potential is present in the 4th aquifer, which has less suitable hydrological characteristics but is very thick which means that individual systems have a limited subsurface space claim. It is however very questionable whether it is financially viable to drill wells up to 300 m depth, with >100 m filter that can only deliver 70m^3/hour. The geological formation comprising aquifer 4, is under investigation in other regions in the Netherlands for high temperature storage (80°C). Using this aquifer for this type of storage might be more financially viable due to the much higher COP in delivering heat to houses. Another advantage is that hot water can be transferred directly to existing central heating systems. However, heat losses will be larger is this case, requiring a more expensive water distribution network that minimizes heat losses. The combined 1st & 2nd aquifer and aquifer 3A are unlikely to be a viable option for ATES. The currently mostly used aquifer 3C has around 700 TJ/year of storage capacity at the OLT scenario. This is just under the required energy storage (746 TJ/year in Table 4.11). This implies that if this aquifer is to be used, additional effort is required to realise efficient thermal energy storage that operate at the currently maximum allowed injection temperature.

The national 'heat map' of Senter Novem, also gives estimates of the heat delivery potential of the subsurface. The map gives a value of 3000GJ of heat/ha/year which compares well with the values for OLT and HT. It is however not clear which aquifer is considered and which temperature differential. If we would only consider the aquifer currently used for ATES, and the currently applied type of ATES systems (SLT), the potential is around 300GJ of heat/ha/year which an order of magnitude lower than the Senter Novem estimate.

4.4 Summarising heat demand, supply end storage

Table 4.11 presents an overview of heat demand, supply and storage. In this table, only demand and supply for space heating are shown, cooling demand is far less. Cooling is mostly required in utility buildings (e.g. Science park) where ATES systems are realized. The overview of demand and supply shows that the bottleneck in the Watergraafsmeer is in demand and supply of heat for space heating. Of the 783TJ demand, only 25% or some 200TJ can be supplied directly from waste heat. Most important are direct use of ATES (in buildings where there is also a cooling demand, to assure an energy balance) and direct harvesting of heat from surface water.

The remaining 580TJ for space heating can nearly completely be harvested from surface water. Storage of thermal energy from the surface water in ATES is essential because the thermal energy is available during the summer period when there is no to little demand. The ATES capacity calculations show that ATES in the aquifers at the currently used temperature differential provides insufficient storage. If the full temperature range, that is currently allowed (T_{max} = 25ºC) is used, sufficient storage is reached in the currently widely applied aquifer 3C.

Heat demand for hot sanitary water can just be met with heat generated within the other item listed for the water system in the Watergraafsmeer. External options could also be evaluated, e.g. heat harvesting from the Amsterdam Rijn channel to be stored in ATES, or waste heat from the Diemen energy plant. However, because hot tap water operates at a much higher temperature than low temperature heating, the COP for hot sanitary will be lower and using low enthalpy waste heat is not a good alternative for gas heated hot sanitary water appliances. A better alternative energy source for hot tap water is provided by thermal solar energy. Or to re-use as much heat generated within households (e.g. with shower heat exchangers) to heat drinking water.

Table 4.11 also clearly presents where efforts should be aimed at to achieve a closed heat balance of the district. Some caution should however be taken: the table does not include information on cost and return on investment.

Table 4.11 Summary of heat demand, supply and storage capacity.

Demand		**Direct supply from water cycle and buildings**		**Indirect supply from water cycle (temporal mismatch, heat to be stored)**		**ATES Storage potential in heat for different ATES types (TJ year^{-1})**			
Item	**Heat (TJ year^{-1})**	**Item**	**Heat (TJ year^{-1})**	**Item**	**Heat (TJ year^{-1})**	**Item[1]**	**SLT**	**OLT**	**MT**
Space heating	753	Direct surface water heat use for heating	74	Surface water using ATES (T_{min} = 16ºC)	556	3rd Aquifer, part B	132	262	256
Hot sanitary	147	In house recovery from sewerage (used for sanitary applications)	41	Local drinking water (Tmin = 17ºC)	24	3rd Aquifer, part C	346	690	673
				Drinking water (Tmin = 17ºC)	22				
				Regional recovery from sewerage	62				
				Direct supply from ATES based on balancing systems for buildings	98				
				Ice skating rink, Jaap Eden baan	19				
				Sciencepark	63				
Total heating	**921**	**Total direct usable heat**	**115**	**Total heat for ATES regeneration and indirect use**	**844**	**Total storage (aquifer 3B & C)**	**478**	**952**	**929**
Balance	**921**	**959**							

Note 1: SLT, standard low temperature ATES system (8-16 ºC), OLT optimized low temperature ATES system (8-25 ºC), MT medium temperature ATES system (8-25 ºC)

Subsurface planning

As discussed in the previous section, heat demand for space heating can roughly be met on a suburb scale by combining surface water heat to regenerate ATES systems. If the total heat demand is to be met, the ATES systems are to be operated on the full currently allowed temperature differential of 8 to 25ºC. This means that a distribution system is to be designed which can convey water at 25ºC with limited thermal losses. The capacity of one ATES system in aquifer 3C is estimated to be around 20TJ, which means that 35 ATES doublets are required.

Another boundary condition for a distribution system is set by the area to be supplied by one ATES system. The total surface area in the Watergraafsmeer is around 600Ha, of which 43% or 258Ha is classified as fully built environment. This class is considered for the surface water/ATES heat supply. One ATES system is thus assumed to supply an area of 258Ha/35 = 7.4ha. Assuming ATES systems are positioned on an rectangular grid, the distance between each ATES system is about 270m. The subsurface claim of one ATES is however nearly 20 Ha. This means that the demand can not be met because the heat demand density is too high.

A way to decrease the subsurface spatial claim is to define criteria for placing ATES wells. This could in a so called subsurface spatial plan, or an ATES master plan. Such a plan is for example made for the UvA Sciencepark where it was anticipated early on that planning the subsurface could boost utilization (Figure 4.11). The advantage of such a planned approach is that in the anticipated fully built situation, maximum benefit can be obtained from ATES. However, in many cases, an a-priori regulation can lead to a situation where ATES systems have to be installed conforming to a plan which can lead to additional cost.

In the case of the remainder of the Watergraafsmeer, ATES would mostly be used for existing housing, so the existing street plan can be used to determine the locations of the systems. The subsurface capacity could be boosted by combining hot wells of multiple ATES doublets. The on-ordered subsurface space claim versus the heat supply area implies that the positioning of ATES systems has be optimized to meet demand.

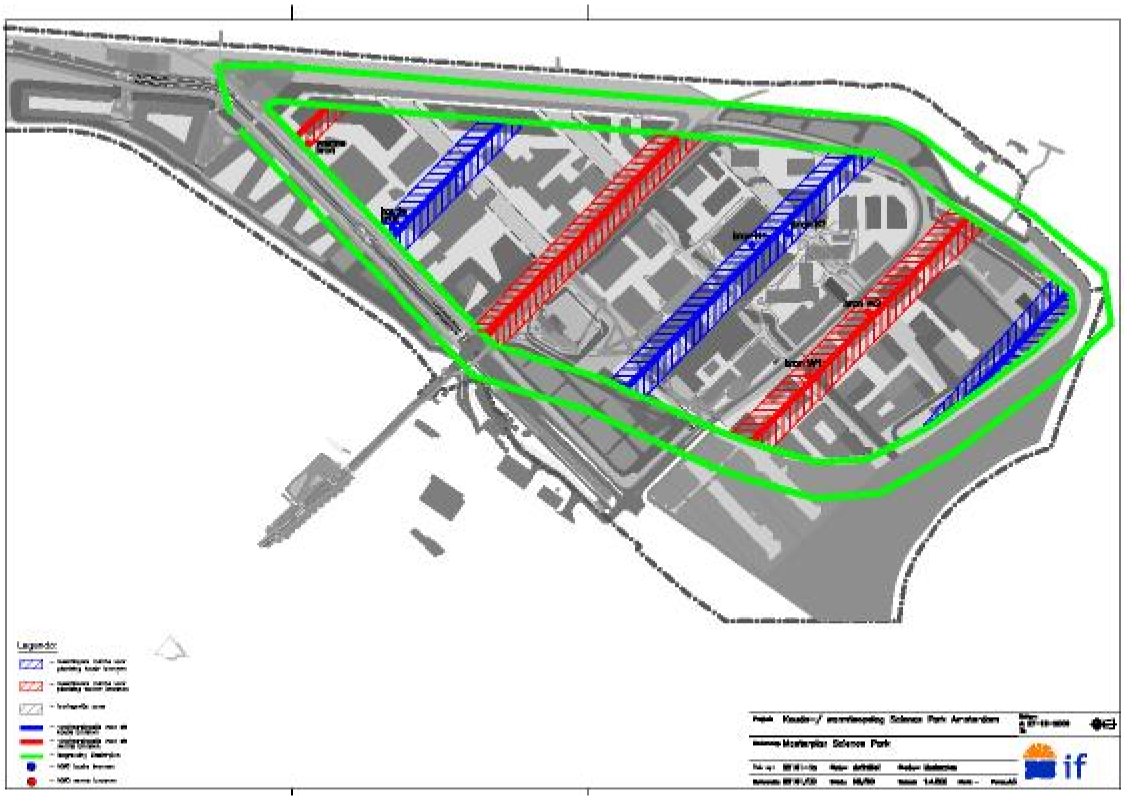

Figure 4.7 ATES subsurface master plan

4.5 Distribution network

Two distribution systems have been proposed and described in Section 2.4:

- A single pipe water mains network;
- A dual pipe water mains network.

4.5.1 Single pipe system

The single pipe system could in theory be implemented making use of the current mains network. To determine whether the capacity of the current system is sufficient, a first estimate has been made.

The capacities of the current drinking water network in the Watergraafsmeer are:

- House connection 1.5 – 2.5m^3/hour;
- Water transmission pipes: 60-90m^3/hour (mainly cast iron pipes).

These form the boundary conditions for the water fluxes, temperature range and consequently heat transfer of the system. In most heat pump applications using water as a heat source, the heat pump delivers the base load while the peak loads are supplied by either an additional electrical heater or peak load boiler. This minimizes costs and heat pumps have a longer life time if they are used for base load and not peak load use. A typical thermal power demand used by a heat pump for a well isolated medium sized house or apartment in the Watergraafsmeer is around 6kW. This covers 80% of the power demand for heating while covering around 98% of the energy use. The remaining 20% power and 2% use are often covered by an auxiliary electrical heater.

Using equation (2.10), a temperature difference of 8°C and a COP of 3.0 for a standard low temperature ATES system, we find a thermal power delivered by the heat pump of 27.9kW. This means that the thermal demand of the house can easily be met with a household tap water connection. The water use of a 6kW heat pump working on 100% capacity at a 8°C temperature difference and a COP of 3.0 is 0.43m^3/hour. This values lies well below the house connection capacity of 1.5 – 2.5m^3/hour.

The distance between the ATES systems along the drinking water network depends on the ratio of household heat and water fluxes and the flux capacity in the transmission pipe. Heat extraction occurs without net water extraction from the transmission pipe. Flow velocities in the network are determined by water extractions by households. In order to assess the required distance between ATES wells required to maintain a sufficient temperature in the water distribution net, we assume that the water in heating mode can not drop below 12°C and is heated in the ATES system to 16°C and two scenario's:

- a typical flow velocity of 0.02m/s in a DN 100mm water pipe (0.57m^3/hour);
- a high flow velocity of 0.1m/s in a DN 100mm water pipe (5.7m^3/hour);
- a maximum flow velocity set by the water capacity set by fire regulations (75m^3/hour).

The flow velocity in the first case is probably a realistic estimate of 'normal' flow conditions, the second flow velocity during peak hours (morning) while the third only occurs during fire fighting water extractions. When using the system for heat supply, the flow velocities should be maintained using booster pumps.

Based on equation 2.11 the number households connected to the water supply system can be calculated. Assuming a single pipe system and a lower temperature limit of the water temperature in the network of 12°C, the following capacities of the water supply network can be calculated based on the different tolerable flow velocities before water temperature in the network becomes too low:

- Flow velocity of 0.02m/s : 0.7 heat pumps;
- Flow velocity of 5.7m^3/hour: 6.6 heat pumps relating to 11 houses assuming a coincidence factor of 0.6;
- Maximum flow velocity: 87 heat pumps relating to 145 houses assuming a coincidence factor of 0.6.

In this calculation we disregard heat losses from the pipe to the soil. In reality this will reduce the capacity of the distribution system, which is further discussed in Section 5.1.1.

4.5.2 Dual pipe system

The main advantage of a dual pipe system over a single pipe system is that the water temperature in the supply pipe is not lowered by returning water from the residences. This means that a separate circulation system is not required.

The number of heat pumps that can be run simultaneously depends on the capacity of the water mains and is therefore equal to the scenario with one distribution pipe where the water is actively circulated. The difference with the one-pipe scenario in energy efficiency is that the supply water in this scenario is higher and the electricity use is lower.

5 Discussion

5.1 Thermal and energetic efficiency

To assess the feasibility of a combined energy and drinking water system for heating supply, a comparison has been made between such a system and a conventional system. In Section 2.2.1 the efficiency of a gas fired heater for space heating is assumed to be 0.9, so 10% energy is lost. The current energy demand for the Watergraafsmeer is estimated to be: 753TJ/year for space heating and 147TJ/year for tap water. From the water system and water cycle in combination with ATES 959TJ/year can be obtained.

Therefore we can assume that sufficient heat is present in the water system of the Watergraafsmeer and no additional thermal energy will be needed to close the energy balance.

Table 5.1 shows the comparison between the traditional system and the system using heat from the urban water cycle and heat pumps for a ATES system operating at the currently allowed legal temperature boundaries (the $ATES_{OLT}$). It can be seen that in this scenario, the primary energy consumption for the traditional system can be reduced with 10% using the heat pump system. Key variables determining the energy use reduction are 1) the Seasonal Performance Factor (SPF) for the heat pump and 2) the conversion factor relating electrical energy to primary energy.

Table 5.1 Overall energy balance and efficiency assuming an ATES system operating at maximum temperature levels (OTL)

Traditional system	Efficiency	Energy (TJ)	Urban water cycle heat pump system	SPF	Energy (TJ/yr)	Source
Heating demand			Indoor heat pumps	4	196	Refer Section 2.3
Natural gas demand	90%	870	ATES pump energy	28	28	Nuiten and van der Ree (2012)
			Pump energy distribution network	56	14	Nuiten and van der Ree (2012)
Hot tap water demand	85%	162	Regenerating with water heat	30	26	Nuiten and van der Ree (2012)
			Distribution losses based on 15000 dwellings and 3 GJ per dwelling loss		45	Nuiten and van der Ree (2012)
			Hot tap water supply	2.2	62.7	Refer Section 2.3
Total gas energy demand	90%	**1032**	**Total electrical energy demand**		**371**	
Conversion factor (thermal to primary energy)		1	Conversion factor (electrical energy from primary energy)		2.5	
Total primary energy consumption		**1032**	**Total primary energy consumption**		**928**	

The first key factor, the SPF, is based on a very high efficiency ATES system working up to 25°C. Although the storage in the subsurface will be possible, it is questionable whether all the thermal energy required for regeneration of the ATES wells in summer can be extracted

(mainly from surface water) at the temperature level of 25°C. If the SPF would drop to 3, a value considered to be more representative for heat pumps performance under the currently used ATES temperature levels, the primary energy consumption is expected to increase to around 1100 TJ/year which is around 7% higher than current use.
The second key factor, the conversion factor between electrical and primary energy use, is overall the most determining factor for the primary energy consumption of the urban water cycle heat pump system. Increasing the share of renewables in the electricity production is thus ultimately required to make heat pumps a truly viable alternative for gas heating. This is also obvious to see from the similarity in order of magnitudes of SPF (3 to 4) and primary to electrical energy conversion (2.5). The conversion factor means that of every 1 GJ of electrical energy, 2.5 GJ of heat is produced, discharged to the environment. The SPF means that for every 1 GJ of electrical energy, 3 to 4 GJ of heat is produced. The difference between these efficiencies, is simply too small or (theoretically) nearly enough to compensate energy demand and losses accounting for regeneration.

In this project the focus was on closing the energy balance over a year. The supply at peak demand during the day has not been investigated. It is expected that the system is insufficient to provide the required energy at these moments. In that case, additional top systems are required to provide additional heating. The effect on the total energy efficiency depends on whether the top system is based on gas, electricity or solar energy.

5.1.1 Heat exchange between water mains network and soil

The advantage of using a pipe material with a low heat conductance is a decrease in energy loss to the soil and vice versa (Figure 4.4).

In winter when most thermal energy is used for space heating, temperature differences between the relatively warm water in the distribution system and the soil is large. The soil temperature in winter at 0.5-1m depth drops to about 5^{o}C and the temperature in the water network is about 16^{o}C and preferably higher. Insulation of the warm water system increases the efficiency.
At the same time, the water in the return pipe cannot lose more energy to the soil and relatively warm water might be pumped into the ATES. As an imbalance, consisting of a shortage of thermal energy, exists this will not be a problem.
In summer, houses need to be or can be cooled to harvest thermal energy that can be stored in ATES for usage in winter. Cooling of houses is most effective when cold water is used. The low temperature should however not cause the air temperature to drop below dew point, otherwise thermal energy is generated due to the condensation of water. The water from the ATES used for cooling has a temperature that rises to about 8^{o}C. In summer, the soil temperature is about 16^{o}C. Insulation of the network pipe can therefore increase efficiency.

A study for Diemen (Deltares, 2012) shows that for a small drinking water network, consisting of PVC and cast iron pipes, thermal energy exchange between soil and water network is significant, especially during off-peak hours. A simulation of the water network, showed that water entering the water network at a temperature 11^{o}C increases in temperature with 3^{o}C in a soil of having a temperature of about 15^{o}C. This occurs over a distance of ca. 500m. This shows that a short distance between energy demand and supply is important and insulation of the pipes can improve efficiency.

In the dual pipe system the temperature of the water in the warm water pipe is always higher than in the soil, while water in the cold water pipe has a lower temperature during a large part of the year. The temperature in the single pipe network is on average more in equilibrium with the soil temperature. Therefore, the need for insulation of the single pipe network is smaller than for the dual pipe system.

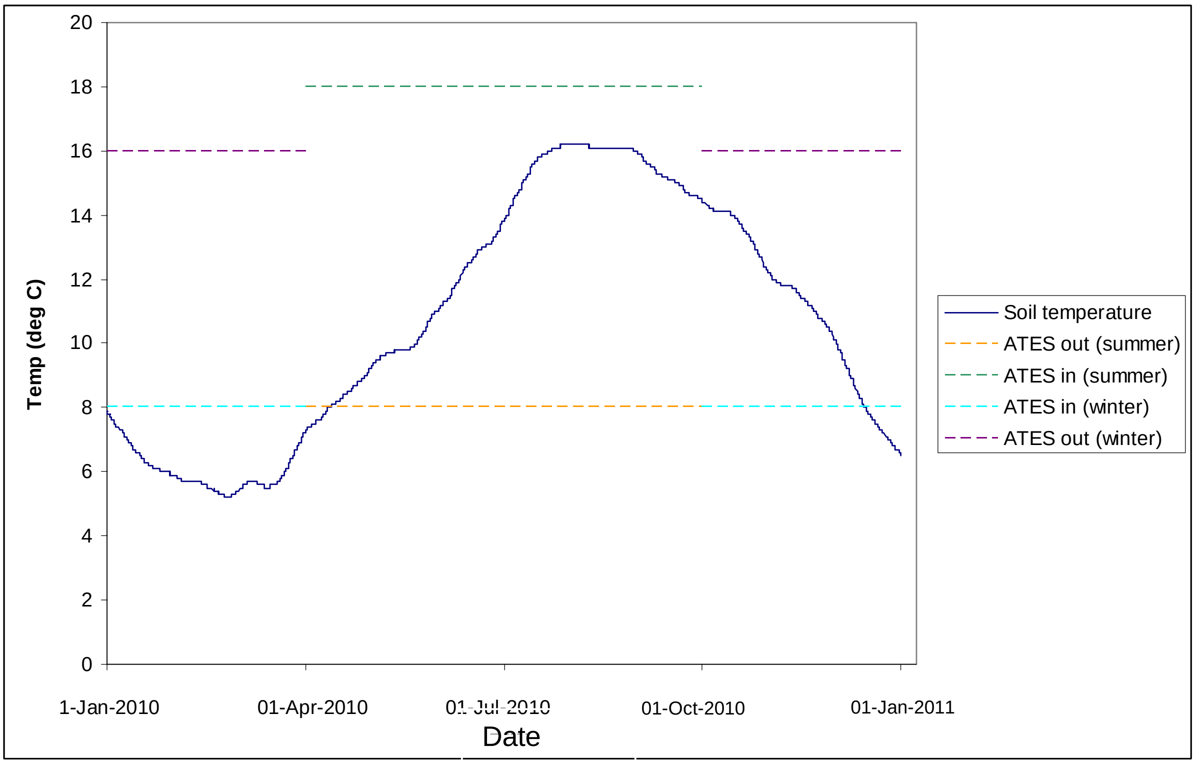

Figure 5.1 *Example of soil temperature at 1m below surface (www.met.wau.nl/haarwegdata/index.html) and an assumed water temperature inserted in or extracted from the ATES.*

5.2 Implications for water quality of the urban water system and cycle

Water quality issues will put important constraints on:

- The temperature of water in the distribution system that delivers both water for cooling and heating and drinking water;
- The water temperature of water to be stored in or extracted from groundwater and surface water.

5.2.1 Drinking water quality and water treatment

Higher temperatures in the water conduct system influences the water quality, disqualifying it for direct consumption. A solution can be purification of water at the tap, but still water quality might constrain maximum temperatures in the conduct system. Furthermore, the water used to transport the energy does not need have the same quality as drinking water; requiring purification at the tap when the water is used for consumption.

Questions that need to be answered, are:

- What are the main risks?
- What are the constraints on water temperature?
- What are the purification methods, to what degree can these be used?

Drinking water in the Netherlands has such a quality that:

- it is microbiologically safe to drink;
- it is toxicologically safe to drink;

- it does not smell or have a colour (aesthetic aspects);
- changes in quality during distribution are limited.

The main risks for human health that are involved in water distribution systems are related to microbial growth and to toxicological risks (Q21 water quality requirements research). Both aspects will be described below. Another risk in water distribution systems is the formation of sediments and corrosion which can damage the distribution system.

In Table 5.2 the risks that are involved when a different temperature in the distribution system is applied, are shown. In the paragraphs below the biological and toxicological risks are further explained.

Table 5.2 Risks involved when for different temperatures in the distribution system.

	Current temperature range (5-25°C)	**Low temperature distribution (16-20°C)**	**Medium temperature distribution (35-40°C)**	**High temperature distribution (60-80°C)**
Microbiological impacts and risks	Low	Low	High	limited
Chemical impacts and risks	Low	Low	low	low
Operational impacts and risks	Low	Low	Low	Low
Required point of use treatment for water that is being consumed	None	None	Yes	Yes

Microbial aspects, Legionella

To reduce the risk of the growth of Legionella the temperature in the water should be below 25 °C or above 60 °C. Other factors that increase the risk of the growth of Legionella are:
- stagnant water;
- biofilm growth in distribution pipes.

When people can come into contact with the water, the temperature of the water should have been below 25 °C or above 60 °C to avoid infection with Legionella (pneumophilla).

It is more energy efficient to deliver water for shower lower than 60 °C. However, when no other types of disinfection are applied, the risk of Legionella infection is high. Alternatives for disinfection by temperature increase are the addition of chemicals like chlorine and UV treatment. In the Netherlands addition of chlorine is not wanted. UV treatment is effective as disinfection, but it does not guarantee the safety after UV treatment in the system until e.g. the shower head. UV treatment does not have an effect on biofilm growth in the distribution pipes after the UV treatment.

Therefore it can be concluded that the water which is used for consumption should have a temperature below 25 °C or above 60 °C.

A structural increase of temperature in the distribution system can alter the quality of the drinking water, even when the temperature remains below 25 °C. As growth of biofilm increases with temperature this contributes to lower water quality. Extra monitoring of the quality of the drinking water is needed when there is a structural change in temperature in the distribution system.

Toxicological risks

As described below, several point-of-use drinking water systems are available to produce drinking water at the tap. In the distribution system the drinking water can have a lower quality. To prevent problems in the distribution system the chemical composition of the water is important to prevent clogging or damage of the distribution system. For example softening is important to prevent scaling and formation of sediments.

Point-of-use drinking water production / water purification

Several units are available on the market to produce water with drinking water quality at the tap, in the house. These systems use several techniques in series, e.g. filtration, reversed osmosis and adsorption on activated carbon. These systems can be installed in each house, producing safe drinking water at the point-of-use.

A point of use system for drinking water should be reliable so that it can produce high quality water for consumption at any time. Such systems should have a regular quality control and standards with requirements should be developed before a wide implementation is possible.

In the Netherlands the quality of drinking water is determined in the law 'Drinkwaterbesluit'. This includes limits for several microbiological, chemical and technical parameters. Details can be found at: http://wetten.overheid.nl/BWBR0030111/geldigheidsdatum_01-04-2012#BijlageA.

5.2.2 Effect of heat extraction and storage on groundwater quality

The effect of ATES on groundwater temperature has been subject of many studies. In general the effect low temperature ATES (<25°C) is assumed to be minimal. Combined with the fact that the technique is widely applied and excepted the implications will be described only briefly.

Measurements at low temperature ATES (<25°C) show that groundwater quality may change by mixing of different groundwater types (Bonte, 2010). Most aquifers in the Netherlands show some vertical quality stratification, often related to redox zones, where this may occur. An ATES system often has its filter set over the entire aquifer thickness to achieve the maximum capacity. Groundwater from the top of the aquifer (sometimes influenced by human activities of point pollutants) is mixed with deeper groundwater (sometimes relatively clean groundwater, but in some cases salinized or polluted with dense non aqueous phase liquids (DNAPLs) (Oostrum 2008, Zuurbier 2010). At poorly built ATES systems, many other risks can be identified such as leaking of shallow groundwater in a insufficiently sealed borehole annulus (Bonte, 2011).

ATES at high temperature (>25°C) can impact on groundwater quality due to changing mineral equilibriums (dissolution of silicates, precipitation of carbonates), changing selectivity of cation exchange (releasing ammonia and potassium), breakdown of organic carbon (increasing dissolved organic matter), desorption of trace elements and increasing rates of sulphate reduction (Brons et al., 1991, Bonte et al., 2011, Griffioen and Appelo, 1993, Holm, 1986, Holm et al., 1987).

5.2.3 Effect heat extraction on surface water

The effect of heat extraction, as described in Section 4.2.1 is not well known, current regulations are based on thermal discharge to surface water and no monitoring studies have been conducted. Therefore, a qualitative description of the effect of heat extraction on surface water is given below.

Water temperature influences a cascade of changes in aquatic systems. Temperature influences nearly all physical, chemical and biological processes in the environment resulting in an impact on densities, production, composition of biological communities, their phenology, abundance and migration patterns.

Changes in water temperature resulting from heat discharge and heat abstractions (cold discharges) can be reviewed in the broader context of climate change induced water quality changes. Climate change influences air temperature (+1 to 2˚C in 2050 compared to 1990) and other important factors affecting water quality, like wind velocity, precipitation and runoff or even carbon dioxide concentration etc..

Climate change causes the surface water temperature to rise resulting in three categories of effects:

1. Shift in climate zones;
2. Shift in lifetime cycle of organisms;
3. Increase in primary production.

Heat discharges cause local heating of surface waters. The CIW (Commission Integrated Water) regulations primarily aim to protect fish from the adverse effects of thermal heat plumes by limiting the plume extension in relation to the dimension of the receiving surface water body, allowing fish to pass the plume. Although effects of heat discharge may seem limited to the local environment of the discharge, their (cumulative) sphere of influence can be large, e.g. the river Rhine at Lobith is still significantly warmer than it would be without the upstream heat discharges.

The effect of rising water temperature in general is judged as negative causing deterioration of water quality in surface waters, lakes canals, ditches etc. Using the reversed arguments the effects of heat abstraction should be judged predominantly as positive as they compensate these effects at least locally.

A detailed list of effects of water temperature increase on water quality and ecology from Dionisio (2008) can be found below:

Oxygen

A decrease in dissolved oxygen concentrations occurs in water, as oxygen is less soluble at higher temperatures. A higher water temperature enhances biological activity and increases production of organic material. The subsequent decay of organic matter is faster and consumes more oxygen.

Stratification
Warmer surface water (epilimnion) increases the stability of stratification, changes in mixing patterns (Jankowski et al. 2006) and results in stronger and longer lasting stratification. The reduced mixing between upper and lower parts of the lake causes a decrease of dissolved oxygen levels in the deeper parts of the lakes (hypolimnion). Decreasing levels of oxygen in the deeper parts of the lake result in an additional release of the nutrient phosphorus from lake sediments (McKee et al. 2003) enhancing algae blooms.

Nutrients
Verdonschot et al. (2007) indicates that ditches in the Netherlands will receive more nutrients from runoff and groundwater as nutrient cycling in soils is enhanced. Phosphorus concentration increases as a result of generally enhanced cycling and low oxygen levels near the sediment-water interface causing additional (chemical) release of phosphorus. For nitrogen a decrease of total summer concentrations is reported, caused by the strong temperature dependence of denitrification; the biochemical process that removes nitrogen from water to the atmosphere.

A*lgae*
Phytoplankton will go through changes in species composition and show higher biomass levels during a longer growth season. Cyanobacteria will more frequently dominate the phytoplankton population (Paerl & Huisman 2008; Mooij et al. 2005). The interaction of phytoplankton with higher topical levels will therefore alter (Gerten & Adrian 2002; Winder & Schindler 2004) having consequences for water quality (Weyhenmeyer 2004).

In shallow lakes a relatively warm winter increases the chance for a Cyanobacteria bloom in spring with 75% whereas a cold winter reduces the chance by 50% (Reeders et al. 1998).
An additional risk is the invasion by the exotic Cyanobacteria such as Cylindrospermopsis (Briand et al. 2004).

Water plants
Algae compete with water plants for light. As climate changes favours algae blooms algae will be stronger competitors for water plants and may more often replace them (Mooij et al. 2005). The reproduction success for water plants strongly depends on other factors such as waves, wind, nutrients (levels depending on precipitation and groundwater levels) all affected by climate change (see e.g Rip et al. 2007). A combination of warmer and wetter winters leads less favourable conditions for Charaphyta.
At ecosystem level, enhanced eutrophication results in more frequent Cyanobacteria dominance over water plants (Van de Bund & Van Donk 2004).

Zooplankton
Higher water temperatures lead to an earlier algae bloom of green algae and diatoms in spring (Winder & Schindler 2004). This bears the risk of a mismatch with zooplankton. In case zooplankton does not show a similar time shift, it will miss it feeding on algae. This may influence the diet of other species, such as fish predating on zooplankton.

Fish

Higher water temperatures will force a northward shift of fish, invertebrates, birds and exotic species (Lake et al. 2000) and may possibly lead to an extinction of species.
Fish will migrate northward as a result of increasing water temperature, if possible. Species that cannot migrate further north run the risk of extinction. Species earlier limited to southern habitats will invade Dutch waters. Warmer water will lead more frequently to oxygen limitation potentially causing fish kill (Grantham et al. 2004).
Warmer water may lead to a mismatch of fish and their food such as zooplankton (Beaugrand et al. 2003). This finding is supported by a model study over the period 1971-2006 in shallow Dutch lakes showing a three week earlier spawning of Bream a result of increased water temperature (Mooij et al. submitted).

5.3 Effects of climate change

According to the KNMI 2006 scenarios the average winter temperature in the Netherlands will have increased with 0.9-2.3^{o}C by 2050. The summer temperature will increase with 0.9-2.8^{o}C by 2050.

Expectantly, heating demand for hot sanitary water will not be dependent on climate change, but for space heating and cooling demand, climate change will have impact.
Specific space heating demand depends on both user behaviour and insulation quality of buildings. The latter is gradually improving in time as renovation of existing buildings and construction of new buildings will have to meet higher standards. However, under unchanged conditions, the demand merely depends on the average outdoor temperature, as represented in the level of degree-days over time.
In general, the normalized heating demand for space heating will decrease by 5% at a 1^{o}C shift upwards of the outdoor temperature compared to the averages so far. Therefore, it can be assumed that the predicted increase in average outdoor temperature results in a 10 % decrease in energy consumption for space heating in 2050.

Climate change will expectantly not affect the energy carriers (gas, electricity) as used for heating and cooling of buildings.

The change in cooling demand under influence of the construction of new buildings will basically be negligible. According to the new building standards, cooling demand will have to be reduced. Space cooling by energy consuming equipment will have a negative effect on the level of the mandatory energy efficiency coefficient, following from the prescribed calculation rules. However, cooling demand will raise due to intensified application and use of electrical equipment in households and most utility buildings.

The temperature of the heat sources in the urban water system will increase with climate change. Surface water temperature will increase with approximately the same magnitude as the average air temperature. Consequently, the efficiency of heat extraction for regeneration of ATES or direct use will increase. The negative effects on increased temperature are described in Section 5.3.3. These effects can (partly) be compensated by cooling the surface water by extracting heat for regeneration of ATES.

The temperature of drinking water in the current drinking water network will also increase due to an increase in air temperature. The effects of increased temperature are described in Section 5.3.1. Also in this case, these effects can (partly) be compensated by extracting heat from the drinking water for e.g. regeneration of ATES.

Current regulation for ATES in the Netherlands is based on a closed energy balance. Therefore, the overall temperature change will be limited. Due to the large distance of ATES aquifers to the surface, the temperature of the aquifer will react slowly to the increased air temperature. Due to the higher temperature of the water used to load the ATES, the efficiency of the ATES for heating will increase. The effectiveness for cooling will however decrease due to an increase in temperature of water used for the cold ATES well. It is assumed that the latter will have a smaller impact on the efficiency than the positive effect of the higher temperature for loading the well.

Overall, it is expected that the imbalance between heat and cold demand will decrease and the efficiency of the system will increase due to climate change.

6 Conclusions

The conclusions are broken down into two parts. In the first part, the feasibility is discussed of a low temperature thermal energy distribution network based on the local water system. In the second part, the feasibility is discussed of such a distribution network in combination with drinking water distribution.

All houses in the Watergraafsmeer are fully equipped with existing infrastructure for gas supply, water distribution and wastewater collection. Conversion to a low temperature system would require a disproportional investment. For our conclusions, we therefore focus on a situation involving newly build houses or renovation projects.

Category	**Space heating demand [TJ]**	**Space cooling demand [TJ]**	**Hot sanitary water demand (gas) [TJ]**	**Hot sanitary water demand (electricity) [TJ]**
Dwellings	385	9.14	118	
Utility buildings	368	138.2	20.1	9.0
Total by function	753	147.3	138.1	9.0

Energy

Energy demand

The current total annual energy demand of the Watergraafsmeer is 753TJ for space heating, 149TJ for hot sanitary water and 147TJ for space cooling. In the present situation, the energy for heating is generated by combustion of natural gas. The energy consumption figures for space heating for dwellings and utility are both approximately 380TJ, and form the main energy demand.

A large energy saving (41 TJ per year) can be obtained by directly recovering heat from waste water from showers, requiring a relatively low investment by installing shower heat exchangers (see section 4.2.3).

Energy supply

The current energy demand in the Watergraafsmeer can largely be met by thermal energy from the local urban water system and water cycle. The largest energy source is thermal energy from surface water (556TJ), while surface water covers only 6% of the surface area.

Harvesting heat from surface water causes a decrease of the surface water temperature resulting in a higher oxygen concentration, lower phosphorous concentration, less algae blooms, lower growth rates of water plants and zooplankton, but the nitrogen concentration might increase. Overall, the extraction of heat from surface water is expected to have a positive effect on surface water quality. The demand for hot tap water can be met by using more advanced heat pumps and/or by usage of solar thermal energy. Both can be combined with electrical heating units to meet top demand.

Energy storage

The temporal mismatch in heat supply in summer and demand in winter can be overcome by use of ATES. The capacity is sufficient to close the balance over the year. The effect of ATES on groundwater quality is limited for low temperature systems. The capacity might be insufficient to meet peak demands during the day.

The geo-hydrological conditions in the WGM are very suitable for ATES. Depending on the type of storage and temperature range, the combined storage capacity of the Watergraafsmeer is estimated to range between 1500 and 3500TJ/year. The potential in the presently used aquifer is at current ATES operating standards only around 0.3 GJ/year. A very large part of the potential is believed to be present in Maassluis formation (aquifer 4), which is less permeable but is very thick. This implies that in order to use ATES efficiently to meet the heat demand of the Watergraafsmeer, ATES systems have to deliver more heat per system than presently and have to be installed in deeper aquifers. This obviously raises issues about the financial viability of the systems.

Energy distribution

Two distribution systems have been investigated, one consisting of a single pipe from which heat can be extracted and to which the cold water is discharged and vice versa. The second system is a dual pipe system, where heat is extracted from the warm water pipe and cold water is discharged to the other pipe, and vice versa. Each system has advantages and disadvantages (Table 6.1). Based on the expected higher thermal efficiency a dual pipe system is preferred over a single pipe system. The advantage of saving one network, compared to the current system is than however gone.

Efficiency

The proposed thermal energy system reduces the thermal energy demand in operation with 70% relative to a traditional gas heated system. A thermal energy system based on the urban water system is therefore feasible based on thermal efficiency.
The total energy consumption for heating will only be reduced with 7% in a system based on heat pumps in an optimal configuration compared to a traditional system. Key variables determining the energy use reduction are the Seasonal Performance Factor (SPF) of the heat pump and the conversion factor relating electrical energy to primary energy. In this study the SPF, was based on a highly efficient ATES system. If the SPF would be lower at a value considered to be more representative for current systems, the primary energy consumption could be 7% higher than of a traditional system. Although the focus of this project was on closing the annual energy balance. It is important to note that to meet peak demand during a (cold) day, the use of top systems could be required. The effect on the energy efficiency strongly depends on the type of top system used (e.g. gas fired, electrical, solar energy).
However, the conversion factor between electrical and primary energy use, is overall the most determining factor for the primary energy consumption of the urban water cycle heat pump system. Increasing the share of renewables in the electricity production is required to make heat pumps a truly viable alternative for gas heating. The difference between the efficiencies of SPF (3 to 4) and primary to electrical energy conversion (2.5), is simply too small or (theoretically) nearly enough to compensate energy demand and losses accounting for regeneration.

Combining the distribution of energy and drinking water

Water demand and supply

Average fresh water demand per person in The Netherlands is about 125l/d of which about 6l/d is used for consumption. This water has to be provided by the distribution network.

Water demand for consumption is relatively low compared to the water demand for transportation of thermal energy. In this study, we assumed that this water is obtained from a central drinking water supply network. In practice this could also be from a local source, when available, with point of use treatment for the water that is being consumed.

Currently, the price of drinking water in the Netherlands is extremely low. From an economic point of view, hardly any improvement can be achieved. Furthermore, the quality and security of availability of drinking water is hard to equal.

Water distribution

In case of combining the thermal energy and drinking water supply, the water temperature in the water mains network will be above 20^oC or even 30^oC during part of the year. The consumption of water is far lower than the volume of water that is needed to transport thermal energy. Therefore, a volume of water is needed to circulate in the water mains system to supply thermal energy, resulting in a longer residence time. The water within the water mains will not qualify for human consumption and additional measures in the form of point source purification will be needed. Such systems should have a regular quality control and standards with requirement that should be developed before a wide implementation is possible.

Due to the low cost and high quality of the current drinking water system a combined system delivering both heating and cooling and drinking water is assumed to be not feasible. The cost and slightly increased risk and responsibility of individuals seem to outweigh the advantage of saving one network system.

Overall conclusion

At this time a more detailed design is needed and more research on both the thermal and economic efficiency. Based on this study it is conclude that the urban water system can provide an effective source of heat for urban areas, but the efficiency gain compared to a traditional system is limited. Delivering both drinking water and thermal energy using the same network is possible but does not seem efficient.

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TNO/DGV (1979)

TNO (1995)

A Cooling and heating demand analysis

Energy demand

Approach for determination of energy demand figures for heating and cooling

Energy supply values are known from the energy network operator (Liander 2010).

These values can be converted into demand figures according to the following approach.

Step 1: Calculating heating demand from energy supply data

Heating demand $Q_{heating}$ [MJ/a] from gas supply is calculated as follows:

$Q_{heating} = G_{supply} * C_{gas} * S_{function} * \eta_{conversion}$

where:

G_{supply}	Annual gas supply	[m^3/a]
C_{gas}	Caloric value (HHV) for gas	[MJ/m^3]
$S_{function}$	Share of total gas supply for a specific function	[%]
$\eta_{conversion}$	Conversion efficiency factor	[%]

Space cooling demand $Q_{cooling}$ [MJ/a] from electricity supply is calculated as follows:

$Q_{cooling} = E_{supply} * C_{electricity} * S_{function} * \eta_{conversion}$

where:

E_{supply}	Annual electricity supply	[kWh/a]
$C_{electricity}$	Caloric value of supplied electricity	[MJ/kWh]
$S_{function}$	Share of total electricity supply for a specific function	[%]
$\eta_{conversion}$	Conversion efficiency factor	[%]

Values for G_{supply} and E_{supply} are available for the postal codes in the area of investigation.

Value for C_{gas} = 35.2 [MJ/m^3]

Value for $C_{electricity}$ = 3.6 [MJ/kWh]

Values for $S_{function}$ are derived and presented further on.

The current gas supply for dwellings is mainly used for the function space heating. If the share of the total supply for a specific function is for instance 70%, than $S_{function} = 0.7$. Please note that the values for $S_{function}$ will change in the future.

Values for $\eta_{conversion}$ are dependent on the energy conversion system and function.

Heating and hot sanitary water

It is assumed that for dwellings and utility buildings, gas boilers are applied for two functions: space heating and hot sanitary water production. In this study the value for $\eta_{conversion}$ for space heating was assumed to be 0.9.

For the function hot tap water production, the conversion efficiency is somewhat lower although generally the same boiler will be applied for both functions. For hot tap water production with gas, the value for $\eta_{conversion}$ was assumed to be 0.85. For hot tap water production with electricity, the value for $\eta_{conversion}$ is 1.

Space cooling

It is assumed that space cooling is provided by electrical heat pumps/air conditioners.

An efficiency factor $\eta_{conversion}$ of 2.25 is applied for dwellings. (COP_{cold} = 2.25).

For the utility sector, an efficiency factor $\eta_{conversion}$ of 3.5 is applied.

Step 2: Temporal distribution of energy demand.

The temporal distribution within a year is performed, based on an allocation factor per month.

The allocation factors are dependent on the function under investigation.

Values and their background are detailed in paragraph 0.

Energy demand/-supply and temporal variation

Temporal distribution characteristics of annual energy demand

In order to calculate the change in energy demand/supply during a full year, a pro rato allocation has been made.

The outdoor temperature provides an important basis for calculation of the climate dependent parameters: the degree-days for heating and the number of cooling days for cooling.

Degree days or cooling days are a measure of how much (in degrees), and for how long (in days), outside air temperature was lower respectively higher than a specific base temperature (level of heating set point). They are used for calculations relating to the energy consumption required to heat or cool buildings.

The typical distribution of degree-days over a full year is represented in the graph below.

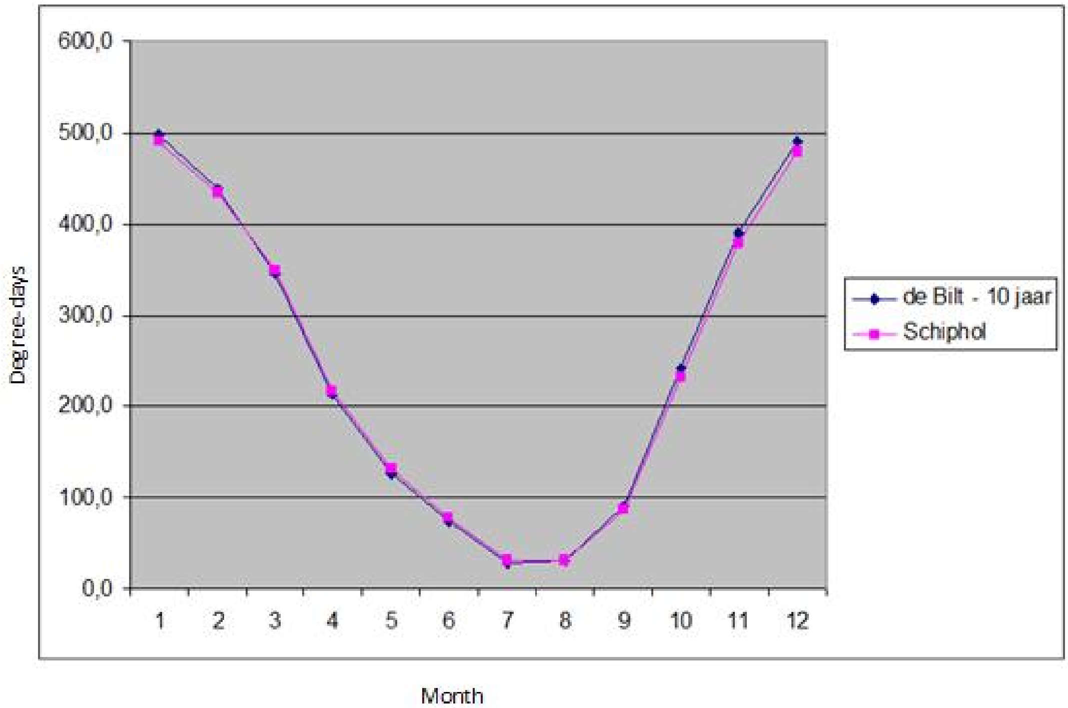

Fig A.1: Degree-days over a calendar year for the Schiphol-region (Source KWA)

Data were derived from the weather station Schiphol Airport. The start temperature for calculating degree-days for heating was 18 ˚C.

The monthly values as a share of the annual total can be used to allocate heating demand on a monthly basis. The degree-day values, as presented in the next table, were used to calculate the allocation values per month.

In a similar way, the number of cooling days per month can be used to distribute the annual cooling demand over time. For utility buildings, the weighing factors for cooling will be different compared to those for dwellings. Cooling in utility buildings is strongly dependent on the type of activity. Generally, the cooling demand will be wider spread over the year compared to dwellings since cooling is more often required in spring and autumn. This effect is considered by lowering the set point for calculation of cooling days compared to the set point for dwellings. Therefore, the monthly averages of cooling days over the years 2009 and 2010 were calculated for two set point levels (14 ˚C for utility and 18 ˚C for dwellings) and are represented in the graph below. In absence of detailed data of utility buildings, the average of cooling days for the two given set points was applied.

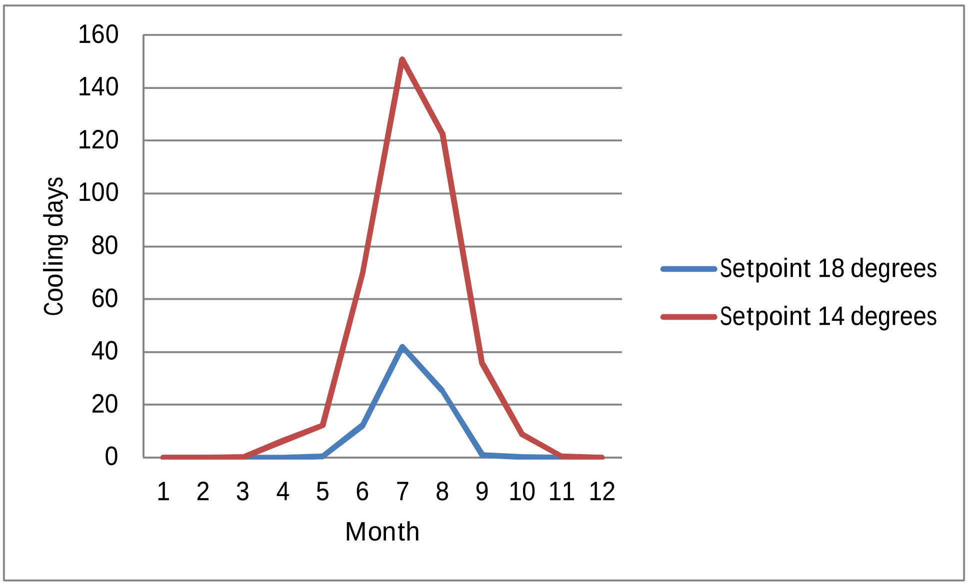

Fig A.2:Temporal distribution of cooling days, calculated for different set point values

The resulting weighing factors per month or quarter, as derived from these considerations are respectively:

Category →	**Dwellings / Utility**		**Dwellings**		**Utility mix**		**Dwellings / Utility**
Function →	**Space heating**		**Space cooling**		**Space cooling**		**Hot water**
Period ↓	**Degree days**	**Share of total**	**Cooling days**	**Share of total**	**Cooling days**	**Share of total**	**Share of total**
Month	[-]	[%]	[-]	[%]	[-]	[%]	[%]
1	490.9	**16.7**	0.0	**0.0**	0	0.0	8.5
2	434.9	**14.8**	0.0	**0.0**	0	0.0	7.7
3	348.4	**11.8**	0.0	**0.0**	0.1	0.0	8.5
4	216.8	**7.4**	0.4	**0.4**	3.1	1.3	8.2
5	131.4	**4.5**	4.5	**4.8**	6.3	2.6	8.5
6	77.9	**2.6**	17.9	**18.9**	41.0	16.8	8.2
7	32.0	**1.1**	46.7	**49.5**	96.4	39.5	8.5
8	30.9	**1.0**	16.3	**17.2**	74.0	30.4	8.5
9	87.3	**3.0**	8.6	**9.1**	18.2	7.5	8.2
10	231.6	**7.9**	0.1	**0.1**	4.5	1.8	8.5
11	379.7	**12.9**	0.0	**0.0**	0.235	0.1	8.2
12	479.2	**16.3**	0.0	**0.0**	0	0.0	8.5
Year	**2940.9**	**100**	**94.4**	**100**	**243.8**	**100**	**100**
Quarter							
Q1	1274.2	**43.3**	0	**0**	**0.05**	**0.0**	**24.7**
Q2	426.1	**14.5**	22.8	**24.1**	**50.4**	**20.7**	**24.9**
Q3	150.2	**5.1**	71.6	**75.8**	**188.7**	**77.4**	**25.2**
Q4	1090.5	**37.1**	0.1	**0.1**	**4.7**	**1.9**	**25.2**

Table A.1: Weighing factors in [%] for temporal distribution, as derived from degree-days or cooling days (Source KWA)

These weighing factors are applied to obtain the temporal distribution of the energy demand per function.

Composition of energy demand figures for dwellings
An approximation of the Dutch average total energy consumption figures by energy carrier are given below.

Gas [m^3/a]	Electricity [kWh/a]
1660	3500

Specification of these values by type and occupation is given in Annex 2.

The gas supply to dwellings is used for **space heating, hot sanitary water production** and (not in this investigation) for food processing (approx. 70 m^3/a).
Electricity supply to dwellings is used for **space cooling**, **hot sanitary water production** and (not in this investigation) for lighting, food processing and household apparatus.

Space heating

Energy source	**Gas [m3/a]**
Level	1200
Temporal distribution	
Annual	Degree-day dependent
Season	Degree-day dependent
Month	Degree-day dependent
Day	Wake-up / evening peak

Hot sanitary water production

Energy source	**Gas [m3/a]**	**Remarks**
Level	390	Proportional to the number of days
Temporal distribution		
Annual	Evenly distributed	
Season	Evenly distributed	
Month	Evenly distributed	
Day	Pattern according to Standard CW-classes	Basically class 3 , trend to class 4

Based on the consumption figures as indicated above, the typical values for the share of the energy input by function ($S_{function}$) are:
For space heating 72,3 [%] $S_{function}$ = 0,723
For hot sanitary water 23,5 [%] $S_{function}$ = 0,235
Please note that the values for $S_{function}$ will change in the future (See page A16)
Electricity demand for hot sanitary water is neglected here. All related energy consumption is considered to be covered under gas consumption.

Space cooling

Space cooling for existing dwelling in the built environment is not a structural application and can hardly be neglected. However, a limited share of the annual electricity demand can be applied as value for the share of energy input for this function. In the calculations, $S_{function}$ = 0,03.

Energy source	**Electricity**
Temporal distribution	
Annual	Cooling-day dependent
Season	Cooling-day dependent
Month	Cooling-day dependent
Day	Mainly afternoon and evening

Characteristic energy demand figures for utility buildings

For a number of subcategories of utility buildings, the typical annual energy demand figures (energy carrier unit per m^2 floor space) are given below.

Sub category	**Gas [m3/m2.a]**	**Electricity** [kWh/m^2.a]
Offices	15	81
Schools prim/sec / univ	12/**12**/13	20/**31**/57
Shops without cooling	14	64
Supermarkets with cooling	16	400
Restaurants	20	87
Care centres	23	65
Hospitals	29	78
Sport centers	55	15
Swimming centre	61	242

Table A2: Specific energy consumption figures for utility buildings (Source Agentschap NL [A-7])

The contribution by function, as share of the total demand [%].

Category	**Gas**			**Electricity**					
	Heating	*Other etc.*	*Hot sanitary water*	*Hot sanitary water*	*Cooling*	*Food processing*	*Lighting*	*Ventilation*	*Other etc.*
Offices	94	5	1	1	10	6	39	6	39
Schools primairy	95	3	2	5	-	6	55	-	39
Schools secondary	93	5	2	2	-	13	52	2	33
Advanced / Univ	86	12	2	1	2	7	48	11	32
Shops without cooling	89	10	1	1	9	2	75	4	10

Category	Gas			Electricity					
	Heating	*Other etc.*	*Hot sanitary water*	*Hot sanitary water*	*Cooling*	*Food processing*	*Lighting*	*Ventilation*	*Other etc.*
Supermarkets with cooling	88	11	1	1	1	1	27	1	44
Restaurants	79	12	9	8	21	4	53	13	8
Care centres	90	5	5	7	1	2	73	7	17
Hospitals	67	18	15	18	-	6	59	22	13
Sport centers	86	5	9	9	-	12	60	21	7
Swimming centre	79	11	10	9	-	8	24	38	30
Average	86	9	5	2	7	6	51	13	25

Table A3: Energy consumption share of total by function for utility buildings (Source Agentschap NL [A-8])

The average values (last row) are used as typical values for the share of energy input by function $S_{function}$.

Hot sanitary water production:

Energy source	Electricity or Gas
Temporal distribution	
Annual	Evenly distributed
Season	Evenly distributed
Month	Evenly distributed
Day	Evenly distributed within working hours

Hot sanitary water for utility buildings is produced by gas or electricity. For calculation results in subchapter 0 it is assumed that 5 % is produced using gas and 2 % by using electricity.

Space heating

Energy source	Gas
Temporal distribution	
Annual	Degree-day dependent
Season	Degree-day dependent
Month	Degree-day dependent
Day	Degree-day dependent

Space cooling

Energy source	Electricity
Temporal distribution	
Annual	Cooling-day dependent
Season	Cooling-day dependent
Month	Cooling-day dependent
Day	Operating hours dependent

Based on the aforementioned considerations, resulting figures for heating and cooling demand by function and energy carrier are presented in the next tables A4-1 .. A4-5.

Share for space heating 0,723 Production efficiency factor 0,9 1 m3 = 35,2 MJ

Postal code	Gas demand (m3)	# of connenctions (dwellings)	Specific demand [kWh/unit]	Specific demand [m³/unit]	Month 1	Month 2	Month 3	Month 4	Month 5	Month 6	Month 7	Month 8	Month 9	Month 10	Month 11	Month 12	Q1	Q2	Q3	Q4	Year
1096H	423040	320	3957	1322	1618160	1434058	1143370	717029	436031	251929	106585	96896	290687	765477	1249956	1579401	4195588	1404989	494169	3594834	9689579
1097C	697076	537	2945	1298	2666368	2363009	1884020	1181504	718482	415123	175629	159663	478988	1261336	2059649	2602503	6913397	2315110	814280	5923488	15966275
1097E	617930	444	2523	1392	2363629	2094713	1670109	1047356	636906	367990	155688	141535	424604	1118124	1825797	2307015	6128450	2052252	721827	5250935	14153464
1097G	462010	346	2728	1335	1767223	1566162	1248696	783081	476198	275136	116404	105822	317465	835992	1365100	1724894	4582081	1534415	539691	3925986	10582173
1097H	691208	493	3185	1402	2643922	2343117	1868161	1171558	712434	411629	174151	158319	474956	1250718	2042311	2580595	6855200	2295621	807425	5873624	15831870
1097J	165478	161	2173	1028	632966	560952	447245	280476	170560	98546	41692	37902	113706	299427	488938	617805	1641163	549581	193301	1406169	3790214
1097K	401728	365	1629	1101	1536640	1361812	1085769	680906	414065	239237	101216	92014	276043	726913	1186985	1499834	3984221	1334208	469273	3413732	9201435
1097L	447285	418	1708	1070	1710899	1516245	1208898	758123	461021	266367	112694	102449	307347	809347	1321592	1669919	4436043	1485511	522490	3800859	10244902
1097M	389477	296	1983	1316	1489779	1320283	1052658	660141	401437	231942	98129	89208	267625	704746	1150787	1454095	3862720	1293520	454962	3309628	8920830
1097N	398714	325	2273	1227	1525111	1351595	1077623	675798	410958	237442	100456	91324	273972	721460	1178080	1488581	3954329	1324198	465752	3388121	9132401
1097P	418244	391	2163	1070	1599815	1417800	1130408	708900	431088	249073	105377	95797	287392	756799	1235785	1561496	4148022	1389061	488566	3554079	9579728
1097R	482760	393	2107	1228	1846593	1636502	1304778	818251	497585	287494	121632	110574	331723	873538	1426410	1802363	4787873	1603329	563930	4102312	11057444
1097S	432739	339	3476	1277	1655259	1466936	1169584	733468	446028	257705	109029	99117	297352	783027	1278613	1615612	4291780	1437201	505498	3677252	9911731
1097T	439622	448	2030	981	1681587	1490269	1188187	745134	453122	261804	110763	100694	302082	795481	1298950	1641310	4360043	1460061	513539	3735741	10069384
1097V	566721	404	2263	1403	2167750	1921120	1531704	960560	584124	337494	142786	129805	389416	1025463	1674490	2115828	5620574	1882178	662008	4815781	12980540
1097W	484073	347	1988	1395	1851615	1640953	1308327	820476	498938	288275	121963	110875	332626	875914	1430290	1807265	4800895	1607690	565463	4113469	11087518
1097X	353091	334	2020	1057	1350600	1196938	954316	598469	363934	210273	88962	80874	242623	638906	1043277	1318250	3501854	1172676	412459	3000434	8087422
1097Z	392643	426	1816	922	1501889	1331015	1061215	665508	404701	233827	98927	89933	269800	710474	1160142	1465915	3894119	1304035	458661	3336532	8993347
1098A	622684	411	6536	1515	2381813	2110828	1682958	1055414	641806	370821	156886	142624	427871	1126726	1839844	2324764	6175599	2068041	727380	5291333	14262353
1098B	582187	408	3063	1427	2226909	1973548	1573504	986774	600065	346704	146683	133348	400044	1053448	1720187	2173570	5773961	1933544	680074	4947205	13334784
1098C	643144	415	3353	1550	2460074	2180185	1738256	1090093	662894	383006	162041	147310	441929	1163748	1900297	2401150	6378515	2135992	751280	5465194	14730982
1098E	626588	425	2947	1474	2396746	2124062	1693509	1062031	645830	373146	157869	143518	430553	1133790	1851379	2339339	6214318	2081007	731940	5324508	14351773
1098G	624171	395	2858	1580	2387501	2115869	1686977	1057934	643339	371707	157261	142964	428892	1129417	1844237	2330315	6190346	2072980	729117	5303969	14296412
1098H	586465	342	3023	1715	2243273	1988050	1585067	994025	604475	349252	147760	134328	402983	1061189	1732827	2189541	5816389	1947752	685071	4983558	13432770
1098J	637600	383	3105	1665	2438868	2161392	1723272	1080696	657180	379704	160644	146040	438120	1153716	1883916	2380452	6323531	2117580	744804	5418083	14603998
1098K	727871	396	3522	1838	2784161	2467400	1967252	1233700	750223	433462	183388	166716	500149	1317058	2150639	2717475	7218813	2417385	850253	6185172	16671623
1098L	482519	353	3034	1367	1845671	1635685	1304127	817842	497337	287350	121571	110519	331558	873102	1425698	1801464	4785483	1602529	563648	4100264	11051924
1098N	741427	382	4465	1941	2836014	2513354	2003890	1256677	764195	441535	186803	169821	509464	1341587	2190693	2768085	7353257	2462407	866088	6300366	16982119
1098P	516098	355	3067	1454	1974113	1749514	1394883	874757	531947	307347	130031	118210	354631	933862	1524914	1926829	5118510	1714051	602873	4385605	11821039
1098R	417299	384	3677	1087	1596200	1414596	1127854	707298	430114	248510	105139	95581	286743	755089	1232993	1557968	4138650	1385922	487462	3546049	9558083
1098S	434938	329	3266	1322	1663670	1474391	1175528	737195	448294	259015	109583	99621	298863	787006	1285111	1623822	4313589	1444504	508067	3695938	9962098
1098V	178033	320	4084	556	680990	603512	481178	301756	183500	106022	44856	40778	122333	322145	526034	664678	1765680	591278	207967	1512857	4077782
1098W	729744	552	4269	1322	2791325	2473749	1972314	1236875	752154	434578	183860	167145	501436	1320447	2156174	2724467	7237389	2423606	852441	6201088	16714524
Total	16814607	12637	2977,121618	1330,585345	64317131	56999613	45445637	28499806	17330963	10013446	4236458	3851325	11553976	30425469	49682095	62776601	166762381	55844215	19641759	142884165	385132520

Table A4-1: Calculated temporal and spatial energy consumption figures, depending on building type and function

Hot water heating demand for dwellings from gas

Gas share for hot water 0,235 Production efficiency factor 0,85 1 m3 = 35,2 **MJ**

Postal code	Gas demand (m3)	# of connenctions (dwellings)	Specific demand [kWh/unit]	Specific demand [m3/unit]	Month 1	Month 2	Month 3	Month 4	Month 5	Month 6	Month 7	Month 8	Month 9	Month 10	Month 11	Month 12	Q1	Q2	Q3	Q4	Year
1096H	423040				252627	228179	252627	244478	252627	244478	252627	252627	244478	252627	244478	252627	733433	741582	749732	749732	2974479
1097C	697076				416273	375989	416273	402845	416273	402845	416273	416273	402845	416273	402845	416273	1208535	1221963	1235391	1235391	4901281
1097E	617930				369010	333299	369010	357106	369010	357106	369010	369010	357106	369010	357106	369010	1071318	1083221	1095125	1095125	4344789
1097G	462010				275899	249199	275899	266999	275899	266999	275899	275899	266999	275899	266999	275899	800996	809896	818796	818796	3248485
1097H	691208				412769	372824	412769	399454	412769	399454	412769	412769	399454	412769	399454	412769	1198362	1211677	1224992	1224992	4860022
1097J	165478				98819	89255	98819	95631	98819	95631	98819	98819	95631	98819	95631	98819	286893	290080	293268	293268	1163509
1097K	401728				239900	216684	239900	232161	239900	232161	239900	239900	232161	239900	232161	239900	696484	704223	711962	711962	2824630
1097L	447285				267105	241256	267105	258489	267105	258489	267105	267105	258489	267105	258489	267105	775467	784083	792700	792700	3144950
1097M	389477				232584	210076	232584	225081	232584	225081	232584	232584	225081	232584	225081	232584	675244	682747	690250	690250	2738491
1097N	398714				238100	215058	238100	230420	238100	230420	238100	238100	230420	238100	230420	238100	691259	698939	706620	706620	2803438
1097P	418244				249763	225592	249763	241706	249763	241706	249763	249763	241706	249763	241706	249763	725118	733175	741232	741232	2940757
1097R	482760				288290	260391	288290	278990	288290	278990	288290	288290	278990	288290	278990	288290	836971	846271	855570	855570	3394382
1097S	432739				258419	233411	258419	250083	258419	250083	258419	258419	250083	258419	250083	258419	750248	758585	766921	766921	3042674
1097T	439622				262529	237123	262529	254061	262529	254061	262529	262529	254061	262529	254061	262529	762182	770650	779119	779119	3091070
1097V	566721				338429	305678	338429	327512	338429	327512	338429	338429	327512	338429	327512	338429	982536	993453	1004370	1004370	3984729
1097W	484073				289074	261099	289074	279749	289074	279749	289074	289074	279749	289074	279749	289074	839247	848572	857897	857897	3403614
1097X	353091				210855	190450	210855	204054	210855	204054	210855	210855	204054	210855	204054	210855	612161	618963	625765	625765	2482653
1097Z	392643				234475	211784	234475	226911	234475	226911	234475	234475	226911	234475	226911	234475	680733	688297	695861	695861	2760751
1098A	622684				371848	335863	371848	359853	371848	359853	371848	371848	359853	371848	359853	371848	1079560	1091555	1103550	1103550	4378216
1098B	582187				347665	314020	347665	336450	347665	336450	347665	347665	336450	347665	336450	347665	1009350	1020565	1031780	1031780	4093473
1098C	643144				384067	346899	384067	371677	384067	371677	384067	384067	371677	384067	371677	384067	1115032	1127421	1139810	1139810	4522074
1098E	626588				374180	337969	374180	362109	374180	362109	374180	374180	362109	374180	362109	374180	1086328	1098399	1110469	1110469	4405666
1098G	624171				372736	336665	372736	360713	372736	360713	372736	372736	360713	372736	360713	372736	1082138	1094162	1106186	1106186	4388671
1098H	586465				350220	316327	350220	338922	350220	338922	350220	350220	338922	350220	338922	350220	1016766	1028064	1039361	1039361	4123553
1098J	637600				380756	343909	380756	368473	380756	368473	380756	380756	368473	380756	368473	380756	1105420	1117703	1129985	1129985	4483093
1098K	727871				434663	392599	434663	420642	434663	420642	434663	434663	420642	434663	420642	434663	1261925	1275946	1289968	1289968	5117807
1098L	482519				288146	260261	288146	278851	288146	278851	288146	288146	278851	288146	278851	288146	836553	845848	855143	855143	3392688
1098N	741427				442758	399911	442758	428476	442758	428476	442758	442758	428476	442758	428476	442758	1285427	1299710	1313992	1313992	5213122
1098P	516098				308198	278373	308198	298257	308198	298257	308198	308198	298257	308198	298257	308198	894770	904712	914653	914653	3628788
1098R	417299				249199	225083	249199	241160	249199	241160	249199	249199	241160	249199	241160	249199	723480	731519	739557	739557	2934113
1098S	434938				259732	234597	259732	251354	259732	251354	259732	259732	251354	259732	251354	259732	754061	762439	770818	770818	3058136
1098V	178033				106316	96027	106316	102886	106316	102886	106316	106316	102886	106316	102886	106316	308659	312089	315519	315519	1251786
1098W	729744				435782	393609	435782	421724	435782	421724	435782	435782	421724	435782	421724	435782	1265172	1279230	1293287	1293287	5130976
Total	16814607				10041186	9069458	10041186	9717277	10041186	9717277	10041186	10041186	9717277	10041186	9717277	10041186	29151830	29475739	29799648	29799648	118226865

Table A4-2: Calculated temporal and spatial energy consumption figures, depending on building type and function

Space cooling demand for dwellings																				
Electricity share for space cooling		0,03	efficiency (COP)		2,25	1	kWh =	3,6	**MJ**											
Postal code	El. demand (kWh)	Month 1	Month 2	Month 3	Month 4	Month 5	Month 6	Month 7	Month 8	Month 9	Month 10	Month 11	Month 12		Q1	Q2	Q3	Q4		Year
1096H	1266352	0	0	0	1231	14771	58160	152323	52928	28003	308	0	0		0	74161	233254	308		307724
1097C	1581586	0	0	0	1537	18448	72638	190241	66104	34974	384	0	0		0	92622	291319	384		384325
1097E	1120103	0	0	0	1089	13065	51443	134732	46816	24769	272	0	0		0	65597	206316	272		272185
1097G	943818	0	0	0	917	11009	43347	113527	39448	20871	229	0	0		0	55273	173846	229		229348
1097H	1570302	0	0	0	1526	18316	72119	188884	65632	34724	382	0	0		0	91962	289240	382		381583
1097J	349931	0	0	0	340	4082	16071	42091	14626	7738	85	0	0		0	20493	64455	85		85033
1097K	594622	0	0	0	578	6936	27309	71524	24853	13149	144	0	0		0	34823	109526	144		144493
1097L	713935	0	0	0	694	8327	32789	85876	29840	15787	173	0	0		0	41810	131503	173		173486
1097M	586896	0	0	0	570	6846	26954	70595	24530	12978	143	0	0		0	34370	108103	143		142616
1097N	738599	0	0	0	718	8615	33922	88842	30870	16333	179	0	0		0	43255	136046	179		179480
1097P	845648	0	0	0	822	9864	38838	101719	35345	18700	205	0	0		0	49524	155763	205		205492
1097R	827970	0	0	0	805	9657	38026	99592	34606	18309	201	0	0		0	48488	152507	201		201197
1097S	1178396	0	0	0	1145	13745	54120	141743	49252	26058	286	0	0		0	69010	217053	286		286350
1097T	909412	0	0	0	884	10607	41767	109389	38010	20110	221	0	0		0	53258	167508	221		220987
1097V	914082	0	0	0	888	10662	41981	109950	38205	20213	222	0	0		0	53531	168368	222		222122
1097W	689818	0	0	0	671	8046	31681	82975	28832	15254	168	0	0		0	40398	127060	168		167626
1097X	674620	0	0	0	656	7869	30983	81147	28196	14918	164	0	0		0	39508	124261	164		163933
1097Z	773410,73	0	0	0	752	9021	35520	93030	32325	17102	188	0	0		0	45293	142458	188		187939
1098A	2686173,35	0	0	0	2611	31332	123368	323106	112271	59399	653	0	0		0	157310	494777	653		652740
1098B	1249751,65	0	0	0	1215	14577	57397	150326	52235	27636	304	0	0		0	73189	230197	304		303690
1098C	1391575,16	0	0	0	1353	16231	63911	167386	58162	30772	338	0	0		0	81495	256320	338		338153
1098E	1252475	0	0	0	1217	14609	57522	150654	52348	27696	304	0	0		0	73349	230698	304		304351
1098G	1129054	0	0	0	1097	13169	51854	135808	47190	24967	274	0	0		0	66121	207965	274		274360
1098H	1033869	0	0	0	1005	12059	47483	124359	43212	22862	251	0	0		0	60546	190432	251		251230
1098J	1189345	0	0	0	1156	13873	54623	143060	49710	26300	289	0	0		0	69652	219070	289		289011
1098K	1394623	0	0	0	1356	16267	64051	167752	58290	30839	339	0	0		0	81673	256881	339		338893
1098L	1071025	0	0	0	1041	12492	49189	128828	44765	23684	260	0	0		0	62722	197276	260		260259
1098N	1705575	0	0	0	1658	19894	78332	205155	71286	37715	414	0	0		0	99884	314157	414		414455
1098P	1088915	0	0	0	1058	12701	50011	130980	45512	24079	265	0	0		0	63770	200572	265		264606
1098R	1412156	0	0	0	1373	16471	64856	169861	59022	31227	343	0	0		0	82700	260111	343		343154
1098S	1074403	0	0	0	1044	12532	49344	129235	44906	23758	261	0	0		0	62920	197899	261		261080
1098V	1306961	0	0	0	1270	15244	60025	157208	54626	28901	318	0	0		0	76540	240734	318		317592
1098W	2356484	0	0	0	2291	27486	108226	283450	98492	52109	573	0	0		0	138003	434050	573		572626
Total	37621885,89	0	0	0	36568	438822	1727860	4525349	1572444	831933	9142	0	0	0	0	2203251	6929726	9142		9142118

Table A4-3: Calculated temporal and spatial energy consumption figures, depending on building type and function

Space heating demand of utility buildings in MJ

Share for space heating 0,86 Efficiency fac 0,85 1 m3 = 35,2 MJ

Postal code	Gas demand (m	Month 1	Month 2	Month 3	Month 4	Month 5	Month 6	Month 7	Month 8	Month 9	Month 10	Month 11	Month 12	Q1	Q2	Q3	Q4	Year
1096B	6499954,8	27931023	24753242	19735693,2	12376621,13	7526324	4348543	1839768	1672516	5017549	13212879	21575461	27262017	72419959	24251487	8529833,5	62050357	167251637
1097D	2350287,9	10099447	8950408	7136135,91	4475203,873	2721408	1572369	665233	604757,3	1814272	4777583	7801369	9857544	26185990	8768980,6	3084262,1	22436495	60475728
1098S	1485338,97	6382666	5656494	4509907,38	2828247,004	1719880	993708,4	420415,1	382195,5	1146587	3019345	4930322	6229787	16549067	5541835,3	1949197,3	14179455	38219554
1098X	1197493,32	5145761	4560315	3635926,93	2280157,569	1386582	801136,4	338942,3	308129,4	924388,2	2434222	3974869	5022509	13342003	4467876,3	1571459,9	11431601	30812940
1096C	991446,33	4260354	3775643	3010310,25	1887821,682	1148000	663288,7	280622,1	255111	765333,1	2015377	3290932	4158310	11046308	3699110,1	1301066,3	9464619,5	25511104
1098T	746648,27	3208430	2843399	2267034,4	1421699,541	864547	499516,1	211333,7	192121,6	576364,7	1517760	2478368	3131581	8318863,5	2785762,6	979819,95	7127709,9	19212156
1097A	530883,48	2281265	2021720	1611911,74	1010859,906	614712,1	355167	150263	136602,7	409808,1	1079161	1762175	2226624	5914896,5	1980739	696673,72	5067959,8	13660269
1097B	502708,67	2160195	1914424	1526365,08	957212,0024	582088,4	336317,7	142288,3	129353	388058,9	1021888	1668653	2108453	5600983,7	1875618,1	659700,16	4798995,3	12935297
Total	14304761,74	61469140	54475645	43433284,9	27237822,71	16563541	9570046	4048866	3680787	11042361	29078216	47482150	59996826	159378071	53371409	18772013	136557192	368078685

Hot water heating demand of utility buildings in MJ

Gas share for hot water heating 0,05 Efficiency fac 0,8 1 m3 = 35,2 MJ

Postal code	Gas demand (m	Month 1	Month 2	Month 3	Month 4	Month 5	Month 6	Month 7	Month 8	Month 9	Month 10	Month 11	Month 12	Q1	Q2	Q3	Q4	Year
1096B	6499954,8	777287,7	702066,4	777287,746	752213,9473	777287,7	752213,9	777287,7	777287,7	752213,9	777287,7	752213,9	777287,7	2256641,8	2281715,6	2306789,4	2306789,4	9151936,4
1097D	2350287,9	281055,8	253856,8	281055,798	271989,4819	281055,8	271989,5	281055,8	281055,8	271989,5	281055,8	271989,5	281055,8	815968,45	825034,76	834101,08	834101,08	3309205,4
1098S	1485338,97	177622,1	160432,9	177622,124	171892,3783	177622,1	171892,4	177622,1	177622,1	171892,4	177622,1	171892,4	177622,1	515677,14	521406,88	527136,63	527136,63	2091357,3
1098X	1197493,32	143200,5	129342,4	143200,516	138581,1448	143200,5	138581,1	143200,5	143200,5	138581,1	143200,5	138581,1	143200,5	415743,43	420362,81	424982,18	424982,18	1686070,6
1096C	991446,33	118560,7	107087,1	118560,683	114736,1451	118560,7	114736,1	118560,7	118560,7	114736,1	118560,7	114736,1	118560,7	344208,44	348032,97	351857,51	351857,51	1395956,4
1098T	746648,27	89286,86	80646,2	89286,8594	86406,63815	89286,86	86406,64	89286,86	89286,86	86406,64	89286,86	86406,64	89286,86	259219,91	262100,14	264980,36	264980,36	1051280,8
1097A	530883,48	63484,94	57341,23	63484,9374	61437,03615	63484,94	61437,04	63484,94	63484,94	61437,04	63484,94	61437,04	63484,94	184311,11	186359,01	188406,91	188406,91	747483,94
1097B	502708,67	60115,69	54298,05	60115,6932	58176,47732	60115,69	58176,48	60115,69	60115,69	58176,48	60115,69	58176,48	60115,69	174529,43	176468,65	178407,86	178407,86	707813,81
Total	14304761,74	1710614	1545071	1710614,36	1655433,249	1710614	1655433	1710614	1710614	1655433	1710614	1655433	1710614	4966299,7	5021480,9	5076662	5076662	20141105

Hot water heating demand of utility buildings in MJ

Electricity share for hot water heating 0,02 Efficiency fac 0,8 1 kWh = 3,6 MJ

Postal code	Electricity dema	Month 1	Month 2	Month 3	Month 4	Month 5	Month 6	Month 7	Month 8	Month 9	Month 10	Month 11	Month 12	Q1	Q2	Q3	Q4	Year
1096B	67683900,53	331113,4	299070,1	331113,35	320432,2743	331113,4	320432,3	331113,4	331113,4	320432,3	331113,4	320432,3	331113,4	961296,82	971977,9	982658,97	982658,97	3898592,7
1096A	32716153,19	160049,2	144560,6	160049,214	154886,3362	160049,2	154886,3	160049,2	160049,2	154886,3	160049,2	154886,3	160049,2	464659,01	469821,89	474984,76	474984,76	1884450,4
1097D	28880790,9	141286,4	127613,5	141286,412	136728,7854	141286,4	136728,8	141286,4	141286,4	136728,8	141286,4	136728,8	141286,4	410186,36	414743,98	419301,61	419301,61	1663533,6
1096C	13905231,04	68025,15	61442,07	68025,1522	65830,79243	68025,15	65830,79	68025,15	68025,15	65830,79	68025,15	65830,79	68025,15	197492,38	199686,74	201881,1	201881,1	800941,31
1098X	5865226,06	28693,01	25916,26	28693,0073	27767,42639	28693,01	27767,43	28693,01	28693,01	27767,43	28693,01	27767,43	28693,01	83302,279	84227,86	85153,441	85153,441	337837,02
1097A	4784161,83	23404,38	21139,44	23404,3818	22649,40176	23404,38	22649,4	23404,38	23404,38	22649,4	23404,38	22649,4	23404,38	67948,205	68703,185	69458,165	69458,165	275567,72
1098E	1175449,31	5750,362	5193,876	5750,36243	5564,86687	5750,362	5564,867	5750,362	5750,362	5564,867	5750,362	5564,867	5750,362	16694,601	16880,096	17065,592	17065,592	67705,88
1098T	918626,66	4493,972	4059,071	4493,97196	4349,005119	4493,972	4349,005	4493,972	4493,972	4349,005	4493,972	4349,005	4493,972	13047,015	13191,982	13336,949	13336,949	52912,896
1097B	830307,64	4061,91	3668,822	4061,91047	3930,881101	4061,91	3930,881	4061,91	4061,91	3930,881	4061,91	3930,881	4061,91	11792,643	11923,673	12054,702	12054,702	47825,72
Total	156759847,2	766877,8	692663,8	766877,762	742139,7696	766877,8	742139,8	766877,8	766877,8	742139,8	766877,8	742139,8	766877,8	2226419,3	2251157,3	2275895,3	2275895,3	9029367,2

Space cooling demand of utility buildings in MJ

Electricity share for space coo 0,07 efficiency (COP) 3,5 1 kWh = 3,6 MJ

Postal code	Electricity dema	Month 1	Month 2	Month 3	Month 4	Month 5	Month 6	Month 7	Month 8	Month 9	Month 10	Month 11	Month 12	Q1	Q2	Q3	Q4	Year
1096B	67683900,53	0	0	12243,0681	765191,759	1530384	10045437	23604635	18125862	4462598	1095755	55093,81	0	12243	12341013	46193096	1150848	59697200
1096A	32716153,19	0	0	5917,89317	369868,3233	739736,6	4855631	11409698	8761441	2157072	529651,4	26630,52	0	5918	5965236	22328211	556282	28855647
1097D	28880790,9	0	0	5224,12994	326508,1211	653016,2	4286399	10072123	7734324	1904195	467559,6	23508,58	0	5224	5265923	19710642	491068	25472858
1096C	13905231,04	0	0	2515,26123	157203,8271	314407,7	2063772	4849424	3723844	916812,7	225115,9	11318,68	0	2515	2535383	9490081	236435	12264414
1098X	5865226,06	0	0	1060,93712	66308,56984	132617,1	870498,9	2045487	1570717	386711,6	94953,87	4774,217	0	1061	1069425	4002916	99728	5173129
1097A	4784161,83	0	0	865,387763	54086,73521	108173,5	710050,7	1668468	1281207	315433,8	77452,2	3894,245	0	865	872311	3265108	81346	4219631
1098E	1175449,31	0	0	212,622291	13288,89319	26577,79	174456,6	409935,8	314787,3	77500,83	19029,7	956,8003	0	213	214323	802224	19986	1036746
1098T	918626,66	0	0	166,166676	10385,41727	20770,83	136339,8	320369,4	246009,8	60567,75	14871,92	747,75	0	166	167496	626947	15620	810229
1097B	830307,64	0	0	150,191005	9386,937788	18773,88	123231,7	289568,3	222357,8	54744,62	13442,09	675,8595	0	150	151393	566671	14118	732331
Total	156759847,2	0	0	28355,6573	1772228,584	3544457	23265817	54669707	41980551	10335637	2537831	127600,5	0	28355,657	28582503	106985895	2665431,8	138262185

Table A4-4: Calculated temporal and spatial energy consumption figures, depending on building type and function

Temperature level for heating demand

The temperature levels for heating demand can be categorized as follows:

	Heat supply temperature level		
	Low	Medium	High *)
Space heating	35	45	80
Hot sanitary water		40	70

*) High reflects the “traditional” situation.

The current “traditional” system for heating is a high efficiency boiler, for space heating combined with radiators, operating at a high temperature level.

For new / future buildings, medium or low temperature levels might be applied if the heating equipment is fitted to these “non-traditional” conditions.

Here, dimensioning of space heating radiators for the medium temperature level or applying a floor heating system is optional.

For developing alternatives to cover heating demand, the temperature levels as indicated above could be the basis.

Capacities for heating

Capacities for space heating equipment can be calculated, based on 10% of full-load hours on a yearly basis.

This leads to the following required capacity level:

Dwelling – heating: 10 kW. The total maximum capacity for the area, based on the 10% full-load parameter is 280.000 kW.

For utility buildings, the required capacities for space heating are strongly dependent on the type of building. Reliable estimates are difficult to make. However, the total maximum capacity for the area, based on the 10% full-load parameter, is 124.600 kW.

When designing a supply network, this value can be reduced for temporal uneven demand on dwelling level.

The typical value for the capacity for hot sanitary water production for dwellings is approximately 22 kW.

In case of production using a buffer vessel, a much lower capacity of 0,5 kW can be considered.

Development of energy demand

During the recent decades, the energy demand in buildings is gradually reduced.

The improved building insulation quality and the increased efficiency of technology is responsible for this development.
Statistical figures show that for the full mix of dwellings this decrease is approximately 2% per year.

Continuation of this decrease for the future decade (2011 -2020) can be assumed.

For the periode 2021-2030, a slighter slope should be assumed, e.g. 1,5% per year.

This means that the values for heating and cooling demand, as presented in the tables on pages 67 and following, could be reduced by 20% respectively 15%.

However, for future buildings, it should be noted that:

the balance between heat demand for space heating and hot sanitary water production will shift towards a higher share for the latter.

The level of energy demand for passive buildings is predicted to become 1,5 m^3/m^2.

These developments will influence the calculation input values ($S_{function}$, $\eta_{conversion}$).

At the same time, other applicable temperature levels for the heat demand will have a significant impact on the long term energy supply options for the built environment.

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B Heat from surface water

Model setup

Surface water temperature model

The existing hydrodynamic SOBEK (Rainfall Runoff coupled to Flow) of Watergraafsmeer (Figure B.7.1) was extended with the water quality module, which is used to calculate the water temperature resulting from ambient meteorological conditions.

The hydrological model (Figure B.7.1) has several rainfall runoff nodes (tetragons) through which rainwater is transferred from paved and unpaved nodes to surface water. Drainage of the surface water system occurs through two water-level boundary nodes in the southeast and northwest (pink squares). Figure B.7.1 shows the yearly averaged flow pattern in the water system. Average flows are around 0.05 $m^3.s^{-1}$ and maximum flows do not exceed 0.15 $m^3.s^{-1}$.

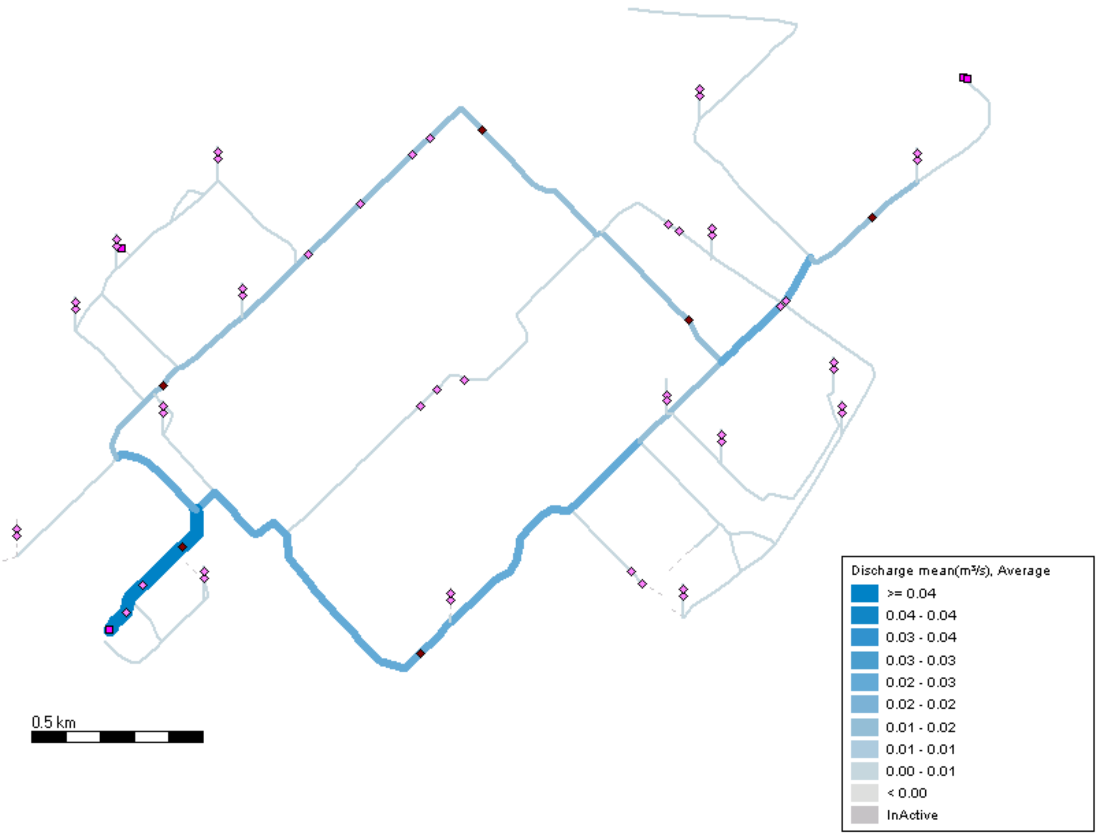

Figure B.7.1 Spatial distribution of the yearly averaged circulation in the Watergraafsmeer.

The data listed below were added to the water quality model:

- meteorological data for station Schiphol: air temperature, global radiation, air temperature, air humidity and cloud cover;
- water temperature for model boundaries;
- water temperature for lateral flows (rainfall runoff).

Calculations were made for the period 2005 to 2007. The three summers in this period were quite different. The number of days in which the water temperature exceeded 18˚C is given in Table B.7.1 for reference. Compared to the average over the period 2000-2009 the summer of 2007 is cool, the summer of 2005 is average and the summer of 2006 is relatively warm.

Table B.7.1 Number of days in which the water temperature in a Dutch water of 1.5 m deep exceeds 18 ˚C (source Report WKO Hoog Dalem, 2010).

2005	83
2006	103
2007	65
Average 2000-2009	78

Water temperature measurements for the model boundaries are not available. Therefore we used simulated values, obtained from a separate model (Landelijk Temperatuurmodel) which simulates water temperature for an isolated water body with a depth of 1.5 m using Schiphol meteorology. The simulated water temperature is fed to the boundaries of the Watergraafsmeer model (Figure B.7.2).

In practice this implies that al boundaries of the Watergraafsmeer model have the same water temperature forcing:

- unpaved (Flow - RR connection on channel)
- paved (Flow - RR connection on channel)
- Flow - Lateral flow
- Flow – Boundary.

The model can be improved by applying more realistic water temperatures to these boundaries, preferably measured data (if these are available) or other wise the following improvements are possible:

- on-line coupling with the Landelijk Temperatuurmodel;
- use different temperature for water entering the model through rainfall runoff via paved nodes (e.g. use air temperature);
- use different water temperature for water entering model through rainfall runoff via unpaved nodes (e.g. use water temperature simulated by a deeper water body, e.g. 5 m deep to account for the fact that water from unpaved nodes has a sub-surface component and thus has a delayed response to atmospheric changes).

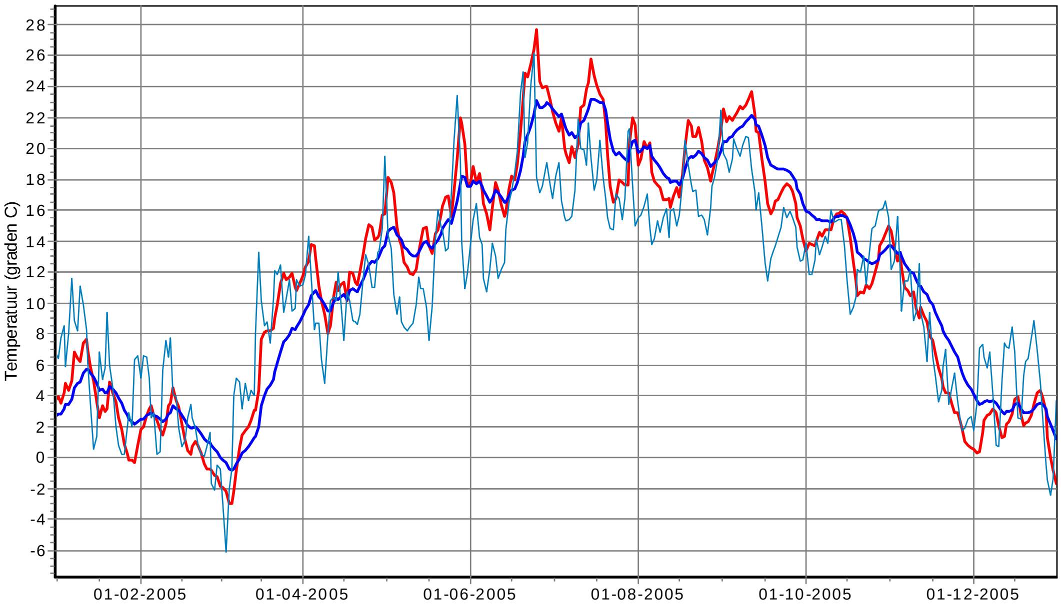

Figure B.7.2 Air temperature (thin blue line) and simulated water temperature from the Landelijk Temperatuurmodel for an isolated water body of 1.5 m (red line) and 5.0 m (blue line) for the year 2005.

Heat and cold inputs to surface water model

The total area of the surface water in the Watergraafsmeer model equals 295.000 m^2. Dividing the total heat demand (372.9 TJ/year) over this area results in a yearly average of 40 $W.m^{-2}$ (see Table B.7.2 for monthly values). Knowing that this amount of heat cannot be extracted from surface water in all months, the heat demand function was arbitrarily reduced before forcing it to the model. Reduction was done by:

- excluding heat extraction in the winter months (January-March and December),
- reducing the heat demand for the month April and October-November,
- meeting the heat demand for the summer months (May-September).

The amount of heat extracted from the surface water in the model then equals 20% of the yearly demand in Table B.7.2. Figure B.7.3 shows the demand (red bars) and the function used in the model (orange bars).

Table B.7.2 Summary of calculated values of heating and cooling demand [TJ] for Watergraafsmeer per month (columns 2-3) and the same data expressed as W.m^{-2} area surface water (columns 4-5).

	Heating demand	Cooling demand	Heat demand per area surface water	Cooling demand per area surface water
	TJ	TJ	W/m2	W/m2
January	62.3	0.0	79	0
Febrary	55.2	0.0	77	0
March	44.0	0.0	56	0
April	27.6	0.0	36	0
May	16.8	0.4	21	1
June	9.7	1.7	13	2
July	4.1	4.5	5	6
August	3.7	1.6	5	2
September	11.2	0.8	15	1
October	29.5	0.0	37	0
November	48.1	0.0	63	0
December	60.8	0.0	77	0
Year	372.9	9.1	40.3	1.0

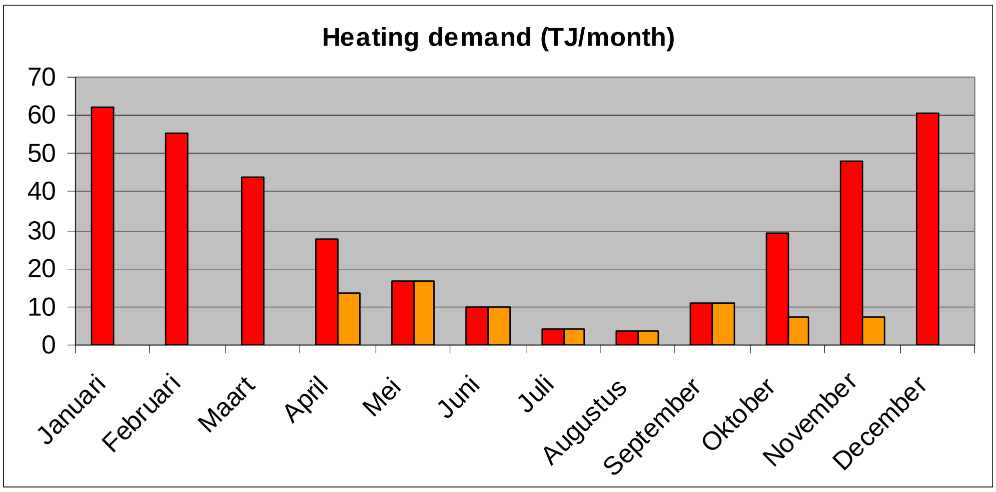

Figure B.7.3: Heating demand per month. Orange bars are heat demands extracted from the surface water in the Watergraafsmeer temperature model.

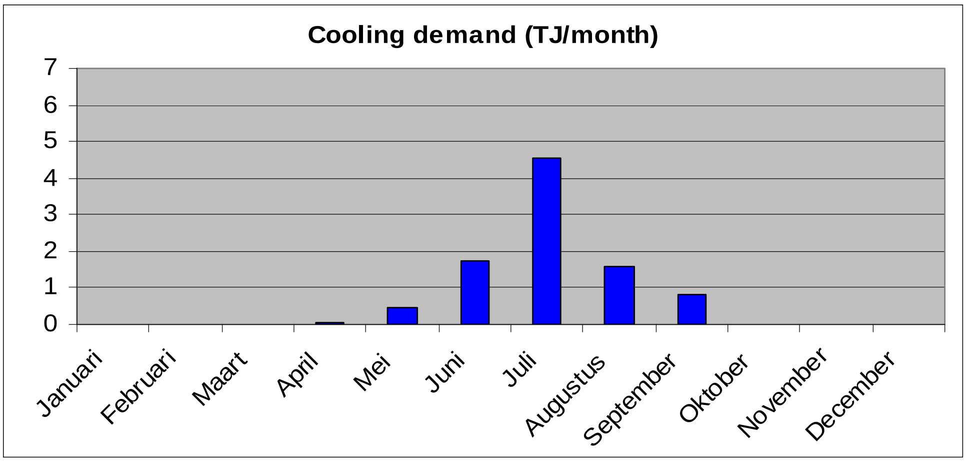

Figure B.7.4: *Cooling demand per month. This demand is forced to the Watergraafsmeer temperature model.*

Heating and cooling potential of surface water

The situation with heat extraction and storage are shown below and are compared to the reference situation without heat extraction and storage.

Heat extraction - heating

Figure B.7.5 shows that at the four location where the heat is extracted from the surface water (orange tetragons) the lowering of the water temperature is clearly visible. Because the water in the Watergraafsmeer is fairly stagnant, the sphere of influence is limited more or less to an area around the points of cold discharge. In the simulations the cooler water is not transported to the peripheral parts of the network, therefore the extracted heat affects only around 20% of the available water. This implicates that the effect that the heat extraction has on the water temperature is higher compared to a situation where a larger part of the available water would be affected (using the same demand function). This can be achieved by circulating the water artificially, as is e.g. done e.g. in Hoog Dalem and at many other places to prevent water quality problems. Note that forced circulation would hardly increase the amount of heat that can be extracted outside the summer season. To obtain heat for winter use the summer heat should be stored in a buffer, such as groundwater (WKO).

In one simulation year (2005) 74 TJ of heat has been extracted over an eight month period (April-November) lowering the water temperature with several degrees Celsius (ranging from 1 to 7) in about 20% of the water. The average atmospheric heat exchange over this period and water surface equals 60 $W.m^{-2}$. This value is in the same order of magnitude as is the case in Hoog Dalem.

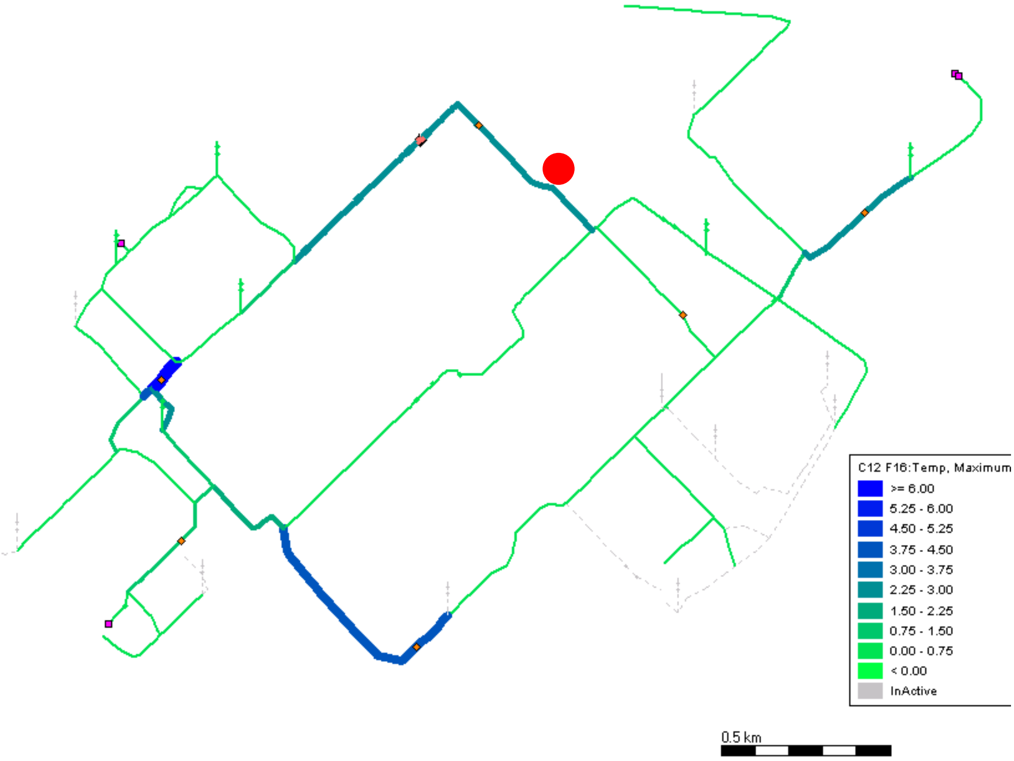

Figure B.7.5: Simulated difference in water temperature (˚C), averaged over the period April-November. As a result of heat extraction (see Figure B.7.3 for the amount) from surface water the water is up to 7˚C cooler compared to the reference situation (without heat extraction)..

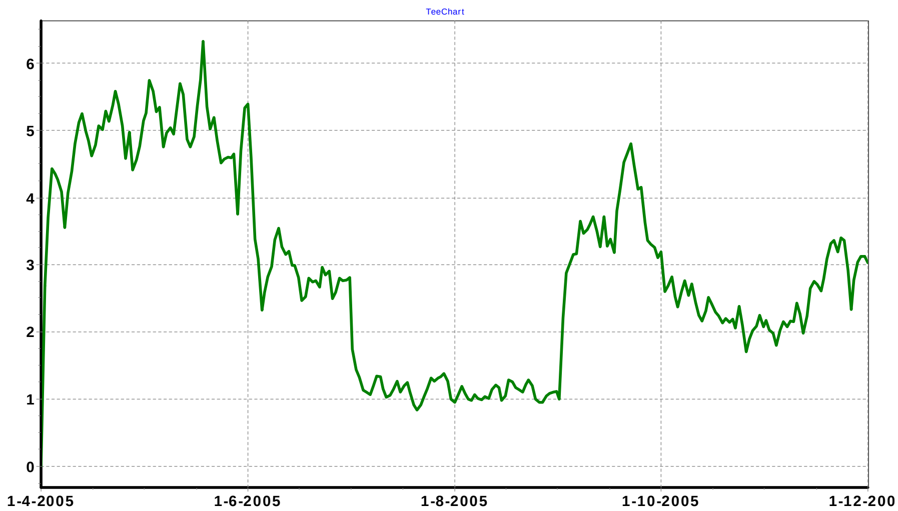

Figure B.7.6 : Simulated difference in water temperature (˚C), over the period April-November at the location indicated in Figure B.7.5 (red circle). The water is cooler compared to the reference situation.

Heat storage - cooling

Cooling demand is substantially lower compared to heat demand, even in summer. The effect cooling demand on surface water (which is the same as heat discharge to surface water) is fairly limited, see Figure B.7.7.
Through enhancement of the circulation in the water the effect can be further minimised and would suite environmental requirements.

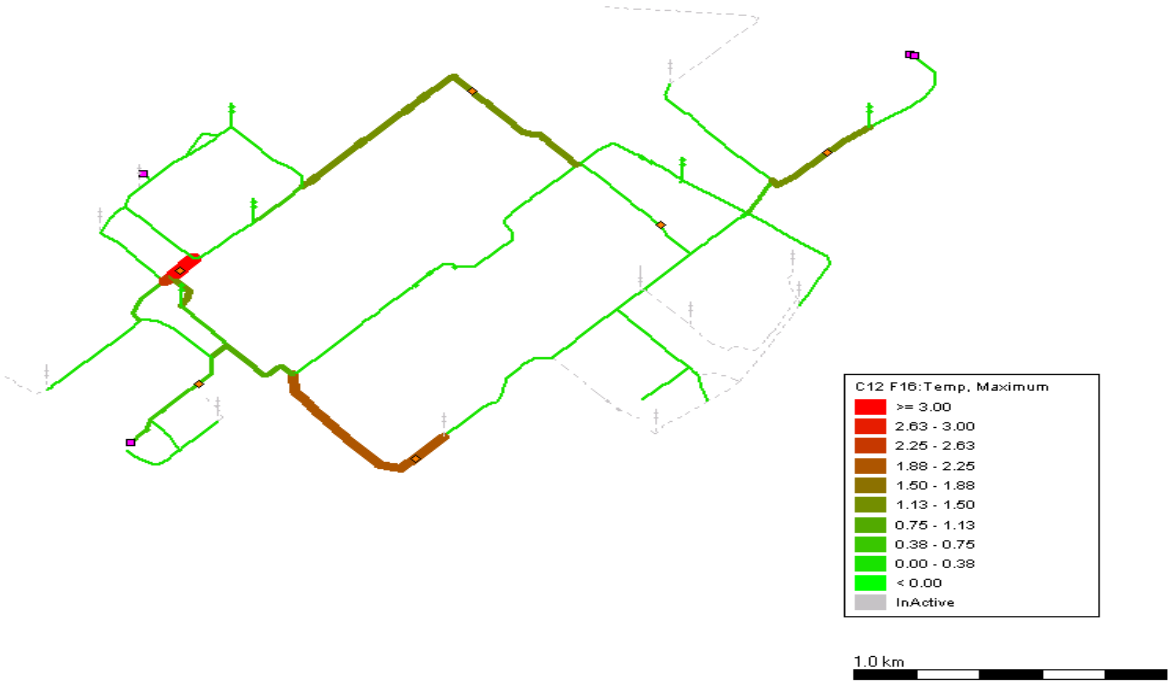

Figure B.7.7: Simulated maximum difference in water temperature (˚C), in the period May-September as result of cold extraction/heat discharge from surface water (see Figure B.7.4 for the amount). The water is heated less than 3˚C compared to the reference situation. The average heating in this period is around 1˚C.