Need for Heat: meeting European collective heat demand with surface water and ATES

Master's Thesis Sustainable Development: Energy and Resources

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ABSTRACT

Aquathermal heat – withdrawing heat from surface water – is a proven alternative technology to the current fossil-fuelled heat system. It can be combined with seasonal storage in subsurface layers to solve the mismatch in peak heat demand and peak surface water heat supply. The little research that has been performed on the subject has a strong focus on the Netherlands. In this research, the technical potential of combining aquathermal heat and aquifer thermal energy storage (ATES) to meet the collective European heat demand is studies. The objective is to obtain a quick-scan for aquathermal heat opportunities in Europe. Using GIS, spatial datasets for the European heat demand, supply and storage are developed. These datasets are integrated to find out where the supply and storage can meet the demand, which is used to calculate the aquathermal heat potential. The results show that for many cities and regions, aquathermal heat can meet significant shares of the heat demand, reaching up to a sevenfold in certain regions. In interpreting the results, four aspects are found to be critical. (1) The potential can highly vary between regions, cities and even neighbourhoods. However, since many cities tend to be located near rivers, a large share of cities have significant potential in some areas. (2) A large limitation is posed by the distance over which heat can be transported. The aquathermal heat potential of cities' neighbourhoods that are located further away from surface water are impacted by this. Hence, using a district heating approach instead of a neighbourhood approach can greatly benefit the aquathermal heat potential, as a district heating system can connect a larger part of the city to surface water. (3) Using aquathermal heat directly (without ATES) decreases the energy efficiency of the system but offers opportunities if (sufficient) storage is unavailable. However, direct aquathermal heat use is not always feasible due to low surface water temperature in winter or high electricity prices. (4) The absence of heat accounting (the consideration that aquathermal heat can only be used once) leads to overestimations of the potential. Future research on a local level should therefore take into account the aquathermal heat demand of neighbouring and up-and downstream areas. All in, this research provides an overview of where possibilities for aquathermal heat lie. Yet, while this research shows that many European cities can benefit from aquathermal heat, in-depth research is necessary to prove whether it is locally feasible.

List of abbreviations:

XGDH	= X^{th} Generation Heat Demand
ATES	= Aquifer Thermal Energy Storage
CHP	= Combined Heat and Power
CLC	= Corine Land Cover
COP	= Coefficient of Performance
DH	= District Heating
ΔT_{sw}	= Temperature difference of surface water
ΔT_{ATES}	= Temperature difference of aquifer thermal energy storage
GIS	= Geographical Information Systems
HDD	= Heat Demand Density
HRE	= Heat Roadmap Europe
NDC	= Nationally Determined Contribution
RES	= Renewable Energy Sources
UTES	= Underground Thermal Energy Storage
WSHP	= Water Source Heat Pump

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1 INTRODUCTION

1.1 BACKGROUND

It is generally agreed that the amount of carbon dioxide that has accumulated in the atmosphere is causing major issues around the globe, which will only increase in number and intensity. In short, the CO2 level in the atmosphere has reached alarming levels. To minimize the consequence for later generations, future CO2 emissions need to decrease drastically on a global level (IPCC, 2018). The achievement of the Paris agreement in 2015 as an international response to the alarming CO2 levels was a historical moment since it was the first of its kind and adopted by 195 states. In the agreement, countries acknowledge climate change and bind themselves to limit the rising global temperatures to 2°C, while aiming for 1.5°C by 2100. To achieve this, the European Union (EU), has set the goal to reduce its greenhouse gas (GHG) emissions by 80-95% in 2050 compared to the 1990 levels (European Union, 2015).

The potential for decarbonizing the European heating and cooling sector is significant, as it currently represents the second largest energy sector, accounting for approximately 50% of final energy demand (Mathiesen et al., 2019). According to Connolly, et al. (2014), 64% of the European residential heat supply in 2010 was fuelled by fossil fuels. Due to the continuous need for heat, and the high CO2 emissions associated with it, the heating sector has a large role in achieving the EU's climate goal. Compared to the electricity sector, renewable heat integration lags in many industrialised countries (Bloess, Schill, & Zerrahn, 2018).

Nowadays, district heating is conceived as one of the most important urban energy-efficient heat supply technologies available (Persson, U., Möller, & Werner, 2014). In fact, the Heat Roadmap Europe (HRE) deems district heating (DH) essential for the decarbonization of Europe. In the pathway outlined in HRE, renewable sourced district heating will supply 50% of total heat demand from the built environment in 2100 (Connolly et al., 2014). In Europe, DH presence is predominantly limited to the Nordic and Eastern European countries, with very low shares in other European countries. While DH in Scandinavia is mostly demand-driven and of low temperature, the Eastern European countries have a DH system that is generation-driven and characterised by its high temperature and inefficiency (Fleiter et al., 2017). DH can be sourced by traditional heat generators, like a combined heat and power (CHP) plant or waste incinerators, but also alternative and renewable sources, like excess heat from industrial processes, biomass, solar thermal and geothermal (Mathiesen et al., 2019).

Another low-temperature heat source for district heating has recently been brought under the attention by two engineering companies, CE Delft and Deltares (Kruit, Schepers, Roosjen, & Boderie, 2018). They researched the benefit of using water as a heat source for DH, referring to this combination with the word 'aquathermal' (see section 4.1.4). Currently, the potential for heat from surface, drinking and wastewater has been researched in the Netherlands. Aquathermal heat relies on the extraction of heat from water, to supplement heat in DH systems. The need for seasonal storage using aquifer thermal energy storage (ATES) is required when heat extracted in summer is used in winter (Kruit et al., 2018). Furthermore, heat pumps are required to upgrade the low-temperature water. It is unclear what the exact energy reduction of aquathermal heat use is compared to traditional ways of heating because it is a combination of mature technologies and the final configuration is case-specific. However, since aquathermal is a combination of technologies with significant electricity demand, it can still cause significant CO_2 emissions when electrified by grey electricity (Kruit et al., 2018). Therefore, for aquathermal to be successful in reducing the GHG emissions of the heating and cooling sector, it is essential that the electricity mix predominantly relies on RES.

Kruit, Schepers, et al. (2018) calculated the potential of surface water aquathermal heat in the Netherlands, using Dutch temperatures of surface water and the subsurface conditions. It was calculated that more than 40% of heat demand from households could, in theory, be covered by surface water heat combined with subsurface heat storage. The Netherlands already has over 150 cases where aquathermal is being successfully deployed, but the current output is nowhere near the calculated potential. Hence, this research has been an incentive for the government to look further into this (Netwerk aquathermie.). Because deployment of aquathermal in the Netherlands is characterised by a bottom-up strategy, there is neither a complete archive of the projects available nor has holistic research been performed on aquathermal yet. In line with this, there is also a lack of European research on aquathermal.

1.2 SOCIETAL RELEVANCE

Decreasing global CO_2 emissions is essential to ensure future liveability on our planet. Following the Paris agreement, the EU has bound itself to stringent goals for 2030 and 2050 and all states have been called upon to submit a long-term climate strategy in 2020. Countries do this through nationally determined contributions (NDCs) that outlined their post-2020 climate-actions (United Nations, 2015). It has been researched that countries often leave many RES unused in their NDCs. Not only does that lead to an underestimation of the RES potential in a country, but it can also lead to a discouragement of additional investments in RES (Wuester et al., 2017). For aquathermal to be included in climate strategies, it needs to be recognised as a viable alternative to current heating strategies, not only by scientists but also by local decision-makers. Therefore, it is necessary to investigate the possibilities of this technology on a European level. To aid local governments, the dataset that will be developed for this research can provide a first ‘quick-scan’ for aquathermal feasibility on a local scale.

1.3 SCIENTIFIC RELEVANCE

The high energy demand of the heating and cooling sector forces countries to find low-carbon alternatives to heat households. Considering the increasingly important role that is envisioned for DH coupled with heat pumps, research to ease the integration of these technologies is advantageous (Paardekooper et al., 2018). Even though DH and heat pumps are viewed as essential because they ease the integration of RES and excess heat sources, it is also acknowledged that DH systems and areas with insufficient excess heat sources are in the need of an alternative source. Hence, additional research on alternative heat sources is essential. Moreover, while the use of low-temperature heat sources combined with seasonal heat storage like ATES is a promising technology that is increasingly implemented in the Netherlands, there is a lack of scientific literature on the subject (Fleuchaus, Godschalk, Stober, & Blum, 2018). Considering the high technical potential of aquathermal in the Netherlands and the fact that it is still in its infancy in Europe, it is highly interesting to research what it could mean for the European heating sector.

With more than 150 successful cases of aquathermal in the Netherlands, it has proven to be a promising technology in decarbonising the heating and cooling sector (Bloemendal et al., 2016a). Yet, while there has been much research on aquathermal in the Netherlands, international literature has rarely considered aquathermal as a promising technology. A comprehensive study, albeit on a large scale, can show the potential of aquathermal heat to serve as an alternative and renewable heat source for collective heating.

1.4 Research question

The objective of this thesis is to find out what the role of aquathermal heat in the sustainable heating system can be on a European scale, and where opportunities for aquathermal heat in Europe exist. This objective is both to put it in the scientific 'spotlight', but also to aid local decision-makers in finding alternative heat strategies. This is done by calculating the potential of aquathermal to supply heat for the collective heat demand in Europe, both by coupling aquathermal with and without ATES. The strategy used by (Kruit et al., 2018)will be followed, although adaptations have to be made due to differences in data formats. To reach the objective, an answer to the following research question and sub-questions will be formulated:

What is the current potential of the application of combining surface water heat and ATES to meet the collective heat demand in Europe?

Sub-questions:

1. *What is the collective heating demand in Europe in areas suitable for DH?*
2. *What are the boundary conditions for surface water aquathermal?*
    a. *How much heat can surface water supply?*
    b. *What is the spatial storage capacity of ATES in Europe?*
3. *How can the heating demand and supply be matched, considering geographic constrains of transporting heat?*

The main research question consists of a supply and demand side; respectively calculating surface water heat supply and defining the ATES capacity, and calculating the heat demand in Europe. The demand side concerns the heat demand in areas that pre-defined areas suitable for DH and corresponds to sub-question 1. The supply-side relates to the total heat that can be supplied by the available surface water and the possible limitation of ATES capacity and is further addressed in sub-questions 2a and 2b. Integrating sub-questions 1 and 2 leads to sub-question 3, which answers whether supply can meet demand. The results will be two-fold by researching the overall potential but also looking at the local match between heat demand and supply.

1.5 Scope of research

This thesis focuses solely on the current heat demand in the EU-27[1] and United Kingdom. Due to the time restrictions of this research, choices had to be made about geographical and temporal

[1] The 27 member states of the European Union as of 2020 are: Belgium, Bulgaria, Czech Republic, Denmark, Germany, Estonia, Ireland, Greece, Spain, France, Croatia, Italy, Cyprus, Latvia, Lithuania, Luxembourg, Hungary, Malta, Netherlands, Austria, Poland, Portugal, Romania, Slovenia, Slovakia, Finland and Sweden.

limitations. The main decisions were made on energy demand, time, region and depth of the potential study. This section aims to provide arguments for these decisions.

The time scope of this research is limited to the current – most recently available – heat demand. Therefore, the most recent energy demand data will be used, and the current proven and available technologies are assumed for the technical potential.

Furthermore, the focus is on the European technical potential of aquathermal. The reason for this large spatial extent is supported by the aim of this thesis, which is to provide a large scale and first analysis of the aquathermal potential. Because this thesis concerns the collective heat demand, heat demand is limited to areas where DH can be deployed. This also involves areas where DH is currently not present yet but meets the requirements for district heating.

Multiple potential definitions are used in the literature. Each potential includes more limitations and stricter boundary conditions – most commonly used are respectively from broad to specific: theoretical, technical, economic, market, and societal potential. More in-depth potential studies tend to be of a smaller spatial scale due to the need for consistent and high-resolution data. In this study, the technical potential is calculated (see figure 1).

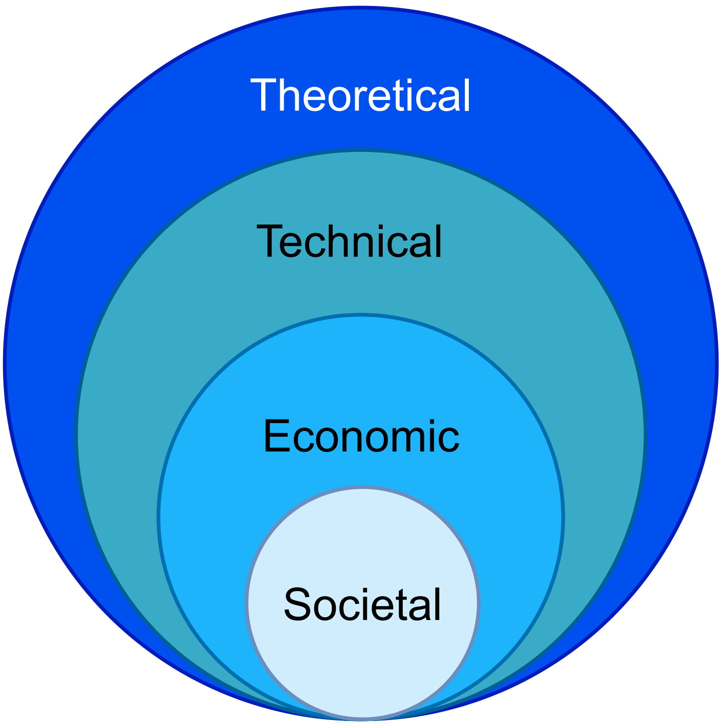

Figure 1. Theoretic: the amount of energy that is in the water system and can theoretically be used. Technical: The potential heat that can be extracted and stored in the subsurface based on current technologies. Economic: the aquathermal heat supply that is economically profitable. Societal: potential for which there is societal support. Modified from Kruit et al. (2018).

2 LITERATURE REVIEW

This chapter aims to support this research with the required theory to properly understand the research and its underlying assumptions.

2.1 AQUATHERMAL HEAT

2.1.1 Concept and technology configuration

Aquathermal is the technique of harvesting thermal energy from water (see figure 2) for a water-source heat pump (WSHP) system. Aquathermal is a combination of several mature technologies including heat exchangers, distribution networks, heat pumps, and often an ATES system. The three most dominant applications are heat from wastewater, groundwater and, surface water. In this thesis, there is a focus on surface water. Using heat exchangers, a portion of the surface water heat (SWH) can be extracted, and the body of water is cooled down by a pre-set temperature, for which (Kruit et al., 2018) use 3°C. The output of the heat exchanger will have the same temperature as the surface water. A WSHP system is used to reach the desired temperature, which theoretical efficiency is defined by (1) (Lowe, 2011).

$$COP = \frac{T_w}{T_w - T_c} \qquad (1)$$

In this formula, T_w is the desired temperature while T_c is the initial temperature. Following formula (1), the difference between the surface water temperature and desired temperature (ΔT) defines the coefficient of performance (COP) of the WSHP, which is a measure for heat pump efficiency. Conversely, when domestic heat demand is highest, surface water heat supply tends to be at its lowest. To counteract this mismatch in supply and demand and to increase the efficiency of the process, seasonal energy storage in ATES systems can be used in regions with suited subsurface conditions. In summer, European water bodies can reach temperatures up to 25°C and can therefore function as a low-temperature heat source. Hence, a major increase in efficiency can be reached by extracting heat in summer and storing it until winter. In winter, the stored heat is extracted from the ATES heat source and upgraded by a central WSHP, after which it is delivered through a district heating system (Kruit et al., 2018).

In regions where subsurface conditions are not suited for ATES, aquathermal can also be performed without seasonal storage. Here, ΔT will be larger and the process will have a lower COP, hence the efficiency will be lower. However, projects like this can still be economically feasible. An example of this is seen in Drammen, Norway, where aquathermal without ATES provides heat for 90% of the city. This heat pump uses seawater from the Drammensfjorden, whose water is around 8-9°C, and reached a COP of 3.3 (Hoffmann & Forbes Pearson, 2011).

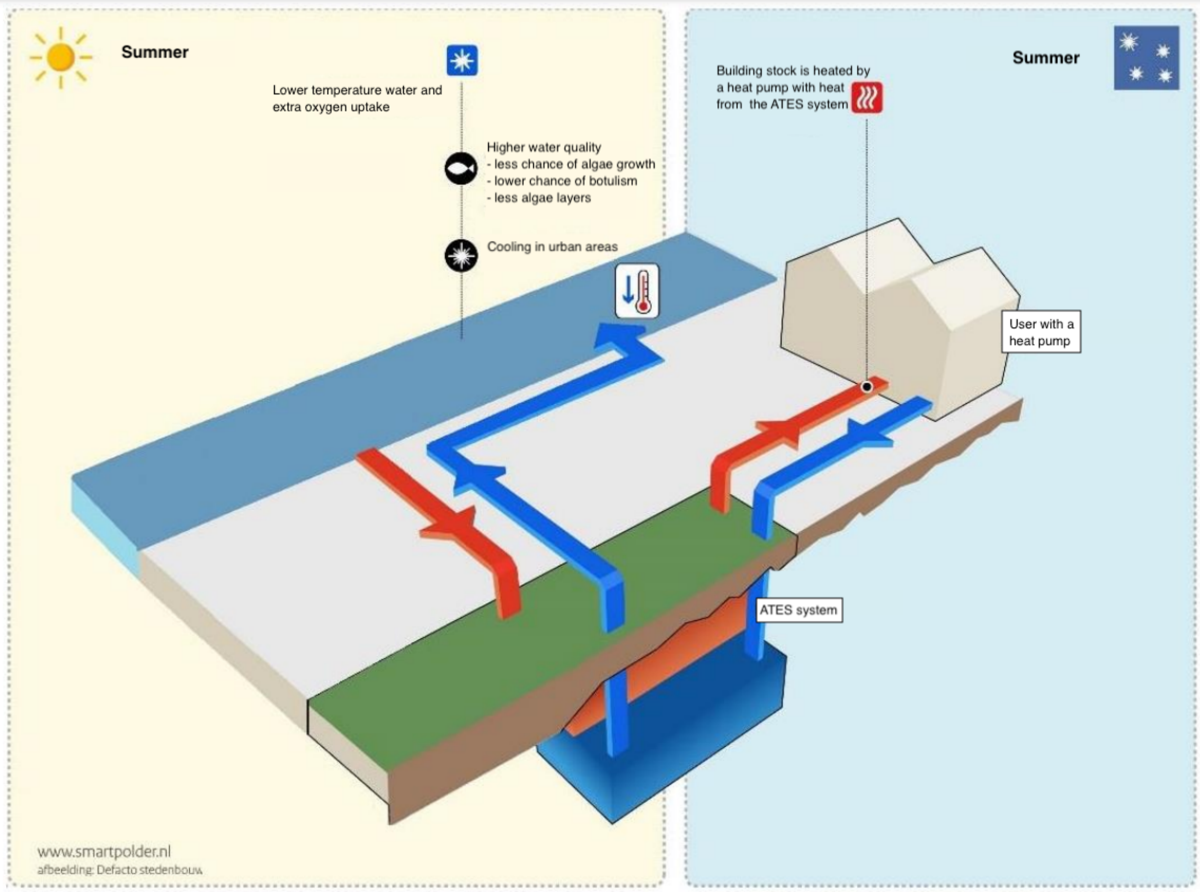

Figure 2. Aquifer thermal energy storage. In summer, cold water is used to cool the buildings. This water warms up and is stored. In winter, the process is reversed, and the warm water is used for heating purposes. Modified from Kruit et al. (2018)

The total energy saving potential of aquathermal heat is very site-specific and strongly depends on the configuration of the different technologies involved: WSHP, ATES and district heating. It has therefore rarely been considered in the international scientific literature. Some similar technologies have been researched, albeit in different circumstances. Zhang, Ge & Ye (2007) found heat savings of approximately 16% for the heat pumps energy use when they modelled energy use of a space heating and cooling system with an insulated pond as seasonal energy storage (Zhang, Ge, & Ye, 2007).

Surface water can contain a considerable amount of thermal energy, which is predominantly influenced by atmospheric conditions like solar insulation and wind, but also delivered through discharge. Heat is absorbed from the sun and air during spring and summer, and released when air temperatures and solar insulation drop in winter. Hence, rivers and lakes partly follow the ambient air temperatures, but with a time lag and smaller temperature shifts (Gaudard, Wüest, & Schmid, 2019). The temperature of rivers also strongly depends on their water source and flow properties. Low discharge and slow flow can cause rivers to be more strongly influenced by temperature and solar insulation. An approximation of the thermal energy in stagnant and flowing water has been developed by IF Technology (2019), upon which is further elaborated in section 0.

When using SWH, the thermal regime mustn't be altered significantly, as it can potentially harm the ecosystem. Although no legal guidelines are present, Kruit et al. (2018), generally maintain a temperature difference 3°C, while stressing not to extract more than 6°C from the surface water to minimize unknown ecological effects. Also, summer heat extraction starts at 15°C, limited by the rule that the water temperature cannot reach below 12°C. See figure 3 for how the thermal regime could look under these circumstances. Studies about the ecological effects have been performed, and no negative impacts were found with this thermal regime. In fact, in the same study found that aquathermal is likely to have a positive effect on its surrounding ecosystems by reducing temperature variation and peak heat stress (De Lange, Jacobs, & Boderie, 2017). Contrary to the 12°C limit that Kruit et al. (2018) maintain, De Lange et al. (2017) concluded that a safe reduction limit to a minimum temperature is still missing. Therefore it is unclear what the effects are of heat extraction in winter.

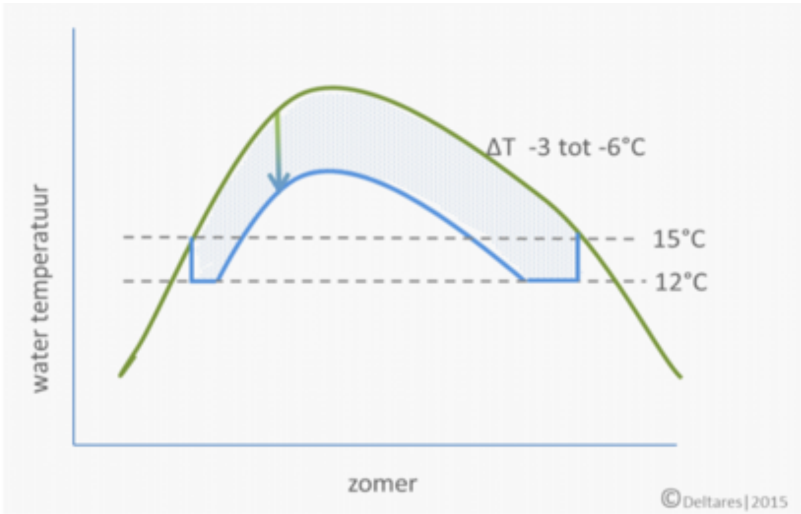

Figure 3. Possible thermal regime of a water body when extracting heat for aquathermal. (Kruit et al., 2018)

2.1.2 Application of aquathermal in Europe

Using heat from water has been in use for a while. However, it has never been categorized under a specific term, leading to inefficient knowledge dissemination and a lack of scientific literature on the subject. Also, while DH is often included in the system, ATES is not.

Under the HRE, (David, Mathiesen, Averfalk, Werner, & Lund, 2017) researched large scale heat pumps (with installed capacity >1MW) operating in European DH systems. They estimate that 24% of all installed large scale heat pump capacity is currently represented by surface water heat pumps. The rest comes from heat pumps sourced with sewage and geothermal water, industrial waste heat and flue. In Sweden, there was a total of 1527 MW installed capacity of large heat pumps coupled with DH in 2013. Of this capacity, 27% originated from ambient surface water, while the rest came from sewage water or industrial excess heat (Averfalk, Ingvarsson, Persson, Gong, & Werner, 2017). Furthermore, a neighbourhood in Budapest uses sewage water heat pumps for the DH system, providing direct heating and cooling for over 100,000 inhabitants. Seawater can also be used and is in place in multiple locations in Europe, like the previously mentioned example in Drammen.

Feasibility studies for WSHP in Glasgow and Norwich, United Kingdom are positive about the viability but conclude with many barriers that need to be overcome. This exemplifies that there are many barriers to the final implementation of WSHP. Furthermore, the reports remark the costs of transporting the heat. It can be concluded that, while ATES is not widely used, large-scale heat pumps coupled with DH are frequently mentioned in reports as an alternative heating solution. However, when no DH system is present, this poses the highest investments costs and therefore the largest barrier to implementation (Atkins, 2015).

2.2 District heating

2.2.1 Concept and development

A DH system is a shared heating system for multiple buildings, a neighbourhood, town, or even a whole city. It comprises a network of well-insulated pipes that connects one or multiple heat generators to users. The generated heat is fed into the carrier, usually water or steam, and is transported to its users. The used heat carrier is then returned to the DH system to be heated again. Different types of DH exist and are generally divided into generations based on heat carrier, temperature and corresponding efficiency. Around 1880, the 1st generation DH (1GDH) used very high temperature (>100°C) steam or pressurized water as heat carrier. Following, DH became more efficient as temperature decreased and insulation technologies advanced. Currently, the 3rd generation DH (3GDH) is most dominant, which is characterized by higher efficiency and the integration of high-grade renewable energy. The temperature in the 3rd generation DH is about 50-70°C. Progress has already made on the 3rd generation DH, introducing the 4th generation DH (4GDH) (Lund et al., 2014).

2.2.2 Energy efficiency of district heating

Already in 2012, it was concluded that DH would play a significant role in the future European energy system (Fleiter et al., 2017). HRE calls DH the enabler of the decarbonisation of the European heating sector because it is a future-proof measure to efficiently supply heat. HRE also calls for modernising existing generation driven 1st and 2nd generation HD to the more efficient and demand-driven 3rd or 4th generation DH systems. These 3GDH and 4GDH are suitable for low-temperature heat carriers, and therefore suited for aquathermal heat. This specific trait of 3GDH and 4GDH is important for transitioning to renewable sources.

The later generations DH systems are characterized by the lower temperature of the heat carrier, resulting in a significant reduction of heat loss during transportation and distribution: heat losses could go as high as 50% for 1GDH, while it is 5-30% for the 3GDH and 4GDH. Because renewable and alternative heat sources like excess heat from data centres and renewable energy sources (RES) are generally characterized by a low temperature, modern DH systems allow for better integration of multiple lower-quality heat sources. While DH is viewed by many as essential in decarbonizing the heating and cooling system (Lake, Rezaie, & Beyerlein, 2017), it is also emphasized that the current DH systems and building stock must undergo a radical change to adapt a system that supports a low-temperature heat source (Lund et al., 2017). Next to reducing the operating temperatures, grid losses can be reduced by improving the pipe insulation and optimizing the networks' dimensions. This last option can mean that an alternative routing of the pipes is necessary, but is dependent on the heat source(s) of the network (Lund et al., 2018).

For a DH network to be economically viable, sufficient heat demand and heat demand density are needed. The exact requirements are situation-specific and partly depend on the temperature of the heat carrier (Lake et al., 2017). The energy efficiency of the building stock also determines whether DH is feasible, as low insulated houses require higher heating temperatures. Among others, the economic profitability of DH systems depends on electricity prices and the reference scenario.

Additionally, the proximity of DH systems to industrialized areas can serve as a benefit, as DH enables the use of various heat sources that would have been wasted otherwise (Werner, 2013).

2.2.3 District heating in Europe

Nowadays, DH is present in most European countries, albeit in some countries in low percentages. HRE divided European countries into three categories concerning the 4GHD. Countries with high amounts of DH (Scandinavia) tend to have a modern building stock and demand-driven heat distribution infrastructures with high interconnectedness. This enables optimal exploitation of resources and high integration of renewables. The Baltic states and Eastern European countries have less efficient heat infrastructures and outdated building stock. DH systems are present but build for high temperature and generation-driven heat distribution. Therefore, these countries face the issue of modernising and expanding existing systems, while establishing new systems and retrofitting the building stock to make it suitable for low-temperature DH. The last category entails countries with no or very low shares of DH, such as the gas dominated countries (the Netherlands and the United Kingdom), warmer South European countries, but also some parts of Germany, Belgium and France. These countries could approach the DH problem by starting with low-cost heat sources in areas with high demand. Here, DH systems should be developed while keeping future expansion and required building stock renovations in mind (Fleiter et al., 2017).

2.3 THERMAL ENERGY STORAGE

2.3.1 Concept

Thermal energy storage (TES) is done when a temporal mismatch exists between heat supply and heat demand. Due to the high storage efficiencies and sufficient space available, TES is most sensibly done underground. Underground thermal energy storage (UTES) has multiple different varieties depending on the possibilities in the subsurface, but can most easily be divided into open-loop or closed-loop systems. In an open-loop system, water is injected and under controlled circumstances allowed to move freely in the subsurface layer. The injected water in closed-loop systems has no contact with the underground layer and is therefore not dependant on the permeability of the subsurface (Fleuchaus et al., 2018). This paper focuses on the open-loop ATES system because this is characterised by the highest storage capacity and is most commonly installed in buildings (Bloemendal, Olsthoorn, & Boons, 2014). ATES is the storage of low-temperature heat in shallow (30-250m) subsurface water-bearing layers (Fleuchaus et al., 2018). Generally, ATES is used to provide seasonal storage, so that warm water that is injected in summer, can be extracted to use for heating purposes in winter. The cold water can be used for cooling buildings in summer, which in turn heats the water and balances the heat supply. Overall, buildings can significantly reduce their energy use when connected to an ATES system (Bloemendal et al., 2014).

The idea of aquifer use has been around since the mid-1960s when it was used to counter subsidence caused by long-term groundwater extraction. It was found out that the injected water sustained its temperature over periods of several months. Since then, ATES has received much attention and system improvements. There is not one defined ATES system, but instead, it comes in many different shapes based on the subsurface structure, building characteristics, operational design, subsurface characteristics, and system size (Fleuchaus et al., 2018). ATES can be done with a mono-well (hot and cold reservoir are vertically distributed) or a doublet (hot and cold reservoir horizontally distributed, see figure 4). Doublet systems can be deployed in thinner aquifer layers, but have higher investment costs due to drilling costs. Whether ATES can be applied at a location is site-specific and bound by geologic, climatic, and building-specific requirements. However, the key requirement for ATES is the presence of an available aquifer – a permeable water-bearing layer in the subsurface – at a reasonable depth (30-250m). Aquifer depth, permeability and layer thickness are the most critical parameters to consider the suitability of the location for ATES (Fleuchaus et al., 2018). Aquifers are usually made up of gravel, sand or silt, and have different porosities based on their composition. Karst or fissured aquifers also exist but are not suitable for ATES. The porosity of sedimentary layers is dependent on multiple factors, including whether the sand is consolidated or not, and how well-sorted and fine-grained the material is. Sand layers generally have a porosity that ranges from 30% to 50% (Earle, 2019).

2.3.2 Application of ATES

Although the literature on worldwide ATES application is insufficient, 85% of the 2800 registered projects are situated in the Netherlands and mainly provide heat to public buildings. Regardless of the large difference in ATES application worldwide, it is expected to rise as more countries show interest in the technology. Moreover, the combination of DH and ATES provides a promising solution that is interesting for many countries (Fleuchaus et al., 2018). Exemptions exist about where ATES systems can be deployed for geohydrological, ecological, or societal reasons. The main limitations are posed due to geohydrological reasons, as the aquifer needs to be permeable enough to allow the necessary flowrate to supply heat. If the permeability is not sufficient, more wells need to be drilled, resulting in higher costs (Fleuchaus et al., 2018). Moreover, as an increasing amount of buildings rely on ATES to meet energy savings goals, pressure on the subsurface space in urban areas increases. Hence, to enhance the efficient use of the subsurface, it is necessary to regulate and monitor the heat and cold

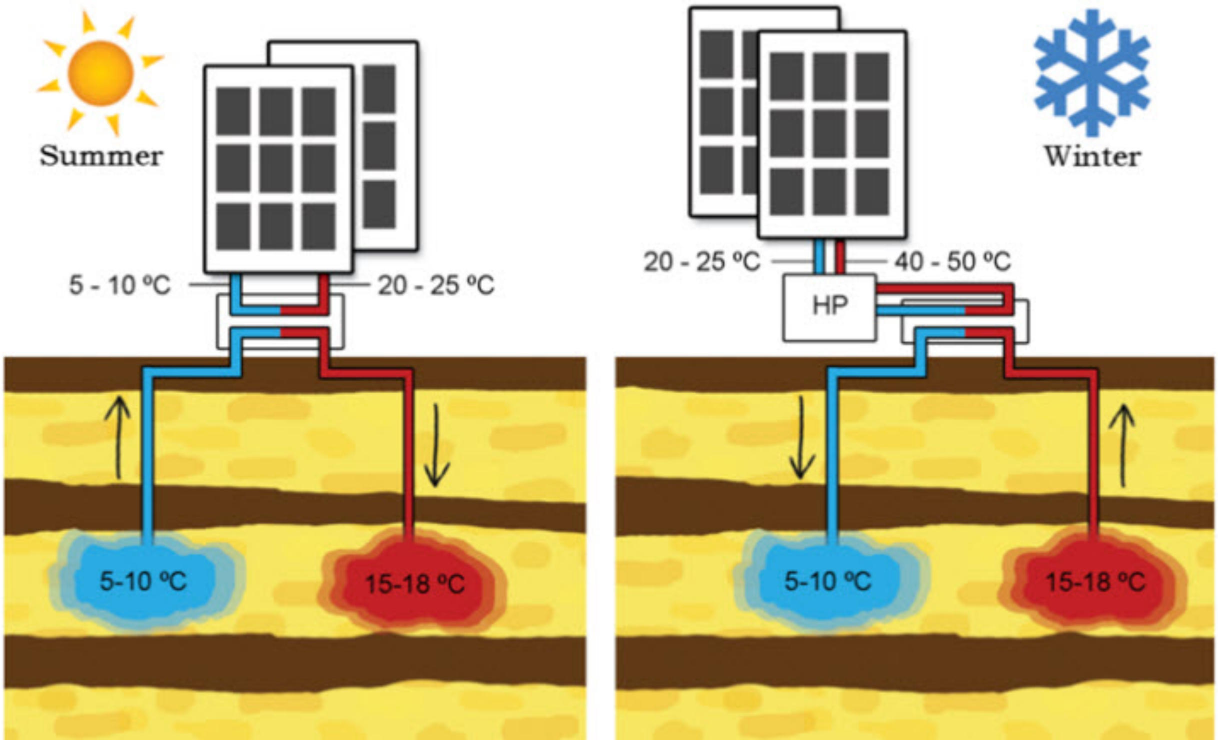

Figure 4. Schematic view of (doublet) ATES. In summer extra heat is supplied from summer SW. In winter, heat is used and the subsequent cold water flows back to the ATES system. *(Kruit et al., 2018)*

reservoirs (Bloemendal et al., 2014). For instance, the thermal radii of individual ATES systems need to be considered as they can interfere with each other, causing mixing of hot and cold reservoirs. Additionally, it is modelled that it can take hundreds to thousands of years for the reservoirs to disperse and diffuse; far longer than the lifetime of buildings (Bloemendal et al., 2014). This can also cause problems when ATES is already in place when the heating and cooling demand of a building or area changes, resulting in systems that function sub-optimal over time. Regulation of sustainable ATES use differs per country and generally avoid that ATES systems cause pollution of groundwater and its ecology, or interfere with other ATES or subsurface technical systems. For this research, the maximum and minimum temperature of groundwater is most important. Few European countries have regulations in place for this; Denmark maintains a maximum of 25°C and a minimum of 2°C, while France set the maximum temperature difference for groundwater to 11°C. Liechtenstein, albeit rather small with only 35.500 inhabitants, has very strict regulations related to ATES use and only allows cooling of 3°C and heating of 1,5°C relative to the undisturbed groundwater temperature. The Netherlands, a pioneer in ATES maintain a maximum temperature of 25°C and a minimum of 5°C (Haehnlein, Bayer, & Blum, 2010). Kruit et al. (2018) maintain a maximum temperature difference of 6°C while acknowledging that this is a conservative value.

2.3.3 ATES in Europe

There are more than 2800 ATES systems in the world, yet almost all are situated in only a few north-western European countries (Fleuchaus et al., 2018). In fact, ATES is predominantly limited to the Netherlands. Due to the country’s dense heat demand and suitable subsurface conditions, it is now an established technology. However, the actual numbers do not come close to the predicted 20.000 systems that could have been developed in 2020, according to a publication of a Dutch engineering company in 2009 (Godschalk & Bakema, 2009). To make ATES a widely applied technology, legislative and regulatory barriers have to be overcome. For instance, Italian regional authorities caused a lot of bureaucracy by doubting the new ATES technology. The legislative barrier is exemplified by Spain, which considers the return stream in a doublet system as wastewater. On the contrary, other countries, such as Belgium and the Netherlands, have formed standardized procedures that ease the implementation of ATES (Bloemendal et al., 2016b).

3 METHODOLOGY

This chapter aims to address the methods used in each step of the research and is divided according to the research framework. Most of this research was performed in a Geographical Information System (GIS), using spatial analysis. Spatial analysis is a type of analysis that aims to explain geographical patterns and their spatial expression. GIS is a term for programs that can collect, store, retrieve, and analyse spatial data. Spatial analysis is a process where problems (in this case matching supply and demand) are geographically modelled using a layer-based approach. The computer derives results based on the input you give, which are datasets and certain spatial requirements. This analysis is based on secondary datasets collected through literature research. The data that is used in this thesis were mainly found on the internet and is predominantly quantitative. All datasets are GIS files, meaning they have a strong spatial component. For the three main subjects, heat demand, heat supply and ATES, a short overview of the datasets and their sources is provided in table 1. For an overview of the method, see figure 5.

Category	Subject	Developer	Based on	Time scope	Source
Heat demand	District heating areas	sEEnergies	Heat Roadmap Europe 4	2020-2100	(Persson, Urban, Möller, & Wiechers, 2017)
Heat demand	Annual heat demand	Hotmaps	Literature space heating demand	2015	((Fleiter et al., 2020)
Heat supply	River discharge	Copernicus Climate Change Service	LISFLOOD hydrological model and the European Flood Awareness System (EFAS)	Summer average over 2010, 2014 and 2018	(Mazzetti et al., 2019)
Heat supply	Corine Land Cover	Copernicus Land Monitoring Service	Sentinel-1 and Landsat-8 imagery	2018	(Büttner, 2014)
Heat supply	Global Surface Water Explorer	The European Commission's Joint Research Centre	Landsat-8 imagery	1990-2020	(Pekel, Cottam, Gorelick, & Belward, 2016)
Storage	ATES capacity	BGR	International Hydrogeological Map of Europe	-	(Duscher et al., 2015)

Table 1. Datasets used in this thesis.

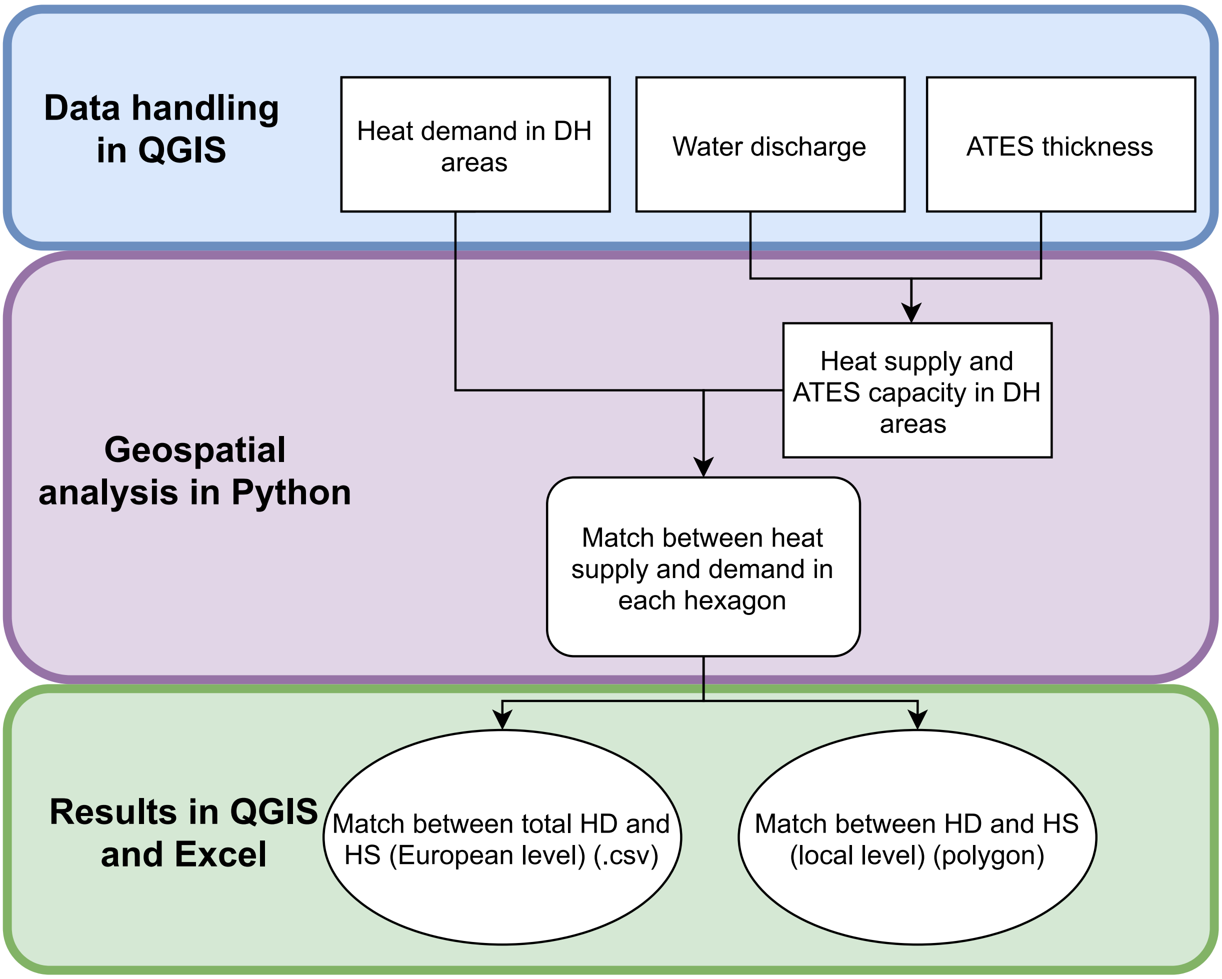

Figure 5. Overview of analysis input, operations and output. The blue shape merely entails the data handling, and are explained in section 4.1. The purple shape indicates the operations performed in Python. The final results are indicated in the green part and are discussed in chapter 5.

3.1 Data collection and processing

All datasets were collected on the internet (see table 1). In the following subsections, these datasets will be elaborated upon. Additionally, it is explained what relevant information the dataset proved, and how the irrelevant information was filtered out. The flowcharts give supporting information in a schematic format about the data input and output, file format and GIS operations.

3.1.1 Heat demand

Since the focus of this research is on collective heat demand, the relevant heat demand is defined by the limitations of heating districts. The heat demand data are developed by Hotmaps (Kranzl & Pezzutto, 2019), and the DH areas by sEEnergies (Fleiter et al., 2020) (see figure 6).

Hotmaps is an open-source mapping and planning toolbox for the heating and cooling sector in the EU28. The Hotmaps toolbox is based on a variety of sources and resolutions, including building stock characteristics, land cover and settlements, and energy consumption data. The resulting dataset is a combination of both a top-down statistical approach that includes national energy consumption and data on a regional level, and a bottom-up engineering approach that is based on modelling and simulations of buildings' energy demand (Kranzl & Pezzutto, 2019).

3.1.1.1 Data handling

According to (Fleiter et al., 2020), DH networks are economically and physically viable when the heat demand density (HDD) threshold passes 500GJ/ha. (Fleiter et al., 2020) developed a map of areas where DH is viable, for which the input was a HDD map by sEENergies. From this map, the potential DH areas were mainly determined using the 500GJ/ha threshold. Other assumptions underlying these expected DH areas can be found in (Persson et al., 2017). Furthermore, the current existing European DH systems were added according to the Halmstad University District Heating and Cooling database (Persson et al., 2017). These DH areas were used to delineate the edges of relevant heat demand in the Hotmaps heat demand map (Kranzl & Pezzutto, 2019).

The relevant heat demand was overlain by a hexagon grid to divide the large DH areas into smaller 'neighbourhoods'. Using the QGIS tool 'zonal statistics' the hexagons were designated the average heat demand per hectare. The hexagons have a diameter of 2km and a corresponding area of approximately 346 ha. See figure 7 for the overview flowchart of the mapping methodology for the heat demand, including the used data, main GIS operations and generation outputs.

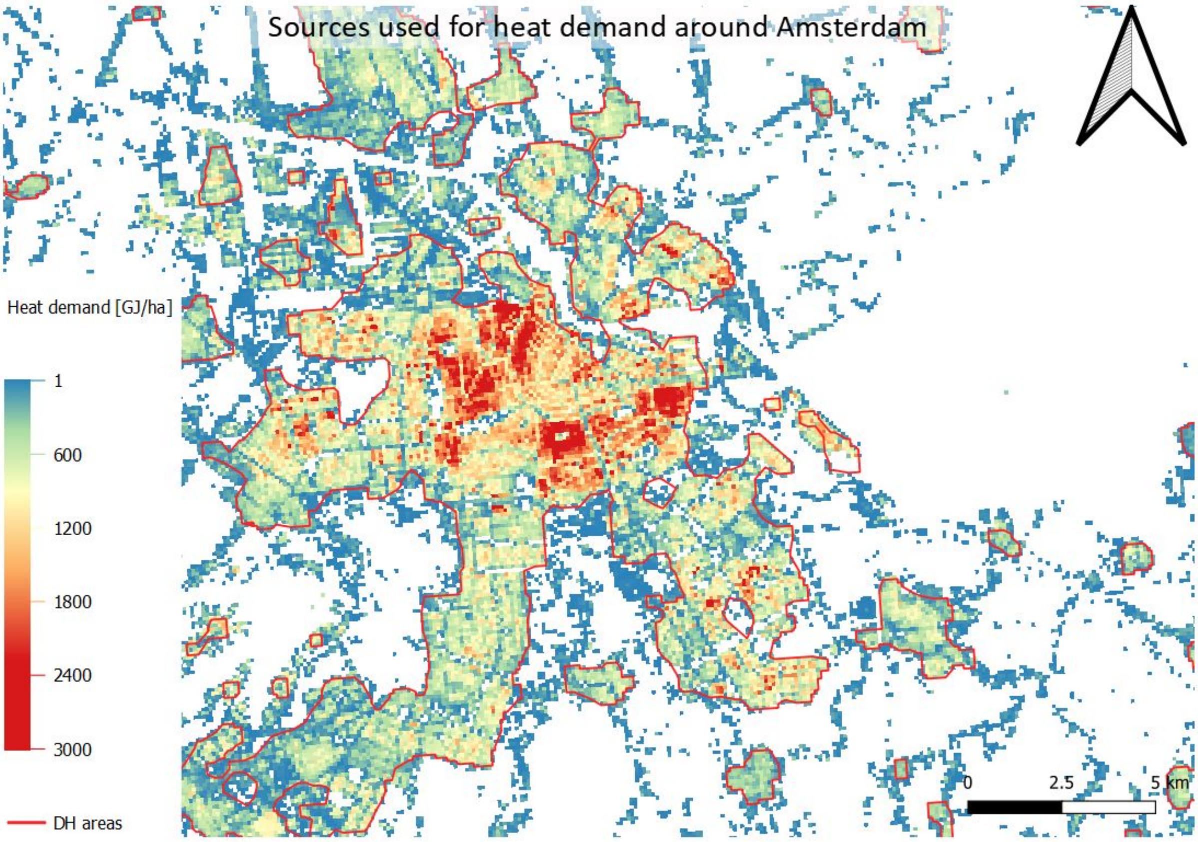

Figure 6. View of the two datasets that are used as input for the heat demand map.

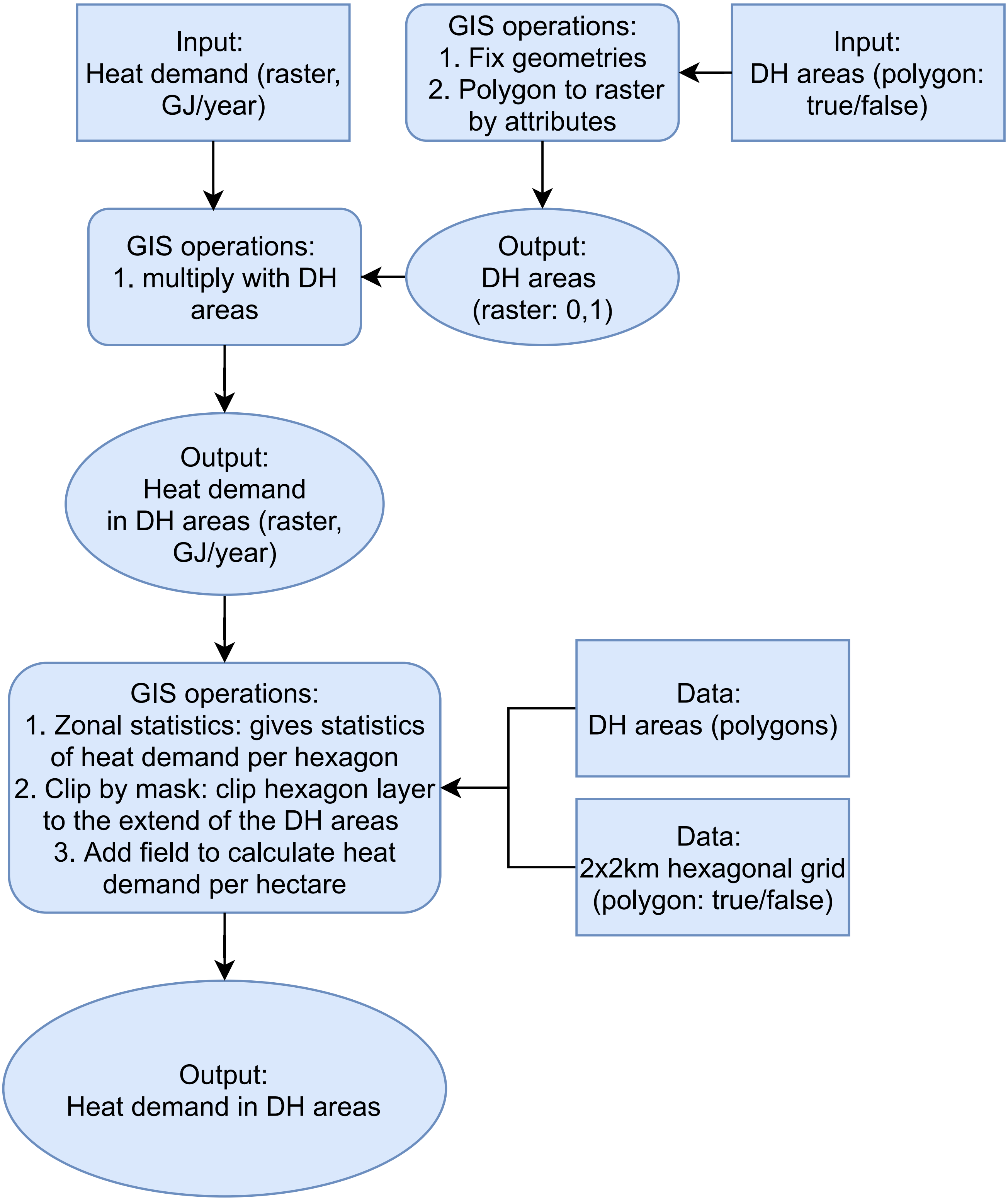

Figure 7. Flowchart of data handling operations in GIS to develop the heat demand dataset.

Due to inconsistencies between the Hotmaps dataset, which represents the heat demand, and the areas suitable for DH from sEEnergies, a discrepancy occurred in the heat demand in DH areas. Although these DH areas were defined as being areas with a heat demand of >500GJ/ha, when coupled with the Hotmaps dataset, this was not always the case. The cause for this discrepancy is a difference in the calculation method and underlying assumptions in developing the Hotmaps and sEEnergies heat demand datasets. For this reason, it was chosen to discard all areas with an average heat demand <200GJ/ha. Although this threshold is significantly lower than the former proposed value of 500GJ/ha for 'suitable' areas for DH, it is a compromise that is inherent to using different datasets and shows the limitation of the data available.

3.1.2 Heat supply

3.1.2.1 Method

Heat is naturally transferred to a water body in two ways. First, trough heat conduction and radiation between the atmosphere and the water surface, and second trough convection of upstream water. This is represented by equation (2) for stagnant water and equation (3) for flowing water.

$$E_{stag} = (A * Z * \Delta\mathrm{T}_{SW} \ * \mathrm{t})/10^9 \qquad (2)$$

$$E_{flow} = (Q * \Delta\mathrm{T}_{SW} * \rho \ * \ \mathrm{C} \ * \ \mathrm{t})/10^6 \qquad (3)$$

In which A is the water surface area, Z is the heat exchange coefficient in W/m^2/K, ΔT_{SW} the temperature change of the surface water body, Q the discharge in m^3/s, t the total full load hours per year in seconds, and ρ and C respectively the density (998 kg/m^3) and heat capacity (4,185 kJ/kg °C) of water. The heat exchange coefficient represents the heat exchange processes at the atmosphere-water interface and depends on temperature and wind speed. Using a default of 10 W/m^2/K, a conservative number is used, based on a wind speed of 0 m/s and a water temperature of 15°C (lower temperature limit for heat withdrawal) (Broderie & Visser, 2007). However, the true heat exchange coefficient is highly variable and could thus result in higher heat withdrawal capacities. ΔT_{SW} is the temperature change caused by heat withdrawal and is dependent on the ecological effects are considered when defining ΔT. Currently, a ΔT of 3°C is the default, but this is subject to change in the future. It is assumed that 2000 full load hours per year are sufficient to cover the heat demand.

As the total heat withdrawal capacity of a water body is the sum of both the water surface and discharge component, formulas (2) and (3) are summed. This leads to equation (4), which represents heat extraction from a water body in GJ/year. See appendix A for the full derivation of this formula.

$$E_{tot} = 0.216A + 90215Q \qquad (4)$$

Q represents the maximum discharge found in the area. This could lead to an overestimation of the discharge component when more areas use the same river for heat withdrawal. However, this method is necessary because it is not possible to measure heat withdrawal capacity per area with discharge data. Hence, it is impossible to take into account the upstream heat withdrawals that lead to lower heat potentials downstream. On a European scale, it is not expected to cause problems for policymaking, since it is currently unlikely that the full potential of aquathermics will be used in the near future. Still, it is something that needs to be taken into account when planning local aquathermics projects.

3.1.2.2 Data

This section discusses the datasets were used to represent the term in formula (4); water surface area and water discharge. Both datasets originate from the Copernicus programme, the earth observation programme from the European Union and based on satellite earth observations and in-situ data (Büttner, 2014; Mazzetti et al., 2019)

River discharge data were produced by forcing of the LISFLOOD hydrological model, a spatially distributed rainfall-runoff-routing model (Mazzetti et al., 2019). The data output is a raster file with daily river discharges of 5x5km across Europe (see figure 8). From this dataset, and average water discharge was extracted using daily time-series of four months from three different years; May, June, July and August of the years 2010, 2014 and 2018.

To identify the areas where surface water is present, the Corine Land Cover (CLC) 2012 was used (Büttner, 2014). This is an inventory that was created in 1985, with updates every six years from 2000 on. The CLC represents the land cover in 44 classes with a minimum mapping unit of 25 ha for areal phenomena and 100 m for linear phenomena, meaning anything smaller is not indicated on this map (European Union, 2012). CLC is produced by the majority of European countries by visual interpretation of satellite imagery.

Figure 8. Mean river discharge from 1991-2018 in LISFLOOD EFAS 4.0 (map 2.1). (source: Mazzetti et al. (2019))

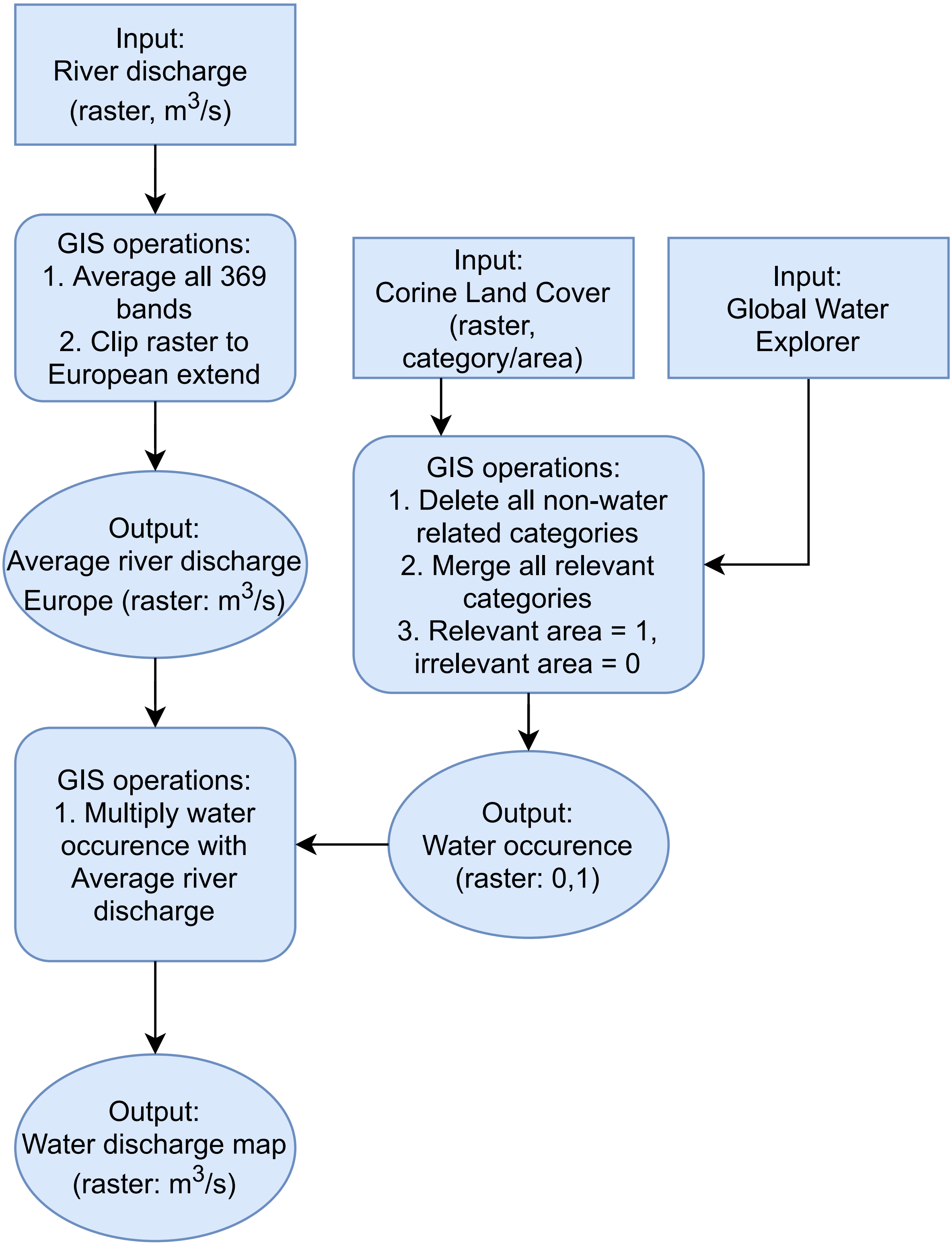

Figure 9. Flowchart of data handling operations in GIS to develop the water discharge dataset.

3.1.2.3 *Data handling*

See figure 9 for the overview flowchart of the mapping methodology for the river discharge, including used data, main GIS operations and generation outputs.

Data about water surface area were found on the CLC in several classes. These classes were kept, while the rest was discarded. Most classes that were discarded were obvious (e.g green urban sites, pastures, and forest), yet some asked for more information than only the label (e.g. peat bogs, and inland marshes). For these categories, supplemental information from the Global Surface Water Explorer was used (Pekel, Cottam, Gorelick, & Belward, 2016). This is a dataset that among others, shows the occurrence of water throughout the last 30 years. The categories that did not create obvious distinction were validated by determining whether categories have sufficient presence of water. Five randomly picked locations from each remaining category were checked. Categories that did not have water present >97% of the time were discarded. Furthermore, random locations from all categories were located on Google Maps to determine the nature of the water body and check the validity of discarded categories. The following seven classes were extracted from the original document, while the remaining area was discarded:

- Salines
- Intertidal flats
- Watercourses
- Water bodies
- Coastal lagoons
- Estuaries
- Sea and ocean

For river discharge, 369 maps for river discharge (one for each summer day in 2010, 2014 and 2018) were averaged. This way, an image of expected river discharge could be made. Although it should be noted that river discharge can be significantly lower in dry years, these periods usually result in warmer surface water and high energy, counteracting the drought effect. Following, the river discharge data were delineated by the water surface area. This developed a raster file with null pixels where no water occurs, and pixels with the corresponding river discharge in the case water was present. This means that although lakes have a value of non-zero, the heat supply by the current will be insignificant to the component of heat supplied through the atmosphere-water heat exchange.

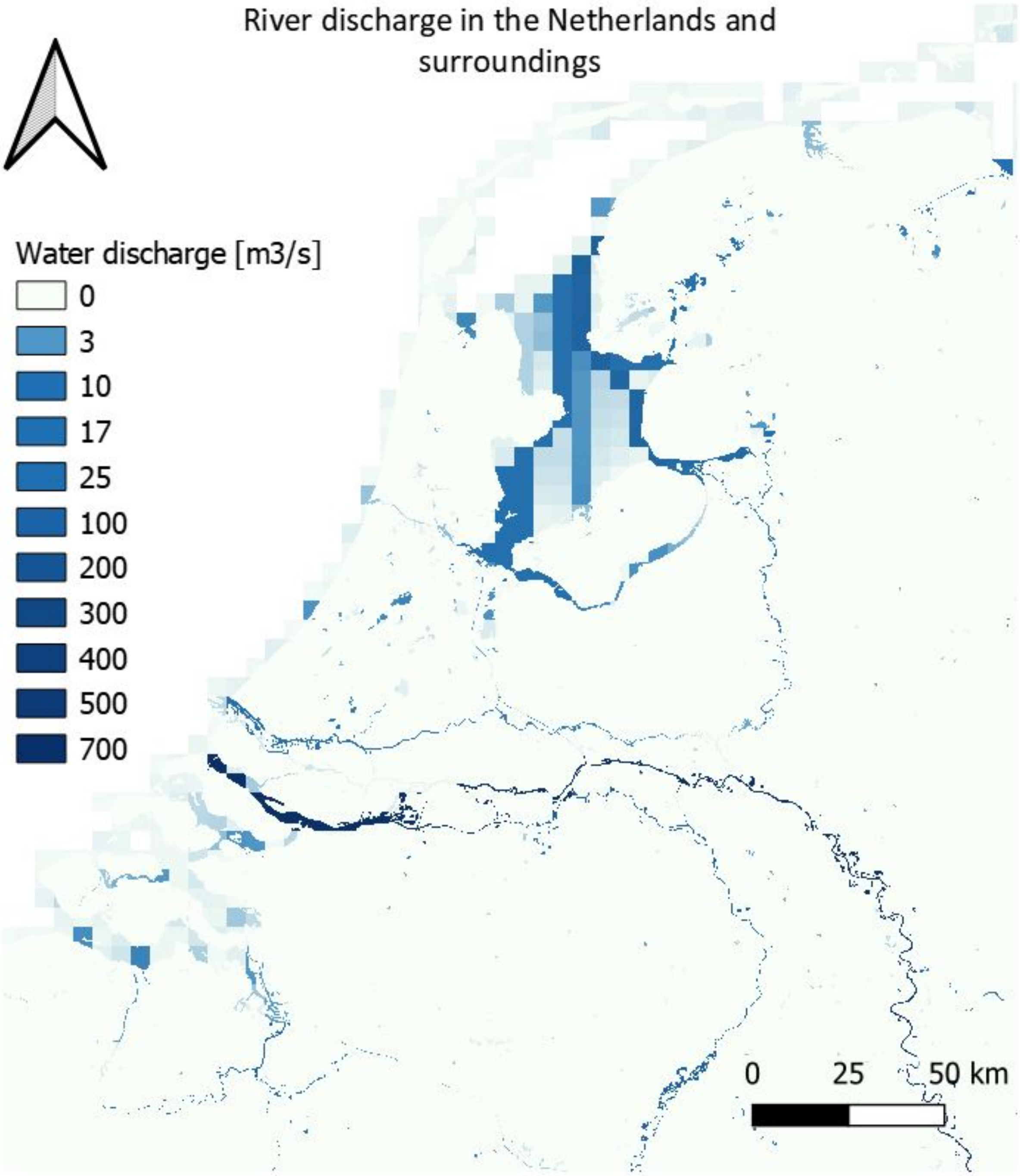

Figure 10. Water discharge in the Netherlands and surroundings. Note how the legend is not linear, nor is it similar to the legend in figure 8.

3.1.3 Storage capacity

3.1.3.1 Method

The storage capacity of an aquifer is predominantly defined by the thickness of the sandy layer and its porosity. Boundary conditions are defined by technical conditions, like the difference in in- and outflow temperature and maximum filter length. This leads to the following formula.

$$Q_{ATES} = (\rho * C * d * A * \Delta T_{ATES} * \Theta * 0.56)/10^6 \quad (5)$$

In which:

Q = energy capacity [GJ/year]
ρ = density water = [998 kg/m3]
C = heat capacity water = 4.185 [kJ/kg °C]
d = aquifer thickness [m]
A = aquifer surface [m^2]
ΔT_{ATES} = in and outflow temperature difference [°C]
Θ = porosity

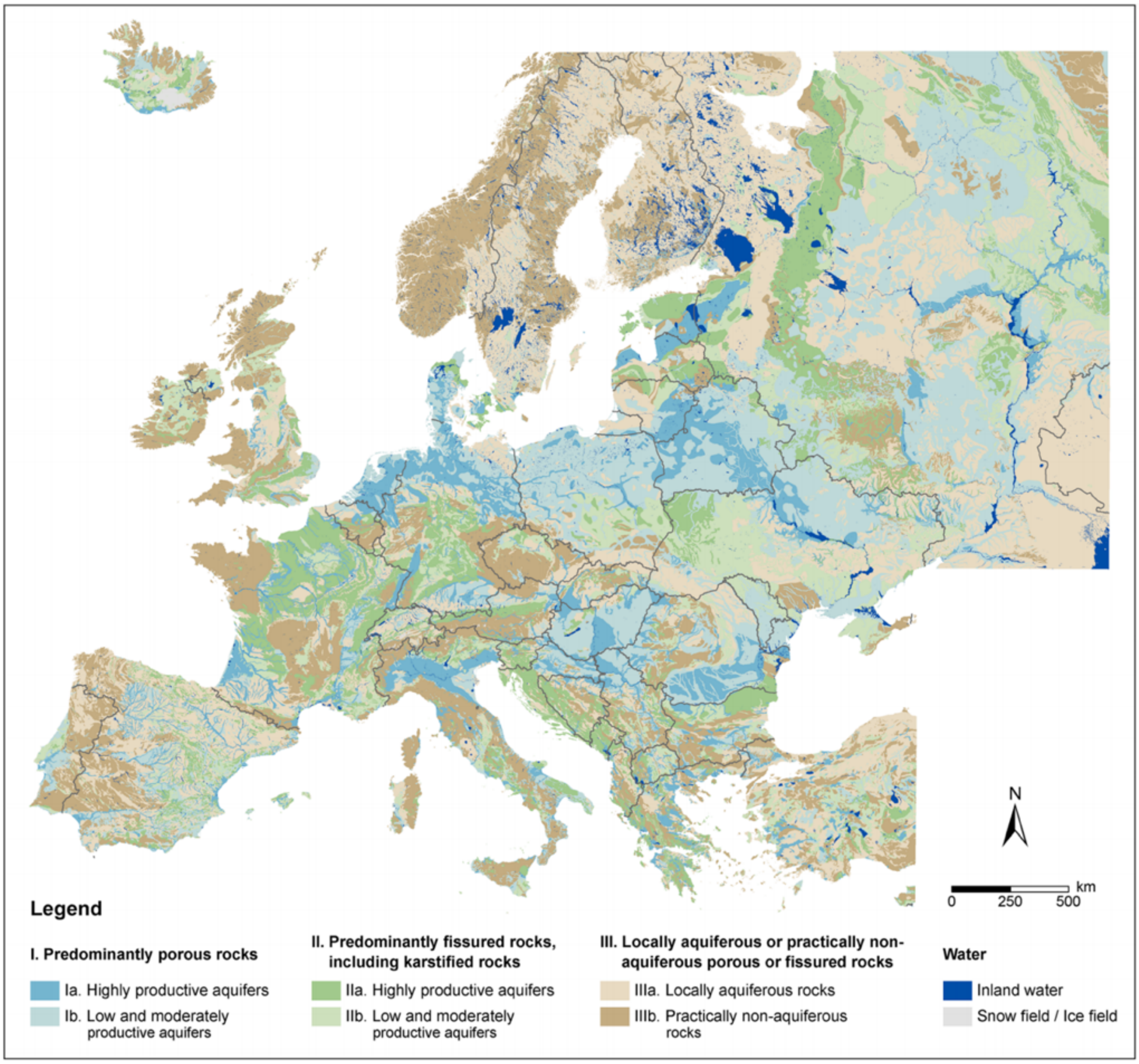

Figure 11. IHME1500 showing aquifer types (source: Dusher et al., 2015)

Where Q is the heat capacity of the ATES in GJ, ρ and C respectively the density and heat capacity of water, d the thickness of the aquifer layer in meters, A the surface area in m^2, ΔT_{ATES} the temperature difference in °C of the in- and outflowing water, and Θ the porosity. The last term is defined by the maximum filter length of 80% of the sand layer and a maximum usable area of 70% (Kruit et al., 2018). Porosity is defined by the pore space between the sand grains in sandy layers. With a porosity of 0.3 (conservative value for sandy layers) and a temperature difference of 6°C , the storage capacity of aquifers is 21 GJ/ha per meter of filter length. The value for porosity is a default conservative estimate of average porosity of sandy layers.

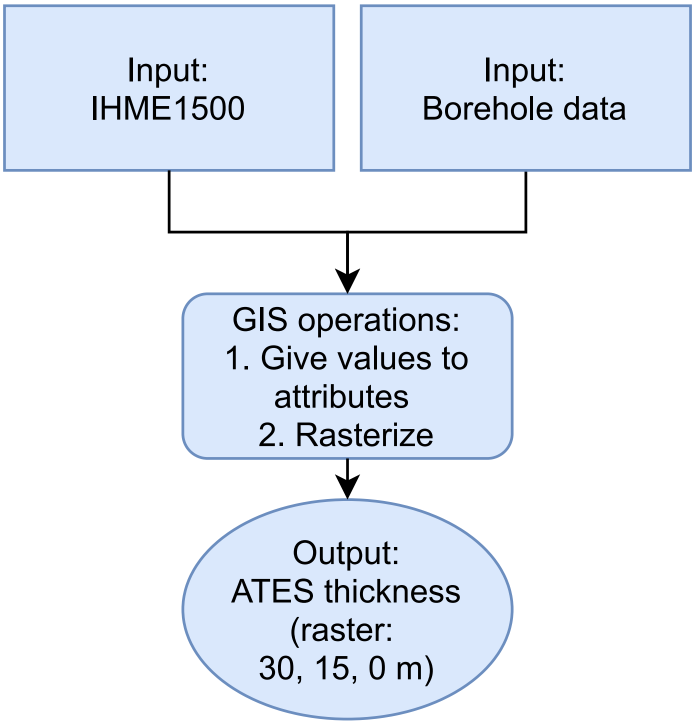

Figure 12. Flowchart of the data handling operation in GIS to develop the ATES thickness dataset.

3.1.3.2 Data

To identify the presence and productivity of aquifers, the International Hydrogeological Map of Europe (IHME1500, see figure 11) (Duscher et al., 2015). The IHME1500 provides a map of European potential groundwater resources and is developed over multiple decades, based on national contributions. Development of the map was initiated by the International Association of Hydrogeologists already in the 1960s. The scientific editor is the German geological service; the Federal Institute for Geosciences and Natural Resources (BGR). The map represents the superficial geology of Europe. Because IHME1500 provides information about the superficial subsurface structures, it is assumed that the depth of the aquifer layer is suitable for ATES.

The IHME1500 divides Europe into three categories with each two subcategories:

1. Porous aquifers
    - Highly productive
    - Moderately productive
2. Fissured aquifers
    - Highly productive
    - Moderately productive
3. Insignificant aquifers
    - Local and limited groundwater
    - Essentially no groundwater

These classifications are further complemented by a lithological specification of each spatial unit. Although these categories do not represent a quantitative overview of ATES capacity, it provides the basis for calculations that give an approximation of the capacity. Accordingly, it is supplemented with European borehole data that indicated the thickness of the present sandy layers. Based on the above categories, only areas of category one (porous aquifers) were considered suitable, because fissured and insignificant aquifers do not have the requirements necessary for ATES, like sufficient porosity and heat insulation.

Due to the lack of large scale consistent data and because the region of interest is large, it is not possible to find the exact thickness of all aquifer represented in the IHME1500. Additionally, although the IHME1500 map contains sheets with aquifer thickness, these are not publicly available. Therefore, it was necessary to assume the thickness regarding the IHME1500 data. Based on the expert judgement of Dr M. Bloemendal, a scholar on the subject of ATES, it was agreed to base the aquifer thickness on the categories of the IHME1500 map, supplemented with borehole data (personal correspondence, 24-11-2020). Borehole data were used to obtain subsurface information about random locations that were indicated as being highly and moderately productive aquifers by the IHME1500 map. About 20 locations with sufficient borehole data were found, spread across Denmark, Germany, Flanders, and The Netherlands, including subsurface cross-sections in the latter two (BGR, ; Geology Survey of Denmark and Greenland, ; Oorts, V Vanwesenbeeck, Damme, & Buyle, 2019; TNO Geologische Dienst Nederland,). It was difficult to include more countries, due to a lack of well documented or publicly available borehole data.

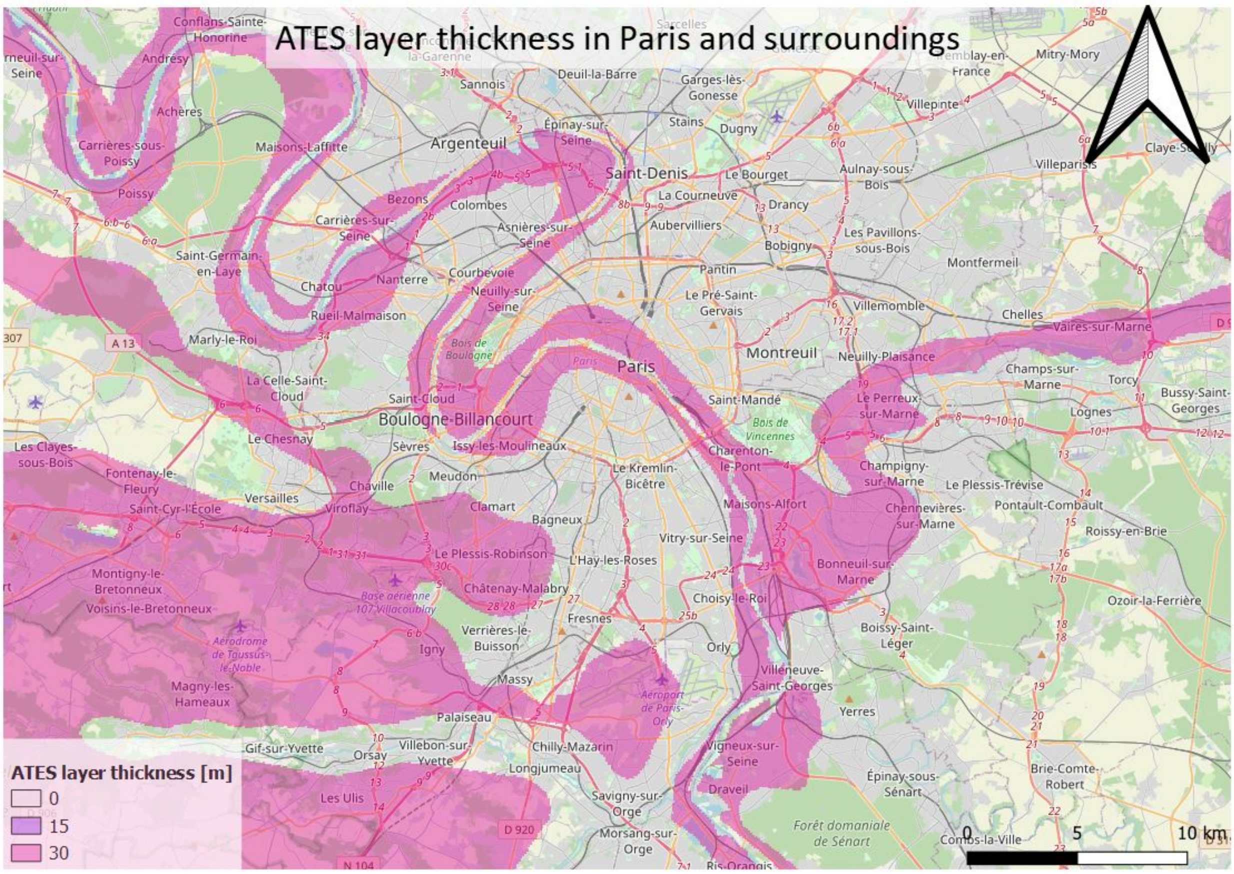

Figure 13. ATES thickness approximation in Paris and surroundings. Note how the sedimentary deposits of the Seine functions as aquifer.

While only few countries could be included in this validity check, it provided an overview of the subsurface characteristics of the two classes at hand and indicated the thickness of aquifers in general. However, these classes were not developed to indicate aquifer thickness, hence addressing a value for thickness to each class will be too generic and not realistic. For that reason, it was chosen to use the minimum thickness of the two classes, which was more consistent over the regions that were investigated using borehole data. Using this information, the minimum thickness of 'highly productive aquifers' and 'moderately productive aquifers' were found to be respectively ~30 and 15m, which were administered to all the respective areas (see figure 13). The ATES capacity that this value yields will therefore be a conservative estimation of the true ATES capacity in the region. For the used data, main GIS operations and generation outputs, see figure 12.

3.2 MATCHING HEAT DEMAND AND SUPPLY

The end products of the operations described in the sections above are used as input in the last phase of the analysis. Because it eases the sensitivity analysis, this part was performed in Python.

In this geospatial analysis, the three files are combined to yield the total and local heat demand and supply match. Figure 14 provides an overview of these operations in purple. The end products in green will be discussed in the next chapter.

For each area, heat demand, heat supply and ATES capacity are calculated and summed. The share of heat that can be supplied by aquathermal is calculated by dividing the lowest value of ATES capacity and heat supply (to determine the limiting factor for aquathermal with ATES) over the heat demand of each individual area (equation 6). The heat supplied by aquathermal is calculated by multiplying this share (cut off at a maximum of 100%) with the heat demand (equation 7). This is summed and divided over the total relevant European heat demand to find the European potential of aquathermal heat (equation 8). The same is done for the potential of aquathermal heat without ATES, leading to the potential without ATES to be the same or higher in all cases.

Per area:

$$HS_{aquathermal}(\%) = \frac{\min(ATES_{cap},\ HS)}{HD} * 100 \tag{6}$$

Total region:

$$HS_{aquathermal\ (\frac{PJ}{year})} = HD\ if\ HS_{aquathermal} > 100\%, else \frac{HS_{aquathermal}}{100} * HD \tag{7}$$

$$Potential = \frac{sum(HS_{aquathermal} of\ all\ areas)}{sum(HD\ of\ all\ areas)} \tag{8}$$

It should be noted that during the final analysis, the respective heat demand and supply spatially correspond. Therefore, this is a calculation that is individually done for each area, after which the potential of each area in Europe is summed. Because of the spatial boundary that exists between heat demand and supply, this is of importance to avoid overestimation of the potential. Furthermore, the consideration that regional aquathermal heat supply in practice will never be higher than its corresponding heat demand is also taken into account by the cut-off at 100% in equation 7.

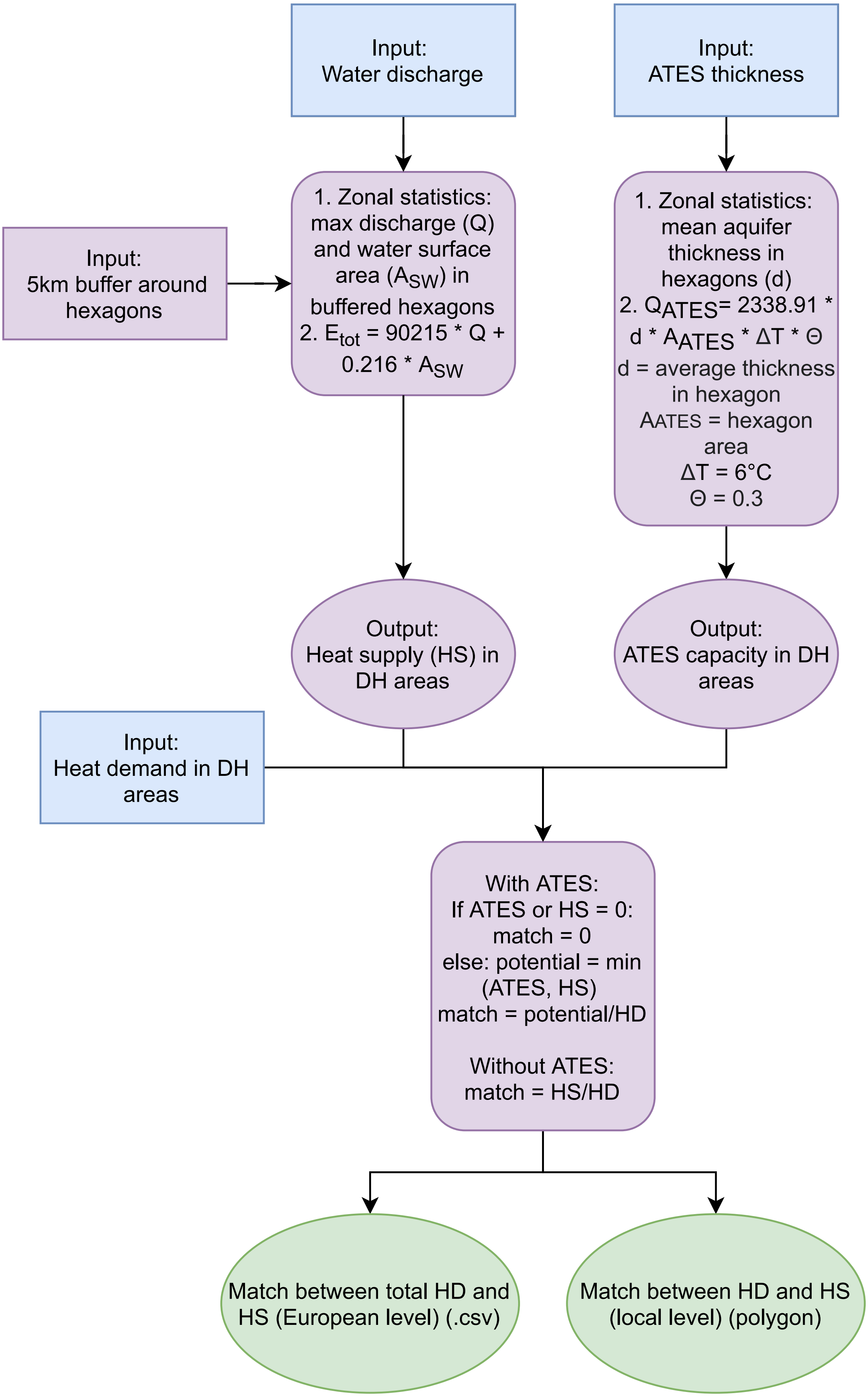

Figure 14. Flowchart of operations in Python. See Appendix C for full script.

3.3 Sensitivity analysis

The results in this analysis are for a large part dependable on the quality of the input data. Although it was strived for to find spatial datasets that represent the variability of the subject, this was not always possible, due to the large extent of the research, the lack of consistent data and case-specific circumstances. Hence, even though uncertainty exists for all data, including the spatial datasets, some parameters had to be given one general value for the whole of Europe. Here, it was strived for to obtain a realistic value, while avoiding an overestimation of the aquathermal heat supply.

The results of this thesis will be twofold, showing both local and European potential. This means that both European and local potential may be interpreted with a different view. Therefore, it is not preferable when a local municipality obtains a higher potential due to using an average value for a parameter, even though this means the European potential may likely be lower due to an underestimation of other municipalities. Hence, to not locally overestimate the aquathermal heat supply in Europe, it was chosen to stay on the conservative side of the range of realistic values.

To test the potential range of outcomes and the impact of the variables chosen, a sensitivity analysis is carried out. This helps to get insight in determining the parameters that are of most influence on the analysis and evaluating the uncertainties of the research. Table 2 represents all the variables that are partly based on assumptions, and the parameters subject to the sensitivity analysis.

Category	Value	Unit	Value range for SA
Heat demand			
Heat transport distance	2500	m	500, 5000
Heat demand	Hotmaps values	GJ/year	200%
Water heat withdrawal capacity			
Heat exchange coefficient	10	$W/m^2/K$	200%, 300%
$\Delta T_{surface\ water}$	3	°C	5°C
System load hours	2000	h	
ATES			
ΔT_{ATES}	6	°C	200%, 300%
Porosity	0,3	-	
Thickness	15-30	m	

Table 2. All variables in the research and the variables subject to the sensitivity analysis

4 RESULTS

This chapter contains the results of the analyses that were performed to answer the three sub-questions. These entail the collective heat demand in DH areas first, then the boundary conditions for seasonal aquathermal heat, and third the matching.

4.1 COLLECTIVE HEAT DEMAND IN AREAS SUITABLE FOR DISTRICT HEATING

The areas suitable for DH were found in the sEEnergies dataset and complemented with the Hotmaps dataset to find the heat demand (figure 15). Given the heat demand threshold, cities and larger villages are mainly included in this dataset. The highest heat demand modelled in found in Paris, where an area in the city centre has a yearly heat demand of 1,6 PJ/yr. The minimum heat demand was set at 200GJ/ha, necessary because of the aforementioned discrepancy between the Hotmaps and sEEnergies datasets.

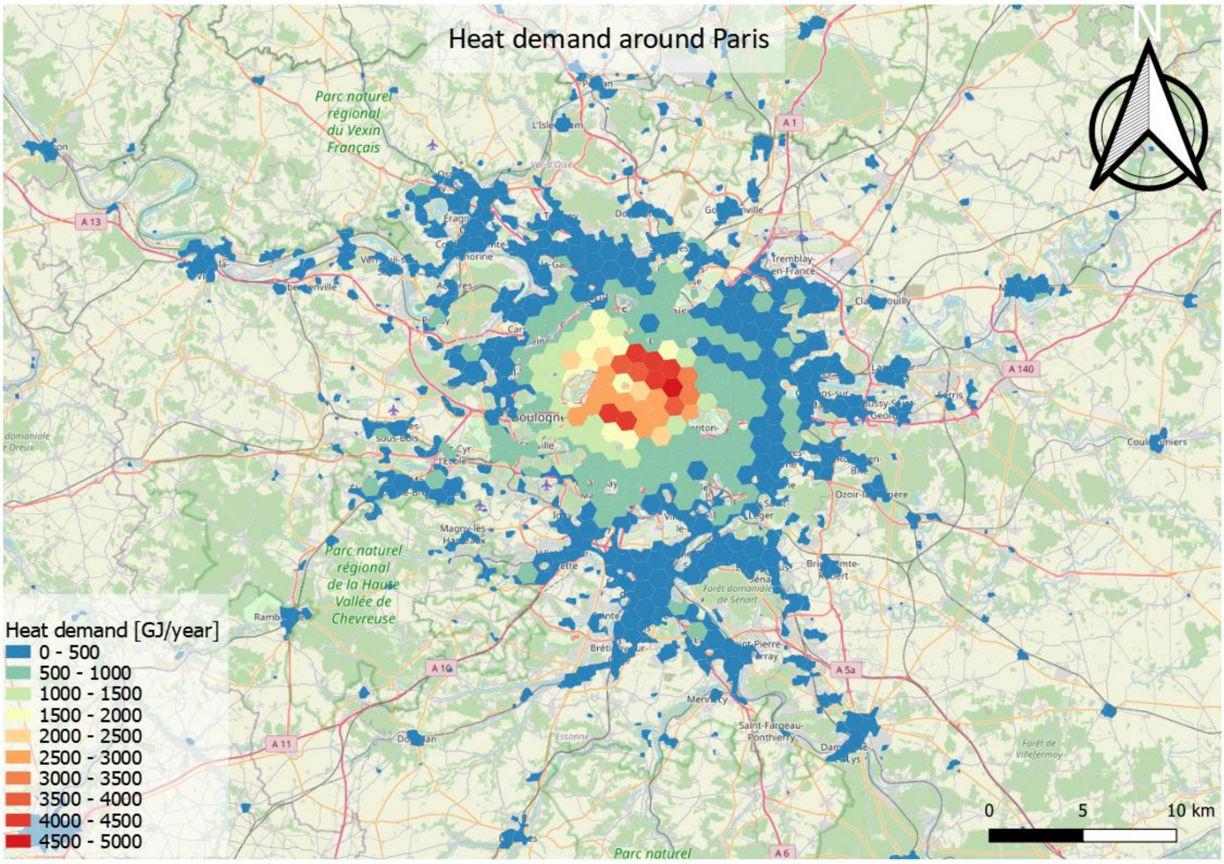

Figure 15. Illustrative map of the hexagons representing heat demand around Paris.

4.2 BOUNDARY CONDITIONS FOR SURFACE WATER AQUATHERMAL

In this section, the two questions that make-up sub-question 2 are answered. This part focusses on the heat supply and storage, necessary for surface water aquathermal.

4.2.1 Surface water heat

For seasonal aquathermal heat to be supplied, two conditions have to be in place. First, surface water needs to be within the areas' reach. Figure 16 shows a high aquathermal heat supply around the major rivers and lakes, with a default heat transport distance of 2,5km. The red areas do not have surface water within reach and will not be able to withdraw aquathermal heat with this heat transport distance. A higher heat transport distance will cause more areas to be in reach of aquathermal heat. The results also show that the heat supply skyrockets when an area is within reach of surface water, causing the heat supply from surface water to easily cover the heat demand in most areas.

4.2.2 ATES capacity

Second, the ATES capacity is necessary for seasonal storage. When ATES is not in place, aquathermal heat can still be used, depending on the winter temperature of surface water. Figure 17 shows the areas and their corresponding ATES capacity. An average thickness of 30m and 1m correspond to a capacity of respectively 1263 GJ/ha and 42,1 GJ/ha. While aquifers are thickest in sedimentary basins or deltas (Dutch and Po delta), they can also be found along rivers due to the sedimentary deposits. That is why aquifers are also found in Southern Germany and Austria, while they would not be expected due to the Alpine bedrock.

4.3 MATCH

The result of the final integration can be interpreted twofold. First, by looking at a large scale: the total match between head demand and heat supply and storage in Europe. This provides one number for the whole area under research, and can therefore indicate the feasibility of aquathermics as a technology for the region as a whole. However, that number only provides a very generic view; looking at smaller regions provides more nuance and accurate to this overall number. Therefore, several regions will be featured to identify certain patterns in matching that are influenced by the parameters outlined in this section.

4.3.1 Total match

There are a total of 65668 2x2km areas in Europe with a heat demand above 200GJ/ha, which are responsible for a total heat demand of 2155,85 PJ/year. The potential for ATES coupled aquathermal heat with a maximum heat transport distance of 2,5km is 27,7%. This represents the share of the included European neighbourhoods that can be covered with the local summer heat supply and ATES. This number does not take into account that a certain aquathermal heat supply can only be used once. Thus, no consideration was given to aquathermal heat accounting. Table three shows the results of the match, based on the parameters as outlined in table 2.

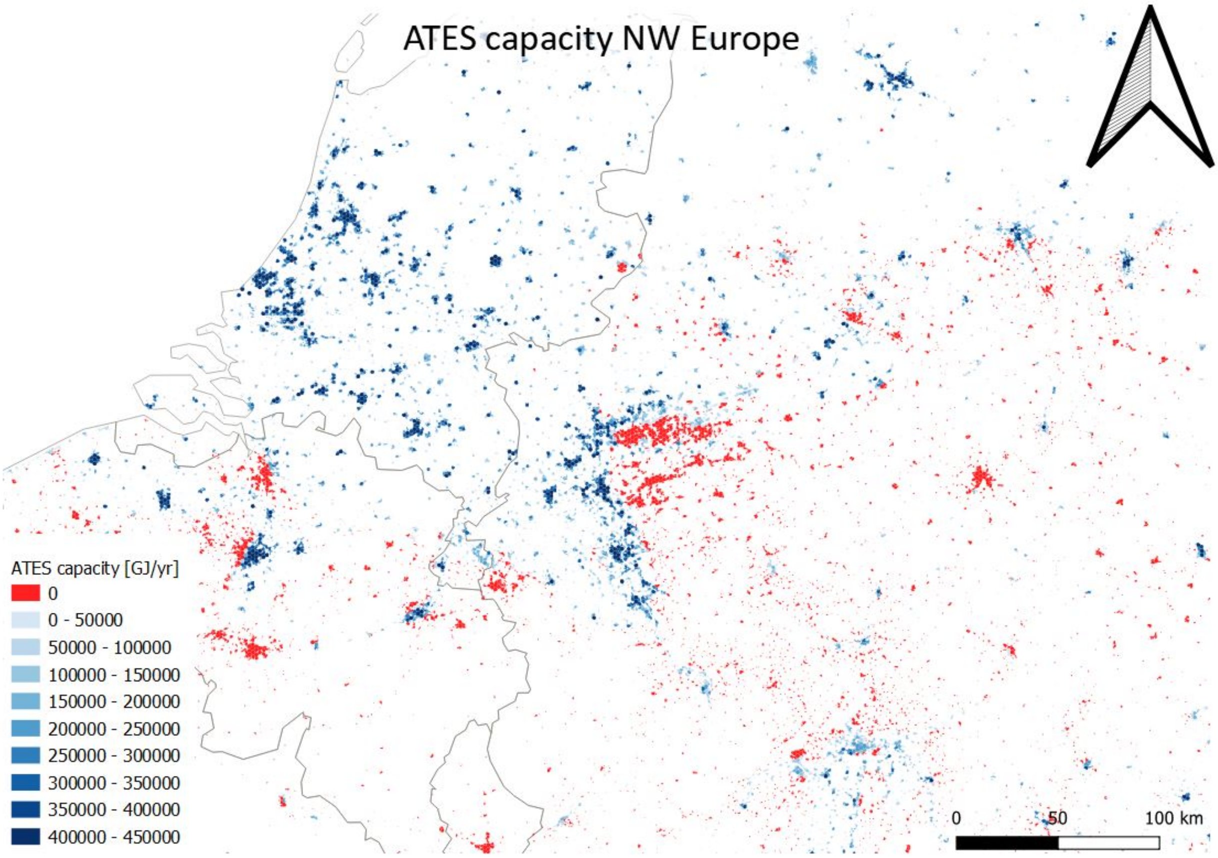

Figure 17. Map overview of ATES capacity in NW Europe. In areas with shallow bedrock, sedimentary deposits of river courses are noticeable in the ATES capacity pattern.

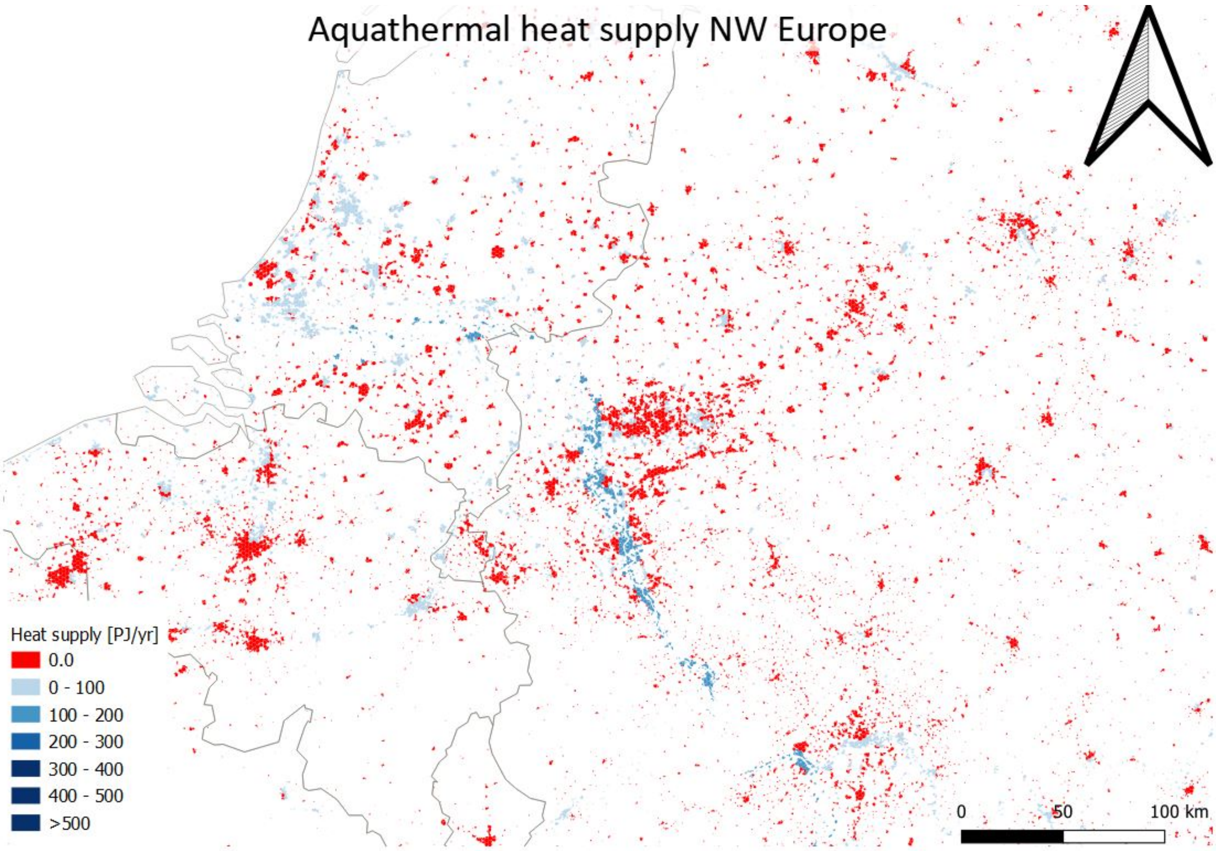

Figure 16. Map overview of aquathermal supply in NW Europe. The Rhine is clearly visible due to its high heat withdrawal capacity. The Meuse and Scheldt rivers are also visible.

Heat demand [PJ/Year]	**Heat supply [PJ/summer]**	**ATES capacity [PJ/Year]**	**Aquathermal heat supply incl. ATES [PJ/Year]**	**Aquathermal heat supply excl. ATES [PJ/Year]**	**Potential incl. ATES**	**Potential excl. ATES**
2155,85	332656,41	2809,95	474,59	834,61	22,0%	38,7%
Heat demand in all relevant areas (>200 GJ/year).	Summer heat supply in a radius of 2,5km around relevant areas.	ATES capacity in the relevant areas, based on average thickness.	Heat demand that can be spatially met by aquathermal heat supply and storage.	Heat demand that can be spatially met by aquathermal heat supply.	Percentage of heat demand that is met by heat supply and storage in the area.	Percentage of heat demand that is met by heat supply in the area.

Table 3. European results for the aquathermal heat potential.

The first three values are the input for the final match. The first column represents the heat demand of all relevant neighbourhoods in Europe and is the sum of all neighbourhoods that have a heat demand greater than 200GJ/ha. Heat demand is not influenced by the parameters in table 2. The heat supply is the total summer heat supply that can be withdrawn from the surface water in a 2,5km radius around the relevant areas. The ATES capacity is the subsurface capacity in the relevant areas, based on their average thickness.

The aquathermal heat supply including ATES represents the total heat demand that can be spatially met by summer heat supply and stored in ATES. When heat demand exceeds both summer heat supply and ATES capacity, then one of the latter two is the limiting factor that determines the potential. The calculation is the same for the potential without ATES, apart from the limiting factor being only the heat supply. Therefore, the aquathermal heat potential excluding ATES is always equal to or higher than the option including ATES. The final potential is the aquathermal heat supply divided by total relevant heat demand in Europe. It represents the share of heat demand in European neighbourhoods (with a heat demand >200GJ/ha) that can be spatially met by aquathermics.

The matching can be interpreted as average heat demand that can be met by heat supply. However, the match varies between 0 and 100% and is in fact predominantly either 0% or larger than 100%. This is a consequence of high heat withdrawal and ATES capacities. When both are present (and hence the match is >0%), the high heat withdrawal capacity of the water and the large storage capacity cause the heat supply to almost always exceed heat demand. However, when both water and ATES are absent from the area, the match is 0%. In fact, of the total 65668 areas with a relevant heat demand in Europe, only 8034 areas have both heat supply and ATES storage and can be covered by aquathermal heat. The individual matching will be further elaborated upon in section 4.2.

4.3.2 Local match

In this section, a more in-depth perspective will be given to show local variations in potential. This is relevant to understand the mechanics that determine the overall potential as defined in section 4.1.

	Incl. ATES	Excl. ATES
Aarhus	64%	76%
Amsterdam	89%	91%
Berlin	50%	53%
London	19%	35%
Paris	18%	57%
Rome	26%	40%
Warsaw	31%	41%

Table 4. Local aquathermal potentials for different European cities including and excluding ATES.

4.3.2.1 Overall trend

The spatial trend that is visible on a local scale is mainly determined by the heat transport distance. This determines how far heat supply from surface water can be transported to a certain area. If any surface water is available, it is in most cases the ATES capacity that will determine the maximum potential, as surface water heat supply tends to exceed heat demand.

Paris has been shown several times in this thesis, which is the reason for also using it as the example here. Heat demand in Paris ranks among the highest in Europe and is concentrated in the inner-city centre, which is likely a consequence of the high population density and low housing insulation in this area. The Seine river provides the main heat supply of the city. The aquathermal heat potential in and around Paris is delineated by both the heat supply from the Seine and the ATES capacity.

Since urban settlements historically especially thrived in the proximity of large rivers and open sea, Europe's major cities tend to be located near rivers. This characteristic is especially interesting for aquathermal heat because rivers do not only supply heat, but their sediments can also provide heat storage. Areas close to rivers tend to have relatively large ATES capacity; a by-product of the river's sedimentary depositions throughout the ages. For cities located in regions with bedrock that is not suited for ATES application, a rivers' sedimentary depositions can provide storage capacity. This is for instance the case in Southern Germany for Munich and Stuttgart. For Paris, there is also a clear correlation between the Seine river and ATES capacity.

The aquathermal heat potential in and around Paris ranges from 0% in the east of the city due to an absence of both water and ATES capacity, to approximately 400% in the north-western corner. This is caused by the high heat withdrawal and ATES capacity of the Seine river, and a relatively low heat demand density in this part of the city. The gross of the areas with a potential >0% are situated around the Seine river, also in the old centre of the city. Here, high heat demand density with maxima up to 4400GJ/ha lead to a lower aquathermal heat potential. Hence, it should be noted that the potential is relative to the total heat demand. Therefore, this high heat demand causes the aquathermal heat supply and aquifer capacity to be – relatively – low. Yet, the potential excluding ATES reach much higher numbers, indicating that ATES is limiting in this region (see section 4.2).

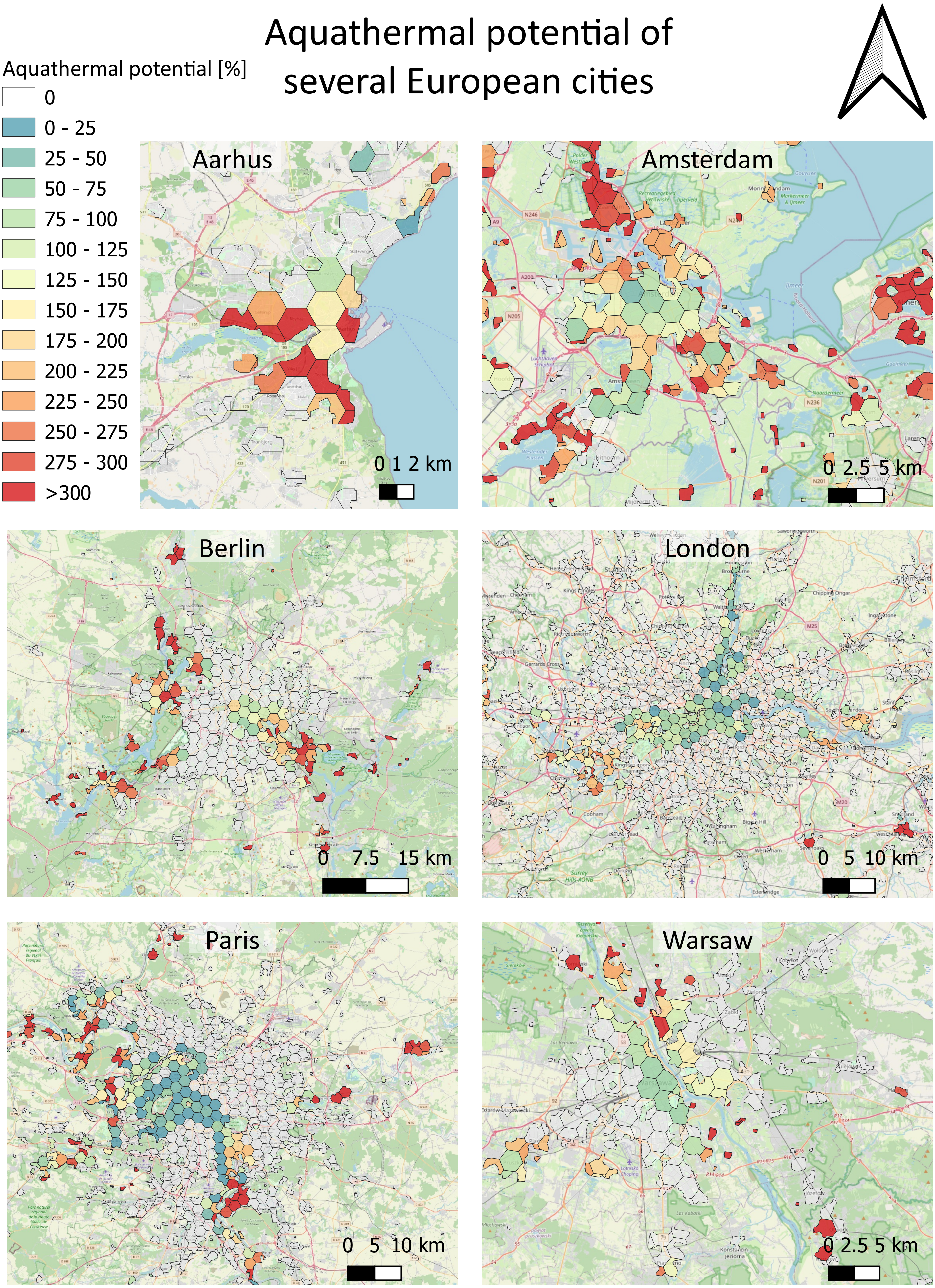

Figure 18. Overview of aquathermal potential of European cities.

4.3.2.2 *The effect of ATES exclusion*

In some regions where ATES capacity is very limited or non-existent, the option without ATES gives promising results. The image below shows the difference between the aquathermal heat potential of Paris with and without ATES. As shown in figure 19, ATES capacity is mainly distributed along the Seine river. This distribution can be partly explained due to the transport distance of heat but is predominantly defined due to the aquifer availability. In the situation without ATES, heat supply is only defined by the heat transport distance, hence the higher heat potential in areas in 2,5km proximity of surface water.

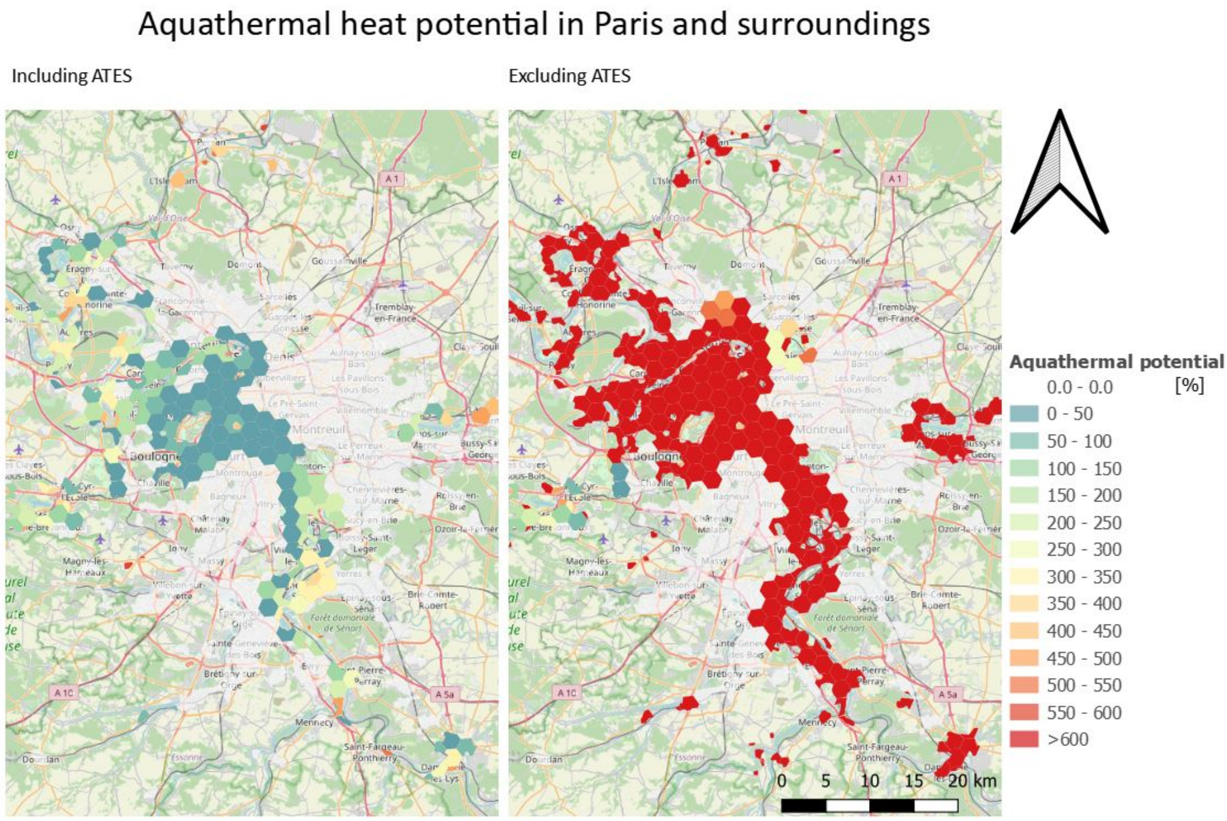

Figure 19. Aquathermal potential with and without ATES.

4.4 Sensitivity analysis

The sensitivity analysis was carried out according to the values given in table 2. The heat transport distance, ΔT of surface water and ATES, and heat exchange coefficient are discussed in this section. Furthermore, due to the discrepancy between the DH areas of >500GJ/year and the heat demand, this is also tested in the sensitivity analysis.

The distance heat is transported is the most influential factor in determining the potential. The largest increase comes from areas where no heat supply is present within the buffer distance at all. When surface water is already present at a certain distance, the potential tends to be higher than 100% (due to the high heat supply from surface water). Therefore, an increase in heat transport distance is predominantly influential for areas where no surface water exists in the shorter transport distance. This causes a high increase in potential with higher heat transport distance, visible in figure 20. Although an increase of ΔT of surface water results in an increase in heat supply, it does not show the same increase for the potential. The same mechanism seems to be true for the heat exchange coefficient. The reason for this is that the heat supply often greatly exceeds the heat demand and sometimes also the ATES capacity, causing a surplus that is not counted in the potential.

The increase in ΔT for ATES has a large effect on the ATES capacity, while its influence on aquathermal heat potential seems limited. The small effect is likely because ATES is not in all situations the limiting factor for the aquathermal heat potential. Only in regions where ATES is limiting the heat supply, a capacity increase can lead to an increase in the potential.

This sensitivity analysis shows that multiple scenarios for the aquathermal heat potential in a region are possible. The aquathermal heat potential is dependent on the heat demand relative to the smallest factor in either surface water heat supply and the ATES capacity. The consequence is that the potential will not always increase when the heat supply increases. This happens only in two cases; first, the ATES capacity needs to be able to store the amount of heat withdrawn from the surface water. Second, heat supply does not exceed the demand, as the potential is calculated to be maximal 100% of the heat demand.

An increase in heat demand influences heat supply because more heat demand is covered by the aquathermal heat supply. Therefore, it does raise the absolute heat supply but does not change the potential in the same way. Although the total heat supply increases, the potential decreases. This is because relative to the heat demand, heat supply decreases. Furthermore, the limitations posed by ATES capacity do not change.

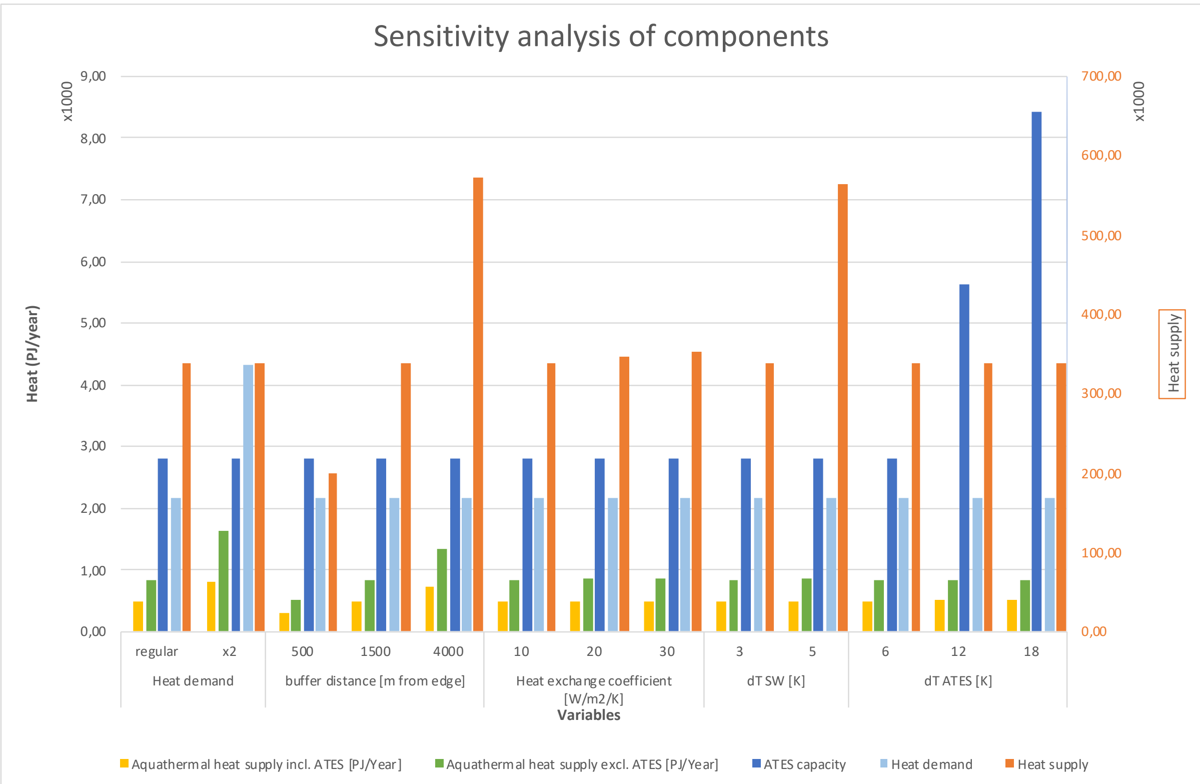

Figure 20. Sensitivity analysis on the different components that define aquathermal heat potential. Note the secondary axis for heat supply on the right.

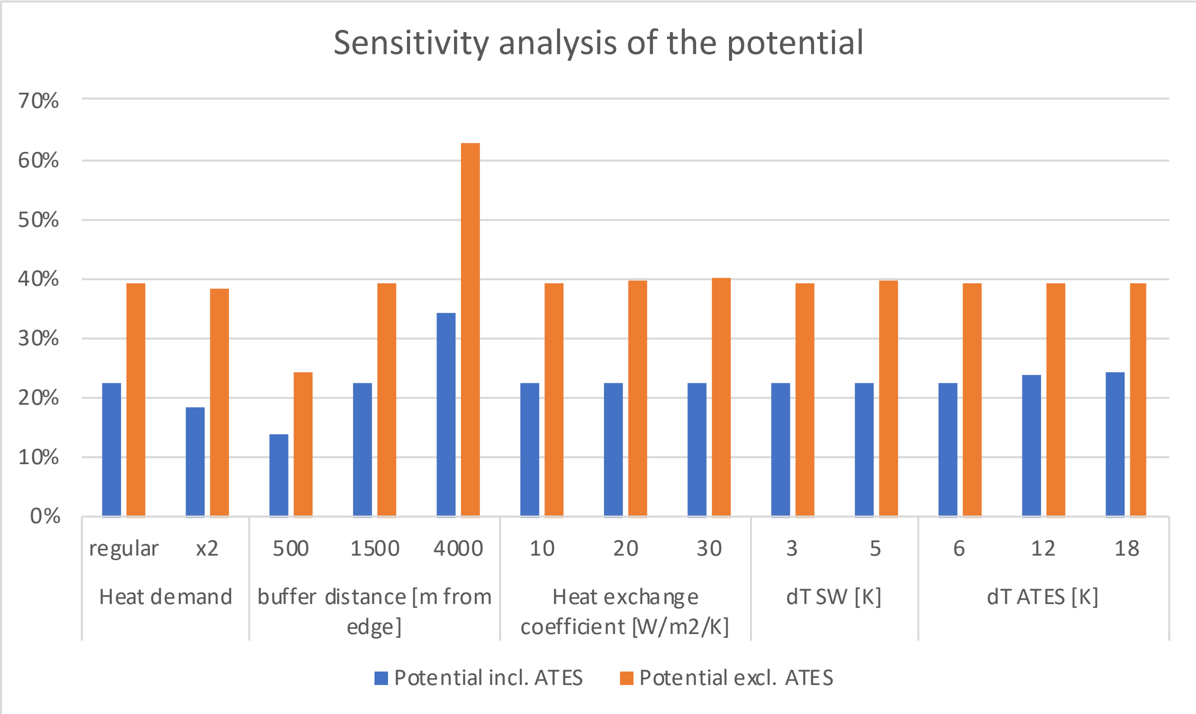

Figure 21. Sensitivity analysis on the potential of aquathermal heat.

5 DISCUSSION

5.1 RESEARCH LIMITATIONS

Although the three datasets used in this thesis were used after careful consideration, they were not developed for this research and thus required adaptations to fit the research. These adaptations, as well as choices made in the research design pose limitation to the research and are discussed in this section.

5.1.1 Heat demand

It seems that a discrepancy exist between the Hotmaps heat demand map and the sEEnergies DH areas map which became clear while matching the DH areas to the heat demand dataset. The resulting heat demand dataset should have been a cut-out of the heat demand map that only included areas with a heat demand >500GJ/ha. Although some differences were expected due to the smoothing of the DH areas in the sEEnergies map, the resulting areas were up to a twofold lower per area than expected. Therefore, it was chosen to subject the heat demand to a sensitivity analysis (see section 4.3). The result shows that the potential decreases by 3% as a result of the head demand increase, indicating that an underestimation in the heat demand can lead to an overestimation of the total potential. This overestimation only occurs when the heat supply is lower than the heat demand. Yet, when the model is run with a double heat demand, the overall potential does not change is relatively small. This indicates that the aquathermal heat supply is in general higher than the current heat demand. Nonetheless, care should be given to the heat demand to avoid overestimation.

5.1.2 Water discharge

The river discharge map has two minor drawbacks. First, surface water smaller than 25 ha is not included in the map. Yet, in dense urban spaces, suitable surface water bodies are often smaller and can be a welcome addition to the heat supply. Therefore, to get a better understanding of the role these smaller surface water bodies can play, more in-depth studies could consider these.

The second drawback of the river discharge map is the low resolution of the discharge data. Currently, the pixel size is 5x5km; much larger than the average European river. Because the discharge map is used as input for the surface water map, it is possible that a lake nearby a river is appointed the value of the river. Vice versa, the same can happen for a meander in a river that falls just outside the river pixel, onto a pixel that was intended for an area with lower discharge.

5.1.3 ATES

The choice to categorise the whole subsurface into three classes (0, 15 and 30m thickness) was necessary due to limitations in data sources. The IHME1500 is scientifically very sound, but not made for a quantitative approach to aquifer capacity. Furthermore, it could be argued that when the subsurface is characterised as a productive aquifer, it does not mean is it directly suitable for ATES. Because subsurface structures can be extremely complex, more information is necessary to define the exact capacity.

5.1.4 Scope

The limitation to the content of this research is mainly posed by the scope of the thesis. First, it is limited to the EU-27 and UK, a large extent that causes difficulties for in-depth analysis. Although the datasets are location-specific (spatial datasets), some parameters that were necessary in calculating ATES capacity and heat withdrawal capacity were not spatially available. Hence, assumptions were made that should be more specific once a smaller region is investigated.

Furthermore, the research is limited to the heating demand. Currently, cooling demand accounts for 2% of total energy demand, contrasting with 56% for heat demand (Fleiter et al., 2017). Although cooling demand is expected to rise in the future, research in this thesis is limited to the current energy demand. Furthermore, data on cooling demand was inconsistent with heating demand and therefore believed to be of insufficient quality to include. For these reasons, the focus of this research is on heat demand.

Finally, this thesis studies the technical potential. This limitation was set because the objective of this study is to provide a first 'quick-scan' for aquathermal heat in Europe. Moreover, due to the large region that is under investigation, it is not possible to find consistent data for more in-depth potentials.

5.2 Interpretation and implications

In the default settings, the results indicate that the aquathermal heat potential for the European collective heat demand is 27,7%. However, this says little about the aquathermal heat potential of specific cities. For instance, the results also indicate that the potential of Amsterdam is close to 90%, while Paris and London reach lower potentials (respectively 24% and 12%). This is both explained by their lower suitability to aquathermal heat as a whole and by the higher heat demand in the latter two cities. Still, even with low potentials, cities can greatly benefit from aquathermal heat. As described in HRE, DH benefits from a variety of heating sources, as it can stabilize and increase the security of heat supply.

5.2.1 Comparison to literature

When compared to the Dutch aquathermal potential of 43% by Kruit et al. (2018), the European aquathermal potential is expected to be lower, certainly given the high amount of surface water and sandy subsurface in the Netherlands. However, when only looking at the potential in the Netherlands, (78%) this is much higher than the aforementioned result by Kruit et al. (2018). This is caused by the absence of heat accounting in this thesis, whereas in Kruit et al. (2018) heat is limited to be used only once. This is in line with reality, where a surface water body cannot supply more energy once its heat has been withdrawn. Accounting of surface water heat is necessary once a more in-depth study of a specific area is performed, to identify the relevant bottlenecks in the heat supply and allocation of heat. Because the objective of this thesis is to provide an overall view of aquathermal heat in Europe, it is outside of the scope to include this. Excluding this heat accounting, the result for the Dutch aquathermal potential is 91.3% (Kruit et al., 2018). Comparing this result to the Dutch potential found in this study, there is a difference of 13%. Two possible reasons were hypothesised for this difference. First, it could be caused by the usage of a smaller ATES capacity than used in Kruit et al. (2018). Because of limited data, the aquifer thickness of the Dutch subsurface was set at 30m. However, the option without ATES results in a potential of 77%. Hence, although this contributes to the difference in potentials found, it does not fully explain it. Second, it is possible that a difference in area size influences the aquathermal potential. Since the share of areas within the heat transport distance is the largest determinator for the large-scale aquathermal potential, areas that are on average larger lead to a higher aquathermal potential. Yet, in Kruit et al. (2018) and this research, the Netherlands is divided in respectively 12239 and 11992 areas. The difference seems too insignificant to explain the disparity in potential. However, the exact influence of area size and number is unclear, since the shape of the areas can also alter the potential. Unfortunately, the high-resolution data about neighbourhoods is not available for the rest of Europe, thus this hypothesis cannot be verified.

5.2.2 Aquathermal in local context

This research can be applied by policymakers that search for alternative heating technologies or scientists that can use this dataset for further research. Furthermore, the small-scale potential results are suitable for showing the possibilities that aquathermal heat can offer for areas that look for alternative heating solutions. Regardless of the final potential for aquathermal heat in Europe, it is important to show the possibilities for aquathermal heat in certain regions and cities. For instance, while the potential of the city of Duisburg is very high, the juxtaposed city of Essen has a potential close to 0%. Furthermore, Berlin has a potential of 50%, while the total of Germany is 25%. Hence, the large variation in the potential between the different areas causes the total potential to misrepresent a realistic picture for individual areas.

Furthermore, how aquathermal heat will be deployed and what its contribution to the city's sustainability goals will be, differs per city. Placing the aquathermal potential into the context of a region or city can point out the implications that come with societal, geographical and temporal constraints. It shows that the boundary conditions for aquathermal heat – e.g. efficient DH system and well-insulated building stock – are extremely important when assessing heating strategies for a region. For example, even though both have a relatively high potential (respectively 31% and 64%)

Warsaw and Aarhus maintain very different heating strategies and will therefore see different opportunities in aquathermal heat (see box 1).

Box 1

Warsaw, Poland

Poland has one of the most extensive DH systems Europe and is fuelled by 75% coal, 8% gas, 4% oil and 8% RES. The Polish government aims for more RES integration, but the outdated DH system is not suited for LT heat sources yet (Wojdyga & Chorzelski, 2017). Once a state-of-the-art technology, the Warsaw DH system that commenced in the late 19th century is now outdated and has high transportation losses. Still, it transports heat to 65% of the cities 1,7 million inhabitants (Zgoda, 1986). Additionally, the Warsaw building stock is characterized by low insulation. This shows the necessity of the modernization of the energy system before LT heat can be utilized. Currently, Warsaw's energy systems are being modernized by the development of a gas-fired power plant, incentivised by increasing carbon emissions costs (Wojdyga & Chorzelski, 2017). Furthermore, societal implications of increasing heating costs include poorer households that may switch to individual heating systems fuelled by solid fossil fuels or waste, worsening the overall carbon emissions. Although the aquathermal potential for Warsaw is relatively high, the boundary conditions that apply for aquathermal heat are not in place yet.

Aarhus, Denmark

Denmark, one of the leading countries on RES in the EU, also has an extensive DH system that serves 65% of all citizens. Renewable heat feeds 60% of the DH systems, and is supplemented by renewable electricity sourced heat pumps only when there is a surplus. Denmark's target is to ban fossil fuels from heat production in 2030. Aarhus is the fastest growing city in Denmark and aims to be CO_2 neutral in 2030. 65% of the city is connected to DH, of which the heat supply temperature will be reduced from 75-85°C to lower temperature heat (60°C in summer and 70° in winter) (Richter, 2020). This allows higher integration of low temperature RES and is in line with the plans the city has for exploring geothermal heat in the region (Munk Jensen, 2019). Simultaneously, this development in temperature is also suitable for aquathermal heat technologies. In fact, small projects including WSHPs coupled to the fluctuating energy prices are already being investigated for their potential to lower heat prices. Furthermore, the high involvement of citizens through community energy projects has raised the support base for RES (Roberts, Bodman, & Rybski, 2014). Considering that Aarhus' heat system design is already more suitable for aquathermal heat and a large support base for RES is present, it is likely that the potential will actually utilized.

Local regulations can also incentivise renewable heat regulation. An example is the village of Broager, Denmark, where a DH system is deployed even though the heat demand density is significantly lower than the threshold used in this research (500GJ/ha) (Lauersen & Moesgaard, 2020). A DH system can become increasingly more desirable if the alternative scenario is discouraged by, for instance, a carbon tax and electricity is cheaper because of surpluses in renewable electricity generation.

These examples show that possibilities for aquathermal heat are highly dependent on the context in which they are placed. The scope of this study is limited to the technical potential; hence the main limitations are technical – surface water availability, DH requirements and sufficient ATES capacity. Therefore, to use the results of this thesis, it is important to understand the barriers that come into play when focusing on a smaller region. Accordingly, societal and economic conditions are important factors to consider when interpreting the result of this thesis for a specific location.

5.2.3 DH and heat transport distance

The sensitivity analysis of the potential found that the heat transport distance is the most influential factor in determining the potential. It determines if surface water bodies fall within the reach of a DH network and thus whether an area can receive aquathermal heat. The heat transport distance is most influential for those areas that do not have access to surface water within a shorter distance. In other words, when an area already has access to surface water, extra heat supply rarely adds to the potential. This is due to the high heat supply of water, and heat demand and ATES capacity being limiting.

Although the heat transport distance is one of the most influential factors in this research, a different approach should be taken when multiple neighbourhoods deploy DH networks in a city. In this scenario, the neighbourhood approach is not realistic, because one interconnected DH network can be formed (David et al., 2017). Instead of using the heat transport distance from the neighbourhood edge, a DH area approach should be used when considering a heat source. Consequently, DH networks connected to areas with an aquathermal potential that exceeds the heat demand can benefit from this surplus in heat supply and distribute it to areas with lower or no potential. A DH approach would greatly increase the potential because trough the DH network, more areas can reach surface water. However, ATES capacity for storage of the collective heat demand is not guaranteed.

5.2.4 Excluding ATES

While aquathermal heat supply is defined by the heat transport distance and can therefore overlap between areas, ATES capacity is not overestimated because it is area-bound. The exclusion of ATES provides more insights into both the opportunities and limitations set by ATES capacity. On the one hand, it provides a more efficient heat system, while on the other hand, it limits the use of aquathermal heat. Therefore, for areas where the temperature of surface water does not drop below the heat withdrawal limit in winter, the option without ATES would be viable. Corresponding, an additional analysis for aquathermal heat withdrawal in winter based on winter surface water temperature could lead to more understanding of the possibilities of direct aquathermal heat use.

Additionally, the exclusion of ATES also shows that the aquathermal heat supply can reach sevenfold of the heat demand when not limited to ATES. This means that neighbourhoods with low or no potential, either due to distance to surface water or limited ATES capacity, could still receive aquathermal heat supply when connected to a DH system that is fed with aquathermal heat. Although less energy efficient, the investment costs are lower due to the absence of ATES related costs (e.g. analysis, drilling, monitoring etc.).

5.2.5 Allocation of heat sources

When heat is scarce, the allocation of heat sources with limited capacity should be regulated. In this thesis, the exclusion of heat accounting could lead to possible overestimations of the aquathermal heat supply. Local overestimations can take place when the aquathermal heat potential (excluding ATES) is between 0-100%, although this rarely occurs due to the high heat withdrawal capacity of water causing the potential to be greater 100%. However, the aquathermal heat potential is overestimated when heat demand is factored in too low, reinforcing the issues with heat allocation. Furthermore, it is possible that, despite the extremely high aquathermal potential of rivers, upstream regions with high heat demand (e.g. the Ruhr area) use heat that is also needed downstream. Still, it is currently unlikely that the full potential is used for one area, since most neighbourhoods will have multiple heat sources connected to a DH system. However, when aquathermal heat becomes a scarce good, it is necessary that policy is developed for heat allocation on a fluvial scale (e.g. upstream and downstream Rhine). Solid regulations of the right to withdraw heat can facilitate and ease the process of allocating heat.

5.3 Recommendations for further research

5.3.1 Data

The data used in this thesis was not developed for this particular research, resulting in the need for concessions in the chosen method. The following sections give a better understanding of these concessions, and how to improve further research.

5.3.1.1 River discharge

It was already described how limitations in water discharge and land cover data may have led to an over-or underestimation of the aquathermal heat supply. Higher-resolution data can help solve this problem as it can cover small-scale variations. While the underrepresentation of surface water due to relatively low-resolution land cover data may not be significantly altering the regional aquathermal heat study, the low-resolution water discharge data does alter it significantly. It is recommended to look for or develop higher resolution discharge data.

5.3.1.2 ATES

Because the IHME1500 only has two categories that were suitable as input data, the representation of the European subsurface is very homogenised. Hence, the subsurface data could be improved by also including information about the aquifer thickness and lithology (including porosity). Furthermore, extra information about protected groundwater and nature areas, and archaeological sites could be added, as this could restrict ATES appliance.

5.3.2 Research design

Although only heat demands were included in this thesis, cooling demands will become more dominant in the future. Since heating and cooling can balance each other in ATES systems, and therefore decrease the pressure on exterior heat sources, meeting cooling demands can add an efficiency benefit to the energy system. Due to global warming, cooling demands are likely to rise in the future, causing research on cooling strategies to be ever-rising in relevance. For future research, it is therefore interesting to include the cooling demand in potential studies.

5.3.3 Applicability

A main take-away from this research's discussion is the applicability of this study. Because more research is always necessary for the actual deployment of aquathermal systems, this research can give a first overview of locations where a high likelihood exists for a certain aquathermal heat supply. As explained, local context is extremely important and can make or break plans for aquathermal heat deployment. Economic and societal factors, as well as more information about the physical and technical specifications, are necessary additions for successful in-depth feasibility studies.

6 CONCLUSION

To aid the shift to a future without fossil fuels, the European heating systems must undergo large change. Aquathermal heat is a renewable heat source that is withdrawn from surface water. Because DH is deemed essential for the future heating system, the aquathermal heat potential to meet the collective heat demand of Europe was researched in this paper. The objective of this thesis was to show where opportunities for aquathermal heat in Europe exist, both to put it in the scientific 'spotlight' and to aid local decision-makers in finding alternative heat strategies. The main research question was as follows:

What is the current potential of the application of the combination of surface water heat and ATES to meet the collective heat demand in Europe?

This question was approached by analysing several spatial datasets on heat demand, DH, surface water, water discharge and aquifer availability data. Both ATES capacity and aquathermal heat supply were calculated using the aforementioned datasets and integrated using an algorithm that spatially compared the heat demand of each area to the heat supply. This yielded an aquathermal heat potential for each area under research, and a general number for the whole of Europe.

The aquathermal heat potential to cover European heat demand is found to be 27,7%. However, the discussion clarified why this number is not as straightforward as it looks because it is an average number for Europe as a whole, from which individual areas and cities deviate greatly. Also, physical and technical conditions determine whether aquathermal heat is available, but economic and societal conditions determine whether the energy can be used. This map shows where opportunities to use aquathermal heat lie, and where it is worthwhile to do further research. Furthermore, several points need to be given special attention for the application of this research.

First, the aquathermal heat potential could be greatly increased when a DH approach is used. In the case of one large interconnected DH network, more areas would be in reach of surface water heat. Therefore, DH provides the opportunity to raise the aquathermal heat potential and use it more efficiently.

Second, although direct aquathermal heat use may result in lower energy efficiency than using seasonal storage in ATES, it provides many opportunities for regions that do not have (sufficient) ATES capacity. In line with this, including winter surface water temperatures is recommended to better understand possibilities for direct aquathermal heat use.

Third, excluding heat accounting can lead to a local overestimation of the potential. If an area has a potential (without ATES) exceeding 100%, this is less of a problem. However, when the potential is between 0-100%, aquathermal heat supply may be insufficient due to heat withdrawal upstream or by other areas in the neighbourhood. If aquathermal heat demand exceeds supply, prioritisation regulations are necessary to ensure fair heat usage.

In conclusion, aquathermal heat seems a viable option for many areas in Europe. Although the potential varies greatly, aquathermal heat supply is technically feasible in many cities and regions. It should definitely be considered as a very promising alternative heating solution. Although there are still many barriers to implementation, local feasibility studies have the means to understand and overcome these. With district heating as backbone, aquathermal heat has the potential to play a significant role in the heating system

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APPENDIX A: EQUATIONS FOR HEAT WITHDRAWAL AND ATES CAPACITY

<u>Heat withdrawal capacity: surface</u>
Pt [kW]
= (A * Z * ΔT_{SW}) / 1000
= (A * 10 * 3) / 1000
Pt = 0.03 * A

E [GJ/year]
= Pt * H * 0.0036
= Pt * 2000 * 0.0036

E = 2000 * 0.0036 * Pt
7.2 * Pt =
7.2 * 0.03A =
E_{stag} = 0.216 * A

<u>Heat withdrawal capacity: discharge</u>
Pt [kW]
= Q * ΔT_{SW} * ρ * C
= Q * 3 * 998 * 4.185

E [GJ/year]
= P * H * 0.0036
= P * 2000 * 0.0036
E = 7.2 * P = 7.2 * 12 529 Q =
E_{flow} = 90215 * Q

<u>Total</u>
E_{tot} = 90215 * Q + 0.216 * A

A: water surface [m2]
Z: cooling number = 10 [W/m2°C]
ΔT_{SW}: temperature difference = 3 [°C]
H: system load hours = 2000 h
Q: discharge [m3/s]
ρ: density water = [998 kg/m3]
C: heat capacity water = 4.185 [kJ/kg°C]
P: thermal power [kW]
E: energy [GJ/a]

ATES Capacity

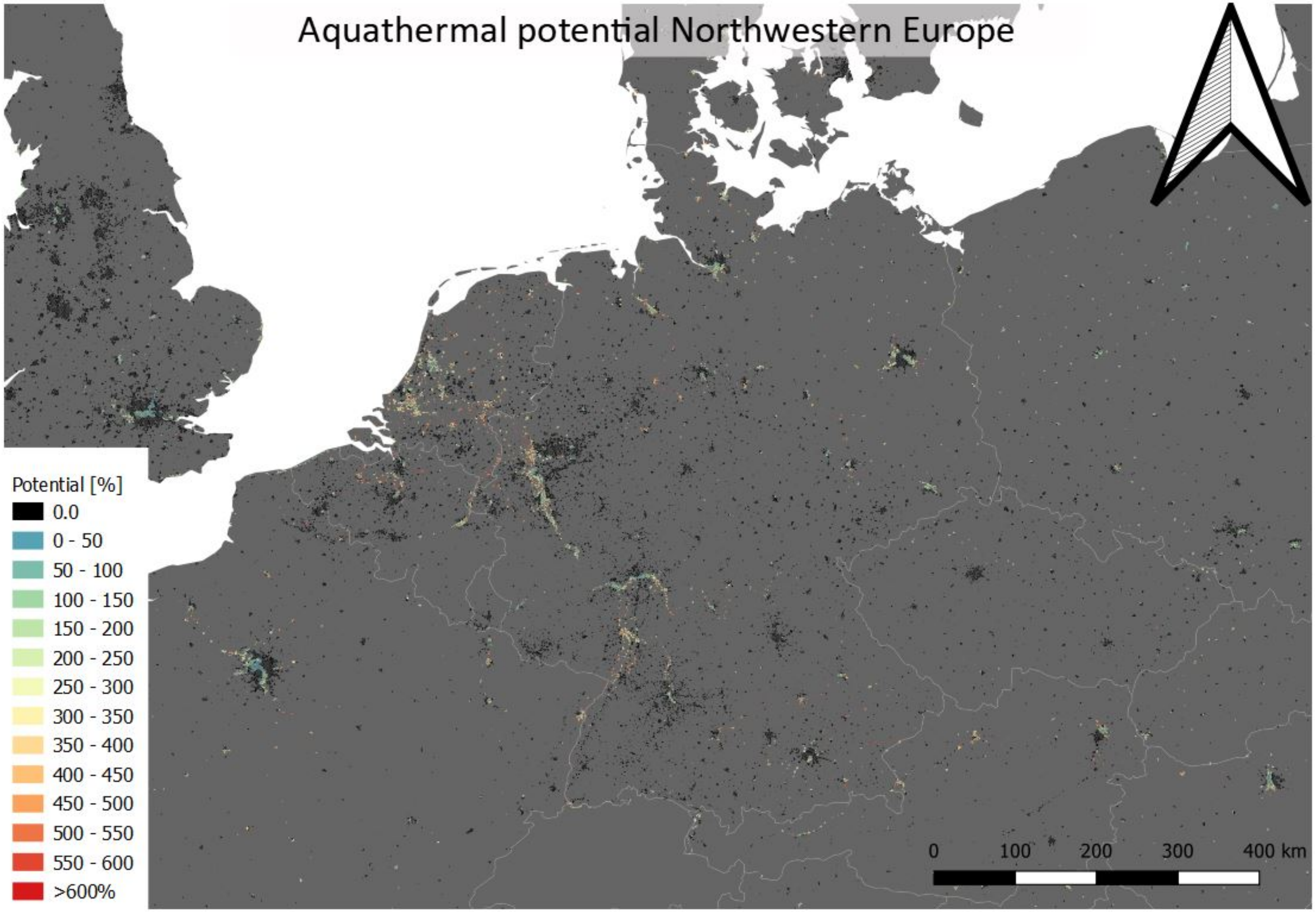
$Q_{ATES} = 0.56 * \rho * C * d * A * \Delta T_{ATES} * \Theta$

$= 0.56 * 998 * 4.185 * d * A * \Delta T_{ATES} * \Theta$

$= 2338.91 * d * A * \Delta T_{ATES} * \Theta$

Q: energy capacity [GJ/year]
ρ: density water = [998 kg/m^3]
C: heat capacity water = 4.185 [kJ/kg°C]
d: thickness [m]
A: aquifer surface [m2]
ΔT_{ATES}: temperature difference [°C]
Θ: porosity

APPENDIX B: MAP OF AQUATHERMAL HEAT POTENTIAL NW EUROPE



Appendix C: Python script

```
# ----------------------------- Packages -------------------------------------
import os
import pandas as pd
import geopandas as gpd
import numpy as np
import rasterio

from rasterstats import zonal_stats
from datetime import datetime

# ----------------------------- Functions -----------------------------------

def import_shp(file_in, **kwargs):
    ''' Function to import shapefiles '''
    df = gpd.read_file(file_in, **kwargs)
    return df

def makedir(path):
    ''' Function to create new path if path does not exist yet '''
    if not os.path.exists(path):
        print("path doesn't exist. trying to make")
        os.makedirs(path)

#def count_data(x):
   # return int(np.ma.sum(x > 0.))

def count_data(x):
    try:
        return int(np.ma.sum(x > 0.))
    except:
        return None


def calc_aquifer_cap(d, A, dT=6., phi=0.3):
    ''' Function to calculate the aquifer capacity
    Parameters
    ----------
    d   : Layer thickness in m.
    A   : Aquifer surface in m2.
    dT  : Average temperature difference in degrees celcius. The default is 6.
    phi : Porosity. The default is 0.3.

    Returns
    -------
    Aquifer capacity in GJ/yr

    '''
    return ((2338.91/1E6) * d * A * dT * phi)
```

```
def calc_match(hwc, ates, hd):
    ''' calculate the match of the hexagons based on the subsurface
        storage capacity, extration capacity and heating/cooling demand '''

    if np.isnan(hwc) or np.isnan(ates):
        return np.nan
    else:
        potentie = min(hwc, ates)
        frac_hd = potentie / hd

    return frac_hd


#%%
print(datetime.now().strftime('%H:%M:%S') + '->' + "start")
# ----------------------------- Script settings ------------------------------

# define name heat demand column in attribute table
hd_col = "HD_sum"

# buffer in meters
dist = 1500
buf = f"{int(dist/1000)}km"

# create dictionary to store matching results
totmatch= {}
#%%
# ----------------------------- File settings --------------------------------

#put rootfolder here
rootdir = r"/Users/ "
demand_path = os.path.join(rootdir, "Heat_demand.gpkg")
demand_buf_path = os.path.join(rootdir, f"Heat_demand_final_{buf}buf.shp")
aqf_path = os.path.join(rootdir, "ATES_thickness.tif")
hwc_path = os.path.join(rootdir, "Water_Discharge.tif")

# output files
match_csv_path = os.path.join(rootdir, "total_match_1,5km.csv")
match_shp_path = os.path.join(rootdir, "match_1,5km.shp")

#%%
# ------------------------------ Import data ---------------------------------

# heat demand (GJ/ha)
hexagons_org = import_shp(demand_path)
hexagons = hexagons_org.copy()

# add buffer
hexagons_buff = hexagons_org.copy()
hexagons_buff['geometry'] = hexagons_buff['geometry'].buffer(dist)
```

```
# export to new shapefile
hexagons_buff.to_file(demand_buf_path)

print(datetime.now().strftime("%H:%M:%S") + "->" + "start zonal statistics hwc")

#------------------------------ Water capacity -------------------------------
# open GeoTIFF
with rasterio.open(hwc_path) as dataset_in:
   # pixel resolution (meters)
   resolution = dataset_in.transform[0]

# determine zonal statistics (documentation:
https://pythonhosted.org/rasterstats/manual.html#zonal-statistics)
stats_wb = zonal_stats(demand_buf_path, hwc_path,
                  stats=['max'], add_stats={"count_wb":count_data},
                  all_touched=True)

# convert list of dictionaries to pandas dataframe
df_stats_wb = pd.DataFrame(stats_wb)
# rename columns
df_stats_wb = df_stats_wb.rename(columns={"max":"q_max"})

# join dataframes
hexagons = hexagons.join(df_stats_wb)

# parameters for calculating hwc
dTsw = 3.
Z = 10.

hwc_a = (dTsw * Z)/1000 * 2000. * 0.0036

# calculate hwc_A
hexagons[f"hwc_a_GJy_{buf}"] = [hwc_a * (n * (resolution*resolution)) for n in
hexagons["count_wb"]]

# calculate hwc_Q
hexagons[f"hwc_q_GJy_{buf}"] = [Q * dTsw * 30071.7 for Q in hexagons["q_max"]]

# calculate total hwc
hexagons[f"hwcGJy_{buf}"] = hexagons[f"hwc_a_GJy_{buf}"] + hexagons[f"hwc_q_GJy_{buf}"]

# ------------------------ Aquifer capacity ------------------------------

print(datetime.now().strftime("%H:%M:%S") + "->" + "start zonal statistics ates")

# determine zonal statistics (documentation:
https://pythonhosted.org/rasterstats/manual.html#zonal-statistics)
stats_aqf = zonal_stats(demand_path, aqf_path,
                  stats=["max","mean"],
                  all_touched=False)

# convert list of dictionaries to pandas dataframe
```

```
df_stats_aqf = pd.DataFrame(stats_aqf)
# rename columns
df_stats_aqf = df_stats_aqf.rename(columns={"max":"aqf_max", "mean":"aqf_mean"})

# join dataframes
hexagons = hexagons.join(df_stats_aqf)

# calcute ates and add as new column to dataframe.
hexagons['atesGJ'] = calc_aquifer_cap(hexagons['aqf_mean'], hexagons["geom_Area"])

#%%
# ------------------------- Matching (per hexagon) -------------------------
print(datetime.now().strftime('%H:%M:%S') + '->' + "start match")


# calculate exact match (return -1 if the heating/cooling demand is zero)

# calculate match (inclduing ates) per hexagon and add result to dataframe
hexagons[f'match_{buf}_ates'] = [calc_match(hwc, ates, hd) * 100 if hd>0. else -1 for hwc, hd, ates\
                                 in zip(hexagons[f'hwcGJy_{buf}'], hexagons[hd_col],
                                 hexagons['atesGJ'])]

# calculate match (no ates) per hexagon and add result to dataframe
hexagons[f'match_{buf}'] = [hwc/hd * 100 if hd>0. else -1 for hwc, hd \
                            in zip(hexagons[f'hwcGJy_{buf}'], hexagons[hd_col])]

# ------------------------------- Total match --------------------------------


# calculate total heat demand of all hexagons
demand = np.nansum(hexagons[hd_col])

# calculate total potential Europe, taking ates into consideration
potential_ates = np.nansum([x if y>100 else (y/100)*x if y>0 else 0 for x, y in \
                 zip(hexagons[hd_col], hexagons[f'match_{buf}_ates'])])

# calculate total potential Europe, ignoring ates capacity
potential = np.nansum([x if y>100 else (y/100)*x if y>0 else 0 for x, y in \
            zip(hexagons[hd_col], hexagons[f'match_{buf}'])])

# calculate total ates cap and heat supply only
storage_ates = np.nansum(hexagons['atesGJ'])
supply = np.nansum(hexagons[f'hwcGJy_{buf}'])

# add information gathered above to dictionary and calculate match
totmatch = {f'totmatch_{buf}': {'bu_vraag_PJ': demand/1E6,
                   'aanbod_inclates_PJ': potential_ates/1E6,
                   'aanbod_PJ': potential/1E6,
                   'aanbod_HS_PJ': supply/1E6,
                   'ates_cap_PJ': storage_ates/1E6,
                   'match_inclates': (potential_ates/demand)*100,
                   'match': (potential/demand)*100}}
```

```
# convert dictionary to pandas dataframe (df)
df_totmatch = pd.DataFrame.from_dict(totmatch, orient='index')

# ------------------------------ Export ----------------------------------

# export totmatch dictionary to cvs
df_totmatch.to_csv(match_csv_path, sep =';', index=True, decimal = ',')

# export hexagons geodataframe to new shapefile, .to_file is a function to save a geodataframe (gdf)
as shp
hexagons.to_file(match_shp_path)

print(datetime.now().strftime('%H:%M:%S') + '->' + "finished")
```