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Assessing the seasonal potential of wastewater and rivers as heat sources for district heating: Methodology and example application for the federal state of Hesse, Germany

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ABSTRACT

The transition to a sustainable energy system requires the consideration of all available renewable heat sources. This study assesses the potential of wastewater and river heat for district heating networks in the federal state of Hesse, Germany, considering the seasonality of available heat and heat demand. Using standardised temperature and flow profiles for 443 wastewater treatment plants as well as interpolated river temperature and flow data for approx. 1,500 km of rivers, the study quantifies the heat extraction potential. By matching with heat demand profiles at daily resolution, based on forecast heat demand data for the year 2045, the long-term usable potential is determined. Possible heat network areas are identified based on the heat density indicator. For all building blocks with heat densities above 175 MWh/(ha·a), the usable heat potential amounts to 4.5 TWh/a for river heat pumps and 4.9 TWh/a for wastewater heat pumps. Applying a higher threshold of 415 MWh/(ha·a) reduces the potential to 1.3 TWh/a and 2.4 TWh/a, respectively. The usable potential of both sources together corresponds to 11 % to 28 % of Hesse's heating demand for space heating and domestic hot water. Using a new 1D energy balance model for an exemplary river, it is shown that the heat extraction from the river is acceptable concerning cumulative cooling. The study provides municipalities with a comprehensive database that facilitates the incorporation of these underutilised heat sources into their mandatory heat planning. The methodology presented can be adapted to other regions.

Keywords

River heat utilisation;
Wastewater heat recovery;
Municipal Heat Planning;
District heating;
GIS-based potential assessment

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1. Introduction

Decentralised air-to-water heat pumps (HPs) have been demonstrated to be technically and economically viable [1]. However, in densely populated areas, even in smaller municipalities, there are reasons that favour a grid-connected heat supply [2]. These include noise issues, renovation bottlenecks, or lack of space. Moreover, such grids offer the possibility of integrating previously unused environmental heat sources by using HPs and other heat sources like biomass to meet the peak heat demand during wintertime.

The recovery of wastewater heat can be a particularly attractive option due to its high temperature level compared to other environmental heat sources. The extraction of heat can be implemented prior to, during or subsequent to a wastewater treatment plant (WWTP) [3]. The process of extracting heat from the effluent of a WWTP has been demonstrated to be a viable option, without negative effects on the purification process. This approach has been adopted in large-scale projects for the integration of wastewater heat into DH networks, e.g. in several cities in Switzerland and Scandinavia [4], Vienna [3], Hamburg [5] or Berlin [6].

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List of Abbreviations

DH	*District heating*
FFH	*Fauna-Flora-Habitat*
GAM	*Generalised additive model*
HP	*Heat pump*
LAWA	*German Working Group on water issues*
(M)LQ	*(Mean) low flow*
MQ	*Mean flow*
PE	*Population equivalents*
(S)COP	*(Seasonal) coefficient of performance*
WPG	*German Heat Planning Act*
WWTP	*Wastewater treatment plant*

Another interesting source of environmental heat are rivers, which enable more efficient operation of HPs compared to ambient air due to their higher temperatures during the heating period and better heat transfer [7]. A few examples of large-scale river HPs are known to date, e.g. in Seoul [8], Mannheim [9], Rosenheim [9], and Glasgow [10].

However, the available potential of these two promising heat sources is unknown in many places. In Germany, the Heat Planning Act (WPG) has made municipal heat planning mandatory [11]. The objective of this study is to provide municipal authorities in Hesse with a realistic estimate of the potential offered by wastewater and rivers during the planning process.

1.1 State of research

A GIS-based study for the Baltic states examined, among others, river water and treated wastewater as potential heat sources [12]. Using GIS data, the authors show that most of the existing DH areas are close to at least one of these heat sources and provide some information on their temperatures and techniques for the exploitation of the potential. However, the paper does not quantify the heat potential of these heat sources. Most of the available studies examine the potential of either wastewater or rivers as a heat source. The following two subsections provide an overview of these studies.

1.1.1 Wastewater heat recovery

For Europe, only a limited number of country-specific studies have assessed the potential for heat recovery at WWTPs across an entire region, including investigations in Italy [13], Austria [14] and Serbia [15], as well as in the German states of Baden-Württemberg [16] and North Rhine-Westfalia [17]. All these studies assume an average temperature difference at the HP evaporator of 4 to 5 K and a steady annual flow rate (e.g. based on annual average values or estimates derived from per-capita flow rates) to estimate the heat potential for the considered WWTPs. This approach is appropriate for identifying areas with high theoretical heat recovery potential.

Some studies have modelled seasonal fluctuations in wastewater heat potential, which arise from variations in wastewater temperature and flow and are relevant for comparison with seasonal heat demand. A Swiss study takes into account average temperature variations during summer and winter and variations in heat demand, using simple approximations [18]. Further, the project MEMPHIS 2.0 developed a model with varying temperatures for spring, summer, autumn and winter to represent heat extraction from sewer networks as well as from industrial and service sectors which has been applied to a few selected cities [19]. Seasonal fluctuations are relevant for accurately characterising the heating period. Nevertheless, finer temporal resolution (e.g. weekly or daily) improves the representation of transitional phases between the seasons.

Temporal fluctuations in wastewater heat potential throughout the year in higher resolution are taken into account in some individual case studies, e.g. [20] for WWTP Tullamore (Ireland) and [4] for WWTP Mokrawica (Poland). These studies demonstrated that such fluctuations exert a significant influence on daily heat potential. Accordingly, a knowledge gap remains in existing large-scale studies concerning detailed seasonal assessment of wastewater heat potential.

1.1.2 River heat utilisation

When utilising heat from rivers, the properties of the water body must not be negatively affected, in accordance with the prohibition of deterioration stipulated in the EU Water Framework Directive [21]. The German Working Group on water issues (LAWA) has developed guidelines that consider the ecological aspects of river heat utilisation [22]. Although these are not legally binding, they currently represent the most comprehensive planning framework available in Germany.

Several studies have been carried out to assess the potential for river thermal energy utilisation (see Table 1). In these studies, the heat *extraction* potential is specified

Table 1: Overview of some current studies on the heat potential of river HPs.

Potential study	Area studied	Usable flow rate	Cooling of entire river	Remarks
[9]	Bavaria	Total flow at the last measuring point	0.5 – 3 K	Explicitly "theoretical potential"
[23]	80 major German cities	mean annual flow (MQ) at respective location	2 K	
[24]	Brandenburg	25 % MQ per water body	2 K	Throughout the year
[25]	North Rhine-Westphalia	Low flow (LQ) per water body	1.5 K	Distribution across 100 locations
[26]	Germany	Mean low flow (MLQ) at respective location	1 – 2 K (depending on the dominant fish species)	50 km distance between HPs
[27]	East Flanders	MQ	< 3 K (including search for the most sensible allocation)	Dynamic thermal modeling of flowing waters

based on a flow rate and an assumed cooling rate, that are applied at each heat extraction location or once for the whole river.

The mentioned studies come to very different conclusions due to the different conditions selected for usable discharge, cooling of the water, and, in some cases, repeated withdrawals. When comparing the studies, a plausible value of 2 K emerges for the maximum possible cooling, which corresponds to the specification for temperature-insensitive fish communities from [22].

However, the assumptions regarding discharge vary widely. Since the construction of a river HP involves a high investment, in practice, the HP will be designed to reach a high utilisation rate. In addition, a high availability of the heat source is necessary. Therefore, it seems justified to use the total flow or MQ to calculate *theoretical* potentials, but in practice this approach proves to deliver unrealistically high results. Instead, the MLQ, i.e., the value that is typically not undercut, is a good basis for calculating the *realistically usable* potential.

The potential studies reviewed did not consider the following important constraints for the use of flowing waters as a heat source (except partially [27]):

- Restricted operation and interruptions due to low water temperatures
- Seasonal comparison with local heat demand
- Regeneration of the temperature of the river, i.e., the reheating of the water by solar radiation, heat transfer, and inflows after cooling (neglecting regeneration may lead to a significant arbitrary underestimation or overestimation of the potential).

However, these important boundary conditions must be considered if a *realistic usable* potential is to be identified.

1.2 Research objective

The overarching research objective is to quantify the extent to which the heat demand in Hesse can be met by river and wastewater heat utilisation. This requires a differentiated consideration in terms of time (seasonal course of relevant quantities) and space (localization of supply and demand).

Firstly, heat *extraction* profiles in daily resolution are developed for the two heat sources under consideration. This requires temperature and flow profiles at all relevant locations for both heat sources and a method to derive the heat *extraction* potential from this information. Secondly, the usable heat potential of HPs that cover the heat demands is quantified. This requires determining local heat demand profiles and matching these with the local heat source profiles.

To the best of our knowledge, such a comprehensive approach has not been followed yet concerning these heat sources.

2. Methodology

To determine the potential for heat utilisation from wastewater and rivers, assumptions about technical, regulatory and climatic conditions are required. This section details the data and methodology used for calculating the potentials. A distinction was made between:

1. Heat extraction potential: Heat that can be extracted from the wastewater or river
2. Heat supply potential: Heat that can be provided by the heat pump
3. Usable heat potential: Portion of the heat supply potential that can be used after matching with the heat demand in areas suitable for heating networks

An important basic assumption for the potential assessment is the choice of the weather conditions, as their seasonal profile affects heat demand as well as the river temperatures. To get conservative results that can be expected to hold true even in a cold year, the weather year 2021 was used whenever weather data matters, as it is the coldest of the recent years. While the annual heat demand was projected to 2045 (renovation-related reduction, see also 2.4.1), we cannot rule out with certainty that by the mid of the century a year as cold as 2021 may occur, so that for weather data no projection was applied.

2.1 Wastewater heat recovery

A high temporal data resolution is required to estimate the heat *extraction* potential from the effluent of a WWTP. However, in a study covering a large geographical area, high-resolution data is not usually available for the whole area. Consequently, in this study standard annual profiles, considering seasonal fluctuations around the annual average temperature and dry-weather flow, were derived from available data of seven WTTPs. This allows to project the annual heat extraction potential for all WWTPs.

2.1.1 Input Data

There are 475 WWTPs in Hesse with a minimum capacity of 1,000 population equivalents (PE). Values for the annual wastewater volume (2020 - 2022) are available for 443 (93%) of these plants [28]. WWTPs with a capacity of fewer than 1,000 population equivalents (PE) were excluded from this study, as such small-scale facilities are often designed as constructed wetlands and typically lack the infrastructure required for the installation and operation of heat pump systems. As the average annual wastewater temperatures of the individual WWTPs in Hesse are not recorded centrally, an average annual temperature of 12 °C was assumed for all WWTPs. The measurements for at least three years between 2019 and 2022 of daily discharge and temperature from the operating logs of seven WWTPs (size 2,000 to 95,000 PE) are available for further analysis.

2.1.2 Standardised annual profiles for temperature and dry weather flow

To generate standardised annual profiles, measurement data in daily resolution from the seven sample WWTPs was used. Since daily discharge is measured at the WWTPs, the daily dry weather flow was determined following [29] by applying the moving minimum method. Seasonal fluctuations in dry-weather flow are primarily caused by extraneous water, most notably groundwater infiltrating into the sewer from the surrounding soil. Time series analysis [30] identified daily deviations from average annual temperature and dry weather flow for each sample WWTP.

The daily deviations in temperature were approximated using a sine function. The dry weather flow curves from the time series analysis were smoothed using a generalised additive model (GAM) followed by Fourier approximation. The fitted profiles from the seven WWTPs were averaged arithmetically to derive a standard annual profile for both temperature and dry-weather flow.

2.1.3 Heat extraction potential of wastewater treatment plants

The daily heat *extraction* potential $\dot{Q}_{WW,d}$ from wastewater was calculated from the daily dry weather flow $\dot{V}_{WW,d}$:

$$\dot{Q}_{WW,d} = c_{p,W} \cdot \rho_W \cdot \dot{V}_{WW,d} \cdot \Delta T_{WW,d} \tag{1}$$

The specific heat capacity and density of the water were assumed to be constant at $c_{p,W}$ = 4.19 kJ/(kg·K) and at ρ_W = 1000 kg/m³. The maximum temperature difference $\Delta T_{WW,d}$ by which the wastewater is cooled at the HP evaporator in regular operation was assumed to be 7 K [31]. To prevent ice formation at the HP evaporator, the minimum temperature of the wastewater after cooling must be limited. While a currently commonly used limit is 4 °C [16], temperatures down to 1 °C seem technically feasible. If the temperature would undercut this limit, the achievable temperature difference $\Delta T_{WW,d}$ was constrained accordingly.

2.2 River heat utilisation

Critical parameters for the thermal potential of river HPs are flow rate and water temperature. The flow rate essentially determines the available heat extraction capacity, while the temperature determines the coefficient of performance (COP) of the HP and the availability of the heat source in winter. Since rivers are also an important habitat for many animal and plant species, ecological aspects must be considered when planning river HPs.

2.2.1 Selection of relevant river sections

The course of all Hessian rivers, including catchment areas and kilometre markers, was taken from data based on the 1:25,000 digital landscape model (DLM25) [32]. Values for the MLQ at approx. 100 measuring points were extracted from [33], [34] and [35]. These measured values of MLQ were interpolated along the river courses according to the respective catchment area of each river kilometre.

Based on [22], a MLQ of 0.5 m³/s or higher was considered suitable for river heat utilisation, taking ecological aspects into account. The heat *extraction* potential from watercourses was only evaluated for municipalities in which part of the river lies outside Fauna-Flora-Habitat (FFH) areas and protected biotopes, using geospatial data from [36].

2.2.2 River temperature data

Data for daily average water temperature were obtained for a total of 111 stations (data sources: [37], [33]). Where available, data from 2000 to 2024 was considered. The data was checked for plausibility (drop: values ≤ 0 °C, repeated values, sudden temperature jumps and significant deviations from seasonally expended value). In total, about 500.000 data points were analysed, of which 8 % were dropped due to the aforementioned criteria. Gaps were filled based on local daily average air temperature (data from [38]) using a moving average approximation with exponentially decreasing weighting. Finally, the measured values were interpolated linearly along the rivers between the measurement stations considering the distance to the measuring points and, if applicable, the amount of discharge of the measuring points located upstream.

2.2.3 Heat extraction potential of rivers

For each municipality located along one of the selected rivers, the heat *extraction* potential was determined under the following assumptions and boundary conditions:

- There is exactly one extraction point per municipality (simplified assumption to avoid excessive cooling due to multiple extractions and distribute the potential across all municipalities along the river).
- Water temperature data from 2021 is used (cold year to get a conservative result).
- Water temperatures are reduced by 0.5 K to account for previous heat extractions.
- The extraction volume flow corresponds to 10 % of the MLQ. At rivers that constitute the border of Hesse (Rhein, Neckar and Weser), this extraction volume flow is halved to take heat extraction from the respective neighbouring federal state into account.
- The extracted water is usually cooled by 5 K.
- Extraction is restricted or completely stopped if the river cools down too much:
  - Minimum temperature of extracted water after heat extraction: 1 °C
  - Minimum temperature of watercourse after mixing: 3 °C

The daily heat *extraction* potential $\dot{Q}_{R,d}$ for one river section was calculated with specific heat capacity $c_{p,W}$ = 4.19 kJ/(kg·K), density of the water ρ_W = 1000 kg/m³ and mean low flow volume flow rate $\dot{V}_{\mathrm{MLQ}}$:

$$\dot{Q}_{R,d} = c_{p,W} \cdot \rho_W \cdot 0.1 \cdot \dot{V}_{\mathrm{MLQ}} \cdot \frac{(24 \cdot 3600)\mathrm{s}}{\mathrm{d}} \cdot \Delta T_{R,d} \quad (2)$$

The daily possible temperature difference at the HP evaporator $\Delta T_{R,d}$ was calculated using the daily average water temperature $T_{R,d}$ of the river section, considering the above-mentioned boundary conditions.

2.3 Simulation of heat extraction from rivers

The extraction of heat from rivers reduces their temperature, which can be tolerated within certain limits. However, numerous heat extractions along the river could lead to an impermissible cooling. The reduced water temperature regenerates due to energy exchange processes with the environment and inflowing (uncooled) water. Therefore, a simple model for rivers was developed to simulate heat extraction and regeneration and verify that the cooling stays within acceptable limits.

2.3.1 Model description

None of the available models for river flow and temperature is suitable for representing the requirements and boundary conditions of this research. Computational fluid dynamics models are much too detailed for the research objective (effort for parametrization and computation for a whole river), although a use case found in the literature is the simulation of temperature stratification in river weir pools ([39], using the “Princeton Ocean Model”). Another class of models are water balance models, that may include temperature calculation, such as “LARSIM” [40]. As their focus is on water balance, such models require a profound parametrization concerning the land and soil properties, while the temperature calculation remains quite basic. Finally, there are simple 1-D models for rivers such as SNTEMP [41] and the similar SSTEMP [42]. Although these models are quite close to meeting the requirements being rather simple 1-D river model with a focus on water temperatures, they still need too many input parameters (e.g. detailed information about vegetation on the river banks). Thus, a new model was developed to validate the calculated heat *extraction* potentials. The model structure and the calculation of the energy balance are based on existing models [40,42] and publications [43–46].

Our stationary 1-D node model reproduces the course of the river as a chain of perfectly mixed control volumes for which the energy balance is calculated (Figure 1). The spatial resolution can be freely selected (1 km in this research). For each node, the model first calculates the total volume flow and the mixing temperature from the inflows with their respective volume flows and temperatures. The energy balance for all relevant energy exchange processes on the surface (short- and long-wave radiation, sensible and latent heat transfer and potentially heat extraction by HPs) is then calculated and the temperature change of the water is determined. Heat exchange with the riverbed is low in comparison to the other heat transport processes and is thus neglected [47]. Finally, the new temperature of the total volume flow is calculated, which then becomes the inflow for the river section below.

The heat transport processes scale with the river surface and depend on the water temperature and environmental parameters (air temperature, humidity and pressure, as well as wind speed, cloud cover and global radiation). In addition, the shading of the water plays an important role for short-wave radiation.

The stationary model uses daily average values. Due to the model and calculation structure, it is not necessary to iteratively approximate the solution. This enables fast calculation, so that numerous river sections can be simulated over longer periods of time. However, the model is not suitable for calculating temperature profiles within a single day. Since the model also does not contain any storage terms, it immediately delivers significantly different results in the event of sudden changes in environmental conditions (weather changes), whereas in reality, the storage capacity of water and the riverbed cause a dampened temperature change.

2.3.2 Verification of heat extraction potentials

The new model was applied to simulate the Nidda River for the year 2021, assuming that the full heat *extraction* potential is utilised, to assess cumulative cooling and water temperature regeneration. Figure 2 shows the course of the river in the simulated area (about 50 km in total) with five heat extraction locations.

The measured temperatures and volume flows were applied to the tributaries in the simulated area. Additional tributaries were also applied along the route so that the volume flows at the measuring points in the area corresponded to the respective measured values. The weather parameters were applied as daily averages (data from [38]). The width of the river was determined from a simple approximation based on the square root of the MLQ for each model node. A scenario without heat extraction and one with heat extraction were calculated

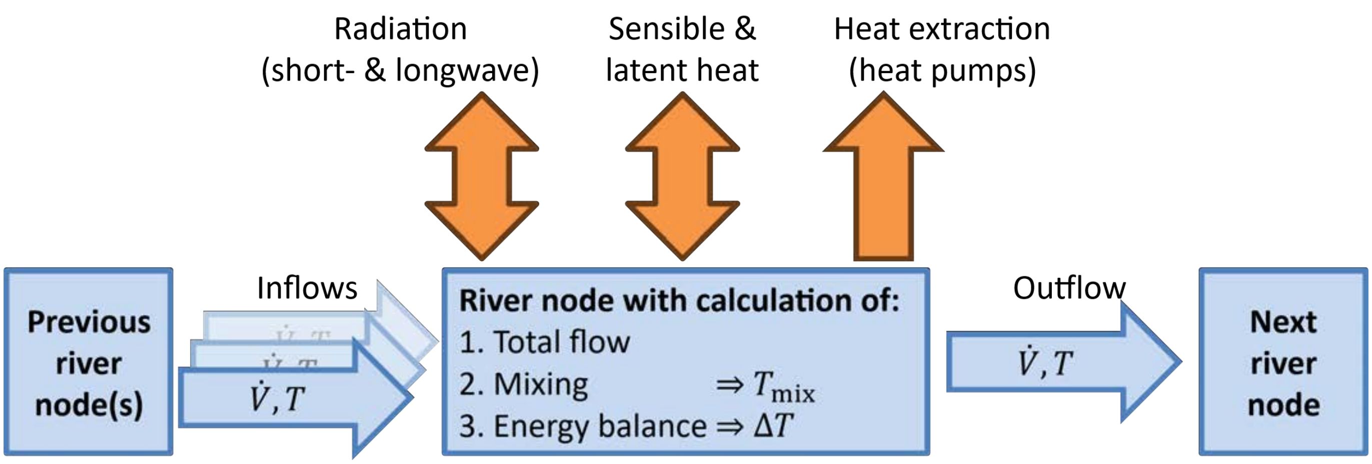


Figure 1: Schematic representation of the new stationary 1-D node model for river water flows and temperatures.

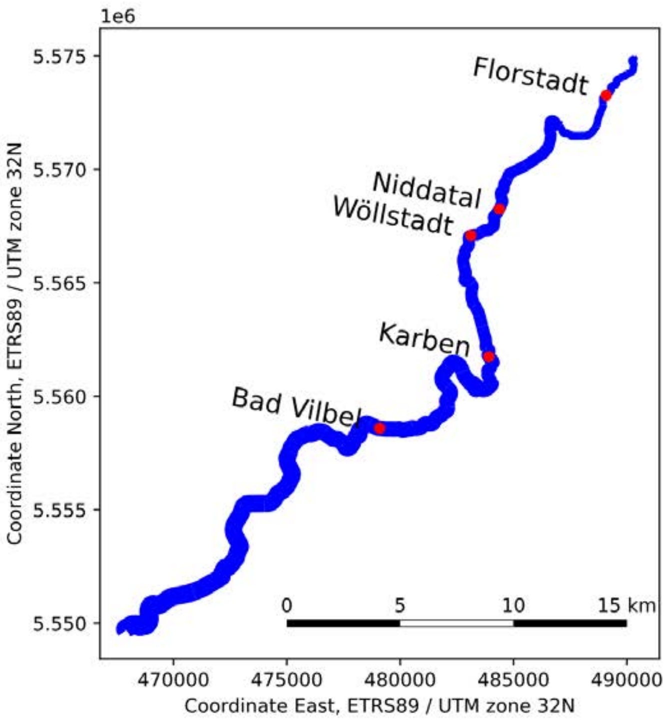


Figure 2: River Nidda with simulated heat extraction locations.

to evaluate the cooling effect compared to the undisturbed state.

2.4 Usable heat potentials

To assess what proportion of the identified heat extraction potential can be utilised, a comparison was made with the heat demand in areas suitable for heating networks.

2.4.1 Spatial and temporal analysis of heat demand

The heat demand in 2045 of all 421 municipalities in Hesse was provided by the Hessian heat atlas, accounting for projected reductions due to building renovations [48]. The demands are based on building-level modelling (type, age, geometry). The heat demand for 2045 (target year for achieving greenhouse gas neutrality in Germany) was used to be able to assume that the identified DH areas will remain economically viable for DH in the long term and to take into account the fact that the implementation of heating networks on a larger scale takes several years. The annual specific heat demand aggregated to building-block-level was used to identify areas suitable for DH using the heat density criteria. Two thresholds typically used in municipal heating planning were analysed, to represent a realistic demand range for DH areas [49]. There are approximately 45,520 ha of settlement areas with heat demand densities above 175 MWh/(ha·a), corresponding to a total demand of 13 TWh/a. Areas exceeding 415 MWh/(ha·a) comprise around 5,429 ha with a total demand of 3.4 TWh/a. According to the heat atlas, the total demand in Hesse for 2045 is 26.2 TWh/a.

The Hessian Heat Atlas classifies each building as either residential or non-residential, with non-residential buildings predominantly belonging to the commercial, retail, and service sector [48]. Residential buildings with a current heat demand of over 50 MWh/a were considered multi-family homes according to [50]. Daily heat demand profiles were derived for each municipality for the two heat demand density thresholds. This was achieved using characteristic functions (combination of linear and sigmoid) for ambient temperature dependency of the heat demand of the three consumer types single family homes (Type EF33), multi-family homes (Type MF33) and commercial, retail and service properties (Type GHD33) based on [51].

The analysis was based on the average daily heat demand, implicitly assuming that the heat supply system includes a heat storage that can balance out peaks in demand throughout the day. DH network losses were estimated to be 15 % of the heat transported. Since the heat atlas provides weather-independent heat demands, heating degree days were used to adjust for weather conditions in the year under review, 2021 [52].

2.4.2 Heat pump modelling

To determine the sink temperature T_{DH} of the HP, a newly constructed DH network with a supply temperature of 70 °C was assumed for ambient temperatures above 10 °C. In colder weather, the supply temperature was assumed to be raised linearly to 80 °C at an ambient temperature of - 10 °C (Figure 3). This temperature level was chosen, because it allows to connect existing buildings that rely on these temperatures for peak load heating or for fulfilling hygienic requirements in the hot water preparation and circulation. Due to the required temperature rise ΔT_{HP} of approx. 55 to 75 K, a HP with a two-stage compressor using the natural refrigerant ammonia was considered. The COP of the HP depends on ΔT_{HP} and was calculated using a model derived from real system data according to [53].

2.4.3 Matching demand and supply profiles

Daily heat demand was compared with the heat *extraction* potential. Wastewater potential was prioritized (if a suitable river and WWTP are available) due to typically higher wastewater source temperatures during the heating period. The daily difference between demand and wastewater heat extraction potential was calculated; if insufficient, river potential was considered. The portion of demand that cannot be supplied is referred to as residual heat demand.

3. Results

The following section presents the results of determining the potentials of utilising heat from wastewater and rivers in Hesse.

3.1 Heat extraction potential

In this section the results of calculating the heat *extraction* potentials are shown.

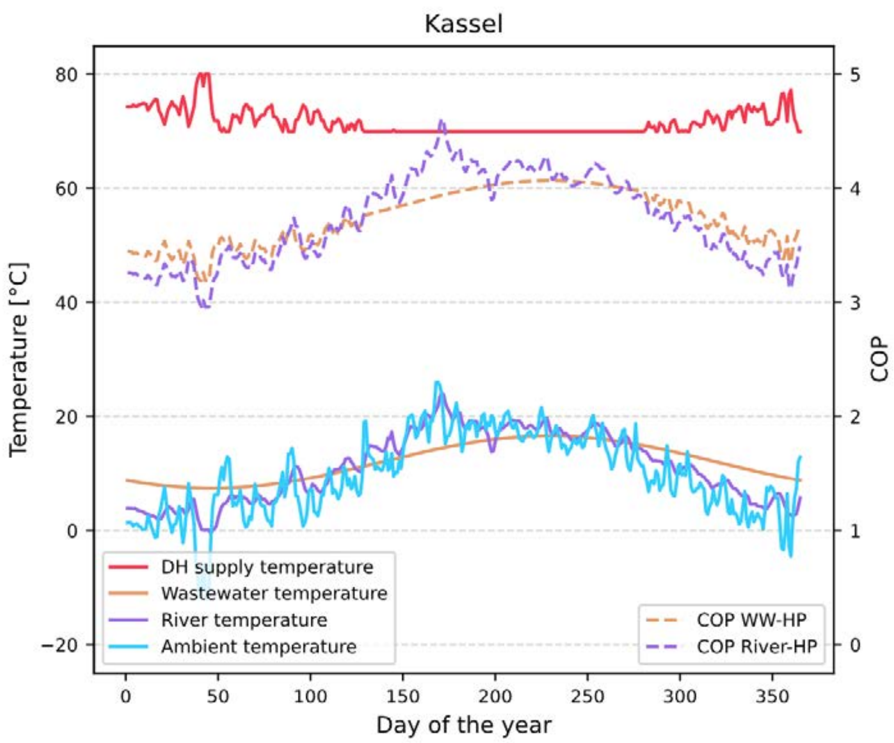


Figure 3: Daily average values for source temperatures, sink temperatures, ambient temperatures and COPs of river and wastewater HPs over the course of a year for the city of Kassel.

3.1.1 Heat extraction potential at wastewater treatment plants

As a result of the evaluations, the annual profile of the wastewater temperature $T_{WW,d}$ can be described by a sine function depending on the day of the year *d* and the annual average temperature T_{aM}:

$$T_{WW,d} = -4,6 \cdot \sin\left(2 \cdot \pi \cdot \frac{(d+44,52)}{365}\right) \cdot T_{aM} + T_{aM} \quad (3)$$

Analogous the standard profile for the daily dry weather flow $\dot{V}_{WW,d}$ can be described by the following function, depending on the average annual wastewater volume $V_{WW,a}$ and the day of the year *d*:

$$\dot{V}_{WW,d} = \begin{pmatrix} 0.000 + 0.2253 \cdot \sin\left(2\pi \cdot \frac{d}{365}\right) + 0.1597 \cdot \cos\left(2\pi \cdot \frac{d}{365}\right) \\ + 0.0656 \cdot \sin\left(4\pi \cdot \frac{d}{365}\right) + 0.0201 \cdot \cos\left(4\pi \cdot \frac{d}{365}\right) \end{pmatrix} \cdot \frac{V_{WW,a}}{365} + \frac{V_{WW,a}}{365} \quad (4)$$

The profiles for each of the seven sample WWTPs and the derived standard profiles as mean of the seven WWTPs are shown in Figure 4.

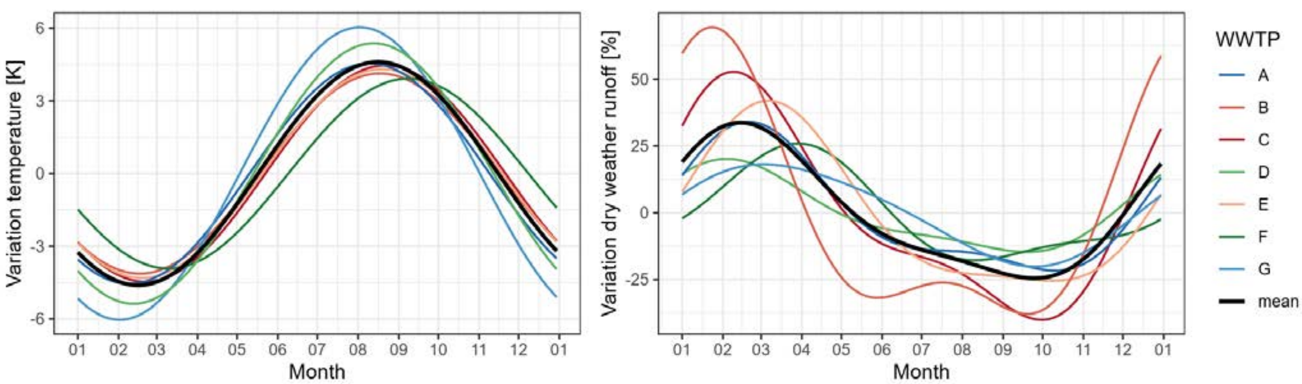
While the temperature of wastewater is higher in summer than in winter, high dry weather flow occurs mainly in winter (Figure 4). This opposing seasonality attenuates the seasonal fluctuation in heat *extraction* potential.

As validation, for the seven example WWTPs, the heat *extraction* potential calculated using the standard profiles was compared to values calculated using the measurement data for wastewater temperature and dry-weather flow. Figure 5 shows the comparison for two sample WWTPs. A significant variance in the wastewater heat extraction potential is observed when comparing individual years.

By smoothing flow peaks driven by extraneous water, the methodology systematically underestimates the heat *extraction* potential of WWTPs compared to the measurement-based values in winter. The assumed average wastewater temperature of 12 °C implies an underestimation of the potential for WWTPs with a higher average temperature.

Figure 6 shows the influence of the average annual wastewater temperature on the heat *extraction* potential calculated using the standard profiles for an average dry weather flow of 10,000 m³/d. At higher average wastewater temperatures, a decrease of the limitation of the potential in the cold months due to the temperature limit after cooling (here: 4 °C) can be observed.

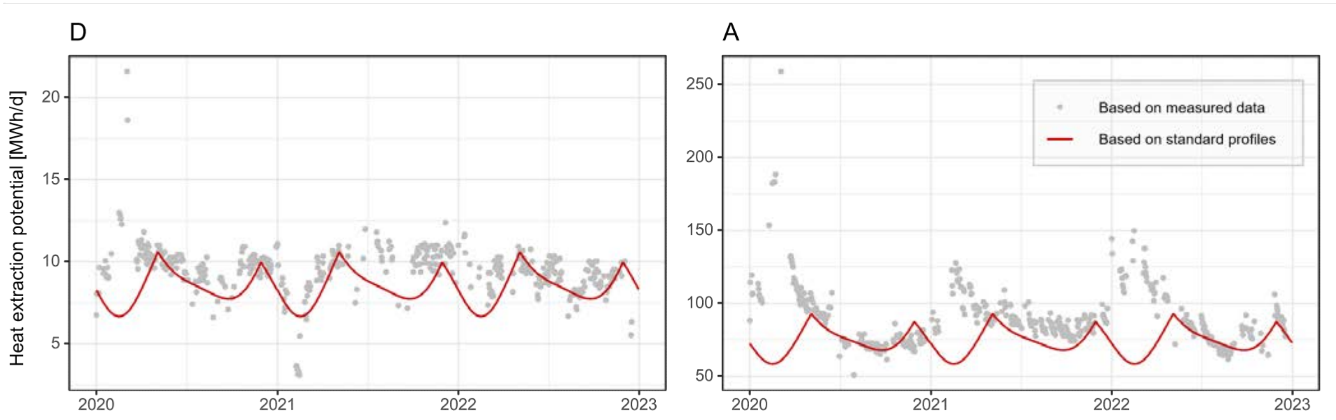
Figure 7 shows the cumulated heat *extraction* potential from wastewater in all Hessian municipalities. While the currently commonly used limit after cooling of 4 °C enables a total potential of 3.5 TWh/a, the technically feasible limit of 1 °C enables 4.2 TWh/a. The latter limit is used in the following for comparison with the heat



A

B

Figure 4: Profiles for the deviation of wastewater temperature (A) and dry weather flow (B) from the annual average for the seven WWTPs examined, as well as the arithmetic mean of the profiles as the standard profile used.



A B

Figure 5: Wastewater heat extraction potential based on measurements (grey dots) and standard profiles (red lines) for two WWTPs.

demand, to reflect the technically feasible potential. The potential is particularly concentrated in the municipalities with the largest WWTPs, with 37 % of the total potential attributed to the 10 municipalities with the greatest potential.

3.1.2 Heat extraction potential from rivers

25 rivers in Hesse (total length 1,467 km) are large enough to be considered for heat extraction. These rivers are situated in 173 of 421 municipalities in Hesse. Figure 8A shows the location of these rivers and provides an overview of their respective MLQ. Due to FFH and protected biotopes, 29 of 173 municipalities with sufficiently large watercourses (17 %) are excluded from the analysis (Figure 8 B and C).

The interpolated temperatures for two selected days and the location of the stations are shown in Figure 9. There is a significant spread of temperatures (4.5 K on 01.01.2021 and over 12 K on 30.06.2021) and a general trend that rivers become warmer with increasing size and are warmer in southern Hesse than in northern Hesse. The influence of two larger reservoirs (Diemelsee

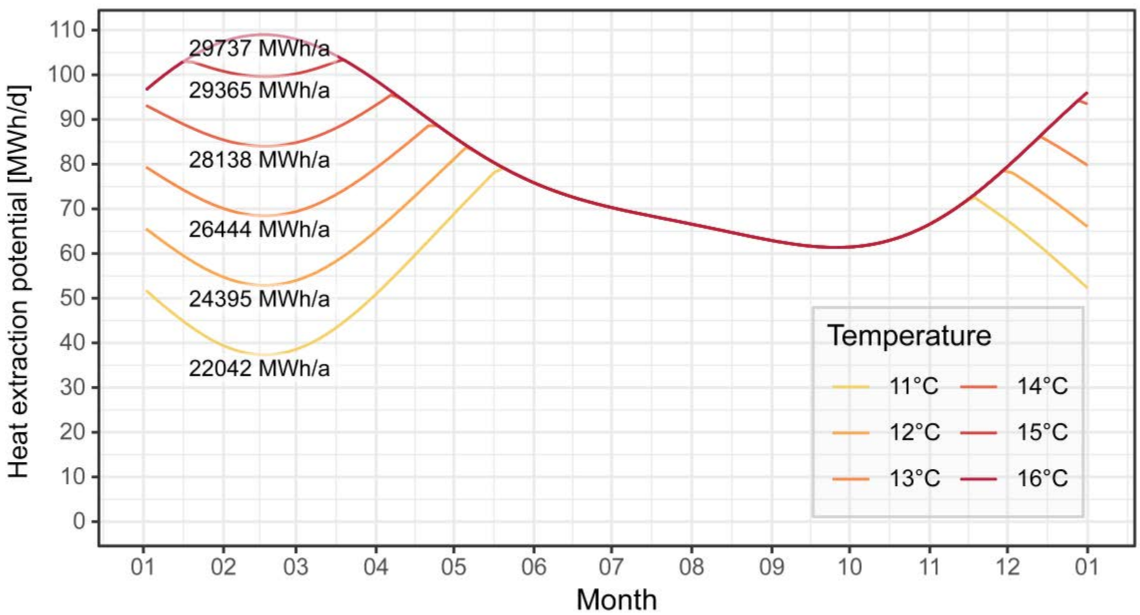


Figure 6: Influence of the average annual wastewater temperature on the wastewater heat extraction potential calculated using the standard profiles (average dry weather flow 10,000 m³/d, temperature limit after cooling 4 °C).

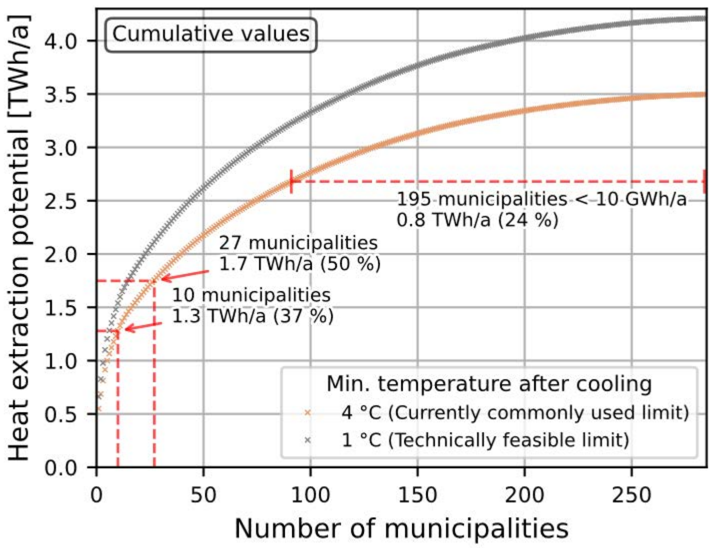
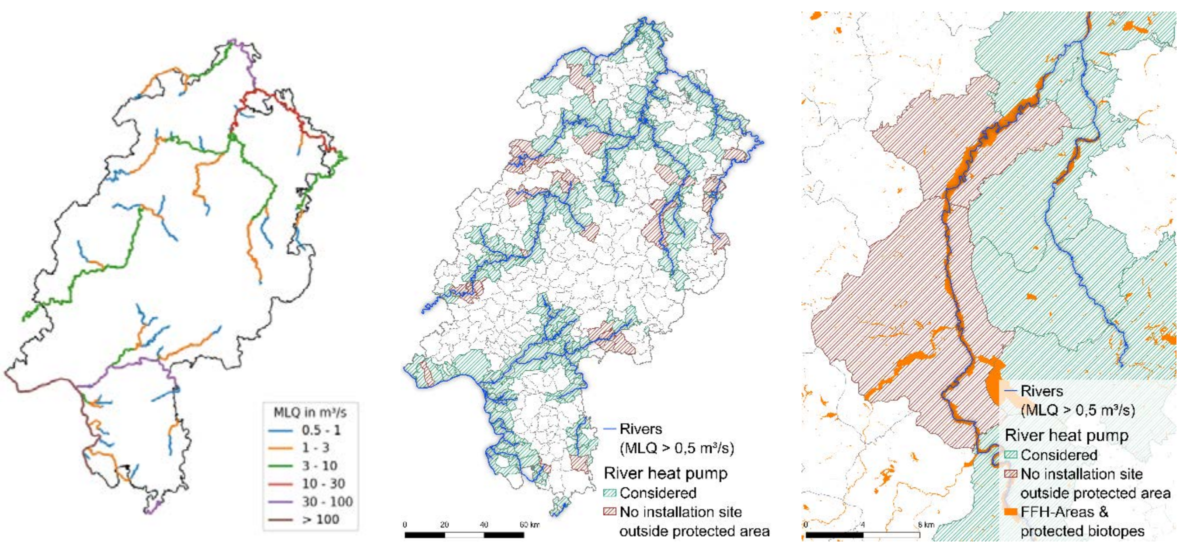


Figure 7: Cumulative representation of the distribution of the heat extraction potential from wastewater across municipalities.

and Edersee) with cold summer temperatures and warm winter temperatures is also clearly visible.

Over the course of the year, water temperatures generally follow a sinusoidal seasonal variation. However, the temperature curves for 2021 (Figure 10) for two different rivers reveal that there are also short-term fluctuations due to the weather and significant differences in temperatures between different watercourses. For example, in 2021 Fulda at Kassel (Northern Hesse, MLQ 20 m³/s) was significantly cooler than Main at Frankfurt (Southern Hesse, MLQ 60 m³/s), with this difference being particularly pronounced in summer.

The heat *extraction* potential from rivers was calculated for each suitable municipality as a time series with daily resolution. Since the MLQ was used for the calculation and not the current discharge, the



A B C

Figure 8: Selection of rivers based on minimum MLQ (A). Municipalities that are excluded due to FFH and protected biotopes (B) and detail view to demonstrate how FFH do in fact cover the entire river course within a municipality (C).

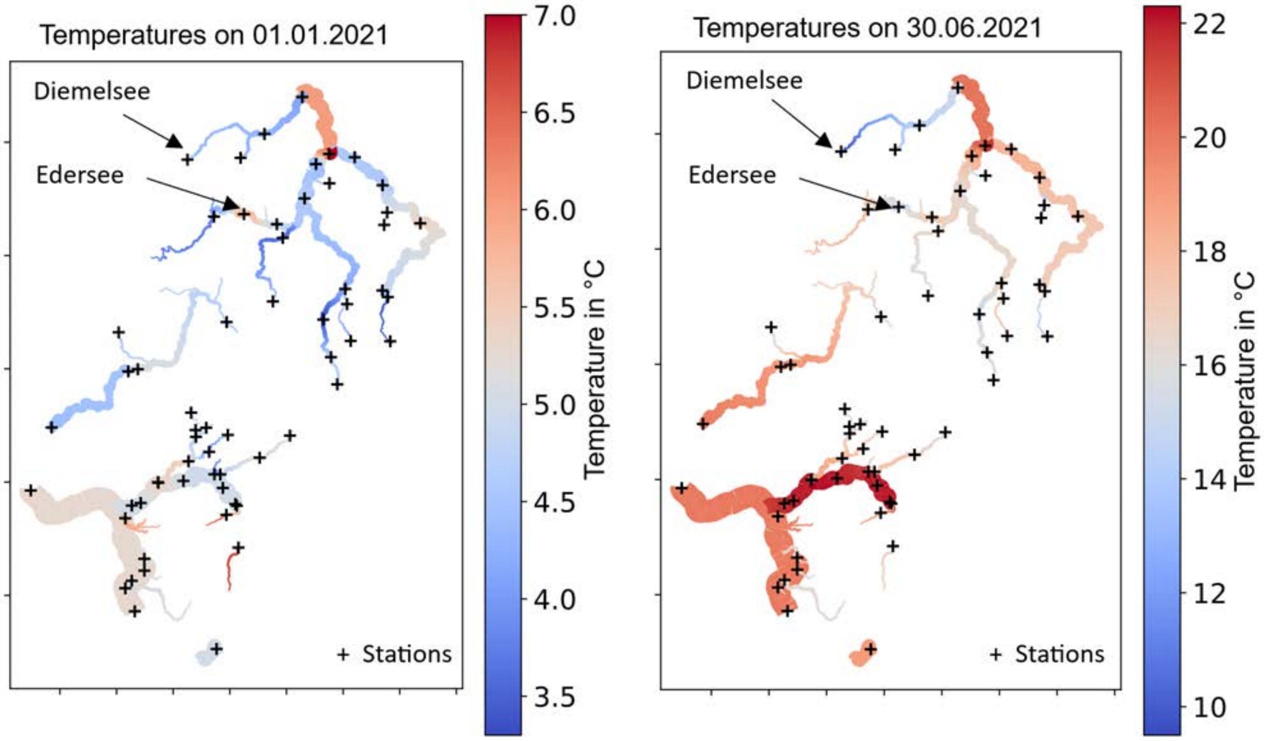


Figure 9: Measured and interpolated temperatures of rivers in Hesse for two exemplary dates.

extraction potential remains essentially constant throughout the year with a temporary reduction (down to 0 MWh/d) when the river water is too cold in winter (Figure 11). On median, the municipalities under consideration experience operational restrictions for 80 days and operational interruptions for 21 days during the year.

The total heat *extraction* potential from rivers in Hesse results to 111 TWh/a. A large proportion of this potential is attributable to the two largest rivers, Rhine and Main

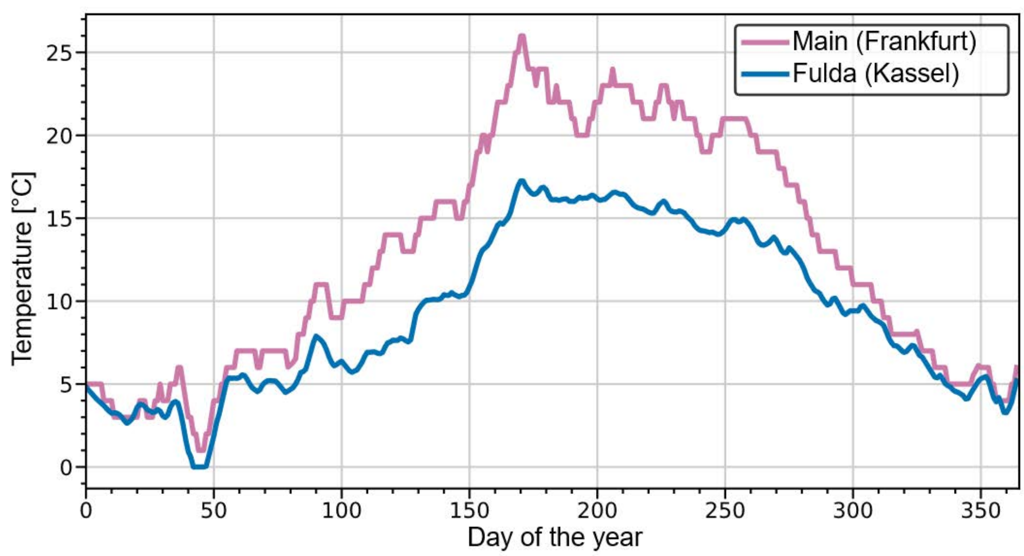
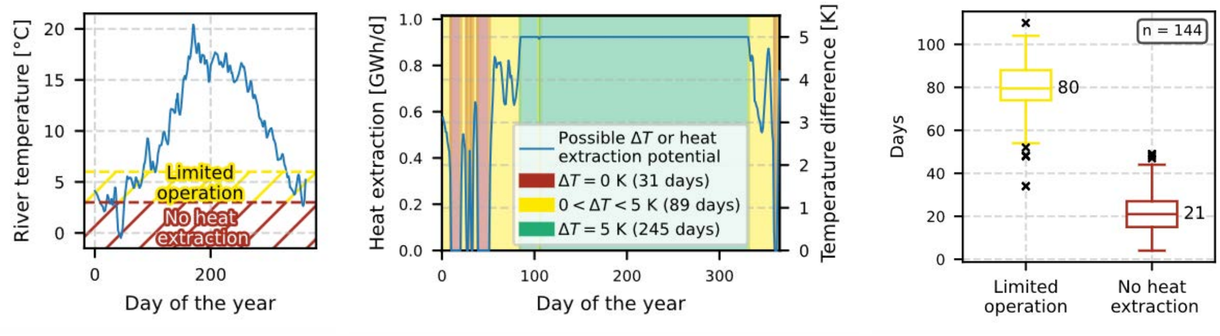


Figure 10: Water temperature profiles for two different rivers for the year 2021.



A B C

Figure 11: Annual river water temperature for an example river section (A). Annual variation in heat extraction potential (left axis) and the possible temperature difference at the HPs evaporator (right axis) for the same river section (B). Days with limited operation and interruption of operation across all Hessian municipalities with suitable river section (C).

(100 TWh/a, 90 %). For most smaller rivers, the heat extraction potential is in the single- to double-digit GWh range.

3.2 Simulation results of thermal regeneration of rivers

The simulation provides average temperatures for each kilometre of the river for each day of the year 2021. Figure 12 shows examples of the discharge (including MLQ for comparison) and temperatures of the river Nidda, along about 50 km downstream from the source to the mouth of the river. The simulations were carried out without and with heat extraction for two days along the simulated river course. The two major confluences Wetter and Nidder cause flow and temperature jumps. The temperature curve with heat extraction also shows clear downward jumps at the five heat extraction points. In both examples, cooling can be seen compared to the undisturbed state, which decreases downstream if no further heat is extracted.

The main difference between the two examples is, that Figure 12 A shows a situation with high flow, resulting in little cooling due to heat extraction, while Figure 12 B shows a day with very low flow, resulting in the highest cooling compared to the undisturbed state for the simulated year on that day.

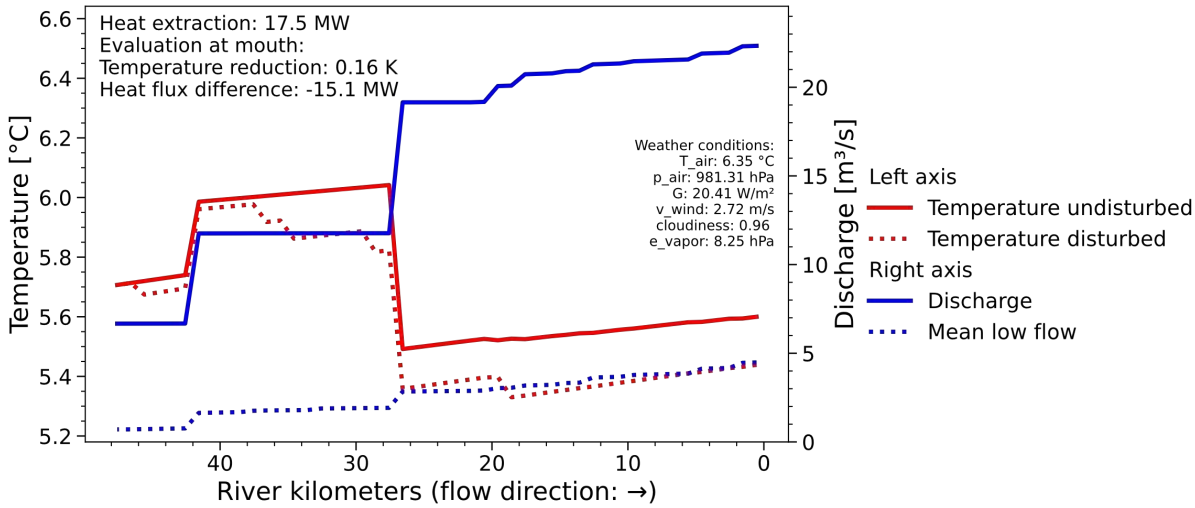
The cumulative cooling compared to the undisturbed state reaches a maximum value of -1.2 K when the heat *extraction* potential is fully utilised (Figure 13). This value occurs in October at a time when the discharges correspond approximately to the MLQ, i.e. are very low. This means that the maximum cooling that occurs is only about half of what would be expected if no regeneration was considered (five heat extractions with 0.5 K cooling each). This regeneration is partly due to inflowing water with a higher temperature than the cooled water.

However, a significant proportion of regeneration also occurs because the reduced water temperature influences the heat transfer processes with the environment in such a way that cooling is dampened. In the example evaluated for 10 October 2021 this means that with a total heat extraction of 19.3 MW, only a heat flow reduction of 10.1 MW can be observed at the mouth (Figure 12 B). Half of the heat extracted was thus regenerated by heat transfer processes with the environment. On days with higher volume flows, the cooling is significantly lower and therefore regeneration is also lower. However, as these days are characterised by low cooling anyway, the lower regeneration is not critical for the use of HPs.

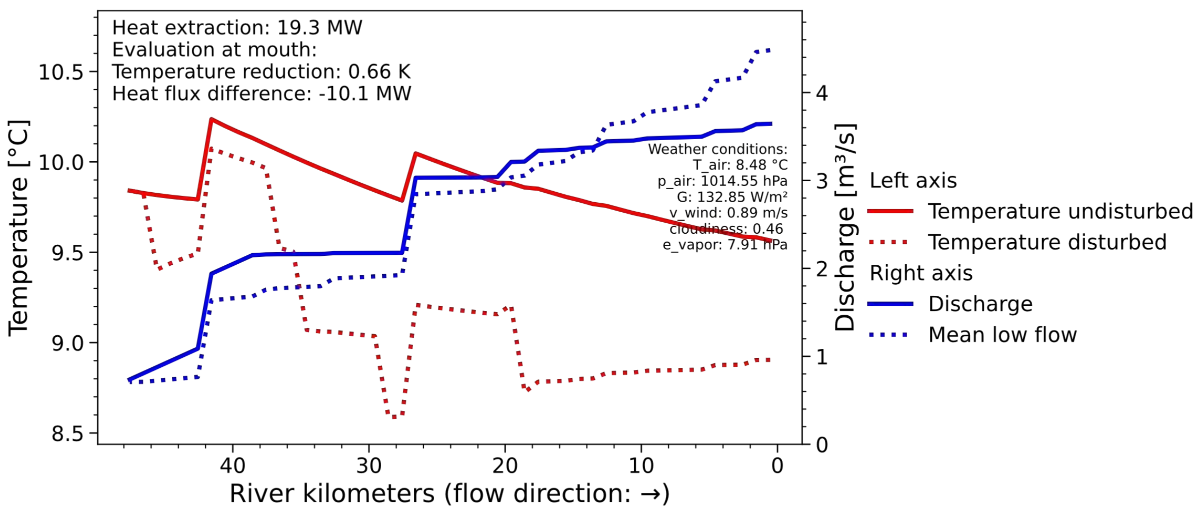
The simulation results show that, on average over the year, a maximum cooling of 0.39 K occurs immediately before heat extraction points, so that the assumption of 0.5 K cooling due to previous heat extraction seems conservative and therefore justified when determining the heat *extraction* potential.

3.3 Usable heat potential in municipalities

Figure 14 presents annual *usable* heat potential (daily resolution) from wastewater and rivers for one municipality, comparing demand-supply matching at the two considered heat density limits (> 415 vs. > 175 MWh/(ha·a)). Since the higher limit value covers a significantly lower proportion of the municipality's total heat demand, higher coverage rates are possible. While the usable potential of the wastewater HP shows only minor fluctuations, the



A



B

Figure 12: Temperatures and discharge of the river Nidda downstream from the source to the mouth of the river. Simulation result at high discharge in winter (A: 22.01.2021) and at lowest discharge (B: 10.10.2021). The graphs show flow rate and temperature (with and without heat extraction) along the section of the Nidda under consideration. The two large temperature jumps are caused by the confluence of major tributaries (Wetter and Nidder).

usable heat potential of the river HP is subject to periods of operational restrictions or interruptions.

Depending on the specific local conditions (size and availability of river and WWTP, level of heat demand), the potential coverage ratios for the heat sources under consideration can vary considerably (Figure 15). Due to higher source temperatures the wastewater HP have slightly higher SCOP values.

The evaluations yield usable heat potentials from wastewater and river HPs in Hesse as shown in Figure 16. While 84 % of the heat demand in building blocks with a heat demand density > 415 MWh/(ha·a) can be met through river and wastewater HPs, in the > 175 MWh/(ha·a) variant 56 % of the significantly higher total demand can be met. The *usable* heat potential from wastewater HPs is between 2.4 and

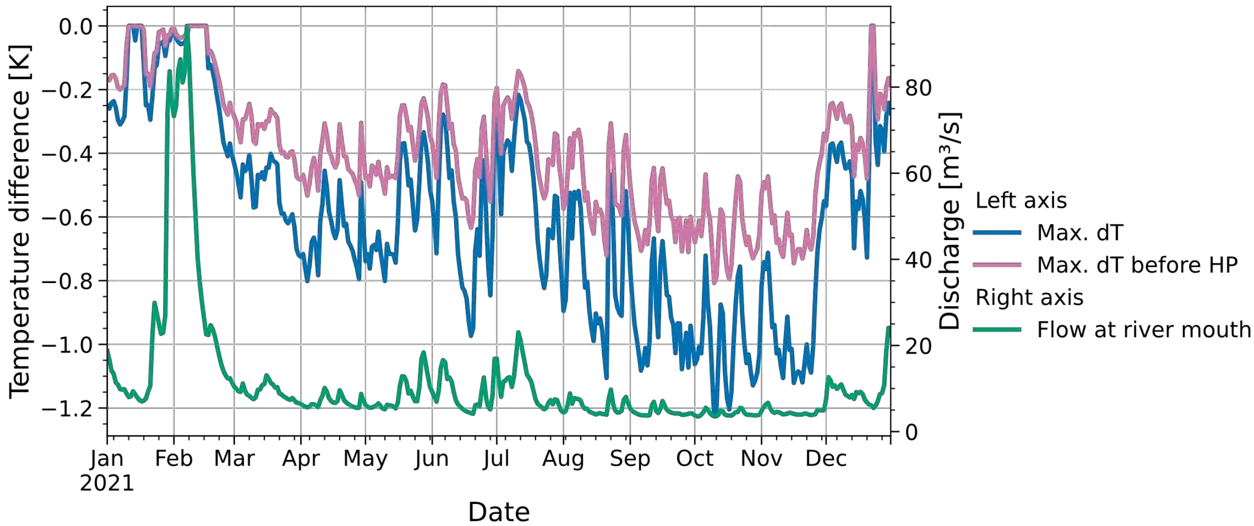


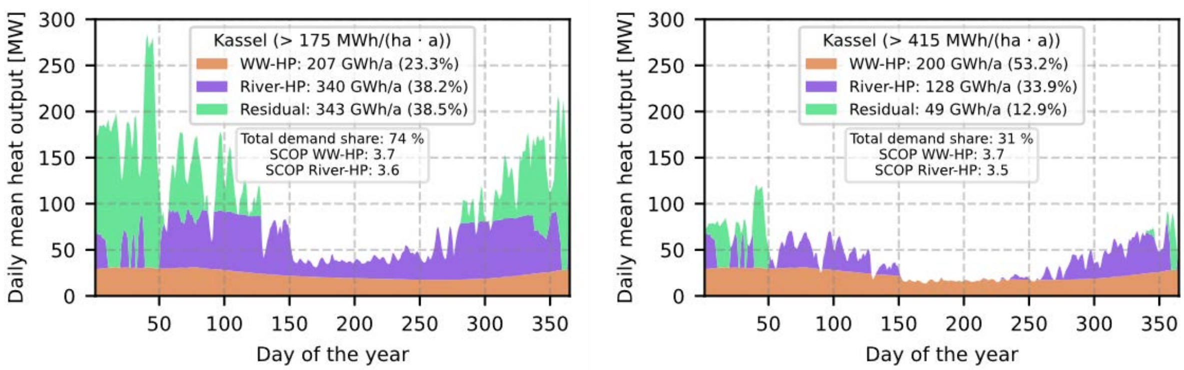
Figure 13: Simulation result for the maximum cooling occurring along the river Nidda due to heat extraction, shown before and after HPs. For better interpretation, the outflow at the mouth is also shown.

4.9 TWh/a and from river HPs between 1.3 and 4.5 TWh/a.

In 421 municipalities in Hesse, there are building blocks with a demand density of more than 175 MWh/(ha·a), with a large proportion of this demand coming from the larger cities (Figure 17 A). River HPs can contribute to heat supply in 144 municipalities (Figure 17 B) and wastewater HPs in 285 (Figure 17 C). In 65 municipalities neither of these two heat sources are available.

4. Discussion

When comparing the *usable* heat potentials with the heat *extraction* potentials, it should be noted that the HP (and thus the electrical energy) is included in the calculation of the *usable* heat potential. Nevertheless, in areas with a heat demand density > 175 MWh/(ha·a), a large part of the wastewater heat extraction potential of 4.2 TWh/a could be used as a heat source for the HP, as 4.9 TWh/a is provided by the HPs. In the case of rivers, however, a large proportion of the heat extraction potential of 111 TWh/a remains unused (usable heat potential: 4.5 TWh/a). While there is a direct correlation between population size, heat demand and WWTP size in a municipality, no such correlation exists for the size of the river in a municipality. Additionally, the heat extraction potential from rivers is available without restriction and in excess during the warm season,



A B

Figure 14: Seasonal heat demand compared with the extraction potential of river and wastewater for the city of Kassel. Two limit values for building block-related heat density of A: > 175 MWh/(ha·a) and B: > 415 MWh/(ha·a) are shown.

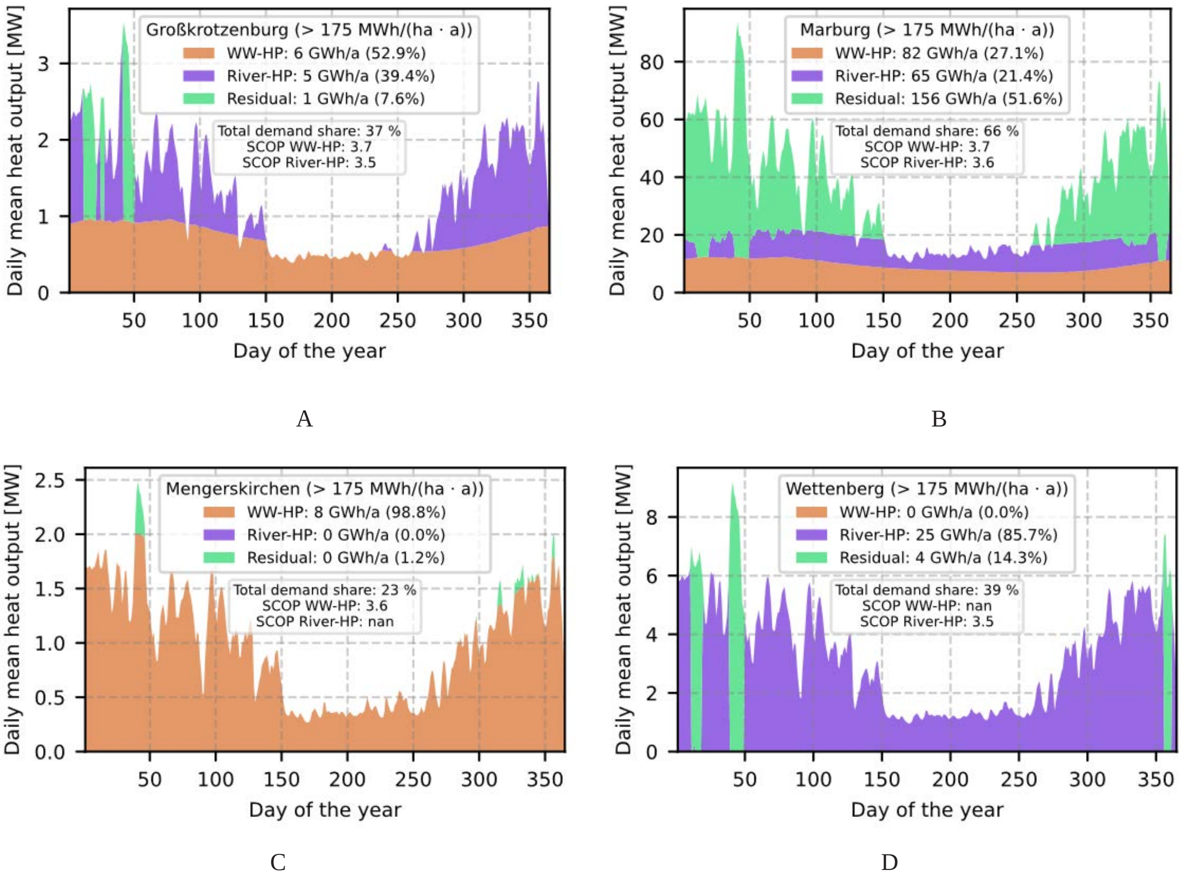


Figure 15: Seasonal heat demand (limit value for building block-related heat density of > 175 MWh/(ha·a)), compared with the extraction potential of river and wastewater for four municipalities. Shown are characteristic examples of: Almost complete coverage (A), high residual demand (B), only wastewater heat potential available (C) and only river heat potential available (D).

whereas during the cold season, when heat demand is high, restrictions may apply. In addition, the wastewater HP was prioritised in the order of use, which means that the base load in summer, when available, is always covered by the wastewater HP.

It is important to keep in mind that the methodology and assumptions are deliberately chosen to ensure conservative results, that are likely to hold true even under unfavourable conditions (e.g. in a cold year). This means that in warmer years higher water temperatures in rivers lead to a higher heat extraction potential. The number of days with operation limitations or even interruption is especially sensitive to this, as it results from sharp threshold values. This particular result should thus be interpreted as worst-case that must be considered when planning a heat supply system with river heat pump but should not be seen as the average number that will occur over several years.

The differences between heat *extraction* potentials and *usable* heat potentials show how important it is to consider heat demand in potential DH areas to assess the utilisable potential. Particularly in municipalities with high possible coverage rates, the potential of the heat source cannot be fully utilised in summer.

4.1 Limitations

The WWTP model provides a robust representation of the seasonal fluctuations of wastewater heat potential. However, several limitations introduce uncertainties in the potential estimates. Although the assumed average annual wastewater temperature of 12 °C offers a reasonable base for assessing the theoretical potential, individual WWTPs can be characterized more accurately using

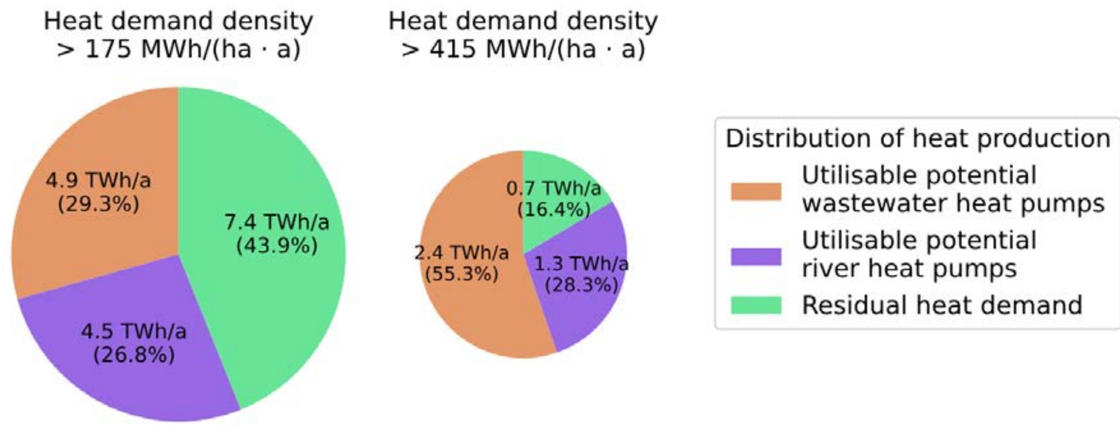


Figure 16: Possible coverage shares of the heat sources river and wastewater from the heat demand of the building blocks with a heat demand density > 175 MWh/(ha·a) or > 415 MWh/(ha·a).

site-specific average temperatures. While the standard profiles derived from seven WWTPs capture general trends in seasonal fluctuations, they cannot quantify correlations between seasonal fluctuations and plant-specific factors that influence dry weather flow and temperature (e.g., extraneous water, industrial discharges), leading to uncertainty for WWTPs with extreme conditions.

When calculating the potential for river HPs, the quality of the available data represents a source of uncertainty. River temperature data may contain errors due to improper sensor calibration or poor representation of mean temperature (especially at low flow velocities). These uncertainties may potentially cause random over/underestimations of winter HP availability, as the operation limitations are very sensitive to minor temperature changes. However, the random nature of these errors suggests the medians of limited or restricted operation and the overall heat extraction potential remain unaffected. An uncertainty in the exclusion of protected areas was that the available geospatial data, especially for protected biotopes, is outdated (last update 2006).

The Hessian heat atlas underestimates heat demand and densities due to incomplete commercial, trade &

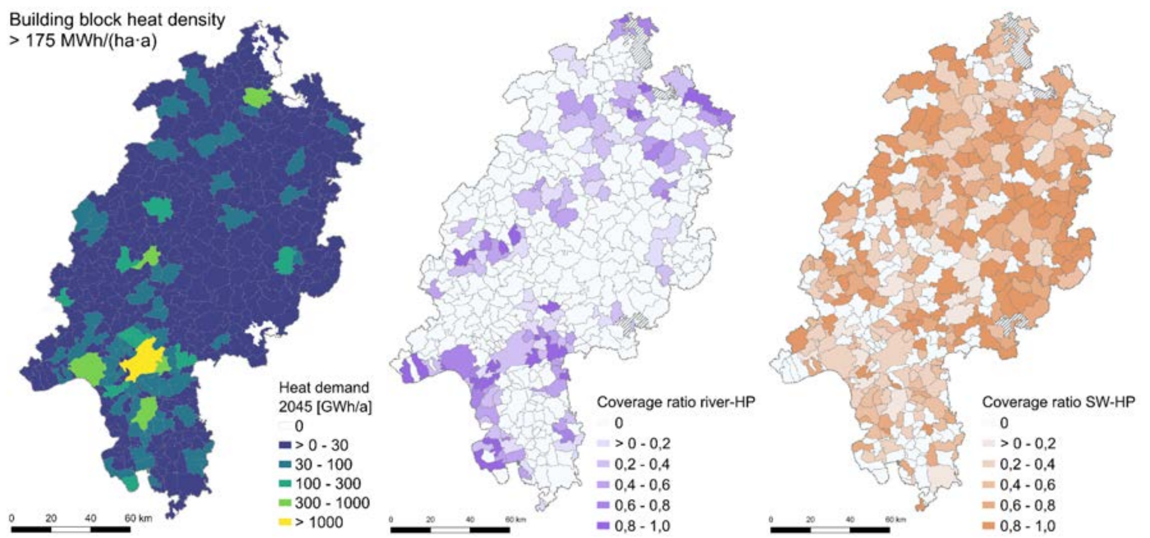


Figure 17: Total heat demand of building blocks with demand density > 175 MWh/(ha·a) in all Hessian municipalities (A). Possible share of this demand covered by river HPs (B) and wastewater HPs (C).

services sector data and excluded industrial sector data [48]. Demand estimation for residential buildings via typology is also associated with inaccuracies. For detailed heat planning or even project development, it is important to collect data on heat consumption locally.

The method for identifying DH network areas based on heat density thresholds is approximate, since the spatial location of these areas was not examined in detail. This likely leads to overestimation of DH network coverage, as single DH networks may not serve all areas in a municipality, counteracting the Hessian heat atlas's demand underestimation.

The study assumes feasible connections between heat sources and demands without considering the spatial localisation within the municipalities in detail. This study also did not consider whether and to what extent existing DH networks already exist in the individual municipalities, as there was no comprehensive data available.

Although river and wastewater heat pumps were the only heat sources considered in this study, they are often expected to be used as part of a complex system consisting of various heat sources and storage units. This creates further opportunities and challenges that could not be considered in this large-scale study. For instance, existing district heating networks in larger cities frequently incorporate waste incineration plants. As their primary function is waste disposal, these plants produce a relatively constant amount of heat throughout the year. This covers at least part of the summer base load in such networks, reducing the economic efficiency of an additional heat pump. Furthermore the combination with seasonal storage would enable the transfer of otherwise unused extraction potential from the warm season to periods of high heat demand.

4.2 Further research

This study meets its objective of characterizing the substantial theoretical wastewater heat potential of WWTPs in Hesse, accounting for seasonal variations throughout the year. Nevertheless, the model offers scope for further refinement, particularly through a more detailed examination of the relationship between the proportion of extraneous water and seasonal fluctuations in dry-weather inflow. Pilot projects with scientific monitoring should be initiated to validate the assumptions made and further improve the wastewater potential estimates.

The estimation of the heat extraction potential from rivers directly depends on the assumption about the permissible extraction volume flow. In this study 10 % of MLQ was chosen, which is an amount that is always available and is expected to have no negative ecological effects [22]. Our exemplary simulation of the river Nidda (see section 3.2) shows that at this river this heat extraction does not lead to excessive accumulative cooling. Extracting a higher volume flow results in a higher heat extraction potential but entails a greater risk of unacceptable cumulative cooling. Thus, the potential assessment can be improved with a simulation of all rivers under consideration with their actual discharge and heat balance under given weather and heat extraction circumstances. This way, the permissible extraction volume flow rates could be derived for each municipality individually, while ensuring the cooling of the river stays within acceptable limits. Increased heat extraction potentials in the municipalities are expected, as during times with discharge well above the MLQ, higher heat extraction will be acceptable. Wherever the simulation might reveal conflicts of river heat utilisation between municipalities (unacceptable cooling), the model could be used to develop and evaluate strategies for fair and efficient usage of the limited potential. Furthermore, such a model can enable the authorities to monitor the cumulative effects of repeated heat extraction from the same river in the future and base decisions about additional river heat pumps on this insight.

The heat demand-source matching can be improved compared to the method based on building block heat density by designing heating networks. Therefore, algorithms based on graph theory can be used to optimize pipe routing, utilising building-specific consumption data while meeting minimum thermal line density requirements to ensure economic feasibility. Additionally, research on criteria for automated river HP location selection is needed.

5. Conclusion

HPs at WWTPs and rivers can significantly contribute to heating demand in areas suitable for DH in many municipalities. Such HPs could meet up to 28 % of the heat demand covered by the Hessian heat atlas, considering the entire heat demand all building blocks with heat density of more than 175 MWh/(ha·a). This is reduced to 11 % when only blocks of more than 415 MWh/(ha·a) are included, while in this case the coverage ratio in the potential DH areas of the individual municipality often increases.

Depending on the load scenario, the *usable* heat potential ranges from 2.4 to 4.9 TWh/a for WWTPs and 1.3 to 4.5 TWh/a for rivers. However, the availability varies greatly from place to place. While three quarters of municipalities have a WWTP where a HP could be installed, only one third has a suitable river section.

Although the specific results apply for Hesse, we are confident that general trends hold true for other areas with similar boundary conditions (climate, population density, housing structure) and that the methods can be applied to any other area.

Standardised profiles for the annual variation in wastewater temperature and flow rate were created to determine the heat *extraction* potential from wastewater. These are well suited for an initial assessment of potential. For detailed planning, measurement data is preferable.

One challenge for the operation of HPs in flowing waters are the periods of restricted operation (median: 11 weeks) or even operational interruptions (median: 3 weeks), during which other heat generators must be available as back-up due to low water temperatures. The application of a novel thermal 1D simulation model to an example showed that, under the assumed design boundary conditions, no critical cooling of the flowing water is to be expected because of multiple heat extractions along the river.

Acknowledgements

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