Environmental Science
Water Research & Technology

PAPER

View Article Online
View Journal | View Issue

Cite this: *Environ. Sci.: Water Res. Technol.*, 2021, 7, 1760

The heat recovery potential of 'wastewater': a national analysis of sewage effluent discharge temperatures†

M. P. Wilson * and F. Worrall

Final sewage effluent (FSE) is typically warmer than the rivers it is often discharged to. The excess heat energy could be recovered and utilised to help meet climate change targets. Using data from England for 2000–2019, we show that FSE temperatures were on average 2.2 °C higher than river temperatures, with a corresponding annual heat recovery potential of ~18.3 TW h which could meet ~3.6% of the UK's heat demand. Crude sewage temperatures were on average 1.5 °C higher that FSE temperatures, implying that a further ~12.5 TW h is lost annually during treatment prior to discharge. The largest temperature differences between FSE and rivers, and crude sewage and FSE, occurred during the autumn and winter months, meaning that the greatest seasonal heat recovery potential coincides with the greatest heat demand. The temperature difference between FSE and rivers increased at an average rate of ~0.03 °C per year from 2000 to 2019. Therefore, and in addition to predicted population growth, wastewater heat is a growing resource. The largest temperature differences between FSE and rivers would generally be expected to occur in northeast England. However, FSE discharges with sufficiently large temperature differences between FSE and rivers were demonstrated to exist across England and were not restricted to one region or water company. Wastewater treatment works discharge effluent continuously and occur nearby to domestic settlements, which account for the majority of the UK's heat demand. Therefore, there is clear local potential to recover heat and meet national emissions targets whilst further reducing environmental impact on rivers.

Received 15th June 2021,
Accepted 16th August 2021

DOI: 10.1039/d1ew00411e

rsc.li/es-water

Water impact

Sewage effluent discharged from wastewater treatment works is warmer than river water. The excess heat could be recovered and used for low-carbon heating to help meet emissions targets, whilst also reducing thermal loading to rivers. This study is the first to estimate national scale heat recovery potential of sewage effluent, thereby highlighting a currently wasted sustainable warm water resource.

1. Introduction

Carbon dioxide emissions from the combustion of fossil fuels have led to, and are continuing to lead to, human-induced climate change.[1] To minimise the effects of climate change there is a need to drastically reduce global greenhouse gas emissions. Under the 2015 Paris Agreement, nations legally committed to reducing their emissions with the aim of achieving a climate neutral World by 2050.[2] Implementation of the Paris Agreement within each nation is self-determined, for example the United Kingdom (UK) has committed to reducing its annual greenhouse gas emissions by 100% by 2050 under an amendment to its Climate Change Act 2008,[3] but fundamentally, nations must exploit alterative low-carbon sources of energy for key areas such as heating. Heating accounts for over a third of the UK's greenhouse gas emissions. Although improvements in energy efficiency can be made, there is a need to decarbonise heat by switching from predominantly natural gas-based heating systems to low-carbon forms of heating.[4] Warm water is often considered a possible source of low-carbon heat energy and naturally occurring warm water from geothermal heat is exploited globally by humans for both power production and heating.[5] However, one potential source of warm water that has received limited attention to date, despite being an everyday waste product of human activity, is wastewater flowing to or discharging from wastewater treatment works (WWTW‡). These wastewaters are often warmer than ambient

Department of Earth Sciences, Science Laboratories, Durham University, Durham, UK. E-mail: miles.wilson@durham.ac.uk

† Electronic supplementary information (ESI) available. See DOI: 10.1039/d1ew00411e

‡ In this study we use the term 'wastewater treatment works' to encompass sewage treatment works (commonly abbreviated to STW) as well as those that treat other types of wastewater, for example industrial trade effluent.

air temperatures and the water bodies they are commonly discharged to,[6] thereby favouring the implementation of heat recovery systems.

Wastewater-source heat pumps date back to at least 1975: Obermeilen WWTW in Zürich, Switzerland.[7] As of 2008 Switzerland had 20 WWTW using treated wastewater for district heating and cooling.[8] One of the World's largest operational wastewater heat recovery plants is in Stockholm, Sweden, which annually produces 1235 GW h of heat from treated wastewater. This heat is used to heat 95 000 residential buildings.[9] Finland has also installed a heat pump system at its Lapua WWTW to recover heat from treated wastewater. The Lapua WWTW scheme is a 120 kW system and uses the recovered heat to heat the buildings of the WWTW, with estimated annual savings of €20 000 and a payback period of two to three years.[9] Scotland is currently delivering the UK's first treated wastewater-based district heat network in Stirling, which will provide low-carbon heat to several public buildings,[10] whereas in England a £120 million development is underway to heat two commercial greenhouses in Norwich and Bury St Edmunds, East Anglia, using recovered heat from the discharges of two WWTW.[11] An alternative method of wastewater heat recovery is to extract heat from sewers prior to entering WWTW. This approach has been taken in Vancouver, Canada, at the False Creek Neighbourhood Energy Utility. The utility began operation in 2010 and recovers sewer heat to provide space heating and hot water to 534 000 m^2 of residential, commercial and institutional space.[12] Similarly, in Sandvika, Norway, a heat exchanger in the main community sewer extracts heat which covers more than 50% of the energy consumption of the supplied office and residential buildings.[9] Scotland implemented the UK's first sewer heat recovery system in December 2015 at Borders College, Galashiels. The system now provides ∼95% of the heat demand of the college campus buildings.[13] Notably, many of the examples above are restricted to non-peer reviewed literature.

Wastewater heat recovery systems implemented in sewers or at WWTW discharge locations have their own advantages and disadvantages.[8,14] In sewers, wastewater temperatures may be higher than at discharge because of closer proximity to source, which is also an advantage in minimising heat loss before reuse. However, sewer flow rates are less consistent than WWTW discharges, wastewaters are much less clean which may negatively affect heat exchangers, retrofitting (and then maintaining) developed complex sewer networks would be a highly disruptive and costly activity, and temperature decreases prior to treatment might negatively affect biological processes within WWTW (a maximum cooling limit of 0.5 °C has been suggested).[8,15] Heat recovery from final sewage effluent§ (FSE) discharge may be technically easier and more commercially attractive, despite concerns of heat loss between WWTW and end-users. Furthermore, reducing discharge temperatures has the environmental benefit of minimising or eliminating thermal impacts to rivers. Temperature is considered a ‘master’ variable of water body quality and plays a fundamental role in controlling biological, chemical and physical processes within rivers.[16,17] River water temperature (referred to herein as river temperature) variations can control the growth rates of aquatic organisms,[18–20] the availability of food and nutrients,[21] and determine the spatial distribution of suitable habitats within a river.[22,23] To minimise the negative thermal impacts of FSE discharge to rivers, discharge temperatures are usually regulated. In England, FSE temperatures must meet conditions agreed in site-specific discharge permits, which usually take the form of a maximum compliance limit, which no temperature sample should ever exceed,[24] and a risk assessment to ensure water quality of the receiving water body does not deteriorate and that it meets its target quality standard.[25] Temperature standards for rivers in England allow a 2 or 3 °C increase or decrease in relation to ambient river temperatures, as an annual 98 percentile, from surface water discharges (Table S1†).[25] Therefore, although discharge temperatures are strictly regulated, FSE discharges are typically warmer than river temperatures and so have an environmental impact. Furthermore, temperature regulation implies that effluent temperatures might be higher and are suppressed prior to discharge.

Despite growing global interest in wastewater heat recovery, focus has been primarily on application to single WWTW or particular urban areas, with examples largely limited to technical reports or non-peer reviewed literature. To meet required emissions targets, nations need to consider the application of low-carbon technologies across multiple locations and thereby assess national potential. To date, no publications in peer-reviewed scientific literature have investigated national-scale treated wastewater heat recovery potential and the only technical report we are aware of is for Switzerland, which showed that ∼2 TW h of Switzerland's annual heat demand could be provided by wastewater heat recovery.[8,26] However, the study is only available in German and was only possible because of the provision of private discharge and temperature data for 296 WWTW. An annual 20 TW h of sewer heat recovery potential in the UK has been claimed,[14] but this was only based on a seemingly arbitrary heat recovery temperature of 3 °C. Considering the advantages of FSE heat recovery over sewer heat, we use publicly available water quality monitoring records of the English Environment Agency (EA) and air temperature records of the UK Met Office to quantitatively compare FSE, crude sewage, river and air temperatures across England. We combine these results with water company reported annual wastewater volumes to estimate the heat recovery potential of FSE discharge in England. The specific questions this study aims to address are:

§ Defined as the final liquid waste from sewage that has been treated to meet regulatory environmental standards prior to release into the natural environment.

– How warm is FSE relative to rivers and, therefore, what excess heat is present in FSE discharge that could be recovered?

– Has FSE discharge temperature regulation been effective and is there a temperature difference between crude sewage and FSE, thereby implying WWTW might be wasting additional heat energy to meet required discharge regulations?

– How have (and will) temperature differences between FSE and rivers changed through time? In other words, how do temperature differences vary seasonally and is wastewater heat a growing resource?

– Which locations have the largest temperature difference between FSE and rivers and, therefore, which locations might preferentially be targeted for heat recovery?

– What is the annual volume and heat recovery potential of treated wastewater leaving WWTW?

2. Approach and methodology

The approach taken was a statistical analysis of 20 years of national FSE, crude sewage (assumed to be influent to WWTW), river and air temperature data collected as part of routine and regulatory compliance monitoring. The water quality monitoring records of the EA are publicly available and are extensive in time and space, covering all regions of England from the year 2000 onwards. The UK Met Office air temperature data are also publicly available and cover the same spatial and temporal extent. These data enabled a statistical comparison between FSE, crude sewage, river and air temperatures, as well as investigation into spatial and temporal temperature variations. Considered alongside wastewater treatment volumes of water companies, relative temperature differences could be used to estimate heat recovery potential.

2.1 Water temperature data

FSE, crude sewage and river temperatures for England were extracted from the EA Water Quality Archive (WQA)[27] for the years 2000 to 2019, inclusive. Temperatures recorded from pollution incidents or collected as part of specific investigations were excluded so as not to bias the dataset with the inclusion of non-routine monitoring measurements. Entries with miscellaneous names and arbitrary grid references were also removed. Consistent with previous EA-led studies,[28] all entries with river temperatures below 1 °C or above 35 °C were removed because they are improbable extreme values and are most likely recording or typing errors. Entries with FSE temperatures below 1 °C or above 40 °C were also removed for the same reason. A higher temperature cut-off was employed for FSE temperature data to account for FSE typically being several degrees warmer than river temperatures. It was not necessary to implement temperature cut-offs for crude sewage data because temperatures ranged between physically reasonable values. Unique measurement locations were identified whereby a location was considered unique if its combined identification code, location name, and easting and northing coordinates (British National Grid, BNG) were different to all other locations – this was necessary as some WWTW have multiple discharges. Only unique locations where a monthly mean temperature could be calculated for each month of the calendar year were included. In total 352 739 FSE temperature measurements from 2696 locations, 575 crude sewage temperature measurements from eight locations, and 1 178 973 river temperature measurements from 9188 locations were included in this study (Fig. 1). The FSE temperatures were a mixture of private discharges and discharges from water company owned WWTW, but it was not possible to unambiguously distinguish between the two.

2.2 Air temperature data

Air temperature data for England were extracted from the Met Office's Historic Station Data Archive[29] for the years 2000 to 2019, inclusive. Temperatures noted as 'estimated' were removed from the dataset prior to analysis. Monthly mean air temperatures were calculated from the average of the mean daily maximum and minimum temperatures. Consistent with the water temperatures, only data from locations where a monthly mean temperature could be calculated for each month of the calendar year were included. In total 4374 monthly mean air temperatures from 19 locations were included in this study (Fig. 1). Missing data and removal of estimated air temperatures accounted for the 186 monthly mean air temperatures missing from the possible 4560 temperatures. One location (Lowestoft, Suffolk) underwent a local re-location change in August 2007 and observed daily maximum and minimum temperatures only run until October 2010. The coordinates used in this study for Lowestoft refer to the original station location. All station elevations were lower than 200 m above mean sea level, ranging from 6 to 169 m, and therefore lapse rate effects were ignored.

2.3 Analysis of variance

To assess the differences and temporal variation between FSE, river and air temperatures, the temperature data were subjected to three-way analysis of variance (ANOVA). Two ANOVAs were carried out which considered three factors and two covariates. In both ANOVAs the three factors considered were 'Type', 'Year' and 'Month'. The type factor had three levels; 'FSE', 'River' or 'Air' temperature. The year factor had 20 levels (2000 through 2019); one for each calendar year extracted from the EA WQA and Met Office Historic Station Data Archive. The month factor had 12 levels (January through December); one for each month of the year. The factors and factor interactions of interest to identify significant differences and temporal variation were: type (three levels); type with year (60 levels); and type with month (36 levels). The month and year factors alone, as well as their interaction, were not directly of interest because they did not

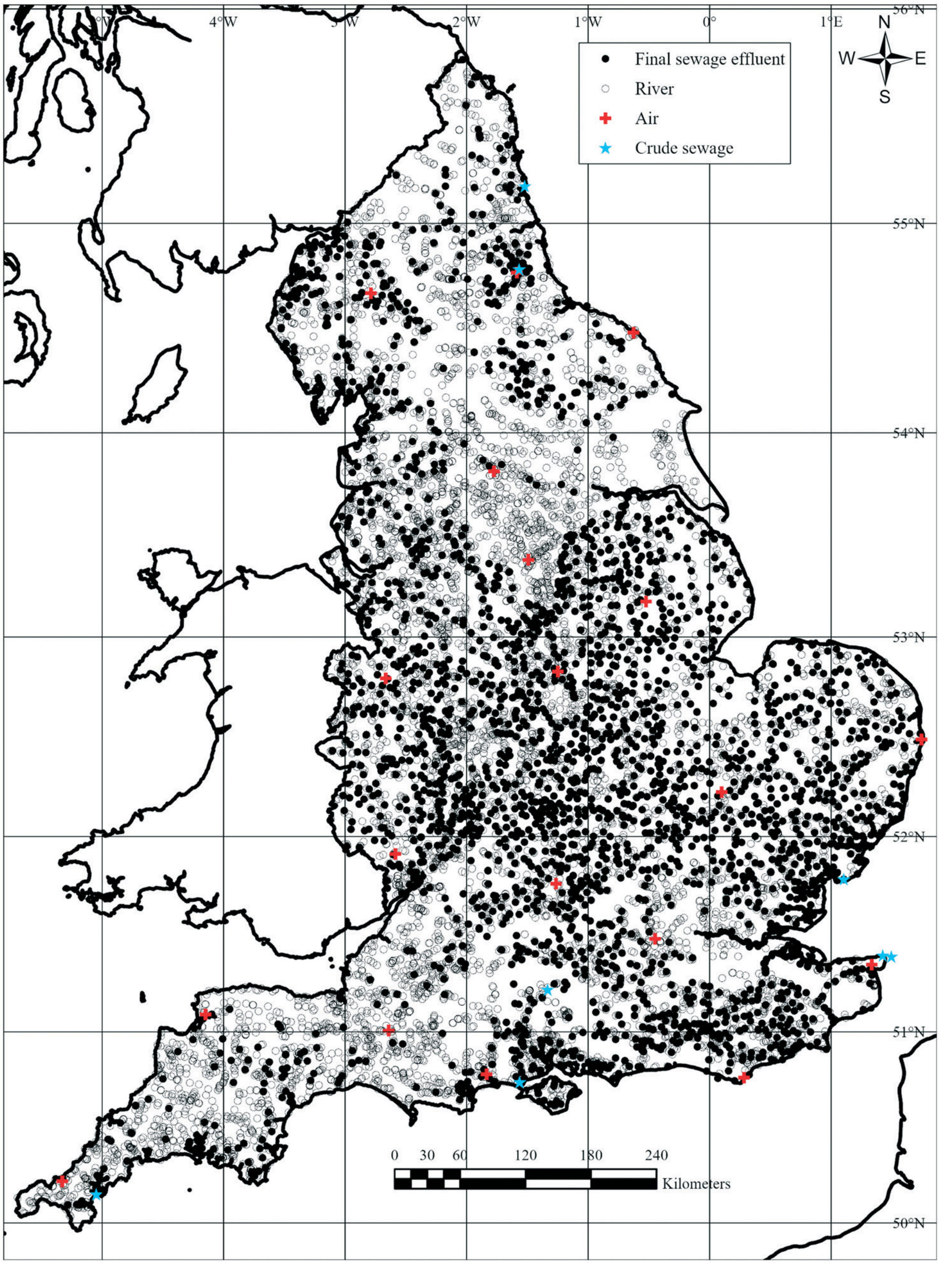

Fig. 1 Map of England showing the location of FSE, crude sewage, river and air temperature measurements used in this study.

distinguish between FSE, rivers or air. No covariates were included in the first ANOVA. In the second ANOVA the two covariates considered were 'Easting' and 'Northing' coordinate. Location coordinates were included in the second ANOVA to see if inclusion explained away the significance of factors and investigate if there was any significant spatial variation in FSE, river or air temperatures. Spatial variations in FSE, river and air temperatures were quantified using multiple regression analysis (section 2.5). A third ANOVA was carried out exclusively on the crude sewage temperature data, which were not included in the previous ANOVAs because the number of crude sewage temperatures was substantially fewer than those for FSE, rivers and air. The one factor included in the crude sewage ANOVA was Month to compare intra-annual variation to FSE. A year factor was not included because crude sewage temperatures were only available from 2000 to 2009.

Prior to ANOVA, all temperature data were tested for normality using the Anderson–Darling test[30] and were log-transformed for ANOVA if transformation improved normality. Statistical significance was judged at the 95% probability (P-values $\leq$ 0.05) of the factor or interaction not having zero effect. The proportion of the variance explained by significant factors, interactions and covariates was calculated using the generalised ω^2 method.[31] Where factors or interactions had more than two levels, *post hoc* Tukey tests were carried out to confirm where significance lay within factors and interactions. Results are presented as least squares means. All analysis was performed using Minitab v.18.

2.4 Linear mixed effects analysis

To quantify any trends in annual mean FSE, river and air temperatures over the study period, the data used in ANOVA were also subjected to linear mixed effects analysis. Mixed effects models are less affected by missing values than ANOVA and were therefore more appropriate for assessing trends in annual mean FSE, river and air temperatures where locations were not necessarily sampled at regular time intervals but drawing upon the pooled dataset gave greater sensitivity in trend estimation. Linear mixed effects models were constructed separately for each of the FSE, river and air temperature locations and a linear best-fit trend was fitted to the data across the study period. The linear mixed effects models were calculated using the lme4 library within R. The trend calculated for each location was assessed for significance at the 95% probability. Prior to linear mixed effects modelling, the temperature data were assessed as for ANOVA.

2.5 Multiple regression analysis

The FSE, river and air temperatures were not co-located. Therefore, multiple regression was used to construct surfaces to investigate spatial trends in FSE, river and air temperatures, the differences between them, and thereby enable site-specific comparisons to be made. The single temperature used for each location in the multiple regression analysis was an annual mean temperature calculated from the monthly mean temperatures at that location. Annual mean temperatures were calculated using this approach to negate sampling bias caused by the sometimes-uneven distribution of temperature measurements across a calendar year, and thus seasons.

Multiple regression analysis was carried out independently of ANOVA and in a stepwise manner for the annual mean FSE, river and air temperatures. The variables used were easting and northing; and the interaction between the two. The stepwise approach ensured only significant terms were included in the models. Statistical significance was judged at the 95% probability of the factor or interaction not having zero effect. Power or log-transformed annual mean temperatures were considered but made negligible difference to the regression model results, and are therefore not presented. Similarly, the use of power-transformed easting and northing coordinates also did not improve model results.

2.6 Heat recovery potential

Heat recovery potential was estimated using the annual volumes of wastewater receiving treatment at WWTW (converted to average flow rates), temperature differences informed by ANOVA and multiple regression analysis, and eqn (1):[32]

$$\mathrm{HP} = Qc\rho\Delta T \tag{1}$$

where HP is heat potential (W), Q is the effluent flow rate ($m^3\ s^{-1}$), c is the specific heat capacity of the effluent (J kg^{-1} °C^{-1}), ρ is the effluent density (kg m^{-3}), and ΔT is the change in effluent temperature (°C). The specific heat capacity of the effluent was assumed to be 4.18 kJ kg^{-1} °C^{-1} (ref. 33) and density was assumed to be that of freshwater (1000 kg m^{-3}).

Although the volumes of FSE entering rivers are not reported as part of the EA WQA, all nine water companies in England declare volumes of wastewater receiving treatment at WWTW as part of annual performance reports. These volumes can be used as a proxy for total annual sewage effluent discharge.[34] Annual performance reports were publicly available online for each water company for the financial years (1st April to the following 31st March) 2016–2017 to 2019–2020.[35–43] Foul, surface water drainage and highway drainage volumes were extracted from the annual performance reports and summed to give annual volumes of wastewater treated at WWTW. Volumes are reported without uncertainty and were used as such within this study. Both Southern Water and Wessex Water reported surface water drainage and highway drainage volumes to be equal within each reporting year. Without further knowledge of why, it was assumed that highway drainage was classed the same as surface water drainage by these companies, and therefore only one value was included in each annual summation. Although the annual volumes of wastewater receiving treatment at WWTW were used as a proxy for annual FSE discharge to rivers, this total volume excludes private discharges but does include discharges to water bodies other than rivers, for example the sea. Nevertheless, the proxy was appropriate because WWTW discharges represent the bulk volume of FSE entering rivers, most WWTW discharge to river networks, and heat could still be recovered from coastal discharges.

Site-specific temperature differences between FSE and rivers were estimated from annual mean FSE temperatures and predicted annual mean river temperatures calculated using the best-fit multiple regression surface, which also provided the numerical distribution of temperature differences. Temperature differences between FSE and air were also estimated. It was important to consider the difference in FSE temperatures relative to river or air temperatures because it is the excess heat in FSE compared to rivers and air that is a currently wasted resource. If FSE is not warmer than local river or air temperatures then there is no benefit of extracting heat from FSE compared to extracting heat directly from air or river water.

Three national-scale heat recovery potential scenarios were considered. Firstly, annual heat recovery potential was estimated using the difference between annual mean FSE and river temperatures, as identified from ANOVA. The inclusion of the month factor in the ANOVA also enabled monthly heat recovery potential to be estimated, and thus enabled consideration of seasonal variation. The second scenario built on scenario one by considering the temperature difference between crude sewage and FSE. Higher crude sewage temperatures might indicate that influent to WWTW loses heat throughout the treatment process or is deliberately cooled prior to discharge to meet permit regulations. Therefore, there may be additional opportunities within WWTW to recover heat in addition to that which is currently lost as discharge. The third scenario estimated national annual heat recovery potential by estimating and summing the heat potential of all FSE locations where FSE temperatures were greater than predicted river temperatures from the multiple regression analysis. Without discharge rate data included in the EA WQA, the third scenario required the assumption that the treated wastewater volume was equally split across all 2696 FSE locations. This assumption was appropriate for calculating national heat recovery potential but is clearly erroneous for specific sites. To demonstrate the importance of local discharge rate data for future heat potential estimates, discharge rates for two FSE locations were manually obtained from permit information held within the EA Consented Discharges To Controlled Waters With Conditions[24] and used to estimate site-specific heat recovery potential. However, a methodology fully combining this database with the EA WQA, and thereby associating all 2696 FSE locations with discharge rate data, remains unresolved and the subject of future work.

3. Results

The number of FSE temperature measurements has declined from a peak of 29 377 in 2004 to 8940 in 2019 (Fig. S1a†). Similarly, the number of river temperature measurements has declined from a peak of 84 617 in 2000 to 37 631 in 2019 (Fig. S1a†). The number of crude sewage temperature measurements peaked at 83 in 2006 and declined to zero by 2010. The mean monthly number of FSE temperature measurements was 29 400 ± 3240 (first standard deviation), with the lowest number of measurements (21 184) occurring in December (Fig. S1b†). The mean monthly number of river temperature measurements was 98 248 ± 10 401, with the lowest number of measurements (74 757) also occurring in December (Fig. S1b†). The mean monthly number of crude sewage temperature measurements was 48 ± 5, but the lowest number of measurements (39) occurred in April. The maximum FSE and river temperature measurements were 38.53 and 33.58 °C, respectively. The minimum temperatures were 1.0 °C, which corresponded to the imposed temperature cut-off used to remove improbable extreme values. The maximum and minimum crude sewage temperature measurements were 21.0 and 3.7 °C, respectively. The maximum and minimum monthly mean air temperatures were 22.5 and −2.8 °C, which were recorded for July 2006 at Heathrow, Greater London, and December 2010 at Newton Rigg, Cumbria, respectively.

3.1 Analysis of variance

Anderson–Darling tests indicated no transformations of temperature data were necessary prior to ANOVA. In the first ANOVA the best-fit model explained 77.8% of the variation in the temperature data (Table 1). As measured by ω^2, the type factor accounted for the most variation within the model (49.4%). The type with month and type with year interactions accounted for 1.9 and 0.4% of the variation, respectively (Table 1). The inclusion of easting and northing as covariates improved the model fit to 79.4%, with northing accounting for 15.9% of variation and easting accounting for 1.7% (Table 1). The covariates explained away 12.6% of variation from the type factor and 2.7% of variation from the month factor but did not affect the significance of factors and interactions (Table 1). The third ANOVA (exclusively on the crude sewage temperatures) had a model fit of 71.4% and the month factor explained 70.9% of the variation (Table 1).

All three ANOVAs showed that all included factors, interactions and covariates had a significant effect on temperature variation (Table 1). The significance of the type factor in the first two ANOVAs meant that FSE, river and air temperatures were significantly different to each other. This

Table 1 ANOVA results for FSE, river, air and crude sewage temperature data

	ANOVA 1		ANOVA 2		ANOVA 3	
R^2 (%)	77.8		79.4		71.4	
Factor, interaction or covariate	P-Value	ω^2 (%)	P-Value	ω^2 (%)	P-Value	ω^2 (%)
Type	<0.0005	49.4	<0.0005	36.8	—	—
Month	<0.0005	24.1	<0.0005	21.4	<0.0005	70.9
Year	<0.0005	0.2	<0.0005	0.2	—	—
Type with Month	<0.0005	1.9	<0.0005	1.7	—	—
Type with Year	<0.0005	0.4	<0.0005	0.2	—	—
Month with Year	<0.0005	1.0	<0.0005	0.9	—	—
Type with Month with Year	<0.0005	0.6	<0.0005	0.5	—	—
Easting	—	—	<0.0005	1.7	—	—
Northing	—	—	<0.0005	15.9	—	—

result was confirmed by Tukey tests whereby no levels of the type factor shared a group (*i.e.* their means with standard error did not overlap). Mean FSE, river and air temperatures were 13.1 ± 0.004 °C, 10.9 ± 0.002 °C and 10.6 ± 0.03 °C, respectively. These means and the results in the following sections refer to the ANOVA with covariates. The significance of the type with month and type with year interactions meant that FSE, river and air temperatures all varied significantly by month and year, which is discussed further in section 3.2. Mean crude sewage temperature was 14.5 ± 0.1 °C and the significance of the month factor showed that crude sewage temperatures also varied significantly by month. The significance of easting and northing in the second ANOVA suggested that FSE, river and air temperatures all significantly varied by coordinate defined location. Spatial variations in FSE, river and air temperatures are investigated in section 3.3.

3.2 Temporal variation

3.2.1 Intra-annual temperature variations. Within the factor interaction of type with month, the Tukey test showed that eight of the possible 36 levels were significantly different to all other levels: mean FSE temperature in May; mean river temperatures in April, May, July, August, September and November; and mean air temperature in May. Fig. 2a shows monthly mean temperatures for FSE, rivers and air, with non-overlapping standard error bars within a month showing significant differences between FSE, river and air temperatures. Mean FSE temperatures were lowest in January and February (8.4 ± 0.01 °C), highest in July and August (18.2 ± 0.01 °C) and were significantly higher than mean river and air temperatures for every month (Fig. 2a). Monthly mean river temperatures were significantly higher than respective air temperatures for November to May and significantly lower for June to September but were not significantly different in October (Fig. 2a). Crude sewage temperatures were lowest in January (10.8 ± 0.2 °C), highest in August (18.7 ± 0.3 °C) and were higher than FSE temperatures for all months except July (Fig. 2a). Monthly mean FSE, crude sewage, river and air temperatures all followed the same seasonal pattern with the highest temperatures occurring in summer months and the lowest temperatures occurring in winter months (Fig. 2a).

The difference in monthly mean FSE and river temperatures was lowest in May (1.5 °C) and highest across October, November and December (2.7 to 2.8 °C) (Fig. 2b). Across the year the mean temperature difference between monthly mean FSE and river temperatures was 2.2 °C. Comparatively, the mean temperature difference between monthly mean FSE and air temperatures was 2.5 °C. The difference in monthly mean FSE and air temperatures was lowest in July (1.2 °C) and highest in December (4.0 °C) (Fig. 2b). The difference in monthly mean river and air temperatures was highest in December (1.3 °C) but lowest in July and August (−0.8 °C, with the negative difference occurring because air temperatures were higher than river temperatures) (Fig. 2b). The difference in monthly mean crude sewage and FSE temperatures was lowest in July (−0.1 °C) and highest in December (2.8 °C) (Fig. 2b). The mean temperature difference between monthly mean crude sewage and FSE temperatures was 1.5 °C.

3.2.2 Inter-annual temperature variations. Within the factor interaction of type with year, the Tukey test showed only three of the possible 60 levels were significantly different from all other levels: annual mean FSE temperatures in 2006, 2008 and 2012. Annual mean FSE temperatures were always significantly higher than respective annual mean river or air temperatures (Fig. 2c). The lowest annual mean FSE temperature occurred in 2010 and 2013 (12.3 ± 0.02 °C) and the highest annual mean FSE temperature occurred in 2006 (13.7 ± 0.01 °C) (Fig. 2c). The lowest and highest annual mean river temperatures occurred in 2010 (10.2 ± 0.01 °C) and 2006 (11.4 ± 0.01 °C), respectively (Fig. 2c). The lowest and highest annual mean air temperature occurred in 2010 (9.3 ± 0.1 °C) and 2014 (11.2 ± 0.1 °C), respectively (Fig. 2c). The difference in annual mean FSE and river temperatures showed no obvious systematic increase or decrease from 2000 to 2019 but river and air temperatures appear to have converged across 2014 to 2019 (Fig. 2d).

For annual mean FSE temperatures, the trends at unique locations ranged from −0.05 ± 0.002 °C per year to 0.09 ± 0.002 °C per year, with a mean trend of 0.01 °C per year across all locations and ∼83% had significant increases in annual mean temperatures from 2000 to 2019. For annual mean river temperatures, the trends at unique locations ranged from −0.02 ± 0.001 °C per year to −0.01 ± 0.001 °C per year, with a mean trend of −0.02 °C per year and all locations had significant decreases in annual mean temperatures from 2000 to 2019. Location trends in annual mean air temperatures ranged from −0.001 ± 0.0004 °C per year to 0.02 ± 0.0004 °C per year, with a mean trend of 0.01 °C per year across all locations. All air temperature locations but one had significant increases in annual mean temperatures from 2000 to 2019. Newton Rigg had a significant decrease in annual mean temperatures. The mean trends for FSE, river and air temperatures across all locations are illustrated in Fig. 3a. Fig. 3b alternatively plots the temperature difference in the annual mean trends. Since both annual mean FSE and air temperatures increased at ∼0.01 °C per year, the temperature difference between them remained constant at ∼2.5 °C (Fig. 3b). However, as already suggested by Fig. 2c and d, the difference between river and air temperatures decreased on average over the study period, reaching approximately zero temperature difference around 2016 (Fig. 3b). Fig. 3b also highlights that on average over the 20 year study period, the temperature difference between FSE and rivers has increased from ∼2.0 to 2.6 °C, equivalent to a relative rate of ∼0.03 °C per year.

3.3 Spatial temperature variation

Multiple regression analysis quantified spatial variation in FSE, river and air temperatures, thereby enabling a prediction of which FSE discharge locations have the largest

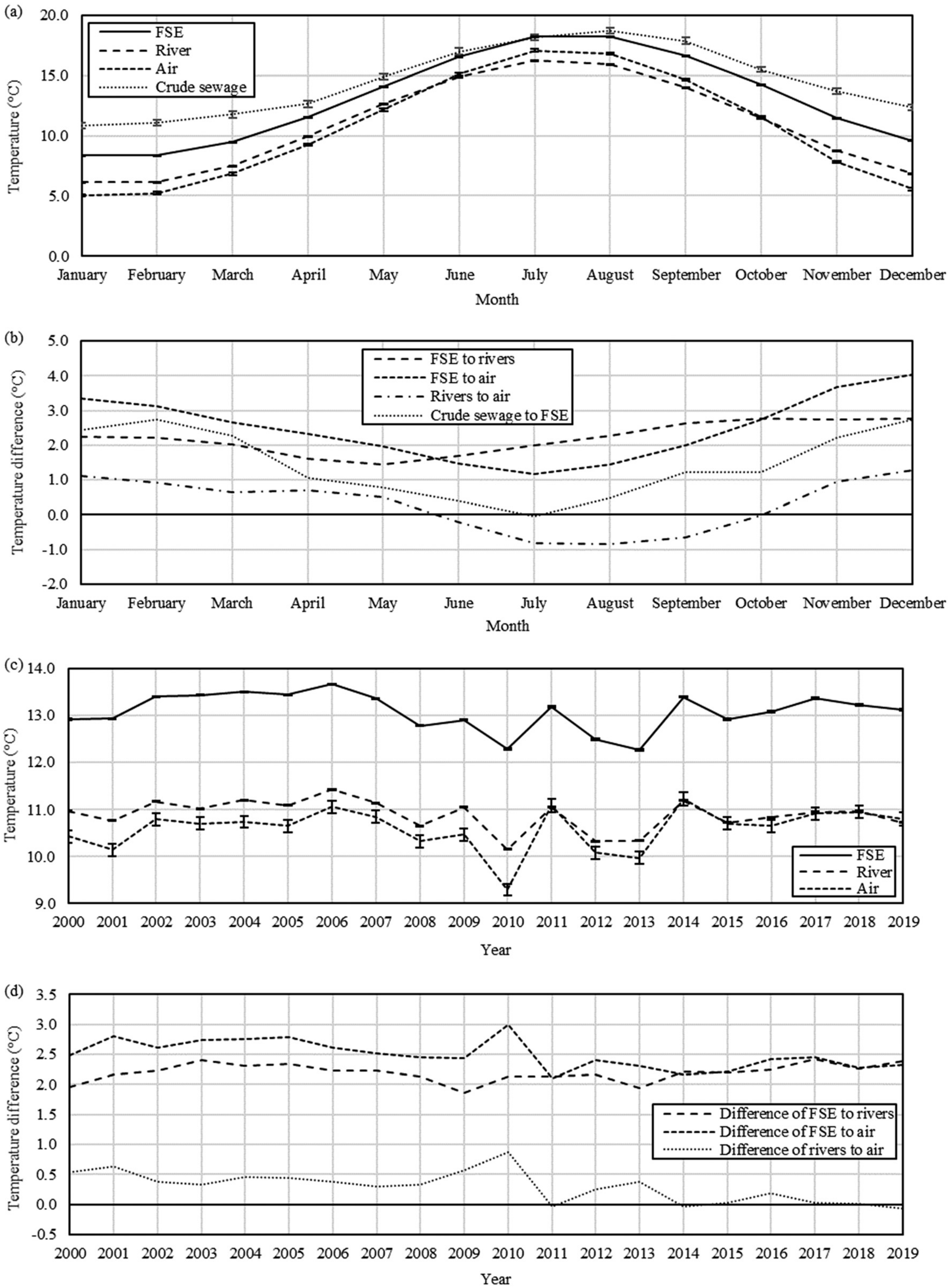

Fig. 2 (a) Monthly mean FSE, river, air and crude sewage temperatures. (b) Differences between monthly mean FSE, river, air and crude sewage temperatures. (c) Annual mean FSE, river and air temperatures. (d) Differences between annual mean FSE, river and air temperatures.

temperature difference between FSE and river water, and therefore might be targeted for heat recovery. The analysis indicated that easting and northing were significant factors in predicting annual mean FSE, river and air temperatures across England (Table 2). The interaction of easting with northing was only significant for predicting annual mean river temperatures. Of the best-fit models, air temperatures had the highest model fit (R^2 = 80.5%) whereas FSE

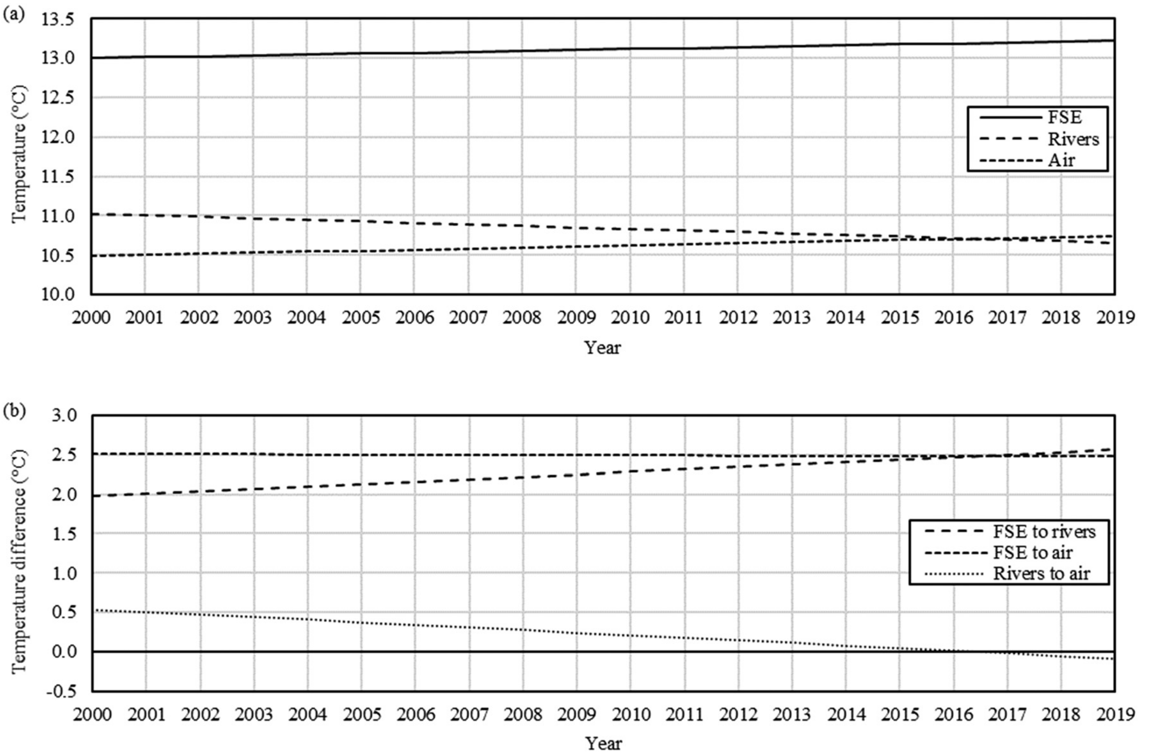

Fig. 3 (a) Mean trends of annual mean FSE, river and air temperatures. (b) Difference between mean trends of annual mean FSE, river and air temperatures.

temperatures had the lowest model fit (R^2 = 23.4%) (Fig. S2†). The best-fit regression models for annual mean FSE (FSE), river (R) and air (A) temperatures had the following respective regression equations:

$$T_{\mathrm{FSE}} = \underset{(0.1)}{13.7} + \underset{(2.4\times10^{-7})}{1.5\times10^{-6}}\ \text{Easting} - \underset{(1.7\times10^{-7})}{4.4\times10^{-6}}\ \text{Northing} \quad (2)$$

$$T_{\mathrm{R}} = \underset{(0.1)}{11.5} + \underset{(1.8\times10^{-7})}{1.0\times10^{-6}}\ \text{Easting} - \underset{(3.1\times10^{-7})}{5.1\times10^{-6}}\ \text{Northing} + \underset{(7.9\times10^{-13})}{2.9\times10^{-12}}(\text{Easting}\times\text{Northing}) \quad (3)$$

$$T_{\mathrm{A}} = \underset{(0.3)}{11.0} + \underset{(7.0\times10^{-7})}{1.8\times10^{-6}}\ \text{Easting} - \underset{(5.4\times10^{-7})}{4.4\times10^{-6}}\ \text{Northing} \quad (4)$$

where T is annual mean temperature (°C), easting and northing are BNG easting and northing coordinates to six figures, respectively, and the brackets below the equations are the standard error in the coefficients or constant terms.

Table 2 Multiple regression analysis results for annual mean FSE, river and air temperatures

	FSE	River	Air
R^2 (%)	23.4	32.7	80.5
Factor or interaction	*P*-Value		
Easting	<0.0005	<0.0005	0.019
Northing	<0.0005	<0.0005	<0.0005
Easting with Northing	—	<0.0005	—

Eqn (2) indicates annual mean FSE temperatures increase by 0.15 ± 0.02 °C for every 100 km further east and decrease by 0.44 ± 0.02 °C for every 100 km further north. Eqn (3) indicates annual mean river temperatures increase by 0.10 ± 0.02 °C for every 100 km further east and decrease by 0.51 ± 0.03 °C for every 100 km further north. Eqn (4) indicates annual mean air temperatures increase by 0.18 ± 0.07 °C for every 100 km further east and decrease by 0.44 ± 0.05 °C for every 100 km further north.

Annual mean FSE, river and air temperatures all generally decreased with northing coordinate whereas temperature minima were observed between easting coordinates 300 000 to 400 000 m, before increasing both in westerly and easterly directions (Fig. 4). The minimum was most pronounced for annual mean river temperatures at an easting coordinate of ∼400 000 m (Fig. 4d).

3.4 Heat recovery potential

Temperature differences between annual mean FSE and river temperatures varied from −1.0 to 10.5 °C, with a mean of 2.2 °C (Fig. 5a). All but fifteen locations had annual mean FSE temperatures higher than predicted annual mean river temperatures. Temperature differences between annual mean FSE and air temperatures varied from −0.6 to 10.8 °C, with a mean of 2.5 °C (Fig. 5a). All but four locations had FSE temperatures greater than predicted air temperatures. The distributions of annual mean FSE temperatures and the temperature difference to rivers are shown in Fig. 5b.

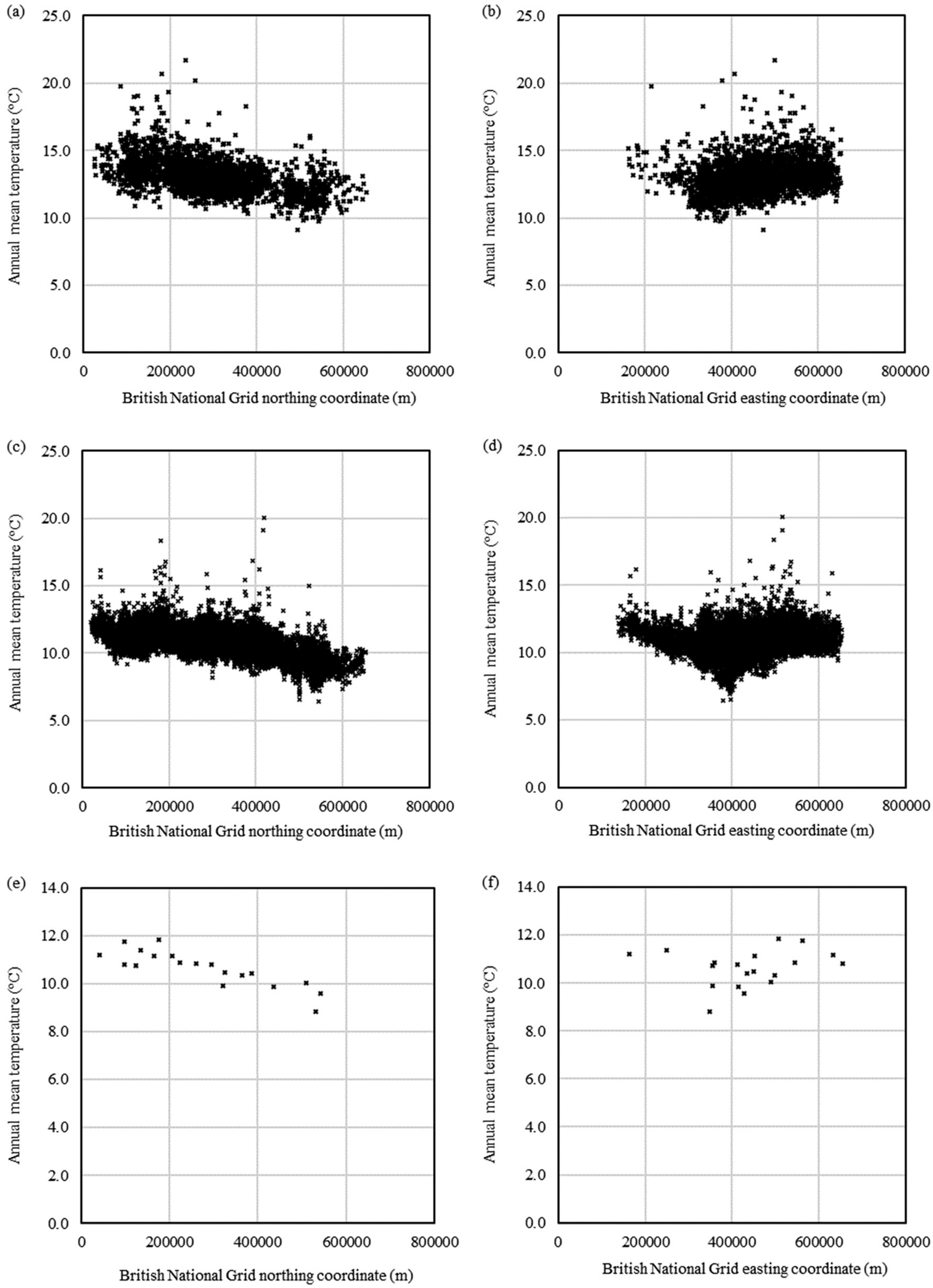

Fig. 4 Annual mean FSE temperatures by BNG (a) northing and (b) easting coordinates; annual mean river temperatures by BNG (c) northing and (d) easting coordinates; and annual mean air temperatures by BNG (e) northing and (f) easting coordinates.

3.4.1 Scenario one. The mean annual volume of wastewater receiving treatment at WWTW in England between the reporting years 2016–2017 and 2019–2020 was ~6 310 000 Ml. However, the volume of wastewater receiving treatment has increased on average by ~30% from 2016–2017 to 2019–2020, which relates to increased volumes of

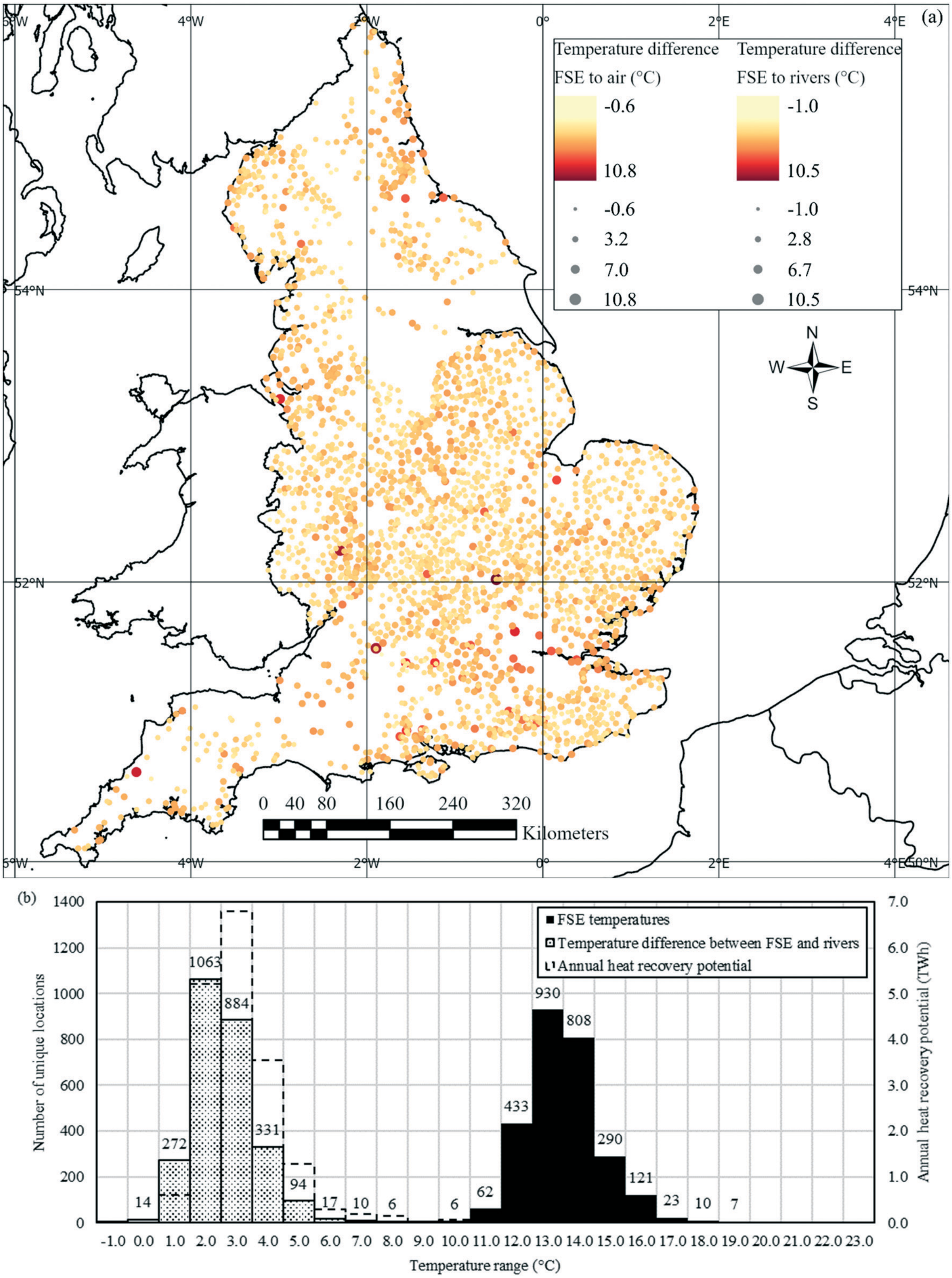

Fig. 5 (a) Map of differences between annual mean FSE temperatures and predicted river and air annual mean temperatures. (b) The distributions of annual mean FSE temperatures and the difference between FSE and predicted river temperatures. Column labels are only shown for temperature categories with five or more locations and *x*-axis labels refer to the upper temperature of each category. Also included is the annual heat potential associated with locations in each temperature category.

surface and highway drainage receiving treatment (Fig. S3†). The 2019–2020 annual treatment volume of 7 175 238 Ml (Fig. S3†) equates to an average FSE discharge flow rate of ~228 $m^3 s^{-1}$ if it is assumed that all wastewater treated at WWTW discharges as FSE. From eqn (1), if heat recovery methods extracted 2.2 °C (the difference in annual mean FSE and river

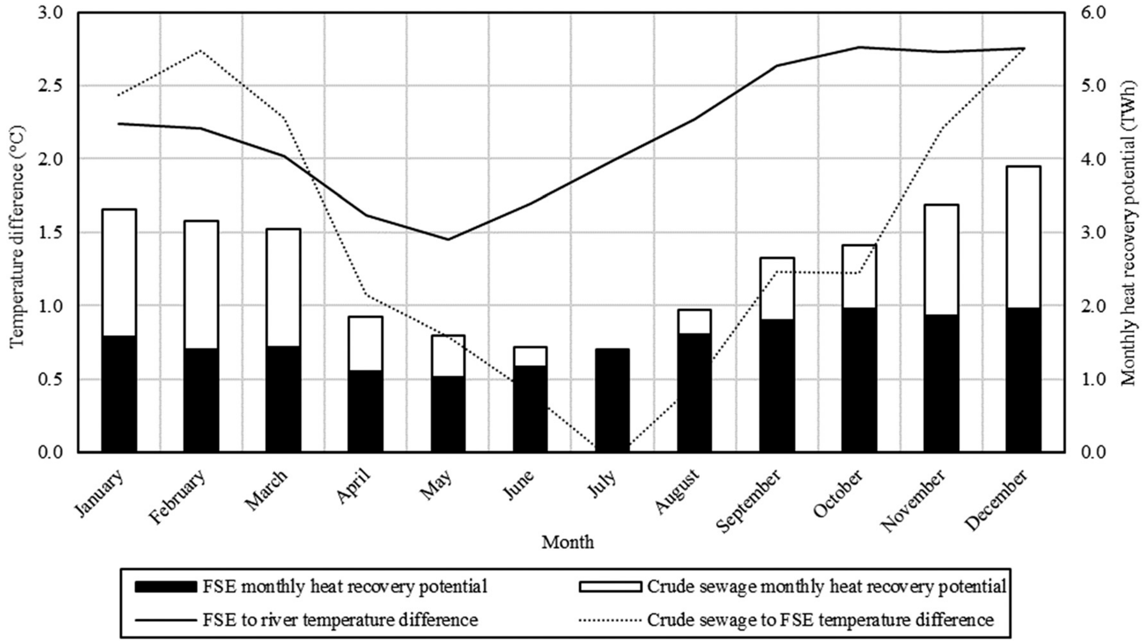

Fig. 6 Estimated monthly heat recovery potential from the temperature differences between monthly mean FSE and river temperatures, and crude sewage and FSE temperatures.

temperatures from section 3.2) from FSE so that on average nationally FSE discharge temperatures equalled river temperatures, then there is currently ~2090 MW of heat recovery potential in FSE from water company owned WWTW in England. Annually, this potential equates to ~18.3 TW h of heat energy. Alternatively, taking the temperature difference in monthly mean FSE and river temperatures from section 3.2.1 and assuming the annual treatment volume of 7 175 238 Ml is equally distributed across all months (although monthly volume might be expected to vary with seasonal rainfall because of the contribution of surface drainage), heat recovery potential ranges from ~1.0 TW h in May to ~2.0 TW h in October and December (Fig. 6).

3.4.2 Scenario two. The ANOVAs demonstrated that monthly mean crude sewage temperatures were warmer than monthly mean FSE temperatures for all months except July (Fig. 2a) and were on average across the year 1.5 °C higher. Assuming that this 1.5 °C represents the temperature lost from influent during the treatment process and in cooling prior to FSE discharge, there may be a further 1.5 °C that might be recovered in addition to the 2.2 °C from scenario one. Therefore, from eqn (1) with the flow rate of ~228 m^3 s^{-1}, there may be an additional ~12.5 TW h that might be recovered annually from water company owned WWTW in England, bringing the total annual heat recovery potential to ~30.8 TW h. Alternatively, taking the temperature difference in monthly mean crude sewage and FSE from section 3.2.1 and assuming the annual treatment volume of 7 175 238 Ml is equally distributed across all months, the additional heat recovery potential ranges from 0 TW h in July (because the temperature difference was negative) to ~2.0 TW h in December (Fig. 6).

3.4.3 Scenario three. Scenarios one and two calculated annual heat potential using national average temperature differences between FSE and rivers from ANOVA. However, the multiple regression analysis enabled a prediction of the temperature differences to river water at each of the 2696 FSE locations (Fig. 5a). Assuming the 2019–2020 annual treatment volume of 7 175 238 Ml and discharge rate of ~228 m^3 s^{-1} is equally distributed across all 2696 FSE locations, eqn (1) can be used to estimate the heat potential of the 2681 FSE locations with FSE temperatures warmer than predicted river temperatures (Fig. 5b). In total, this methodology estimates an annual heat recovery potential ~18.2 TW h, which is similar in magnitude to the estimation from scenario one.

3.4.4 Selected locations. To highlight the importance of using site-specific flow rates for future calculations of heat recovery potential, two discharge locations were selected and flow rate information available in the EA Consented Discharges To Controlled Waters With Conditions[24] was used to re-calculate annual heat recovery potential. The location with the largest temperature difference between annual mean FSE temperatures and predicted annual mean river and air temperatures was Centre Parcs Woburn Forest, Bedfordshire. FSE temperature measurements for Centre Parcs Woburn Forest were available from 2016 to 2019 and ranged from 16.0 to 27.2 °C, with an annual mean temperature of 21.7 °C (Fig. S4a†). Using eqn (1), the FSE to river temperature difference of 10.5 °C from the multiple regression analysis, and the combined maximum permitted daily flow rate of 1534 m^3 per day from the package treatment plant and membrane filtration at the site (dry weather flow rate or mean flow rate were not available),[24] ~6.8 GW h of heat recovery potential might exist annually. In comparison, the annual heat recovery potential for Centre Parcs Woburn Forest from scenario three was overestimated at ~32.6 GW h. The WWTW with the largest permitted dry weather flow rate for FSE in England (Beckton, London)[24] had a flow rate of 2 730 000 m^3 per day and a 6.3 °C difference between annual mean FSE temperatures and predicted annual mean river temperatures (Fig. S4b†). Using eqn (1), FSE discharge from Beckton may have an annual heat recovery potential of ~7.3 TW h. In comparison, the annual heat potential for Beckton from scenario three was substantially underestimated at ~19.6 GW h. The much higher discharge rates at Beckton mean the annual heat recovery potential is over a thousand times greater than that estimated for Centre Parcs Woburn Forest.

4. Discussion

4.1 How warm is FSE relative to rivers?

The ANOVAs showed that mean FSE and river temperatures in England were 13.1 ± 0.004 °C and 10.9 ± 0.002 °C, respectively, and therefore the difference between the two was 2.2 °C. The difference of 2.2 °C also held true when considering annual averages of monthly mean FSE and river temperatures. Therefore, on average across England, an excess temperature of 2.2 °C is present in FSE discharge relative to ambient river temperatures. This excess heat could be commercially recovered for low-carbon heating whilst also minimising thermal impacts from discharges to rivers. Importantly, our suggestion of recovering 2.2 °C from FSE on a national scale is physically based on over a million temperature measurements and is not an arbitrary temperature as appears to be sometimes used in wastewater heat recovery potential estimates.[14]

4.2 Has FSE discharge temperature regulation been effective and is there a temperature difference between crude sewage and FSE?

The temperature difference of 2.2 °C between FSE and rivers lies between the temperature standards for rivers in England, which allow a 2 or 3 °C increase or decrease in relation to ambient river temperatures, as an annual 98 percentile, from surface water discharges (Table S1†).[25] Therefore, FSE discharge temperature regulation in England appears to have been effective when considered nationally (site-specific effectiveness was not measurable using the data available). The requirement for and successful implementation of discharge temperature limits implies that heat is required to be lost prior to discharge, either as part of routine treatment processes within WWTW or in dedicated cooling immediately prior to discharge. Further evidence for this heat loss was that monthly mean crude sewage temperatures were on average 1.5 °C higher than monthly mean FSE temperatures. Therefore, there may be additional heat to recover within WWTW as well as that which is already wasted in FSE.

4.3 How have (and will) temperature differences between FSE and rivers changed through time?

Monthly mean FSE temperatures showed significant seasonal variation, with the highest temperatures in summer and the lowest temperatures in winter (Fig. 2a). This seasonal variation is the same as that found in central Tokyo, Japan, where between 1965 and 2004 the lowest wastewater effluent temperatures occurred across December to March and wastewater effluent temperatures peaked in August.[6] Monthly mean river temperatures followed the same seasonal trend as FSE but the difference in monthly mean FSE and river temperatures was lowest in May (1.5 °C) and highest across October to December (2.7 to 2.8 °C). Notably for heat recovery, the larger temperature differences occur in the autumn and winter months, meaning that the greatest heat recovery potential occurs at times of the year when heat demand is greatest. This seasonality contrasts with other low-carbon technologies such as electric heating from solar power, which would have its greatest potential in summer when heat demand is at its lowest.

The linear mixed effects analysis showed that ~83% of FSE locations had significantly increasing annual mean temperatures over the study period, with a mean temperature increase of ~0.01 °C per year (Fig. 3a). Similarly, annual mean wastewater effluent temperatures in Tokyo increased from 1965 to 2004, but at a higher average rate of 0.14 °C per year.[6] The temperature data publicly available through the EA WQA do not enable the investigation of FSE temperatures prior to 2000. Likewise, it is also unknown whether annual mean wastewater effluent temperatures in Tokyo after 2004 have stabilised, declined, or continued to increase as they had since 1965. Therefore, the analysis of temporal changes in English FSE temperatures from the 20th century into the 21st century is not possible and a directly equivalent comparison to Tokyo cannot be made.

All river locations in this study had significantly decreasing annual mean temperatures over the study period, with a mean rate of approximately −0.02 °C per year (Fig. 3a) – the reasons for this decline in opposition to climate change is not the subject of this study. Critically, the temperature difference between FSE and rivers is increasing at a rate of ~0.03 °C per year (Fig. 3b). Although undesirable from an environmental perspective because river organisms tend to be more sensitive to temperatures above their thermal maximum than temperatures below their thermal minimum,[44] this trend shows wastewater heat is a growing resource. Furthermore, the UK population has grown year-on-year from ~58.9 million in 2000 to 66.8 million in 2019, with growth expected to continue to 72.0 million in 2041.[45] Therefore, there is likely going to be a corresponding increase in the volume of wastewater requiring treatment and discharge from WWTW, although it must also be acknowledged that changes in treatment efficiency and regulations may reduce wastewater volumes and counteract predicted population growth effects.

4.4 Which locations have the largest temperature difference between FSE and rivers?

The multiple regression analysis showed that annual mean river temperatures decreased by 0.51 ± 0.03 °C for every 100 km further north and increased by 0.10 ± 0.02 °C for every 100 km further east. These results were of broadly similar magnitude to spatial variation in FSE temperatures, which decreased by 0.44 ± 0.02 °C for every 100 km further north and increased by 0.15 ± 0.02 °C for every 100 km further east, as might be expected *a prior* because FSE discharge temperatures are permitted relative to local river temperatures.[24,25] The difference in the rates of temperature change between FSE and rivers indicates that the largest temperature differences between the two would generally be expected to occur in northeast England.

The spatial trend in river temperatures enabled a prediction of river temperatures at each FSE discharge location and consequently identified locations with the largest temperature difference between FSE and river water (Fig. 5a). For a distinct discharge location, the most environmentally friendly scenario would be to discharge at a temperature equal to the receiving river temperature. Therefore, FSE discharges that might preferentially be targeted for heat recovery are those with the largest temperature difference between FSE and river water. Fig. 5a demonstrates that FSE discharges with sufficiently large temperature differences between FSE and river water likely exist across England and are not restricted to one region or water company.

4.5 What is the annual volume and heat recovery potential of treated wastewater leaving WWTW?

In 2019–2020 the volume of wastewater receiving treatment at WWTW in England was 7 175 238 Ml. Based on this volume and a theoretical situation whereby FSE discharge temperatures from water company owned WWTW in England were required to equal river temperatures, our three scenarios estimated national annual heat recovery potentials of ~18.3, 30.8 and 18.2 TW h. The first and third scenarios assumed that heat was only recovered from FSE discharge, whereas the second scenario assumed that the additional heat in influent relative to FSE could also be recovered within WWTW in addition to the excess heat in FSE relative to rivers. In 2019 the UK consumed ~507 TW h of natural gas for space heating, cooking, and hot water across domestic (~310 TW h), non-domestic (~94 TW h) (*e.g.* workplaces and public buildings) and industrial sectors (~102 TW h).[46] Although natural gas consumption has declined by ~15% since peaking in 2005, natural gas still accounted for ~31% of the UK's energy consumption in 2019.[46] Based on our three scenarios we suggest that ~3.6 to 6.1% of UK heat demand could instead be met by recovering heat from wastewater at WWTW in England. Inclusion of heat recovery from private discharges and WWTW in Scotland, Wales and Northern Ireland would further increase these percentages. For example, scaling the heat recovery potential for England to the UK based on 2019 population proportions[45] indicates ~21.6 to 36.6 TW h of heat energy could be recovered (4.3 to 7.2% of UK heat demand).

It is highly improbable that wastewater heat recovery could ever solely meet UK heat demand because demand is greater than the possible supply. For a localised case study in Ireland, it was shown that due to temporal mismatches between demand and supply, there were 21–123 days where heat supply from the WWTW was insufficient to meet demand in the required urban zones.[47] Nevertheless, the heat recovery potential estimates of this study suggest that wastewater heat recovery, even at the final, coolest stage of the treatment and disposal process, could play an important role in meeting heat demand and emissions targets. Recovered heat could be fed into district heat networks which heat the very places producing the warm wastewater. The advantages of wastewater heat recovery are that: wastewater heat extraction technology already exists and has been successfully demonstrated with various projects both nationally and internationally; wastewater is already produced (it is not a new resource with large resource or environmental uncertainties) and will continue to be produced indefinitely by humans; and wastewater is produced at and treated nearby to the places with greatest heat demand, urban areas. Comparatively, although it has been estimated that 36 000 000 TW h of geothermal heat storage capacity exists in the UK's 23 000 abandoned coal mines, only 40% of UK housing stock lies directly above these mines and heat would not travel well to the remaining 60%.[48] Similarly, projects which extract geothermal heat from hot subsurface rocks such as granites,[49] or from hydrocarbon fields and wells,[50,51] are also geographically restricted, and may also come with subsurface risks such as induced seismicity.[52,53] These potential limitations in comparison to wastewater heat recovery does not mean to say that these other technologies should not be pursued. Ultimately national heat demand and emissions targets are likely going to need to be met at local scales with a variety of low-carbon technologies best-suited to local resources and conditions.

4.6 River and air temperatures in England

Although the focus of this study has been on heat recovery potential from FSE, this study also compiled and analysed 20 years' worth of national river and air temperature data from one of the most closely monitored nations in the world. Prior to this study only two studies[28,54] had previously investigated river temperatures across England.[55] Both studies used river temperature data from the EA Surface/Fresh Water Temperature Archive (1980 to 2007), which has since been superseded by the EA WQA.

Using 88 sites across England and Wales from 1989 to 2006, Garner *et al.* identified a seasonal river temperature trend which peaked in July and was at a minimum in January (air temperatures showed a similar peak in July–August and minimum in January–February).[54] Our results were consistent with this seasonal trend (Fig. 2a). Garner *et al.* also observed that the coldest river temperatures occurred in northern

England and became warmer towards the southwest.[54] Our spatial results also showed that the warmest river temperatures were in southwest England. However, Fig. 4d and f further showed that annual mean river and air temperatures increased both westwards and eastwards from a minimum at an easting coordinate of ~400 000 m. We suspect that these minima relate to the topographic high which runs centrally north–south through north to central England.

Orr *et al.* observed increases in river temperatures at 86% of 2773 locations in England and a mean increase of 0.03 ± 0.002 °C per year from 1990 to 2006, which they attributed to increases in air temperature from climatic warming.[28] In contrast, our linear mixed effects analysis showed that all considered river locations from 2000 to 2019 had significantly decreasing trends in annual mean temperature, with a mean of approximately −0.02 °C per year. These conflicting results could be a result of the different datasets used, a real change in river temperature trends, or that river temperatures in England are not as sensitive to air temperatures as previously thought. The linear mixed effects analysis showed that air temperatures across England have risen at most locations over the study period. Furthermore, the mean increase of ~0.01 °C per year corresponds to long-term averages, for example an increase in mean air temperature of ~1.8 °C in England (or ~1.5 °C for the UK) from 1884 to 2020.[56–58]

4.7 Limitations and need for future work

A limitation of this study was the lack of publicly accessible site-specific discharge rate data, which would be needed in future work to enable accurate site-specific heat recovery potential estimates across seasons. Seasonal potential will be important to consider because the greatest heat demand occurs in the colder months of the year but these months also tend to be associated with greater volumes of surface drainage which may dilute the warmer foul waters. Furthermore, because river temperatures were not co-located with FSE discharge locations in the EA WQA, we used spatial trends in river temperatures to predict site-specific temperature differences between FSE and rivers. The availability of river temperature data at FSE discharge locations would further improve heat recovery potential estimates and enable testing of the spatial trend used in this study. This study also suggested, using crude sewage data, that heat is likely lost within WWTW. There is therefore scope to investigate where this heat is lost and establish if it could be recovered in addition to that which is already wasted in FSE discharge. Such further work would need to consider temporal variation in influent temperature because influent temperature changes with time of day and weather. Alternatively, heat recovery can be implemented earlier in the wastewater collection process when temperatures are higher than at discharge, for example in domestic wastewater systems[59] or from mains sewers carrying crude sewage prior to entering WWTW.[13,32] Although we are of the opinion that targeting FSE is the simplest and least disruptive heat recovery option, collaborative research with water companies is needed to quantify the advantages and disadvantages of all heat recovery options. Finally, although this study has calculated annual heat recovery potential from FSE, these estimates do not consider the efficiencies of thermal exchange technologies or heat loss which may occur during transport to end users.

5. Conclusions

Analysis of temperature data for England for 2000 to 2019 has shown that FSE temperatures were on average 2.2 °C higher than river temperatures and 2.5 °C higher than air temperatures. Recovering this excess heat relative to rivers could contribute to achieving net-zero by providing up to ~18.3 TW h (~3.6%) of the UK's annual heat demand, which is currently mostly met using natural gas. Crude sewage temperatures were on average 1.5 °C higher than FSE temperatures, implying that a further 12.5 TW h is lost annually during treatment at WWTW. The largest temperature differences between FSE and rivers, and crude sewage and FSE, occurred during the autumn and winter months, meaning that the greatest seasonal heat recovery potential occurs when heat demand is greatest. Annual mean FSE temperatures were higher than river and air temperatures for every year included in the study and the temperature difference between FSE and rivers increased, on average, at a rate of ~0.03 °C per year from 2000 to 2019. Therefore, and in addition to predicted population growth, wastewater heat is a growing resource. Spatial trends indicated that the largest temperature differences between FSE and rivers would generally be expected to occur in northeast England. However, FSE discharges with sufficiently large temperature differences between FSE and river water were demonstrated to exist across England and were not restricted to one region or water company. Predicted temperature differences between annual mean FSE and river temperatures varied from −1.0 to 10.5 °C and 2681 of 2696 FSE discharge locations had FSE temperatures higher than predicted river temperatures. There are currently only a handful of examples of wastewater heat recovery in the UK but WWTW discharge warm effluent continuously and occur nearby to domestic settlements, which account for most of the UK's heat demand. Therefore, there is local potential to recover heat and help meet heat demand whilst also contributing to meeting national emissions targets. Furthermore, recovering heat from FSE would reduce anthropogenic thermal loading on river networks and thus reduce environmental impact.

Data availability

All data used in this study are publicly available from the English Environment Agency's Water Quality Archive,[27] the

UK Met Office[29] and water company annual performance reports.[35–43]

Conflicts of interest

There are no conflicts of interest to declare.

Acknowledgements

This work is part of the EQUIPT4RISK project funded through Natural Environment Research Council Grant: NE/R017832/1. We thank three anonymous reviewers for their supportive comments and suggestions, which have improved the manuscript.

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