Department
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National Heat Map:
Water source heat map layer

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Executive summary

A detailed water source heat map has been developed for local authorities, community groups and private developers to highlight the opportunities for deploying innovative heat pump technology, particularly at larger scales (e.g. for heat networks).

Last year, DECC published a 'high level' water source heat map[1], which raised awareness of water source heat pumps and provided an early estimation of the potential to generate heat from 39 English rivers. The purpose of this more detailed study was to produce a more robust estimate of the potential for water source heat pumps across England. The output, a Water Source Heat Map (WSHM) layer, has been integrated into the National Heat Map (NHM)[2]. The NHM provides heat demand and sources (e.g. local CHP generation stations) in an accessible way to support DECC's vision for low carbon heat[3].

This study has drawn together a number of existing data sets and methods to produce a new model providing a strategic assessment of the suitability of England's waterbodies for heat extraction. It has identified areas where environmental factors may potentially constrain water source heat pump installation, and the locations with the highest potential for open loop water source heat pumps.

At a strategic level this study has come to the following conclusions about the heat capacity of England's waterbodies:

- The total heat capacity of **rivers** is strongly proportional to flow. Urban areas on larger rivers are therefore prime candidates for water source heat pumps, and linking up to heat networks in the future. Urban areas close to rivers with over 100 MW total capacity are identified on the rivers Ouse (Yorkshire), Trent, Thames, Severn, Aire and Wye. Particularly promising urban areas include Nottingham, Hereford, Pontefract and London.
- A comparison with the results from the previous 'high level' study shows some significant differences. The approach used in this study has given equal weight to small and large urban areas. Consequently small urban areas on large rivers are more prevalent. Additionally, the previous study did not include any locations on the River Severn.
- The total heat capacity from rivers is estimated at approximately 6GW.

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1 https://www.gov.uk/government/publications/water-source-heat-map

2 http://tools.decc.gov.uk/nationalheatmap/

3 Department of Energy & Climate Change, "The Future of Heating: Meeting the challenge," March 2013. [Online]. Available: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/190149/16_04-DECC-The_Future_of_Heating_Accessible-10.pdf

- The study suggests that smaller urban areas with lower heat demands (less than around 500 GWh per year) on larger rivers can have their entire heat demand satisfied by the river alone. Examples include Egham, Tewkesbury, Bewdley, Stourport-on-Severn, Chertsey, Ross-on-Wye, Goole, Gainsborough, Wallingford and Selby.
- The flow and lower temperatures in **canals** restrict their heat capacity significantly in comparison to large rivers. However, in locations where the canal network is a significant waterbody compared with local rivers (e.g. West Midlands) canals may be the best source of heat.
- The total heat capacity from canals is estimated at approximately 84MW.
- **Estuarine** and **coastal water** temperatures are also favourable for heat extraction especially in the south west and south of England. The saline water may allow for a longer operating window due to the decreased tendency for ice crystal formation.

There are a number of limitations to those conclusions that must be borne in mind while reading this report and viewing the NHM:

- Environmental designations and constraints have been added to the NHM layers for information. However, as with the design of any scheme, local issues would have to be investigated in more detail during a feasibility assessment.
- A simple comparison with the heat demand areas on the NHM has been undertaken. Aggregated demand totals (kWh) were compared with the largest river heat capacities (kW) in a qualitative sense. A more detailed comparison of heat demand against heat capacity could be considered in the future.
- The non-consumptive nature of open loop abstraction and discharges means that water resource stress is likely unaffected by the installation of heat pumps. However, there will be local factors to consider if a large flow rate (abstraction and discharge) is proposed.
- The main constraint on extracting heat from waterbodies is the temperature limit and gradient at the heat exchanger. Mean winter temperatures calculated in this study are mostly in the 4 – 8 °C range. This means there is likely to be only a small temperature gradient in most cases and this will limit the size and efficiency of the heat pump.
- There is some uncertainty about utilisation and reliability due to variations in winter water temperatures around the mean. Local temperature measurements and analysis will need to be undertaken during scheme feasibility to understand these variations.
- This study is based on natural winter flow estimates. Many waterbodies may be influenced by non-natural abstractions and discharges that alter both flows and temperatures.
- Recommendations for addressing some of these limitations have also been developed as part of this study, and can be found at the end of this report.

Introduction

Background

As set out in the Government's 2013 policy paper The Future of Heating, Meeting the Challenge[4], wide scale deployment of heat pumps and heat networks are central to our vision for the UK's energy future. Alongside other low carbon forms of heating, they will play an important part in safeguarding the UK's future energy security and cutting greenhouse gas emissions.

There is latent heat available in our rivers and canals, and in the seas that surround us. Many of our towns and cities are located close to large water sources.

Water source heat pumps operate by taking heat from water, boosting its temperature and feeding it into local heat networks or single buildings. There are very few large scale water source heat pumps in the UK, but there is significant potential in utilising water as a heat source in this way, to supply renewable heat at scale to our homes and businesses.

High level water source heat map

DECC published a 'high level' water source heat map in August 2014. This map was produced to raise awareness of this potential heat source and provided an early estimate of the potential of 49 English rivers, estuaries and from coastal sites.

The output of this first heat map was indicative and has been used to differentiate between areas of higher or lower potential.

Since August we have been developing a detailed map to produce a more robust estimate of the potential, and to integrate the map into the National Heat Map. The National Heat Map, which provides information on modelled estimates of annual heat demand, allows users to undertake initial investigations on modelled energy use at buildings and street level. This supports heat mapping by local authorities as part of an area-wide exploration of heat network opportunities.

Combining a detailed water resource map with the National Heat Map means that we can now match the potential of this heat resource against heat demand densities. This will guide where heat networks, making use of water source heat pumps, are more likely to be viable.

Water source heat pumps

Although the detailed water source heat map provides the starting point to investigate the potential of water source heat pumps, a number of other barriers will need to be addressed if this potential is to be fully realised. These barriers centre on a lack of experience of this innovative technology.

DECC has focused on simplifying the processes that need to be followed ahead of water source heat pump installation. This includes work on:

- Developing a simple **'customer journey'**, where we have mapped some of the processes required for anyone wishing to install a water source heat pump.

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[4] https://www.gov.uk/government/publications/the-future-of-heating-meeting-the-challenge

- Working with other organisations to help those looking to install water source heat pumps, to help them understand key processes and to raise awareness. This has led to:
    - The **Environment Agency** improving its application forms for the necessary environmental permits, backed up with a central point of contact to facilitate early pre-application discussions.
    - The Chartered Institution of Building Services Engineers (CIBSE), together with the Heat Pump Association, and Ground Source Heat Pump Association are developing a DECC-funded **Code of Practice** to drive up technical standards. This should be available later this year.
    - Setting up **a roadshow to run later this year**, focusing specifically on those looking to install water source heat pumps.

DECC has already addressed some barriers by establishing:

- The Heat Network Delivery Unit's and its work in providing advice to local authorities interested in heat networks. The Unit is assisting over 122 projects, and this includes nine where local authorities are investigating water source heat pumps as a potential heat source;
- A £7m Heat Networks Demonstration Competition which is supporting a water source heat pump project through Phase One of the competition;
- The Renewable Heat Incentive (RHI), the world's first long-term financial support mechanism for renewable heat technologies, including water source heat pumps.).

Aims and objectives

The aim of this work is to produce a WSHM (as a map layer on the NHM) of prospective resource potential for water source heat pumps across England's water courses in areas of suitably high heat demand (i.e. for heat networks applications).

The key objectives of this project are:

i. To identify areas where environmental factors may potentially constrain water source heat pump installation, and

ii. To identify the highest resource potential locations for open loop water source heat pumps.

Terminology

The evaluation of water source heat pumps necessarily requires an understanding of the technical terms from the fields of thermodynamics and hydrology. A select number of technical terms have been used throughout this report for which a more detailed explanation is required to remove any ambiguity in their definition:

- **NHM -** the National Heat Map (NHM)[5] is based on modelled estimates of annual heat demand. The map allows users to investigate modelled energy use at buildings and street level, supporting the development of heat networks across the country. It acts as

[5] https://www.gov.uk/government/publications/water-source-heat-map

an evidence source for local authorities, developers and community groups, providing heat demands and potential sources in an accessible way.

- A **waterbody** is a discrete portion of surface water (including rivers, lakes, estuaries and coastal waters) with similar physical and chemical properties (which are likely to support similar types of ecosystem). These areas are designated as part of the Water Framework Directive (WFD – see below) and are the unit that is used for assessing water quality and environment targets. National datasets are available at the waterbody level, and therefore are the basis for spatial resolution used in this study. It is important to note that waterbodies are not uniform in size. For example river headwaters are typically divided in to small reaches where there are more confluences and rapid changes in hydrology.
- A **heat pump** moves heat energy from one location to another. Heat pumps are designed to do this against the natural direction of heat flow (i.e. from a colder location to a warmer one). An example of a heat pump is found in a refrigerator which moves heat from the inside to the air in the kitchen in order to keep your food cold. The heat pumps considered here take heat from a local water source and pump it to your home, in order to warm it (see Figure 9). An **open loop** system takes the water from the source to the exchanger and then returns the colder water back. An **abstraction licence** is generally required from the Environment Agency to take more than 20 cubic metres (20,000 litres) per day, and a **discharge consent** will generally be required for the water being returned to the environment after it has flowed through the heat pump.
- **CAMS** – Catchment Abstraction Management Strategies. These are developed for the management of water resources at a local level. They provide information on water resources and licensing practice to allow the needs of abstractors, other water users and the aquatic environment to be considered in consultation with the local community and interested parties.
- **EFIs** – Environmental Flow Indicators, which provide national flow screening thresholds. They are intended to inform abstraction licensing decisions and strategy (including CAMS). Flows below the EFIs indicate where flow pressure may compromise Water Framework Directive (WFD) ecological status. EFIs do not actually identify whether or not good ecological status can be achieved.
- **LFE** – LowFlows Enterprise was created to estimate river flows for any river reach within the UK as represented by annual and monthly flow duration statistics, even where measured flow data is not available. The LowFlows methods have been widely adopted by the UK regulatory agencies, and are available through the LowFlows 2 or LowFlows Enterprise software or as a service provided by Wallingford HydroSolutions Ltd. The software and underpinning science have been widely published in the scientific literature. Its development was jointly funded by the Centre for Ecology and Hydrology Wallingford and the Environment Agency. It is used as a best practice tool for estimating low flows in ungauged catchments by the Environment Agency, the Scottish Environment Protection Agency, the Northern Ireland Environment Agency and UK water companies.

- **WFD** – Is the Water Framework Directive. European Union legislation - Water Framework Directive (2000/60/EC) - establishing a framework for European Community action in the field of water policy.
- **FDC - Flow Duration Curve.** This is the statistical representation of flow rates in rivers. They are typically reported as annual distributions that state the flow exceedances for different portions of the year (as percentiles). An example FDC is shown below as Figure 1. For example, the 70th percentile flow exceedance value is the flow that is equalled or exceeded for 70% of the time. High percentiles (e.g. 95) therefore correspond to low flow values. Conventionally river flow (usually expressed in units of cubic metres per second (m^3s^{-1}) or ‘cumec’) is assigned the variable ‘Q’ and common parlance uses the shorthand Q95 to refer to the flow equalled or exceeded for 95% of the year unless another period is specified.

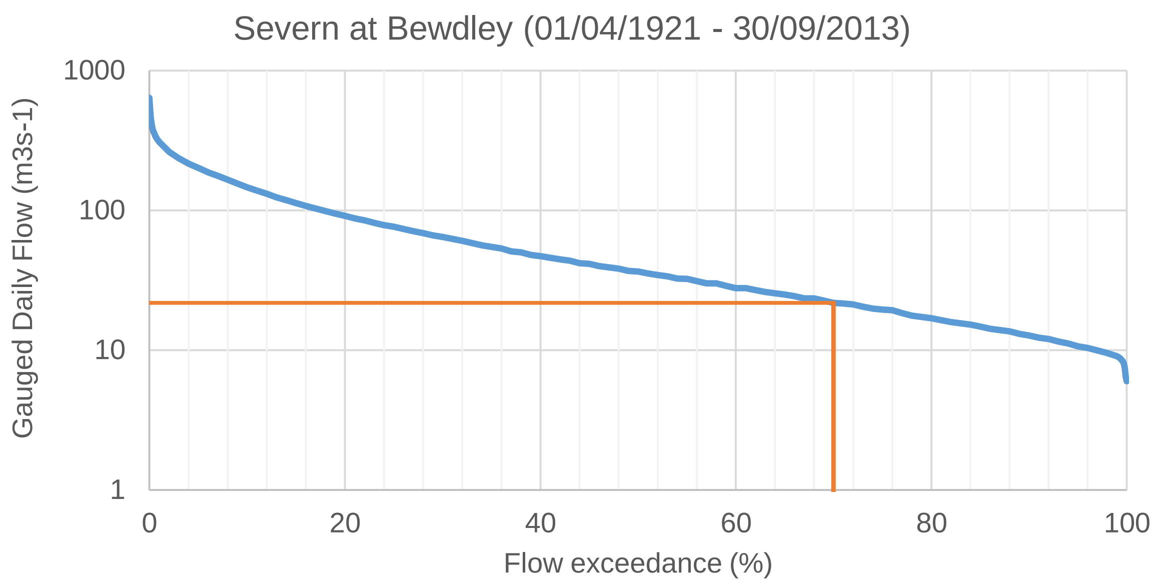

Figure 1 Example flow duration curve in blue, the orange line explains Q70 as the gauged daily flow equalled or exceeded 70% of the time.

In the context of this study we are interested in heat generation for mainly space heating. It is important to recognise that space heating demand only exists for part of the year; namely the winter months. Therefore the flow during this portion of the year is more important than the annual flows. This nuance has been included in this study by evaluating flow statistics during the winter months only, defined here as December to February (abbreviated as DJF).

Coverage

This work considers the heat available from river, canal, estuary (sometimes called transitional) and coastal waterbodies across the whole of England. Water Framework Directive waterbodies[6] were used for the rivers, estuaries and coastal areas, and data were also supplied on canals by the Canal & River Trust (CRT). The numbers of waterbodies considered are summarised in Table 1.

Table 1 Waterbody types and numbers considered in this project

Type of waterbody*	Number considered
River	3,769
Canal	53 'CRT features', 40 of which had flow estimates
Estuary (transitional)	135
Coastal	84

*See description in the text

[6] More information on the WFD waterbodies can be found at www.wfduk.org

Constraint mapping

Overview

In addition to the physical constraints on extracting heat from a waterbody, environmental constraints must also be considered. It is acknowledged that a national scale quantitative assessment of heat capacity cannot cover all the site specific constraints and qualitative assessments that would be required to implement a particular scheme. However there are national datasets that provide a high level indication of whether a site could be particularly sensitive.

This section outlines the methodology used to produce environmental constraints layers relevant to the development of this water source heat map. This assessment has used a Geographic Information System (GIS). If any part of a waterbody overlaps an environmentally protected or sensitive area it will be flagged appropriately. A table of the attributes provided is shown in Annex A. Currently, this constraints information is available as a displayable attribute for each waterbody, but not in GIS format.

This assessment is indicative only; the development of a heat pump would require a more detailed site-specific analysis. The presence of a designated area does not completely discount the possibility of development. For this reason the heat capacity estimates have been calculated at all waterbodies regardless of the presence of the constraints discussed here. Consultation with the local Environment Agency office is therefore a prudent first step in the planning and design of any specific scheme.

Environmental designations

The Joint Nature Conservation Committee (JNCC), the government's advisory body on nature conservation, describes protected sites as a key policy tool for conserving important habitats and species.

"Legal protection prevents damaging activities. Some of the sites, known as Special Protection Areas (SPAs) for Birds and Special Areas of Conservation (SACs), are of European importance. They have been created under the EC Birds Directive and Habitats Directive. In the UK they form part of a larger European network called Natura 2000. Within the UK sites that are nationally important for plants, animals or geological or physiographical features are protected by law as Sites of Special Scientific Interest (SSSIs)… This system provides the underpinning statutory protection for all sites, including those which are also of international importance."[7]

For this work, the following environmental designations have been assessed for all waterbody types:

- Sites of Special Scientific Interest (SSSI)
    - SSSIs are the best examples of our natural heritage of wildlife habitats, geological features and landforms. An SSSI is an area that has been notified as being of special interest under the Wildlife and Countryside Act 1981. (https://www.gov.uk/sites-of-special-scientific-interest-and-historical-monuments)

[7] Joint Nature Conservation Committee, "UK Protected Sites", [Online] Available: http://jncc.defra.gov.uk/default.aspx?page=4

- Special Protection Areas (SPA)
    - Special Protection Areas (SPAs) are strictly protected sites classified in accordance with Article 4 of the EC Directive on the conservation of wild birds (79/409/EEC), also known as the Birds Directive, which came into force in April 1979. They are classified for rare and vulnerable birds, listed in Annex I to the Birds Directive, and for regularly occurring migratory species. In the UK, the first SPAs were identified and classified in the early to mid-1980s. Classification has since progressed and a regularly updated UK SPA Summary Table provides an overview of both the number of classified SPAs and those approved by Government that are currently in the process of being classified (these are known as potential SPAs, or pSPAs). (http://www.jncc.gov.uk/page-162)
- Special Areas of Conservation (SAC)
    - SACs are strictly protected sites, designated under the EC Habitats Directive. Article 3 of the Habitats Directive requires the establishment of a European network of important high-quality conservation sites that will make a significant contribution to conserving the 189 habitat types and 788 species identified in Annexes I and II of the Directive (as amended). The listed habitat types and species are those considered to be most in need of conservation at a European level (excluding birds). Of the Annex I habitat types, 78 are believed to occur in the UK. Of the Annex II species, 43 are native to, and normally resident in, the UK (http://www.jncc.gov.uk/page-23).
- Ramsar
    - An intergovernmental treaty which provides the framework for national action and international cooperation for the conservation and wise use of wetlands and their resources. There are presently 158 Contracting Parties to the Convention, with 1752 wetland sites, totalling 161 million hectares, designated for inclusion in the Ramsar List of Wetlands of International Importance. (http://www.ramsar.org/).

Figure 2 illustrates the distribution of environmental designations assessed as part of this project. Note that many of the designations are overlapping (i.e. an area has more than one designation). These designations have been captured in the mapping to provide an initial indication. The map will not state definitively that a site within or upstream of a designation is protected from the development of a heat pump scheme. Many of the designations will be unaffected by changes in water temperature, but a site-by-site analysis is needed during a feasibility or planning process.

In addition, the freshwater fisheries status and Catchment Abstraction Management Strategy (CAMS) water resource status has been mapped below for river waterbodies, and shellfish water designations have been reported for coastal and transitional waterbodies. Note however that the CAMS water resource status is not shown in the NHM due to licence restrictions.

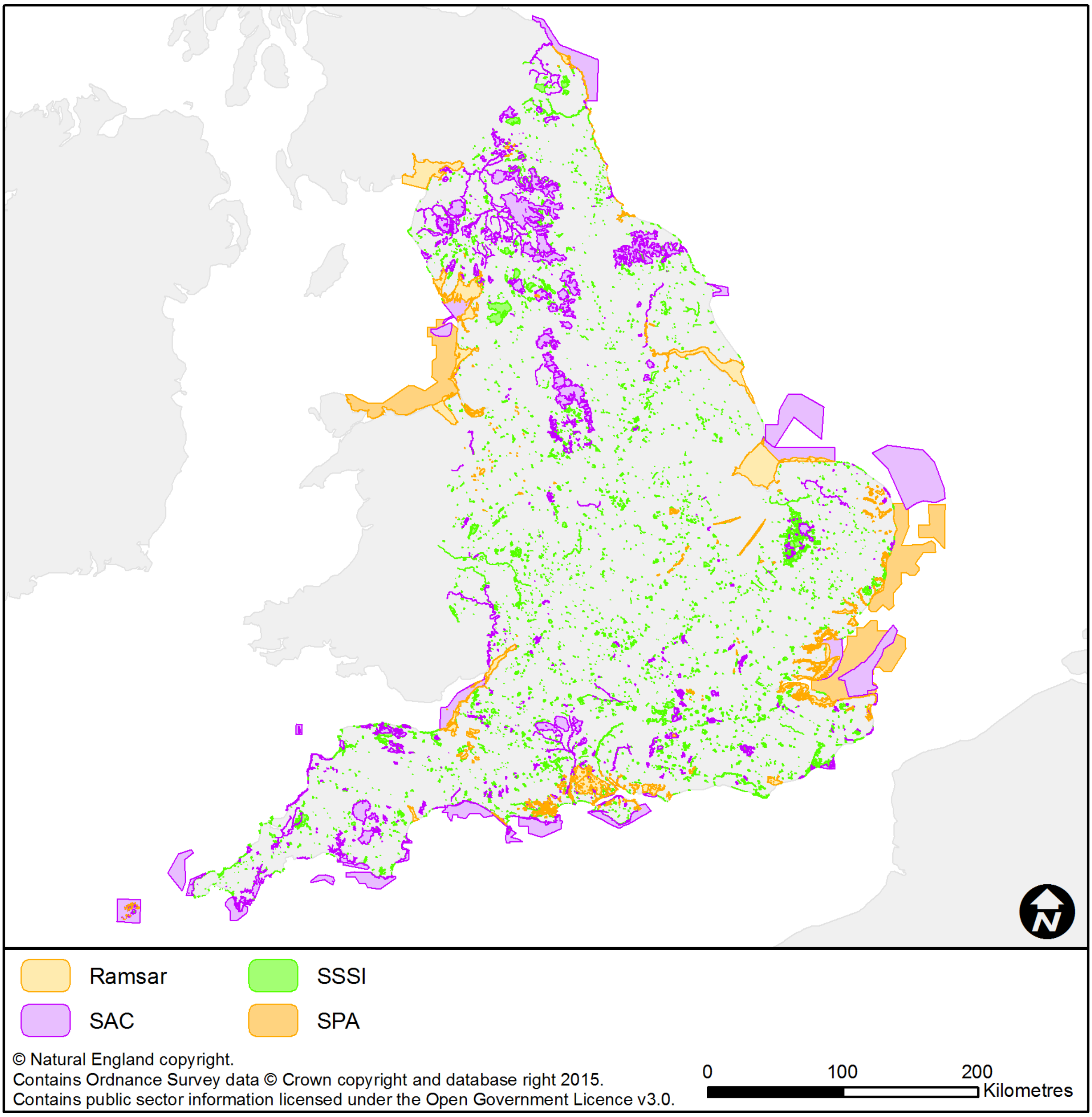

Figure 2 Environmental Designations

Rivers

The WFD river waterbodies GIS layer was used in the assessment of the rivers, and is shown in Figure 3. There are a total of 3769 river waterbodies in England with a length of 46,938 km. Of these 3640 waterbodies had sufficient information to estimate heat capacity. It should be noted that the assessment of environmental designations for river waterbodies is for the entire length of each river waterbody.

Each river waterbody has been checked to see where it intersects with the four environmentally designated areas mentioned above and then separately for protected freshwater fisheries interests and for water resource availability.

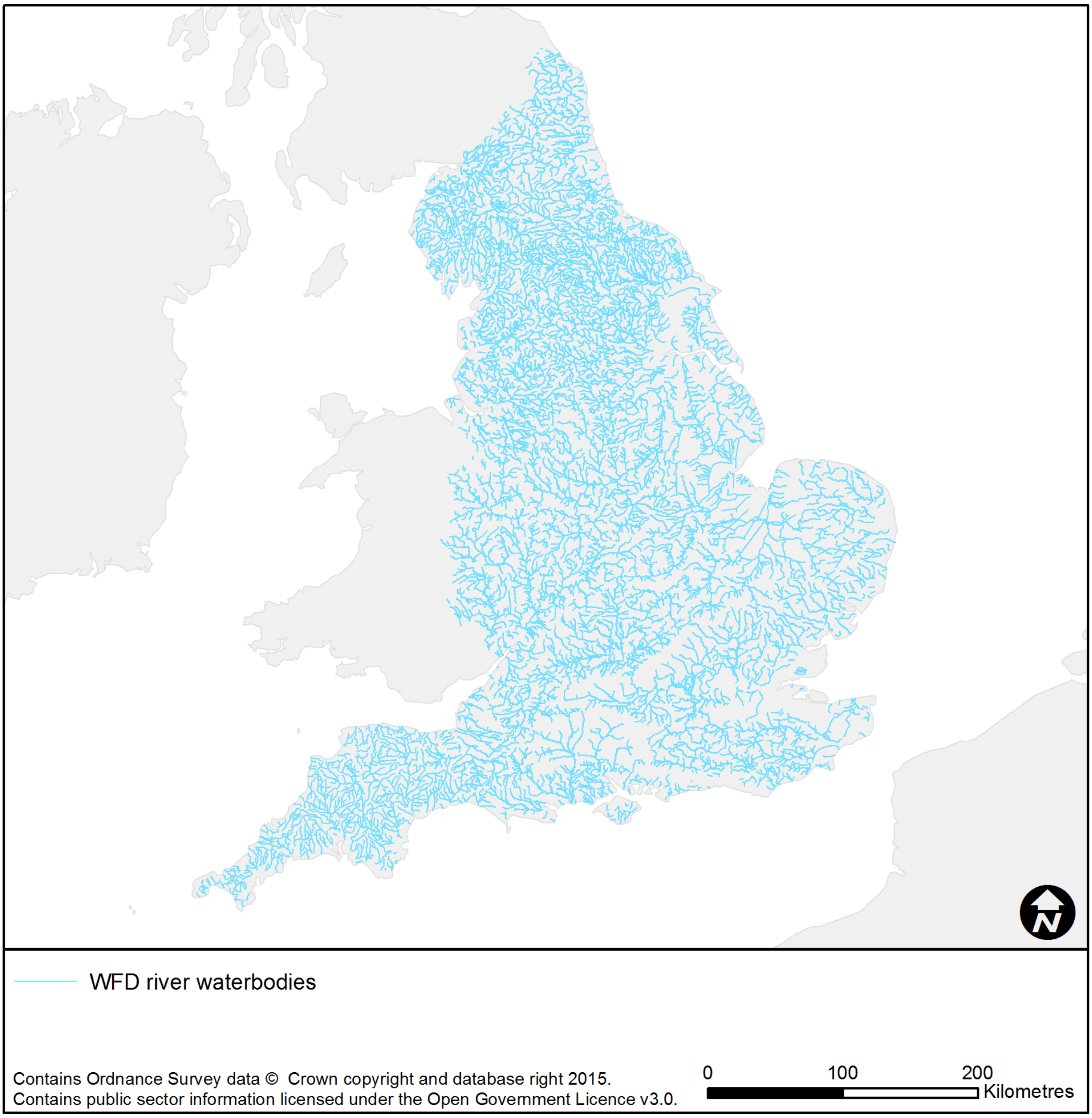

Figure 3 River and canal waterbodies

Figure 4 shows the freshwater fisheries status[8] for river waterbodies in England. Salmonid fish spawning is likely to be more susceptible to colder water temperatures in the winter which may affect the timing of hatching. Cyprinid fish spawning is likely to be less affected due to spawning through the summer months.

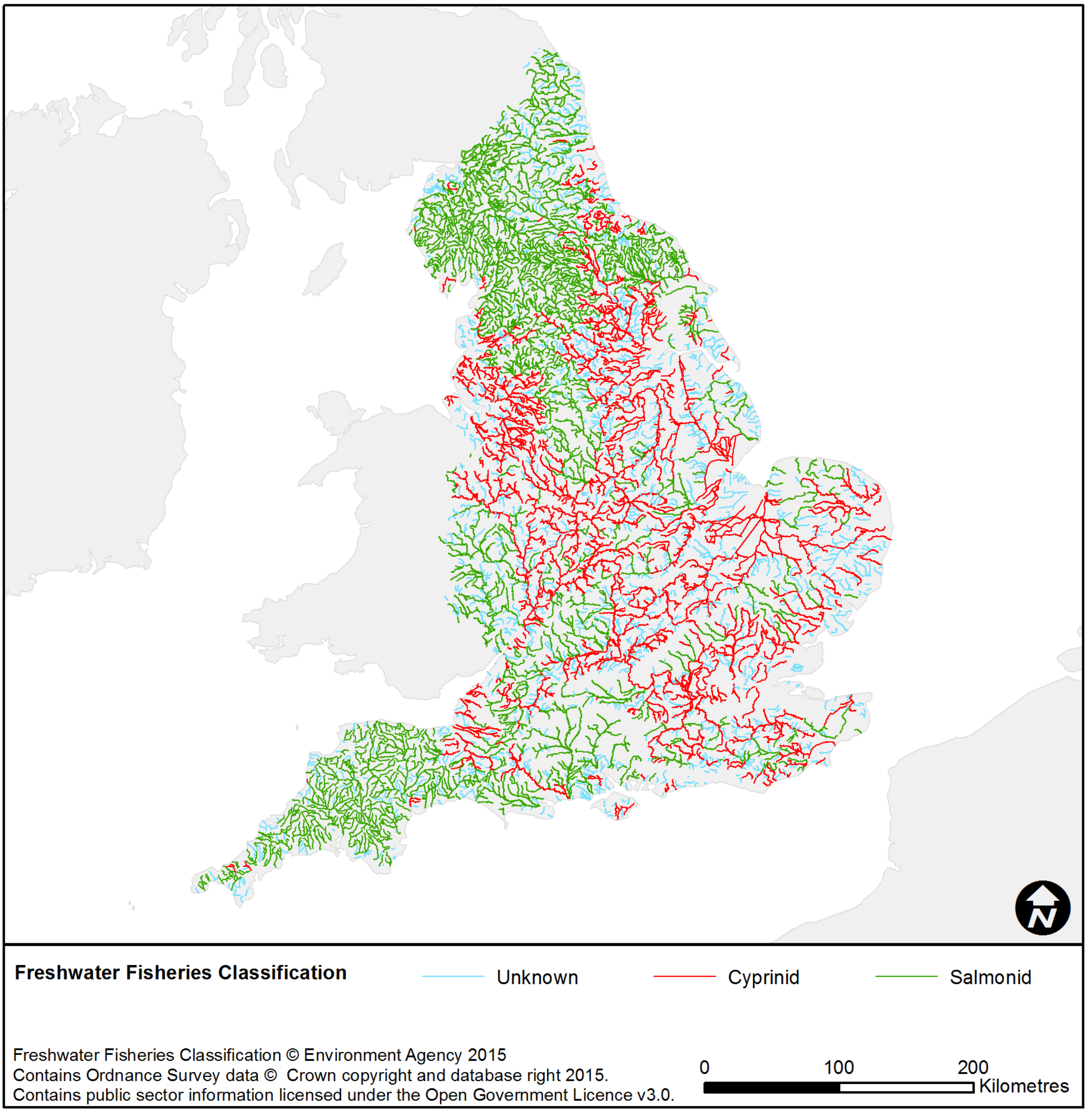

Figure 4 Freshwater Fisheries Classification

[8] The repealed Freshwater Fish directive defined:

Salmonid as fish belonging to species such as salmon (Salmo salar), trout (Salmo trutta), grayling (Thymallus thymallus) and whitefish (Coregonus), and

Cyprinid as fish belonging to the cyprinids (Cyprinidae), or other species such as pike (Esox lucius), perch(Perca fluviatilis) and eel (Anguilla anguilla)

Water resource availability

The CAMS water resource status has also been reported for river waterbodies at Q30, Q50, Q70, and Q95, where Q30 is the flow exceeded for 30% of the time. Note that these percentiles are for annual flows, rather than being specific to the winter months most relevant to the use of water heat source pumps. Also, the status refers to (specifically the outflow from) each of the river waterbody catchment area; i.e. the area of land draining to the downstream point of the river in each waterbody.

The CAMS status is one of: “Water Available”, “Restricted Water Available” or “Water Not Available”, and is provided for information only, as the non-consumptive nature of the heat pump abstraction reduces the impact on the river. As such non-consumptive abstraction could be permitted in a “Water Not Available” area. Figure 5 illustrates the CAMS water resource status for the annual Q95 flows using a traffic-light colouring scheme. This information, along with EFI, is not available on the NHM due to licensing constraints with the source data.

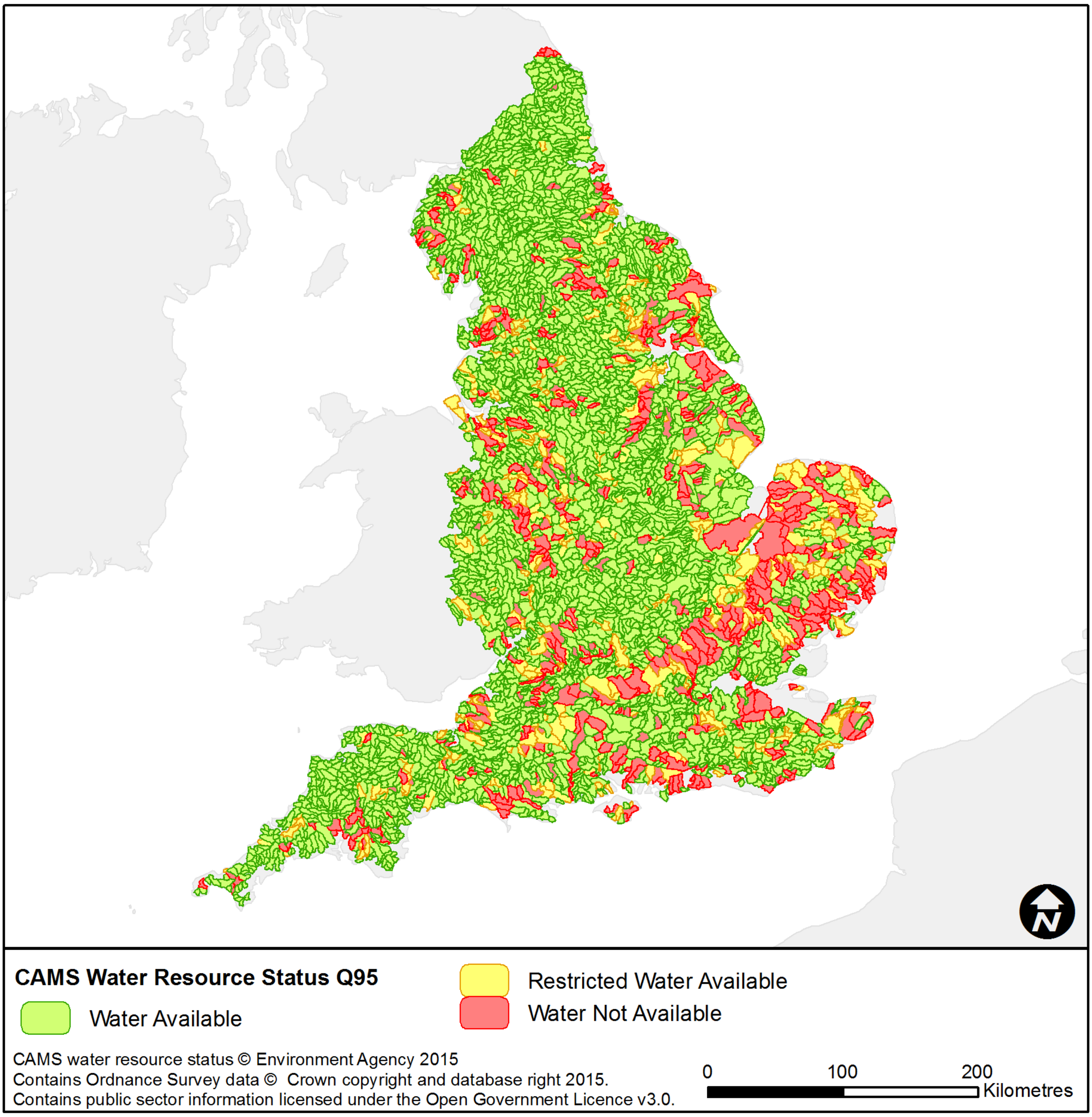

Figure 5 CAMS Water Resource Status for Annual Q95 flows

Canals

The Canal & River Trust (CRT) have provided two GIS layers representing canals in England and Wales: One dataset includes flow estimates, which are used in the heat pump model; the other identifies the name and location of the canals subdivided into smaller reaches. The former dataset provided 53 canal features, 40 of which had flow estimates. The second dataset has been used in the assessment of environmental constraints in order to provide a higher resolution output. The canals data (Figure 6) has been processed in the same way as the river waterbodies, but only against the environmentally designated areas as canals do not have protected freshwater fisheries or CAMS resource status. It is noted that other canal waterways, not operated by CRT exist, but no flow data was available to include them in this study.

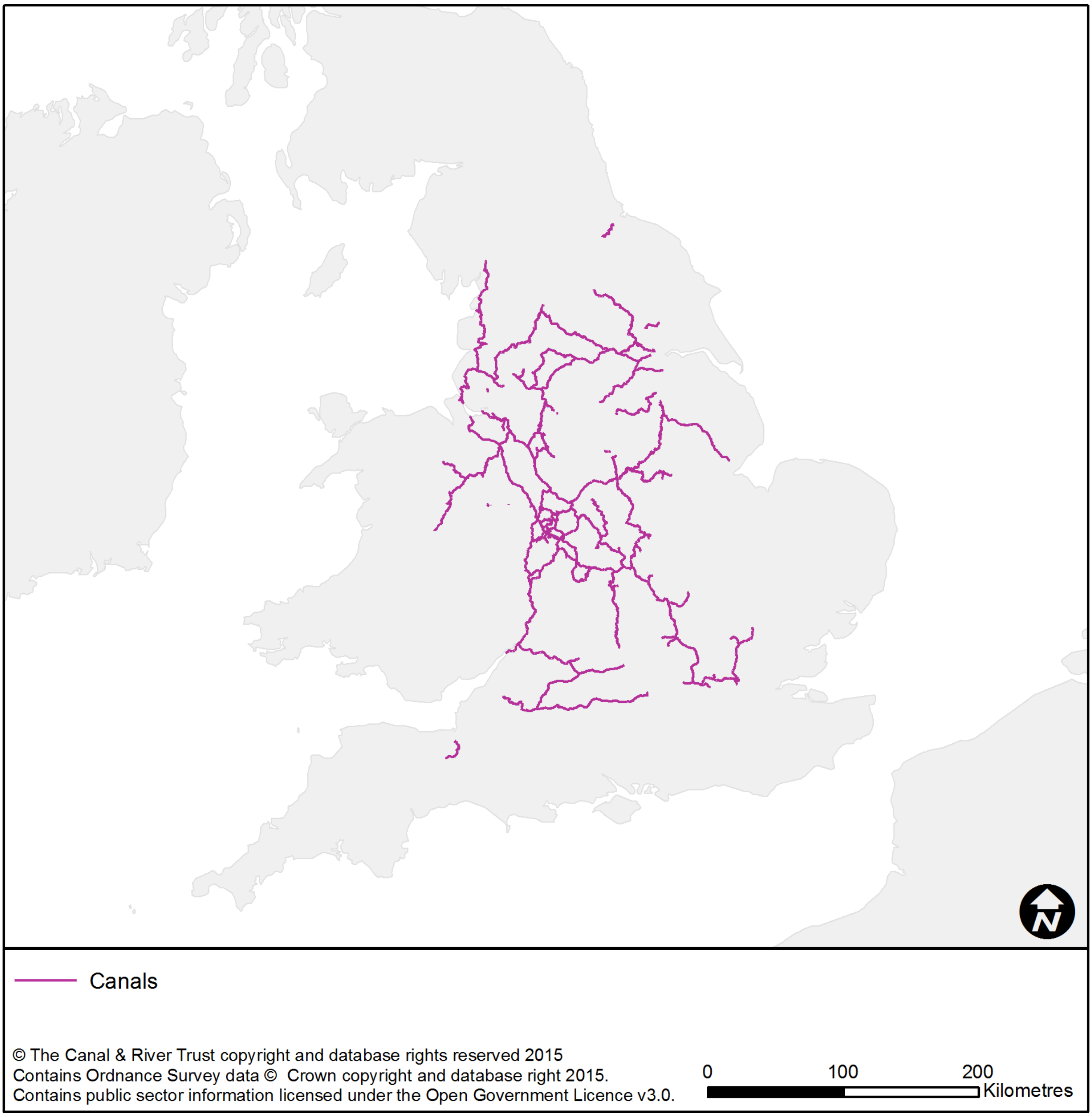

Figure 6 Canal and river waterbodies

Coastal and transitional waterbodies

The coastal and transitional waterbodies data (Figure 7) has been processed in the same way as the river waterbodies, against the environmentally designated areas. However, there is no relevant CAMS resource status and it is the protected shellfish waters designation that is relevant here rather than freshwater fisheries. There are 84 coastal and 135 estuarine waterbodies.

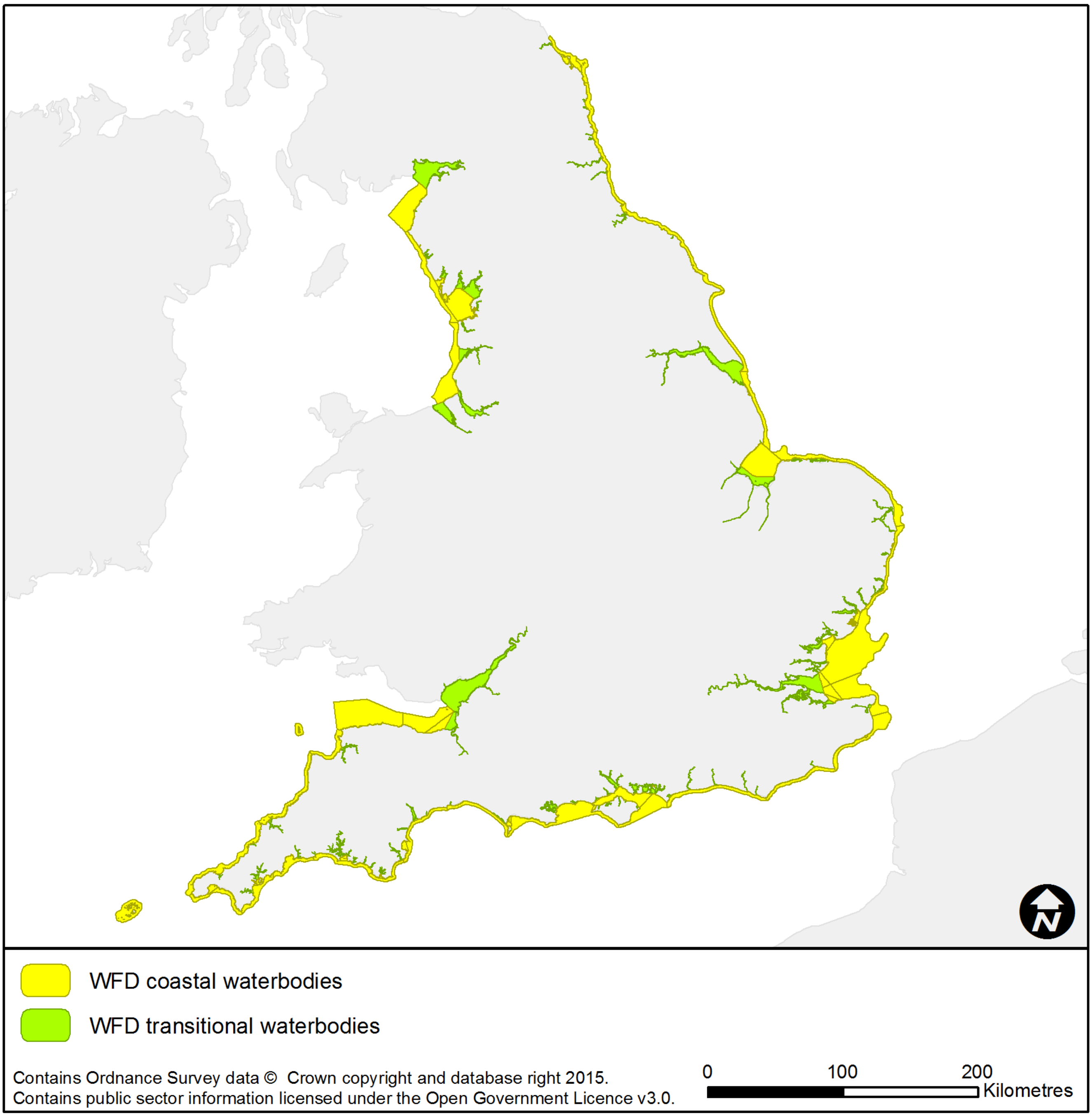

Figure 7 Coastal and estuarine (referred to as transitional in the WFD) waterbodies

Calculating water source heat capacity

This section provides a brief summary of the methodology used to calculate water source heat capacity. The reader is encouraged to read the more detailed account given in Annex B:

Water temperature

Data on winter water temperatures is vital for determining heat capacity. The Environment Agency (EA) has compiled a database of national water temperature records up to 2007, but with the caveat that it contains raw measurements and is not comprehensively quality assured. The Environment Agency undertook an analysis of river data[9] to discover trends, seasonal and regional differences. An upward trend in temperatures over the last 20 to 30 years was identified; particularly apparent in Anglian, Thames and South West regions.

For this study the river temperature database was interrogated to find appropriate winter temperatures to apply at each waterbody. This calculation was made by taking the mean winter (December – February, referred to as DJF) temperature for each assessment point in the temperature database. These points were then mapped to the river network and an interpolation algorithm used to estimate a temperature at the same points for which flow estimations are available (flow estimates being described later in this section).

The EA database contained adequate records for rivers, canals and estuaries but there was less data for coastal locations. As a result, for coastal waterbodies, Centre for Environment, Fisheries & Aquaculture Science (Cefas) monitoring data was used. Winter mean temperatures were calculated from each of the Cefas stations and interpolated on to the coastal waterbody areas. Figure 8 shows the temperature values used for the river, estuary and coastal waterbodies. There is a strong trend to warmer waters in the south-west as expected from the lower latitudes and influence of the Gulf Stream. Canals are not shown as they would not be clearly visible when overlaid with the waterbody catchment areas.

[9] Environment Agency, "Climate change impacts and water temperature," July 2007. [Online]. Available: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/290975/scho0707bnag-e-e.pdf

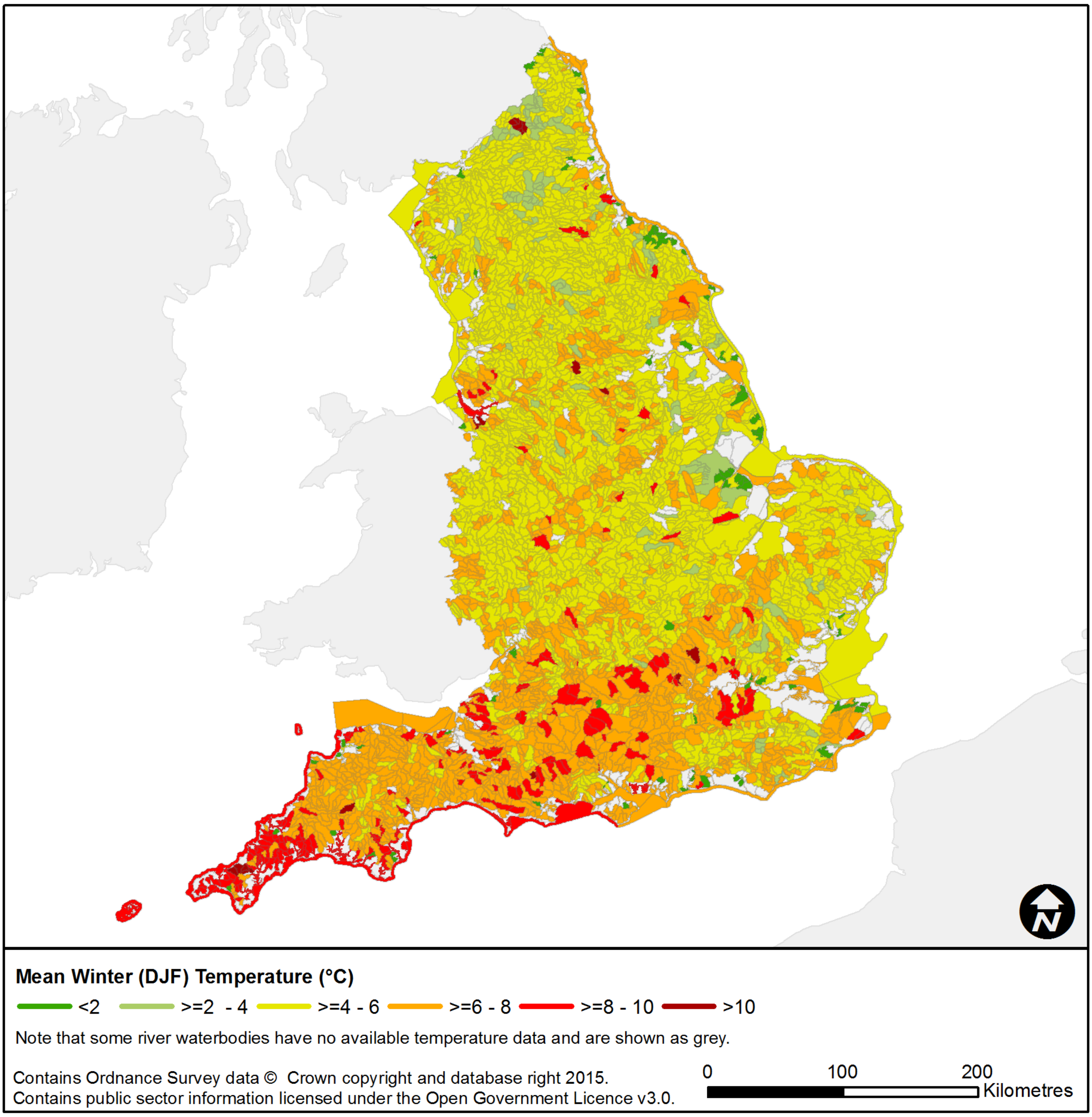

Figure 8 Mean winter (DJF) temperature °C for river, transitional and coastal waterbodies

Changes to temperature

A maximum temperature change of 3 °C for the fully mixed waterbody temperature has been used as an absolute limit to heat abstraction, when using a water source heat pump. This limit is based on recommendations from WFD technical advice[10] but is not defined as a standard. The recommended standards are defined as 98th percentile absolute maximum temperatures, and therefore only concern discharges *increasing* water temperature (whereas the heat pumps of interest in this study decrease water temperature). This national study has estimated heat capacity based on average temperature changes and has not undertaken a detailed analysis of

[10] UK Technical Advisory Group, "UK Environmental Standards and Conditions (Phase 2)," March 2008. [Online]. Available: http://www.wfduk.org/sites/default/files/Media/Environmental%20standards/Environmental%20standards%20phase%202_Final_110309.pdf

daily temperature profiles at each location. Further clarification of guidelines and standards with the local Environment Agency office and other stakeholders will be necessary when developing a specific site.

Given the scale of the project and the data used, the results are not intended to replace any part of an individual site assessment. This is necessary before any proposed scheme can be considered for approval, by the EA and other regulatory bodies.

It is noted that changing a waterbody's temperature by 3 °C in winter is not always possible due to the physical limits of the heat exchanger. It is also assumed that winter mean temperatures should not be reduced below 3 °C, so any waterbody temperature below 6 °C will have a smaller limit on the temperature change allowed. Thus, a mean temperature of 4 °C, means only a 1 °C is allowed in the assumptions for this project.

Heat pumps

In order to determine the heat capacity of a waterbody, a simple model of a heat pump is required to set the physical constraints of the system. This study has assessed an open loop setup that abstracts water from the environment, passes it through a heat exchanger and subsequently discharges the cooler water back to the environment. A diagram of the system is shown in Figure 9. The system illustrated includes a filter between the pump and the heat exchanger which helps to prevent build-ups of impurities from the water source (such as sediment) inside the heat exchanger.

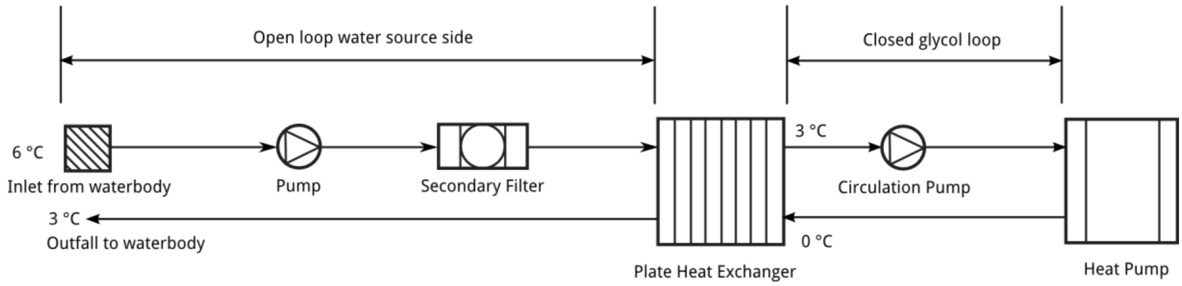

Figure 9 Heat pump schematic

A critical value for the calculation of heat capacity is the minimum temperature at which the heat exchanger can operate without unacceptable ice crystal formation. In freshwater this value has been taken to be 3 °C with a minimum of a 1 °C gradient[11] (i.e. abstracted water must be at least 4 °C to ensure a 1 °C difference across the exchanger). In sea water this temperature is assumed to be -2 °C (again with a minimum gradient of 1 °C), and is interpolated for less saline areas. A constraint on the heat capacity is therefore a limit on the absolute temperature change that can be achieved here. Saline waters can operate at lower temperatures due to the lower incidence of ice crystal formation.

Water availability

A second constraint on extracting heat from waterbodies is the volume of water available and a limit on how much could be abstracted. Natural river flow estimates were obtained at 3720 waterbody outlets from Wallingford HydroSolutions (WHS) via their LowFlows Enterprise (LFE) model. This model was used to provide winter (DJF) flow estimates for Q95, Q70 and Q50 percentiles. These values represent the flow which is exceeded for the respective portion of the

[11] This value is based on advice given by several manufacturers of water source heat pumps available in the UK.

season. For example the Q95 flow is exceeded for 95% of the winter (see further explanation in the terminology section near the beginning of this report).

The analysis in this study is based on the Q95 winter flow estimates. While this is a lower than average flow it is used as an indicator of the winter flow which could be relied upon being available for water source heat pumps.

Along with the river flow available in a river there is also a constraint to the amount that could be abstracted from it. The Environment Agency's Environmental Flow Indicator (EFI) has been used for this constraint. The EFI is a threshold change in natural river flow, defined at annual flow exceedances, above which adverse impacts on ecology could occur. It has been used in this study to define the maximum abstraction that a single heat pump scheme could make from a river or canal. However, it is recognised that water source heat pump abstractions are non-consumptive and the volume is fully returned to the river. Therefore multiple abstractions, each extracting additional heat, could be possible.

For coastal and estuarine waterbodies defining abstraction limits is difficult without more complex models. This is especially true due to the non-consumptive nature of the discharges. Therefore calculations of heat capacity have been made on a per unit (m^3s^{-1}) abstraction rate.

Aggregating urban areas

The methodology described so far has concerned the evaluation of a single heat pump scheme. On rivers and canals this is restricted to a maximum abstraction rate based on the EFI. At coastal and estuarine locations this is estimated per unit abstraction. However these values are not related to areas of heat demand.

In order to compile an aggregated list of heat capacity at heat demand locations further spatial analysis was undertaken. Ordnance Survey data on Developed Land Use Areas (DLUA) from the Meridian 2 dataset was used to identify areas of urban development; the largest area included in the study is London (136,421 hectares), while the smallest is Thornton (in West Yorkshire) which has an area of only 3.3 hectares. The resulting areas were evaluated to determine if a river was within 1 km. Where a section of river was present within an urban area the most downstream point was used to evaluate the heat capacity. Where multiple independent rivers were present each was evaluated separately and their heat capacities summed.

The output of this analysis is a maximum heat capacity that might be achieved in each area. These areas are shown as 'settlements' on the NHM.

This calculation assumes there is sufficient distance to locate multiple heat pumps within the developed area to extract the total heat capacity while remaining within the single scheme abstraction limits (here assumed to be within the EFI).

These urban areas or 'settlements' were also combined with the existing heat demand information from the NHM. Consequently there is a water source heat capacity (from rivers only) and heat demand for each area.

Summary of input datasets and associated licencing

This section provides an overview of the various input datasets used in the calculation of heat capacity, and associated licencing. A flowchart showing the inter-relationship between these datasets within the methodology is provided in the following section.

Table 2 Input datasets used in the calculation of heat capacity

Dataset name	Licence information	Waterbody types
Environment Agency Surface Water Temperature Archive	Open Government Licence	Rivers, estuaries and canals
Cefas temperature database	Data is © Cefas, accessed via publically available information provided on their website	Coastal
WFD River Waterbodies Cycle 2 Draft[12]	Open Government Licence	Rivers
WFD Transitional Waterbodies Cycle 2 Draft[12]	Open Government Licence	Estuaries
WFD Coastal Waterbodies Cycle 2 Draft[12]	Open Government Licence	Coastal
Canals (including flow estimates)	Licenced to DECC for this project by CRT	Canals
WHS LowFlows flow estimates	Licenced to DECC for this project by WHS[13]	Rivers
Ordnance Survey Developed Land Use Areas (DLUA)	OS OpenData Licence	Rivers

[12] We are currently approaching the end of WFD management Cycle 1. The Cycle 2 “draft” layers are the best available data, but will remain “draft” until the beginning of Cycle 2 in 2016.

http://ec.europa.eu/environment/water/water-framework/info/timetable_en.htm

Summary of heat capacity findings

This section provides a summary of the findings of the analysis undertaken in this study. An overview of the impact of the identified constraints is given as well as a quantitative summary of the heat capacity estimates.

Rivers

Each of the river waterbodies and canal reaches has been assessed for heat capacity as described in the previous section and Annex B. The most detailed analysis can be undertaken on river waterbodies as there are much more detailed flow, temperature and constraints data sources available.

Figure 10 shows the spatial distribution of river flows and heat capacities in English rivers. This map highlights the rivers with the largest heat capacity based on a single abstraction. Those rivers with higher flow are plotted with a wider line and correlate (as in Figure 13) with heat capacity. The rivers with the largest capacities are therefore the Ouse (Yorkshire), Trent, Thames, Severn, Aire and Wye).

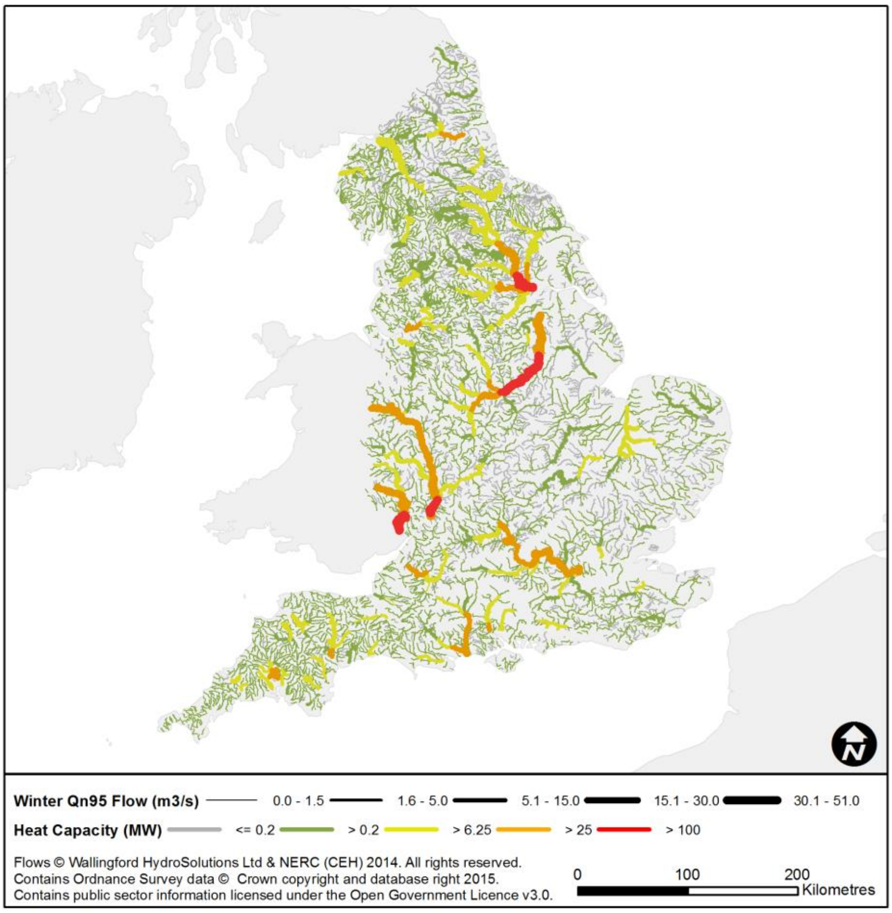

Figure 10 River EFI heat capacity

The following figures help to illustrate the relationships between river flow, winter temperature, and heat capacity of a single scheme. Each point on the graphs represents an assessed river waterbody. The colour of each point represents the flow available based on the EFI (see the earlier section on “Water availability” for more details).

- Figure 11 plots the river bodies’ winter temperatures against the winter Q95 flow. Each water body is represented by a coloured point indicating its EFI value, given by the key on the right.
- More extreme water temperatures are generally restricted to rivers with small flows, with large rivers all falling within the 4 – 8 °C range. This important result shows that large rivers typically have winter mean temperatures warm enough to extract heat within the constraints described here.
- However, in addition to previously stated limitations, there is no guarantee that the monitoring agencies have used a consistent period for the temperature interpolation for different waterbodies. Some of the variation in temperatures could therefore be biased due to meteorological conditions during the period of sampling that fed into the interpolation.
- The red shaded area represents the river temperature range (<4 °C) where the heat exchanger cannot operate in fresh water.
- The yellow shaded area represents the river temperature range (4 °C to 6 °C) where temperature is the limiting factor restricting total heat capacity.
- Warmer rivers (>6 °C) are not limited by the absolute temperature because the environmental constraint limits temperature change to at most 3 °C.

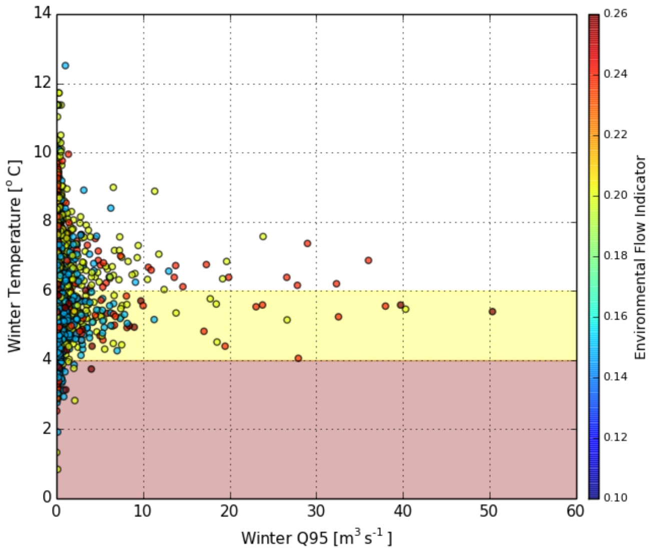

Figure 11 Relationship between winter river flow and temperature

The colour scaling shows the EFI proportion based on the annual equivalent of the winter Q95 flow. See “Water availability” for more details.

- Figure 12 plots the maximum heat capacity of a heat pump against the river flow rate. The maximum heat capacity is subject to the EFI and the temperature gradient across the heat exchanger. There is a strong correlation between the maximum heat capacity and the river flow.
    - The EFI heat capacity (Figure 12a) defines the maximum size of a heat pump scheme that could reasonably be expected with a single open loop. Here the limit is the size of abstraction defined by the EFI and the temperature gradient across the heat exchanger. There is a strong relationship with winter flow, as the abstraction is limited by the EFI which is a proportion to the winter flow.
    - The full heat capacity (Figure 12b) is calculated by assuming that the river temperature can be varied up to its maximum limit. This limit is constrained by either the absolute gradient across the heat exchange (if the river is not above 6 °C; yellow shaded area in Figure 11), or the maximum change of 3 °C defined by the environmental constraint. This second constraint defines a fixed relationship (dashed line) on which the environmental temperature limit is constraining heat capacity rather than the heat exchanger.

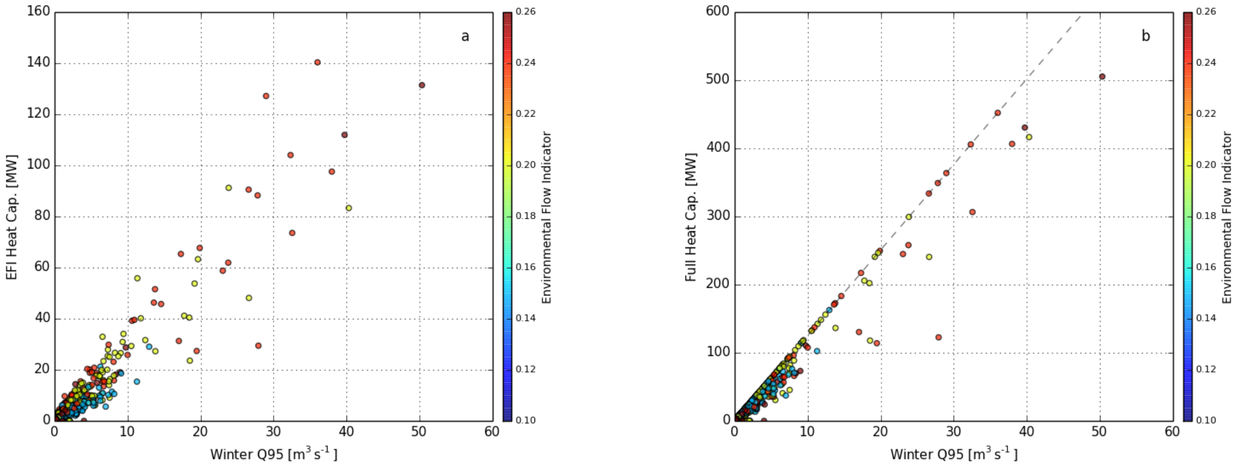

Figure 12 Relationship between river flow and heat capacity

The colour scaling shows the EFI proportion based on the annual equivalent of the winter Q95 flow. See “Water availability” for more details.

- Figure 13 shows the ratio of full heat capacity to EFI heat capacity. This ratio shows an estimate of how many schemes, limited by the EFI abstraction rate, are required to reach the full heat capacity. The calculation is an approximation as it does not account for the progressive cooling or surface heat gain between schemes. It should also be noted that more highly sensitive rivers (bluer shaded circles) typically have lower winter flows.

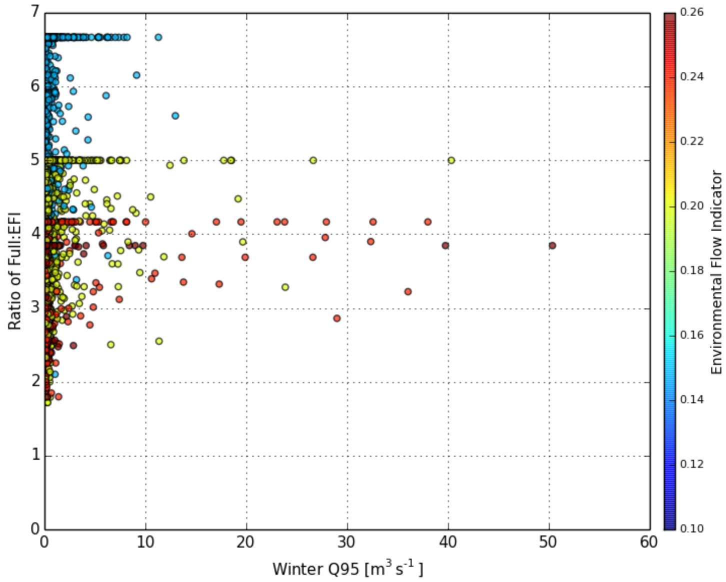

Figure 13 Relationship between river flow, EFI and heat capacity

The colour scaling shows the EFI proportion based on the annual equivalent of the winter Q95 flow. See "Water availability" for more details.

Urban areas

Aggregating the heat capacity from rivers at urban areas reveals those developed areas with the largest total heat capacity. Figure 14 shows how these urban areas are located on the larger rivers in England.

In most cases the urban areas are dominated by a single river from which the majority of the heat capacity is taken. However London is different due to its large size, encompassing many different tributaries into the Thames estuary. The additional heat capacity provided from the estuary itself (like the Mersey, Tyne, etc.) is not included in this plot of freshwater rivers.

A similar aggregation for coastal and estuarine water is not possible, as their heat capacities have been calculated in MWm^3s^{-1} (power per unit abstracted) rather than MW (power). In practice it would be possible for an urban area such as London to extract heat from multiple waterbody types (i.e. rivers and the Thames estuary). For this reason, the heat capacities shown on the map are underestimates of the total heat capacity for urban areas near the coast or on an estuary.

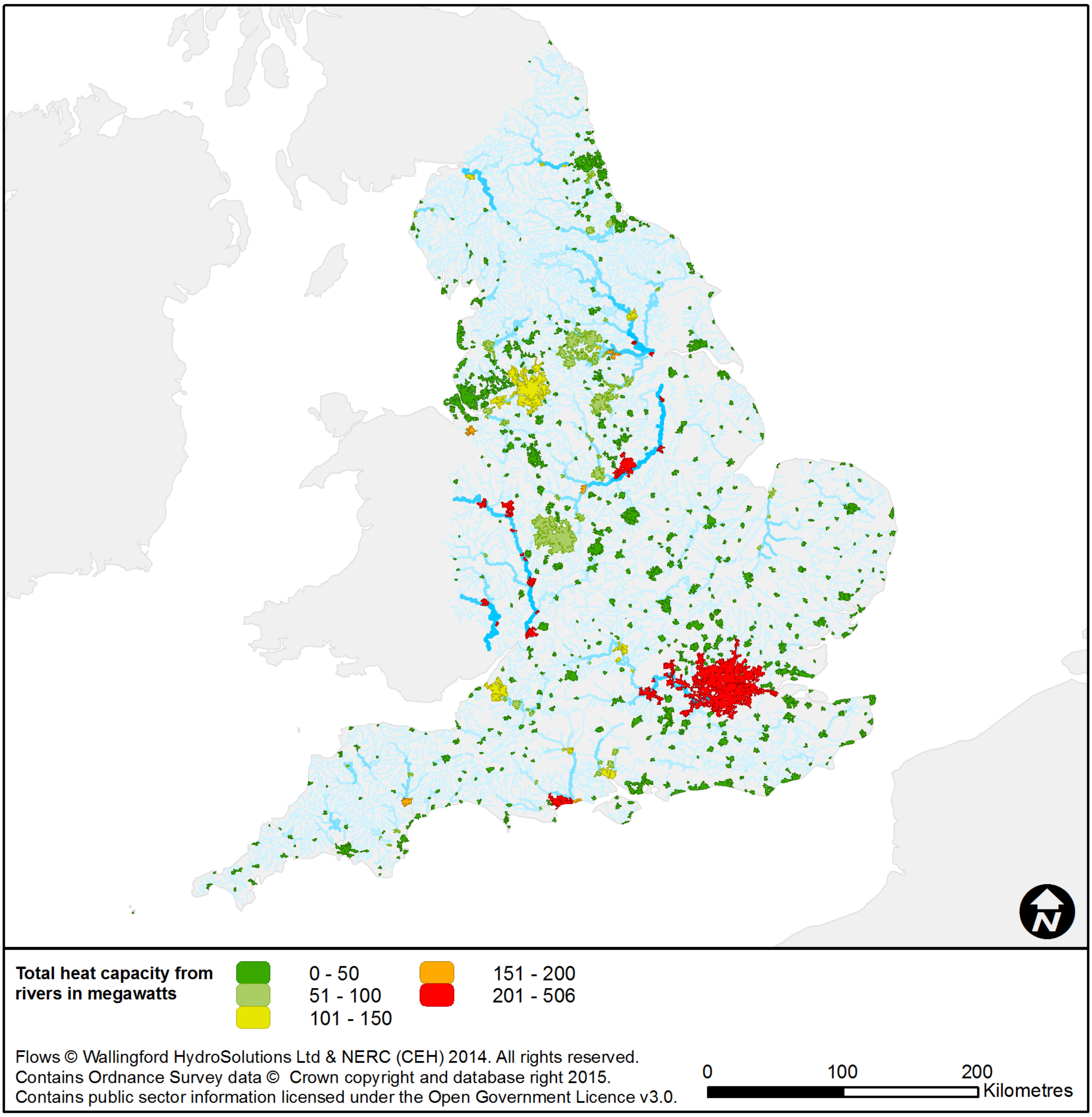

Figure 14 Total heat capacity from rivers in megawatts for urban areas

Taking the data from the above analysis it is possible to create a ranked list of urban areas based on the total heat capacity. The list of all (49) urban areas with river heat capacity greater than 100 MW is provided in Table 3. There are repeated occurrences of urban areas on England's largest rivers: Ouse (Yorkshire), Trent, Thames, Severn, Aire and Wye.

Heat demand data from the NHM has also been aggregated for these areas in the table below. These are categorised in Table 3 as 'Very High', 'High', 'Medium' and 'Low' for annual demands greater than 10,000, 1,000, 100 and 0 GWh respectively.

Table 3 Urban areas and rivers ranked by river heat capacity > 100 MW

Rank	Urban Area (River)	Heat Cap. (MW)	Demand	Rank	Urban Area (River)	Heat Cap. (MW)	Demand
1	Selby (Yorkshire Ouse)	505	Medium	26	Marlow (Thames)	241	Medium
2	Goole (Yorkshire Ouse)	505	Medium	27	Ross-on-wye (Wye)	241	Low
3	Nottingham (Trent)	453	High	28	Burton upon Trent (Trent)	202	Low
4	Newark-on-Trent (Trent)	452	Medium	29	Christchurch (Stour) *	199	Medium
5	London (Thames and tributaries) *	444	Very High	30	Chester (Dee)	198	Medium
6	Tewkesbury (Severn)	430	Low	31	Pontefract (Aire)	186	Medium
7	Gloucester (Severn)	418	Medium	32	Knottingley (Aire)	175	Medium
8	Gainsborough (Trent)	407	Medium	33	Castleford (Aire)	173	Medium
9	Weybridge (Thames)	406	High	34	Exeter (Exe)	173	Medium
10	Stourport-on-Severn (Severn)	350	Low	35	Wallingford (Thames)	143	Low
11	Egham (Thames)	336	Low	36	Warrington (Mersey)	141	High
12	Chertsey (Thames)	334	Low	37	Southampton (Test and Itchen) *	137	High
13	Worcester (Severn)	307	Medium	38	Prudhoe (Tyne)	136	Medium
14	Hereford (Wye)	305	Medium	39	Hexham (Tyne)	136	Medium
15	Telford (Severn)	304	High	40	Manchester (Irwell)	135	Very High
16	Slough (Thames)	275	High	41	Lymm (Manchester Ship Canal†)	132	Low
17	Reading (Thames)	273	High	42	Carlisle (Eden)	131	Medium
18	Shrewsbury (Severn)	258	Medium	43	Rothwell (Aire)	122	Medium
19	Bournemouth (Stour) *	254	High	44	Irlam (Manchester Ship Canal†)	117	Medium
20	High Wycombe (Thames)	251	Medium	45	York (Yorkshire Ouse and Foss)	115	High
21	Maidenhead (Thames)	250	Medium	46	Oxford (Thames and Cherwell)	108	High
22	Windsor (Thames)	250	Medium	47	Abingdon (Thames)	108	Medium
23	Bewdley (Severn)	245	Medium	48	Salisbury (Avon)	104	Medium
24	Bridgnorth (Severn)	245	Low	49	Bristol (Bristol Avon)	101	High
25	Henley-on-Thames (Thames)	241	Medium				

† The Manchester Ship Canal is classified as a WFD River

* The heat capacity given in the table is for abstraction from rivers only. These locations could also extract heat from either coastal or estuarine waterbodies.

In order to calculate the total heat capacity available from rivers in England, the waterbodies were first grouped into catchments (i.e. they share a common downstream waterbody). For each catchment the waterbody with the highest heat capacity was identified. These values were then added together to estimate the total heat capacity available.

The total heat capacity available from rivers is estimated at approximately 6 GW. The 5 rivers with the highest heat capacities (Ouse, Severn, Trent, Wye and Thames) contribute approximately 2 GW to this total.

To calculate the total heat capacity available from canals the heat capacities from each individual canal were added together. This assumes there is no interconnection between the flows in the canals, which is not strictly true. The total heat capacity available in canals is estimated at approximately 84 MW.

As the availability of water from estuaries and the sea is not a practical limitation, it is not possible to calculate a total heat capacity in the same sense as for rivers and canals.

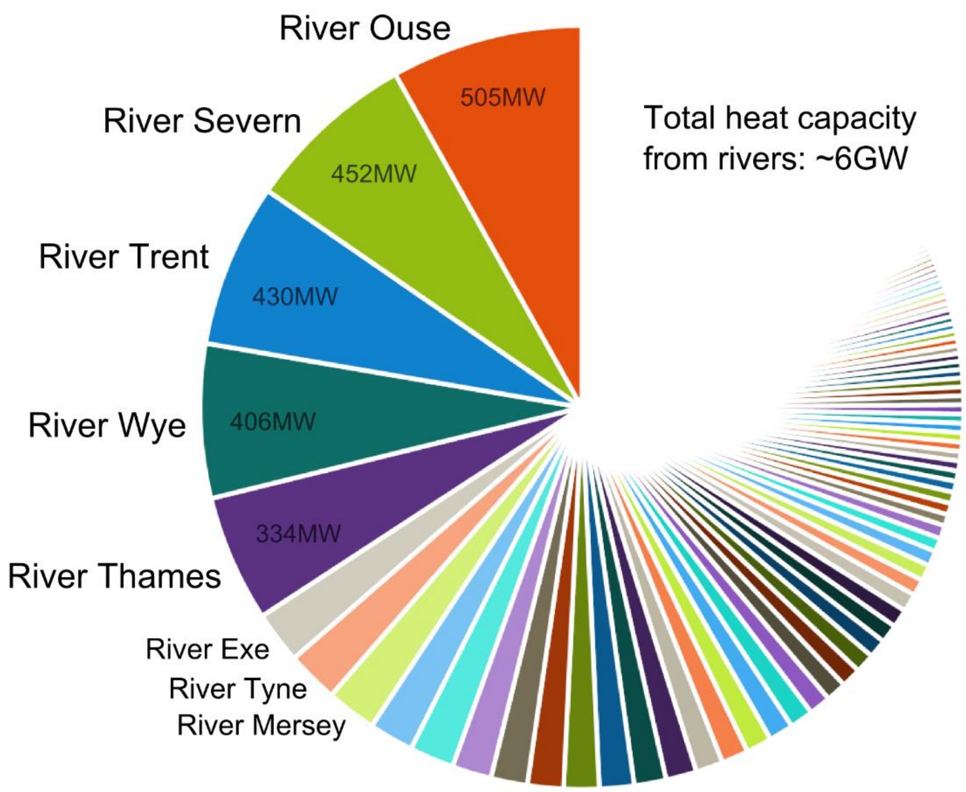

Figure 15 Estimated total heat capacity from rivers in England

The 39 rivers/cities identified in the previous high-level study are provided as Table 4 for reference[14], along with the heat capacity estimated in this study (at winter Q95). Note that the previous study did not provide a quantitative estimate of heat capacity for each location. Also note that the river names given have been taken as-is from the original report.

[14] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/342354/High_Level_Water_Source_Heat_Map__River_locations_list_31_July_2014_V2.pdf

A comparison of Table 3 and Table 4 shows some significant differences in the two lists. The approach used in this study has given equal weight to small and large urban areas. Consequently small urban areas on large rivers are more prevalent in Table 3; examples include Goole, Selby and Gainsborough. Table 4 does not include any locations on the River Severn, whereas 8 have been identified in Table 3 (e.g. Tewkesbury, Gloucester and Worcester). In addition Table 3 is filtered to show only locations with greater than 100 MW heat capacity, but this does not imply locations with smaller heat capacities are unviable. Readers are referred to the NHM for the heat capacity for their location of interest.

Table 4 Locations identified in the previous high-level study with the "highest potential for water source heat pump deployment in areas of high heat demand".

	Location (River)	Heat Cap. (MW)		Location (River)	Heat Cap. (MW)
1	London (Thames)	444 (includes Thames and other tributaries, inc. Lee)	21	Burton on Trent (Trent)	199
2	Manchester (Irwell)	135	22	Bedford (Ouse)	21
3	East Greater London (Lee)	(not assessed separately from London)	23	Cambridge (Cam)	22
4	Warrington (Mersey)	141	24	Hull (Hull [sic])	28†
5	Bradford/Leeds (Aire)	64 (Bradford) and 67 (Leeds)	25	Lancaster (Lune)	37†
6	Newcastle upon Tyne (Tyne)	5†	26	Birmingham (Cole)	51
7	Middlesbrough (Tees)	2†	27	Barnsley (Dearne)	10
8	Windsor (Thames)	250	28	Chesterfield (Rother)	12
9	Huddersfield (Calder)	94	29	Ipswich (Gipping)	8
10	Sheffield (Don)	60	30	Colchester (Colne)	6
11	Leicester (Soar)	13	31	Stoke on Trent (Trent)	17
12	Nottingham (Trent)	453	32	Bristol (Frome & Avon & Chew)	101
13	Sunderland (Wear)	1†	33	Norwich (Wensum and Tud)	37
14	Derby (Derwent)	92	34	Reading (Thames & Kennet)	273
15	Stockport (Tame)	(not assessed separately from Manchester)	35	Oxford (Thames & Evenlode)	108
16	Southampton (Itchen)	137	36	Preston (Ribble & Darwen)	96
17	York (Ouse)	114	37	Gillingham (Len & Medway)	13
18	Bournemouth (Stour)	254	38	Northampton (Wootton Brook & Nene/Brampton & Nene/Kislingbury)	12
19	Doncaster (Don)	59	39	Chelmsford (Chelmer & Can)	12
20	Peterbourgh (Nene)	37			

† Considered an estuary at this location

Sensitivity analysis

As with any model a sensitivity analysis of the major input values provides further insight into its behaviour. The river outputs have been tested for sensitivity to uncertainties in the winter flows and water temperatures. The results of the temperature sensitivity are shown in Figure 16 which compares the full heat capacity (excluding EFI) calculated with the mean winter temperatures against that with the minimum winter temperatures. The minimum temperatures were found using the same interpolation methodology as used for the mean temperatures. The sensitivity results in a large reduction in heat capacity. This is because the minimum temperatures often drop below the critical levels for the heat exchangers to operate.

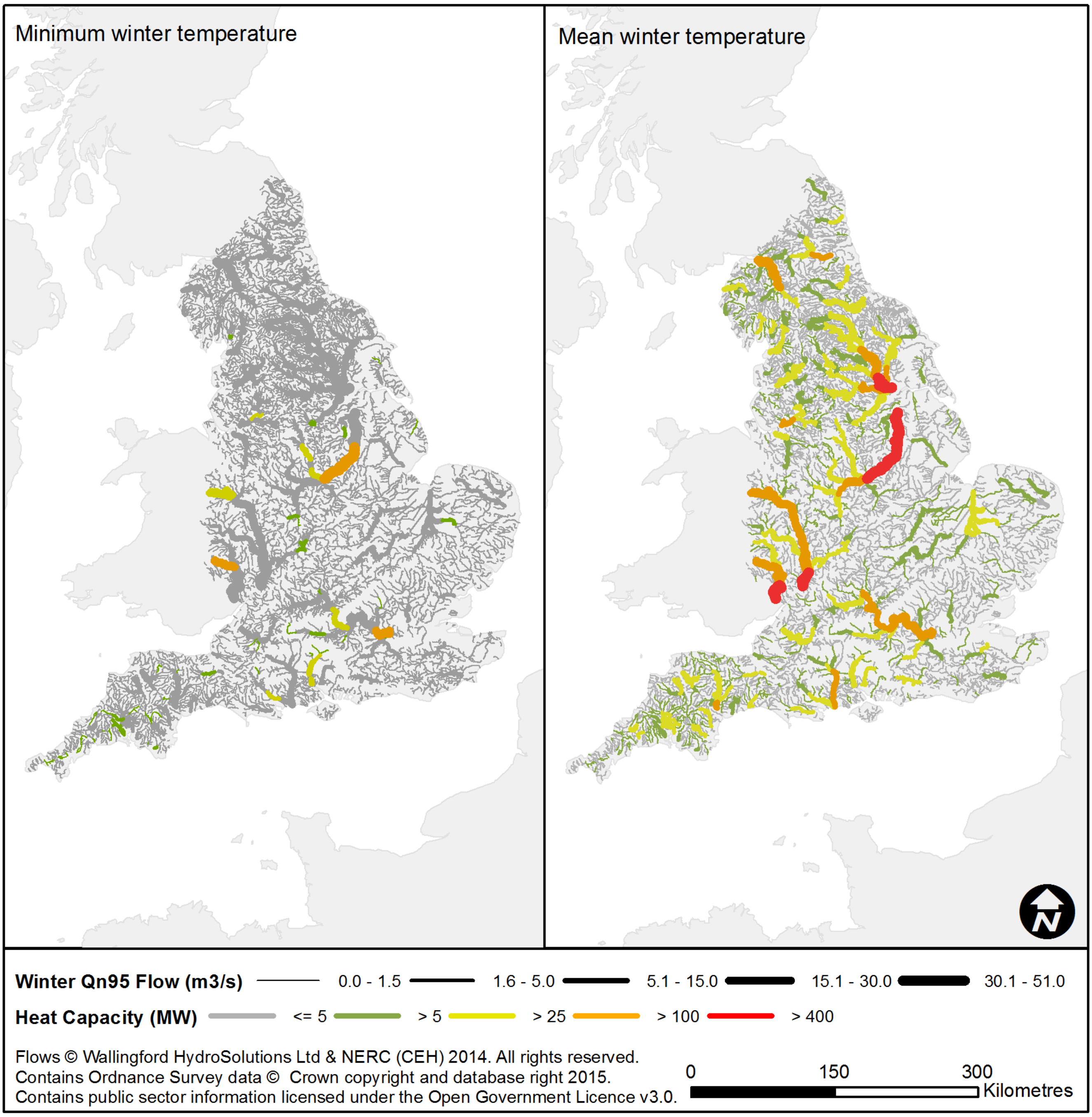

Figure 16 Comparison of heat capacity estimated using minimum and mean winter temperatures

Figure 17 shows a further sensitivity analysis of heat capacity calculated using winter Q95 and Q70 flows. The results show an increase in heat capacity by using the higher flow percentile. However this results in the heat capacity becoming less reliable due to flow only exceeding this value 70% of the winter.

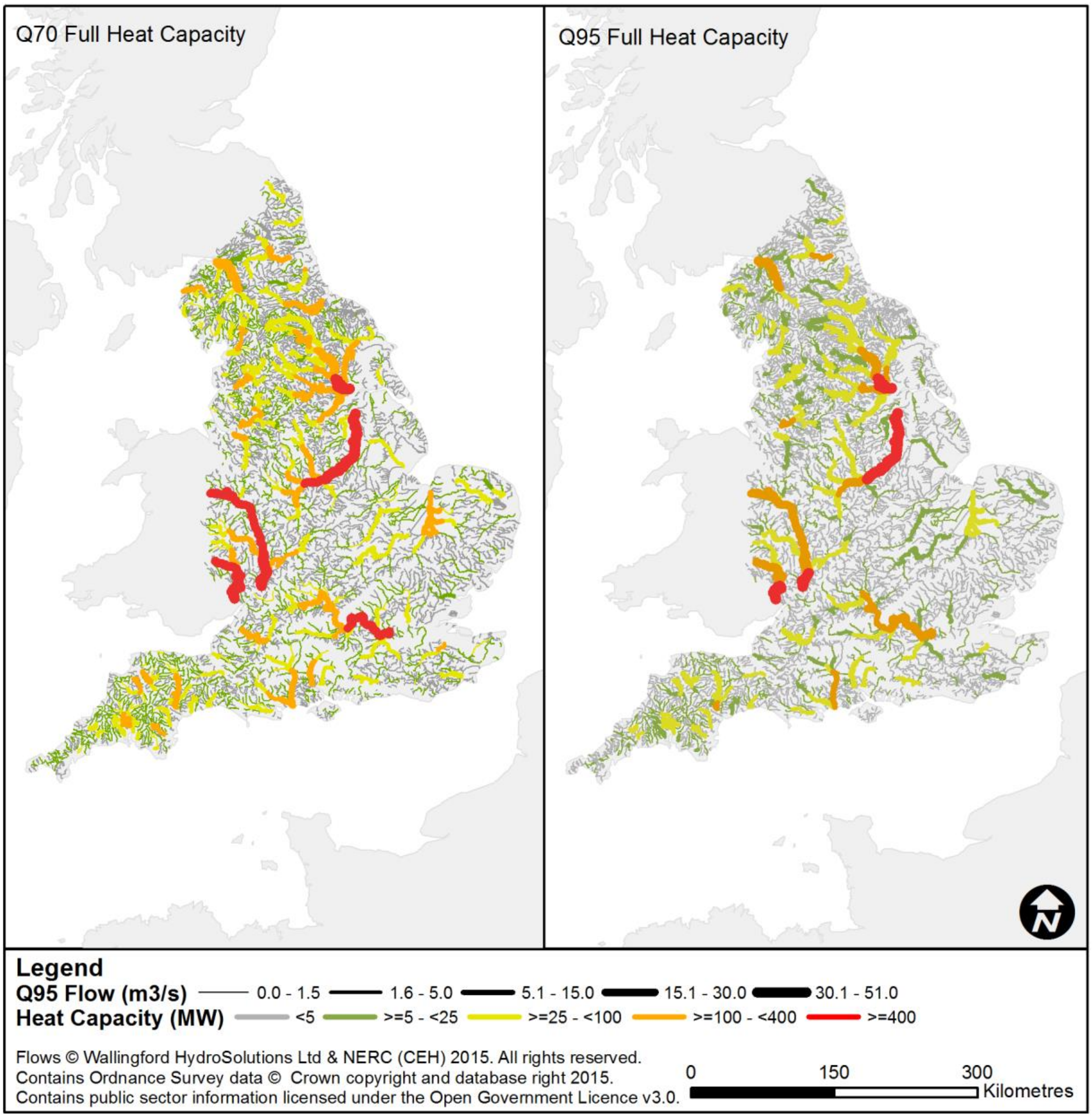

Figure 17 Comparison of heat capacity estimated using Q70 and Q95 winter flow

Canals

The analysis of canal heat capacity is somewhat limited by the available data, specifically flow estimates and temperature data. Typically flow data was available for large stretches of the network, but these may not be fully representative of flows during winter or of variations along those lengths. Nonetheless the typical flow rates are about 4 – 13 m^3s^{-1} which is a similar order of magnitude to winter Q95 flow rates seen in the rivers.

Canal winter temperatures are cooler than river temperatures, which limits the heat capacity due to the heat exchanger constraints.

It is noted that the assessment methodology used for canals is based on the same as that used for rivers, and is therefore proportionate to flow rate. Surface exchange may be a more important contributor to heat capacity in canals but there was insufficient data to determine this definitively.

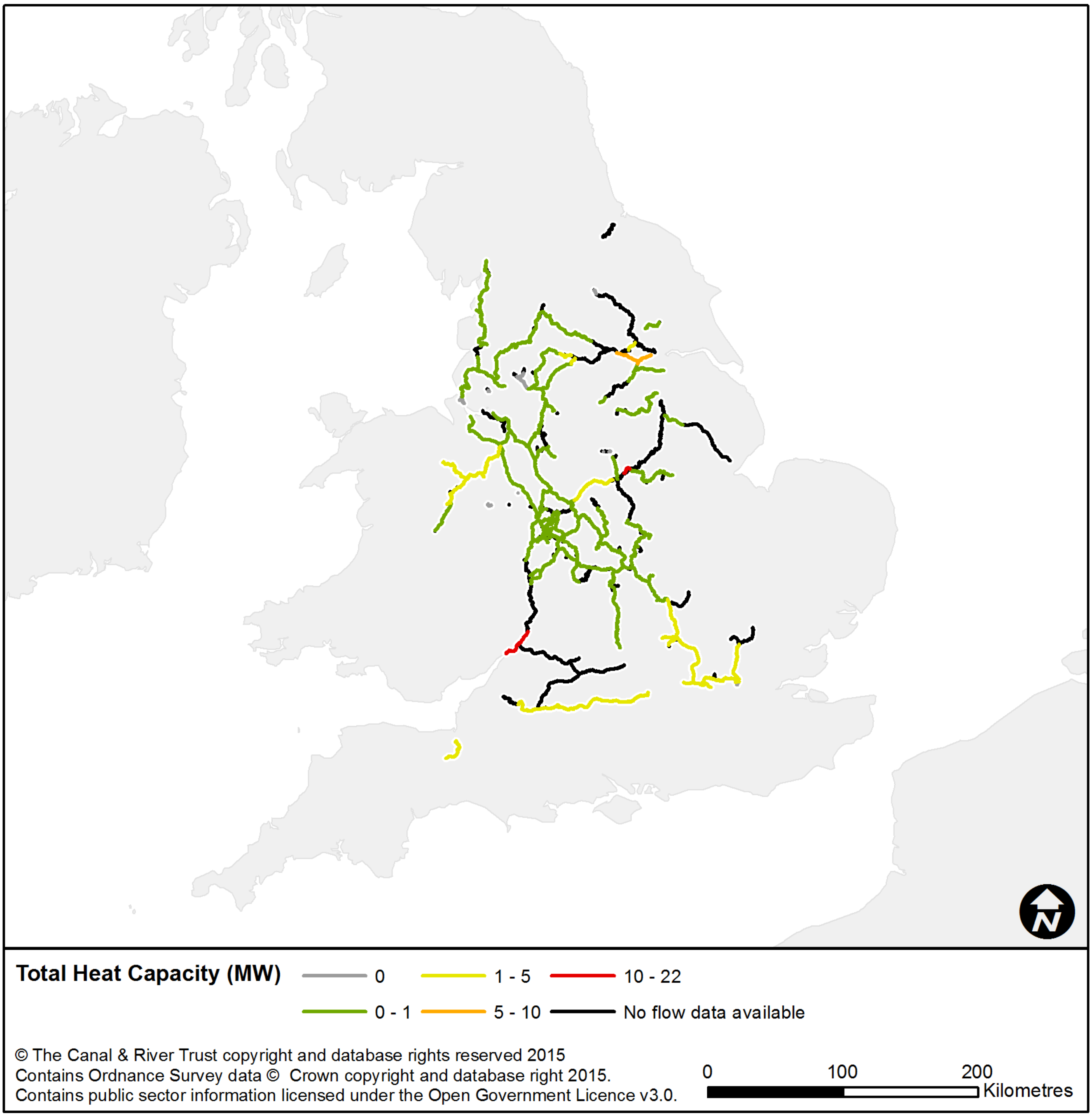

Figure 18 Canal total heat capacity (excluding EFI)

Canals with the highest heat capacity are the Gloucester & Sharpness Canal and Nottingham & Beeston Canal with around 20 MW. Several canals with zero flow, and therefore no heat capacity, are found across the country. However it should be noted that these canals may support small schemes that utilise local conditions.

Coastal and estuary

The heat capacity of transitional and coastal waterbodies has been calculated per unit of abstraction ($MWm^{-3}s$), as the availability of water is not a practical constraint with regard to water source heat pumps. With the influence of flow removed the heat capacity equation is driven by water temperature. The sea is warmest in the southwest and south of England, with colder temperatures found in the northwest and east (Figure 8). Estuaries tend to be slightly warmer than the coastal waterbodies they flow into, although this could be an artefact of the different data sources used for transitional and coastal temperatures.

An important consideration for the application of water source heat pumps in coastal and estuarine locations is the increased salinity of the water. This may allow the heat exchanger to operate at lower temperatures, as assumed in this study, and therefore extend the operating window. However the saline water is also likely to make maintenance of any heat exchanger more costly due to increased corrosion rates.

Table 5 shows the 10 estuary and coastal sites identified in the previous high level study. The heat capacity per unit abstraction calculated in this study is given for each of these sites. Of these Bournemouth, Plymouth and Portsmouth have the largest heat capacities due to the relatively warmer water to the South of England.

Table 5 Estuary and coastal sites identified in the previous high-level “within suitable heat demand locality”.

	Location (River)	Heat Cap. ($MWm^{-3}s$)		Location (River)	Heat Cap. ($MWm^{-3}s$)
1	Southend on Sea	30	6	Liverpool	29 – 42
2	Brighton	36	7	Blackpool	29
3	Portsmouth	38	8	Hull	25 – 29
4	Bournemouth	42	9	Southampton	33
5	Grimsby	29	10	Plymouth	38 – 46

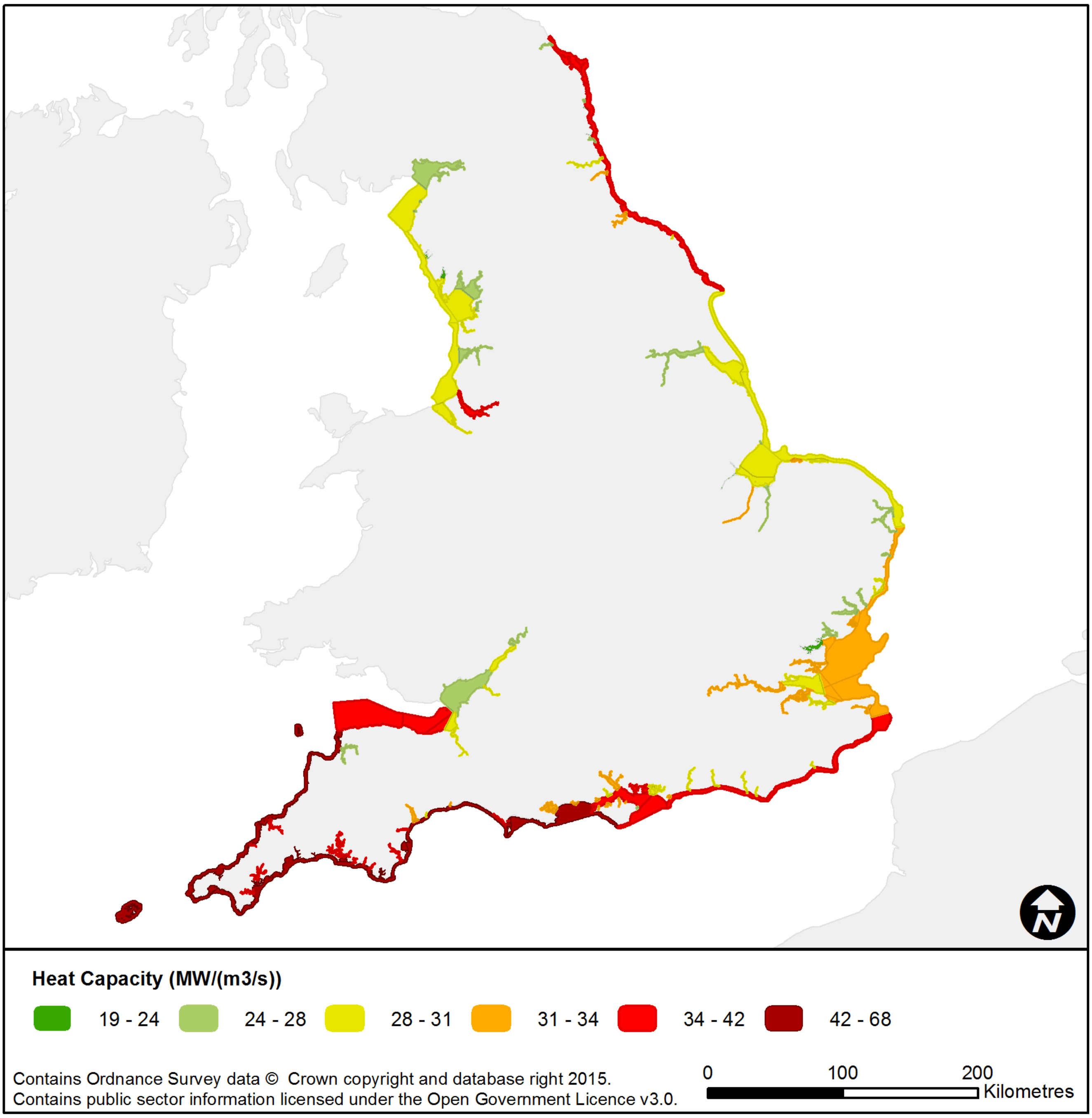

Figure 19 Heat capacity per unit abstraction for coastal and transitional waterbodies

Conclusions

This study has drawn together a number of existing data sets, models and methods to produce a strategic assessment of the suitability of England's waterbodies for heat extraction. It has identified areas where environmental factors may potentially constrain water source heat pump installation, and the highest resource potential locations for open loop water source heat pumps.

The output from the assessment has been produced in a form suitable for incorporation into the National Heat Map (NHM). Readers are encouraged to look at the outputs from this study in their local area of interest on the NHM. This will be of interest to local authorities, developers and community groups; providing heat demands and potential sources in an accessible way and so supporting DECC's vision for low carbon heat.

At a strategic level the study has come to the following conclusions about the heat capacity of England's waterbodies:

- The total heat capacity from rivers is estimated at approximately 6GW. This heat capacity of rivers is strongly proportional to flow. Urban areas on larger rivers are therefore prime candidates. Urban areas close to rivers with over 100 MW total capacity are identified on the rivers Ouse, Trent, Thames, Severn, Aire and Wye.
- The total heat capacity from canals is estimated at approximately 84MW. The flow in canals restricts their heat capacity significantly in comparison to large rivers. However in locations where the canal network is a significant waterbody compared with local rivers (e.g. West Midlands) canals may be the best source of heat. However the analysis of the temperature archive suggests that canal temperatures may be lower than those found in rivers.
- Estuarine and coastal water temperatures are also favourable for heat extraction especially in the south west and south of England. The saline water may allow for a longer operating window due to the decreased tendency for ice crystal formation. However the saline water is likely to make maintenance of any heat exchanger more costly due to increased corrosion rates.

Limitations

There are also a number of limitations to those conclusions that must be borne in mind:

- There are few environmental designations or constraints that exclude large areas or regions from suitability for water source heat pumps. Areas of environmental designation (e.g. SSSI, SAC, etc.) may or may not be relevant to adjacent waterbodies. Even if they are, it is not a definitive constraint on a development that may just reduce water temperature. As with the design of any scheme, local issues with environmental designations and other constraints would have to be investigated in more detail during a feasibility assessment. This study has provided heat capacity estimates at all waterbodies regardless of the environmental constraints identified.

- The non-consumptive nature of open loop abstraction and discharges means that water resource stress is unaffected by the installation of heat pumps. However, there will be local factors to consider if a large flow rate (abstraction and discharge) is proposed.
- The main constraint on extracting heat from waterbodies is the temperature limit and gradient at the heat exchanger. Mean winter water temperatures, especially for larger river flows, are in the 4 – 8 °C range and so close to assumed limits of 3 °C in freshwater and -2 °C in seawater. This means there is only a small temperature gradient in most cases and this will limit the size and efficiency of the heat pump.
- The above conclusion regarding temperature constraints leads to some uncertainty about the reliability or utilisation of any scheme. This study has used natural winter Q95 flows to ensure that it is based on what might be a reliable flow, but mean winter temperatures have been used for the primary outputs. The sensitivity analysis for temperature used minimum values to reassess heat capacity. This showed a significant reduction in heat capacity due to the drop below the heat exchanger's minimum requirements. This indicates there is some uncertainty in the reliability of heat capacity calculated due to variations in winter water temperatures.
- Finally it is noted that the study is based on natural winter flow estimates from the LowFlows Enterprise model. Many waterbodies may be influenced by non-natural abstractions (such as for public water supply or agricultural irrigation) and discharges (such as waste water treatment works) that alter both the flow and temperature regime.

Further recommendations

The following recommendations are made as part of the conclusion of this study,

- The Environment Agency's temperature archive is a valuable resource for the evaluation of water source heat pumps. However it is currently in a format that is very difficult to access and inspect[15]. The analysis undertaken for this project was limited to interpolation of mean winter river records and a brief sensitivity analysis. However it was not possible to quality assure the measurements used (aside from sense checking and crude filtering) or to ensure that there was a consistent length of measurement over similar period of time. Therefore further inspection and evaluation of the temperature archive is recommended. This could take several forms:
- A more thorough assessment at those promising urban areas identified in this study. Some of this data could be made available via the NHM.
- An evaluation of the distribution of winter temperatures throughout the season. This analysis would inform the reliability of a heat pump scheme with respect to expected variations in temperatures below the critical thresholds.
- An evaluation of the strength of the relationship between winter flow and temperature.
- Determine if there is any residual effect from thermal discharges that is noticeable in the temperature archive. A list of thermal discharge consents was provided by the EA for

[15] It is noted that it is not the Environment Agency's duty to collect data in a form suitable for this type of study, and that this recommendation is a not a criticism of the data collection.

this study, but it lacked any information regarding the discharge temperature uplifts. Therefore it was impossible to determine the quantity of additional heat being added to waterbodies by these discharges.

- A direct comparison with the heat demand areas on the NHM has not been possible due to an incompatibility in the data sets. The heat demand data is reported as an annual total in kWh, but the rates calculated here are typically in MW for mean winter temperature and flow conditions. To reconcile these differences further information on the winter profile of heat demands, and how this might relate to water temperatures and flow is required. There is likely a strong correlation between low water temperature and high heat demand in colder weather conditions. This correlation may have a strong influence on the economic feasibility of any particular scheme.
- Further analysis, perhaps on a catchment scale, of the best candidate rivers should be undertaken. Such a study should determine the interconnectivity and downstream implications of heat extraction at the top of a catchment. It would allow a more detailed inspection of the local temperature measurements, and thermal discharges.

Annex A: Constraint Mapping

Data structure

In addition to the fields included in the source data for the waterbodies, the following fields have been added.

Field Name	Field Type	Description
Constraint	String	Comma separated list of designations
SSSI	String	True if intersects a SSSI, False otherwise.
SAP	String	True if intersects a SAP, False otherwise.
SAC	String	True if intersects a SAC, False otherwise.
Ramsar	String	True if intersects a Ramsar site, False otherwise.
Shellfish	String	True if intersects a Shellfish waters, False otherwise.
FWF	String	'S' for Salmonid, 'C' for Cyprinid and NULL for unknown.
CAMSclrQ30	String	CAMS water resource status at Annual Q30 flow
CAMSclrQ50	String	CAMS water resource status at Annual Q50 flow
CAMSclrQ70	String	CAMS water resource status at Annual Q70 flow
CAMSclrQ95	String	CAMS water resource status at Annual Q95 flow

Summary of input datasets and associated licencing

This section summaries the input datasets used in the constraints mapping, and associated licencing.

Table 6 Input datasets used in the constraints mapping

Dataset name	Licence information	Waterbody types
Sites of Special Scientific Interest (SSSI)	Open Government Licence	Rivers, Canals, Estuaries, Coastal
Special Protection Areas (SPA)	Open Government Licence	Rivers, Canals, Estuaries, Coastal
Special Areas of Conservation (SAC)	Open Government Licence	Rivers, Canals, Estuaries, Coastal
Ramsar	Open Government Licence	Rivers, Canals, Estuaries, Coastal
Shellfish Waters	Public Sector Mapping Agreement (PSMA)	Estuaries, Coastal
CAMS water resource status	Licenced for this project to DECC by EA	Rivers, Estuaries
Freshwater fisheries status	Licenced for this project to DECC by EA	Rivers
WFD Waterbodies (Cycle 2 Draft)	Open Government Licence	Rivers, Estuaries, Coastal
Canals	CRT Licence	Canals

Annex B: Detailed Methodology

Overview

This annex is a description of the technical methodology to be applied for the DECC Water Source Heat Map project. The methodology outlines:

- The approach to calculating maximum heat extraction at given water temperatures.
- How the heat availability at each different type of waterbody is constrained by water availability and changes to temperature.

The assessment of heat availability has been undertaken at two spatial resolutions. The first assesses the size of a single scheme and those constraints on water abstraction. The second integrates the heat capacity to large urban areas to give a total water source heat availability for these locations.

Methodology flowchart

Figure 20 illustrates the relationships between the key datasets, algorithms and outputs of the methodology as a flowchart. The "heat pump model" (the large purple component in Figure 20 represents Equations 1, 2 and 3 in this section.

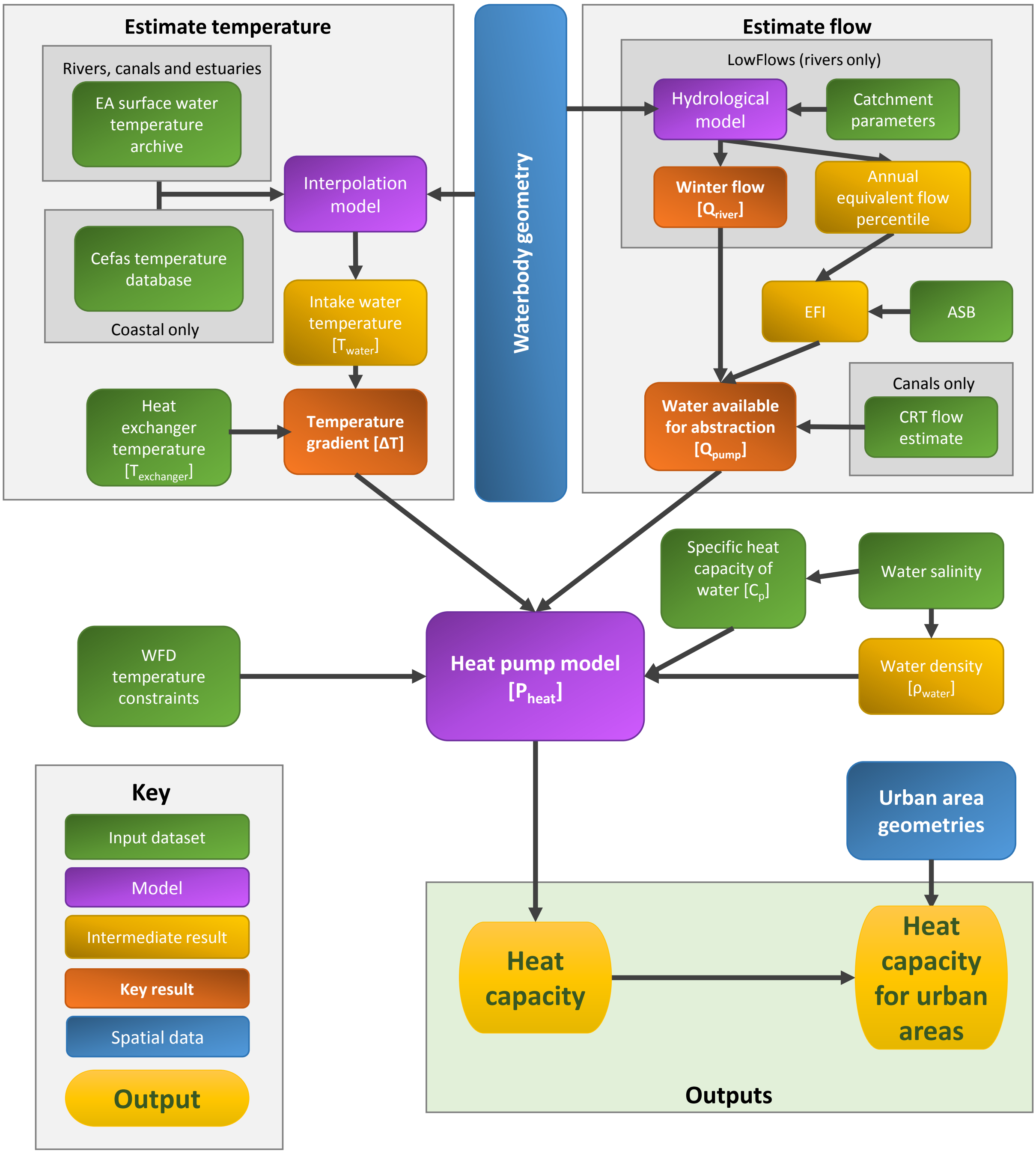

Figure 20 Flowchart illustrating relationships between key input data, algorithms and results

Key assumptions

A list of the key assumptions made in this study is given below. These points are discussed further in the relevant sections.

- The study assessed an open loop system, that abstracts water from the environment, passes it though a heat exchanger and subsequently discharges the cooler water back to the environment
- Winter is defined as December to February inclusive; referred to as DJF in abbreviations.
- The quality of the results is dependent primarily on the quality of the input data. With that in mind there are further assumptions specific to the different datasets used:
- Environment Agency Water Framework Directive Cycle 2 Draft waterbodies:
  - WFD waterbodies are the base unit of assessment used in the study.
  - It is important to note that waterbodies are not uniform in size. For example river headwaters are typically divided in to smaller reaches where there are more confluences and rapid changes in hydrology.
- Wallingford HydroSolutions (WHS) Low Flows Enterprise (LFE) natural river flows:
  - There are 3769 river waterbodies in England, of which WHS were able to provide modelled flow estimates for 3720.
  - Estimates are for natural flows, and do not include artificial impacts (i.e. abstractions and discharges).
  - The heat capacities on the online map are shown for winter Q95 (i.e. the flow exceeded 95% of the time in winter and so can be considered to be reliably available).
  - The flow estimated is for the outflow from each waterbody (i.e. the most downstream point).
  - Environment Agency surface water temperature archive, and Cefas coastal waters temperature data:
  - The raw temperature data is known to lack rigorous quality assurance, but is the best available data.
  - The mean winter temperature is calculated at each monitoring location.
  - Only samples with an absolute temperature of less than -50 °C or more than 70 °C were classified as erroneous and were excluded to maintain the largest dataset possible.
  - Locations with less than 5 samples were excluded, leaving a total of 18559 monitoring locations remaining. Of the rivers with available flow estimates, 3640 waterbodies also had at least one temperature monitoring point (within 50km).
  - For rivers, temperatures were interpolated (using inverse distance weighting, measured along the river length) to the location of the flow estimate (i.e. the waterbody outflow).
  - For canals and estuaries the water temperature was taken as the mean of the sample locations within the waterbody.
  - For coastal waterbodies the nearest Cefas monitoring location was used instead.

- Canal flows
  - The flow estimates for canals were provided by the Canal & River Trust, and represent "typical flows" in the canals.
- The relative temperature of a waterbody must not be lowered by more than 3 °C, based on standards set for the Water Framework Directive (WFD).
- For freshwater (rivers and canals) the absolute temperature must not be lowered below 0 °C, to prevent freezing inside the heat exchanger.
- For brackish or salt water (estuaries and coastal) the absolute temperature can be lowered to -2 °C, as saline water has a lower freezing point.
- A minimum gradient of 1 °C is required between the cool and warm side of the heat exchanger for the heat pump to be viable. Based on the previous constraints, this implies a minimum feasible temperature of 4 °C for freshwater and 2 °C for saline water.
- For rivers and canals, the amount of water available for abstraction at a single location is limited by an Environmental Flow Indicator, which is itself based on the waterbody's Abstraction Sensitivity Band defined by the Environment Agency. However, the non-consumptive nature of the heat pumps modelled mean that with sufficient spacing the full heat capacity should be available, constrained only by the total flow in the river and water temperature.
- The specific heat capacity of water varies depending on salinity. Fixed salinities were used; 0 PSU for freshwater, 25 PSU for estuaries, and 35 PSU for coastal waterbodies.
- The environmental designations and CAMS water resource status are provided for reference and must be considered for any future development of water source heat pumps. That information was not used in the calculation of heat capacity.
- The heat capacities of rivers and canals are largely limited by their available flow, and are calculated in kW (or MW for urban areas). The availability of water from estuaries and the sea is not a practical limitation, and heat capacities are instead calculated in kW/m3/s where the flow in m3/s is the flow of water from the environment and through the heat exchanger.
- The heat capacity calculated for urban areas is based on heat capacity from rivers only.
  - This was calculated by adding the heat capacity of the most downstream waterbody passing through the urban area. This was done to avoid double counting of available heat, as extraction of heat energy from a river upstream will impact those downstream.

Water temperature

The efficiency of a water source heat pump depends (in part) on the temperature gradient across the heat exchanger. This drives a need to know the absolute temperature of a water body during the winter heating season. This study has estimated these temperatures for rivers, canals, estuaries and coastal waters.

Intake temperature for rivers, lakes and reservoirs

The intake water temperature for rivers and canals has been estimated using the Environment Agency's Surface Water Temperature Archive[16]. This dataset consists of temperature data collected by a mixture of spot sampling and continuous monitoring in England and Wales until 2007 (see Figure 21). The dataset is the most comprehensive collection of surface water temperature available, although there are some concerns over a lack of rigorous quality assurance for the data[17].

The minimum, mean and maximum temperature measured at each monitoring location during the winter season (defined here as December to February, inclusive) has been calculated from all the data available. Samples with a temperature less than -50°C or greater than 70°C were discarded as erroneous. Locations with less than five samples in this period were also discarded. The mean winter temperature was used for the assessment of heat availability.

As the temperature sampling locations are not usually located at the Water Framework Directive (WFD) waterbody outflow points, the data needs to be interpolated spatially. A model has been developed to do this based on the assumption that the temperature of water in a river at a given point is dependent solely on the temperature of the water upstream of that point. The algorithm traverses the river network upstream, collecting a list of the temperature monitoring locations it finds. Each branch of the network is followed until either a maximum search distance (50 km) is travelled, or a monitoring location is reached. In lieu of detailed flow estimates for each branch of the river network within a catchment, inverse distance weighting (IDW) interpolation is used to calculate a single representative temperature value at each water body outflow point. This method assumes that the temperature at nearby monitoring locations is more representative of the local temperature than those further away. The number of sample points at each location was not included in the weighting.

Intake temperature for estuaries and the sea

The temperature of transitional waterbodies was also estimated using data from the Surface Water Temperature Archive. The data was filtered and summarised in the same way as for rivers. The temperature of an estuary was taken to be the mean of estuarine temperature samples within the waterbody boundary. If no samples were found, the search distance was extended to up to 1km from the waterbody and river samples were also included. If still no samples were found the temperature was transferred from a manually selected nearby "donor" waterbody.

The temperature of coastal waterbodies has been estimated using data collected by the Centre for Environment, Fisheries & Aquaculture Science (Cefas). The monitoring network consists of 39 sites around the coasts of England and Wales (see Figure 21). The results are presented as monthly mean sea surface temperatures, with most locations having data from the 1960s or 1970s onwards. In a similar fashion to the river temperatures, a mean winter temperature was calculated based on the average of the monthly mean values taken from the nearest Cefas station.

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[16] Environment Agency Surface Water Temperature Archive, http://www.geostore.com/environment-agency/WebStore?xml=environment-agency/xml/ogcDataDownload.xml

[17] Environment Agency, 2007. Climate change impacts and water temperature. Science Report: SC060017/SR. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/290975/scho0707bnag-e-e.pdf

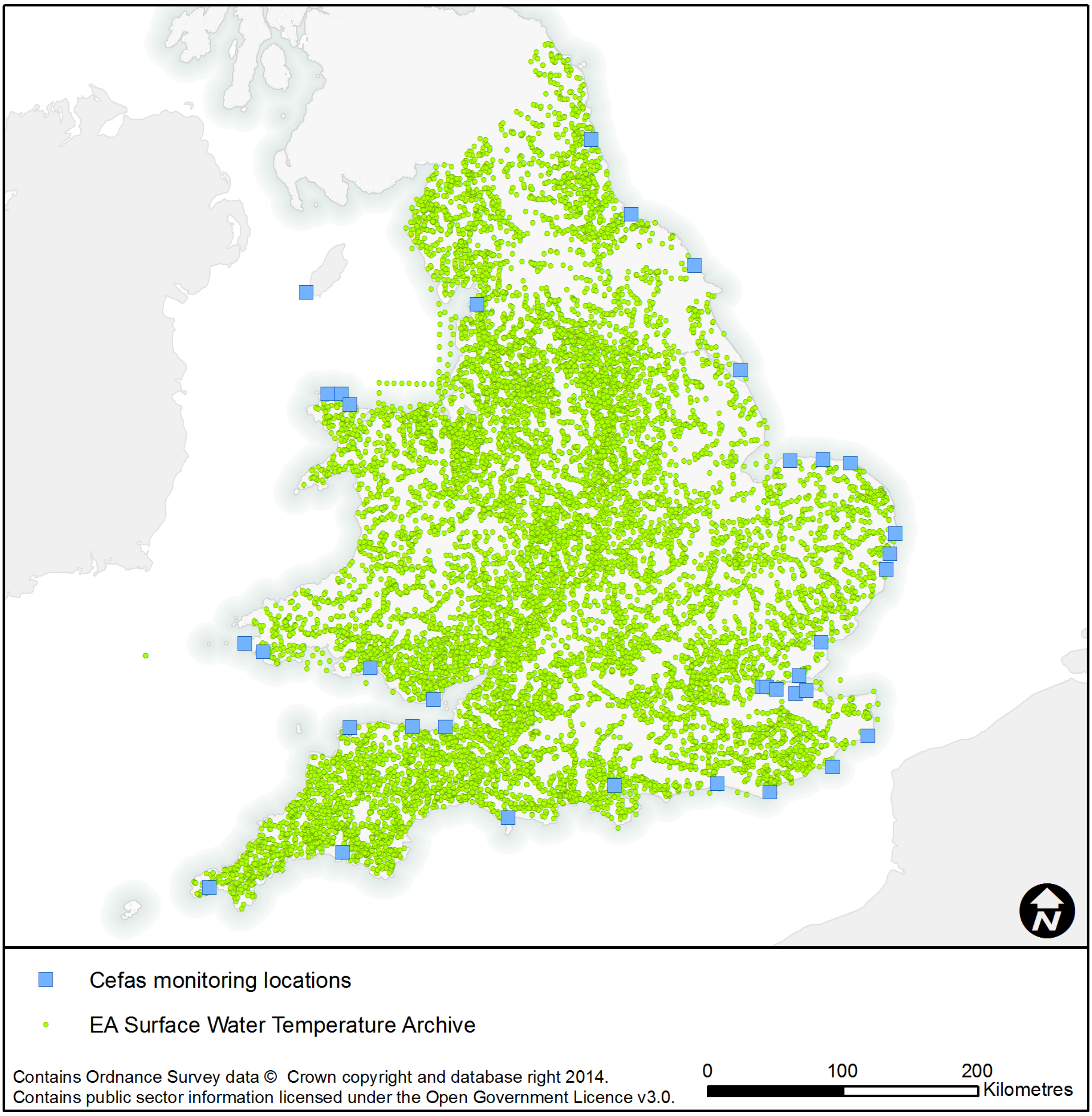

Figure 21 – Water temperature monitoring locations

Limits to changes in water temperature

Central to the assessment of heat availability is any environmental limit on changes to water temperatures. The WFD standards on temperature[18] categorise waterbodies as either cool-water or warm-water, depending on the species of fish it supports. Absolute maximum temperatures for the 98th percentile at the edge of the mixing zone are set (for example, 23 °C for "good status" in cool water), as well as a maximum temperature change of 3 °C outside for the mixing zone, or 2 °C for waterbodies of "high ecological status". As of the 2014 assessment there are only four waterbodies in England and Wales which achieve high ecological status[19]; these catchments are in remote upland regions, not suitable for the development of heat networks due to a lack of demand, and so this constraint is not included explicitly in the analysis.

For this study, the maximum change in water temperature in all waterbodies is taken to be up to 3 °C, based on the standards described above. Using a change in temperature rather than absolute limit also greatly simplifies the calculations. This is deemed suitable for a strategic assessment but will not remove the need for local studies based on absolute temperature impacts for individual schemes.

Water availability

The amount of water available for abstraction from a waterbody is limited by environmental constraints. Determining abstraction limits is difficult for a strategic assessment where each scheme would be subject to detailed design, abstraction licensing and environmental permitting considering the local situation. However, in view of the strategic nature of this study pragmatic decisions have been made which are felt to be appropriate for each waterbody.

As noted previously, the assessment of heat availability has been undertaken at two spatial resolutions:

The first assesses the maximum heat capacity of a single scheme for each waterbody, accounting for environmental constraints on changes to both water flow and temperature. This estimate is based on available data, and calculated at the outflow point of the waterbody (i.e. the most downstream location). This method acknowledges that extracting the total heat available from a waterbody with a single abstraction is not acceptable due to the aforementioned environmental limits. However, it is recognised that water source heat pump abstractions are non-consumptive and the volume abstracted is fully returned to the river. Therefore, multiple abstractions, each extracting a proportion of the total available heat energy, could be possible. To account for this a second calculation has been done, without the impact of the Environmental Flow Indicator, in order to estimate the total available heat capacity of a waterbody.

- The second aggregates the total heat capacity of multiple rivers to large urban areas, to give a total water source heat available for these locations. This retains the assumption of a maximum change in temperature of 3 °C. This is also subject to a limit on the heat exchanger temperature gradient. This estimate has been used at the city scale to determine the total capacity available. This calculation assumes there is sufficient

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[18] UKTAG, 2008. UK Environmental Standards and Conditions (Phase 2) Final. http://www.wfduk.org/sites/default/files/Media/Environmental%20standards/Environmental%20standards%20phase%202_Final_110309.pdf

[19] Environment Agency, 2014. WFD Surface Water Classification Status and Objectives. http://www.geostore.com/environment-agency/WebStore?xml=environment-agency/xml/ogcDataDownload.xml

distance to locate multiple heat pumps within the developed area to extract the total heat capacity while remaining within the single scheme abstraction limits (i.e, the EFI).

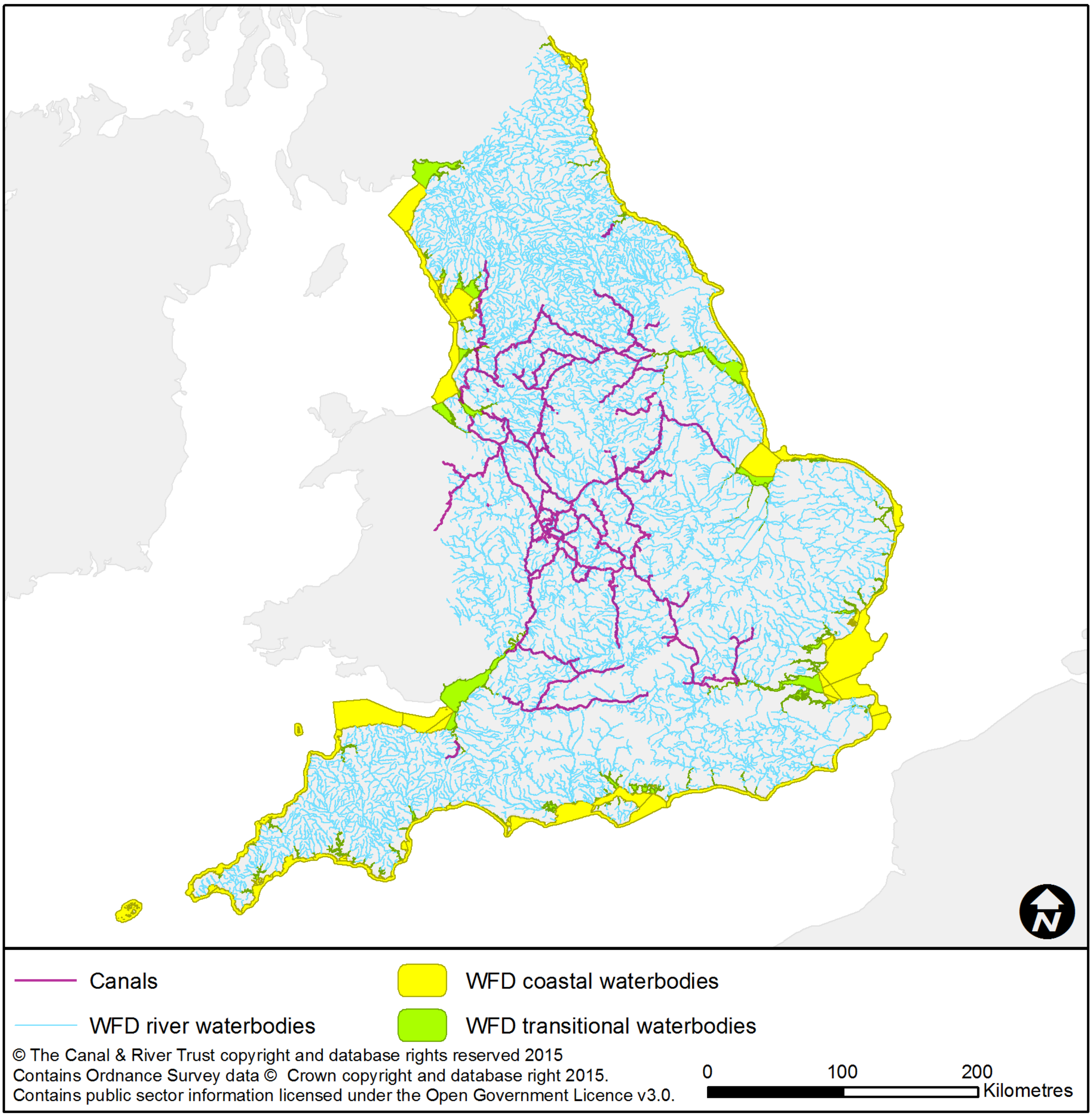

Figure 22 – Water sources: rivers, canals, estuaries and the sea

River flow

Wallingford HydroSolutions (WHS) has provided a dataset of winter (December- February or DJF) Q50, Q70 and Q95 flows produced using the LowFlows Enterprise model[20]. These flows represent the naturalised flow (i.e. without any artificial influences such as abstractions and discharges) that will be equalled or exceeded for 50%, 70% and 95% (respectively) of the winter season. The flows have been calculated at each of the WFD river waterbody outflow points.

[20] http://www.hydrosolutions.co.uk/products.asp?categoryID=4780

Thus, there are 3,769 points in total across England (see Figure 22). Note that Figure 22 shows points in Wales this study only covers England and no data has actually been provided for the Welsh waterbodies.

The total heat capacity in a river is calculated by multiplying the river flow (Q_{river}) by the change in temperature ($\Delta T_{river(ds)}$), and the density (ρ_{water}) and specific heat capacity ($C_{p\,water}$),

$$P_{heat\,(A)} = Q_{river}\ \ \rho_{water}\ \ C_{p\,water}\ \ \Delta T_{river(ds)} \qquad \textbf{Equation 1}$$

In order to determine what proportion of a river might be possible to abstract for a single heat pump scheme the Environment Agency's environmental flow indicator (EFI) has been applied. The EFI provides an indicator of abstraction pressure and here is assumed to represent the change in a river's natural flow that might be allowable before undesirable impacts on habitats and species. It is acknowledged that the EFI is not a target and that detailed design of any scheme would need to consider local river flows and environmental impact in more detail. Heat pump schemes are non-consumptive and are therefore less of a concern for river flows (i.e. change in temperature is more important). However any scheme is still required to abstract and return a fixed volume or water (and the more water that is taken, the larger the heat demand that could be satisfied). Therefore the EFI percentages have been used here as maximum flow constraints.

The EFI percentages are shown in Table 1 and are applied to the annual flow-duration statistics as shown. However heat pump schemes will be heavily biased toward winter use. It was for this reason that winter flow statistics were estimated by WHS. For this reason, WHS also provided the annual flow statistic equivalent for each of the winter statistics. For example a Winter Q95 might correspond to annual Q80 because the winter flows are higher than the rest of the year. How extreme the annual equivalent value is relative to the winter value will depend on each river's hydrology. The annual equivalent value is then used to determine the EFI percentage by looking up values in Table 1. In the previous example an annual Q80 in a low sensitivity river would correspond to an EFI of 24% (taking the Q70 value). Therefore 24% of the winter Q95 could be used by a heat pump.

Table 7 Percentage allowable abstraction from natural flows at different abstraction sensitivity bands[21]

Abstraction sensitivity band	Q30 (high flow)	Q50	Q70	Q95 (low flow)
ASB3: high sensitivity	24%	20%	15%	10%
ASB2. moderate sensitivity	26%	24%	20%	15%
ASB1. low sensitivity	30%	26%	24%	20%

Canals

The Canal and River Trust has provided a dataset of "typical" flow values and a flow range for each canal in England and Wales (see Figure 22). This data is at a much lower spatial resolution that what is available for the river network, with a single value for each canal (the longest of which is 344 km). The implication of this is that each canal will be assessed to have a single heat capacity as there is no spatial information to distinguish capacity along its length.

[21] Environment Agency (2011), *The Environmental Flow Indicator*

There are no equivalent low flow analyses that can be applied to canals. In discussion with CRT it was agreed that the full flow could be used because the abstraction is not consumptive. Therefore an equivalent EFI of 100% has been used. In this sense the canals have been assessed in the same way as rivers, with Equation 1 being used for the total heat capacity.

Estuaries & coast

Estuaries and coastal locations are more challenging from a flow constraint perspective. For the scale of abstraction considered here, coastal locations could be considered unconstrained provided sufficient care was taken with the location of intakes and discharges. For this reason the heat capacity at estuaries and coast has been calculated per unit abstraction (i.e. MW per m^3s^{-1} or $MWm^{-3}s$). This allows an individual scheme to be estimated based on the size of the abstraction required.

The density of water is assumed to be a constant 1000 kg m^{-3} for fresh water and 1027 kg m^{-3} for saline water. Salinity values of 25 and 35 PSU have been used for estuaries and coastal waterbodies respectively. These values are used to interpolate the appropriate density to use in the following equations.

Heat pumps

A simple model of the amount of heat that a heat pump could extract from a waterbody was required to estimate the heat capacity. This model provides some empirical constraints to the heat extraction rate based on the engineering limits of the system. The figure below shows a schematic of a water source heat pump system. Note that the water source is separated from the heat pump by a plate heat exchanger. The heat exchanger allows heat from the water source to be transferred to a closed glycol loop. It is the glycol loop that circulates through the heat pump evaporator.

This level of separation ensures that the heat pump can run within its operating limits and water quality standards which are defined by the manufacturer. It is not recommended to pass water direct from the source through the heat pump as this will result in premature wear to the evaporator, the replacement of which is extremely costly due to its connection to the refrigerant circuit. It is therefore considered good practice to provide an intermediate plate heat exchanger which can be selected to handle the water from source and is more readily maintainable.

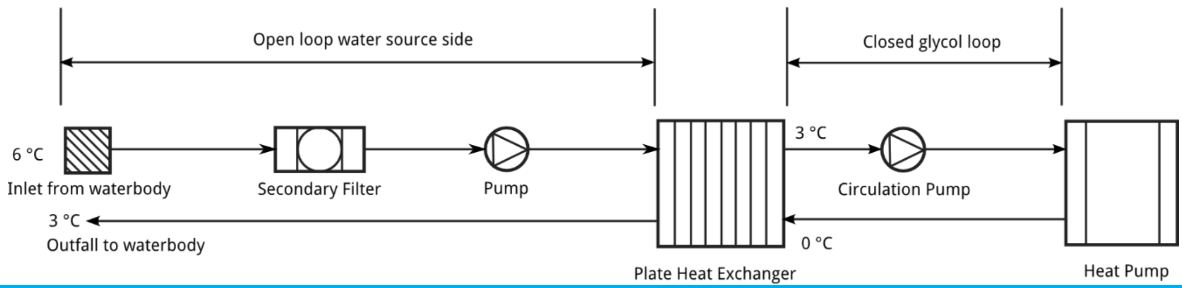

Figure 23 Schematic of a water source heat pump

This study investigated the possibility of including estimates of coefficient of performance (COP) as part of the heat pump model. However calculation of this values is dependent on specific heat pump and design of the open and closed loop circuits. Larger schemes may have significant pump requirements that will lower the overall COP of scheme. Due to the complexities in estimating the pump requirements for a scheme, wide variation in heat pump COPs and range of outlet temperatures this study has not attempted to estimate COP.

Rate of heat extraction

The maximum rate of heat extraction of a heat pump is constrained by the temperature gradient achieved across the heat exchanger and is given by Equation 2, where: T_{water} is the temperature of the abstracted water, Q_{pump} is the abstraction flow rate and $T_{exchanger}$ is the temperature of the cool side of the exchanger, ρ_{water} is the density of water, and $C_{p\ water}$ is the specific heat capacity of water.

$$P_{heat\ (B)} = Q_{pump}\ \rho_{water}\ C_{p\ water}\ \left(T_{water} - T_{exchanger}\right) \qquad \textbf{Equation 2}$$

Therefore, the achievable power available for abstraction from the system is the minimum of Equation 1 (total available) and Equation 2 (total extractable),

$$P_{heat} = \min\left\{P_{heat\ (A)}, P_{heat\ (B)}\right\} \qquad \textbf{Equation 3}$$

It is assumed that for the heat pump to be viable a minimum temperature gradient between the warm and cool side of the heat exchanger of 1 °C is required[22].

Based on advice from plate heat exchanger manufacturers it would be difficult to control ice crystal formulation in fresh water with a return temperature lower than 3 °C. This implies a minimum feasible intake temperature of 4 °C. However in areas of saline (sea) water, freezing occurs at lower temperatures and the return water could operate at -2 °C (implying minimum intake temperature of -1 °C). Linear interpolation between freshwater (0 PSU[23]) and sea water (35 PSU) is used in estuarine areas.

[22] This value is based on advice given by several manufacturers of water source heat pumps available in the UK.

[23] PSU = Practical Salinity Units. For all practical purposes salinity in PSU has the same numerical value as salinity in parts per thousand (ppt).

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URN 15D/091- National Heat Map: Water source heat map layer.