Identifying potential receptors to ground source heating and cooling systems

Chief Scientist's Group report

September 2024

Version: SC220017/R2

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Email: research@environment-agency.gov.uk

Author(s): Justin Brassett, Suzanna Fairbairns, Aidan Foley, Xanthe Polaine

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Research contractor:
Mott MacDonald Ltd
8-10 Sydenham Road
Croydon
CR0 2EE
0208 774 2000

Environment Agency's Project Manager:
Sian Loveless

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Dr Robert Bradburne
Chief Scientist

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Executive summary

As part of its Net Zero strategy, the UK Government has set ambitious targets to increase the numbers of heat pumps installed from 55,000 a year to 600,000 per year by 2028 (HM Government 2020a, 2021a, 2021b). Ground source heat pumps (GSHP) are a type of heat pump that use the ground's relatively stable ambient temperature to provide heating or cooling. The above and below-ground parts of the heat pump can be referred to as a ground source heating and cooling (GSHC) system. Some open-loop GSHC systems[1] are regulated by the Environment Agency through the Water Resources Act and Environmental Permitting Regulations (EPR)[2]. Amendments to the Environmental Permitting Regulations (EPR) in 2023[3] recognised heat as a pollutant in groundwater[4] and allow for the regulation of closed-loop GSHC systems[5],[6].

GSHC systems can alter the temperature of the ground. Larger GSHC systems, or high densities of smaller systems, could potentially impact the subsurface and perhaps connected environments. While comprising only 9 % of the current UK heat pump market in England currently, it is important that we understand the potential impacts of GSHC systems on the wider environment so that we can regulate these appropriately.

This report is part of a series of reports completed as part of the same project undertaken in 2023/2024 that will improve our understanding of the possible environmental impacts from GSHC:

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[1] Open-loop GSHC systems abstract groundwater and use this as the medium for heat exchange, see Environment Agency (2024a) for more details. Open-loop GSHC systems that abstract > 20 m^3 per day are licensed by the Environment Agency.

[2] https://www.gov.uk/guidance/open-loop-heat-pump-systems-permits-consents-and-licences

[3] See https://www.legislation.gov.uk/uksi/2016/1154/contents/made for the 2016 EPRs and https://www.legislation.gov.uk/uksi/2023/651/regulation/5/made for 2023 EPR amendments (accessed 04/10/2023).

[4] Heat, as a pollutant, is already recognised and able to be regulated in surface water.

[5] Closed-loop GSHC systems are those that use a heat transfer fluid circulating within a pipe in the ground to transfer heat to the surface. The pipes can be horizontal or vertical. See Environment Agency (2024a) for more details.

[6] https://www.gov.uk/guidance/closed-loop-ground-source-heating-and-cooling-systems-when-you-need-a-permit

- “Ground source heating and cooling (GSHC): Status, policy, and market review” (Environment Agency, 2024a).
- “Temperature changes in the environment around ground source heating and cooling systems: Thermal plume modelling and literature review” (Environment Agency, 2024b).

This report describes work that was undertaken by the contractor Mott MacDonald on behalf of the Environment Agency to understand the possible wider environmental impacts of heating or cooling in the subsurface environment from GSHC systems. This information is captured in a systems map[7] that should be viewed along with this report.

The systems map shows the processes that might change because of temperature changes (heating or cooling) in the ground due to GSHC systems, and biotic and abiotic receptors that could potentially be impacted as a result. The work sought to determine the factors that mean receptors could be more or less sensitive to temperature changes from GSHC and thus those that are at greatest and least risk.

This report describes the open-access systems map developed using the software Kumu and the Participatory Systems Mapping (PSM) approach that was taken to develop it. The systems map provides a way of structuring and visually representing complex systems and interactions as well as current knowledge and experience related to subsurface temperature change impacts and associated receptors.

The systems map’s receptors are categorised into 7 linked sub-systems that have been identified as key receptor areas that could be impacted by the temperature changes. These are: (1) Aquifers; (2) Groundwater dependent terrestrial ecosystems, wetlands, and springs; (3) Surface waters (aquatic ecology); (4) Water quality and resources; (5) Buildings and other (non-water resources) infrastructure; (6) Soils and geomorphology; (7) Other GSHC infrastructure (excluding mine water systems). Links to further literature and evidence is provided within the map and the accompanying spreadsheet (see Appendix II).

Literature relating to the direct and indirect impacts of GSHC-associated temperature impacts is limited, although critical references and relevant processes that can be inferred through the literature are included in the map. Information on the temperature ranges for specific ecological groups and species was gathered through the PSM approach. This information is summarised through tables and graphs within this report (see Section 3 and Appendix III).

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[7] The systems map is available through the software Kumu here: https://kumu.io/csgnz/environment-agency-gshc-systems-map-2024 and instructions for navigating the map are included in Appendix I.

The main environmental impacts from temperature changes resulting from GSHC-associated temperature impacts identified in the literature and through SME engagement were i) geochemical reactions and contaminant mobilisation; ii) changes in microbiological or wider organism community composition as a result of temperature changes in aquifers, groundwater, surface waters and soils, and; iii) environmental risks associated with either or both of the former.

It is important to note that the site-specifics of each GSHC scheme (for example, variations in geology, hydrogeology, surface water connectivity, GSHC size and design etc.) will have a significant role in determining the variety and severity of the potential impacts of GSHC-associated temperature changes.

The systems map can be used by decision-makers or the GSHC industry to inform understanding of the range of processes and receptors that could be impacted by non-specific temperature changes in the ground. It does not:

- Represent spatial, temporal, or scale aspects of GSHC installations;
- Model actual temperature impacts in the ground, or;
- Consider the site-specific details (variations in geology, hydrogeology, surface water connectivity, GSHC design) of a specific GSHC installation.
- Provide quantitative results,
- Consider possible non-temperature related impacts from GSHC systems.

1 Introduction

As part of its Net Zero strategy, the UK Government set targets to increase the number of heat pumps installed in the UK from 30,000 per year in 2020[8] to 600,000 per year by 2028, (BEIS 2020). This is because heat pumps (air, water, and ground source) represent one of the main low carbon solutions for heating buildings[9]. Although estimates of industry growth in the next 5-10 years are highly uncertain, under a moderate growth scenario industry installation rate could be 3,000 to 4,000 per year, possibly up to 20,000 per year under a high growth scenario (Environment Agency, 2024a).

This report focuses on one type of heat pump: ground source heating and cooling (GSHC) systems. GSHC systems use the temperature of the ground around them, through the extraction or reinjection of heat directly or via groundwater, to heat or cool buildings. There are two types of GSHC systems: (1) closed-loop systems that circulate heat carrier fluid through pipes laid either horizontally or vertically in the ground; and (2) open-loop systems that pump groundwater directly from aquifers via borehole systems (Abesser and Walker, 2022). As GSHC systems function by using the temperature of the ground around them, the extraction or reinjection of heat can cause cooling or heating of the ground, respectively. If this exceeds the capacity of the environment to either provide or tolerate such changes, this could lead to geotechnical, ecological, or geochemical risks (Banks, 2012). Of particular concern are the potential heating impacts from GSHC systems as, since October 2023, heat has been recognised as a pollutant in groundwater[10] in amendments to the Environmental Permitting Regulations[11] (EPRs), in-line with surface

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[8] A second part of this project provided an understanding of the current state of the Ground Source Heating and Cooling (GSHC) industry and how it may develop over the next 5-10 years. This is summarised in “Ground Source Heating and Cooling: UK Status, Policy, and Market Review, state of the industry report” (Environment Agency, 2024a). It found that the total number of Microgeneration Certification Scheme (MCS) accredited ground source heat pump (GSHP) installations in 2020 was 20,000. An upper estimate for current total operational installations is between 30,000 to 38,000 GSHP installations in the UK (Environment Agency, 2024a).

[9] For example, in the UK, 16 shared vertical closed-loop ground source systems supplying 400 flats is estimated to have saved 773 tonnes of carbon emissions per year compared with the previous system (Abesser and Walker, 2022).

[10] Heat was already recognised and could therefore be regulated in surface water.

[11] See https://www.legislation.gov.uk/uksi/2016/1154/contents/made for the 2016 EPRs and https://www.legislation.gov.uk/uksi/2023/651/regulation/5/made for 2023 EPRs amendments (accessed 04/10/2023).

water and will therefore be regulated by the Environment Agency. These changes will also allow for regulation of closed-loop ground source heating and cooling systems.

This report describes work that was undertaken by the contractor Mott MacDonald on behalf of the Environment Agency to understand the possible wider environmental impacts of heating or cooling in the subsurface environment from GSHC systems. This information is captured in systems map[12] that should be viewed along with this report.

The systems map considers possible impacts of temperature changes in the subsurface from GSHC systems on receptors[13] in the subsurface and connected environments. It includes possible impacts occurring as a direct result of a change in temperature, and indirect impacts from changes to environmental processes. While there could be other environmental benefits and disbenefits from GSHC systems, this work focused on the temperature change impacts. The report describes the systems mapping approach (Section 2), the structure of the systems map (Section 3.1) and provides a summary of the receptors (Section 3.2). It also discusses further considerations for prioritising receptors (Section 3.3). A summary and conclusions are presented in Section 4.

[12] The systems map is available through the software Kumu here: https://kumu.io/csgnz/environment-agency-gshc-systems-map-2024and instructions for navigating the map are included in Appendix I.

[13] A receptor is defined by the Environment Agency as ‘people, animals, property, and anything else that could be affected by the hazard’ (Environment Agency, 2023).

2 Methods

This section details the systems approach used to collect, organise, and validate the data used to build an understanding of the potential receptors to subsurface GSHC-induced temperature changes.

The UK government recommends taking a systems approach[14] to understand, analyse, and respond to complex socio-environmental processes. Systems approaches provide a structured co-learning process, bringing together interested parties to work through complexity, allowing them to see the big picture, share knowledge and experience, understand dependencies, and consider different perspectives. This is key to informing more holistic considerations around socio-environmental issues and can be used by policy and decision makers to account for interdependencies in systems, identify and manage trade-offs, and reduce the risk of missing unintended negative impacts.

There are many definitions of systems, approaches to systems thinking, and systems mapping[15]. It is generally agreed, however, that a system is made up of (Williams and Hummelbrunner, 2011):

- Elements: all the parts that make up the system;
- Relationships: the links between elements, that is the processes and interrelationships that hold the parts together;
- A boundary: the limit that determines what is inside and outside the system.

The systems mapping process seeks to identify the elements of a system of interest and the causal relationships between them. This also involves a decision as to what is considered inside or outside the system and is determined by agreeing the system boundary.

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[14]See HM Treasury Magenta Book: Central Government guidance on evaluation (2020) and HM Government Environmental Improvement Plan (2023) for example (accessed 16/06/2023).

[15] An overview of wider systems mapping approaches their uses, pros and cons is given by Barbrook-Johnson and Penn (2022).

2.1 Participatory systems mapping (PSM)

In this work, a type of systems mapping called Participatory Systems Mapping (PSM)[16] was used. PSM is a collaborative process that is used to develop a qualitative visual representation of a system, showing the elements that make up the system and how the behaviour of the system is affected by the causal relationships between these elements. It is a collaborative process that draws on perspectives, experiences, and knowledge, across a diverse group of people. PSM promotes discussion with and between participants and builds a shared understanding of a system which also aids buy-in to the approach by those most relevant to and/or involved in using the outputs of the study. The software used to conduct the systems mapping part of PSM was Kumu[17] (see Appendix I for more detail about this software).

[16] Defra recommend using PSM for creating a shared understanding of environmental issues. See Defra: Integrating a systems approach into Defra (2022), Section 2.2.3 (last accessed 16/06/2023).

[17] https://kumu.io/

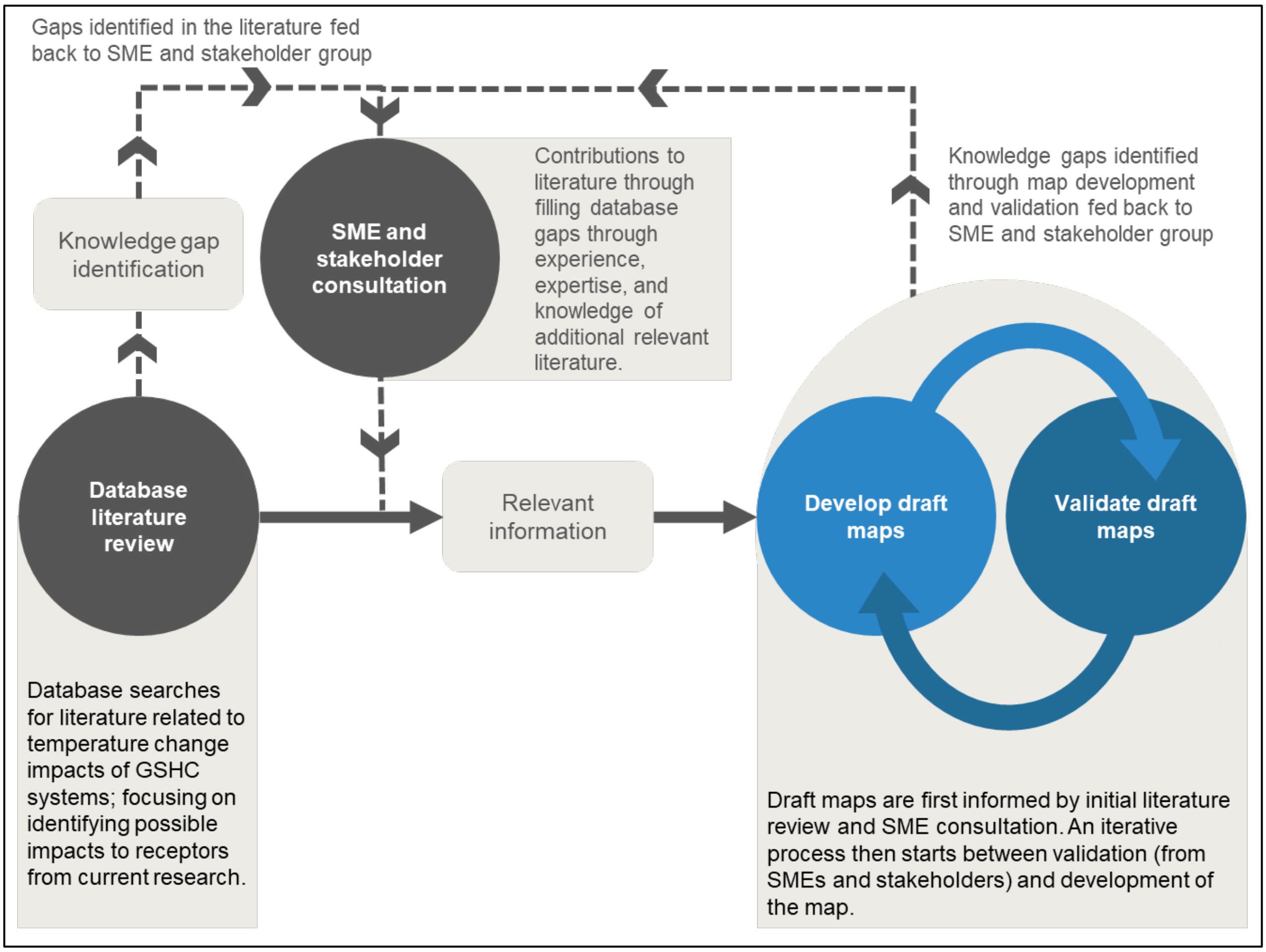

Figure 1. The participatory systems mapping approach to developing the systems map.

The PSM approach drew on knowledge from literature review, the Environment Agency steering group, and external subject matter experts (SMEs). This followed the process demonstrated by Figure 1; a collaborative and iterative process of literature review, SME consultation, and the iterative process between developing draft maps and validating them. Throughout this process, there was frequent contact with the Environment Agency's steering group. The PSM approach provided a means to capture and summarise available literature and Environment Agency and external SME knowledge of potential subsurface impacts that could result from the injection or extraction of heat to/from the ground by GSHC schemes.

2.2 PSM process

The collaborative development of the systems map involved a number of stakeholders and stakeholder groups. These were identified by the project team and the Environment Agency's steering group. This included 52 SMEs covering a wide range of government, industry, and academic organisations. Expertise covered a broad range of specialisms including groundwater ecology, aquifer geochemistry, surface water ecology, water resources infrastructure, and net-zero strategy, all of which have a stake in the possible subsurface temperature impacts from GSHC systems.

To begin the PSM approach, and as part of the initial engagement, a survey was sent out to inform SMEs about the project and ask them to share any initial comments and evidence. Questions included (with respect to GSHC systems):

1. What do you believe are the key receptors (i.e. users/species and habitats/settings within groundwater, soil, groundwater fed rivers, wetlands and lakes) that could be affected by temperature changes?
2. Can you comment on how sensitive receptors or habitats are to heating and cooling? For example, changes in average temperatures including upper and lower thresholds of tolerance and rates of change.
3. Which receptors or habitats (that could be affected by heating and cooling caused by GSHC systems) should be of most interest to the Environment Agency? If possible, please comment on your reasoning.

The responses, combined with literature from database searches, helped identify the range of receptors and processes that would need to be considered as part of the systems map, as well as some sub-systems (i.e., groupings of receptors). An initial version of the map that built on this evidence was presented at the first formal SME engagement workshop in May 2023. The workshop consisted of 16 SMEs, 6 members of the research contractor’s project team, and 8 members of the Environment Agency’s steering group. This workshop aimed to further probe the elements, relationships, and boundaries of the initial system concept of subsurface impacts from GSHC systems and gather feedback. Participants were divided into breakout groups for discussions on specific processes, receptors, and habitats that had been identified in the initial review of literature and, in some cases, individual follow-up calls / emails were undertaken with SMEs for a more in-depth discussion where relevant. Information and comments from the first engagement workshop were used to develop a second version of the systems map which was presented to the Environment Agency steering group in July 2023 and repeated a similar process.

A literature review was conducted as part of the systems map development to understand the available and existing evidence on potential subsurface temperature impacts of GSHC systems on the environment. This helped identify system elements, relationships, specific processes, and possible receptors. The literature was gathered from recommendations (i.e. from stakeholder engagement described in the paragraph above), snowballing (the process of identifying sources from references within other documents), and internet and database searches (for example, Scopus, Web of Science). Searches used relevant keywords, including: ‘ground source heating’, ‘ground source cooling’, ‘temperature change’, ‘geothermal’, ‘groundwater’, ‘groundwater receptors’. An initial assessment, however, indicated a relatively small body of literature addressing direct and indirect subsurface temperature impacts specifically relating to GSHC systems.

Figure 1 shows how knowledge gaps were addressed as part of the PSM method through a collaborative and iterative process of knowledge gathering and literature gap-analysis with SMEs. Over 150 journal articles, books, scientific reports and government publications were identified as potentially relevant to identifying environmental impacts from temperature changes around GSHC systems. This included a mixture of grey (for example, reports not produced in commercial publications) and academic literature. These were systematically screened using the Quick Scoping Review (QSR) approach (Collins, 2015) to identify the degree of relevance and value of each publication for the literature review. The most relevant publications are summarised within the literature review spreadsheet (Appendix II). Findings from the literature review were used to support decisions about whether nodes and linkages should be included in the systems map and how they should be categorised. Approximately 30 publications were reviewed in detail, with an additional 50 drawn upon for supplementary context, data and information (Appendix II).

A second SME workshop was conducted in September 2023, towards the end of the PSM. This workshop involved 16 SMEs, 6 members of the research contractor's project team, and 6 members of the Environment Agency's steering group. There was an additional focus group with 4 SMEs for those who could not attend the workshops. In total, 32 SMEs attended across these 2 sessions. The second engagement workshop provided an opportunity for SMEs to feed back on the systems map and its groupings (sub-systems), elements (sources, processes, and receptors), and linkages (pathways between elements). Feedback from this workshop was used to review the map and ensure the system pathways and receptors were correct. Following this workshop, the Environment Agency steering group were consulted to finalise the systems map and discuss degrees of sensitivity of different parts of the environmental system.

3 The systems map

3.1 Overview and purpose

The systems map is intended to:

- Provide a high-level guide to which processes and receptors could be impacted by heat or cool extraction or reinjection and the resulting heating or cooling of the ground by GSHC systems;
- Raise awareness of the possible impacts of subsurface temperature changes from GSHC schemes;
- Provide information for an initial assessment of potential source-pathway-receptor (SPR) linkages from GSHC-induced subsurface temperature changes;
- Highlight gaps where more information is required to better understand the subsurface temperature risks associated with a GSHC systems.

The systems map **does:**

- Summarise the potential environmental impacts of subsurface heating and cooling (not in a building);
- Provide a map of realistic pathways from GSHC induced subsurface temperature changes to receptors, including those that are indirect (for example, as a result of chemical changes);
- Provide a way of structuring and visually representing current knowledge and experience related to subsurface temperature change impacts and associated receptors.

What the map **does not** do:

- Represent spatial, temporal, or scale aspects of GSHC systems;
- Model actual temperature impacts in the ground, or;
- Consider the site-specific details of a GSHC system.
- Provide quantitative results or site-specific analysis of potential impacts of a GSHC installation.

It is important to note that the systems map is intended to capture potential pathways between sources and receptors, independently of how probable or important such pathways and impacts could be. The user will use their own background knowledge and experience, or the additional information provided, to assess how important each pathway and receptor is for their situation

3.1.1 Systems map layout

The final systems map (Figure 2) is comprised of 7 receptor groups, represented as sub-systems. Each sub-system is discussed in Section 3.2:

1. Aquifers
2. Groundwater dependent terrestrial ecosystems (GWDTEs), wetlands and springs
3. Surface waters (aquatic ecology)
4. Other GSHC infrastructure (excluding mine water systems)
5. Soils and geomorphology
6. Buildings and infrastructure
7. Water quality and resources

The interactive version of the map is available online at https://kumu.io/csgnz/environment-agency-gshc-systems-map-2024, Figure 2 shows a static version. Instructions for how to navigate and explore the online map are given in Appendix I. A table detailing all elements, processes, and links within each sub-system in the map is provided as a spreadsheet in Appendix II. It structures these in an SPR format with supporting evidence. This can be used in conjunction sub-system descriptions in Section 3.2.

The source term for all potential impacts across the systems map is a temperature increase or decrease within the aquifer sub-system (the ‘Temperature increase/decrease’ node). The map is therefore structured around this sub-system. This heating/cooling is then reflected as nodes within sub-systems to which temperature changes could transfer directly from the ‘Aquifers’ sub-system: ‘Temperature increase/decrease in wetlands’, ‘Temperature increase/decrease in surface waters’, ‘Temperature increase/decrease in repurposed mine systems’, and ‘Temperature increase/decrease in soils’.

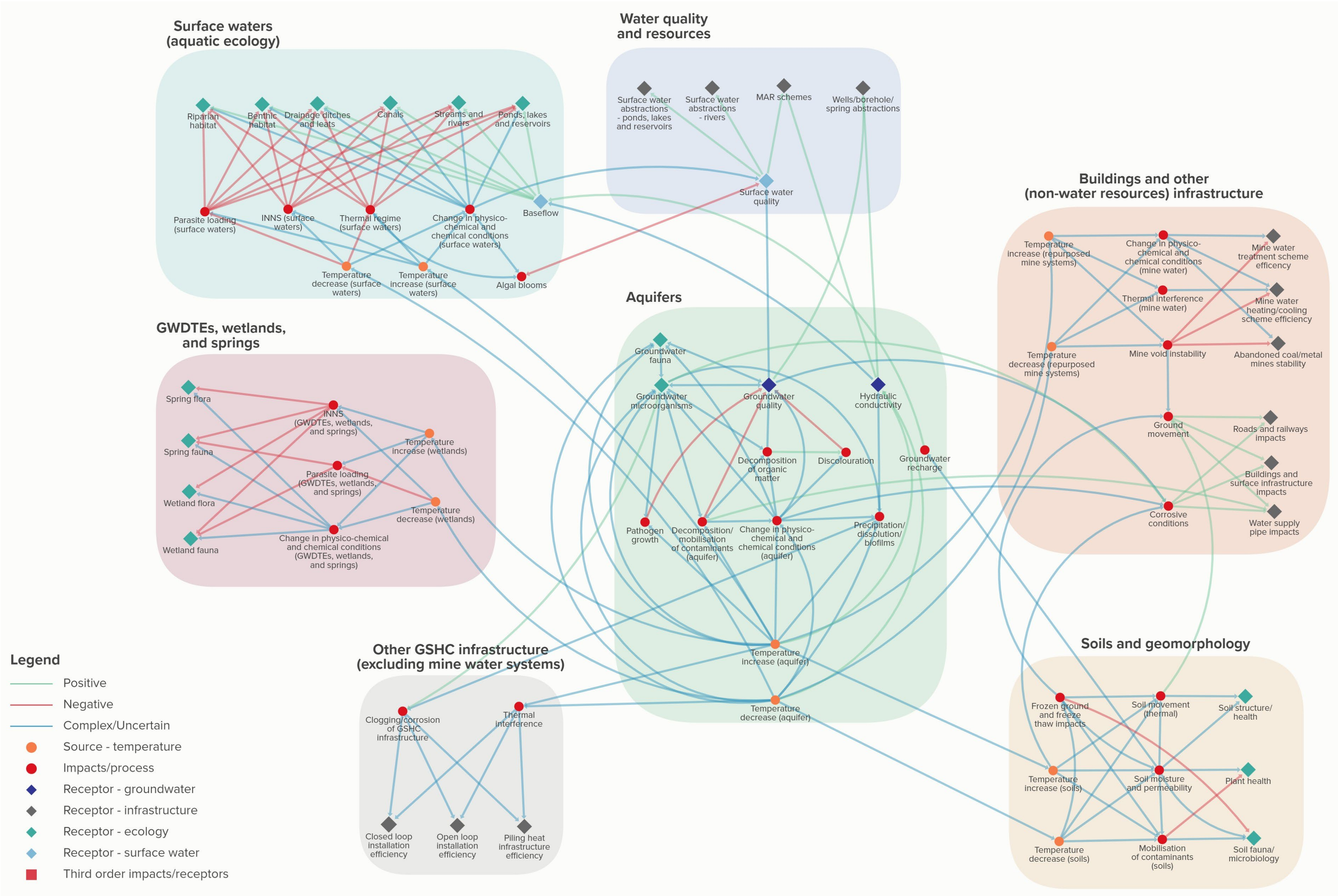

Figure 2 Screenshot of the systems map showing nodes (elements), linkages (causal relationships), and subsystem layout. This view can be seen in Kumu when all layers are selected in the 'Select a subsystem' filter in the top left.

3.1.2 Node and linkage types

There are 7 types of node in the systems map (Table 1), 5 of which could also be considered types of receptor. There are 3 types of linkage relationships possible between a pair of nodes; positive, negative, and complex/uncertain (Table 1).

Table 1. Systems map legend

Symbol	Label	Description
●	Source – temperature	The source of temperature change from the heat injection or heat extraction by GSHC installations causing heating or cooling of the ground, respectively.
●	Impacts/processes	Processes or impacts from temperature changes that provide a pathway from source (temperature change) to the receptor but are not receptors themselves.
■	Third order impacts/receptors	Receptors/processes external to the immediate environmental system.
◆	Receptor – groundwater	Identified potential receptors of GSHC-induced temperature changes within different sub-systems.
◆	Receptor – infrastructure	
◆	Receptor – ecology	
◆	Receptor – surface water	
—	Link – complex/uncertain	A complex link between nodes where behaviour is inconsistent, variable under different conditions, or uncertain.
—	Link – positive	Positive link between nodes where behaviour mirrors each other i.e., if node A goes up, node B goes up, if node A goes down, node B goes down.
—	Link – negative	Negative link between nodes where behaviour is inverse to each other i.e., if node A goes up, node B goes down, if node A goes down, node B goes up

3.2 Receptor sub-systems

As previously mentioned, the systems map provides a qualitative representation of the SPR links that could be affected by temperature changes from a GSHC system. A wide range of generic receptor types are identified across the systems map and their relationships can be explored and interrogated within the map. Further detail and supporting literature is identified in the map and Appendix II. Appendix III provides specific ecological temperature sensitivities, including for (surface) freshwater flora and fauna, groundwater fauna, and microbes. Section 3.3 describes further site-specific sensitivities that are relevant to these sub-systems, which could be considered for understanding the temperature impacts of GSHC systems.

3.2.1 Aquifers

Groundwater quality and hydrochemistry are controlled by many factors including groundwater origin, aquifer matrix properties and interaction, degree of oxygenation (reduction/oxidation or redox conditions), water residence time, anthropogenic influences (for example, pollution), and physicochemical and biological processes (Freeze and Cherry, 1979; Hiscock and Bense, 2014; Griebler et al., 2016). Among these, temperature is a central factor controlling the composition of groundwater chemistry, with direct relationships to the density and viscosity of water, geochemical processes such as dissolution or precipitation of minerals, microbial processes, and the solubility of gases (Di Lorenzo et al., 2023).

The aquifer sub-system (Figure 3) shows 4 main receptors of GSHC-induced heating and cooling of the ground within aquifers: groundwater fauna, groundwater microorganisms, groundwater quality, and hydraulic conductivity. The processes impacting these receptors are driven by changes in the physico-chemical, chemical, and biological conditions from the baseline range because of heating or cooling the aquifer. Temperature changes in the aquifer and many of the impacts/processes that take place in the aquifer because of heating or cooling, go on to directly influence processes in hydrologically connected systems. For example, a temperature increase or decrease in an aquifer could contribute to temperature increases or decreases in any connected GWDTEs, surface waters, soils, and repurposed mine systems, water quality and resources.

Although not included in the map, greenhouse gases such as carbon dioxide and methane could be released from processes described in the aquifer sub-system. Volatile organic compounds (VOCs) and other gases could be released and would be relevant to human health or climate change thus linked to the public health (indoors and outdoors) receptor.

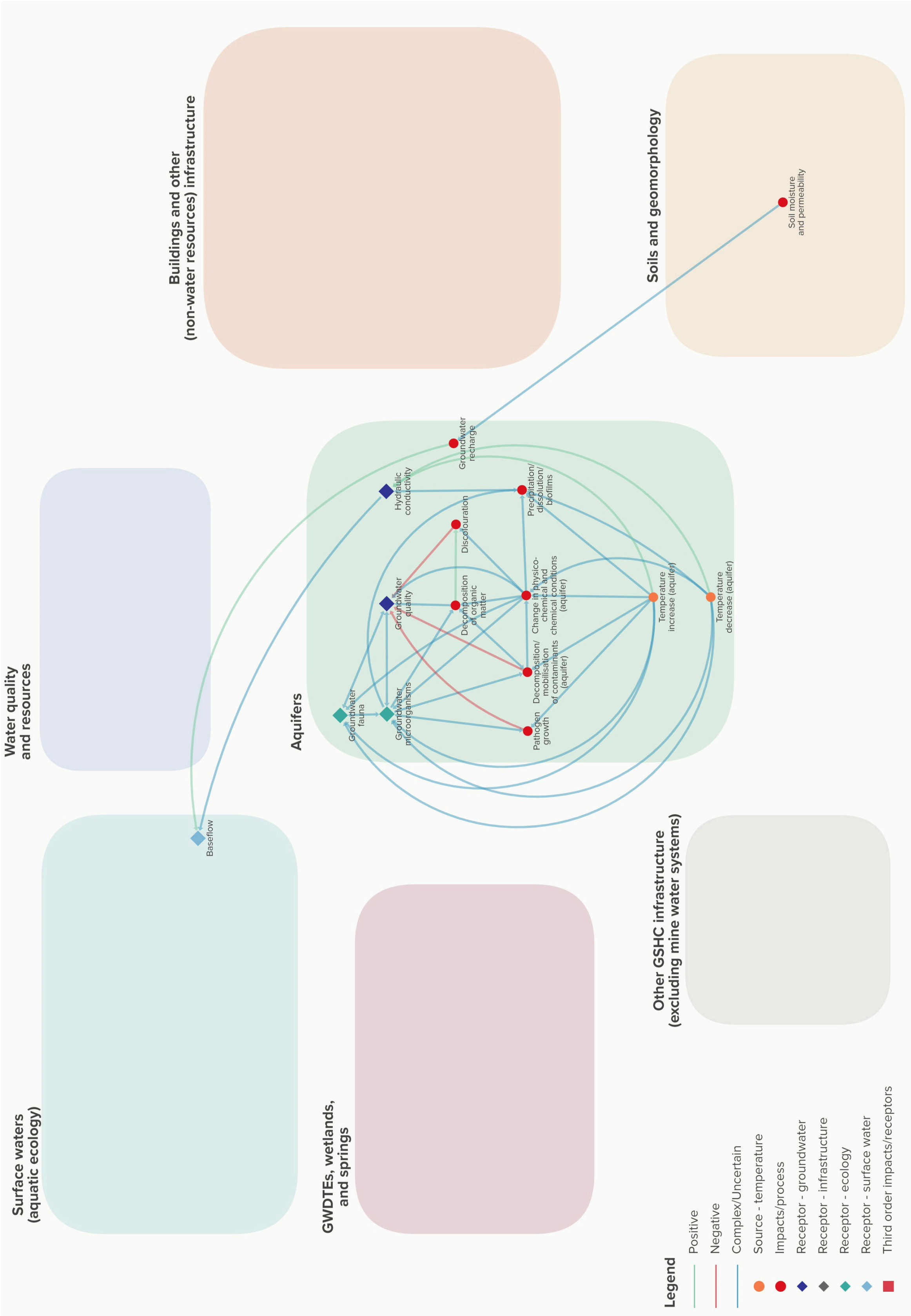

Figure 3. Aquifer sub-system, view from the Kumu systems map where only the 'Aquifer' sub-system layer is selected from the 'select a sub-system' filter. Elements are represented by circular, and diamond-shaped nodes, causal

relationships are represented by green (positive), red (negative), and blue (complex) lines.

3.2.2 GWDTEs, wetlands, and springs

Groundwater dependent terrestrial ecosystems (GWDTEs) are defined in the Water Framework Directive (WFD) as “wetlands identified as being directly dependent on groundwater bodies” (UK TAG, 2005). GWDTEs can be fed by springs, seeps or baseflow directly to the wetland or to associated watercourses. GWDTEs may form small individual features a few metres across, or extensive mires hundreds or thousands of square metres in extent. Due to the range of types of GWDTEs, wetlands and springs, some of these may contain habitats that are suitable for certain species of fish (for example, channels within wetlands) or may have little or no running water or connectivity to surface waters.

Springs are locations at which groundwater emerges at the surface. They exhibit great variability in geological and hydrological settings. Groundwater can flow via many pathways to emerge at a given spring, and springs often represent mixtures of waters recharged at different times and in different places across a spring catchment. Springs can emerge in riverbeds and contribute to baseflow or can form the headwater of a watercourse. They can contribute flow directly to GWDTE and wetlands, or even be the dominant source of water to them. Springs can be individual or grouped, have steady flow rates throughout the hydrological year or be highly variable; typically depending on the geology and the climatic regime. Overall, temperature impacts to springs and wetlands are likely to be similar to those for both aquatic ecosystems (surface waters) and groundwater fauna, given the relative contributions of both types of system to spring/wetland function.

GWDTE, wetlands, and springs can be fed partially or wholly by groundwater and therefore direct or indirect changes to groundwater from changing temperatures in an aquifer could result in changes in these environments (Figure 4). Warmer or cooler water temperatures could change physico-chemical and chemical conditions, influence the prevalence of invasive non-native species (INNS), and increase parasite loading. This can contribute to changes in the receptors of spring and wetland flora and fauna. However, the relationships are complex due to a wide range of possible temperature changes and impacts.

It is possible that increases in temperature could also lead to increased oxidation of organic matter and release of greenhouse gases via microbial respiration. Please refer to comments on greenhouse gases made in the previous section (3.2.1).

Factors affecting the hyporheic zone of surface waters are covered in aquifer receptors and processes/pathways (for example, changes in physico-chemical parameters etc). Third order impacts could lead to socio-economic impacts such as the amenity value of wetlands.

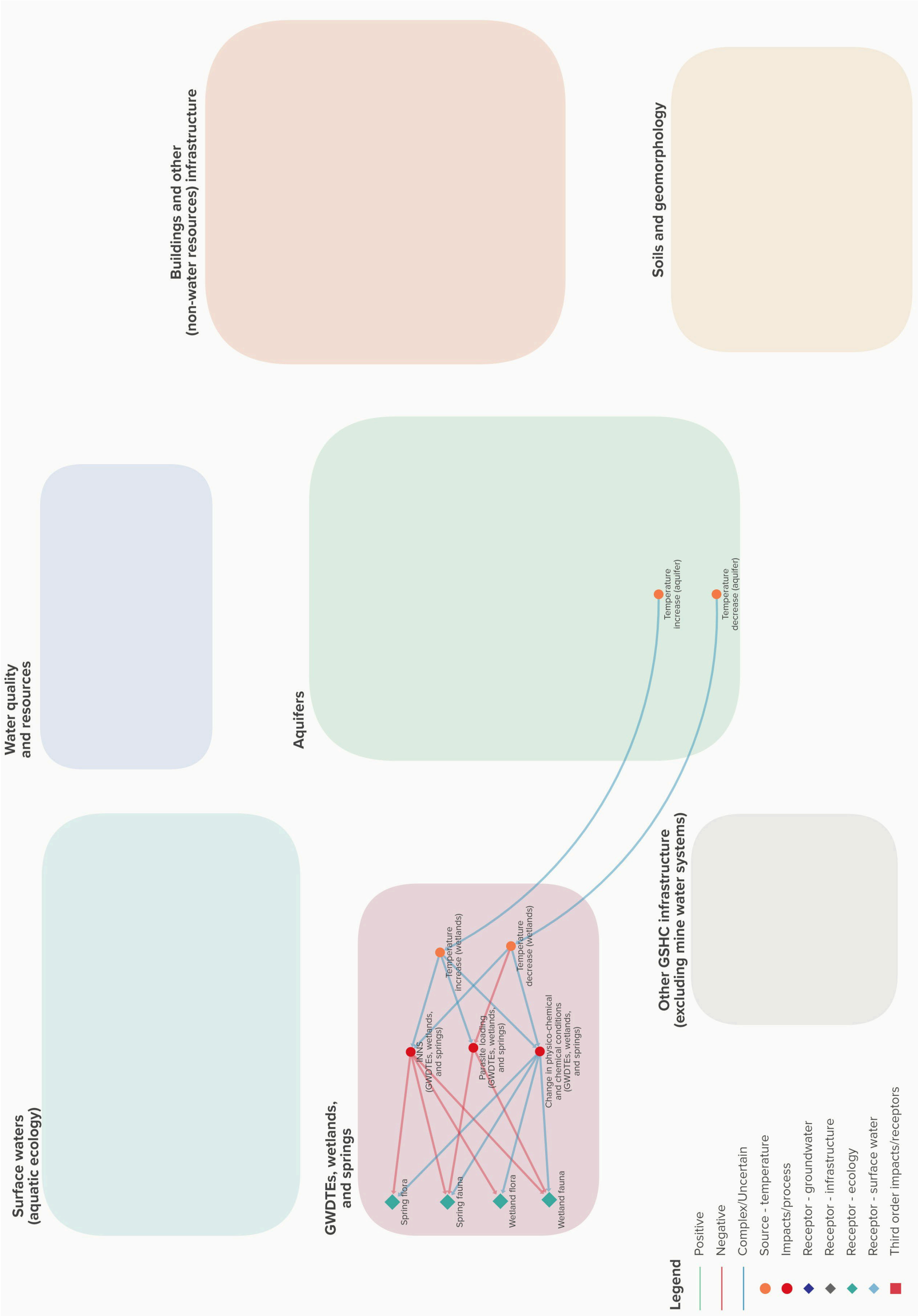

Figure 4. GWDTE, wetlands, and springs sub-system. This view is from the Kumu systems map where only the ‘GWDTEs, wetlands, and springs’ sub-system layer is selected from the ‘select a sub-system’ filter. Elements are represented by circular, and diamond-shaped nodes, causal relationships are represented by green (positive), red (negative), and blue (complex) lines.

3.2.3 Surface waters (aquatic ecology)

Virtually all surface streams and rivers have some component of baseflow. The temperature of rivers and streams that have a higher proportion of baseflow will be moderated by groundwater temperature. These surface waters will support a range of local species and habitats that could potentially be impacted by GSHC-heated or cooled groundwater. The scale of the impacts will depend on the relative size of the GSHC system (or systems), proportion of baseflow, and the size of the watercourse, amongst other factors (for example, distance to the GSHC system, hydraulic gradient, thermal gradient etc.).

The surface water (aquatic ecology) sub-system (Figure 5) could be impacted by temperature changes in surface waters caused by GSHC-temperature changes in the aquifer. Habitats and fauna within this sub-system could be impacted by increased parasite loading, the presence of INNS, thermal stratification, and thermal barriers, and changes in physico-chemical and chemical conditions, which could be caused by temperature changes in surface waters. Changes to baseflow, as a result of temperature-induced changes to hydraulic conductivity (in the aquifer sub-system) and groundwater recharge (in the soils and geomorphology sub-system) could impact receptors in this sub-system, although such changes are likely to be minor or negligible.

Physico-chemical and chemical conditions and thermal stratification in this sub-system can impact surface water quality both directly and indirectly, which can also impact water resources. Third order impacts could lead to socio-economic impacts such as amenity value of aquaculture.

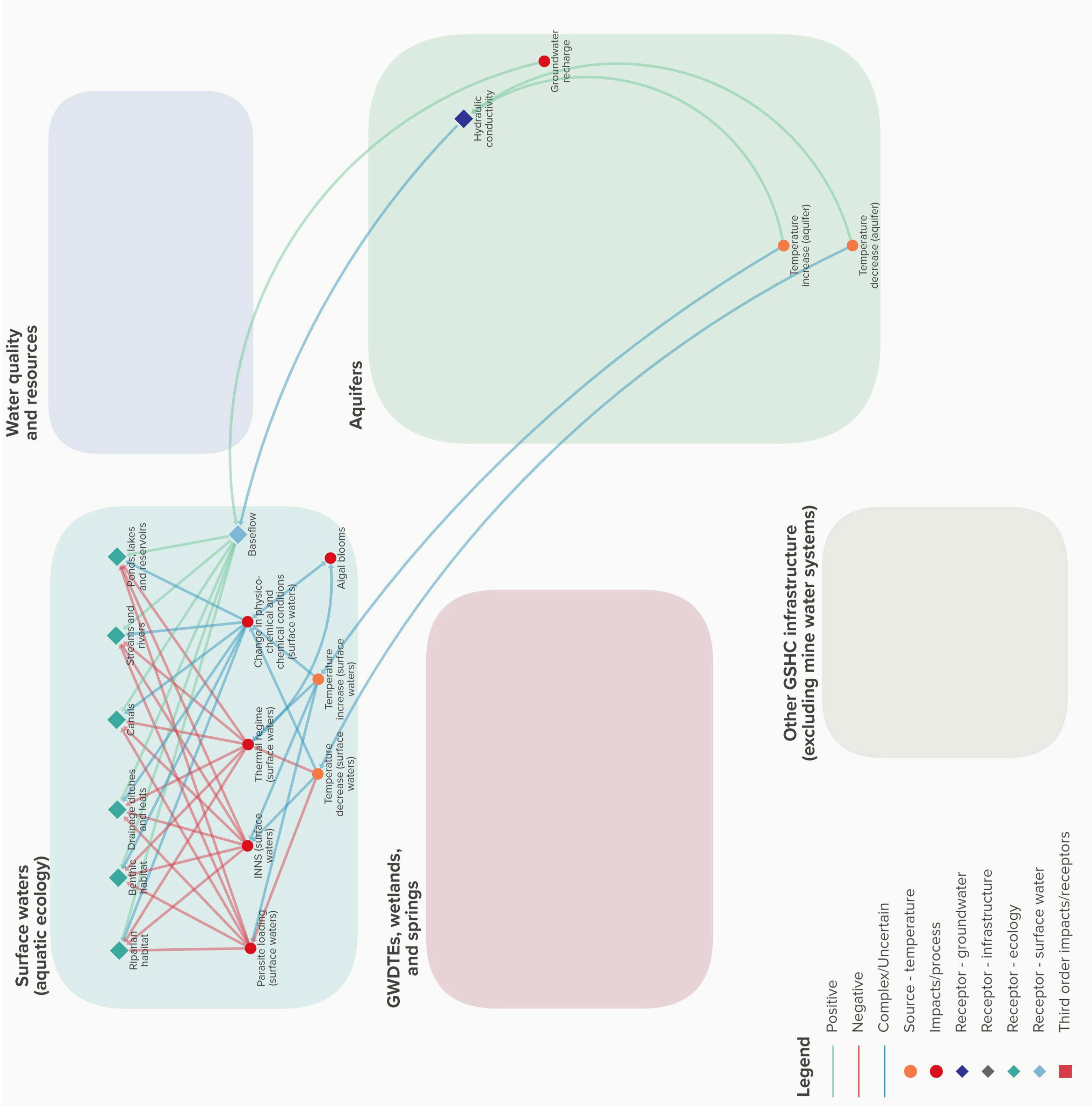

Figure 5. Surface waters (aquatic ecology) sub-system. This view is from the Kumu systems map where only the 'Surface waters (aquatic ecology)' sub-system layer is selected from the 'select a sub-system' filter. Elements are represented by circular, and diamond-shaped nodes, causal relationships are represented by green (positive), red (negative), and blue (complex) lines.

3.2.4 Water quality and resources

Changes in geochemistry and microbiology increasingly impact groundwater quality as temperature increases which could impact water resources and water infrastructure. Whilst GSHC-associated temperature changes could trigger changes in physical, chemical, and microbial processes in the subsurface and water resources environment (Saito et al., 2016), the vulnerability to this is highly dependent on the specific hydrogeological characteristics and surface activities. Impacts of temperature changes from GSHC will also be influenced by aquifer type, degree of urbanisation, GSHC operational conditions, local climate change impacts, subsurface infrastructure, surface connectivity, agricultural activity etc. (Bonte et al., 2013a; García-Gil et al., 2018; Saito et al., 2016).

The water quality and resources sub-system (Figure 6) has no temperature source nodes or temperature-induced processes nodes within the sub-system. This is because receptors in this sub-system are mediated primarily by surface water or groundwater quality, which is impacted by processes in the aquifer and surface water (ecology) sub-system. The strength of the links between the aquifer and surface water sub-systems and water quality and resources will differ depending on the proportion that each provides to water resources in a particular region.

Changes to the receptors in this sub-system could have consequences for agricultural productivity, water treatment and maintenance costs, and could pose some public health risks.

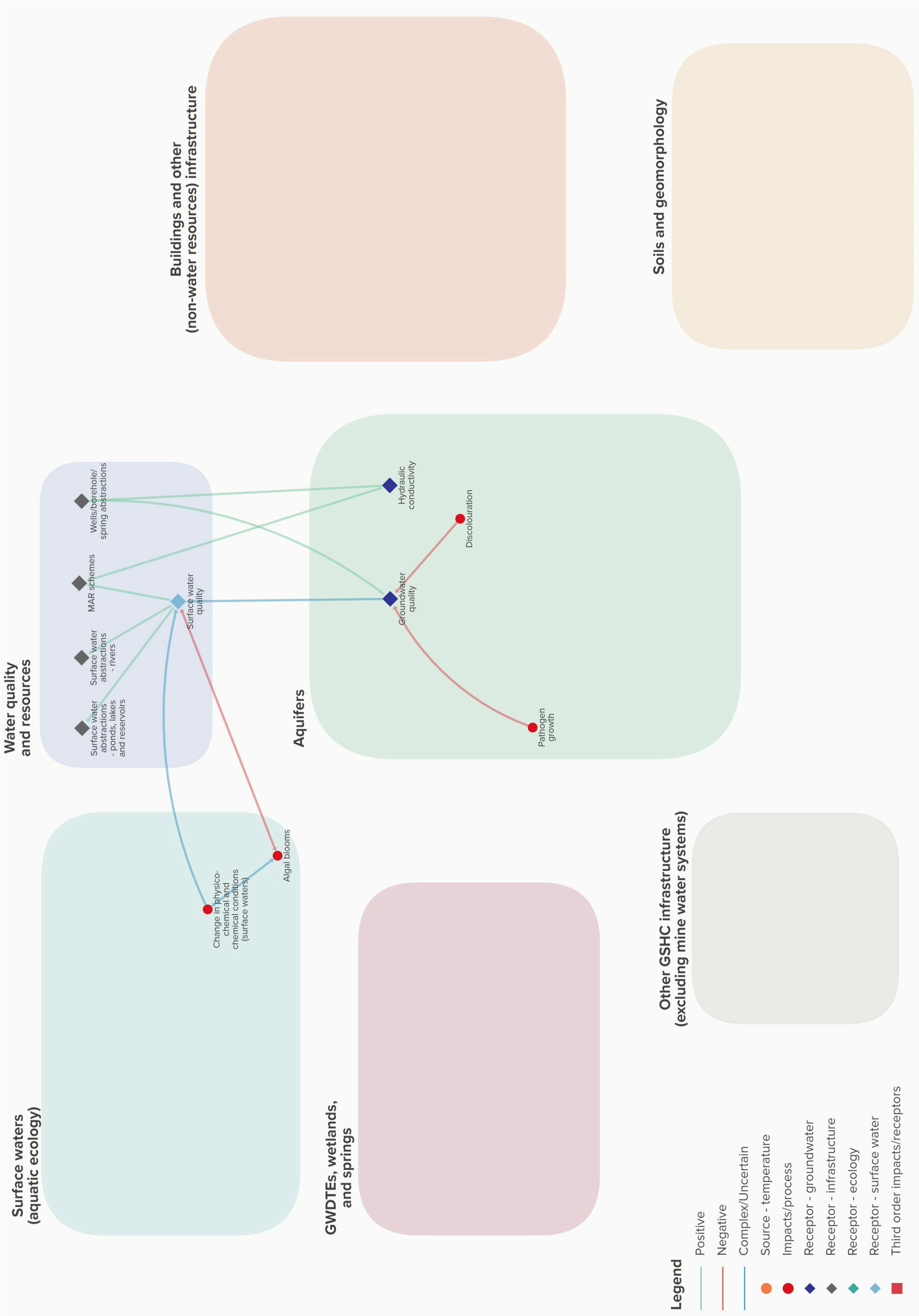

Figure 6. Water quality and resources sub-system. This view is from the Kumu systems map where only the 'Water quality and resources' sub-system layer is selected from the 'select a sub-system' filter. Elements are represented by circular, and diamond-shaped nodes, causal relationships are represented by green (positive), red (negative), and blue (complex) lines.

3.2.5 Buildings and other (non-water resources) infrastructure

Buildings and infrastructure could be impacted by GSHC schemes. The main temperature-related impact associated with an increase in temperature is the potential switch in microbial communities from nitrate and iron reducing bacteria to sulphate reducers (Jesußek et al., 2013; Bonte et al., 2013b) or an increase in sulphur-cycling organisms is associated with the corrosion of infrastructure (Ura-Binczyk et al., 2019). This microbial shift is exaggerated in geothermal energy operations at higher temperatures (Lerm et al. 2013; Westphal et al. 2016; Würdemann et al. 2016).

The potential receptors in this sub-system (Figure 7) includes surface/near surface infrastructure (roads and railways, buildings and public services[18] and repurposed geothermal mine systems[19]). This infrastructure is largely impacted through ground movement (caused by temperature changes within soils) and corrosion (which can be enhanced due to temperature changes in groundwater and soils). Repurposed mine systems could be directly impacted through changes in temperature in the ground, or indirect changes in physico-chemical conditions, thermal interference between other GSHC schemes, and mine void instability.

Impacts on receptors in this sub-system could incur economic costs (insurance, repair, losses) and pose potential public health risks.

[18] Piped water and wastewater services, for example.

[19] Disused mines have the potential to be repurposed for GSHC infrastructure as flooded mines provide a means of heat distribution and storage; mines are natural storage spaces for thermal energy and very high volumes of available water and the resultant high abstraction rates make disused mine systems ideal for large-scale open-loop GSHC systems (Abesser and Walker, 2022).

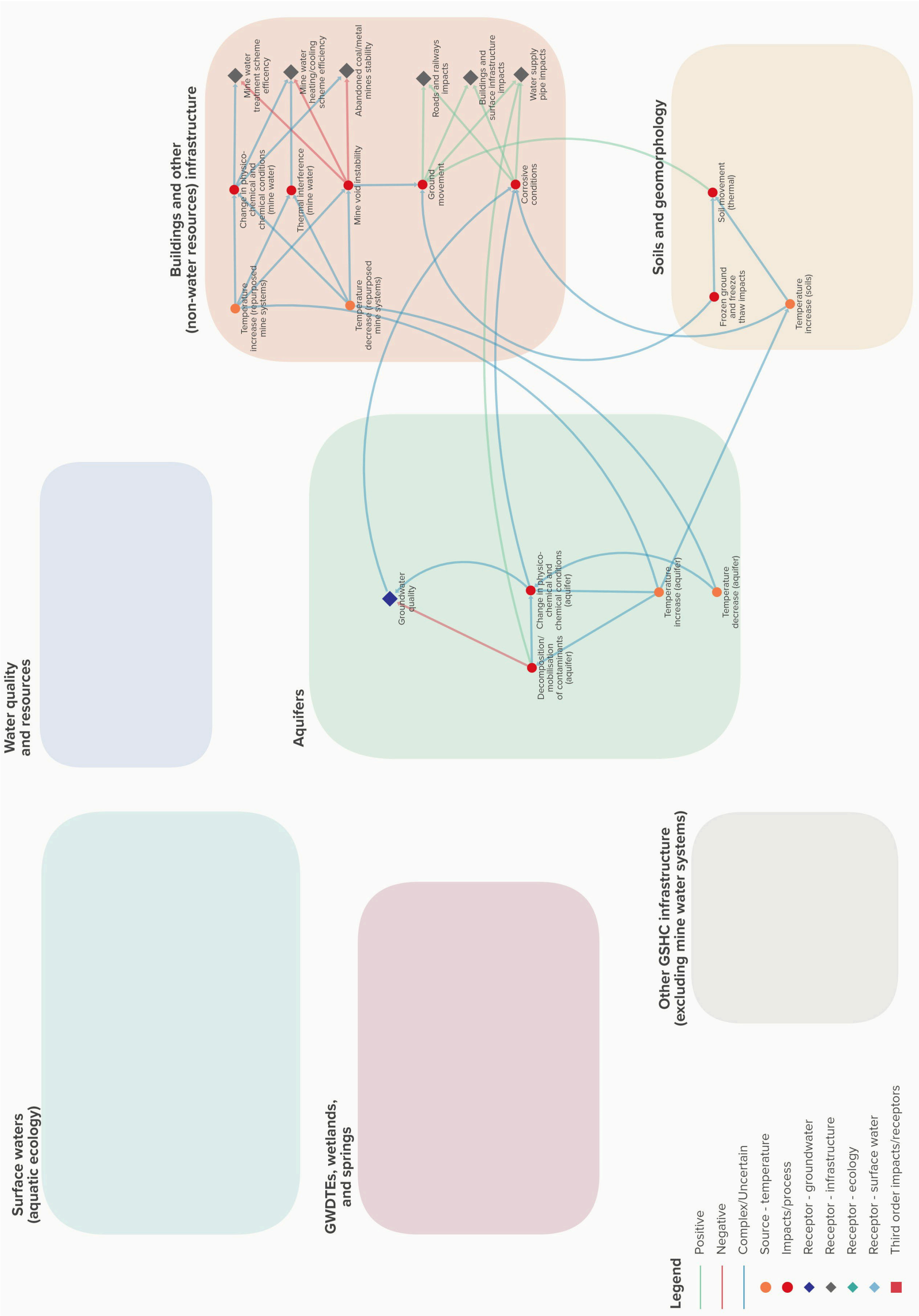

Figure 7. Buildings and other (non-water resources) infrastructure. This view is from the Kumu systems map where only the 'Buildings and other infrastructure' sub-system layer is selected from the 'select a sub-system' filter. Elements are represented by circular, and diamond-shaped nodes, causal relationships are represented by green (positive), red (negative), and blue (complex) lines.

3.2.6 Soils and geomorphology

The properties and dynamics of soils are complex and influenced by multiple factors (such as soil composition, moisture content, ground cover, contamination, seasonality and depth), making it difficult to provide an assessment of the impacts of temperature changes (SoBRA, 2022). Whilst soils in the UK are naturally exposed to annual seasonal temperature variations of at least 20°C (Banks, 2012), GSHC-induced temperature changes have the potential to affect the chemical, physical and biochemical properties and behaviour of soils and possibly shallow groundwater (Banks, 2012; Morton, 2016; SoBRA, 2022).

Receptors in the soils and geomorphology sub-system (Figure 8) could be impacted through temperature changes caused within the soil caused by very shallow GSHC schemes or by conduction or dissipation from GSHC-induced temperature changes in the underlying rock. There are links with the buildings and other (non-water resources) infrastructure sub-system due to the impacts of soil movement and freeze thaw impacts on ground movement and stability. There could be impacts to surface water run-off, and therefore flood risk, as well as agricultural productivity caused by impacts to soil moisture.

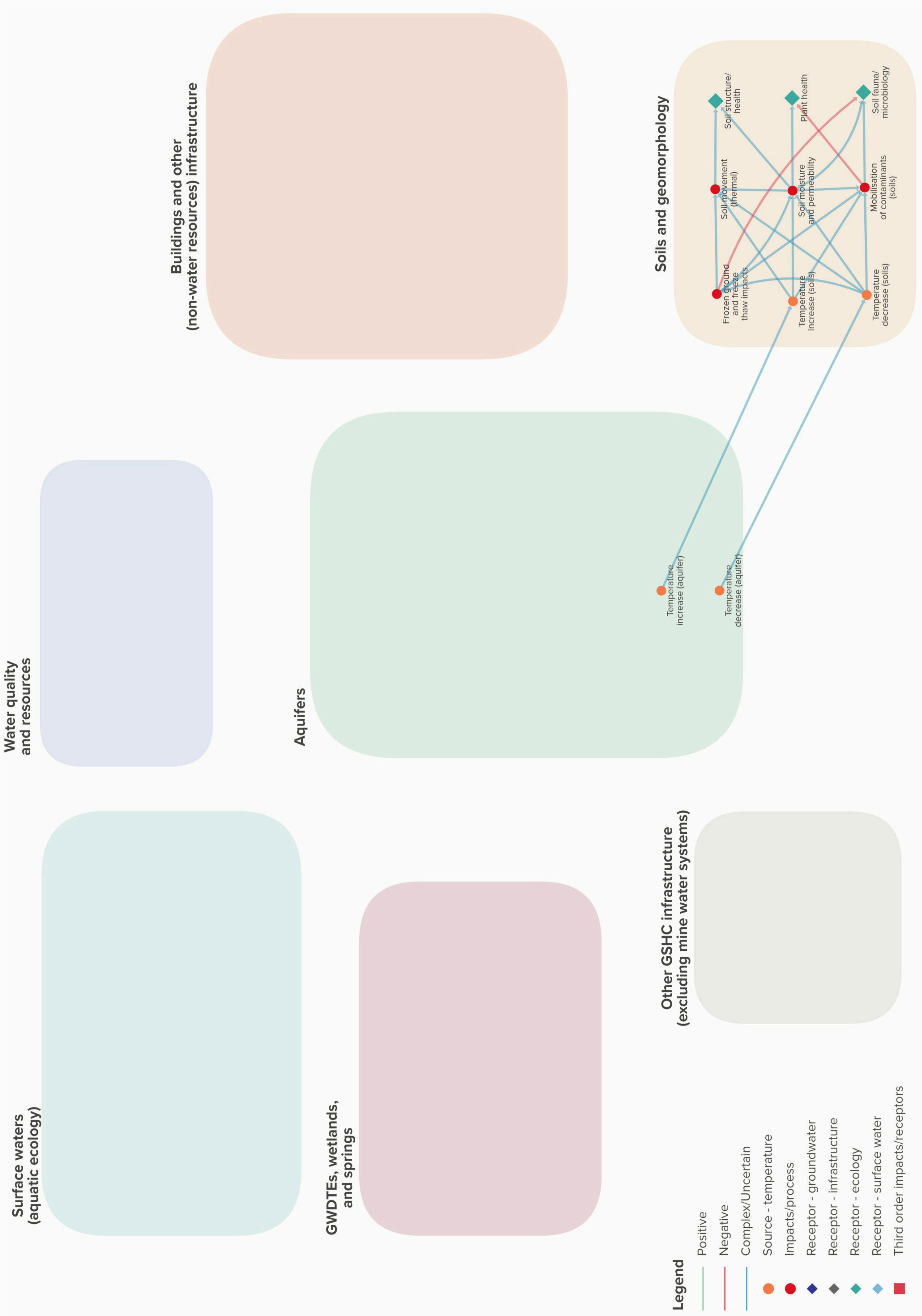

Figure 8. Soils and geomorphology sub-system. This view is from the Kumu systems map where only the 'Soils and geomorphology' sub-system layer is selected from the 'select a sub-system' filter. Elements are represented by circular, and diamond-shaped nodes, causal relationships are represented by green (positive), red (negative), and blue (complex) lines.

3.2.7 Other GSHC infrastructure (excluding mine water systems)

Existing GSHC schemes could be impacted by the installation of new closed or open-loop GSHC systems. The primary cause for concern is thermal interference [20] between GSHC schemes (see Figure 9) which can reduce their performance and efficiency and lead to them becoming potentially economically unviable (Abesser and Walker, 2022; Birks et al., 2015).This could be a particular challenge in areas of high GSHC scheme density. In addition, there could be greater temperature-induced clogging/corrosion.

[20] For example, the close proximity of abstraction and discharge wells could mean that discharged water from one system affects the temperature of the abstracted water of another system (Environment Agency, 2011).

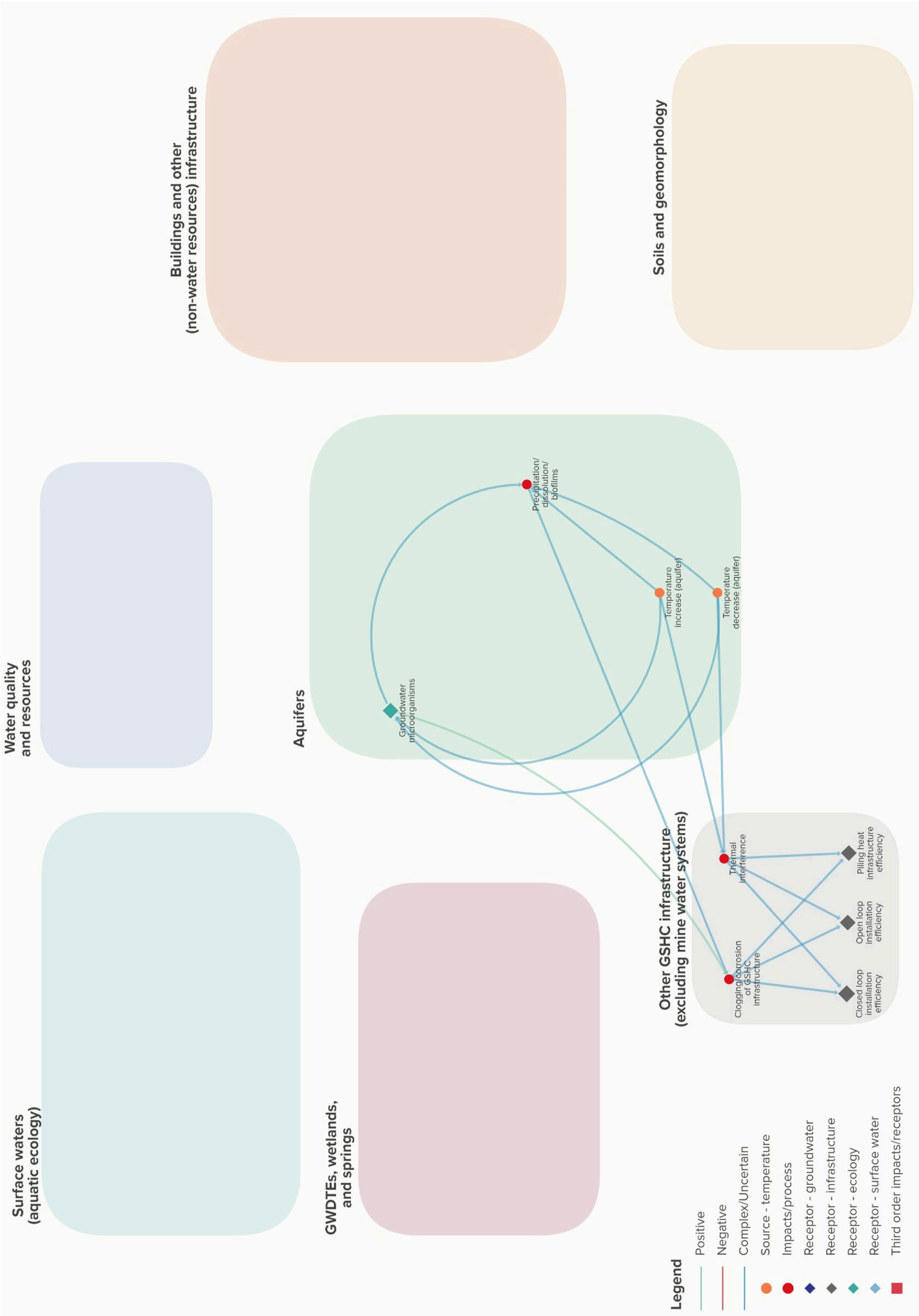

Figure 9. Other GSHC infrastructure (excluding mine water systems). This view is from the Kumu systems map where only the ‘Other GSHC infrastructure’ sub-system layer is selected from the ‘select a sub-system’ filter. Elements are represented by circular, and diamond-shaped nodes, causal relationships are represented by green (positive), red (negative), and blue (complex) lines.

3.3 Identifying vulnerable environmental receptors and tolerable ecological temperature ranges

Each individual GSHC system will have site-specific features that will determine the vulnerability (for example, sensitive, protected, high value, high risk etc) of receptors. The systems map presents generic receptor types and does not differentiate between their vulnerability or provide an indication of sensitivity to heating/cooling impacts. Some suggestions of receptors that might be more sensitive to temperature changes are provided in this Section. Section 3.3.1 discusses environmental receptors that might be considered as more vulnerable in terms of their sensitivity and importance. Section 3.3.2 provides a synthesis of tolerable temperature range data for specific ecosystems and species that were identified through the literature review.

3.3.1 Potentially vulnerable environmental receptors

Certain GSHC sites could be in or near environmental settings that are considered more sensitive due to specific ecological, water resource, or amenity value. In addition to environmental receptors, certain buildings (for example, those of national or international heritage importance) or critical infrastructure could also be considered as important receptors, but these are not discussed further here.

The following provides an indication of statutory and non-statutory environmental receptors that might require further analysis should they be identified within the vicinity[21, 22] of a proposed GSHC:

- **Statutory ecological sites designated or classified under international conventions or European legislation, including:**
  - World Heritage Sites
  - Biosphere Reserves
  - Wetlands of International Importance (Ramsar sites – including proposed Ramsar sites)
  - Special Areas of Conservation (including candidate SACs)
  - Special Protection Areas (including proposed SPAs)

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[21] Note: Receptor/scheme distances are not specified within this report or the systems map. Suitable distances for screening in/out of GSHC Environmental Impact Assessments are subject to regulatory agreement.

[22] Recommendations on distances within certain specific guideline aquifer/GSHC scenarios are due to be made in 2024.

- **Statutory ecological sites designated or classified under national legislation, including:**
  - Sites of Special Scientific Interest (SSSIs)
  - Marine Protected Areas and Marine Conservation Zones (including proposed or recommended sites)
  - National Nature Reserves

- **Ecological sites designated or classified under local legislation**, **including:**
  - Designated wildlife sites
  - Local Nature Reserves
  - Country parks

- **Aquifer, groundwater, and surface water receptors (including water quality and resources)**
  - Source Protection Zones (SPZs)
  - Drinking Water Protected Areas (DrWPAs)
  - Principal and Secondary Aquifer sites[23]
  - Chalk Streams[24]
  - Surface water and groundwater water (drinking water) abstractions

- **Soils**
  - Contaminated land sites (whether formally designated or not)[25]. Note, these are not likely to be considered high value receptors in and of themselves but are likely to require assessment due to the possibilities of mobilising existing contamination.

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[23] In line with https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/692989/Envirnment-Agency-approach-to-groundwater-protection.pdf (Section R – Ground source heating and cooling) for example (Environment Agency, 2017).

[24] See https://www.gov.uk/government/news/new-chalk-streams-strategy-launched-to-protect-england-s-rain-forests and https://catchmentbasedapproach.org/learn/chalk-stream-strategy-3/.

[25] In line with https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/692989/Envirnment-Agency-approach-to-groundwater-protection.pdf (Section R – Ground source heating and cooling) (Environment Agency, 2017).

- Landfill sites.

For ecological receptors, the Chartered Institute of Ecology and Environmental Management (CIEEM) highlights some important ecological features as priority for consideration across key habitats and species for biodiversity and nature conservation in the UK (CIEEM, 2018). These could be considered along with the systems map for a greater understanding of site-specific receptor sensitivity. CIEEM (2018) include the following areas:

- **Habitats and species of principal importance for the conservation of biodiversity: England, Wales and Scotland Biodiversity List**.
  - Ancient woodland inventories for England, Ireland, Northern Ireland, Scotland and Wales.
  - UK Habitats and species of principal importance (first identified in the UK Biodiversity Action Plan (BAP).

- **Receptors including red listed, rare, legally protected species:**
  - Species of conservation concern, Red Data Book (RDB) species
  - Birds of Conservation Concern
  - Nationally rare and nationally scarce species
  - Legally protected species
  - OSPAR Commission list of threatened/declining species in the North-east Atlantic

3.3.2 Ecological temperature ranges

While the systems map can be used to qualitatively identify possible ecological receptors, further quantitative investigation would be required to determine the level of risk to any identified receptor in the site-specific setting of an individual GSHC system. Specific ecological temperature ranges may be used as a guide to ecological sensitivity to potential temperature changes. A series of summary graphs (Figures 10 to 13) show these ecological temperature ranges[26]. Appendix III provides data tables for the data underlying the figures.

The figures are presented as box-and-whisker plots. Reading the graphs:

- The ‘box’ represents the interquartile range, bound by the upper (75th percentile) and lower (25th percentile) quartiles.

[26] Only flora and fauna present in the UK was included in the sensitivity graphs.

- 'X' indicates the mean value. Where this exists without a box and whisker, it indicates an upper temperature limit where there was only one data point (i.e., not a range of values).
- The middle horizontal line within the 'box' represents the median value.
- The thinner parts of the line (the whiskers) indicate the upper and lower data ranges of thermal tolerance for that species / ecosystem.
- Data points outside of the box and whisker (and are not an 'X' but a dot) are data points outside this range, i.e. outliers.

Figures 10 to 13 show temperature ranges and maxima for several categories of organisms and specific species, including fish (Maitland, 2003; Maitland and Hatton-Ellis, 2003; Webb and Walsh, 2004; UKTAG, 2008), some crustacea (Ginet, 1960; Knight and Johns, 2015; Di Lorenzo et al., 2023; Malard et al., 2023), and microbial communities (Brock, 1975; Bonte et al., 2013a; Garcia-Gil et al., 2018).

Figure 10 shows temperature sensitivities for broad categories of organisms, including bacteria, protozoa, eukaryotic algae, fungi, mosses, vascular plants, insects and fish and other aquatic vertebrates (after Brock, 1975). It does not cover other broad categories, crustaceans for example, that make up the majority of groundwater fauna aside from insects. Figures 11 to 13 show more specific receptors within various categories of ecosystem and those that might be more sensitive to impacts from GSHC systems such as freshwater fish (Figure 11), groundwater fauna (Figure 12) and microbial communities (Figure 13).

In many cases, only maximum temperature tolerances of species are reported. However, more information is available for numerous species or ecosystems, and where available these demonstrate the variation in tolerable temperature ranges across an ecosystem (presented as box-and-whisker plots on the graphs). In cases where multiple references report temperature ranges for single species, ranges tend to overlap but not completely coincide.

Similarly, with regards the sensitivity of receptors to temperature change, this will depend on the baseline range of temperatures at a receptor and how close those are to threshold temperatures for species. For example, a non-statutory designated environmental receptor (for example, a pond in a local nature reserve) that exhibits baseline temperatures at the upper tolerable range limit for a species could be more sensitive to GSHC-induced temperature changes than one that has a baseline range closely around the median value of a species' tolerable range (for example, a SSSI with red list species). The latter could be the more nationally important ecological receptor, but less sensitive to temperature change than the pond, as the GSHC scheme will not put it outside the tolerable temperature range for a given species. A similar example would be a river with a high flow rate and good vegetation cover keeping waters cooler, versus one with a lower flow rate and no vegetation such that it is unable to moderate temperatures.

This example highlights the complexities associated with *a priori* determination of sensitivity of types of ecological receptor to GSHC induced temperature changes. However, it can be broadly stated that species with narrow tolerable temperature ranges are likely to be more sensitive to temperature changes than those with broad tolerable temperature ranges because baseline conditions are more likely to be at or closer to narrower range limits.

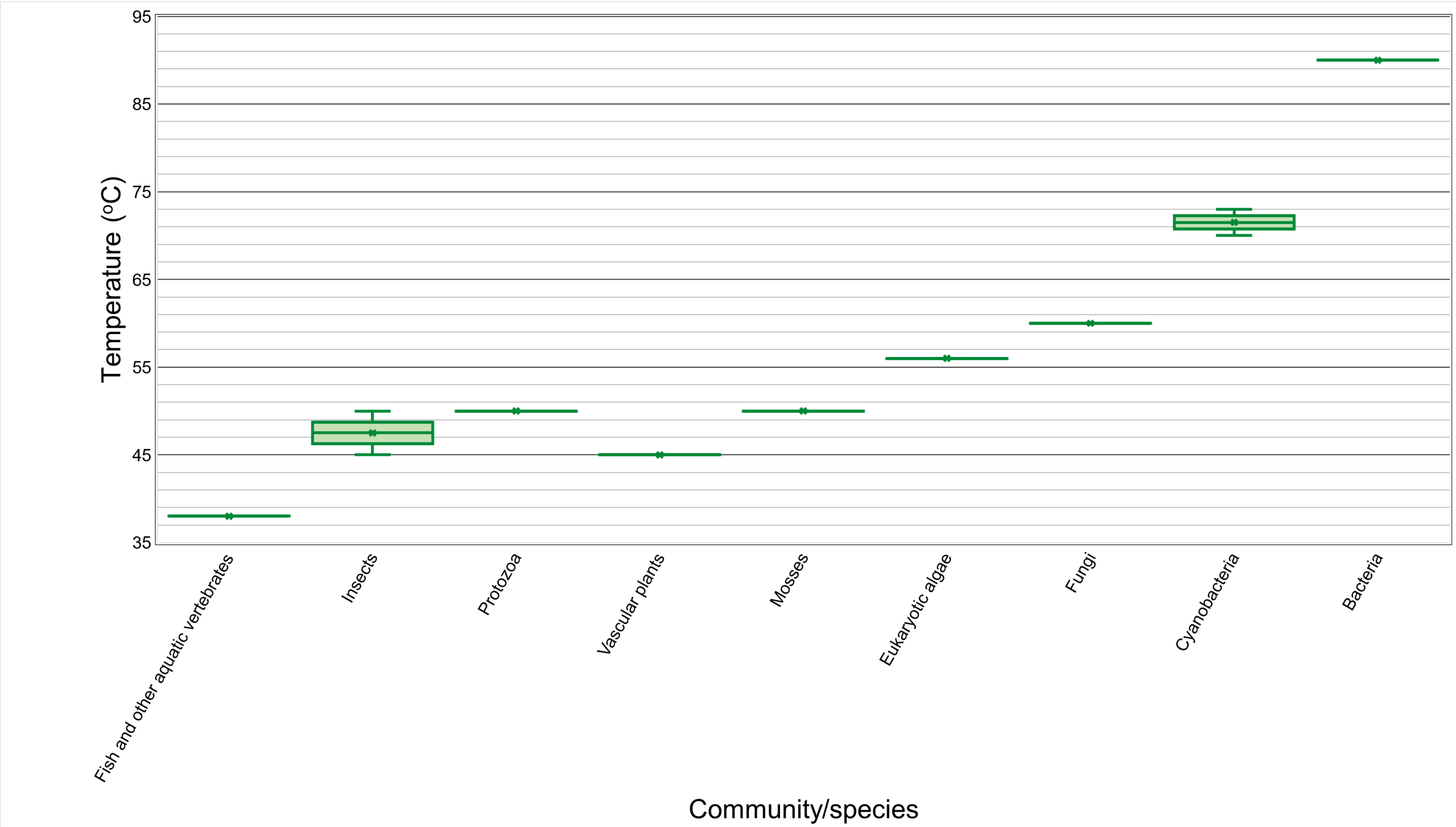

Figure 10 Maximum temperatures that can be tolerated by certain ecological receptors and ecosystems (after Brock (1975). Maxima shown as single lines, ranges shown as box and whiskers. Please note that the group 'insects' does not cover all invertebrates.

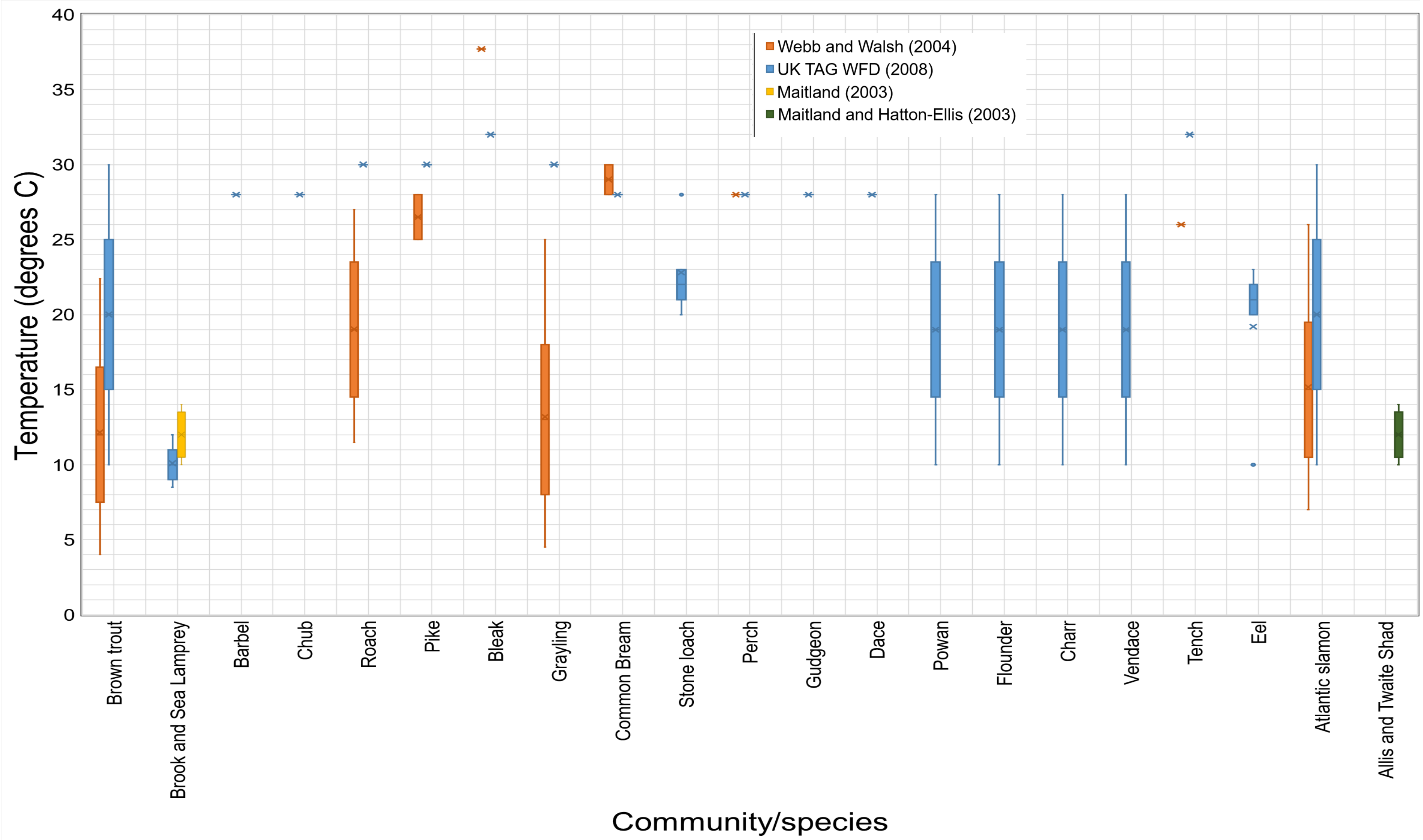

Figure 11. Freshwater fish temperature tolerances (maxima, as given by crosses) and ranges (given by box-and-whiskers) in the UK from literature review (sources indicated in key).

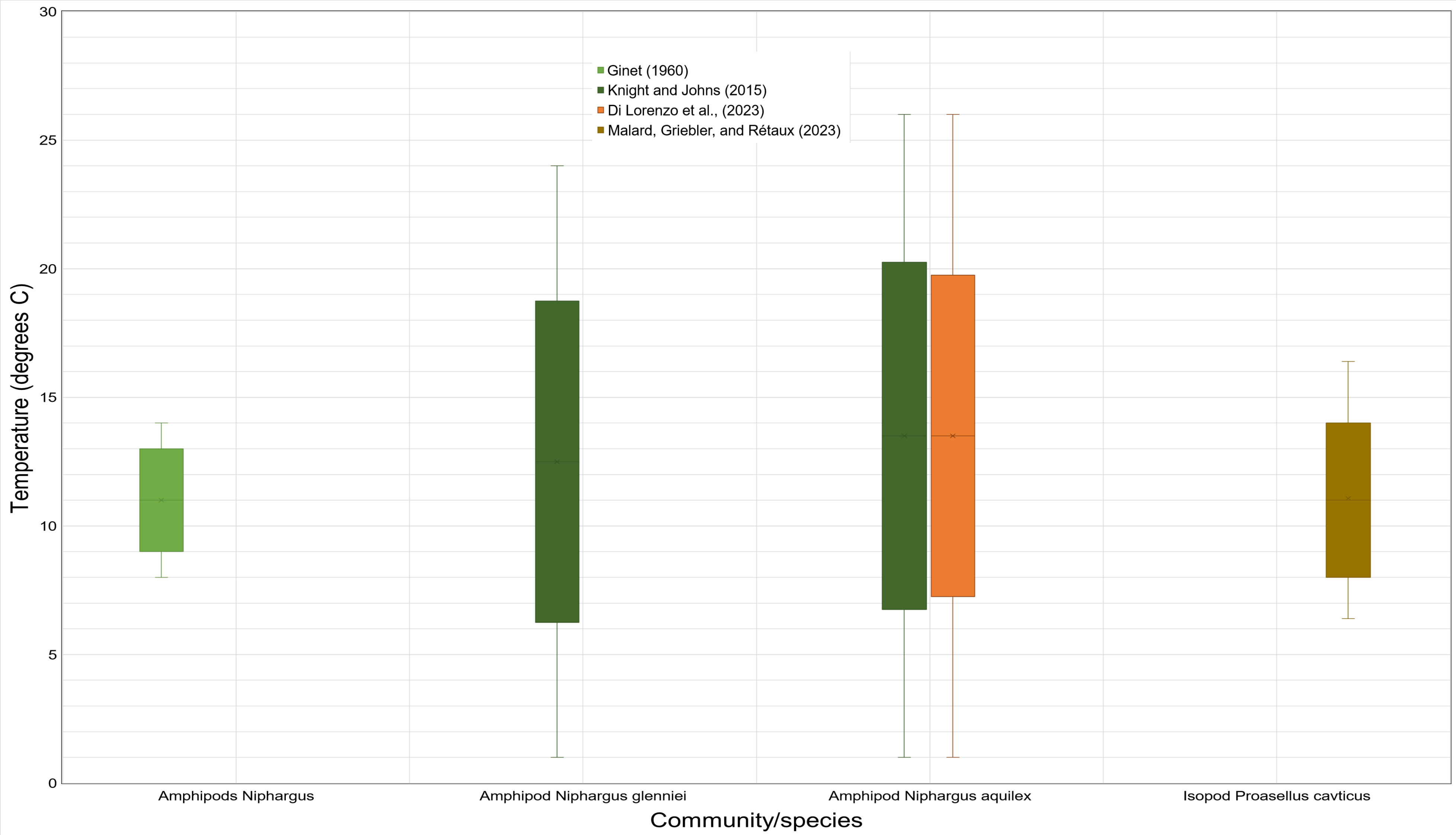

Figure 12. Groundwater ecology temperature ranges in England from literature review (sources indicated in key).

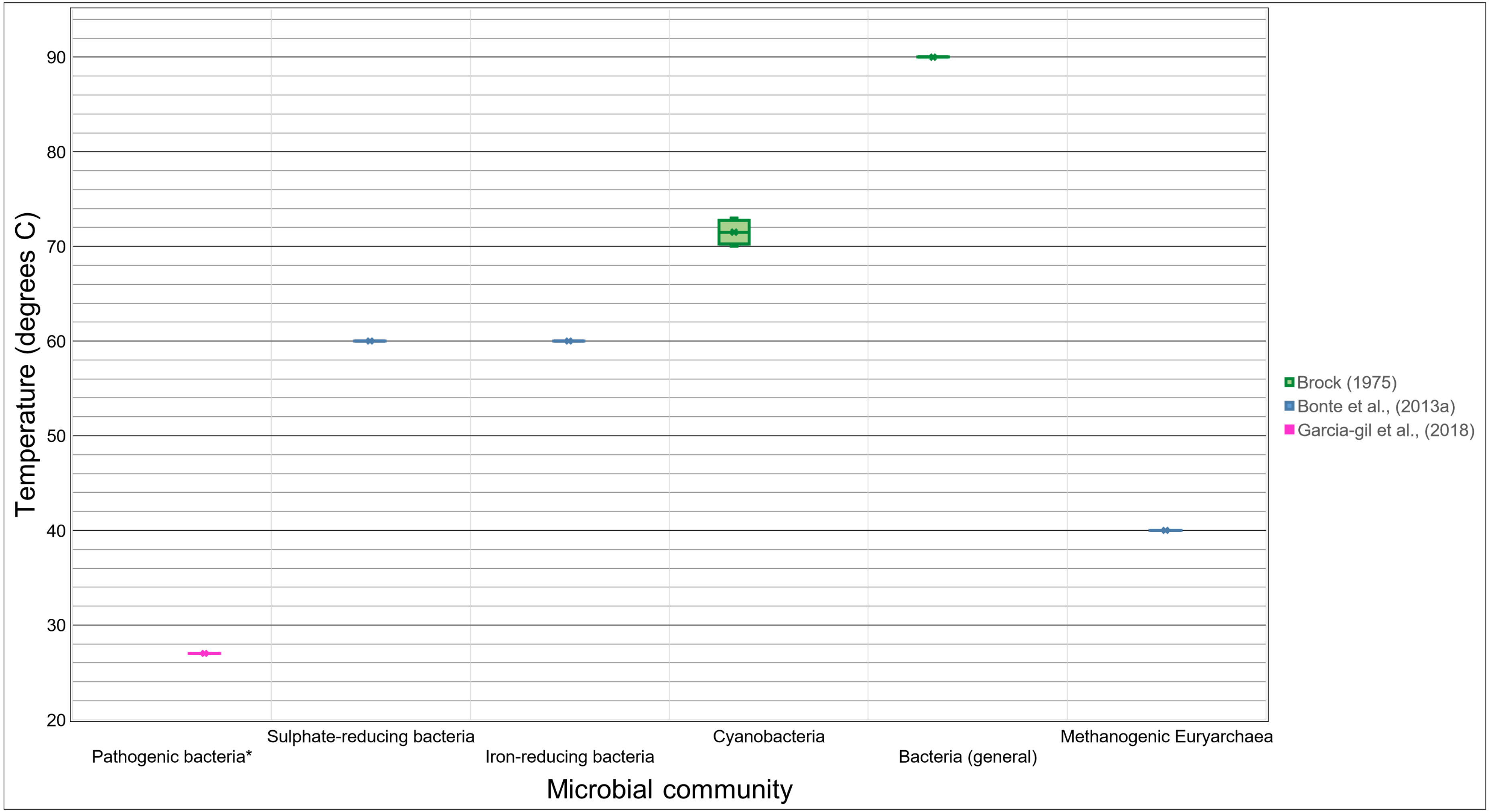

Figure 13. Microbial community temperature tolerances (maxima, as given by crossed lines) and ranges (given by box-and-whiskers). *Garcia-gil et al., (2018) observed that whilst this temperature range would be expected to increase pathogenic bacteria, heat shock from GSHC systems actually reduced their presence (due to direct contact with heat exchangers at 40-60°C).

4 Summary and conclusions

A systems map[27] of environmental receptors that could be impacted by GSHC induced ground heating or cooling has been developed through a literature review and subject matter expertise across multiple stakeholders, the Environment Agency steering group, and the project delivery team. The information embodied within the map demonstrates not only the potential receptors of GSHC-associated temperature changes in the ground, but also the processes and interactions between them. The map also provides references for further details.

The systems map helps improve our understanding of the environmental settings and receptors that could be impacted by temperature changes from GSHC schemes. This information will contribute to proportional and evidence and risk-based regulation of heat with respect to GSHC systems. It will also help industry and decision makers identify potential receptors and proactively manage risks from GSHC through the permitting process. However, it is important to note that use of the systems map is **not** a requirement in the environmental permitting process under EPR regulations.

The main purposes of the systems map are to:

- Summarise the potential environmental impacts of heating and cooling in the ground (not in a building);
- Provide a general map of all realistic pathways from GSHC induced ground temperature changes to receptors;
- Provide a way of structuring and visually representing current knowledge and experience related to ground temperature change impacts and associated receptors.

The map does not:

- Represent spatial, temporal, or scale aspects of GSHC installations;
- Model actual temperature impacts in the ground, or;
- Consider the site-specific details of a specific GSHC installation.
- Provide quantitative results, site specific analysis, or conclusive evidence for the approval of a GSHC installation.

Appendices provided in this report explain the use of the systems map. The systems map comprises 7 sub-systems interlinked by various processes, and hosting a wide

[27] https://kumu.io/csgnz/environment-agency-gshc-systems-map-2024

variety of receptors that could be potentially impacted by GSHC induced temperature changes. The 7 sub-systems are:

- Aquifers
- Groundwater dependent terrestrial ecosystems (GWDTEs), wetland and springs
- Surface waters (aquatic ecology)
- Other GSHC infrastructure (excluding mine water systems)
- Soils and geomorphology
- Buildings and infrastructure
- Water quality and resources

Across these sub-systems, the most consistently noted GSHC-associated temperature impacts[28] identified either within the literature or in discussion with SMEs were:

I. Heat induced changes in physico-chemical properties and contaminant mobilisation in soils and groundwater;
II. Temperature-induced changes in microbiological, floral or faunal community composition; and
III. Environmental and public health risks consequent upon either or both of the former (i.e. second- or third-order impacts / indirect impacts).

There were some knowledge gaps and complexities associated with ground heating and cooling impacts from GSHC and with the formulation of the map:

Knowledge gaps and complexities associated with GSHC environmental impacts:

- There is not a well-developed body of literature relating to the direct and indirect impacts of GSHC-associated temperature impacts on the environment, although some important references do exist and are highlighted in **bold** in the References;
- Uncertainties associated with understanding the effects of GSHC in combination with other potential heating impacts for example, urban heat islands, climate change impacts, wastewater etc;
- Ground cooling is generally perceived to be less of a problem than heating within the literature and among SMEs, although many ecological receptors are sensitive to temperature range (i.e. lower as well as higher temperatures). On the other hand, cooling may offer additional environmental benefit to otherwise heat-stressed systems in certain locations, although the relationships are complex;
- ‘Extreme’ temperatures are referred to in the literature (for example, SoBRA, 2022) but precise temperatures are not defined. The term ‘extreme’ therefore

[28] Please note that these are qualitative and not related to specific temperature changes.

appears to be defined by the thermal tolerance of specific organisms than to definitive temperatures (i.e. an extreme temperature for one organism is one that will kill it).

Knowledge gaps and complexities associated with realisation of the systems map:

- Difficulty in concluding specific temperature ranges and sensitivities for receptors without quantitative studies at a site-specific level to determine how specific receptors will respond to heating and/or cooling;
- Possible impacts of temperature changes on organic matter in wetlands;.
- The sensitivity of ecological receptors to temperature change depends on the baseline range of temperatures at a receptor and how close those are to threshold temperatures for the species;
- This implies complexities associated with *a priori* determination of sensitivity of types of ecological receptor to GSHC induced temperature changes. However, broadly speaking, species with narrow tolerable temperature ranges are likely to be more sensitive to temperature changes than those with broad tolerable temperature ranges, because baseline conditions are more likely to be at, or closer to, narrower range limits.
- Geochemical and hydrochemical interactions are highly complex with many factors besides temperature controlling water quality via the formation, mobilisation and movement of aqueous chemical species (i.e. dissolved elements and compounds), including contaminants. Aqueous geochemical and groundwater transport modelling is required to assess such changes in detail at a site-specific level.

Further to the identification of knowledge gaps and complexities, some recommendations arising from the work include:

- Prioritisation of specific pathways identified within the systems map might help focus efforts on key areas of the map. The systems map does not provide an indication as to the sensitivity or likelihood of impacts to particular pathways. For example, the pathway running through 'mobilisation of contaminants (aquifer)' node in the aquifer sub-system to a groundwater quality receptor is likely to be widely recognised as a potentially widespread and commonly realisable risk in certain areas. By contrast, impacts to the 'roads and railways' receptor node via a 'ground movement' pathway in the buildings sub-system is less likely to present such a widespread risk.
- Improve understanding of thermal plume extent and temperatures, and the likelihood of temperature change at given distances with regards with specific installations.
- It would be useful to identify typical situations (for example, distances and GSHC system size) at which GSHC heat sources could realistically pose risks to receptors of different sorts. This would help identify receptors in a particular vicinity and justify prioritisation of receptors across scenarios.

All of the above would help focus future investigations (for risk assessment or research) on key areas of the map. However, ultimately each GSHC scheme site is unique and, at each scheme, variations in (among other factors) soil type, geological characteristics, hydrogeology, surface water / groundwater connectivity, surface activities, and GSHC operation and design, will all be determinants of the variety and severity of the potential impacts of GSHC-associated temperature changes. Therefore, assessment of risks to site-specific receptors should take account of the distinct characteristics of any individual GSHC scheme. The systems map can be used to help with such assessments[29]. It is important to note that the systems map is most appropriately used for:

- Qualitative identification of potential receptor types that should be considered when assessing impacts from proposed GSHC schemes;
- Identifying the principal mechanisms by which impacts could occur at receptors;
- Identifying relevant information sources when examining specific mechanisms by which impacts occur, and;
- Determining levels of input required for subsequent assessment stages.

[29] For example, at an early stage of risk assessment (i.e. desk-study), with a view to determining which pathways may be usefully taken forward for further consideration at semi-quantitative and fully quantitative assessments. A fully quantitative study may model pathways identified form the systems map, but would take a much more refined conceptual view of a specific system in order to do so.

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Note – key references are listed in bold

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List of abbreviations

DOC	Dissolved organic carbon
EPRs	Environmental permitting regulations
GSHC	Ground source heating and cooling
GWDTEs	Groundwater dependent terrestrial ecosystems
INNS	Invasive non-native species
MAR	Managed aquifer recharge
MCS	Microgeneration Certification Scheme
PSM	Participatory systems mapping
SME(s)	Subject matter expert(s)
SPR	Source-pathway-receptor

Glossary

Amphipod	Small invertebrate crustaceans that live in various aquatic habitats.
Bacteria	A group of microscopic single-celled organisms, including some that can cause disease.
Baseflow	Proportion of river flow that does not come from run-off from the land (for example, through the ground or from groundwater).
Baseline (range)	The range of the natural or original states (for example, of temperature, pH, chemical composition, etc) to which comparisons are made.
Benthic habitat	Habitat in the beds of surface waterbodies.
Closed-loop GSHC systems	"Systems that extract heat or cold from the ground by circulating a heat carrier fluid around an array of closed pipe loops (borehole heat exchanger)" (Abesser and Walker, 2022).
Dissolved organic carbon (DOC)	Dissolved organic carbon is the total dissolved organic chemical species (i.e. different compounds) dissolved in an aqueous mixture.
Ecological receptors	Sensitive sites, habitats, ecological features, assemblages, species or individuals
Ecosystem functioning	Capacity or capability of the ecosystem to support life systems.
Eukaryotic algae	Organisms that include three organelles: the nucleus, the chloroplast, and the mitochondrion.
Fauna	Animals, specifically those of a particular area or region.
Flora	Plants, specifically those of a particular area or region.
Fungi	Multicellular microorganisms that break down nutrients in the ecosystem including mushrooms, yeasts, and moulds.
Generation times	The time it takes a population of microorganisms to double in number.
Groundwater fauna	Animals, specifically those of a particular area or region, that exist in groundwater systems.

Groundwater microorganisms	Microorganisms (for example, bacteria, archaea, algae, protozoa, fungus) that exist in groundwater systems. Retter et al. (2021) identify microbes as dominant in the groundwater food web.
GWDTEs (Groundwater dependent terrestrial ecosystem)	Terrestrial ecosystem that is dependent on the water level in or flow from a groundwater body
Hydraulic conductivity	The ability of fluid to pass through pores and fractured rocks.
INNS	Invasive non-native species. Any species not originating within the British Isles and with the ability to spread and cause harm to native ecosystems.
Iron reducing bacteria (IRB)	Iron reducing bacteria (IRB) is bacteria that can react directly with the rocks in the reservoir to reduce iron (Jesußek et al., 2013; Bonte et al., 2013b).
Isopod	Small crustaceans that can be aquatic or terrestrial, i.e. woodlice.
MAR	Managed aquifer recharge, intentional recharge of water to aquifers for use or environmental benefit.
Microbe	Microscopic organisms that can exist as a single-cell or as a colony of cells.
Microgeneration certification scheme (MCS)	"A standards body that certifies, quality assures and provides consumer protection for microgeneration installations and installers" (Abesser and Walker, 2022).
Mosses	Flowerless and non-vascular plants.
Oligotrophic	Used to refer to an environment where concentrations of nutrients are very low or absent or microorganisms that grow under such conditions.
Open-loop GSHC systems	"A geothermal system that typically pumps warm groundwater directly from an aquifer or flooded mine system via a production borehole and, after heat extraction, returns the cooled water to the system via an injection" (Abesser and Walker, 2022).
Parasite	Organisms living in or on another organism.

Participatory systems mapping (PSM)	A collaborative system mapping process where the system representation (map) is created through discussion and co-learning that prioritises the knowledge and experience of those involved in the system.
Pathogen	A microorganism that can cause disease in other organisms for example, viruses and bacteria
Physico-chemical conditions (P-C conditions)	The principles of both physics and chemistry. The physico-chemical properties of water include temperature and dissolved oxygen content.
Physiological	Characteristics of living things.
Physiological performance	The functioning of physiological rates (normal functions of organisms) with respect to the environment.
Precipitation/ dissolution	Referring the chemical processes of solids depositing from solution (precipitation) or being dissolved by solution.
Protozoa	Single-celled microscopic animals which could be parasitic.
Receptor	A receptor is defined by the Environment Agency as 'people, animals, property, and anything else that could be affected by the hazard' (Environment Agency, 2023b).
Redox	A redox reaction is a chemical reaction involving both the reduction (gain of electrons) and oxidation (loss of electrons) of matter.
Riparian habitat	Habitat along the margins of rivers.
Slime/ biofilm	Slimy layers of microorganisms such as bacteria that stick to wet surfaces.
Sulphur cycling	The process by which sulphur moves in different chemical states between systems, including organisms habitats and the atmosphere.
Thermal interference	Temperature changes resulting from one GSHC system impacts on another GSHC system
Thermal stratification	Development of distinct layers of water of different temperatures within water bodies.

Water Framework Directive (WFD)	European Directive that set out to halt deterioration in the status of EU water bodies and achieve good status for Europe’s rivers, lakes and groundwater and still forms part of UK law.
Vascular plants	Plants with vascular tissues (xylem and phloem).
Volatile organic compounds (VOC)	Volatile organic compounds – typically gasses at room temperature.
Volatile	A substance that can be easily evaporated.

Appendices

Appendix I – Using Kumu mapping software

The systems map is available https://kumu.io/csgnz/environment-agency-gshc-systems-map-2024[30]. It is hosted through a mapping software called Kumu. Kumu allows users to understand and navigate system complexity and interact with the systems map in an intuitive way. Kumu enables systems mapping to be:

- Accessible – the map is hosted online and can be easily accessed and shared.
- Intuitive – the mapping functionality and software are easy to use without requiring significant training or technical skills.
- Detailed – the focus and zoom tools enable analysis of relationships between nodes.
- Interactive – connections and feedback loops can be easily explored, enabling greater understanding of specific processes and how they relate to the wider system.
- Layered – the map can be layered up through the selection of individual systems or groups of systems, for ease of analysis in complex systems with multiple sub-systems.
- Annotated – additional information can be provided in descriptive panels associated with nodes.

This section outlines how to use the tools in Kumu to navigate and explore the systems map. Readers are advised to use the guide below in conjunction with exploring the map online.

Basic principles

Systems maps comprise of nodes and links. To read a systems map, it is important to understand the nodes and links in the following ways:

- **Nodes** represent system functions or elements of which there can be more or less. For example, there can be more or less algal blooms, blocked fissures, or an increase/decrease in the number of fauna/flora or their biodiversity etc. Categories of nodes are shown in the legend and classified by colour and shape (see Table 1). More information on each node is provided on a panel to the left of the map which can be opened by clicking on three dots to the far left of the map above the legend.

[30] https://kumu.io/csgnz/environment-agency-gshc-systems-map-2024

The panel can be closed by clicking these dots when it is open – which creates more space for the map to be seen.

- **Links** represent correlations. Positive correlation links are shown using green arrows that demonstrate a mirroring relationship (more of A leads to more of B), negative correlation links using red arrows that demonstrate an inverse relationship (more of A leads to less of B). Complex correlations are shown using blue arrows where the relationship varies or is inconsistent so there is no clear correlation one way or the other. Note, therefore, that green does not necessarily equal good and red does not equal bad.

How to use the map – exploring the system

The integrated systems map covers a total of 7 receptor areas (sub-systems) identified through literature review and stakeholder engagement processes. However, key functionality included in our Kumu maps is the use of layering within each systems map so that each area of the map can be explored separately if required. This enables users to select an appropriate amount of detail and see how the map is built up out of separate groups of nodes and sub-systems.

The map is structured so that the aquifer sub-system is at the centre of the map, with the subsurface receptor areas arranged towards the bottom of the map and the surface receptor areas arranged at higher levels. When the map is opened, the viewer is presented with the links for the aquifer receptor areas only, with the overlays for the other receptor areas shown but without their nodes and links (Figure 14). Other receptor areas of the map can then be layered on and explored by using the drop-down filter in the top left of the page (Figure 15). Layer options become visible when clicking the dropdown filter in the top left corner of the map (labelled ‘Aquifer, Overlay’ on initial opening of the map).

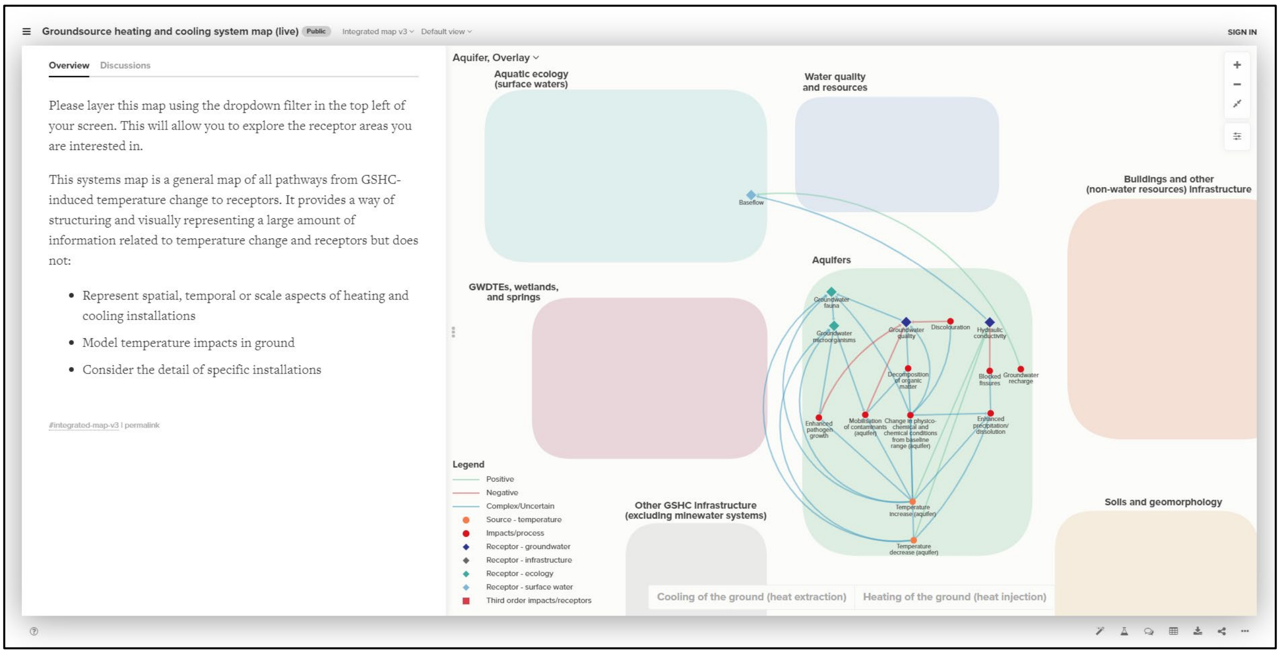

Figure 14. Initial view when opening the systems map in Kumu

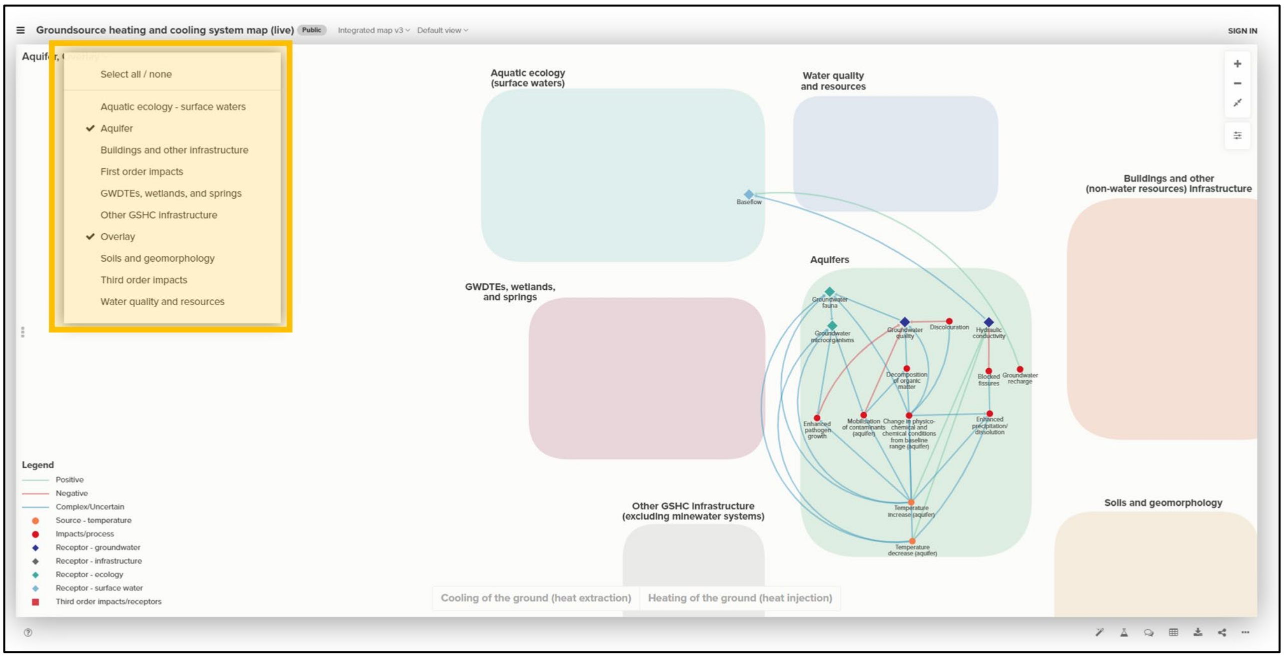

Figure 15. Filters for viewing different layers (receptor areas) in the map (shown in yellow box)

How to read the map – detailed analysis

Hovering over a node will “background” all nodes not immediately linked to that node – thereby highlighting the links relevant to that node. This effect is held by clicking the node and then the focus button to the far right of the map (a circle with four marks like a compass – highlighted in the yellow box in Figure 16). Once the focus mode has been activated then the focus can be expanded or contracted with the arrows to the top and bottom of the focus icon. Clicking on the focus button again will exit the view.

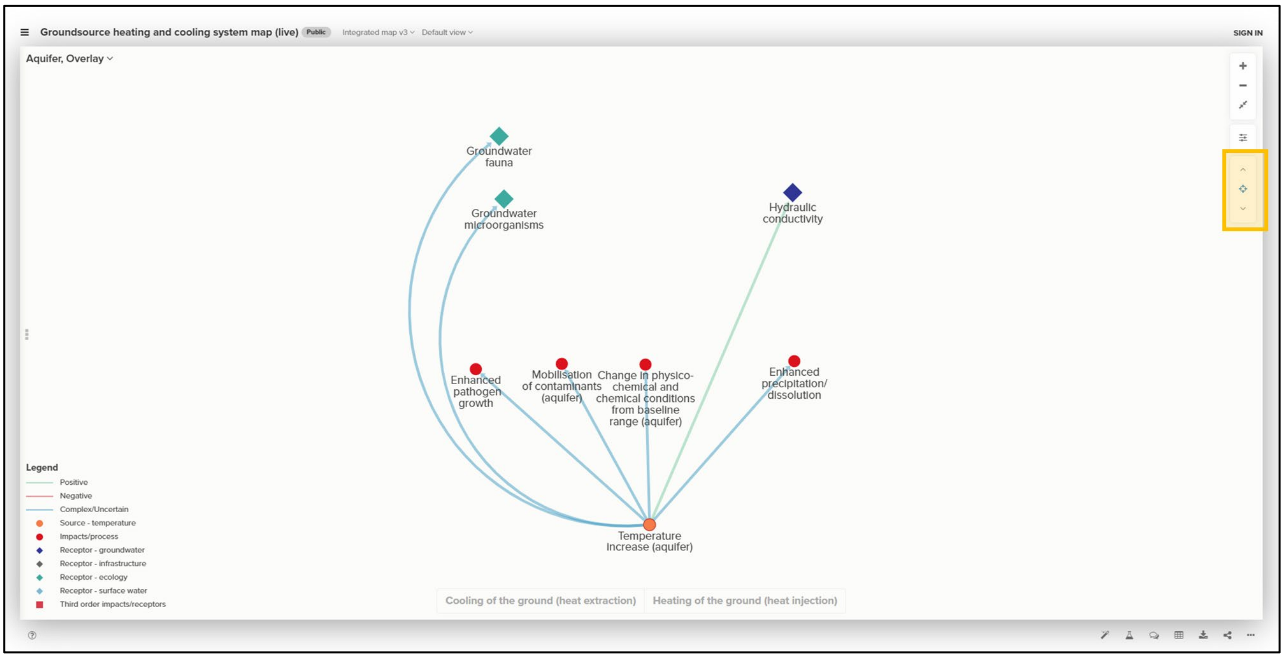

Figure 16. Focus view showing nodes linked to the 'Temperature increase (aquifer)' node with focus tool highlighted in the yellow box.

Filters (Figure 15) can be used whilst in focus mode allowing detailed investigation of one line of influence on a node. During this kind of analysis, the zoom to fit function (highlighted by the yellow box in Figure 17) can be used as the map expands and contracts and the ‘node size’ button can also be used to select a larger view. More than one node can also be selected for focus by selecting nodes while holding the shift key, allowing investigation of links between different nodes.

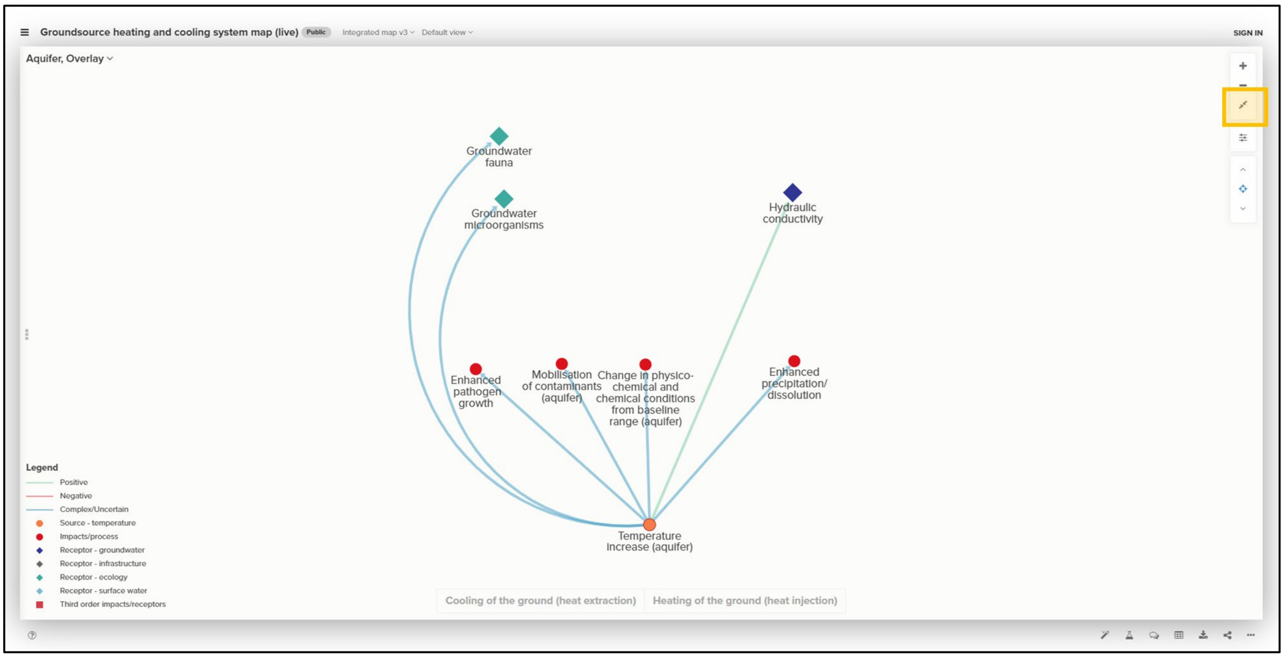

Figure 17. Focus view showing nodes linked to the 'Temperature increase (aquifer)' node with zoom to fit tool highlighted in the yellow box.

Other features of the map

To reflect temperature differences between cooling (heat extraction) and heating (heat injection) of the ground from GSHC-systems, the map can also be filtered using the buttons at the bottom of the map (highlighted in the yellow box in Figure 18). The map also provides descriptions or evidence for most nodes that describe processes and some receptors. Node descriptions can be found by clicking a node and then clicking the three vertical dots to the left of the map above the legend. This will open a panel with a description. To close the panel, click the three dots again.

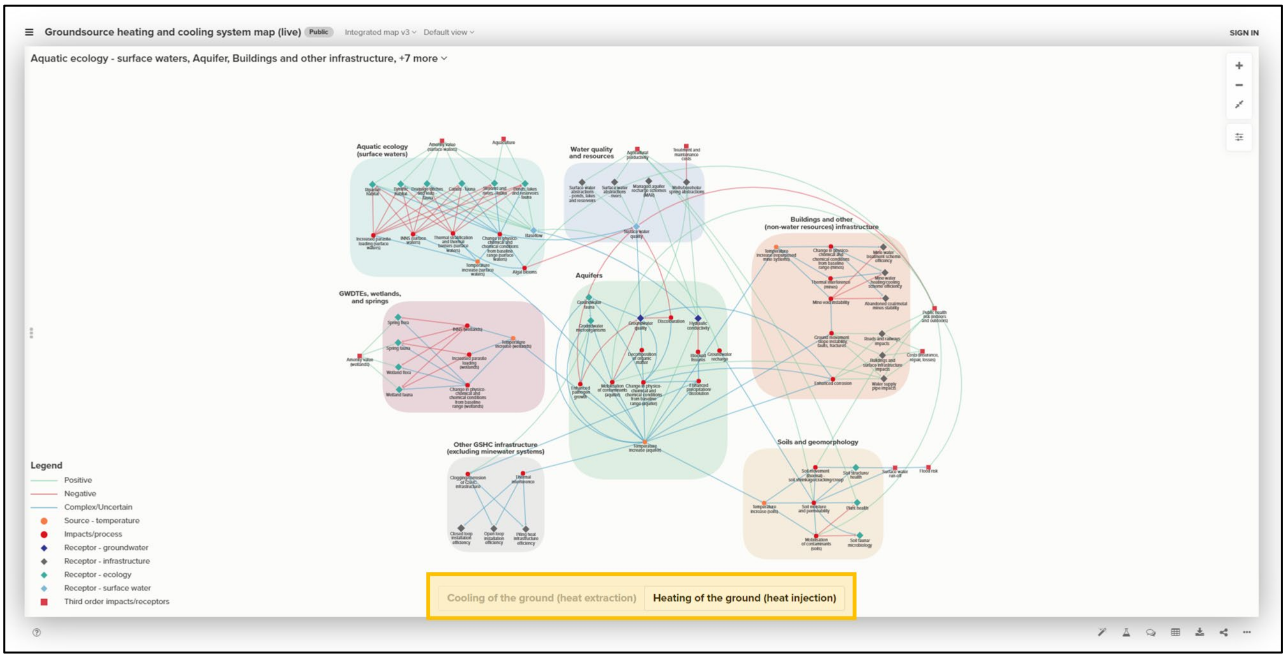

Figure 18. Full map (all filters on) with 'Heating of the ground (heat injection)' filter on, filters highlighted by yellow box

Appendix II – Systems map table and supporting literature

Appendix III – Ecological temperature sensitivities

General ecosystem (note – communities and species are further differentiated in tables below)

Type of sensitivity	Specific community/ species	Sensitivity (°C)	Source
Upper temperature limit	Fish and other aquatic vertebrates	38	Brock (1975)
	Insects	45-50	
	Protozoa	50	
	Vascular plants	45	
	Mosses	50	
	Eukaryotic algae	56	
	Fungi	60	
	Cyanobacteria (blue-green algae)	70-73	
	Bacteria (general)	90	

Freshwater fauna and flora

Type of sensitivity	Specific community/ species	Sensitivity (°C)	Source
Temperature threshold (physiological thermal tolerance)	Brown trout	4-19	Webb and Walsh (2004)
	Brook and Sea Lamprey	10-14	Maitland (2003)
	Barbel	<28	UK TAG WFD (2008)
	Chub	<28	
	Roach	11.5-27	Webb and Walsh (2004)
	Pike	<25	
	Bleak	<37.7	
	Grayling	4.5-21	
	Common Bream	<28	Webb and Walsh (2004); UK TAG WFD (2008)
	Stone loach	<28 (warm water)	UK TAG WFD (2008)
		20-23 (cold water)	
	Perch	<28	Webb and Walsh (2004); UK TAG WFD (2008)
	Gudgeon	<28	UK TAG WFD (2008)
	Dace		
	Powan		
	Flounder		
	Charr		
	Vendace		
	Lamprey	20-23	
	Atlantic Salmon	7-21.9	Webb and Walsh (2004)
	Tench	<26	
	Eel	20-23	UK TAG WFD (2008)
Temperature threshold	Southern Damselfly	4-10	Thompson et al., (2003)
Spawning temperature	Brown trout	10	UK TAG WFD (2008)
	Brook and Sea Lamprey	8.5-12	Maitland (2003)
	Eel	10	UK TAG WFD (2008)
	Atlantic Salmon		
	Lamprey		
	Flounder		
	Charr		
	Vendace		
	Powan		
	Allis Twaite Shad	15<	Maitland and Hatton-Ellis (2003)

Temperature-related behaviour	European otter	Temperature impacts availability of invertebrate and fish prey. Otters eat a wide range of fish, including perch, ruffe, and minnows. They are also very fond of eels, these also have temperature sensitivities.	Chanin (2003)
	Whorl Snail	Additional studies should focus on the relationship between humidity/temperature and how Desmoulin's whorl snail achieves its desired humidity by climbing above wet vegetation during warm periods and descending in cooler parts of the year	Killeen (2003)
	Allis and Twaite Shad	The upstream migration from the estuary appears to be triggered by temperature. Claridge & Gardner (1978) found that twaite shad migration started when the water reached 12ºC, and Aprahamian (1982) confirmed that peak migratory activity occurred at temperatures of 10–14ºC.	Maitland and Hatton-Ellis (2003)
	Brook and Sea Lamprey	Spawning in British rivers starts when the water temperature reaches 10–11ºC, usually in March and April. Lampetra lamottenii (and Petromyzon marinus), ammocoetes are most active at water temperatures between 10 and 14ºC. The onset of ammocoete hatching and metamorphosis of larvae could be dependent on water temperature. The critical spawning period for river lampreys normally lies between 8.5ºC and 12.0ºC	Maitland (2003)
	Ranunculion fluitantis and Callitricho-Batrachion Vegetation	In small streams, shading could be significant and could reduce algae and macrophyte growth in the channel, with the added benefits of reduced temperature, increased cover and inputs of organic debris.	Hatton-Ellis and Grieve (2003).

Groundwater Fauna

Type of sensitivity	Specific community/ species	Sensitivity (°C)	Source
Optimal range	Amphipods *Niphargus*	8-14	Ginet (1960)
	Amphipod (English) *Niphargus glenniei*	1-24°C	Knight and Johns (2015)
	Amphipod (southern Britain and Europe) *Niphargus aquilex*	1-26°C	Knight and Johns (2015); Di Lorenzo et al. (2023)
Thermal tolerance	Isopod (Europe and Britain) *Proasellus cavticus*	11.4 +/- 5°C	Malard et al.(2023)

Microbes

Type of sensitivity	Specific community/ species	Sensitivity (°C)	Source
Upper temperature limit	Pathogenic bacteria*	27	García-gil et al., (2018)
	Sulphate-reducing bacteria	60	Bonte et al., (2013a)
	Iron-reducing bacteria	60	Bonte et al., (2013a)
	Bacteria (general)	90	Brock (1975)
	Cyanobacteria (blue-green algae)	70-73	Brock (1975)
	Methanogenic Euryarchaea	40	Bonte et al., (2013a)

*Garcia-gil et al., (2018) observed that temperatures above this would be expected to increase pathogenic bacteria, heat shock from GSHC systems actually reduced their presence (due to direct contact with heat exchangers at 40-60°C)

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