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ABSTRACT

Water temperature is an important control on processes in aquatic systems and particularly for freshwater fish, affecting growth, survival and demographic characteristics. In recognition of this importance, the Scottish Government has prioritised developing a robust national river temperature monitoring network. Advances in geographical information systems, spatial statistics and field data loggers make large-scale river temperature monitoring increasingly possible. However, duplication of environmental and thermal characteristics among monitoring sites means many networks have lower than expected statistical power. This paper describes a novel methodology for network design, illustrated by the development of the Scotland River Temperature Monitoring Network. A literature review identified processes controlling stream temperature and associated landscape controls. Metrics indicative of these landscape controls were calculated for points every 500 m along the river network. From these points, sites were chosen to cover the full range of observed environmental gradients and combinations of controlling variables. The resulting network contains sites with unique characteristics covering the range of relevant environmental characteristics observed in Scottish salmon rivers. The network will thus have minimal redundancy, often not seen in large networks, and high statistical power to separate the relative importance of predictor variables thereby allowing large-scale water temperature predictions.

Key words | large-scale monitoring, network design, river temperature, Scotland

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INTRODUCTION: CURRENT STATUS AND LIMITATIONS OF LARGE-SCALE RIVER TEMPERATURE NETWORKS

Rising water temperatures (Tw) have the potential to alter the thermal suitability of rivers for freshwater fish, which are frequently the focus of management (Mohseni *et al.* 2003; Isaak *et al.* 2010, 2012). Cold water fish such as salmonids are highly sensitive to river temperature which affects growth, metabolism, performance, survival and demographic characteristics (Elliott 1994; Gurney *et al.* 2008). Atlantic salmon (*Salmo* salar) and, to a lesser extent, brown trout (*Salmo trutta*) have a high economic (Radford *et al.* 2004), recreational and conservation value (Anon 2009). Consequently, there are strong socio-economic drivers for understanding the spatio-temporal dynamics of thermal regimes, their sensitivity to drivers of change and opportunities for management or mitigation of thermal extremes (Malcolm *et al.* 2008; Hrachowitz *et al.* 2010). In recognition of the importance of these issues, CAM-ERAS (Coordinated Agenda for Marine, Environment and Rural Affairs Science), an umbrella group of Scottish Government departments and agencies, prioritised the development of a strategic national water temperature network in their recent freshwater monitoring action plan.

Large-scale *Tw* networks are required to characterise and understand temperature variability and make predictions of current and future *Tw* in monitored and unmonitored rivers (Hrachowitz *et al.* 2010; Deweber *et al.* 2014). However, globally there are relatively few quality controlled long-term networks and even fewer large-scale (at least regional and >100 km^2) planned and coordinated river temperature monitoring networks (Table 1). Many monitoring networks are produced ad hoc, evolving over time with poorly defined objectives or represent aggregations of numerous data sets, spanning multiple regions (e.g., US Geological Survey (USGS), NorWest) or countries (e.g., GEMS/Water). Data are often collected with a range of earlier aims, at varying sampling frequencies, with varying deployment approaches and equipment (Table 1). This can result in spatial and temporal biases. As such, aggregated networks arguably do not provide the consistency necessary for use over wider spatial domains. This is especially important in the context of understanding environmental change where temperature trends may be small relative to measurement bias.

A lack of strategic planning can potentially limit the value of networks if sites are not representative of the parameter of interest or the processes or landscape characteristics that control the parameter (Parr *et al.* 2002; Deweber *et al.* 2014). Where a network contains numerous monitoring sites with similar characteristics, or where a network provides incomplete coverage of process or landscape controls (including spatial coverage) then highly uncertain or biased model fits and predictions will result (Marsh & Anderson 2002; Deweber *et al.* 2014).

Recent advances in geographical information systems (GIS), spatial statistics and inexpensive temperature data loggers now allow the strategic design and deployment of large-scale monitoring networks, making monitoring and modelling of river temperatures increasingly possible (McCullough *et al.* 2009; Thomassen *et al.* 2010; Sowder & Steel 2012). The need for larger-scale monitoring and understanding has been identified by a number of researchers including Tetzlaff *et al.* (2008), who highlighted the need to upscale studies from small (~1 km^2) to larger catchments (~10^2 km^2) to facilitate management. In the context of river temperature, it is not possible to directly upscale process-based energy budget studies to larger spatial scales due to high costs, logistical challenges and the computational burden of such work (Hannah *et al.* 2008; Malcolm *et al.* 2008; Hilderbrand *et al.* 2014).

However, large-scale statistical modelling of *Tw* using landscape characteristics that are proxies for energy exchange processes or controls show significant potential to inform effective environmental management (Isaak & Hubert 2001; Hrachowitz *et al.* 2010; Chang & Psaris 2013). Landscape data provide a cost-effective method of generating environmental data across large spatial scales (Wehrly *et al.* 2009). GIS analysis can be used to determine landscape characteristics at any point on a river network, without the expense of field survey. Furthermore, the availability of inexpensive data loggers has dramatically increased *Tw* monitoring (Sowder & Steel 2012) to the extent that staff time, quality control and appropriate data storage are greater constraints on logger deployment than the cost of instrumentation.

Despite these advances, relatively few studies have modelled temperature distributions across whole basins in relation to environmental and landscape controls (Hrachowitz *et al.* 2010). Additionally, as far as the authors are aware, there have been no attempts to establish a large-scale strategically designed network that meets the requirements for modern spatio-temporal statistical modelling, which include appropriate coverage relative to landscape predictors (covariates), calibration, quality control and data storage. Such a network and associated modelling have the potential to answer critical management questions about the spatial variability in river temperature and its controls, the effects of changing landuse and the likely impacts of climate change. The current paucity of such networks demonstrates a challenge to understanding thermal regimes at multiple spatial and temporal scales (Garner *et al.* 2014) and to informing appropriate management of rivers.

This paper aims to develop a novel methodology for the design of a large-scale water quality monitoring network using the Scotland River Temperature Monitoring Network (SRTMN) as a case study. This initiative aims to produce a network which avoids common limitations exhibited by large-scale networks and has the potential to provide data appropriate for spatio-temporal analysis.

NETWORK DESIGN METHODOLOGY

Strategic network design saves both time and money by ensuring the network can address the research and management objectives (Mishra & Coulibaly 2009; Imholt *et al.*

Table 1 | Summary of large scale (>100 km²) water temperature monitoring networks used in published studies

	Network information	Network used by	Paper objectives	Derived metrics
Network	Environment Agency Surface Water Temperature Archive	Garner *et al.* (2013)	Assess spatial patterns, inter-annual variability and climatic sensitivity to the shape and magnitude of annual river thermal regimes	Mean monthly *Tw* between 1989 and 2006 for 88 sites
Objectives	Original objectives unclear – appears that measurements were taken ad hoc and collated to create the archive			
Spatial scale	National (England and Wales)			
Number of sites	30,000 total but resolution varies some only single readings. 315 – daily spot or continuous sampling			
Sampling	Varies from monthly, fortnightly spot samples. Daily spot or continuous sampling (315 sites)			
Data set length	Varies between sites (<50% >10 years long)			
Quality control	?			
Aim to collate and store water quality data collected by multiple organisations				
Network	USGS National Water Information System	Arismendi *et al.* (2012a)	Assess how stream flow peak timing may decrease intervals between 1 and 7 day moving average of maximum stream temperature (*Tmax*) and discharge (*Qmin*)	22 sites between 1950 and 2010. Calculated 1 day and 7 day moving averages and *Tmax* from daily mean *Tw* values
Objectives	Acquisition processing and storage of water data. To measure water quality at sites which meet needs of all stakeholders to achieve common goals	Arismendi *et al.* (2012b)	Using historical water temperature data compare trends in minimal and highly human impacted sites	Selected sites where *Tw* is monitored all year. 15 minute to hourly measurement intervals. Summarised as daily mean, min and max
Spatial scale	National	Chang & Psaris (2013)	Identify landscape factors driving *Tmax* and sensitivity. Compare relative contributing area and buffer scale analysis. Compare OLS and GWR regression methods	106 sites had min of 1 year continuous daily values recorded. 74 sites were used for analysis, as sites showing hysteresis due to snow melt or reservoir operations were removed. 7 day moving average and *Tmax* calculated
Number of sites	1,747 current water temperature sites (°C)			
Sampling	Varies, commonly 15 min to 60 min continuous. Real-time water quality (RTWQ) is continuous (5 min to hourly)	Isaak *et al.* (2012)	Determine regional and seasonal *Tw* trends. Assess if these varied between natural reaches and those downstream of reservoirs and with air temperature (*Ta*) and discharge (*Q*)	Mean daily *Tw* for 18 sites in Oregon, Montana, Idaho and Washington. Sites queried to have at least 300 daily observations over at least 20 of the 30 years from 1980 to 2009
Data set length	Varies between sites			

Table 1 | continued

	Network information	Network used by	Paper objectives	Derived metrics
Quality control	Use of data quality indicators; RTWQ network loggers have sensor calibration is checked monthly	Deweber & Wagner (2014)	Compared 4 models with different groups of predictors to assess how climate, landscape and land cover can be used to predict Tw	Daily mean Tw from hourly measurements. Used 886 training sites with data between 1980 and 2009. 1 million records and 2,565 sites in total which included data from personal and other organisations data sets
		Hill *et al.* (2014)	Tests a predictive model using Ta and watershed features to assess the vulnerability of USA stream to climate change	569 sites (1972–1998), records from single summers as few USGS sites have long-term data
Network	Arctic River Temperature data (ART-Russia) – Roshydromet	Lammers *et al.* (2007)	Discuss trends in new Arctic temperature data set. Identify climate change and anthropogenic signals	For 27 stations calculated to decade scale (approx. 10 days) energy flux and summary stats
Objectives				
Spatial scale				
Number of sites				
Sampling	10 day time step data (decades) from daily data (2 daily readings at 8am and 8pm)			
Data set length	Varies between sites. 1929–2003, most data between 1930–1990s			
Quality control	?			
Network	GEMStat United Nations Global Environment Monitoring System GEMS/Water Global Network	van Vliet *et al.* (2011)	Impact of Ta and Q on daily Tw globally using a non-linear water temperature model. Data from 157 river temperature stations were used to check model performance	157 stations, 1980–1999 but % of measurements available for the time period varying. High resolution Tw series for 14 station provided by different data sources used
Objectives	To collate and share water quality data sets, to support environmental assessment and reporting of trends in freshwater ecosystems			
Spatial scale	Global (>100 countries involved)	van Vliet *et al.* (2012)	Physically based modelling for water temperatures in large river basins situated in different hydroclimatic zones globally with varying human impacts	Tw data from 13 catchments, using GEMS/Water data sets (and data from other sources) between 1971 and 2000 to validate the modelling approach
Number of sites	4,100 stations measuring >100 parameters			
Sampling	Daily instantaneous (one daily spot sample at a fixed time)			
Data set length	Varies between sites (1977 to present)			
Quality control	Analytical methods document with QA and QC policy; Calibrated thermo-meters/thermistors; Regression analysis of historical data sets			

(*continued*)

Table 1 | continued

	Network information	Network used by	Paper objectives	Derived metrics
Network	STORET Data Warehouse and Water Quality Exchange (WXQ) US EPA water quality data repository	van Vliet *et al.* (2011, 2012)	Same as above	Same as above
Objectives	Collate water quality monitoring data			
Spatial scale	National (USA)			
Number of sites	?			
Sampling	?			
Data set length	Varies between sites			
Quality control	Stores information of methods and QC used but no filters on data. Users are responsible for data screening			

2013; Isaak *et al.* 2013). To avoid issues commonly associated with large-scale networks, the design of the SRTMN was divided into four design stages and an evaluation stage (Figure 1). Stage 1 involved the specification of network aims and a literature review which identified important landscape controls on stream temperature. The latter was used to guide the GIS analysis which, in turn, produced the landscape characteristics that informed site selection. Stage 2 integrated current resources (where possible) to minimise duplication with existing monitoring networks. Stage 3 refined network design to optimise costs, risks and benefits of deployment over the long term and Stage 4 considered quality control procedures. Stage 5 considers likely opportunities and approaches for evaluating and adjusting the network over the longer term after data have been obtained.

Stage 1: deciding the network objectives and defining the resource

It is crucial that the objectives of any monitoring network are defined a priori (Parr *et al.* 2002). In the case of the SRTMN, the network is required to provide data to: (1) characterise spatial and temporal variability in thermal regimes across Scotland; (2) assess climatically sensitive rivers; (3) improve understanding of landscape controls on water temperature and their ability to buffer water temperature changes and extremes; and (4) develop models to predict spatio-temporal variability in river temperature, including in unmonitored catchments and locations. Using the information from 3 and 4, mitigation and adaptation strategies for high temperature may be assessed. Finally, and importantly, the network is expected to provide long-term monitoring of river temperature, covering the range of expected environmental responses across Scotland.

To address these objectives, it was crucial that the sites cover the environmental range and combinations of landscape controls observed in Scotland's rivers. Given the importance of Atlantic salmon as a target species for management and conservation, the environmental range was constrained to accessible rivers using the map of Atlantic salmon distribution originally developed by Gardiner & Egglishaw (1986). In practice, this constrained the altitudinal range from 0 to ca. 700 m, above which any long-term monitoring would also have been impractical. As the SRTMN is a new network, strategically planned from the start, sites could be selected to cover landscape attributes appropriate to the objectives. By covering the range and
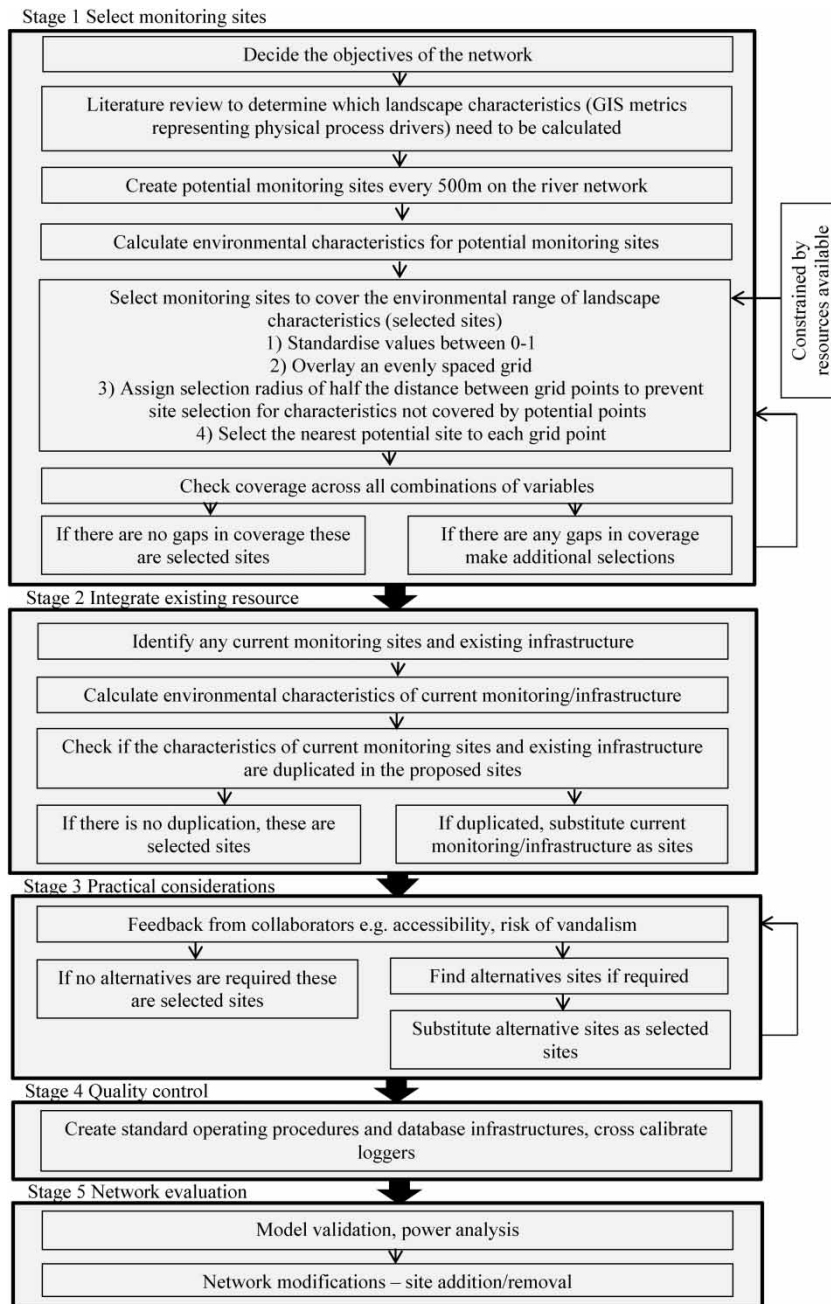
Stage 1 Select monitoring sites

Decide the objectives of the network

Literature review to determine which landscape characteristics (GIS metrics representing physical process drivers) need to be calculated

Create potential monitoring sites every 500m on the river network

Calculate environmental characteristics for potential monitoring sites

Select monitoring sites to cover the environmental range of landscape characteristics (selected sites)
1) Standardise values between 0-1
2) Overlay an evenly spaced grid
3) Assign selection radius of half the distance between grid points to prevent site selection for characteristics not covered by potential points
4) Select the nearest potential site to each grid point

Check coverage across all combinations of variables

If there are no gaps in coverage these are selected sites

If there are any gaps in coverage make additional selections

Constrained by resources available

Stage 2 Integrate existing resource

Identify any current monitoring sites and existing infrastructure

Calculate environmental characteristics of current monitoring/infrastructure

Check if the characteristics of current monitoring sites and existing infrastructure are duplicated in the proposed sites

If there is no duplication, these are selected sites

If duplicated, substitute current monitoring/infrastructure as sites

Stage 3 Practical considerations

Feedback from collaborators e.g. accessibility, risk of vandalism

If no alternatives are required these are selected sites

Find alternatives sites if required

Substitute alternative sites as selected sites

Stage 4 Quality control

Create standard operating procedures and database infrastructures, cross calibrate loggers

Stage 5 Network evaluation

Model validation, power analysis

Network modifications – site addition/removal

Figure 1 | Process for designing the SRTMN.

combination of controlling variables it will not be necessary to predict outside the range of observations. Furthermore, because the landscape covariates are process based, informed by the literature, the resulting statistical models will be transferable, avoiding spurious correlations. Taken together, this should ensure accurate and unbiased predictions for unmonitored locations. Finally, the SRTMN seeks to minimise the amount of changes to monitoring sites post-deployment (cf. Hrachowitz et al. 2010) thereby reducing staff costs as loggers are deployed once and then downloaded bi-annually, across a consistent network.

It is also important to define the available resource which controls the number of monitoring sites and influences the number of covariates upon which sites could be selected. For the purposes of this network, 200 loggers were identified as the preferred number for deployment, rising to a maximum of 250. The additional loggers were held in reserve in case the preliminary deployment plan was unable to cover all environmental combinations and, importantly, to allow batches of loggers to be recalibrated.

Stage 1: literature review of process controls and selection of relevant GIS covariates

A literature review was performed to identify the processes governing stream temperature, the landscape controls that influence energy exchange processes and the GIS derived covariates that had been identified as useful proxies for these processes and controls. The literature review focused on identifying GIS covariates that were significant in previous regression-based stream temperature models and that had underlying physical meaning (Table 2). These landscape controls reflect the physical processes that influence Tw at nested spatial scales (Figure 2, Table 2). Because the landscape controls represent physical process drivers this should ensure that the observed relationships are genuine and transferable to unmonitored locations. The nesting of spatial scales and controls is indicated in Figure 2 and reflected below.

National scale

At the largest spatial scale it was important that the network covered the main climatological, hydrological and geological controls on Tw (Figure 2). Consequently, target catchments were chosen to span the whole of Scotland (Figure 3) with latitude and longitude included as a primary control in the site selection process. The selected catchments are considered to be representative of those across Scotland (Sivapalan *et al.* 2003; Soulsby *et al.* 2006a, 2006b). West to east coverage ensures representation of the dominant precipitation, runoff and evapotranspiration gradients. Significant logistical and cost benefits (travel and staff costs) were also afforded by focusing on a selection of representative catchments rather than spreading effort across all catchments. Distance to coast was calculated to represent continentality and the different energy exchange processes and specific heat capacities of land and sea (Hrachowitz *et al.* 2010; Chang & Psaris 2013).

To maximise the value of the network to government and environment agencies, environmental designations such as Special Areas of Conservation (EU Habitats Directive 92/43/EEC) were considered in the selection of study catchments (where consistent with the required experimental design) so that resulting data could be used for reporting environmental status. Catchments impacted heavily by hydropower and storage schemes were avoided to ensure the network provides an understanding of near-natural spatial variability and long-term change. However, it is important to recognise that truly natural mid/lower rivers in Scotland can be difficult to find due to management modifications (Gilvear *et al.* 2002).

Catchment scale

Elevation can be used as a surrogate for air temperature (Ta), as adiabatic lapse rates reduce Ta with altitude, which influences Tw (Hrachowitz *et al.* 2010; Hill & Hawkins 2014). Therefore, elevation is a significant predictor of Tw, influencing mean monthly and maximum stream temperatures (Imholt *et al.* 2011; Chang & Psaris 2013) and its importance changes over time. For example, Chang & Psaris (2013) found mean elevation to be the only significant predictor of water temperature during wet winter months.

Discharge (Q) is related to thermal capacity and affects rates of heating and cooling. Previous studies have shown an inverse relationship between Q and Tw and increasing rates of warming at lower discharges. For example, van Vliet *et al.* (2011) showed increasing Q by 20% decreased Tw and decreasing Q by 20 and 40% caused an increase in Tw. Unfortunately, it would be impractical to measure discharge at all potential monitoring locations so GIS derived landscape proxies were required. These were derived from a digital elevation model (Ver Hoef *et al.* 2006). Upstream catchment area can be used as a proxy for river discharge (Ver Hoef *et al.* 2006; Hannah *et al.* 2008; Johnson *et al.* 2014) especially where interactions are considered with other covariates that reflect climatological gradients (e.g. latitude and longitude). Downstream reaches have larger

Table 2 | GIS covariates shown to be significant or included in final selected models for large-scale predictions of water temperature (*Tw*)

GIS covariates	Landscape controls and physical process represented	Study	Spatial scale of characterisation	Metrics predicted	Comments
National scale					
Distance to/from coast	Continentality and the different thermal properties (specific heat capacity and heat exchange processes) between land and water	Chang & Psaris (2013)	Observation point	Mean 7 day maximum water temperature (*Tmax*) and temperature sensitivity (TS) which is a linear regression of daily max air temperature (*TaMax*) versus 7 day average daily *Tmax*	Included in all models for TS. Not included in models for *Tmax*
		Hrachowitz *et al.* (2010)	Observation point	Monthly *Tmax* and mean 7 day *Tmax*	Included in May, June, July models
		Imholt *et al.* (2011)	Observation point	Mean monthly *Tw*	Included in August and September models
Latitude	Hydro-climatic gradients	Chang & Psaris (2013)	Observation point	TS; *Tmax*	Included in 1 km RCA and 1 km upstream buffer scale models for TS. Not included in models for *Tmax*
Catchment scale					
Elevation	Air temperature (T*a*) adiabatic lapse rates; Can also be an indication of stream size and width-depth ratios, high altitude reaches may be expected to be smaller channels	Chang & Psaris (2013)	Average of relative contributing area (RCA), which is the catchment area of a site extending only to the next upstream site	TS	Included in RCA and RCA buffer models for TS. Not included in models for *Tmax*
		Hill *et al.* (2013)	1. Mean for the catchment; 2. Within 100 m wide buffer; 3. Observation point	Mean summer (MSST), winter (MWST) and annual (MAST) *Tw*	Included in all 3 models
		Hrachowitz *et al.* (2010)	Stream 1 km; Buffers: 100 m width, 1 km length; 50 m width, 1 km length; 50 m width, 500 m length	*Tmax* for hottest 7 day period of the month	Included in January, February, March, October models
		Imholt *et al.* (2011)	500 m upstream, 1 km upstream	Mean monthly *Tw*	Included in all models
		Moore *et al.* (2013)	Mean of catchment	Maximum weekly average temperature (MWAT)	Included in final model

(*continued*)

Table 2 | continued

GIS covariates	Landscape controls and physical process represented	Study	Spatial scale of characterisation	Metrics predicted	Comments
Catchment area	Used as a proxy for discharge and width-depth ratios, influencing thermal capacity and potential energy exchange. Stream order/ river size	Chang & Psaris (2013)	Observation point	TS; *Tmax*	Included in all models bar RCA buffer for TS. Included in all models bar RCA for *Tmax*
		Deweber & Wagner (2014)	Observation point	Mean daily *Tw*	Included in landform model, forest landscape model and anthropogenic landscape model
		Hill *et al.* (2013)	Observation point	MSST, MWST and MAST *Tw*	Included in all 3 models
		Hrachowitz *et al.* (2010)	Observation point	Monthly *Tmax* for hottest week	Included in all models
		Imholt *et al.* (2011)	Observation point	Mean monthly *Tw*	Included in January, February, March, June, July, November, December
		Moore *et al.* (2013)	Observation point	MWAT	Included in final model
Hillshading	Influences incident incoming solar radiation, shading the reach	Hrachowitz *et al.* (2010)	Stream 1 km; Buffers: 100 m width, 1 km length; 50 m width, 1 km length	Monthly *Tmax* for hottest week	Included in December, January, February models (winter)
		Imholt *et al.* (2011)	500 m upstream, 1 km upstream	Mean monthly *Tw*	Included in December, January, February models (winter)
Baseflow index	Groundwater interactions, which can act as cool (warm) water inputs in summer (winter) months	Chang & Psaris (2013)	RCA, 50 m buffer, 1 km upstream RCA, 1 km upstream buffer area	TS; *Tmax*	Included in all models for TS. Included in all models bar 1 km upstream buffer for *Tmax*
		Deweber & Wagner (2014)	Network	Mean daily *Tw*	Included in landform model, forest landscape model and anthropogenic landscape model
		Hill *et al.* (2013)	1. Mean for the catchment; 2. Within 100 m wide buffer; 3. Observation point	MSST, MWST and MAST *Tw*	Included in summer and winter models
Soil and geological characteristics	Catchment responsiveness	Hill *et al.* (2013)	1. Mean for the catchment; 2. Within 100 m wide buffer; 3. Observation point	MSST, MWST and MAST *Tw*	Measure of soil permeability included in summer and winter models

(*continued*)

Table 2 | continued

GIS covariates	Landscape controls and physical process represented	Study	Spatial scale of characterisation	Metrics predicted	Comments
Catchment landuse	Catchment responsiveness	Chang & Psaris (2013)	% of each land cover. RCA, 50 m buffer scale, 1 km upstream RCA, 1 km upstream buffer area	TS; *Tmax*	Not included in final models for TS. Grassland included in RCA model for *Tmax*
		Deweber & Wagner (2014)	Local	Mean daily *Tw*	% cover of agriculture. Included anthropogenic landscape model
		Hill *et al.* (2013)	1. Mean for the catchment; 2. Within 100 m wide buffer; 3. Observation point	MSST, MWST and MAST *Tw*	% urban and agricultural uses included in all 3 models
% lake and wetland cover in a defined area	Catchment responsiveness and ability to heat the water	Hill *et al.* (2013)	1. Mean for the catchment; 2. Within 100 m wide buffer; 3. Observation point	MSST, MWST and MAST *Tw*	Reservoir index included in all 3 models
		Moore *et al.* (2013)	Catchment	MWAT	Included in final model. Also included % glacier cover
Reach scale					
Stream order	Stream size and width-depth ratios, showing the thermal capacity and potential energy exchange of the reach	Chang & Psaris (2013)	Observation point	TS; *Tmax*	Not included in final models for TS. Included in all models bar 1 km upstream buffer for *Tmax*

(*continued*)

Table 2 | continued

GIS covariates	Landscape controls and physical process represented	Study	Spatial scale of characterisation	Metrics predicted	Comments
Forest cover	Influences incident incoming solar radiation, shading the reach	Chang & Psaris (2013)	Percentage cover: RCA, 50 m buffer scale, 1 km upstream RCA, 1 km upstream buffer area	TS; *Tmax*	Included in 1 km upstream RCA buffer model for TS. Included in RCA buffer and 1 km upstream RCA buffer for *Tmax*
		Deweber & Wagner (2014)	Local: % forest cover in a 60 m buffer (30 m each side) of stream reaches; Network: forest cover in the area upstream	Mean daily *Tw*	Included in forest landscape model
		Hill *et al.* (2013)	1. Mean for the catchment; 2. Within 100 m wide buffer; 3. Observation point	MSST, MWST and MAST *Tw*	Not included in final models
		Hrachowitz *et al.* (2010)	Total forest, proportion coniferous forest: Buffers: 100 m width, 1 km length; 50 m width, 1 km length; 50 m width, 500 m length	Monthly *Tmax* for hottest week	Included in March, April, May, June, July, August, September, October and hottest week models (not winter)
		Imholt *et al.* (2011)	% coniferous forest cover: 500 m upstream, 1 km upstream	Mean monthly *Tw*	Included in March, April, May, June, July, August, September, October models
Aspect	Increased exposure to incoming solar radiation from eastern to western facing catchments	Deweber & Wagner (2014)	Mean network (area upstream) aspect	Mean daily *Tw*	Included in landform model, forest landscape model and anthropogenic landscape model

(*continued*)

Table 2 | continued

GIS covariates	Landscape controls and physical process represented	Study	Spatial scale of characterisation	Metrics predicted	Comments
Slope	Friction	Chang & Psaris (2013)	RCA, 50 m buffer scale, 1 km upstream; RCA, 1 km upstream buffer area	TS; *Tmax*	Included in RCA buffer and 1 km upstream buffer models for TS. Included in RCA model for *Tmax*
		Hill *et al.* (2013)	1. Mean for the catchment; 2. Within 100 m wide buffer; 3. Observation point	MSST, MWST and MAST *Tw*	Included in all models
		Hrachowitz *et al.* (2010)	Buffers: 100 m width, 1 km length; 50 m width, 1 km length; 50 m width, 500 m length	Monthly *Tmax* for hottest week	Included in March, April, May, June, July, August, September, hottest week models
		Imholt *et al.* (2011)	500 m upstream, 1 km upstream	Mean monthly *Tw*	Included in April, May, June, July, August, September, October models
		Moore *et al.* (2013)	Stream segment	MWAT	Included in final model
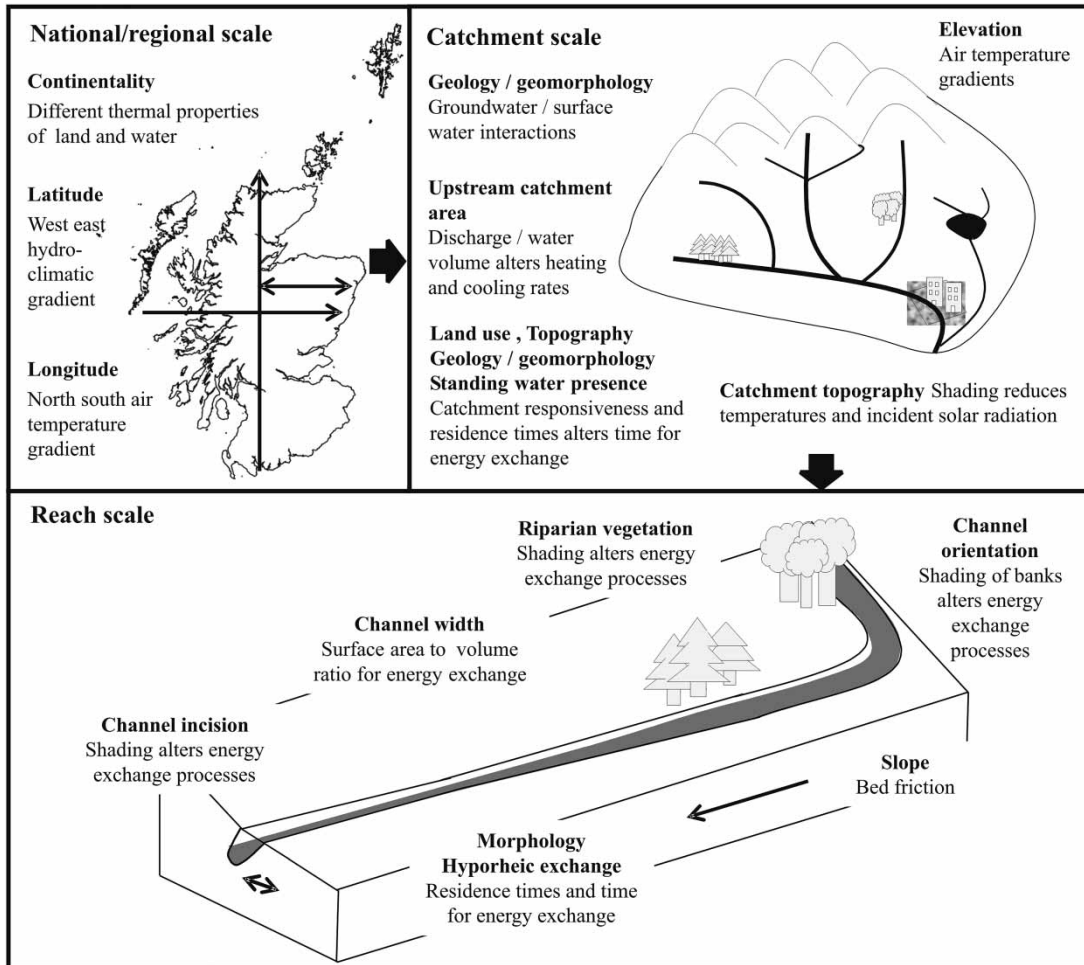
Figure 2 | Conceptual diagram of the controls on water temperature at different spatial scales.

discharges, thus a larger thermal capacity moderating maximum temperatures compared to upland reaches (Imholt et al. 2011).

The land use, geology and the presence of standing water within a catchment also has a key role in controlling thermal regime through effects on catchment responsiveness and residence times, which influence time available for energy exchange processes (Hill et al. 2013). Furthermore, groundwater–surface water interactions at the catchment scale can be inferred from catchment geology. For example, Hill et al. (2013) attributed warmer mean winter Tw to geologic permeability, which was associated with groundwater flow in the catchment.

Catchment topography governs the amount of shading provided by the landscape (herein hillshading) which

strongly influences solar radiation, particularly during periods of low solar angle, like winter (Hrachowitz et al. 2010). Hillshading was therefore calculated for both summer and winter, to encompass the annual variability due to changes in azimuth, zenith angles and day length. As a result, the maximum (winter) and minimum (summer) amount of hillshading were found for each point. The amount of hillshading was calculated for six time points (06:00, 09:00, 12:00, 15:00, 18:00, 21:00); the resulting hillshading values were then weighted depending upon the amount of incoming radiation (Fu & Rich 1999) and averaged to give an overall summer (winter) hillshading value for each point. Azimuth and solar altitude values were found for the centre point of each catchment and this was used for all locations.
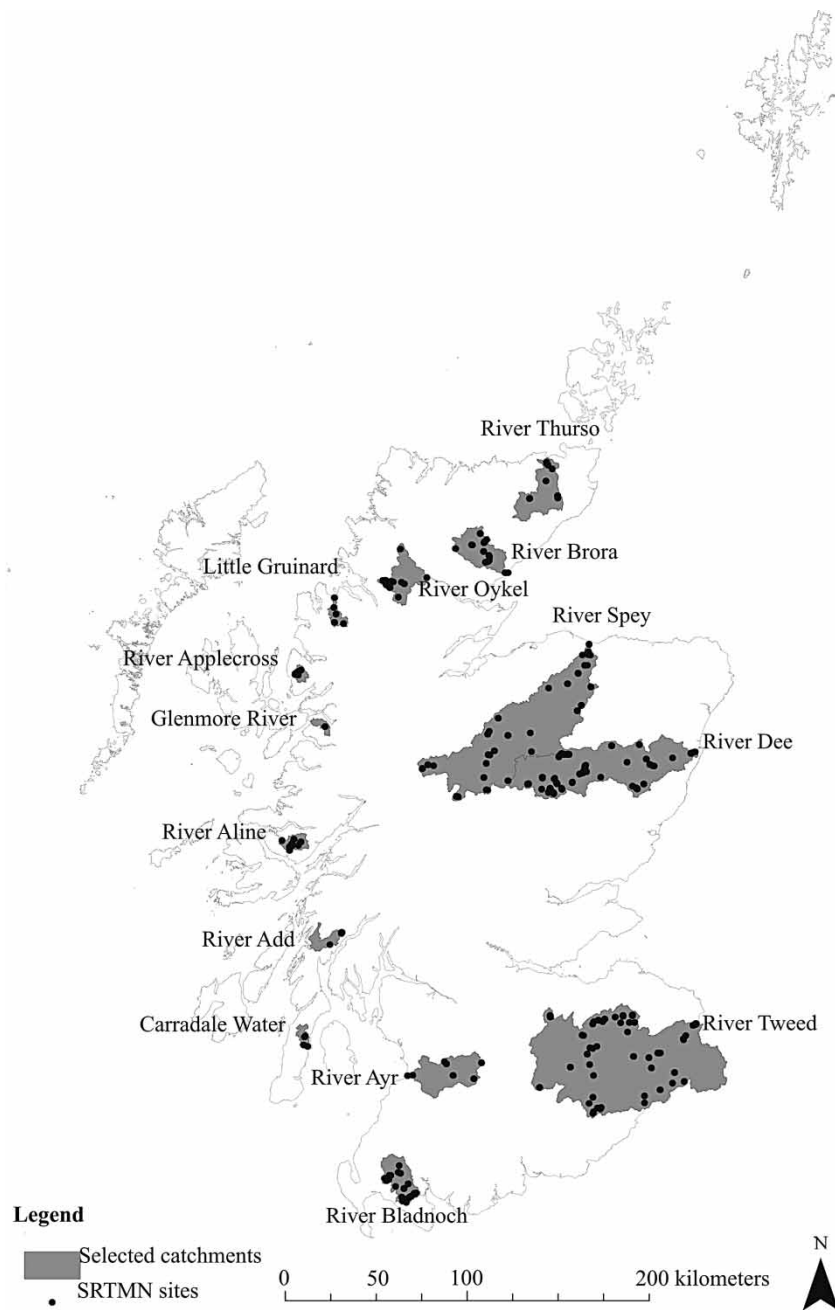
Figure 3 | SRTMN target catchments and sites.

Reach scale

Finally, there are numerous controls that affect energy exchange and thus stream temperature at the reach scale. Topographic controls have been correlated with temperature variability, particularly when characterised for intermediate scales (1 km) around monitoring locations (Hrachowitz *et al.* 2010; Isaak *et al.* 2010; Chang & Psaris 2013). Stream width controls the surface area available for energy exchange and for a given catchment area strongly influences width-depth ratios (Imholt *et al.* 2011). Wide rivers are also characterised by relatively lower topographic and vegetative

shading, increasing sensitivity to solar inputs (Malcolm *et al.* 2004, 2008; Imholt *et al.* 2011; Li *et al.* 2012; Chang & Psaris 2013; Ryan *et al.* 2013). Upstream catchment area can also be a proxy for stream width where this cannot be assessed directly from a GIS, for example, where rivers are represented as lines and have no area attributes (Imholt *et al.* 2011; Peterson & Ver Hoef 2014).

Channel orientation is important for receipt of solar radiation (Guan *et al.* 2013). It affects the amount of solar radiation reaching the stream and the shading effects of banks and vegetation, with north/south channels experiencing maximum exposure to incoming radiation and east/west channels the minimum (Malcolm *et al.* 2004). Orientation is particularly important when considering the effects of land-use as it affects channel shading from riparian vegetation (Ryan *et al.* 2013).

Transit times, bed friction and channel morphology are influenced by channel slope. This can alter the amount of time available for energy exchange processes and also the degree of hyporheic or groundwater exchange. Furthermore, steep channel slopes often result in greater channel incision and thus greater topographic shading (Moore *et al.* 2013).

Riparian planting has been suggested as a potential tool to manage high temperatures and mitigate against the effects of climate change (Malcolm *et al.* 2008; Hrachowitz *et al.* 2010; Garner *et al.* 2014). Numerous studies have found the percentage of forest cover to be an important predictor of maximum river temperature at all the scales assessed (Hrachowitz *et al.* 2010; Imholt *et al.* 2011; Chang & Psaris 2013). ET GeoWizard tools were used to create individual buffers upstream of each potential monitoring site. The percentage of woodland was calculated within each buffer using OS MasterMap for land cover information. It is important to recognise that forestry operations may have altered some of the land cover since the creation of the MasterMap data set in 2012. Consequently, ground truthing riparian vegetation characteristics will be important during network deployment.

Stage 1: application of site selection criteria

GIS-derived metrics were calculated, every 500 m across the river network, using tools within ArcGIS10 and the RivEX river networks tool (Hornby 2015) to generate a data set of potential monitoring locations. To simplify the site selection process all covariates were standardised to range between 0 and 1. To ensure that the 'chosen' monitoring locations represented the environmental range of 'potential' locations a regular grid was placed over the environmental characteristics of all the potential sites. This is akin to (although not as rigorous as) the concept of Latin squares, which ensures coverage of all potential environmental combinations (Gao 2005). Latin square designs ensure that each characteristic occurs only once in the experimental design and that no combinations of characteristics are missing (Gao 2005). Given the spatial coverage of the SRTMN, it would be impossible to replicate all covariate combinations at all geographic locations (Martin 2001) and the limited number of data loggers and upkeep required meant full implementation of a Latin square design was not possible, but the principles remain similar.

Plotting combinations of variables and overlaying a grid demonstrated what a network covering all possible environmental combinations would look like (Figure 4). As selection could not be undertaken using all covariate combinations a two-stage process was implemented as follows. (1) Sites were chosen from each variable plotted against the x and y coordinate which ensured a broad geographic spread of landscape characteristics. The chosen sites were those closest to the grid node, shown by triangles in Figure 5. Where no points were within half the distance between one node to the next, this environmental combination was ignored to avoid duplication of similar characteristics. (2) The resulting data set was visually assessed to ensure that the sites chosen in (1) adequately covered the environmental range of all combinations of variables. The result of this selection process is shown in Figure 6, where black points are the characteristics of the chosen sites. Where any combination of characteristics was not adequately represented (i.e., there was not good coverage across covariate combinations) additional sites could have been added. However, in this case a 'mop up' procedure was not required (Figure 6). The number of nodes in the grids reflected the availability of logger resource, with additional loggers held in reserve in the case of a 'mop up' being required. In this case a 6×6 lattice was produced that results in a systematic sampling strategy similar to that of Martin (2001). Selecting sites in this way allows the effects of individual variables to be
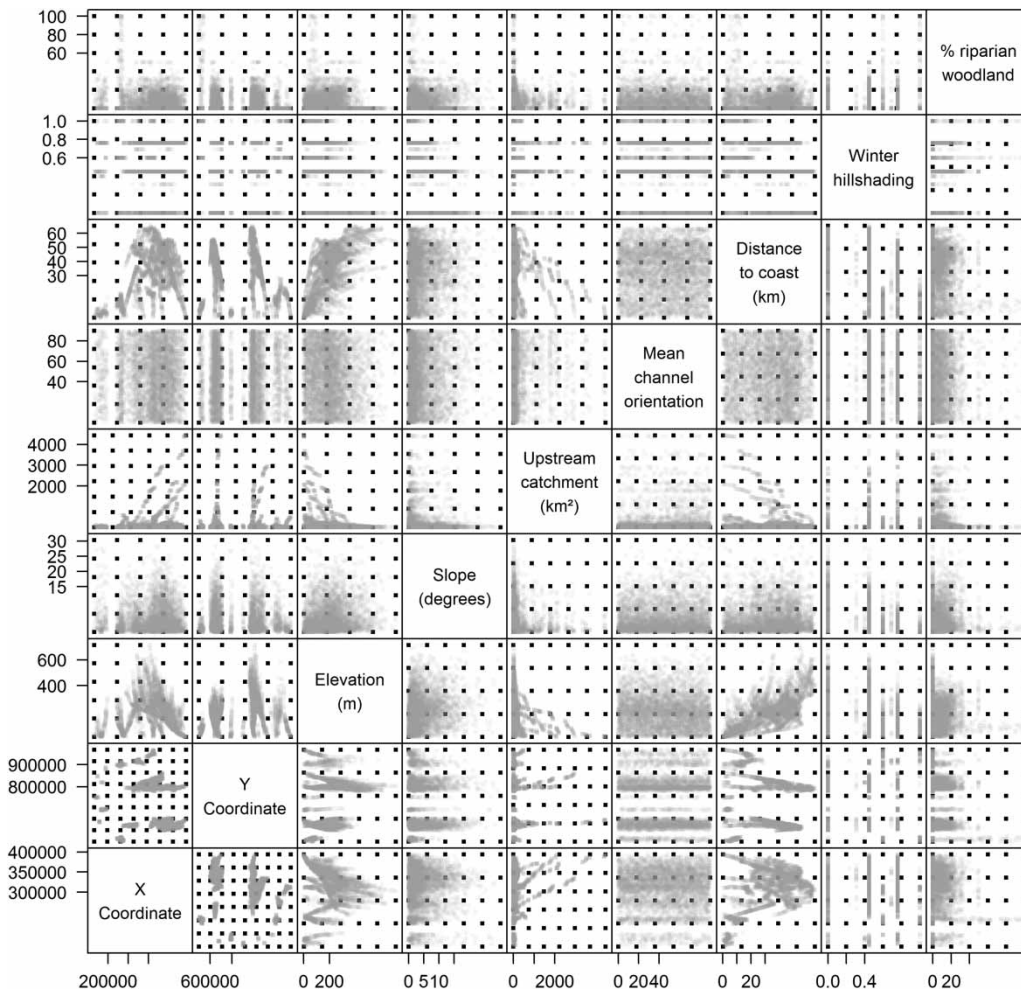
Figure 4 | Environmental range of potential monitoring sites (grey points). The overlaid grid (black points) shows the desired spread over the environmental range. The shade of grey reflects the density of points in that particular range.
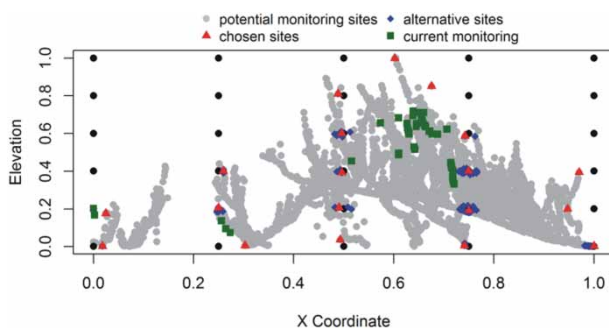

Figure 5 | An example of the site selection process. Grey points show the environmental range and represent all the potential monitoring sites. Red triangles are the chosen sites; these are the locations closest to each grid point (black points). The evenly spaced grid ensures coverage over the environmental range. Blue diamonds are sites within a radius of the desired characteristic (grid point) and are alternative sites if the chosen site cannot be used. Green squares are current monitoring sites. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/nh.2015.106.

assessed; for example, the influence of elevation and distance to coast, which are often correlated, have been separated to give unique combinations including rare characteristics such as high elevation and short distance to coast.

Stage 2: preventing duplication: utilising current monitoring and existing infrastructure

Data sets collated from multiple organisations can contain high levels of redundancy due to poor coordination between agencies (duplication of effort) or offer only limited opportunities for direct comparisons, for example, where loggers are deployed for differing time periods (e.g., limited to summer
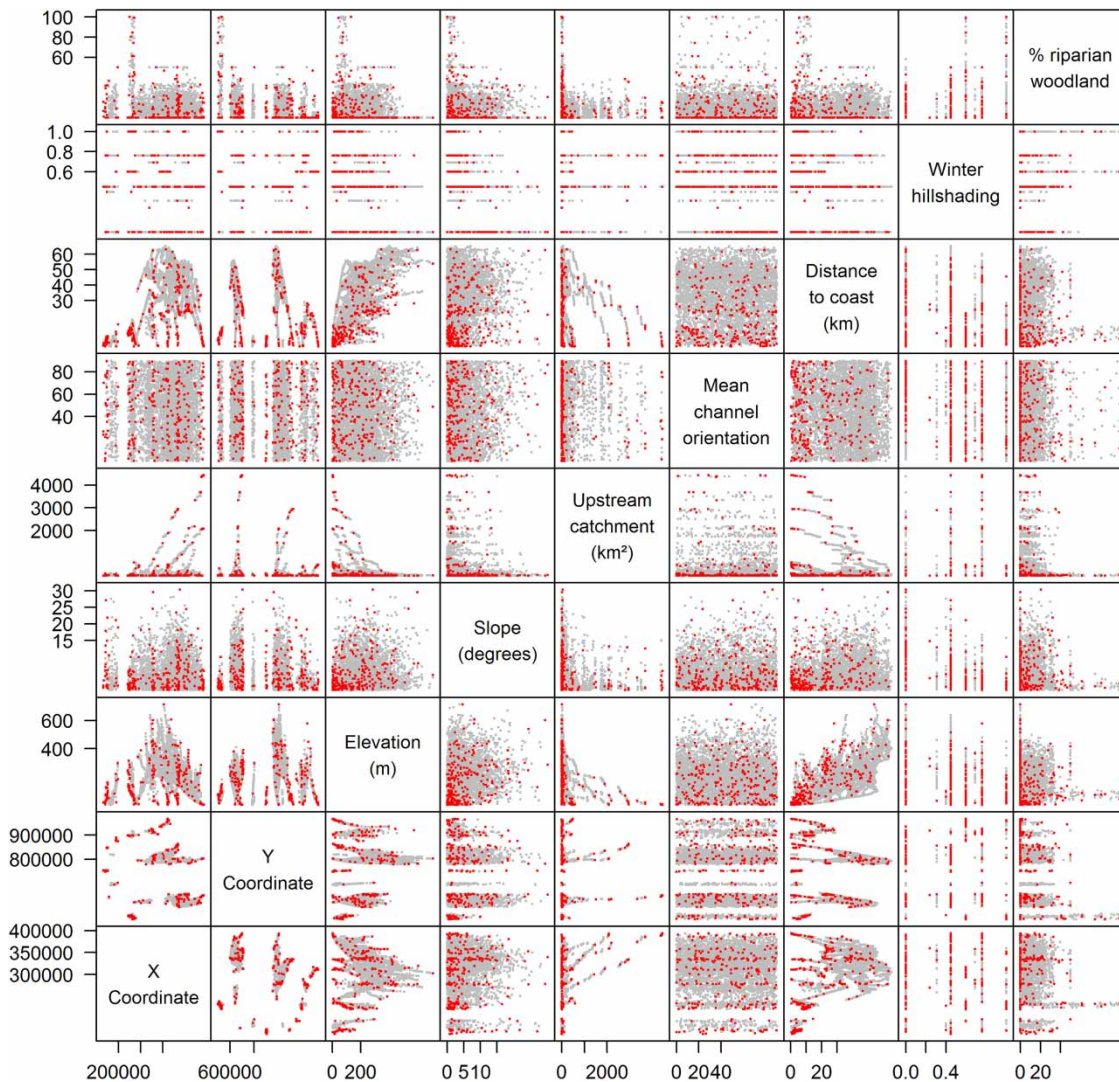
Figure 6 | Chosen sites coverage of the environmental range. Grey points are the potential sites showing the environmental range and black points show the characteristics of the chosen sites.

months) or with different sampling frequencies (Isaak et al. 2012; Mauger et al. 2015). To get the maximum value from existing resources and deployments, the characteristics of current water temperature monitoring locations (Marine Scotland Science (MSS), Scottish Environment Protection Agency (SEPA) and River and Fisheries Trust Tw loggers) and infrastructure (SEPA gauge locations) were calculated. Current Tw monitoring sites were overlaid on the covariate selection plots (Figure 5, squares) and where characteristics were already covered, 'chosen sites' were removed from the deployment plan. For example, in the SRTMN, sites in the Upper Dee were removed as current monitoring undertaken

by MSS and the River Dee Trust already covered the required environmental range and conformed to SRTMN quality control procedures and protocols. Where current monitoring sites did not conform to SRTMN protocols they were brought to the same standard to ensure comparability of data sets (see 'Stage 4: quality control' below).

Similarly, there was a desire to make use of existing telemetry infrastructure even where temperature monitoring did not currently exist. For example, the location of SEPA gauging stations was also overlain on the selection grid and used to replace SRTMN selected sites where they lay within the defined point radius. The addition of gauging

station locations to the network had the added benefit of providing discharge data that are potentially useful for understanding river thermal regimes, even at a small number of sites.

Stage 3: practical considerations for field deployment

The logistics and health and safety involved in maintaining a continuous monitoring site must be considered (Laize 2004). Costs are increased if data loggers are in areas of limited accessibility, involving time-consuming hikes to isolated streams for downloading. This can create problems in maintaining that particular site long-term and requires additional safety considerations. In addition, the loss of equipment, for example, through vandalism, can also affect the long-term viability of a network and the quality of data collected from it. Consequently, local knowledge from collaborators was used to assess the risk of loss, drying out or vandalism. Where this was likely, alternative locations for the originally chosen point were found from other points within a radius (diamonds in Figure 5) of the desired characteristics (black grid points in Figure 5).

Stage 4: quality control

Large-scale networks can be complicated and confounded by differences in monitoring equipment, measurement drift, quality control procedures and data archiving (Parr et al. 2002; Hannah et al. 2011; Mauger et al. 2015). United Nations Environment Programme (UNEP) highlights that robust quality assurance and quality control is crucial when collating data from numerous sources, yet this is more easily stated than achieved (UNEP 2014). To prevent any inconsistencies standard operating procedures were created following Joint Code of Practice (JCoPs) (Anon 2012) to create a robust and comparable data set (Mauger et al. 2015).

There are a variety of methods for anchoring and positioning loggers in the stream, which could influence uniformity of deployment across a large network, creating issues when comparing data. The deployment method of the SRTMN states that loggers should be placed in similar stream areas and should ensure the location is representative of the reach, in a well-mixed water column that will not stratify and is unlikely to dry out during warm periods

(Imholt *et al.* 2011). Loggers were anchored using metal stakes in the stream, where they will remain throughout the monitoring period (Imholt *et al.* 2011). An alternative deployment method using a land anchor and weighted logger was used for deep rivers where it was deemed potentially hazardous to have staff members in the water.

Methods of sensor shading/shielding also vary between published studies and uncertainty remains about how much effect solar radiation has on temperature measurements (Johnson & Wilby 2013; Johnson *et al.* 2014). The SRTMN uses the most common technique of placing loggers inside PVC tubes to prevent exposure to direct sunlight (Hrachowitz *et al.* 2010; Imholt *et al.* 2011; Isaak *et al.* 2013). These tubes are white and have a high albedo to reflect radiation, but are also large enough to allow water to circulate around the logger ensuring the temperature is representative (Brown & Hannah 2008).

All loggers were calibrated against two reference loggers, which were, in turn, calibrated by a UKAS accredited laboratory 0794 (SGS UK Ltd). The reference loggers were calibrated by comparison to Semi-Standard Platinum Resistance Thermometers, in a stirred water bath, with measurements accurate to $\pm 0.0025\,^{\circ}$C. Recalibration of deployed loggers will be undertaken no greater than every three years, to ensure data quality is retained. Reference loggers are calibrated annually. To permit a rolling programme of calibration and uninterrupted data collection, a store of spare loggers was retained at MSS. The size of this store reflected the maximum number of loggers (40) found in a single catchment. This allows a batch of loggers to be sent to a collaborator for them to rotate into the network; the previously deployed loggers are then returned to MSS for recalibration. Once recalibrated these loggers form the next batch of loggers to be deployed and the process is repeated in the next catchment in the schedule.

It is also important that data are traceable, quality controlled and have appropriate metadata (Hannah *et al.* 2011; Mauger *et al.* 2015); consequently, a centralised database (FleObs) was created to house the data collected by the SRTMN. The FleObs database stores information on loggers, sensors, sites and their various combinations and also stores information on the calibration which can be used to correct raw data on export and provide a measure of uncertainty in the resulting measurements. Calibration equations

have valid periods associated with them, and new equations (with their associated valid period) are added when loggers are recalibrated. Therefore, when data are exported from the database they can be corrected using the calibration equation associated with that time period, for that logger. This ensures that all calibration, data quality control and correction are undertaken to traceable and recognised national standards. This is extremely important for a long-term network where data are collected by numerous collaborators.

Stage 5: network evaluation

Following the first year of data collection (Figure 3) and associated modelling it is useful to assess the success of this proposed network design. In brief, this will involve model validation and power analysis to guide network revision. Leave-one-out cross validation, removing single sites or entire catchments, can be utilised for model validation (Hrachowitz *et al.* 2009). This will allow prediction error to be estimated and demonstrate the ability of the models to make predictions for new sites and catchments (Hrachowitz *et al.* 2009). Power analysis can then be used to assess the magnitude of temperature effects that could be detected by different covariates (Isaak *et al.* 2014). Sites may be removed from the network if fitted models suggest that characteristics are not significant predictors of temperature. Alternatively, additional loggers may be deployed to improve estimates of the effects of individual variables including spatial autocorrelation (Isaak *et al.* 2014).

RESULTS AND DISCUSSION

A perfectly gridded coverage, as exemplified in Figure 4, could not be expected for the chosen sites. However, Figure 6 demonstrates a good coverage of the environmental range across all combinations of potential controlling variables. If a network were biased to particular characteristics, uncertainty will be increased for any extrapolation from monitored to unmonitored locations (Wagner *et al.* 2014). As the selected sites for SRTMN cover the environmental range and combinations of variables (Figure 6), this suggests that the relative importance of different controls should be

isolated in future modelling. Consequently, the network should deliver the necessary data requirements to improve understanding of the controls on water temperatures at different spatial and temporal scales. In addition, it is expected that predictions may be made for unmonitored catchments as issues of monitoring deficiency will be avoided (Laize 2004).

Integrating current monitoring sites and infrastructure into the SRTMN avoids duplication and unnecessary maintenance costs (Parr *et al.* 2002; Mishra & Coulibaly 2009). To enable current monitoring sites to be integrated into the SRTMN, sensors and data loggers needed to be calibrated and deployed following the standard operating procedures created for the SRTMN. As a result, any issues of inter-institutional or equipment bias, lack of cross calibration, variability in sensor anchoring and shielding may be avoided. By avoiding duplication of site characteristics, and thus data redundancy, each site will contribute unique information into statistical models, consequently making a useful and cost-effective network (Mishra & Coulibaly 2009).

CONCLUSIONS AND RECOMMENDATIONS

This paper described and evaluated a potential methodology for the design of a new monitoring network. The approach was illustrated using the SRTMN as a real-world, practical case study. The method characterised the environmental characteristics of potential monitoring sites to cover the environmental range of controlling variables, required to: (1) characterise spatial and temporal variability in thermal regimes across Scotland; (2) identify climatically sensitive locations; (3) improve understanding of controls on *Tw*; (4) develop models to predict future river temperatures and predict thermal regimes in unmonitored rivers; (5) assess mitigation and adaptation strategies for high temperature; and (6) provide long-term monitoring of thermal regimes. The network is strategically planned to ensure the desired coverage of controlling characteristics rather than spatially balanced or randomly located sites which are often the focus of previous networks (Isaak *et al.* 2014 considers). It is therefore anticipated that the network will have minimal redundancy and high levels of statistical power and meet the objectives identified at the start of the network design process.

From the development of this method for the SRTMN, the following key recommendations can be made for designing other large-scale monitoring networks:

- Begin with clear network aims and objectives that identify data requirements.
- Where large-scale spatial statistical models are required, undertake a literature review to determine process drivers and more readily obtained proxies (e.g., GIS or remote sensing data) to represent these processes.
- Assess the amount of resource available and consequently the number of sampling sites or samples that can be planned.
- Select sites to cover the range of environmental characteristics which influence the parameter of interest; an adaptation of Latin squares principles may be used.
- Develop comprehensive standard operating procedures and data storage facilities for data quality control.
- Where possible, integrate current monitoring sites and existing infrastructure to make best use of collective resource.

The merits of this network design will be tested further when data are returned and analysis undertaken. Further research could involve implementing the principles of this approach in other large-scale network designs with different research objectives and target parameters (e.g., water chemistry, fish abundance). The principles identified here are likely to be applicable across different large-scale monitoring networks, due to the values of GIS for assessing landscape characteristics at large spatial scales. Upscaling process-based knowledge to larger spatial scales is a major challenge across disciplines and is required to inform appropriate management, but critically requires large-scale high quality monitoring networks such as SRTMN. Finally, adjustments to this methodology could also be used to assess and revise current monitoring networks that have grown organically and potentially contain redundancy.

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REFERENCES

Anon 2009 *EU-UK (SCOTLAND): Focus Area Report on Protection, Restoration & Enhancement of Salmon Habitat.* NASCO Focus Area Report on habitat, IP(09)8.

Anon 2012 Department for Environment, Food and Rural Affairs. Joint Code of Practice (JCoP) Reference: PB13725, first published 20/03/2013.

Arismendi, I., Johnson, S. L., Dunham, J. B., Haggerty, R. & Hockman-Wert, D. 2012a The paradox of cooling streams in a warming world: regional climate trends do not parallel variable local trends in stream temperature in the Pacific continental United States. *Geophys. Res. Lett.* **39**, L10401.

Arismendi, I., Safeeq, M., Johnson, S. L., Dunham, J. B. & Haggerty, R. 2012b Increasing synchrony of high temperature and low flow in western North American streams: double trouble for coldwater biota? *Hydrobiologia* **712**, 61–70.

Brown, L. E. & Hannah, D. M. 2008 Spatial heterogeneity of water temperature across an alpine river basin. *Hydrol. Process.* **22**, 954–967.

Chang, H. & Psaris, M. 2013 Local landscape predictors of maximum stream temperature and thermal sensitivity in the Columbia River Basin, USA. *Sci. Total Environ.* **461–462**, 587–600.

Deweber, J. T. & Wagner, T. 2014 A regional neural network ensemble for predicting mean daily river water temperature. *J. Hydrol.* **517**, 187–200.

Deweber, J. T., Tsang, Y., Krueger, D. M., Whittier, J. B., Wagner, T., Infante, D. M. & Whelan, G. 2014 Importance of understanding landscape biases in USGS gage locations: implications and solutions for managers. *Fisheries* **39**, 155–163.

Elliott, J. M. 1994 *Quantitative Ecology and the Brown Trout.* Oxford University Press, New York.

Fu, P. & Rich, P. M. 1999 Design and implementation of the Solar Analyst: an ArcView extension for modeling solar radiation at landscape scales. In: *Proceedings of the 19th Annual Esri User Conference*, San Diego, CA, USA.

Gao, L. 2005 *Latin Squares in Experimental Design.* Michigan State University, East Lansing, MI, USA.

Gardiner, R. & Egglishaw, H. 1986 *A Map of the Distribution in Scottish Rivers of the Atlantic Salmon,* Salmo salar *L.* Department of Agriculture and Fisheries for Scotland, Freshwater Fisheries Laboratory, Pitlochry, Scotland.

Garner, G., Hannah, D., Salder, J. & Orr, H. 2013 River temperature regimes of England and Wales: spatial patterns, inter-annual variability and climatic sensitivity. *Hydrol. Process.* **28**, 5583–5598.

Garner, G., Malcolm, I. A., Sadler, J. P. & Hannah, D. M. 2014 What causes cooling water temperature gradients in a forested stream reach? *Hydrol. Earth Syst. Sci.* **18**, 5361–5376.

Gilvear, D. J., Heal, K. V. & Stephen, A. 2002 Hydrology and the ecological quality of Scottish river ecosystems. *Sci. Total Environ.* **294**, 131–159.

Guan, H., Zhang, X., Makhnin, O. & Sun, Z. 2013 Mapping mean monthly temperatures over a coastal hilly area incorporating terrain aspect effects. *J. Hydrometeorol.* **14**, 233–250.

Gurney, W. S. C., Bacon, P. J., Tyldesley, G. & Youngson, A. F. 2008 Process-based modelling of decadal trends in growth, survival, and smolting of wild salmon (*Salmo salar*) parr in a Scottish upland stream. *Can. J. Fish. Aquat. Sci.* **65**, 2606–2622.

Hannah, D. M., Malcolm, I. A., Soulsby, C. & Youngson, A. F. 2008 A comparison of forest and moorland stream microclimate, heat exchanges and thermal dynamics. *Hydrol. Process.* **22**, 919–940.

Hannah, D. M., Demuth, S., van Lanen, H. A. J., Looser, U., Prudhomme, C., Rees, G., Stahl, K. & Tallaksen, L. M. 2011 Large-scale river flow archives: importance, current status and future needs. *Hydrol. Process.* **25**, 1191–1200.

Hilderbrand, R. H., Kashiwagi, M. T. & Prochaska, A. P. 2014 Regional and local scale modeling of stream temperatures and spatio-temporal variation in thermal sensitivities. *Environ. Manage.* **54**, 14–22.

Hill, R. A. & Hawkins, C. P. 2014 Using modelled stream temperatures to predict macro-spatial patterns of stream invertebrate biodiversity. *Freshw. Biol.* **59**, 2632–2644.

Hill, R. A., Hawkins, C. P. & Carlisle, D. M. 2013 Predicting thermal reference conditions for USA streams and rivers. *Freshw. Sci.* **32**, 39–55.

Hill, R. A., Hawkins, C. P. & Jin, J. 2014 Predicting thermal vulnerability of stream and river ecosystems to climate change. *Clim. Change* **125**, 399–412.

Hornby, D. D. 2015 RivEX (Version 10.16) [Software] http://www.rivex.co.uk.

Hrachowitz, M., Soulsby, C., Tetzlaff, D., Dawson, J. J. C. & Malcolm, I. A. 2009 Regionalization of transit time estimates in montane catchments by integrating landscape controls. *Water Resour. Res.* **45**, W05421.

Hrachowitz, M., Soulsby, C., Imholt, C., Malcolm, I. A. & Tetzlaff, D. 2010 Thermal regimes in a large upland salmon river: a simple model to identify the influence of landscape controls and climate change on maximum temperatures. *Hydrol. Process.* **24**, 3374–3391.

Imholt, C., Soulsby, C., Malcolm, I. A., Hrachowitz, M., Gibbins, C. N., Langan, S. & Tetzlaff, D. 2011 Influence of scale on thermal characteristics in a large montane river basin. *River Res. Appl.* **29**, 403–419.

Imholt, C., Soulsby, C., Malcolm, I. A. & Gibbins, C. N. 2013 Influence of contrasting riparian forest cover on stream temperature dynamics in salmonid spawning and nursery streams. *Ecohydrology* **6**, 380–392.

Isaak, D. & Hubert, W. 2001 A hypothesis about factors that affect maximum summer stream temperature across montane landscapes. *J. Am. Water Resour. Assoc.* **37**, 351–366.

Isaak, D. J., Luce, C. H., Rieman, B. E., Nagel, D. E., Peterson, E. E., Horan, D. L., Parkes, S. & Chandler, G. L. 2010 Effects of climate change and wildfire on stream temperatures and salmonid thermal habitat in a mountain river network. *Ecol. Appl.* **20**, 1350–1371.

Isaak, D. J., Wollrab, S., Horan, D. & Chandler, G. 2012 Climate change effects on stream and river temperatures across the northwest U.S. from 1980–2009 and implications for salmonid fishes. *Clim. Change* **113**, 499–524.

Isaak, D. J., Horan, D. L. & Wollrab, S. P. 2013 *A Simple Protocol Using Underwater Epoxy to Install Annual Temperature Monitoring Sites in Rivers and Streams.* USDA/Forest Service, General Technical report RMRS-GTR 314.

Isaak, D. J., Peterson, E. E., Ver Hoef, J. M., Wenger, S. J., Falke, J. A., Torgersen, C. E., Sowder, C., Steel, A. E., Fortin, M.-J., Jordan, C. E., Ruesch, A. S., Som, N. & Monestiez, P. 2014 Applications of spatial statistical network models to stream data. *WIREs Water* **1**, 227–294.

Johnson, M. & Wilby, R. 2013 Shield or not to shield: effects of solar radiation on water temperature sensor accuracy. *Water* **5**, 1622–1637.

Johnson, M. F., Wilby, R. L. & Toone, J. A. 2014 Inferring air-water temperature relationships from river and catchment properties. *Hydrol. Process.* **28**, 2912–2928.

Laize, C. L. R. 2004 Integration of spatial datasets to support the review of hydrometric networks and the identification of representative catchments. *Hydrol. Earth Syst. Sci.* **8**, 1103–1117.

Lammers, R. B., Pundsack, J. W. & Shiklomanov, A. I. 2007 Variability in river temperature, discharge, and energy flux from the Russian pan-Arctic landmass. *J. Geophys. Res.* **112**, G04S59.

Li, G., Jackson, C. R. & Kraseski, K. A. 2012 Modeled riparian stream shading: agreement with field measurements and

sensitivity to riparian conditions. *J. Hydrol.* **428–429**, 142–151.

Malcolm, I. A., Hannah, D. M., Donaghy, M. J., Soulsby, C. & Youngson, A. F. 2004 The influence of riparian woodland on the spatial and temporal variability of stream water temperatures in an upland salmon stream. *Hydrol. Earth Syst. Sci.* **8**, 449–459.

Malcolm, I. A., Soulsby, C., Hannah, D. M., Bacon, P. J., Youngson, A. F. & Tetzlaff, D. 2008 The influence of riparian woodland on stream temperatures: implications for the performance of juvenile salmonids. *Hydrol. Process.* **22**, 968–979.

Marsh, T. J. & Anderson, J. L. 2002 Assessing the water resources of Scotland – perspectives, progress and problems. *Sci. Total Environ.* **294**, 13–27.

Martin, R. J. 2001 Comparing and contrasting some environmental and experimental design problems. *Environmetrics* **12**, 273–287.

Mauger, S., Shaftel, R., Trammell, E. J. & Geist, M. 2015 Regional studies stream temperature data collection standards for Alaska: minimum standards to generate data useful for regional-scale analyses. *J. Hydrol. Reg. Stud.* **4**, 431–438.

McCullough, D. A., Bartholow, J. M., Jager, H. I., Beschta, R. L., Cheslak, E. F., Deas, M. L., Ebersole, J. L., Foott, J. S., Johnson, S. L., Marine, K. R., Mesa, M. G., Petersen, J. H., Souchon, Y., Tiffan, K. F. & Wurtsbaugh, W. A. 2009 Research in thermal biology: burning questions for coldwater stream fishes. *Rev. Fish. Sci.* **17**, 90–115.

Mishra, A. K. & Coulibaly, P. 2009 Developments in hydrometric network design: a review. *Rev. Geophys.* **47**, RG2001.

Mohseni, O., Stefan, H. & Eaton, J. 2003 Global warming and potential changes in fish habitat in U.S. streams. *Clim. Change* **59**, 389–409.

Moore, R. D., Nelitz, M. & Parkinson, E. 2013 Empirical modelling of maximum weekly average stream temperature in British Columbia, Canada, to support assessment of fish habitat suitability. *Can. Water Resour. J.* **38**, 135–147.

Parr, T. W., Ferretti, M., Simpson, I. C., Forsius, M. & Kováks-Láng, E. 2002 Towards a long-term integrated monitoring programme in Europe: network design in theory and practice. *Environ. Monit. Assess.* **78**, 253–290.

Peterson, E. E. & Ver Hoef, J. M. 2014 STARS: an ArcGIS toolset used to calculate the spatial information needed to fit statistical models to stream network data. *J. Stat. Softw.* **56**, 1–17.

Radford, A., Riddington, G. & Anderson, J. 2004 *The Economic Impact of Game and Coarse Angling in Scotland*. Research Report, The Scottish Government.

Ryan, D. K., Yearsley, J. M. & Kelly-Quinn, M. 2013 Quantifying the effect of semi-natural riparian cover on stream temperatures: implications for salmonid habitat management. *Fish. Manag. Ecol.* **20**, 494–507.

Sivapalan, M., Takeuchi, K., Franks, S. W., Gupta, V. K., Karambiri, H., Lakshmi, V., Liang, X., McDonnell, J. J., Mendiondo, E. M., O'Connell, P. E., Oki, T., Pomeroy, J. W., Schertzer, D. & Uhlenbrook, S. E. Z. 2003 IAHS Decade on Predictions in Ungauged Basins (PUB), 2003–2012: shaping an exciting future for the hydrological sciences. *Hydrol. Sci. J.* **48**, 857–880.

Soulsby, C., Tetzlaff, D., Dunn, S. M. & Waldron, S. 2006a Scaling up and out in runoff process understanding: insights from nested experimental catchment studies. *Hydrol. Process.* **20**, 2461–2465.

Soulsby, C., Tetzlaff, D., Rodgers, P., Dunn, S. & Waldron, S. 2006b Runoff processes, stream water residence times and controlling landscape characteristics in a mesoscale catchment: an initial evaluation. *J. Hydrol.* **325**, 197–221.

Sowder, C. & Steel, E. A. 2012 A note on the collection and cleaning of water temperature data. *Water* **4**, 597–606.

Tetzlaff, D., McDonnell, J. J., Uhlenbrook, S., McGuire, K. J., Bogaart, P. W., Naef, F., Baird, A. J., Dunn, S. M. & Soulsby, C. 2008 Conceptualizing catchment processes: simply too complex? *Hydrol. Process.* **22**, 1727–1730.

Thomassen, H. A., Cheviron, Z. A., Freedman, A. H., Harrigan, R. J., Wayne, R. K. & Smith, T. B. 2010 Spatial modelling and landscape-level approaches for visualizing intra-specific variation. *Mol. Ecol.* **19**, 3532–3548.

UNEP 2014 Analytical Methods for Environmental Water Quality. United Nations Environment Programme Global Environment Monitoring System (GEMS)/Water Programme.

van Vliet, M. T. H., Ludwig, F., Zwolsman, J. J. G., Weedon, G. P. & Kabat, P. 2011 Global river temperatures and sensitivity to atmospheric warming and changes in river flow. *Water Resour. Res.* **47**, W02544.

van Vliet, M. T. H., Yearsley, J. R., Franssen, W. H. P., Ludwig, F., Haddeland, I., Lettenmaier, D. P. & Kabat, P. 2012 Coupled daily streamflow and water temperature modelling in large river basins. *Hydrol. Earth Syst. Sci.* **16**, 4303–4321.

Ver Hoef, J. M., Peterson, E. & Theobald, D. 2006 Spatial statistical models that use flow and stream distance. *Environ. Ecol. Stat.* **13**, 449–464.

Wagner, M. J., Bladon, K. D., Silins, U., Williams, C. H. S., Martens, A. M., Boon, S., Macdonald, R. J., Stone, M., Emelko, M. B. & Anderson, A. 2014 Catchment-scale stream temperature response to land disturbance by wildfire governed by surface-subsurface energy exchange and atmospheric controls. *J. Hydrol.* **517**, 328–338.

Wehrly, K. E., Brenden, T. O. & Wang, L. 2009 A comparison of statistical approaches for predicting stream temperatures across heterogeneous landscapes. *JAWRA J. Am. Water Resour. Assoc.* **45**, 986–997.