34 *Ecohydrology of Surface and Groundwater Dependent Systems: Concepts, Methods and Recent Developments*
(Proc. of JS.1 at the Joint IAHS & IAH Convention, Hyderabad, India, September 2009). IAHS Publ. 328, 2009.

Modelling the spatial variations of stream temperature and its impacts on habitat suitability in small lowland streams

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Abstract Water temperature strongly impacts stream ecosystem and function. On Sjælland, the main island of Denmark, low summer stream discharge rates are very sensitive to groundwater abstraction, which is therefore also partly responsible for the poor ecological conditions of most streams. However, the combined impacts of water depth, velocity and water temperature on habitat suitability during low-flow conditions are not known. The aim of this study is to measure and model spatio-temporal stream temperature variations as a function of stream surface shade from near stream land cover and to quantify such impacts on stream habitat suitability during low flows. Brown trout is chosen as a bio-indicator of stream ecological conditions because of its well-known preferences for physical habitat conditions such as temperature. A spatially distributed physically-based stream temperature model (Heat Source model) is set up for a 2.4 km reach of Helligrenden stream for a 10-day period in August 2008 at which time low flows are prevailing. Hourly water temperature measurements are obtained from five stream segments representative of meadows and forest stream reaches, and a temperature suitability index representing the fulfilment of temperature requirement of brown trout is calculated for the sites. Water temperatures are found to increase downstream by up to 2°C per km in open meadow reaches, thereby leading to temperature levels which are unsuitable for brown trout. In contrast, cooling rates of as much as –2.4°C per km are simulated for the forest reach. This suggests that planting of trees in riparian zones of downstream stream reaches can significantly improve stream habitat conditions during low flow conditions at Sjælland.

Key words stream temperature; low flow; physical stream habitat suitability; Denmark

INTRODUCTION

The impact of human pressures on freshwater resources and ecosystems is an issue of international concern. Balancing the various consumptive and non-consumptive demands on the world’s water resources to ensure healthy river and coastal ecosystems is complicated by predictions of climate change. Solutions to this intensifying conflict require new modelling tools whereby aquatic biota are related to their physical environment at catchment scale. Indeed, the EU Water Framework Directive (WFD) requires good ecological status of all water bodies before 2015.

Groundwater supplies 99% of Denmark’s water supply. On Sjælland, the major island of Denmark, heavy groundwater pumping has resulted in lower streamflows with adverse impacts on stream ecological conditions (Olsen *et al.*, 2009). Reduced low flows cause streamwater temperatures to respond more strongly to solar radiation load with stream temperatures increasing to levels that are damaging for fish and other aquatic organisms. In order to identify which elements of the physical habitat template should be improved to gain optimum ecological benefit during low flow, knowledge of biological constraints associated with climate and thermal environments, along with hydrological and morphological conditions, are required.

In this paper, an energy-based distributed stream temperature model is used to simulate water temperatures in a small lowland stream in Denmark. The study area is located on the island of Sjælland, which is strongly impacted by groundwater abstraction. The objective of the study was to quantify the impact of stream surface shade by different types of riparian vegetation on physical habitat conditions. Hourly measurements of stream temperature are used to evaluate water temperature simulations for open and forested stream reaches, with habitat suitability being calculated and discussed for meadow and forest stream reaches. Habitat suitability in relation to stream temperature is quantified for brown trout (*Salmo trutta*), an important bio-indicator in the region.

STUDY AREA AND DATA

The study is based on data collected from a small lowland stream, Helligrenden, located on the island of Sjælland (55.6299°N, 11.9126°E). The surrounding landscape is dominated by agricultural land use and has a gentle undulating terrain with the stream being located at 52 m to 5 m above sea level. The total length of the stream is 5 km with bankfull stream widths ranging from 0.5 to 3 m. Water temperature loggers (HOBO, Onset, US) were installed at five locations along the stream (Fig. 1) to record hourly water temperature.

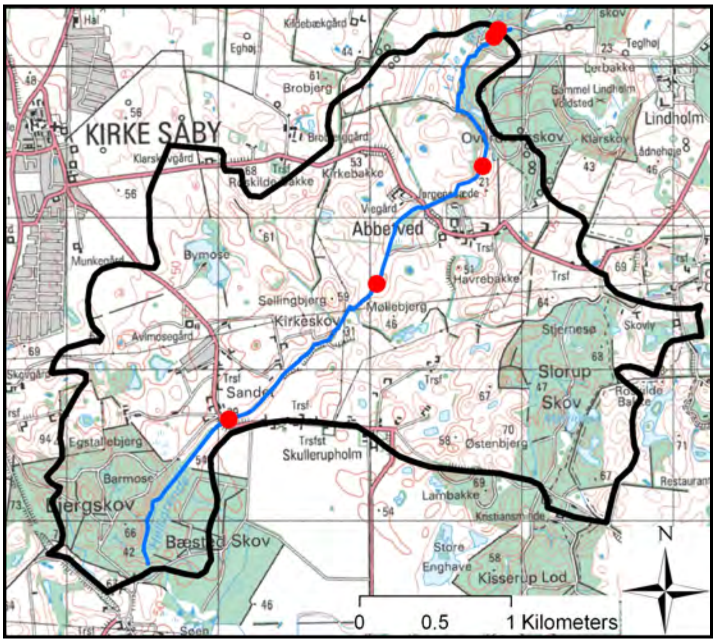

Fig. 1 Stream Helligrenden at Sjælland. Water flow direction is towards North. The figure shows the locations of five water temperature stations (red dots) numbered 1, 2, 3, 4 and 5 in the downstream direction. Mapsource: Kort og Matrikelstyrelsen 1:50 000, 1996 (Copyright, Kort og Matrikelstyrelsen G X-04).

At station 1, the temperature of groundwater being pumped into the stream was measured. Stations 2 and 3 are located in stream segments running through grass meadows characterized by tall and low vegetation heights, respectively, and the stations 4 and 5 are located in forested stream reaches. A water depth logger (WL16, GlobalWater Instrumentation, US) was installed at station 2 and this provided hourly flow rates. Data of instream velocities and river bed substratum were sampled from representative stream reaches as part of habitat survey research activities (i.e. Conallin *et al*., 2007). Climate data to run the model consists of incoming solar radiation, air temperature, air humidity and wind speed, which are available from the weather station of Roskilde University (http://www.geo.ruc.dk/vejr/) located approximately 15 km from the stream sites. Land cover was assessed from a high spatial resolution (20 m) remote sensing based (SPOT satellite) classified land cover map representing summer 2008.

MODEL DESCRIPTION AND SETUP

The stream temperature model

Simulating streamwater temperature is based on calculating all heat energy exchanges with the stream and correcting for the temperature effects caused by the downward movement of water (advection and dispersion) and hyporheic exchange (Boyd & Kasper, 2003). Dynamic flow routing and evaporation calculations make it possible to account for water volumes at any time and any location along the study reach. In this study, 1-D hydraulic flow routing and volume storage were simulated using the Muskingum-Cunge method, which is based on a finite difference solution of the continuity and kinematic wave equations. Model inputs for the water volume storage and flow routing components comprise upstream boundary flow, spatial channel data (geometry and slope), channel roughness and wedge storage.

Simulated water temperature is dependent on both upstream and local conditions. Solar radiation is the most important source of energy for increasing water temperatures and it is influenced locally, by topography and shade from riparian vegetation. In order to calculate stream shading effects due to topography and land cover, solar position is computed based on the geographical position and day/time of year. Geographical coordinates, stream aspect, elevation and riparian land cover are extracted from ArcGIS for each model stream segment (model node) and used to calculate solar radiation load at the stream surface. Other heat exchange components considered in the model are long wave radiation, streambed conduction, stream/air convection and evaporation (Boyd & Kasper, 2003). Solar radiation which reaches the stream surface, is partly reflected, absorbed and transmitted to the stream bed. Heat absorption by the stream bed causes differential heating which is used for calculating the river bed substratum–water column conduction. Part of the solar beam radiation is reflected from the stream bed and transferred back to the streamwater surface. The simulation of heat conduction between the deeper alluvium and the water column requires knowledge about alluvium temperatures which were assumed in this study to be similar to the measured groundwater temperature. The composite river-bed substratum/water weighted conduction properties can be estimated from the dominant particle size and embeddedness of the river bed substratum. Latent heat flux (evaporation) in this study was calculated using mass

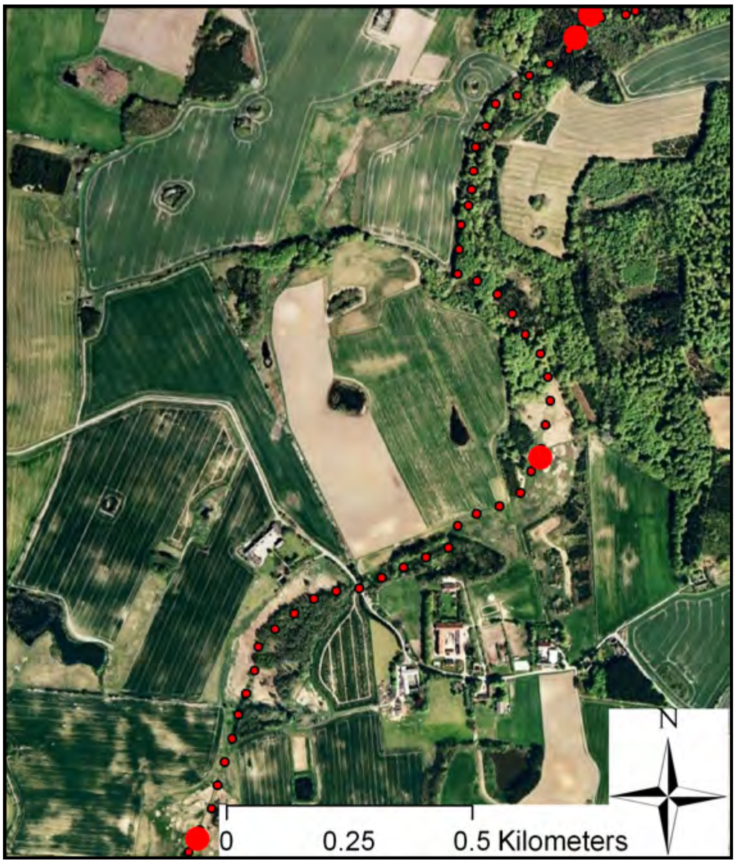

Fig. 2 Aerial photo illustration of land cover, 2006, representative of the 2.4 km stream reach where the stream temperature model is set up. The model is initialized and started at station 2 and ending in the forest. Model nodes (small red dots) have a distance of 50 m. The location of stream stations is also indicated (larger red dots). Map Source: Google Earth.

transfer principles with the Bowen ratio assessed from the stream/air temperature gradients for calculation of sensible heat flux (stream/air convection).

Model setup

The streamwater temperature model was set up for a 2.4 km stream reach between station 2 and the stream outlet. Hourly flow and water temperature measured at station 2 were used as upstream boundary conditions for the model run. The stream was represented by 50-m longitudinal reservoirs and model time steps of 1 minute. Bankfull widths, side slopes and the maximum bank full depth were assessed based on field observations. Silt is the dominant sediment texture and embeddedness was set to 50%. Mannings “n” was set to 0.5–0.8 in order to fit the range of measured stream velocities. In the open meadow reaches, vegetation growth in the stream was represented by the model, thereby reducing radiation penetration and decreasing the local wind speed. Elevation data for the study reach were extracted in ArcGIS for each 50-m model node (Fig. 3) to calculate stream segment gradients and for modelling topographical shade of the stream. The depth of the river-bed substratum was set to 0.2 m, and the alluvium temperature was set to 10°C to represent shallow groundwater temperature.

Land cover data for each model node was extracted in eight directions and in four transverse zones, each having a width of 10 m. The extracted land cover data sets were improved by comparing the results with higher spatial resolution aerial photos available from Google Earth (Fig. 2). Land cover types and their presumed model parameters (height and vegetation densities) are seen in Table 1.

Table 1 Land cover types, derived from classification of SPOT satellite map, and land cover parameters used for calculating shade by riparian vegetation.

Land cover	Height (m)	Density (%)
Urban	10	100
Water	0	0
Conifers	10	90
Deciduous forest	20	80
Maize	2	80
Sunflower	2	80
Wheat, barley	1	80
Meadow, low grass	0.2	70
Meadow, tall	2	70

RESULTS

Diurnal water temperature data

Diurnal variations in stream temperature are lowest at the upstream station 2 (tall grass meadow site) located closest to the groundwater pump (Fig. 2). The highest temperatures are found in the open short grass meadow (station 3) while water temperatures of the forest stream reach (station 4) are lower than at station 3. At station 2, shading by the tall grass vegetation during the morning results in a delay in the diurnal temperature rise in comparison to the open low grass meadow site (station 3). The morning rise in water temperatures at station 4 – the forested site – is also delayed, and the temperature is lower in the forest in comparison to the meadow sites. Data recorded at station 1 are representative of groundwater temperatures, which are relatively constant between 9 and 10°C throughout the day.

Longitudinal shade simulations and stream temperature impacts

The simulated longitudinal variation in effective shade (Fig. 4(a)) reflects the different riparian land cover types whereas topographical shade is less significant. Water flowing initially through a

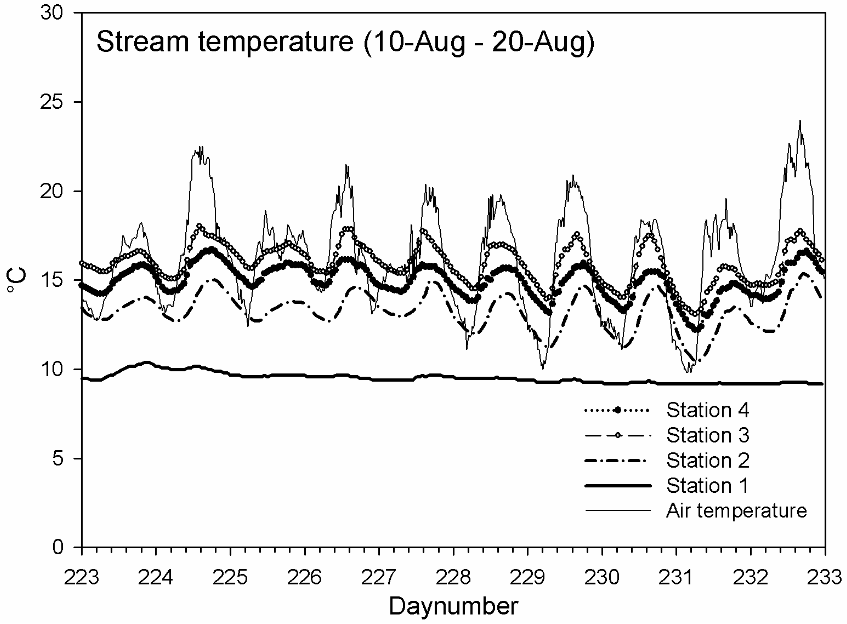

Fig. 3 Measured hourly water temperatures for Helligrenden stream at five stream locations, August 2008. The air temperature is also shown for comparison.

tall grass meadow is characterized by an average effective shade (*S*) of 15–30%. When it runs along the edge of a group of riparian trees the effective shade increases to 55% while in the open short grass meadow, *S* is 5–10% but then rises to approximate 80% in the forest section. Generally, the impacts of solar heating and shading on simulated water temperatures over the study reach are to increase temperatures in the open reaches and cool water in the forest reach (Fig. 4(b)). It is pertinent to note that simulated stream temperature does respond to local vegetation/topographical shade only, and longitudinal temperature variations caused by local groundwater inflows are not considered. However, it appears that even for a short stream reach of 2.4 km, longitudinal warming and cooling rates of 2°C (open meadow) and –2.4°C (forest) are possible for this lowland stream due to solar irradiation and shading by vegetation, respectively (Fig. 4(b)).

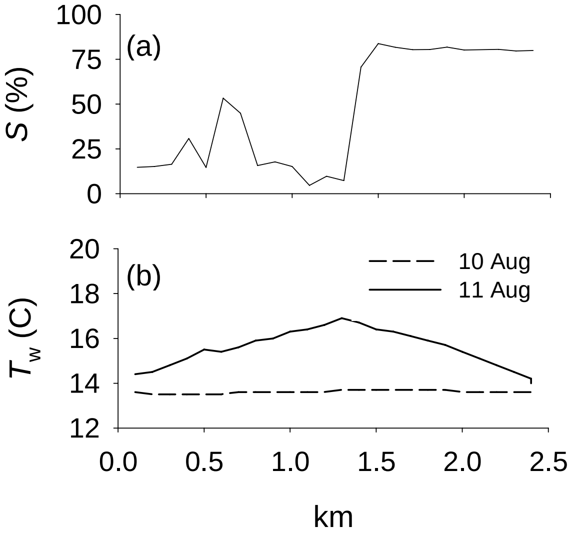

Fig. 4 (a) Simulated averaged effective shade (*S*) of model stream reach. (b) Simulated water temperature (T_w) for an overcast day (10 August) at 14:00 h and a clear day (11 August) at 14:00 h.

Diurnal heat balance and stream temperature simulations

Simulated diurnal stream heat balances of the segments located in the short grass meadow (station 3) and the forest (station 4) sites are provided in Fig. 5(a),(b). The average discharge in the simulated 10-day period was 0.033 m^3 s^{-1}. The large stream surface radiation load of the open short grass meadow (station 3) is associated with the highest water temperatures in the study reach. By comparison, the impact of shade in the forest results in a negative net heat balance causing a reduction in streamwater temperatures (Fig. 5(c)). Although the simulated diurnal variations in streamwater temperatures reflect quite well the field measurements ($r^2 = 0.59$), water temperatures at stations 3 and 4 were underestimated (standard error = 0.65). The high observed water temperature differences between stations 2 and 3 (3–5°C) are thought to be influenced by a water control structure which is installed between stations 2 and 3 at the position where a road crosses the stream (can be seen in Figs 1 and 2). The control structure is not represented in the model but is expected to cause pooling of streamwater, which is therefore being heated more than if water was running freely.

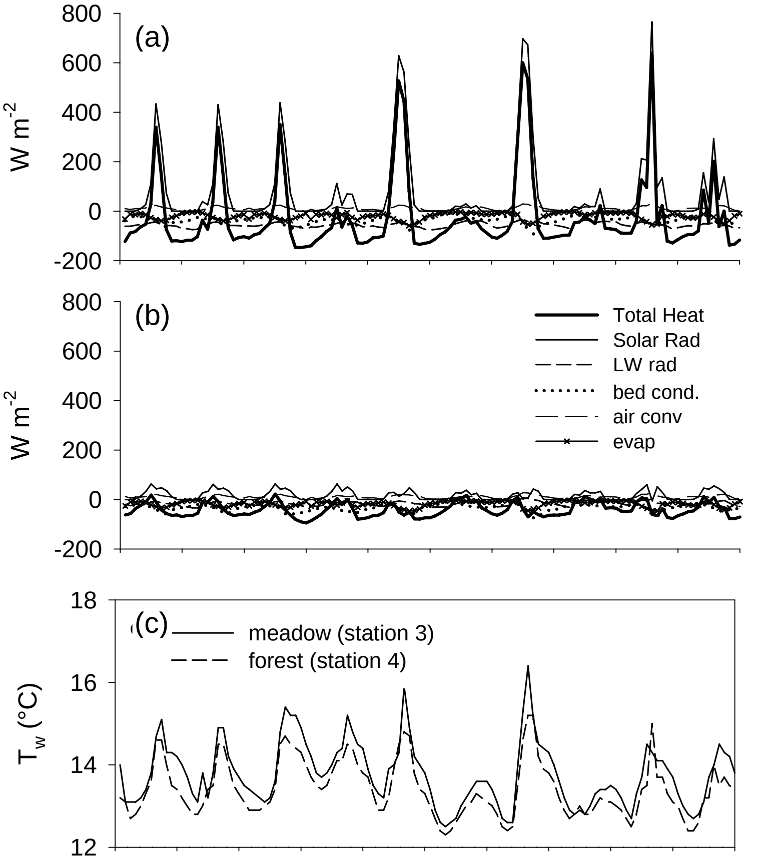

Fig. 5 (a) Simulated hourly heat balance for stream section located in a short grass meadow (station 3), (b) simulated hourly stream heat balance of a forested stream section (station 4), (c) simulated stream temperatures (T_w) of meadow and forest stream sections. Simulated heat balance components in (a) and (b) comprise total heat, solar radiation, long wave radiation, bed conductance, air/stream convection and evaporation (legend is shown in (b)).

Water temperature and habitat suitability

Temperature requirements for brown trout (Elliott, 1994) were used to construct a temperature suitability curve (Fig. 6). Water temperatures above 17°C generally decrease the metabolic activity of brown trout, and at temperatures above 22°C there is a breakdown of vital body processes.

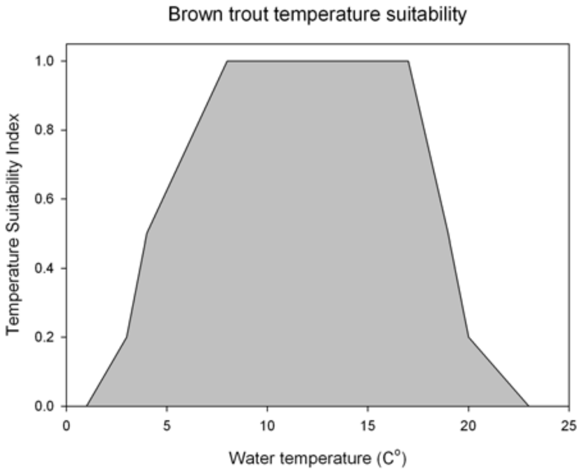

Fig. 6 Temperature suitability index of brown trout.

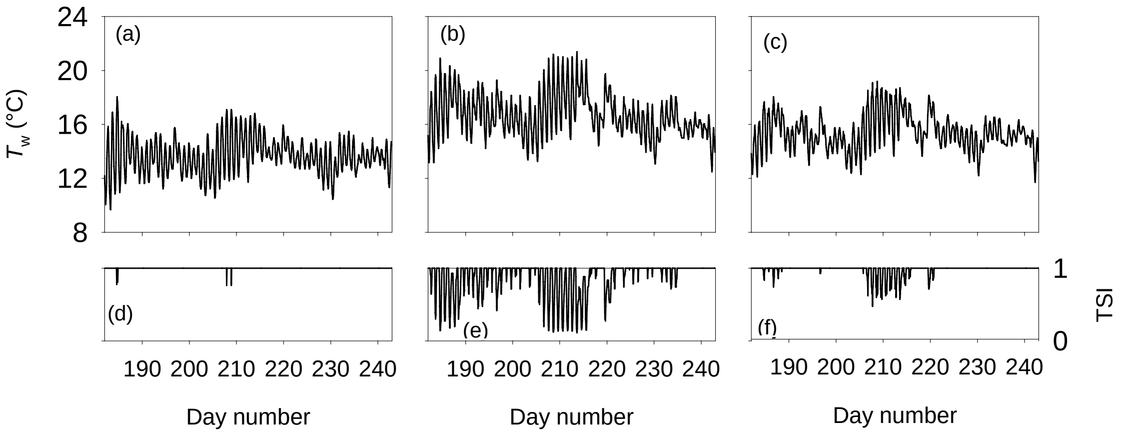

Fig. 7 Measured water temperature (T_w, black line) at (a) station 2 (tall meadow), (b) station 3 (low meadow), and (c) station 4 (forest) in July–August. Calculated temperature suitability index (TSI, black line) of brown trout for: (d) station 2, (e) station 3, and (f) station 4 for the same period. TSI varies between 0 and 1 with 0 representing unsuitable conditions (causing instantaneous death) and 1 representing optimal thermal conditions.

Water temperatures along the study reach increase to harmful levels in July–August, especially at the downstream short grass meadow and forest sites. However, habitat conditions improve in the forest sections (Fig. 7(f)) compared to the open meadow (Fig. 7(e)) because of the impact of the influence of shading on streamwater temperatures (Fig. 7(b),(c)).

DISCUSSION

Streamwater temperatures in the small lowland Helligrenden system increase downstream and reach levels that are unsuitable for brown trout during low flow conditions in August. Based on observed and modelled impact of shade on streamwater temperatures, habitat conditions for brown trout can be significantly improved by planting trees in the riparian zone of small lowland streams like Helligrenden. This is particularly important in downstream reaches where habitat improvement is required. The model developed for this study indicates that streamwater temperatures can be reduced by as much as 2.4°C per km when flowing through forested stream segments. Even though the simulated longitudinal and temporal variations in streamwater temperature looked realistic, the temperature simulations for stations 3 and 4 were consistently underestimated. This is thought to be the result of the influence of a water control structure which was not represented in the model. Uncertainties in streamwater temperature modelling related to groundwater inflow are also important as groundwater inflow may be responsible for large spatial variations in streamwater temperature (i.e. Westhoff *et al*., 2007). In the coming years, a fibre optic temperature cable of 2 km length and 1 m spatial resolution will be used to study the heat and flow processes in relation to the longitudinal characteristics of streams and their spatial environment. This is considered important to improve the understanding and modelling of water flow in the stream and catchment and their significance for stream ecological conditions. Other major uncertainties related to stream heat balance modelling are the spatial variations in microclimate and vegetation density. In this study, vegetation density was kept constant for different land cover types. However, spatial variations in vegetation density can be mapped using remote sensing data and thereby assist the improvement of spatial heat balance modelling.

Acknowledgements The study took place within the framework of the research project "Climate change impacts on ecological conditions in streams" (2007–2010) which is financed by the Danish Research Council for Technology and Production (contract no. 274-06-0474).

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