Received: 12 February 2024 | Revised: 7 May 2024 | Accepted: 9 May 2024
DOI: 10.1002/rra.4324

SHORT COMMUNICATION

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A complete homogenization of water temperatures during widespread flooding

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Funding information
Norsk institutt for naturforskning, Grant/Award Number: SATS-20-39; Norges Forskningsråd, Grant/Award Number: 160022/F40

Abstract

Thermal regimes can vary substantially across small geographic distances in rivers, and the factors responsible for creating a diverse thermal landscape can operate on multiple spatial and temporal extents. This short communication reports on the temperature dynamics in seasonal, off-channel habitats in the lower reach of the Gudbrandsdalslågen River in South-Eastern Norway (61 °N). The river is ordinarily characterized by a snowmelt-driven hydrograph but was subjected to widespread, rain-driven flooding in August 2023. At the onset of spring runoff in mid-May, the differences between cooler and warmer sites exceeded 5°C (range 3–10°C) and continued to diverge until early July (range 6–21°C). Differences persisted through the regular rain-driven spates in summer but were entirely diminished during the flood which started on August 7. By August 10, the water temperatures at all 14 sites had converged at 12.3°C. The homogenization was likely the result of the sheer volume of runoff through Gudbrandsdalslågen, overriding any locally modulating factors such as groundwater inputs and isolation from the main channel. This suggests a relatively strong influence of locally modulating factors in the study area under normal hydrological conditions in summer, and a complete dominance of runoff temperature during the flooding event. Disruptive events such as flooding can hence periodically revert the thermal heterogeneity by changing the relative importance of the factors that create patchy thermal regimes, with potential ramifications for aquatic organisms that occupy relatively warmer habitat patches in summer.

KEYWORDS
extreme events, fish community, habitats, precipitation, thermal regime

1 | INTRODUCTION

Biologists are increasingly viewing water temperature as a heterogeneous and dynamic factor in space and time, creating in a range of conditions to which organisms must adapt (Ward et al., 2001; Webb et al., 2008). Improved availability of high-quality temperature loggers and remote sensing techniques such as thermal infrared imaging has accelerated our understanding of thermal heterogeneity in streams in recent decades (Steel et al., 2017; Webb et al., 2008). River thermal regimes are inherently diverse and context-dependent: global and continental patterns can be generalized coarsely based on large-scale drivers such as geographic position (latitude and longitude) and climatic factors, whereas altitude, geologic conditions, precipitation regimes, groundwater exchanges, and aspect can modulate site-specific thermal regimes at yet smaller spatial scales (Allan et al., 2021; Luce et al., 2014; Ward et al., 2001). Which factor is more important varies geographically, and furthermore, the relative importance of the factors contributing to a river's heat budget can vary seasonally (Webb et al., 2008). Understanding how the mosaic of thermal conditions are created and maintained is valuable in the face of climate change and other changes to the hydrology of watersheds because these changes are likely to be modulated by site-specific factors (Ebersole et al., 2020; Mejia et al., 2023; Steel et al., 2017).

Water temperature affects the distribution and abundance of aquatic organisms through its pervasive controls over biological processes (Allan et al., 2021; Caissie, 2006). For fishes, the length of the summer season (i.e., the number of days above a certain temperature) is of particular importance to spring-spawning species, because it drives the development from eggs to free-swimming stages (Neuheimer & Taggart, 2007). In snowmelt-driven systems (typically at high latitudes or altitudes), access to habitat patches that are relatively warmer than the local average temperature can be important for the local persistence of species (Myrvold et al. *in prep*.). Here, off-channel habitats such as backwater sloughs, flooded wetlands, and side channels can be particularly important because they provide physical shelter from the current and higher temperatures than the main channel. In turn, this local mosaic of physical habitats with variable thermal regimes can support diverse ecological communities in otherwise marginal or unsuitable geographical regions (Allan et al., 2021).

Disruptive events such as flooding can periodically revert the thermal heterogeneity by changing the relative importance of the factors that create patchy thermal regimes. Here, I report on the temperature dynamics in a large inland delta in South-Eastern Norway that was subjected to widespread flooding in August 2023. Storm systems capable of generating large amounts of precipitation over Norway typically form in the North Atlantic Ocean and move east toward the coast. Under normal circumstances, the West Coast receives the highest amounts of precipitation, while eastern portions of the country receive less precipitation due to a mild rain shadow effect (Granerød et al., 2023). The storm "Hans" formed when remnant storms "Petar" and "Antoni," which separately had caused flooding and gusty winds across Central Europe, merged, and tracked in a northwesterly direction across eastern Norway (Granerød et al., 2023). The storm system lingered east of the central mountain range that creates the rain shadow. Whereas the West Coast is characterized by short, steep rivers, the eastern portion of the country has large drainage basins with lesser gradient and is hence prone to greater risk of flooding. An array of temperature loggers originally deployed to monitor the thermal regimes in the delta offered an opportunity to study the effects of flooding on the thermal landscape during a time of the year when such events rarely occur. The objective of this study is to document the thermal landscape before, during, and after the flooding event.

2 | METHODS

The study took place in the seasonal habitats that form in late spring and summer where the Gudbrandsdalslågen River enters Lake Mjøsa (61.14° N, 10.40° E study area center point; Figure 1a). The hydrograph follows a snowmelt-driven pattern, where the annual bankfull flood typically occurs in mid-May to mid-June and rain-driven spates occur sporadically throughout summer and fall. Lake Mjøsa is the largest lake in Norway (362 km^2 surface area) and is regulated 3.6 m at its outlet for flood control and hydropower (surface elevation from 119.6 to 123.2 m above sea level). The lake is drawn down throughout the winter to hit its lowest mark prior to the spring runoff (Figure 1b). The combination of increased runoff through Gudbrandsdalslågen (drainage area 12,552 km^2) in late spring and the gradual filling of the lake inundates sloughs, backwaters, and marshes in the delta. The different levels of connectivity with the main channel create a mosaic of physical habitat conditions with diverse thermal regimes. In an effort to document these conditions, Hobo Pendant MX2201 temperature loggers (Onset Computer Corporation, Massachusetts, USA) were deployed at 14 locations along a 4.5 river-kilometer section previously identified as important spawning and rearing habitats for multiple fish species (Johnsen et al., 2015). Each logger was encased in an open 50 mm PVC pipe placed on the river bottom, with measurements taken every hour from May 17 to October 30, 2023. The data were checked for outliers against air temperatures (Norwegian Meteorological Institute, station Gausdal-Follebu-N13030) to ensure that only water temperatures were recorded. Loggers at sites M, B2, J, and H2 were exposed to air during periods of low discharge, and these data points were consequently removed. Prior to downloading the data, the loggers were kept at the same ambient temperature (at approximately 20°C) to control that the accuracy was consistent. Coincidentally, the spatial distribution of loggers allowed us to uniquely document changes to the thermal landscape during the flooding event following storm "Hans" (Figure 1b).

3 | RESULTS

Water temperature differences across the delta were prevalent throughout the entire summer season, with the exception of the flooding event in August. In mid to late May, water temperatures differed on the order of 10°C between the coldest (H1) and warmest site (M; Figure 1c). Differences peaked in late June to early July at just over 15°C between these sites. Although it should be noted that detailed heat budgets have not been developed in this study, observations suggest that both groundwater inputs and isolation from the main channel contributed to creating site-specific thermal regimes. Sites M and H1 were both isolated from the main channel but represented the extremes recorded in this study. The coldest site (H1) was influenced by groundwater inputs that superseded the effects of isolation from the main channel under normal conditions.

On August 7, the storm front hit eastern Norway, breaking seasonal precipitation records across a large geographical area (Granerød et al., 2023). The discharge in Gudbrandsdalslågen rose rapidly and the stage height in Lake Mjøsa followed subsequently (Figure 1b). The temperature in the warm sites decreased whereas the temperatures in the coolest sites increased. By August 10, the water temperatures at

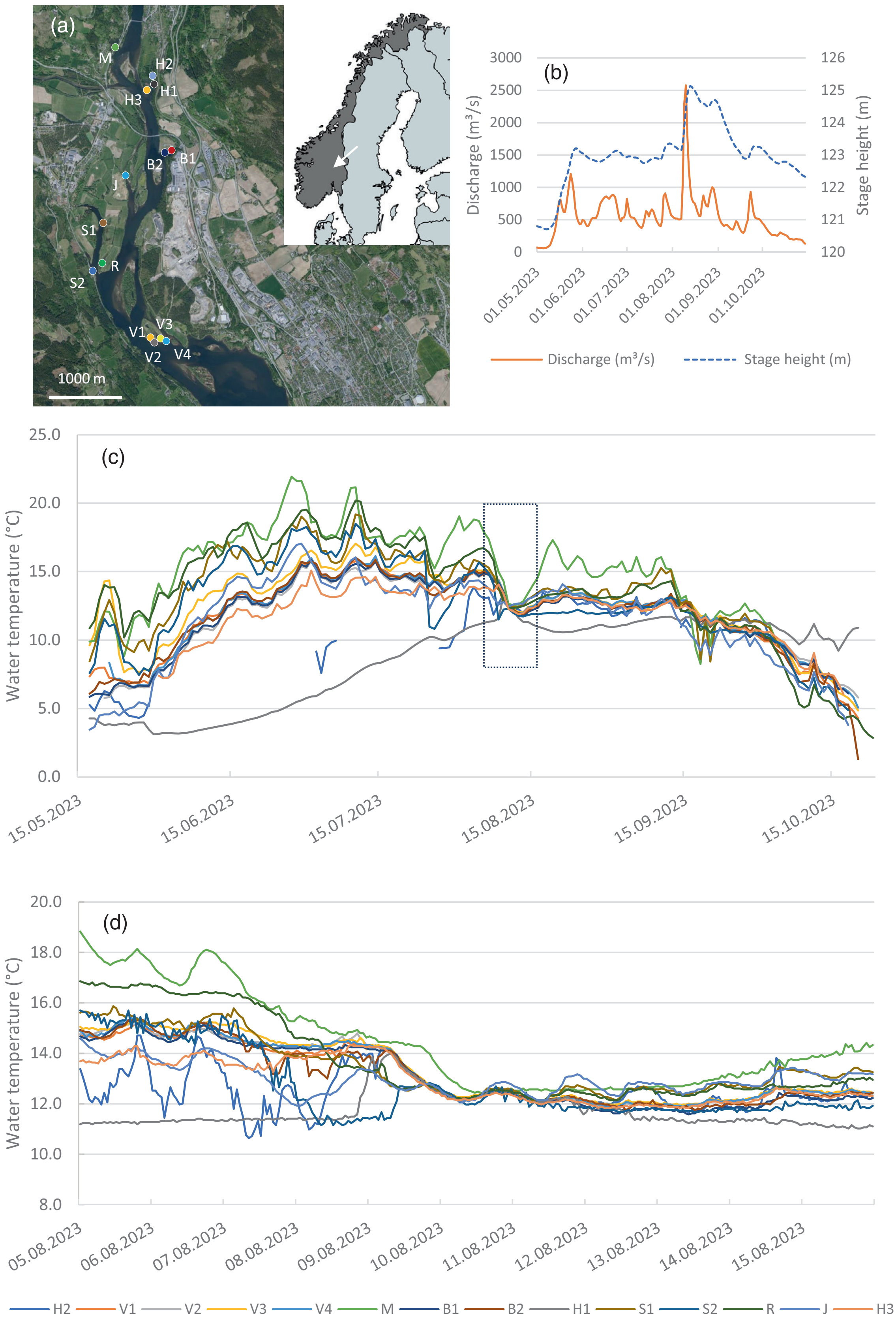

FIGURE 1 (a) Location of temperature loggers in the Gudbrandsdalslågen River delta, and the approximate location of the delta in Norway (inset); (b) Discharge ($m^3 s^{-1}$) in Gudbrandsdalslågen at Losna (NVE gauge 2.145.0) and stage height (m) in Lake Mjøsa (NVE gauge 2.101.0) from May 1, 2023 through October 31, 2023 (daily mean values); (c) Daily mean water temperatures (°C) at 14 sites from May 17, 2023 through October 23, 2023; and (d) close-up view of hourly water temperatures (°C) at the same 14 sites before, during, and after the flooding event from August 5, 2023 through August 15, 2023. Aerial imagery in panel (a) provided by the Norwegian Mapping Authority © norgeskart.no. Map data in panel (a) created with mapchart.net under CC BY-SA 4.0 DEED. [Color figure can be viewed at wileyonlinelibrary.com]

all 14 sites had converged at approximately 12.3°C (Figure 1d). The likely cause for the complete temperature homogenization throughout the delta was the sheer volume of runoff, overriding any locally modulating factors such as groundwater inputs and isolation from the main channel. The discharge in Gudbrandsdalslågen crested on August 10 whereas the stage height in Lake Mjøsa crested on August 13, rising 200 cm in 6 days, and causing a prolonged period with diminished temperature differences between sites. Temperature differences between the coldest and warmest sites remained below 2.0°C until August 14 and exceeded 5.0°C again on August 18.

4 | DISCUSSION

As documented in this study, thermal regimes differed substantially between sites early in the season as the combination of increasing discharge and rising stage height in Lake Mjøsa inundated the delta. During the long days at 61° north in May–July, elevated energy inputs through incident radiation and convection with air result in rapid warming of shallow and stagnant sections such as backwaters and sloughs but are mediated locally by groundwater inputs. Immediately following deployment of the temperature loggers at the onset of spring runoff, the differences between cooler and warmer sites exceeded 5°C and continued to diverge until early July when it hit its maximum at 15°C. These differences persisted through the regular rain-driven spates in summer but were entirely reduced during the flood. This suggests a relatively strong influence of locally modulating factors in creating local thermal regimes under normal hydrological conditions, and a complete dominance of runoff temperature during the flooding event. After storm "Hans," the differences in local temperatures returned but fluctuated around a lower mean. The discharge in Gudbrandsdalslågen remained high through the month of August, presumably due to saturated soils and above-normal precipitation across eastern Norway (Grinde et al., 2023). Furthermore, air temperatures typically drop with the rapidly waning day lengths in late August. It was therefore expected that water temperatures would decrease overall at this point in the summer season.

Abiotic conditions such as temperature are likely disproportionately important at the edges of species distributions, and the way in which they manifest across the streamscape can influence population vital rates and species persistence (Guo et al., 2005). For example, at the southern extent of species distribution ranges it is likely that localized coldwater patches will be increasingly important for the local persistence of coldwater-obligate species during the warmest parts of the year (Mejia et al., 2023). Thermal conditions at the northern extent of species distribution ranges are perhaps less well studied at small spatial extents but do explain range-wide limits for warmwater-adapted species (Oberdorff et al., 1997, 2011). At the leading edge of species distribution ranges, an increased frequency of disruptive events that homogenize temperatures could have negative ramifications for the recruitment of spring spawning species that rely on relatively warmer microhabitats. To both ends, assessing the temporal component of thermal landscapes in the face of extreme events can lend further insights into partitioning the factors that are responsible for creating these patterns, and in turn, understanding the suitability for the organisms that depend on them. Finally, although temperature was the focus of this study, it is necessary to also consider concurrent changes to other abiotic factors as we assess the impacts of the flooding event on aquatic biota and acknowledge the many mechanisms through which these conditions manifest on stream ecosystems.

ACKNOWLEDGMENTS

This study was funded by the Norwegian Research Council (grant # 160022/F40) and the Norwegian Institute for Nature Research (grant no. SATS-20-39). Discussions with colleagues helped frame the study design, and comments by one anonymous reviewer improved the manuscript. Discharge and stage height data were provided by the Norwegian Energy Directorate (NVE; sildre.nve.no) and air temperature data were provided by the Norwegian Meteorological Institute (seklima.met.no). Finally, I thank C. F. Brude and G. Eggebø for finding the logger at site *R* after freeze-up in November.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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How to cite this article: Myrvold, K. M. (2024). A complete homogenization of water temperatures during widespread flooding. *River Research and Applications*, 1–5. https://doi.org/10.1002/rra.4324