



Towards setting environmental water temperature guidelines: A South African example



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ABSTRACT

Water temperature is a primary factor affecting the number and kinds of species in a stream. A key step towards including water temperatures in environmental flow assessments is to develop metrics which describe natural variability in a river's thermal regime. This is best achieved using time series analyses, where metrics are defined based either on time series disaggregation, or shapes of regimes defined using agglomerative techniques. The aim of this paper was to refine approaches in setting environmental water temperature guidelines for inclusion in defining environmental flows assessments. Annual water temperature series from 82 sites sampled across 48 rivers (mainstems and tributaries) in ten catchments in the southern Cape region of South Africa were described using 39 metrics based on the magnitude, frequency, duration and timing of thermal events. Sites were classified into thermal groups using their similarity in multivariate temperature regime and variation amongst groups along important temperature gradients examined. Deviation from a natural range of variability using a thermal confidence envelope is a suitable approach for broad evaluation of thermal guidelines. The approach presented can be applied at multiple levels of complexity to assess which elements of a thermal time series fall outside of reference conditions. Further steps in this approach are to link thermal patterns to biotic metrics, and gain a clearer understanding of interactions between flows, temperatures and biota, particularly below impoundments. Research on improving approaches in defining thermal regions is recommended.

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1. Introduction

1.1. Water temperatures and freshwater ecology

Water temperature is a key factor affecting the number and kinds of species in a stream (Vannote and Sweeney, 1980), and the importance of water temperatures to aquatic biota has been well documented (for example Elliott, 1994; Eaton and Scheller, 1996; Claska and Gilbert, 1998; Sullivan et al., 2000). Annual thermal variation allows closely related species to emerge at different times of the year, thus avoiding competitive exclusion. Daily temperature ranges influence the potential number of species which can coexist at a site within the same season, while the degree of predictability in water temperature provides an indication of the degree of

structure and functional predictability of invertebrate communities (Vannote and Sweeney, 1980).

While the condition of ecosystems is deteriorating globally, freshwater ecosystems are the worst off (Millennium Ecosystem Assessment, 2005), due in part to water abstraction and flow regulation, which both impact on water temperature regimes. Changing the thermal regime of a river significantly alters a component of the environment to which river organisms are adapted (Ward, 1985). Increased water temperatures have been associated with changes in aquatic macroinvertebrate community structure and functional feeding groups, general shifts along the river continuum, and reduced resilience of community states (Bogan and Lytle, 2007; Daufresne et al., 2007). Additionally, generalist and warm-adapted species have been observed and predicted to expand their current and future ranges, while cold-adapted species will experience reduced ranges (Chessman, 2009; Domisch et al., 2011; Rivers-Moore et al., 2012a). Anticipated alterations to the natural thermal regimes of many rivers due to, *inter*

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alia, impoundments, water abstractions, land use and climate change, together with better logger technology, and new data analysis and modelling techniques, has led to recent renewed interest in the thermal behaviour of rivers (Johnson, 2003; Webb et al., 2008).

1.2. Water temperatures and environmental flows

A central goal in water resources management should be to establish environmental flows and water quality necessary for maintaining functional river ecosystem processes. This implies a need for managing water and land such that hydrologic regimes are not altered beyond agreed-upon sustainability boundaries i.e. an allowable depletion or augmentation of baseline condition and variability (Richter, 2010). Significant departures from these regimes results in a system change, and the Great Fish River in South Africa, following on from an inter-basin transfer scheme where flows changed from non-perennial to perennial, is cited as a classic example of a permanently altered system (O'Keeffe and de Moor, 1988).

In South Africa the concept of environmental flows began to be recognised in the 1980s, and this later became legislatively entrenched, where water needs for maintenance of river ecology were recognised (King et al., 2003). South Africa's Water Act is regarded as one of the most advanced pieces of water legislation internationally because of its framework for integrated management of quantity and quality of water. The South African National Water Act provides legal status to the water (quantity and quality) required to maintain ecological functioning of river systems, through the declaration of the "ecological Reserve" (Republic of South Africa, 1998) for all or part of a water resource. Prescribed flows were originally static, but science has advanced to recognise that variation, and how water is shared over the year, are necessary components for ecosystem health. While numerous river systems across South Africa have prescribed flow guidelines determined at various levels of detail for water quantity, water temperatures are currently not factored into environmental flow assessments. For the successful implementation of environmental flow management, both variability in discharge and temperature should be considered (Jackson et al., 2007; Olden and Naiman, 2010). In practice, the scientific understanding of these relationships and data to support hypotheses are limited (Nilsson and Renöfält, 2008). Even when rivers are classified as having excellent habitat structure based on their flow and geomorphology signatures, thermal habitat may be unsuitable (Harris and Silveira, 1999). Although a river's thermal regime is a key component of aquatic ecosystems (Caissie, 2006), this aspect of often neglected in environmental flow impact assessments.

1.3. Approaches to setting environmental water temperature guidelines

While streamflow is perceived as a 'master variable' shaping many fundamental ecological characteristics of riverine ecosystems (Poff and Zimmerman, 2010), temperature metrics are as important as discharge metrics in explaining differences in invertebrate community structure (Jackson et al., 2007). Ecological metrics typically mirror changes in flow and temperature metrics (Jackson et al., 2007; Poff and Zimmerman, 2010), although interpreting this will depend on the spatial and temporal scale such relationships are explored at (Poff, 1997) and confounded by the influence of other environmental factors (Poff and Zimmerman, 2010).

Flow and water temperature metrics are derived from time series, where approaches to describing time series generally attempt to measure variability by either agglomerating or

disaggregating time series data. Agglomerative approaches make use of techniques such as duration curves, while disaggregation approaches make use of indices that focus on state and threshold values using descriptive statistics, and attempt to understand the links between timing, duration and magnitudes of different system states.

Similar to describing a flow regime using a suite of metrics (Richter et al., 1996, 1997; Richter and Thomas, 2007), a stream's thermal regime can be decomposed into metrics describing the magnitude, timing, duration and frequency of (extreme) thermal events (Olden and Naiman, 2010). This approach is enhanced by incorporating the concept of the "natural range of variation", and setting associated exceedance thresholds (Richter et al., 1997; Nelitz et al., 2007). Suitable thresholds need to be assigned to metrics, to give some measure of when conditions are not being met. Thresholds can be either biological (cues) or statistical (e.g. 10th/90th percentiles, as applied in South Africa; DWAF, 2008). The physical tolerances of freshwater species to temperatures allow for setting thermal thresholds against which temperature metrics can be compared, with absolute and cumulative temperatures both being important (Olden and Naiman, 2010). For sub-lethal thresholds, the magnitude and duration of exposure to elevated temperatures is critical. A common index used is a seven-day (7-D) moving average of mean daily water temperatures (Sullivan et al., 2000; Nelitz et al., 2007; Null et al., 2010), even though the optimal moving average length is probably dataset-specific. A 7-D moving average of daily maximum water temperatures has been related to fish distributions (Rivers-Moore et al., 2005) and blackfly outbreak probabilities (Rivers-Moore et al., 2008a). Typically, such magnitudes and durations are derived from hourly time series data which are summarised into daily statistics (mean, minimum and maximum) (Nelitz et al., 2007).

Contextually, these stages should be placed within a larger framework for assessing environmental flow needs, where measures of deviation are characterised as statistical departures of ecologically-relevant components of flows and water temperatures (Poff et al., 2010). Here, hypotheses are developed to describe expected ecological responses to flow or temperature alterations, based on abiotic alteration—biological response relationships. Since flow and thermal regimes vary geographically in response to climate and catchment characteristics (geology, stream order, topography, land cover) (Poff and Zimmerman, 2010), it is useful to classify reference sites into thermal groups based on their metrics. These groups may be spatially represented using a suitable geographic information system (GIS), thereby enabling comparison of a modified site to be made with a reference group (Jackson et al., 2007; Kennard et al., 2010; Olden and Naiman, 2010; Poff et al., 2010). This is typically achieved using a mix of geographic, topographic and climatic variables that can be spatially represented as group discriminators (see, for example, Kennard et al., 2010; Rivers-Moore et al., 2012b). Such a GIS-based approach facilitates postulation and testing of hypotheses on flow/temperature alteration—ecological response relationships (Poff et al., 2010).

Current approaches do not consider return intervals of target water temperatures based on biological thresholds, and daily temperatures which describe seasonal changes and natural variations. Such approaches are typically not explicitly applied within a statistical and/or spatial framework where study sites can be compared with reference sites which come from the same thermal family. The aim of this paper was to refine approaches in setting environmental water temperature guidelines which can ultimately be applied within a spatial framework. We propose an approach based on the 7-D moving average of mean, maximum and minimum daily temperatures, and exceedances of biological thresholds.

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