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Using spatially explicit indicators to investigate watershed characteristics and stream temperature relationships

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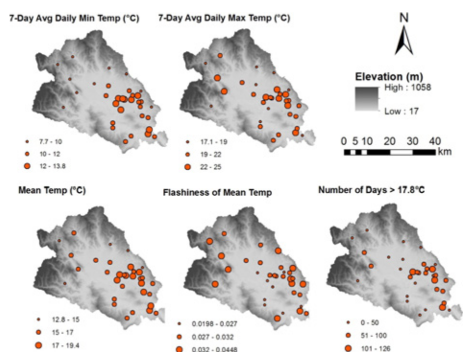
HIGHLIGHTS

- We created novel inverse distance and flow accumulation weighted landscape metrics.
- We studied the relationship between stream thermal properties and landscape metrics.
- Using distance and flow accumulation weighted metrics improved model performance.
- Flow accumulation weighted metrics best explained the variation in temperature.

GRAPHICAL ABSTRACT



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ABSTRACT

We generate a series of novel indicators of spatially explicit watershed permeability and runoff characteristics to examine the relationship between land cover and water temperature parameters in a rapidly urbanizing watershed. Our framework provides a readily adaptable method to examine the thermal sensitivity of streams based upon the underlying geomorphological and surface characteristics of drainage basins. Using four model groups each using a different landscape characteristic weighting scheme (Model Group 1: areal averages; Model Group 2: inverse distance by total flow length; Model Group 3: overland distance to stream network and distance squared; Model Group 4: proportional flow accumulation), we examined the predictive capacity of 19 variables, including combinations of simplified land cover, elevation, slope, and flow accumulation, on five stream thermal properties: seven day moving average of daily minimum and maximum, seasonal mean temperature, a novel metric of thermal 'flashiness', and total days with maximum temperature exceeding 17.8 °C. We find that the use of spatially explicit landscape indicators combining watershed processes improves the performance of regressions for predicting a number of ecologically relevant stream temperature variables. Improved indicators of watershed condition lend themselves for rapid investigation of the relationship between stream thermal conditions and landscape characteristics in watersheds modified by human land uses, ultimately providing a more hydrologically meaningful indicator for the impacts of landscape change.

1. Introduction

Stream ecosystems around the world face increasing threats from climate change and land use change (DÖll and Zhang, 2010; Penaluna

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et al., 2015; Santos et al., 2015). This tends to be amplified in areas affected by land use conflicts (Valle Junior et al., 2015). The thermal regimes of streams fundamentally influence their suitability as habitat for stream biota both directly and indirectly by altering in stream biogeochemical processes, as well as determining the suitability of stream for a wide range of human uses. Summer stream temperature is particularly critical for cold water salmonid species in temperate climates. Salmon abundance has been reduced within much of their historical ranges across the U.S., where considerable resources are invested in restoring aquatic habitats to support wild populations (Yeakley et al., 2014). Yet, streams in the region remain vulnerable to climate and land use changes, especially by reductions in riparian forest cover, agricultural intensification, urban development and increased thermal loading from industry and wastewater treatment (Hrachowitz et al., 2010; Isaak et al., 2012; Chang and Psaris, 2013; Selbig, 2015; Hannah and Garner, 2015).

In order to disentangle these impacts so that we may plan mitigation actions effectively, we require a better understanding of the landscape scale factors affecting seasonal aggregate stream properties as well as indicators of stream temperature variability. Different modes of forest harvesting, riparian vegetation removal (Mitchell, 1999) or shading (Johnson, 2004), built development (Nelson and Palmer, 2007; Kaushal et al., 2010), and agricultural land management (Simmons et al., 2014) all have the potential to influence stream temperature by increasing long wave radiation into the stream and by reducing or increasing air flows over the stream surface. Land uses also modify surface routing and groundwater recharge by altering soil permeability (Webb et al., 2008). All of these impacts of land uses on stream properties are scale dependent (Allan and Johnson, 1997; Allan, 2004; Vondracek et al., 2005), and attempting to model their impacts on stream temperatures at the watershed scale has taken many forms (Gallice et al., 2015; Sun et al., 2015; Daraio and Bales, 2014; Vatland et al., 2015).

Part of such an endeavor requires the creation and landscape scale indicators (Hill et al., 2016), which represent key physical processes (Wente, 2000; Peterson et al., 2011). Peterson et al.'s (2011) hydrologically active inverse distance weighted (HA-IDW) metrics account for the spatial distribution of land uses with variable flow accumulation relative to either the stream network itself or a defined sampling point. These approaches weight watershed properties based on their proximity to the entirety of the stream network, simultaneously representing important buffering processes (Sweeney and Newbold, 2014) and catchment scale properties (Sawicz et al., 2014).

Yet, we can go farther in characterizing physical processes of water movement in the landscape. In particular, the HA-IDW metrics (Peterson et al., 2011) assume that all flow is above ground flow and do not provide a means for evaluating the relative influence of parcels with different soil permeability and slope. Existing methods, such as the runoff curve number method (Cronshey, 1986), a 'mature' and robust method for estimating relative permeability of soil hydrologic types under different land uses (Ponce and Hawkins, 1996), can be adapted to be more spatially explicit watershed runoff characteristics that provide a relative indicator of per-cell permeability. Combining this approach with metrics characterizing the spatial distribution of slopes and flow accumulation, we should be able to provide spatially explicit classification of the basin scale runoff characteristics.

With these considerations in mind, we created a series of novel watershed scale metrics that take into account the spatial distribution and flow accumulation interaction of key watershed characteristics relative to both the stream network and sampling points. We test the utility of these metrics in simplifying complex watershed scale properties for examining summertime stream thermal regimes. Our hypotheses are that (1) models that include distance-weighted watershed parameters that take into account some watershed physical processes can better predict thermal properties of streams than basin average watershed parameters, but (2) the degree of model predictability depends on specific stream temperature indicator used in analysis.

2. The Tualatin Basin study area

The Tualatin River Basin (TRB), west of Portland OR, USA, covers 1844 km^2 of herbaceous (17%), forested (31%), agricultural (27%) and rapidly growing urban areas (~22%) (see Fig. 1a). The Tualatin River originates in the Oregonian Coast range, characterized by high winter rainfall with a notable prolonged dry season (Chang, 2007), and summer river flows are augmented by water release from Hagg Lake dam and inter-basin water transfer from Barney reservoir from the western slope of the Oregon Coast range. Although most of the basin lies in extensive lowland flat plains, steep basin edges create an interesting elevation gradient and precipitation rates tend follow this elevation gradient (Fig.1b − DEM). The lower section of the Tualatin has been subject to severe stream temperature problems (Chang and Lawler, 2011). Climate change and ongoing urban development are likely to exacerbate existing water quality problems in the basin (Praskievicz and Chang, 2009, 2011), although some best management practices and the extensive restoration of riparian vegetation may offset those impacts (Hoyer and Chang, 2014; Psaris and Chang, 2014). Thus, the basin is the site of an ambitious and experimental program of complying with Thermal TMDLs under Clean Water Act regulations through extensive riparian tree planning projects (Cochran and Logue, 2011), which contribute to other natural area conservation measures in the region (EPA, 2007). Historically, the Tualatin basin has also experienced extensive wetlands loss due to drainage, infilling and reductions in beaver (*Castor canadensis*), which has prompted interest in re-establishing wetland areas to improve groundwater infiltration and potentially improve a number of water quality issues (Taft and Haig, 2003).

3. Data and methods

3.1. Stream temperature indices

We obtained continuous hourly temperature data from Clean Water Services (CWS) in the Tualatin Basin from all available sites ($n = 33$) in the year 2011 (CWS, 2015). The year 2011 was chosen because land cover data for the same year were available. Examining hydrographs and temperature distributions for the basin, we selected a period of relatively stable flow bounding a four-month summer period from June 1st to September 30th, 2011. We also used 29 sites that have continuous stream temperature data in summer 2010 for model validation. Examination of the hydrograph for this period found it to be typical of summertime flow conditions in the Tualatin basin, with no anomalous high flow events. Preliminary data treatment examined the normality of hourly temperature data using Shapiro-Wilkes, as well as examining statistically significant differences between all sites using Mann Whitney tests. Given that significant differences existed between sites, and their seasonal hourly temperature values were normally distributed, we calculated five dependent variables. First, we calculated average daily mean temperature for representing average stream conditions for each station. Second and third, we computed the seven day daily moving average for minimum and maximum temperatures (7DADMin or 7DADMax) as reliable indicators of buffered minima and maxima of stream temperature. A fourth metric, the total number of days with 7DADMax exceeding the regulatory threshold of 17.8 °C, was examined as Salmonids prefer temperature ranges of 12.8 (incubation) up to 17.8 (rearing) °C, and extended periods of exposure to above 17.8 °C are known to cause stress and increase fish mortality (OR DEQ, 2001). Finally, we calculated a novel metric of inter-daily thermal variability, a modification of the Richard's Baker flashiness equation (Baker et al., 2004) with the following form:

$$\text{Thermal Flashiness, for all } i = \text{SUM}(T_i - T_{i-1}) / \text{SUM}(T_i) \quad (1)$$

where T_i = daily mean temperature for day i and T_{i-1} = daily mean temperature at day $i - 1$, a metric aggregating the inter-daily range of mean