Impacts of climate variability and change on water temperature in an urbanizing Oregon basin, USA

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Abstract Climate variability and change can impose significant stresses on water quality. Water temperature is one important measure of stream health, and is directly affected by two expected ramifications of climate change: rising air temperature and reduced summer streamflow. We investigated the effects of hydroclimatic variability and potential warming on water temperature in the mainstem of the Tualatin River in Oregon. Analysis of US Geological Survey data for the period 1991–2009 shows that the temporal variations of water temperature can be best explained by lagged air temperature and streamflow amount (R^2 = 0.80). Simulations of synthetic ambient warming (1.5°C, 3°C) and streamflow decline (10%, 20%) scenarios using the water quality model CE-QUAL-W2 showed that: (1) summer water temperature increases are between 45 and 60% of ambient temperature increases, and (2) streamflow decline has a noticeable, but minor impact on water temperature. The number of days on which the 7-day running average of water temperature exceeded 20°C increased substantially during summer months. The spatial extent of reaches that violate the threshold value of temperature also expanded under the combined scenarios. When riparian areas are completely vegetated, water temperatures fall below the threshold level on the majority of summer days. Results of this study would be useful for establishing adaptation strategies in water temperature management under climate change scenarios.

Key words climate change; water temperature; flow; urban basin; Tualatin River, Oregon, USA

INTRODUCTION

Water temperature has long been recognized as a critical aspect of stream health; it directly affects the amount of dissolved oxygen in water, which is critical for fish survival. Water temperature also indirectly affects the overall health of streams through its influence on in-stream biogeochemical cycles. In the Pacific Northwest (PNW) of the USA, summer water temperature is critical for the survival of cold-water species like salmon. Studies have shown that ranges for cold-water fish would be displaced northward with a loss of habitat because cold-water species cannot adapt quickly to abrupt environmental changes (Mohseni *et al.*, 2003).

Changing climate could affect stream temperature through several mechanisms. First, air temperature and water temperature are highly correlated (Webb, 1996). It is well-known that rising air temperature will induce rises in water temperature, although the relation between air temperature and water temperature is not linear. Declining snowpacks and decreased summer precipitation could reduce spring and summer streamflow (Chang & Jung, 2010), which thus could increase summer stream temperatures. Low streamflows coincide with maximum summer air temperatures, and with a resulting rise in stream residence time, temperatures could increase even more than with ambient temperature increases alone. The degree of temperature change will depend on how much streamflow will decrease in the future and the degree to which stream temperature depends on discharge. Stream discharge could further decline as elevated summer air temperature accelerates the rate of evapotranspiration, which will have harmful effects on freshwater habit of Pacific salmon (Mantua *et al.*, 2010).

Land use may also affect stream temperature (Johnson & Jones, 2000; Krause *et al.*, 2004). A reduction of riparian buffers, whether from urban, agricultural or forest land-use practices, and the shade they provide leads to increased levels of solar radiation and increased stream temperatures. Urbanized landscapes with high levels of impervious surfaces can absorb more heat energy than rural landscapes, which also increases surface air temperatures. This effect may be more pronounced during the spring and early summer months, with runoff flowing over the hot surfaces into streams. These overland flows can cause short-term spikes in water temperature (Nelson *et al.*, 2007).

STUDY AREA

The Tualatin River basin, which is located in the southwestern part of the Portland metropolitan area, Oregon, USA, serves as our study site. The 134 km river begins in the eastern side of the Northern Oregon Coast Range (618 m a.s.l.) and flows to the Willamette River in West Linn (18 m a.s.l.). As the home of approximately a half million people, the basin has been used for intensive agriculture (35% agricultural land) in the flat valley area and urban development (15% urbanized land) in the eastern (and downstream) side. Due to a slow movement of water and lack of riparian vegetation in several sections of the river, some sections do not meet the water quality standard for temperature. While some improvements in water quality have been made as a result of riparian restoration and implementation of best management practices (Boeder & Chang, 2008), with expected climate change and ongoing urban development, water quality conditions in the basin may not improve further or may even degrade in the future. Previous studies show that summer flow is projected to decline (Franczyk & Chang, 2009) and that the combined effects of climate change and sprawling urban development further exacerbate existing water pollution problems (Praskievicz & Chang, 2011).

DATA AND METHODS

We used both statistical analysis and modelling to investigate the effects of air temperature and streamflow on water temperature. Statistical analysis is based on empirical daily precipitation, streamflow and water temperature collected for the period between 1991 and 2009. To identify trends in water temperature, we used a nonparametric Kendall's test. Correlation is used to investigate the strength and direction of the association between monthly air temperature and water temperature. Multiple regression is used to identify factors affecting water temperature.

The modelling program used in this study was CE-QUAL-W2 version 3.6, a 2-D hydrodynamic and water quality model used in studying river systems, lakes, estuaries and reservoirs (Berger & Wells, 2008; Risley *et al.*, 2010). The model is capable of simulating a variety of water quality parameters, including water temperature (Cole & Wells, 2008). A Tualatin River model including river mile (RM) 38.4 to RM 3.4 was originally constructed by the US Geological Survey (USGS) using version 2.0 (Rounds *et al.*, 1999). It was subsequently updated by the USGS to version 3.12, and an upstream model for RM 62.4 to RM 38.4 was added and run in series with the downstream section. This two-part model included historical streamflow and temperature data, as well as weather conditions, including hourly values for air temperature, precipitation, wind speed and direction, dew point, and solar radiation over the period 2000–2003. A CE-QUAL-W2 model grid 155 segments long and 16 layers deep was used for the lower section. The upper section had 177 segments and 22 layers, which included short parts of three tributaries.

The model, the starting point for our work, was updated to version 3.6 and water quality modelling for constituents such as phosphorus and phytoplankton was turned off. It was checked against three monitoring stations along the mainstem of the Tualatin River (RM 38.4, RM 24.5, and RM 3.4) and found to agree with metered stream temperatures at each of these stations with a root mean square error of less than 1°C.

We developed synthetic climate change scenarios to represent possible paths of future climate change in the study area. The first scenario (5% summer flow reduction and 1.5°C temperature rise) represents the mid-21st century, while the second scenario (10% summer flow reduction and 3°C temperature rise) represents the late 21st century. These scenarios are approximates of ensemble means of projected climate change in the Tualatin River basin based on multiple climate change projections and two emission scenarios (Praskievicz & Chang, 2011). Riparian vegetation scenarios were created based on the degree of restoration from 10 tributaries of the Tualatin River, resulting in water temperature reductions of –2°C, –4°C, and –8°C from tributaries.

RESULTS

Influence of climate variability on water temperature

As shown in Fig. 1(a), water temperature generally increased throughout the summer near the mouth of the Tualatin River between 1991 and 2009. While there are fluctuations in water temperature following inter-annual climate variability during the study period, the Kendall's test shows that trends are significant for July and the summer season at the 0.1 significance level. Such changes in water temperature are strongly associated with changes in air temperature, which also show significant increases during the study period. The relation between monthly air temperature and water temperature is also very strong and positive, with the highest correlation (r = 0.81) in the month of June (see Fig. 1(b)).

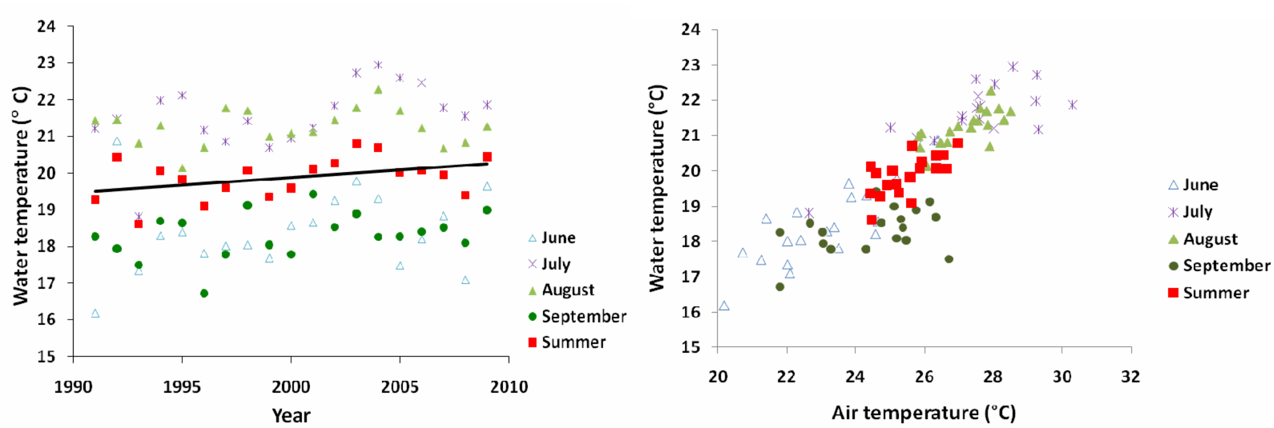

Fig. 1 Trends in water temperature and the relation between monthly air temperature and water temperature, Oswego Dam, 1991–2009.

Influence of air temperature and streamflow on water temperature

Since water bodies absorb and release heat more slowly than land, a statistical analysis was run with a number of different lag times to identify the optimal lag time that best matches variations in daily water temperature (Fig. 2(a)). We found that a lag time of 5 days is the best predictor of water temperature at our study site. As shown in the slope of the regression line, a 1.0°C rise in daily air temperature leads to an approx. 0.46°C increase in daily water temperature. The 5-day lag time explains approximately 62% variations in water temperature. As shown in Fig. 2(b), water temperature is negatively associated with streamflow; variations in summer streamflow explain approximately 32% of variations in water temperature. When both lagged air temperature and streamflow are taken into account, multiple regression models explain approximately 80% variations in water temperature.

Projected changes in water temperature under climate change scenarios

Figure 3 shows the spatial and temporal changes in water temperature between 15 May and 15 October in the lower section of the Tualatin under the baseline and two climate change scenarios. As shown in this figure, both the spatial and temporal extent of higher water temperature expanded under warming and flow reduction scenarios. In particular, under the highest warming and flow reduction scenario, an average water temperature above 24°C is observed in the downstream segments from early to mid August.

Figure 4 shows potential changes in the number of days that water temperature exceeds 20°C in the mainstem of the Tualatin River. Under the baseline scenario (left), only the downstream segments of the river experience water temperatures above 20°C. Under 5% flow reduction and

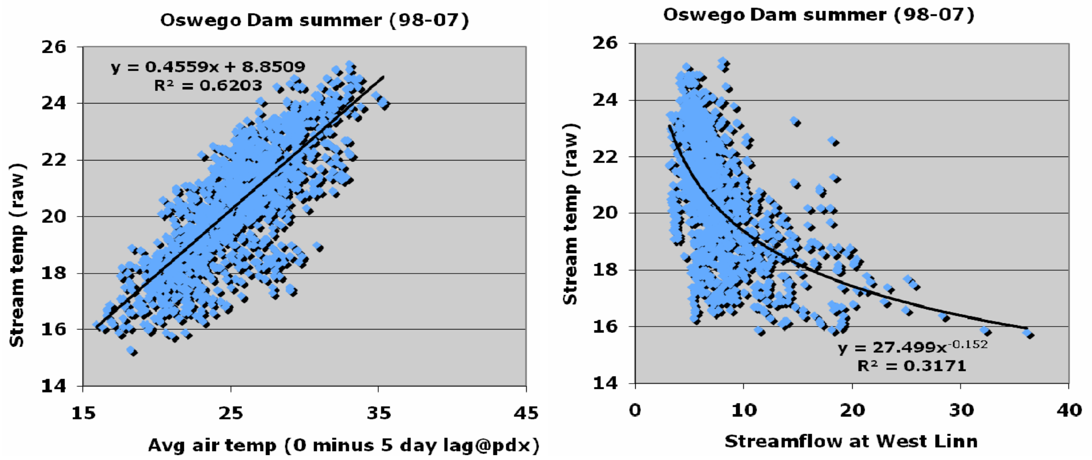

Fig. 2 Effects of air temperature and streamflow on water temperature, Oswego Dam, 1998–2007.

1.5°C air temperature rise scenarios (representing the 2040s), segments with water temperatures in excess of 20°C for more than 60 days expand to include some upstream areas. Under 10% flow reduction and 3°C air temperature rise scenarios (which represents the 2070s), they expand further into upstream areas.

Effects of tributary riparian shading on mainstem temperatures

Under tributary temperature reduction scenarios, which represent stream cooling due to re-vegetation in tributary riparian zones, only a few immediate segments are affected. Figure 5 shows the effects of riparian sharing in all 10 tributary streams on the water temperature of the mainstem Tualatin River. A 2°C drop in tributary temperature simply does not have a significant impact on mainstem temperature downstream. The impact is discernible, but clearly not enough to overcome the additional heat loading caused by climate change. While temperature is projected to decline under more intensive riparian shading (–4°C and –8°C scenarios), tributary cooling cannot overcome the effects of a 1.5°C ambient temperature rise with 5% reduction in flow. This ineffectiveness is likely to be associated with low tributary flow rates in the summer or the distance between the tributary inputs into the Tualatin mainstem. Tributary riparian vegetation scenarios have the most direct impact on middle segments of the drainage under the highest warming scenario.

DISCUSSION AND CONCLUSIONS

In summary, summer (June–September) water temperature in the mainstem of the Tualatin River increased between 1991 and 2009. This is likely caused by the summer air temperature rise and the mix of the cumulative loss of shading from riparian vegetation associated with urban and suburban development. It is unclear how much, if any, of the air temperature change occurred due to the heat island effect of urbanization. Existing studies have demonstrated that stream temperatures depend on riparian vegetation cover as well as air temperatures and discharge, which are inversely related. Our CE-QUAL-W2 modelling results show that future changes in stream temperature in response to climate change in the Tualatin River basin depend on the degree to which warming results in a reduction of late summer streamflow and how riparian vegetation is modified. Warming itself could influence riparian vegetation, and in turn affect summer streamflow in complex ways. Warmer temperatures may increase late-summer evapotranspiration from riparian vegetation, potentially reducing late summer flow, or may even change the types of riparian vegetation that thrive in this watershed. If streamflow in late summer is reduced, with no changes in riparian vegetation cover, stream temperatures may increase. However, increases in riparian

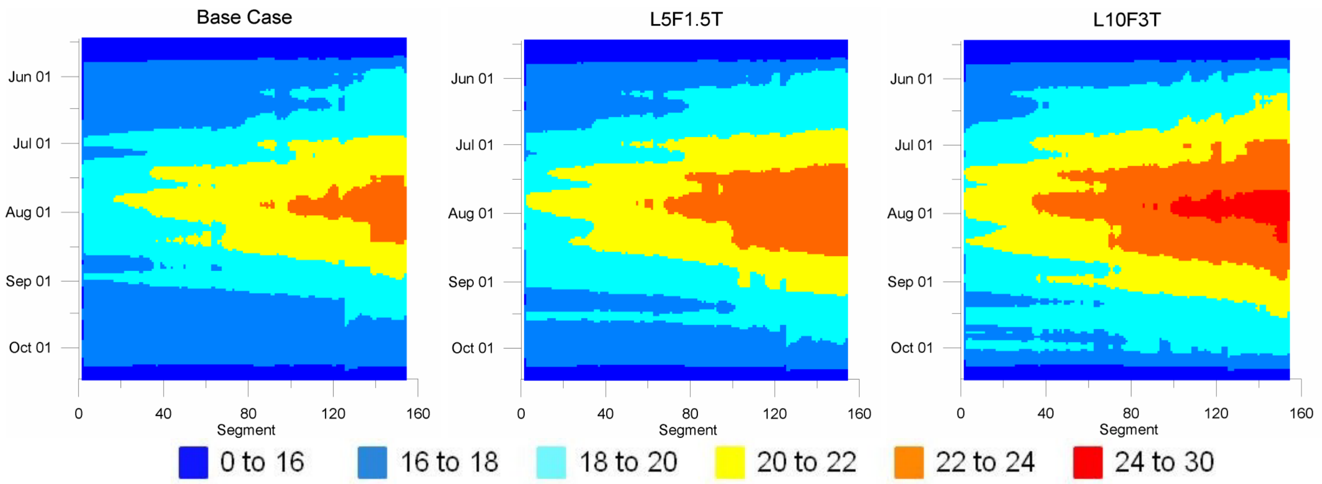

Fig. 3 Projected spatial and temporal changes in water temperature under different climate and flow change scenarios in the Lower Tualatin River (unit: °C).

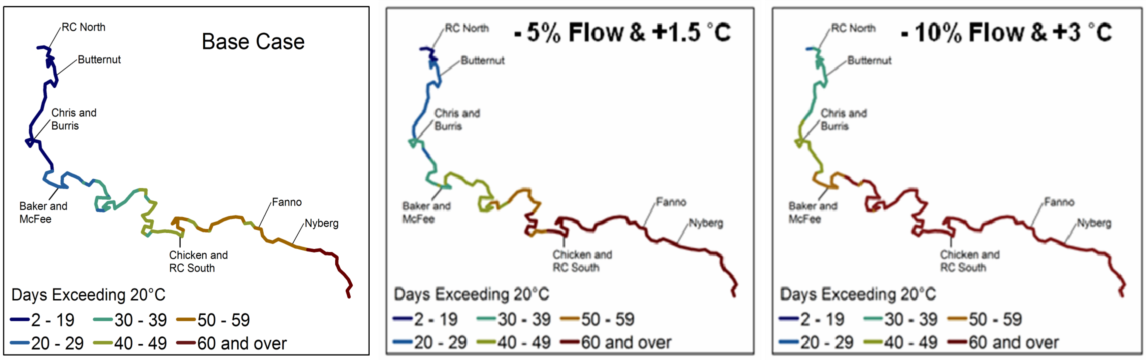

Fig. 4 Number of days that water temperature exceeds 20°C under different combinations of flow and temperature change scenarios in the Lower Tualatin River.

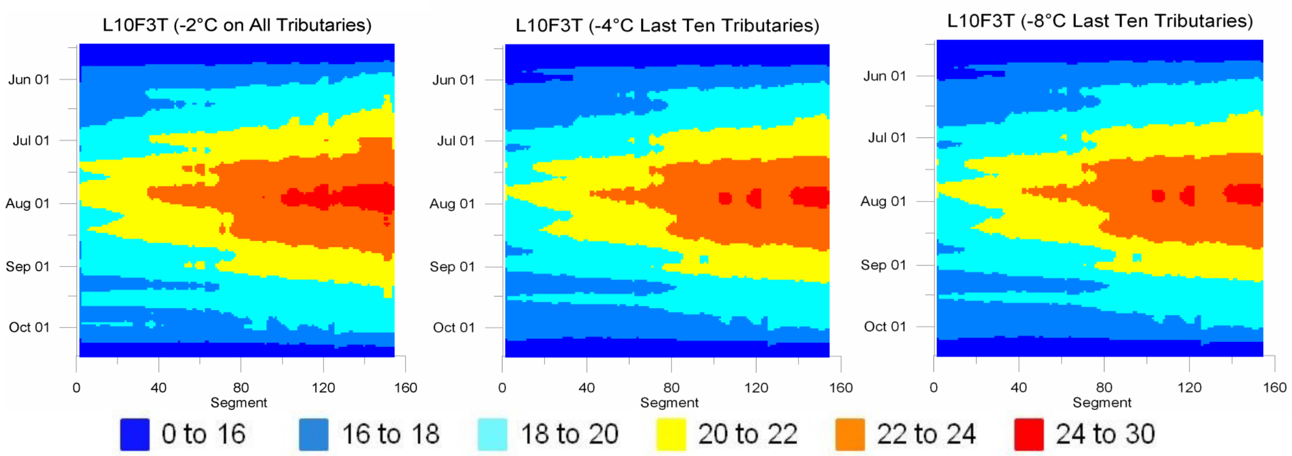

Fig. 5 Projected spatial and temporal changes in water temperature under the combination of tributary riparian shading and climate and flow change scenarios (unit: °C).

vegetation cover (from stream restoration) could partly counteract these effects. In addition, water temperature increases as it passes from typically forested headwaters to more agricultural or urban downstream areas, so stream temperatures in downstream areas may be more sensitive than headwaters to future climate-related warming. Maintaining ambient water temperature in a changing climatic condition requires adaptation management actions that include restoring riparian vegetation from tributaries and sustaining environmental flow requirements (Wilby *et al*., 2010).

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REFERENCES

Chang, H. & Jung, I. (2010) Spatial and temporal changes in runoff caused by climate change in a complex large river basin in Oregon. *J. Hydrol*. **388**(3-4), 186–207.

Cole, T. & Wells, S. (2008) CE-QUAL-W2: A two-dimensional, laterally averaged, hydrodynamic and water quality model, version 3.6. *Instruction Report no. EL-08-1*, Waterways Experiment Station, US Army Corps of Engineers, Vicksburg, Mississippi, USA.

Berger, C. J. & Wells, S. A. (2008) Modeling the effects of macrophytes on hydrodynamics. *J. Environ. Engng ASCE* **134**, 778–788.

Boeder, M. & Chang, H. (2008). Multi scale analysis of oxygen demand trend in an urbanizing Oregon watershed. *J. Environ. Manage* **87**(4), 567–581.

Franczyk, J. & Chang, H. (2009) The effects of climate change and urbanization on the runoff of the Rock Creek in the Portland metropolitan area, Oregon, USA. *Hydrol. Processes* **23**(6), 805–815.

Johnson, S. L. & Jones, J. A. (2000) Stream temperature responses to forest harvest and debris flows in Western Cascades, Oregon. *Canadian. J. Fisheries Aqua. Sci.* **57**, 30–39.

Krause, C. W., Lockard, B., Newcomb, T. J., Kibler, D., Lohani, V. & Orth, D. J. (2004). Predicting influences of urban development on thermal habitat in a warm water stream. *J. Am. Water Resour. Assoc.* **40**(6), 1645–1658.

Mantua, N., Tohver, I. & Hamlet A. (2010) Climate change impacts on streamflow extremes and summertime stream temperature and their possible consequences for freshwater salmon habitat in Washington State. *Climatic Change* **102**(1-2), 187–223.

Mohseni, O., Stefan, H. G. & Eaton, J. G. (2003) Global warming and potential changes in fish habitat in U.S. streams. *Climatic Change* **59**(3), 389–409.

Nelson, K. C. & Palmer, M. A. (2007). Stream temperature surges under urbanization and climate change: Data, models, and responses. *J. Am. Water Resour. Assoc.* **43**(2), 440–452.

Praskievicz, S. & Chang, H. (2011) Impacts of climate change and urban development on water resources in the Tualatin River basin, Oregon. *Annals Assoc. Am. Geogr.* **101**(2), 249–271.

Risley, J. C., Constantz, J., Essaid, H. & Rounds, S. (2010) Effects of upstream dams versus groundwater pumping on stream temperature under varying climate conditions. *Water Resour. Res.* **46**, W06517, doi:10.1029/2009WR008587.

Rounds, S. A., Wood, T. M. & Lynch, D. D. (1999) Modeling discharge, temperature, and water quality in the Tualatin River, Oregon. *US Geological Survey Water-Supply Paper 2465-B*, 121 p.

Webb, B. W. (1996). Trends in stream and river temperature. *Hydrol. Processes* **10**(2), 205–226.

Wilby, R. L., Orr, H., Watts, G., Battarbee, R. W. Berry, P. M., Chadd, R., Dugdale, S. J., Dunba, M. J., Elliott, J. A., Extence, C., Hannah, D. M., Holmes, N., Johnson, A. C., Knights, B., Milner, N. J., Ormerod, S. J., Solomon, D., Timlett, R., Whitehead P. J. & Wood, P. J. (2010) Evidence needed to manage freshwater ecosystems in a changing climate: Turning adaptation principles into practice. *Sci. Total Environ.* **408**(19), 4150–4164.