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Influence of seasonal and inter-annual hydro-meteorological variability on surface water fecal coliform concentration under varying land-use composition

*Jacques St Laurent**, *Asit Mazumder*

Water and Aquatic Sciences Research Program, Department of Biology, University of Victoria, PO Box 3020 Station CSC, Victoria, British Columbia, Canada V8W 3N5

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ABSTRACT

Quantifying the influence of hydro-meteorological variability on surface source water fecal contamination is critical to the maintenance of safe drinking water. Historically, this has not been possible due to the scarcity of data on fecal indicator bacteria (FIB). We examined the relationship between hydro-meteorological variability and the most commonly measured FIB, fecal coliform (FC), concentration for 43 surface water sites within the hydro-climatologically complex region of British Columbia. The strength of relationship was highly variable among sites, but tended to be stronger in catchments with nival (snowmelt-dominated) hydro-meteorological regimes and greater land-use impacts. We observed positive relationships between inter-annual FC concentration and hydro-meteorological variability for around 50% of the 19 sites examined. These sites are likely to experience increased fecal contamination due to the projected intensification of the hydrological cycle. Seasonal FC concentration variability appeared to be driven by snowmelt and rainfall-induced runoff for around 30% of the 43 sites examined. Earlier snowmelt in nival catchments may advance the timing of peak contamination, and the projected decrease in annual snow-to-precipitation ratio is likely to increase fecal contamination levels during summer, fall, and winter among these sites. Safeguarding drinking water quality in the face of such impacts will require increased monitoring of FIB and waterborne pathogens, especially during periods of high hydro-meteorological variability. This data can then be used to develop predictive models, inform source water protection measures, and improve drinking water treatment.

1. Introduction

Fecal contamination of drinking source water results in waterborne disease outbreaks and millions of cases of gastroenteritis throughout the world (Bartram and Cairncross, 2010). Examining the processes that drive variability in source water contamination is therefore critical to improving the safety of drinking water and maintaining public health. The identification and quantification of drivers of contamination allows us to target source water protection efforts and

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* *Corresponding author*. Tel.: +1 250 472 4789; fax: +1 250 472 4766.
E-mail addresses: jacques@uvic.ca (J. St Laurent), mazumder@uvic.ca (A. Mazumder).

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increases our capacity to anticipate variability in source water contamination, which can be used to improve the specificity of drinking water treatment processes (Charron et al., 2004; Delpla et al., 2009).

Climate factors are primary among drivers of source water contamination due to their influence on the transport of contaminants by precipitation-induced runoff. Runoff generated by rainfall and snowmelt (encapsulated by the term hydro-meteorological) is associated with increased levels and variability of fecal contamination in downstream surface water (Kistemann et al., 2002; Cha et al., 2010). However, the relationship between hydro-meteorological variability and fecal contamination levels tends to vary significantly within and among watersheds (Wilkes et al., 2009).

Investigating the strength, influence, and variability of this relationship among surface source water sites is increasingly important given the significant changes to temperature and precipitation patterns observed at local, regional, and global scales (Bates et al., 2008). British Columbia (BC) is projected to experience higher annual mean temperatures, accompanied by increased total precipitation and changes to the fraction of annual precipitation stored as snow (Schnorbus et al., 2011). The corresponding increase in runoff and change to snowmelt volume will likely alter fecal contamination levels and variability in surface source water.

Variability in FC concentration tends to be positively related to precipitation (Cha et al., 2010), therefore increases in total annual precipitation will likely elevate contamination levels, although this relationship has yet to be examined over an inter-annual period. Precipitation is increasing at a rate of around 7% per degree Celsius increase in temperature (Wentz et al., 2007), which will result in a 6–12% increase in mean annual precipitation across BC by 2050 (Schnorbus et al., 2011). The corresponding increase in runoff is likely to elevate the transport potential of fecal contaminants and resultant levels of fecal contamination in downstream surface source water.

Seasonal variability in FC concentration can be influenced by variability in surface runoff (Dorner et al., 2007), therefore current periods of peak fecal contamination may be altered by changes to existing hydro-meteorological regimes. Hydro-meteorological regime is determined by the timing, volume, and extent of snowpack accumulation and associated snowmelt, which vary in relation to cold-season temperatures (Marsh and Woo, 1981). Projected increases in cold-season temperatures are expected to transition nival-regimes towards hybrid-regimes, and hybrid-regimes towards pluvial-regimes (Dery et al., 2009); (descriptions of hydro-meteorological regimes are given in the supplementary material (SM)).

The impact of precipitation-induced runoff on surface water fecal contamination is influenced by land-use and management factors that alter watershed characteristics, such as ground permeability and the presence of riparian vegetation (Perdek et al., 2003; Tate et al., 2004). These factors alter the capacity of surface runoff to transport fecal contaminants into surface water and therefore likely contribute to the high variability observed among relationships between hydro-meteorological conditions and fecal contamination variability (Kay et al., 2008).

The distribution of fecal contaminant sources within a catchment may determine the relative influence of climate variability on source water fecal contamination levels among catchments. Point-source contamination tends to be directly discharged into receiving water, generating contamination variability that is often unrelated to runoff variability. Conversely, diffuse contamination requires transport by means of runoff into surface water (Kloot, 2006). Therefore, variability in surface water fecal contamination may be more strongly associated with runoff in catchments where contamination is associated with diffuse fecal sources.

Although previous studies have provided strong evidence for an association of higher fecal contamination with greater runoff, there is little evidence available to determine the influence of hydro-meteorological variability on seasonal and inter-annual fecal contamination levels (Wilkes et al., 2009; Dorner et al., 2007; Sigua et al., 2010). A better understanding of these interactions is critical for assessing the potential for changes in climate to influence surface source water contamination levels and the risk this contamination will present to public health (Patz et al., 2008).

In this study, we examined climate forcing of surface water fecal contamination across a range of hydro-meteorological regimes and land-use scenarios. We measured the extent to which seasonal fecal contamination variability was determined by snowmelt and rainfall variability, and examined how the strength of this relationship varied in relation to hydro-meteorological regime. We also quantified the relationship between inter-annual hydro-meteorological variability and FC concentration to see how fecal contamination levels responded to long-term changes in snowmelt and rainfall. Site characteristics associated with climate forcing of seasonal and inter-annual fecal contamination were identified in order to categorize those catchments most vulnerable to changes in climate altering surface water fecal contamination levels and variability.

2. Methods

2.1. *Study region*

The province of BC in the west of Canada was selected as a study region due to its complex hydro-climatology, largely resulting from its exposure to the Pacific Ocean in the west, successive mountain ranges throughout the interior, and the continental expanse to its east. Coastal BC has a temperate, mild and wet, oceanic climate due to the Kuroshio Current that transports warm tropical water into the northeast Pacific Ocean. Precipitation decreases towards the interior, due to the rain-shadow cast on the leeward side of successive mountain ranges, and temperature ranges increase in the absence of the ocean to moderate seasonal fluctuations in insolation (Shabbar et al., 1997). These conditions generate a range of hydro-meteorological regimes, which tend to be nival and hybrid in the interior and at higher elevations (>500 m) and pluvial near the coast and at lower elevations (<650 m).

Sample sites were generally located in the south of BC where population density is greatest, between 48.5^0 and 56.1^0 latitude N and 114.9^0 and 124.4^0 longitude E, and had an elevation range of 170 m–1700 m. A map of the study region and sample site locations, and sample site coordinates and