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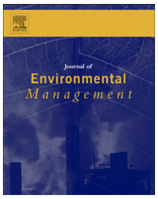

The effect of sampling strategies on assessment of water quality criteria attainment

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ABSTRACT

Sample locations for large river studies affect the representativeness of data, and thus can alter decisions made regarding river conditions and the need for interventions to improve water quality. The present study evaluated three water-quality sampling programs for Total Dissolved Solid (TDS) assessment in the Monongahela River from 2008 to 2012. The sampling plans cover the same 145 km of river but differ in frequency, sample location and type (e.g., river water sample vs drinking water plant intake sample). Differences resulting from temporal and spatial variability in sampling lead to different conclusions regarding water quality in the river (including regulatory listing decisions), especially when low flow leads to concentrations at or near the water quality criteria (500 mg/L TDS). Drinking water samples exceeded the criteria 82 out of 650 samples (12.6%), while river water samples exceeded the criteria 47 out of 464 samples (10.1%). Different water sample types could provide different pictures of water quality in the river and lead to different regulatory listing decisions.

1. Introduction

The Clean Water Act (CWA) was established in 1972 to restore and maintain the chemical, physical, and biological integrity of waters in the United States (US) (USEPA, 2002). Meeting the water quality expectations (called criteria) for rivers and streams is intended to protect water uses for humans as well as aquatic and terrestrial plants and animals (Liebetrau, 1979; Said et al., 2004). Increasing human activities in watersheds often adversely affect ambient surface water quality (Cooper, 1993; Hancock, 2002), which is compared with water quality criteria via sampling (Smith et al., 1997; Strobl and Robillard, 2008). Water bodies not meeting criteria are identified as “impaired” waters and listed following Section 303(d) of the CWA (PaDEP, 2009a). Total Maximum Daily Loads (TMDLs) and compliance plans are developed for listed waters to improve their quality (USEPA, 2012). Inaccurate assessment of water quality can cause loss of value for public use and unnecessary pollution control cost (when pollutants are overestimated), or alternatively, increased risk to human health and the aquatic environment (when pollutants are underestimated) (Nacht, 1983; Dixon and Chiswell, 1996; Smith et al., 2001; Madrid and Zayas, 2007). To ensure accurate assessment of water, significant attention has been paid to analytical method development (Madrid and Zayas, 2007). Similarly, many international studies have focused on developing surface water sampling strategies including selection of sampling locations, frequencies and methods (WFD, 2000; Heald et al., 2009). However, high variability in water quality conditions and heterogeneity in space and time make representative water sampling difficult (Keith, 1990; Shelton, 1994; Crain, 2002; WFD, 2009). Sampling plans for large rivers are often designed based on convenience, experience, expert intuition, and other subjective judgments, which may lead to bias (Dixon and Chiswell, 1996; Madrid and Zayas, 2007; Khalil and Ouarda, 2009). Spatial distribution of sampling sites, sampling frequency, and the number of sampling sites can affect the quality and applicability of the resulting data, and thus can influence the outcome of water quality assessment (Reinelt et al., 1992; McGeoch and Gaston, 2002; Weilhoefer and Pan, 2007). Applications of statistical methods and consideration of cost-effectiveness influence sampling plans as well (Dixon and Chiswell, 1996; Strobl et al., 2006; Strobl and Robillard, 2008; Khalil and Ouarda, 2009).

Currently, there are two dominant approaches in the US for *geographical sampling site selection* in streams and rivers of a large river basin (Magdalene et al., 2008): the targeted sampling

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approach of the US Geological Survey (USGS) National Water-Quality Assessment (NAWQA) (Gilliom et al., 1995; USGS, 2001), and the random sampling approach of EPA's Environmental Monitoring and Assessment Program (McDonald et al., 2002; Stevens and Olsen, 2004). These approaches select sampling sites to evaluate the overall water status of a river, which is ideal if the question of interest is related to in-stream water quality criteria that is protective of aquatic health or human recreational use. However, such sampling approaches may not be ideal for determination of water quality criteria associated with use as a drinking water source due to the significant heterogeneity in large rivers. The use of drinking water intake sampling locations is uncommon in large river assessment, and it is unknown if this sampling method will lead to different results than other sampling approaches. While use of these mixed data *may* not be appropriate for decision-making, it is common for agencies and scientists to acquire all available data and attempt to use them in an integrated manner (Beran and Piasecki, 2008; Maidment, 2008).

Temporal sampling plans are often highly variable in large river systems. Sampling at high frequency with long duration is generally not feasible, and such datasets will not be available for impaired waters in most TMDL studies (Richards, 2004). An extremely useful sampling method in the TMDL process is synoptic survey, which is generally done under low flow conditions with a large number of samples taken at the same time at multiple sites along the river (Richards, 2004). Such sampling may produce unbiased results for low flow conditions, but be a poor representation of average conditions (Richards, 2004).

In the present work, we consider three sampling projects with different goals and different sampling locations and frequency, undertaken in a single river over a three-year period. One project focused on drinking water source quality and thus sampled only at drinking water plant intakes. Another project focused on characterization of the river at well-mixed locations downstream of navigational control structures. The final project included sampling at both drinking water intakes and well-mixed river sites; however, samples were taken only in response to reports of elevated conductivity, resulting in sampling predominately during low flow conditions (similar to synoptic survey). These distinct sampling protocols provide key comparative data to determine the relative representativeness of different collection protocols to answer questions related to in-stream criteria for protection of potable water supplies.

2. Materials and methods

2.1. Field study location

The Monongahela River is 206 km (128 miles) in length; it flows north through West Virginia into Pennsylvania, where it meets the Allegheny River to form the Ohio River at Pittsburgh (Fig. S1). The Monongahela River is navigationally controlled to create a series of pools and maintain adequate water levels for barge traffic and for industrial and drinking water supply withdrawals (Wilson and VanBriesen, 2013a). There are several flow gages on the Monongahela River operated by USGS, but only two gages report daily discharge. Previous study indicates the gages are correlated (Wilson and VanBriesen, 2013a); the daily flow data at the Elizabeth gage (station number 03075070) are used in the present study (USGS, 2013). The Monongahela River serves as drinking water source for 17 drinking water treatment plants, supplying approximately 1 million people. The lower Monongahela River drains $1.92\ 10^4\ \text{km}^2$, and is fed by five major tributaries, with highly variable pollutant loads (Wilson, 2013). The significantly different tributary water quality and the navigationally-controlled flows give the river a high degree of spatial and temporal heterogeneity, which makes water quality assessment through representative sampling difficult. In 2008, the PaDEP observed TDS concentrations that exceeded the secondary drinking water quality standard (500 mg/L maximum monthly average) at all 17 drinking water intakes along the Monongahela River (Warren, 2010; Wozniak, 2011). In response to these reports, the PaDEP and several research teams in the region increased sampling within the River, leading to the data sets evaluated in this work.

2.2. Sampling sites and sample measurement

The sampling sites are located on the main stem of the lower Monongahela River (see Fig. S1), which are identified by river kilometer (KM); KM0 is in Pittsburgh where the Monongahela River meets the Allegheny River to form the Ohio River. Table 1 lists the number of sampling locations and the number of samples collected at these locations by each group. Although each group measured TDS, chloride and sulfate using the same laboratory methods (with the same detection limit), only TDS is evaluated in the present work. Chloride concentrations in the study area were always very low (below 50 mg/L), which is far below its 250 mg/L secondary drinking water standard. The evaluation of chloride concentrations was always in compliance and thus, not as interesting from a regulatory decision-making point of view. Sulfate levels were more variable and could be close to its secondary drinking water standard (250 mg/L) at certain times of year; however, sulfate is regulated in Pennsylvania only at drinking water intakes. TDS is regulated both with a secondary drinking water standard (500 mg/L) that applies in drinking water sources and as an in-stream standard related to aquatic life protection (500 mg/L) (PADEP, 2010). Thus, TDS is likely to be measured at drinking water intakes and river locations with the potential for these data to be used together to make decisions for either in stream aquatic life protection or drinking water protection.

Data Set 1 (DEP): The Pennsylvania Department of

Table 1
Sampling locations and the number of TDS Samples at each location.

	Sample type	Number of sampling sites	Total number of samples	Sampling years[b]			
				Year 1	Year 2	Year 3	Year 4
				Number of samples taken in each year (number of samples taken in summer[c])			
DEP[a]	River water	40	221	74 (0)	51 (39)	69 (9)	27 (16)
	Drinking water intake	14	217	112 (0)	14 (9)	52 (28)	39 (22)
WV	River water	4	243	9 (9)	75 (18)	75 (18)	84 (24)
CMU	Drinking water intake	6	433	0 (0)	200 (71)	157 (57)	76 (23)

[a] DEP stands for the Pennsylvania Department of Environmental Protection data; WV stands for the West Virginia Water Research Institute data; CMU stands for Carnegie Mellon University data.

[b] Sampling years are defined as follows: Year 1 is 09/01/2008 through 08/31/2009; Year 2 is 09/01/2009 through 08/31/2010; Year 3 is 09/01/2010 through 08/31/2011; Year 4 is 09/01/2011 through 08/31/2012.

[c] Summer in the region is defined by typical low flow conditions that occur from June–August.