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Temporal variability in water quality of agricultural tailwaters: Implications for water quality monitoring

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ABSTRACT

Accurate assessments of non-point source pollution and the associated evaluation of mitigation strategies depend on effective water quality monitoring programs. Intensive irrigation season water quality monitoring was conducted on three agricultural drains (6 h to daily sampling) along with analysis of decade long records from two larger agricultural drains (biweekly to monthly sampling) in the San Joaquin Valley, California. Analyses revealed significant temporal variability in concentrations of nutrients, salts, and turbidity over short time-scales ($<$1 day), as well as significant differences in monthly and annual mean concentrations. Statistical techniques were used to evaluate the sampling intensity required to meet rigorous confidence and accuracy criteria, as well as to evaluate the efficacy of different sampling strategies (e.g. grab samples versus composite samples). The number of samples required to determine mean constituent concentrations within 20% of the mean at a 95% confidence level ranged from 2 to 39 samples per month (SPM) for total phosphorus, 1–16 SPM for total nitrogen, 5–25 SPM for turbidity, and 1–3 SPM for electrical conductivity. Using a daily composite sample (4 subsamples per composite) instead of discrete samples was shown to maintain the same accuracy and confidence standards, while reducing the required sample number by up to 50%. This study emphasizes the value of a statistical approach for evaluating water quality monitoring strategies, and provides a framework through which cost–benefit analysis can be implemented in the development of monitoring plans.

1. Introduction

The 2002 National Water Quality Inventory of the Environmental Protection Agency (EPA) identified agricultural non-point source (NPS) pollution as the leading cause of water quality impairment to rivers and lakes in the U.S. (U.S. - EPA, 2002). On irrigated lands, much of the NPS pollution is delivered to surface waters from tailwaters originating from gravity flow (flood or furrow) irrigation methods. Currently about 94,000 km^2, 44% of the irrigated land area in the U.S., utilizes gravity flow irrigation (USDA-ASS, 2002). Due to its diffuse nature, agricultural return flows have remained largely unregulated. In 2003, California began the process of regulating agricultural water dischargers through adoption of the Irrigated Lands Conditional Waiver's Program (ILCWP). The ILCWP mandates that individual landowners or coalition groups develop monitoring programs to document that their contribution of NPS pollutants will not negatively impact surface waters. The current version of the ILCWP requires collection and analysis of one grab sample per month throughout the year (California Regional Water Quality Control Board, Central Valley Region, 2008). As regulation of agricultural NPS pollution becomes a more widespread reality, it is essential that regulators and growers have appropriate information for developing monitoring programs that: (i) document existing background conditions, (ii) identify exceedences of water quality constituents, (iii) verify the effectiveness of mitigation strategies, and (iv) are economically feasible to implement.

The aim of regulatory monitoring is to assess compliance with water quality objectives, usually concentrations or mass loading rates, for a given water body. However, most water quality monitoring programs have been designed on an arbitrary, rather than a statistically defensible basis (Strobl and Robillard, 2008). Proper evaluation of compliance is crucial, as growers may be unfairly punished for "false exceedances", and the efficacy of the program is compromised if exceedances go undetected. The frequency of sampling necessary to accurately characterize water quality is dependent on the statistical distribution of the monitoring data (e.g., seasonal peaks, distribution, variance, and degree of autocorrelation) (Valiela and Whitfield, 1989). In many cases, cost constraints severely limit sampling frequency, despite the fact that accuracy and precision are a direct function of sampling frequency (Moustafa and Havens, 2001). A rational criterion for selecting sampling frequencies for regulatory monitoring is to choose a large enough sample number, based on statistical

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parameters (e.g., variance), to achieve a reasonably small and uniform confidence interval about the mean value (Loftis and Ward, 1980a).

Water quality monitoring involves sampling a "population" that is changing over time. In irrigation tailwater systems, sample statistics (e.g., sample mean) computed from water quality data are affected by: (i) random changes induced by irrigation timing and amount, fertilizer application, contributions from specific fields, etc., (ii) seasonal changes resulting from crop rotation, fertilizer application, plant nutrient demands, etc., and (iii) serial correlation of data (Loftis and Ward, 1980b). Given the diversity of cropping systems, nutrient management, irrigation practices, soils, and watershed size, it is difficult to recommend a universally acceptable monitoring program that transcends all water quality constituents of concern (e.g., nutrients, sediments, salts, and pesticides). There is currently a paucity of data quantifying the variability of water quality contaminants in agricultural tailwaters. Thus, it is generally not possible to evaluate the effectiveness of monitoring programs.

A large portion of the cost of monitoring is related directly to the collection and processing of water samples, so it is important to devise a monitoring scheme that minimizes sample number while preserving accuracy. Methods such as time-composite samples can be used to capture variability without increasing sample number (Moustafa and Havens, 2001). Continuous monitoring for certain constituents, such as salt (specific conductance) and sediment (turbidity) is feasible using microprocessor controlled sensors. However, the technology to quantify many pollutants (e.g., pesticides, nutrients) at a high frequency is either not available or prohibitively expensive. However, in some cases it may be possible to determine an easily measured proxy that displays a strong correlation to more difficult to measure constituents (e.g., turbidity versus total phosphorus, specific conductivity versus nitrate).

The goal of this study was to provide a statistical basis to quantify the variability of selected water quality constituents in five agricultural watersheds in the San Joaquin Valley, California, for the purpose of optimizing monitoring protocols both in terms of cost and accuracy. The number of samples necessary to calculate seasonal mean concentrations within given confidence bounds was evaluated for various sampling strategies (composite versus grab sampling). This is the first study of its type for California irrigation tailwaters, and therefore, it provides information critical for evaluation of the current ILCWP monitoring requirements, as well as a template for regulators and growers to design economically feasible and effective monitoring programs.

2. Materials and methods

2.1. Study sites

Two sets of agricultural watersheds in California's San Joaquin Valley (SJV) were studied at two different temporal monitoring resolutions. Three small watersheds (<5000 ha) were monitored by the University of California, Davis (UC Davis) at a high frequency (6 h to daily), and two large watersheds (86 and 1245 km^2) were monitored by the U.S. Geological Survey and UC Davis (USGS-UC Davis) at a low frequency (biweekly to monthly) over a decade. The high-resolution data were used to evaluate intra-seasonal trends and short-term temporal variability. The low-resolution data were used to detect significant differences in constituent concentrations between years.

The high-resolution study sites consisted of canals draining three separate agricultural watersheds, each draining several agricultural fields. The watersheds have similar land use and soils, but contrast in contributing drainage areas (CDA) and flow rates: watershed 1 (W-1) 420 ha and 14–140 L s^{-1}; watershed 2 (W-2) 2000 ha and 57–226 L s^{-1}; and watershed 3 (W-3) 5000 ha and 113–425 L s^{-1}. Tailwaters originate from both furrow and flood irrigation methods, which are currently used on approximately 57% of the irrigated land area on the west side of the SJV (U.S. Bureau of Reclamation Center for Irrigation Technology, 2003). Dominant irrigated crops were tomatoes, melons, stone fruits, alfalfa, and other legumes. No rainfall occurred during the irrigation season.

Low temporal resolution data were collected for Orestimba Creek (CDA = 86 km^2) and Salt Slough (CDA = 1245 km^2). Water flows for these systems originate almost exclusively from agricultural tailwaters during the irrigation season. Dominant crop types in these two watersheds are similar to those in the three smaller, intensively studied watersheds. Sampling and analytical methods between the USGS and UC Davis laboratories were shown to be consistent for comparison purposes (Kratzer et al., 2004). These data consisted of biweekly to monthly grab samples for the irrigation season (April–September) collected from 1992 to 2006 for Orestimba Creek and 1986 to 1994 and 2000 to 2006 for Salt Slough.

2.2. Sample collection and analysis

Samples were collected from the outlets of W-1, W-2 and W-3 approximately 50 m upstream of the confluence with the San Joaquin River. During the 2006 irrigation season, water samples were only collected from W-1 at a 6-h interval (6-h samples; $n = 557$) between May 15th and October 5th using an ISCO 6712 autosampler (ISCO, Lincoln, NE). In the 2007 irrigation season (April–September), daily composite samples, consisting of four discrete subsamples taken at 6-h intervals, were collected from all three watersheds using autosamplers. Weekly grab samples were also collected from W-1 in 2006 and 2007 and W-2 and W-3 in 2007. Flow volume was measured using v-notch weirs with pressure transducers continuously logging water height.

Samples collected by autosamplers were maintained at ambient temperature in the field, collected weekly, and analyzed for total nitrogen (TN), total phosphorus (TP), turbidity, and electrical conductivity (EC), constituents not appreciably affected by the lack of preservation. Turbidity could not be reliably measured at W-3 because values frequently exceeded the maximum measurable level of 1000 Nephelometric Turbidity Units (NTU). Weekly grab samples ($n \sim 27$ per site) were maintained at 3 °C from the time of collection through completion of analyses. These samples were analyzed for TN, TP, turbidity, EC, nitrate (NO_3-N), soluble reactive phosphorous (SRP), and total suspended solids (TSS).

A non-filtered subsample was digested with potassium persulfate (Clesceri et al., 1998) and analyzed for total nitrogen as NO_3-N [limit of detection (LOD) = 10 μg L^{-1}] using the vanadium (III) chloride method (Doane and Horwath, 2003) and for total phosphorus as SRP (LOD = 5 μg L^{-1}) using the stannous chloride method (Clesceri et al., 1998). EC was measured on unfiltered samples with a Fisher Accumet AB30 conductivity meter and reported on a standardized 25 °C basis. Turbidity was measured using a Hach 2100P turbidimeter (LOD = 0.5 NTU). TSS was determined by filtering 100–500 mL of water through a precombusted, Pall type A/E glass fiber filter, and measuring mass difference upon drying at 60 °C (SM 2540 D; LOD ~1 mg L^{-1}) (Clesceri et al., 1998).

A subsample of all weekly grab samples was filtered through a 0.2 μm polycarbonate membrane (Millipore) within 24 h of collection. The filtrate was analyzed for NO_3-N and SRP as described above. Laboratory quality assurance/quality control included replicates, spikes, reference materials, setting of control limits, criteria for rejection, and data validation methods.