Development and sensitivity of a method to select time- and flow-paced storm event sampling intervals for headwater streams

K.W. King, R.D. Harmel, and N.R. Fausey

ABSTRACT: Water quality research and monitoring programs often form the basis from which related legislation is derived. Yet, no standard, protocol, or method is available for guiding the selection of a water quality sampling strategy for runoff from fields and small watersheds. The objective of this study was to develop a methodology that provides guidance in the selection of a water quality sampling strategy for headwater streams (drainage areas less than 2500 ha; 6,177 ac). The developed method is based on the dimensionless unit hydrograph and relationships of measured pollutant concentrations to discharge hydrographs. The methodology was designed for storm events with a specific return interval and a selected acceptable level of error in pollutant load. Nine input parameters (hydraulic length, watershed slope, curve number, drainage area, runoff coefficient, 10-year, one hour precipitation amount, 100-year, one hour precipitation amount, 10 year, 24 hour precipitation amount, and recurrence interval) were used to develop the design hydrograph. Both time- and flow-paced sampling techniques were considered. A global sensitivity analysis of the method indicated that time-paced sampling was primarily sensitive to parameters included in the time of concentration calculation (hydraulic length, watershed slope, and curve number). Flow-paced sampling showed some sensitivity to all nine input parameters. An example application illustrates the utility of the method. Use of the method should facilitate the selection of water quality sampling strategies for field and small watershed scale studies and aid in budgetary planning for sample collection and analysis. The measurements taken based on the recommended sampling strategy will provide more confidence in the pollutant storm load estimates.

Keywords: Concentrations, hydrographs, pollutant loads, water quality

Water quality research and monitoring relies on the assumption that the utilized sampling program provides a true representation of the actual pollution load. Water quality monitoring and research is generally completed at one of two scales (field and/or headwater streams and large river basins). In the case of large river basins, samples are often collected less frequently and an estimation method is utilized to obtain pollutant load. The estimation methods include interpolation, ratio (Cochran, 1977; Beale, 1962), regression (Ferguson, 1986; Stevens and Smith, 1978; Walling, 1989), and stratified (Kronvang, 1990) approaches. For the case of fields and headwater streams, sample frequency is generally more intense and pollutant load is calculated directly by first multiplying the discharge volume by the concentration and summing over the duration of the sample collection. The underlying assumption is that the measured concentration is representative of the actual concentration for the sampling interval in which it was collected. This study is concerned with the latter case, sampling from fields and headwater streams.

In small watersheds, water quality sampling efforts typically involve the use of an automated water sampler. A sampling strategy involves: 1) the selection of the sampling temporal domain, storm event only or continuous (storm event and baseflow); 2) selection of a threshold value to start and end sampling (e.g. flow depth, flow volume, precipitation depth, intensity, or a combination); 3) designation of a schedule on which to collect samples after the threshold is detected; and 4) determination of whether to collect discrete or composite samples (Harmel et al., 2003). Discrete sampling implies the collection of one aliquot per individual sample interval, while composite sampling involves the combination of two or more aliquots from consecutive intervals to form a sample. Time-paced discrete sampling is based on a pattern of times (e.g. every 15 minutes) while flow-paced discrete sampling is based on flow past a certain point (e.g. every 1.0 mm volumetric depth over the watershed). Discrete time- and flow-paced sampling approaches are illustrated in Figure 1.

Several studies have documented the need for and the use of both discrete and composite flow-paced and time-paced sampling strategies as well as combinations of the two (King and Harmel, 2003; Kladivko et al., 2001; Stone et al., 2000; Izuno et al., 1998; Kronvang and Bruhn, 1996; Tremwel et al., 1996; Thomas and Lewis, 1995; Shih et al., 1994; Smith et al., 1985; Clark et al., 1981; and Stevens and Smith, 1978). King and Harmel (2003) used an analytical approach based on 300 storm events from a wide range of geographic locations, drainage areas, runoff volumes and peak flows to evaluate several time interval and flow-paced discrete and composite sampling schemes. They coupled hypothetical concentration graphs onto the measured hydrographs to calculate loads. Based on averages from the 300 storm events, they concluded that time-discrete sampling at a 15 minute interval or less was required to produce a load estimate that was not significantly different ($\alpha = 0.05$) from the total pollutant load. Discrete flow-paced sampling at or above volumetric depths of 2.5 mm produced pollutant load estimates that were significantly different ($\alpha = 0.05$) from the total pollutant load.

In a similar study, Shih et al. (1994) used analytical and numerical approaches to compare multiple time-paced composite sampling

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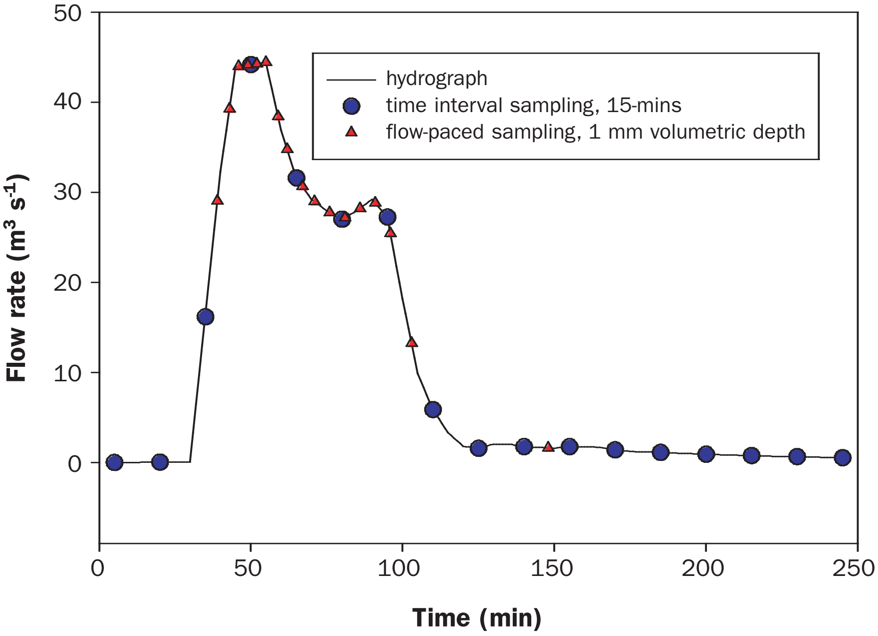
Figure 1

Hydrograph from Walnut Gulch, Arizona (drainage area 824 ha) with discrete time interval and flow-paced sampling strategies overlaid on the hydrograph.



strategies to flow-paced composite sampling strategies for estimating phosphorus loads from agricultural runoff. A combination of measured and generated hydrographs and pollutant concentrations were used to evaluate each sampling strategy. It was noted that when a positive correlation between the flow hydrograph and pollutant concentration existed, load was underestimated. A negative correlation resulted in an over predicted load. They concluded that a minimum of eight time-paced composite samples are needed to capture the same accuracy as demonstrated with flow-paced composite sampling.

Stone et al. (2000) compared four methods (time-paced composite with continuous flow, flow-paced composite with independent measure of flow, grab sampling with instantaneous flow measurements, and grab sampling using U.S. Geological Survey flow measurements) for calculating stream water quality from a 2050 ha (2,050 ac) watershed located in the eastern Coastal Plain of North Carolina. Flow-paced sampling provided significantly different and more accurate loads of nitrate-nitrogen (N), ammonia-N, and total Kjeldahl nitrogen when compared with time-paced composite and grab sampling techniques.

Izuno et al. (1998) used a non-parametric test to compare time- and flow-paced composite water samples over a three years, from ten farms, and 820 sampling events in the Everglades Agricultural Area. Concentrations of total phosphorus from time-paced composite sampling were within one percent of those concentrations found using flow-paced composite sampling while loads using time-paced composite sampling were within seven percent of the loads calculated using flow-paced composite sampling. They concluded the near 1:1 ratio for concentrations and loads was indicative that time-paced composite sampling was acceptable for regulatory purposes in that region.

Tremwel et al. (1996) compared geometrically incremental volume sampling to standard flow-paced sampling for ephemeral channel pollutants from three sites over a near three-year period. The geometrically incremental volume technique provided more samples prior to and after the peak than a constant increment approach. Sampling with the geometrically incremental volume method resulted in a more accurate concentration to hydrograph relationship.

These studies have documented the use and comparison of various time- and flow-paced sampling strategies as well as combinations of the two. Few explain why a specific sampling strategy was selected or more importantly what error in pollutant loadings could be expected. The primary objective of this study is to develop a method to aid in the selection of an efficient water quality sampling strategy for headwater streams (drainage area less than 2500 ha or 6,177 ac). Efficiency here is defined as accuracy compared to the total load and does not consider costs for sample analysis, equipment, or personnel. Specifically, the objective is to develop a method to determine the discrete sampling time-paced interval or flow-paced volumetric depth increment required to assure that the calculated pollutant load be within an acceptable percent error of the total storm load for headwater streams.

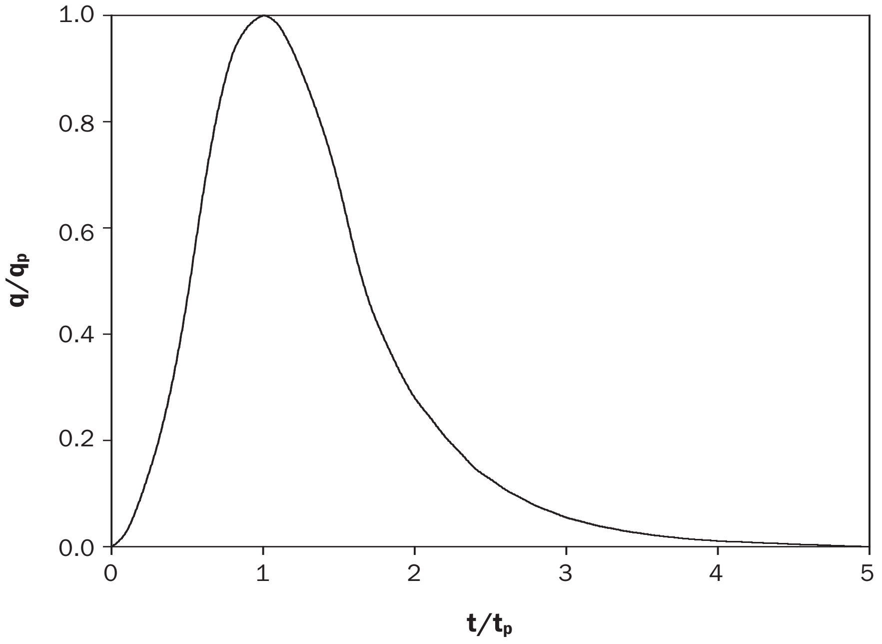
Methods and Materials

Analytical approach. The approach used in this research was to estimate watershed hydrographs and couple these with hypothetical pollutant concentrations and then to identify a sampling strategy (time-paced interval or flow-paced volumetric depth increment for quantifying loads from individual storm events) that can achieve a prespecified accuracy in representing the total load of pollutant delivered by the storm runoff. This section describes the method used to determine storm hydrographs, pollutant concentrations during storm events, total storm loads, efficient sampling intervals, and statistical relationships.

Hydrographs. The first step in the method is to create a representative event hydrograph for the watershed that is to be sampled. The Soil Conservation Service (SCS) dimensionless unit hydrograph approach (SCS, 1972) was selected because it is widely used and accepted for engineering design applications. The dimensionless unit hydrograph (Figure 2) is the product of analysis of a large number of hydrographs collected from a wide range of geographic locations. The hydrograph is dimensionless: i.e. the discharge is represented as a ratio of discharge (q) to peak discharge (q_p) and time is expressed as a ratio of time (t) to the time to peak discharge (t_p). Development of the hydrograph requires estimates of peak discharge and time to peak discharge for the watershed under consideration.

Time to peak discharge can be estimated as one half the time of precipitation plus the watershed lag time (Chow et al., 1988). Assuming that the time of precipitation is equal to the time of concentration and the watershed lag time equivalent to 0.6 times the time of concentration (SCS, 1973), it follows that time to peak discharge is equivalent to 1.1 times the time of concentration, where

Figure 2
Dimensionless unit hydrograph (SCS, 1972).



time of concentration is defined as the time of flow for the most remote point of the watershed to the outlet (the time required for the entire watershed to contribute). Time of concentration can be estimated from the SCS (1973) equation:

$$t_c = \frac{100L^{0.8}\left(\frac{1000}{CN} - 9\right)^{0.7}}{1900S^{0.5}} \qquad (1)$$

where,

t_c (min) = the time of concentration,
L (ft)= the hydraulic length of the watershed (longest flow path),
CN (dimensionless) = the SCS runoff curve number, and
S (%)= the average watershed slope.

Peak discharge can be computed once the time of concentration is estimated. Methods available for estimating peak discharge include: graphical peak discharge method (NRCS, 1986), rational method, U.S. Geological Survey empirical regression models, and the unit hydrograph method (SCS, 1972). The rational method is illustrated in this study because of the method's simplicity, historical use, ability to consider differing return period events, and applicability to small watersheds. Assuming the time of concentration (t_c) is equivalent to the precipitation duration (t), the relationship of Chen (1983),

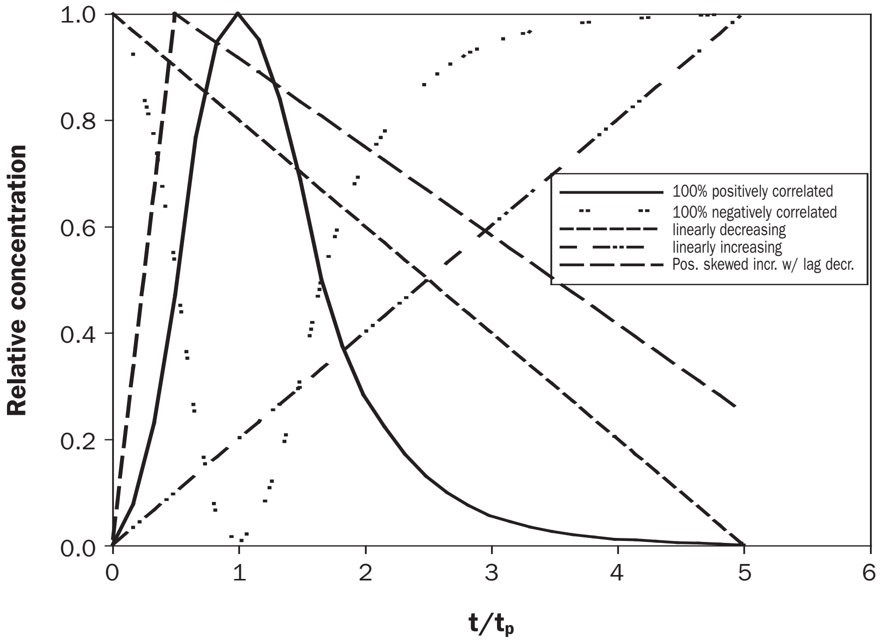
$$R_t^T = \frac{aR_1^{10}\left[(x-1)\,log\left(\frac{T}{10}\right)+1\right]\left(\frac{t}{60}\right)}{(t+b)^c} \qquad (2)$$

can be used to determine the selected return period (T) precipitation amount (in), R_t^T, and intensity, $i = \frac{R_t^T}{t}$. Precipitation amount and intensity are assumed uniform over the watershed area. The remaining parameters of the equation are defined: R_1^{10} is the 10 year, one hour return precipitation (in); x (dimensionless) is the ratio of the 100 year, one hour return precipitation (in) and the 10 year, one hour return precipitation (in) represented as $\frac{R_1^{100}}{R_1^{10}}$; and a, b, and c are standard storm coefficients determined as functions of the relationship between the 10 year, one hour return precipitation (in), and the 10 year, 24 hour return precipitation (in), $\frac{R_1^{10}}{R_{24}^{10}}$. Values for a, b, and c can be determined graphically from Chen (1983). The calculated intensity, i, can then be used with the drainage area of the watershed (A) and a runoff coefficient (C) to determine an expected peak flow ($q_p = CiA$). The resulting peak flow (q_p) and time to peak (t_p) discharge used with the ordinates from the dimensionless unit hydrograph form the anticipated watershed design hydrograph for the selected return period precipitation. This methodology would be applicable to other hydrograph design methods.

Concentration graphs. The second step of the method is to specify the theoretical/hypothetical relationships between pollutant concentrations and storm event hydrographs. Several water quality parameters including sediment, nitrate, and dissolved phosphorus have a definable trend during the discharge event. Concentrations of sediment, total phosphorus, pesticides and other sediment-bound pollutants tend to increase rapidly during the rising limb, peak prior to peak flow and decrease more slowly during the receding limb of the hydrograph (Robertson and Roerish, 1999; Harmel and King, 2005). Nitrate concentrations generally decrease with increasing flows (Tate et al., 1999; Robertson and Roerish, 1999; Peters, 1994). Pesticide concentrations in drainage water generally increase rapidly at the initiation of a drainage event and peak shortly before or coincident with the hydrograph peak before quickly decreasing (Kladivko et al., 2001). Richards and Baker (1993) measured concentrations of seven pollutants during a storm runoff event on Honey Creek in the Lake Erie basin. Concentrations of suspended solids and total phosphorus peaked with the hydrograph peak but declined more rapidly than the receding limb of the hydrograph. In contrast, atrazine, alachlor, and metolachlor concentrations followed a similar pattern on the rising limb but decreased more slowly. They also reported that nitrate plus nitrite concentration generally increased over the flow event, while chloride concentrations were inversely related to the discharge. Martin and White (1982) reported that sediment and nitrate concentrations from a small watershed near Oxford, England generally followed the shape of the hydrograph. In general, pollutant concentrations from small tributaries exhibit pronounced skewed distributions with greater temporal variability when compared to concentrations from larger rivers (Richards and Baker, 1993).

Five simplified (no noise or randomness was introduced) relationships between pollutant concentration and the flow hydrograph were hypothesized. The assumed concentration graphs were: 1) 100 percent positively

Figure 3
Hypothesized relationships of concentrations compared to event hydrograph.



correlated with hydrograph; 2) 100 percent negatively correlated with hydrograph; 3) linearly decreasing over the life of the hydrograph; 4) linearly increasing over the life of the hydrograph; and 5) positively skewed increase with a linear decrease (Figure 3).

Load and error calculations. The third step of the method is to estimate the total storm pollutant load associated with each hydrograph/concentration relationship (five distinct load values dependent upon the specific concentration relationship). Total storm load is assumed to be equivalent to the load calculated from sampling at a 0.1 minute time interval (in a similar study, Kronvang and Bruhn (1996) used a one minute sampling interval as the basis to calculate total load). Thus, total storm load (L_{tot}) can be represented as,

$$L_{tot} = \sum_{j=1}^{\frac{5tp}{y}} \left[Q_{j+\frac{j}{2}} - Q_{j-\frac{j}{2}} \right] C_j \qquad (3)$$

where,

C_j = the pollutant concentration for time step j,
Q = the associated discharge volume,
t_p = time to peak discharge, and
y = the time step (0.1 minute in the case of total storm load).

The incremental discharge volume is calculated from the midpoint of the preceding time interval to the midpoint of the following time interval assuming a linear relationship between hydrograph points.

Estimated loads (L_{est}) using a time-paced approach are calculated using Equation 3 where y takes on the value of the time interval under consideration (0.2 minute, 0.3 minute, 0.4 minute, 0.5 minute, ..., $5t_p$ minute). Estimated loads (L_{est}) using a flow-paced volumetric depth approach are calculated as,

$$L_{est} = Q_{inc} \sum_{k=1}^{\frac{q_{depth}}{n}} C_k \qquad (4)$$

where,

Q_{inc} = the incremental discharge volume,
q_{depth} = the total volumetric depth of runoff,
C_k = the pollutant concentration for the k^{th} interval, and
n = the incremental volumetric depth (0.1 mm, 0.2 mm, 0.3 mm, 0.4 mm, ..., q_{depth}).

The fourth and final step of the method is to determine the most efficient sampling time interval or volumetric depth for each hydrograph/concentration relationship. The error (Err) in the estimated load compared to total storm load,

$$Err = \frac{L_{tot} - L_{est}}{L_{tot}} \qquad (5)$$

is compared to the acceptable level of error. The efficient sampling interval (time or volumetric depth) is that interval, which produces a load estimate that approaches but does not exceed the defined acceptable error. The result of the method is one efficient time- and flow-paced interval for a given acceptable error for each hydrograph/concentration relationship.

Sensitivity analysis. A global sensitivity analysis (Haan, 2002) was completed for each input required to generate the design hydrographs. A global sensitivity provides information on the effects of variation in the inputs while allowing all inputs to vary over their ranges. Global sensitivity analysis provides information over the entire parameter space unlike a local/traditional sensitivity, which provides information on only one value in the range of parameter values. The first step in the global sensitivity analysis is to define the ranges and probability density functions of the parameters required for the design hydrographs (inputs). The second step in the global sensitivity is to simultaneously and independently generate a population of inputs and subsequent outputs (efficient time- and flow-pacing intervals) from which to sample. This step is often completed by using a Monte Carlo simulation. A multiple regression equation can be obtained from the range of inputs and corresponding outputs generated in the Monte Carlo simulation. The regression equation expressed by Haan (2002) is

$$O = b_0 + b_1 P_1 + b_2 P_2 + \cdots + b_n P_n \qquad (6)$$

where,

O = output,
b_i = the regression coefficient, and
P_i = an input parameter.

Each coefficient (b_i) in the regression equation can be normalized by multiplying the coefficient by the standard deviation of the specific input parameter (s_{p_i}) and dividing by the standard deviation of the output (s_O). The resulting value $(\beta_i = b_i \frac{s_{p_i}}{s_O})$ is that parameter's normalized sensitivity index. Thus, one standard deviation change in the i^{th} input parameter will result in a β_i standard deviation change in the output. Less effort can be spent on estimating parameters that have little or no impact on determining the efficient time- and flow-pacing intervals.

Table 1. Input parameter ranges and probability density functions* used for Monte Carlo simulation.

Input parameter	Range	Mean	Distribution
Watershed drainage length (m)	200-10000	2500	triangular
Watershed slope (%)	0.2 - 35	4.0	triangular
Curve number	30 - 99	75	triangular
Runoff coefficient	0.2 - 1.0	0.45	triangular
10-yr, 24-hr return precipitation (mm)	38 - 305	127	triangular
x	1.33 - 1.63	1.48	triangular
y	10 - 60	35	uniform
Return period (yrs)	1.01 - 99.99	10	triangular

*** 10 year, one hour return precipitation (mm) = $y * R_{10,24}$ (Chen, 1983); 100 year, one hour return precipitation (mm) = $x * y * R_{10,24}$ (Chen, 1983); watershed area (ha) = $0.0004 * \text{length}^{1.7}$ (based on data from 81 watersheds used by King and Harmel, 2003).**

Results and Discussion

Sensitivity analysis. Global sensitivities for each parameter used to generate design hydrographs were calculated for both time- and flow-paced sampling strategies. First, a "real world" representative range of input parameter values was selected (Table 1). Where applicable, known probability density functions for the input variables were used (Table 1). For all other cases, parameter distributions were assumed to be triangular. Second, a Monte Carlo simulation was used to generate 25000 observations for each input parameter, resulting in 25000 hydrographs. For each hydrograph and concentration/hydrograph relationship, the efficient sampling time- and flow-pacing interval was calculated. The efficient time- and flow-pacing intervals were calculated for three different levels of acceptable error (5, 10, and 20 percent). A regression equation (Equation 6) was built around each of the nine input parameters for time- and flow-paced sampling, level of acceptable error, and hydrograph/concentration relationship. Coefficients of determination for the regression equations ranged from 0.57 to 0.73 for the time-paced case (Table 2) and 0.69 to 0.89 for the flow-paced case (Table 3). Using the efficient time- and flow-pacing intervals as the output, normalized sensitivity indices, β_i were calculated for each input parameter (Tables 2 and 3). Sensitivity indices were calculated for each acceptable error level and hydrograph/concentration relationship scenario. The magnitudes and variations of the sensitivity indices for a particular parameter generally remained constant across all tested levels of acceptable error.

Hydraulic length, watershed slope, curve number and drainage area were identified as the most sensitive parameters when designing for discrete time-paced sampling (Table 2). Hydraulic length, watershed slope, and curve number are all parameters used to calculate the watershed time of concentration (Equation 1). Hydraulic length was found to be the most sensitive parameter when predicting a time-pacing interval. Hydraulic length is often estimated from field reconnaissance or watershed maps. Because of the methods sensitivity to hydraulic length, this

Table 2. Normalized sensitivity indices and normalized regression equation coefficient of determination for time-paced sampling.

	R^2	Area (ha)	Length (m)	Slope (%)	CN	C	10-yr, 1-hr (mm)	10-yr, 24-hr (mm)	100-yr, 1-hr (mm)	Return period (years)
	5% Acceptable error									
100% Positive correlation	0.72	-0.14	0.54	-0.35	-0.41	0.00	0.04	0.00	-0.04	0.00
100% Negative correlation	0.62	-0.06	0.64	-0.40	-0.47	0.04	0.05	0.02	0.00	0.02
Linearly increases	0.57	0.07	0.57	-0.41	-0.49	0.06	0.04	0.03	0.03	0.03
Linearly decreases	0.72	-0.16	0.57	-0.35	-0.41	0.00	0.04	0.00	-0.04	0.00
Positive skew increases w/ linear decreases	0.69	-0.25	0.75	-0.37	-0.43	0.02	0.06	0.01	-0.03	0.01
	10% Acceptable error									
100% Positive correlation	0.72	-0.14	0.54	-0.35	-0.41	0.00	0.04	0.00	-0.04	0.00
100% Negative correlation	0.63	-0.08	0.66	-0.40	-0.47	0.04	0.04	0.02	0.01	0.02
Linearly increases	0.61	-0.04	0.64	-0.41	-0.48	0.05	0.04	0.02	0.01	0.02
Linearly decreases	0.72	-0.16	0.56	-0.35	-0.40	0.00	0.04	0.00	-0.04	0.00
Positive skew increases w/ linear decreases	0.71	-0.26	0.72	-0.36	-0.42	0.01	0.05	0.00	-0.03	0.01
	20% Acceptable error									
100% Positive correlation	0.72	-0.14	0.54	-0.35	-0.41	0.00	0.04	0.00	-0.04	0.00
100% Negative correlation	0.67	-0.21	0.73	-0.38	-0.44	0.02	0.05	0.01	-0.02	0.01
Linearly increases	0.65	-0.12	0.69	-0.40	-0.46	0.04	0.05	0.02	0.00	0.02
Linearly decreases	0.73	-0.16	0.56	-0.35	-0.41	0.00	0.04	0.00	-0.04	0.00
Positive skew increases w/ linear decreases	0.73	-0.27	0.70	-0.36	-0.41	0.01	0.04	0.00	-0.03	0.00

Table 3. Normalized sensitivity indices and normalized regression equation coefficient of determination for flow-paced sampling.

	R^2	Area (ha)	Length (m)	Slope (%)	CN	C	10-yr, 1-hr (mm)	10-yr, 24-hr (mm)	100-yr, 1-hr (mm)	Return period (years)
	5% Acceptable error									
100% Positive correlation	0.76	-0.22	0.35	-0.11	-0.13	0.27	0.18	0.10	0.16	0.11
100% Negative correlation	0.82	-0.22	0.35	-0.11	-0.13	0.27	0.18	0.10	0.16	0.11
Linearly increases	0.69	-0.31	0.48	-0.13	-0.16	0.24	0.17	0.10	0.11	0.09
Linearly decreases	0.78	-0.28	0.44	-0.13	-0.15	0.26	0.20	0.11	0.13	0.11
Positive skew increases w/ linear decreases	0.79	-0.26	0.42	-0.13	-0.15	0.27	0.20	0.11	0.14	0.11
	10% Acceptable error									
100% Positive correlation	0.83	-0.27	0.43	-0.13	-0.15	0.29	0.20	0.11	0.17	0.12
100% Negative correlation	0.86	-0.21	0.34	-0.11	-0.13	0.28	0.15	0.10	0.21	0.11
Linearly increases	0.76	-0.29	0.45	-0.13	-0.15	0.25	0.21	0.10	0.11	0.10
Linearly decreases	0.82	-0.28	0.44	-0.13	-0.16	0.29	0.21	0.11	0.15	0.11
Positive skew increases w/ linear decreases	0.83	-0.27	0.43	-0.13	-0.15	0.29	0.19	0.11	0.18	0.12
	20% Acceptable error									
100% Positive correlation	0.89	-0.24	0.37	-0.11	-0.12	0.26	0.15	0.10	0.19	0.10
100% Negative correlation	0.87	-0.21	0.35	-0.11	-0.13	0.29	0.14	0.11	0.22	0.11
Linearly increases	0.80	-0.29	0.45	-0.13	-0.16	0.29	0.21	0.11	0.15	0.11
Linearly decreases	0.85	-0.27	0.42	-0.12	-0.15	0.29	0.17	0.11	0.19	0.11
Positive skew increases w/ linear decreases	0.86	-0.26	0.41	-0.12	-0.14	0.29	0.18	0.11	0.19	0.11

parameter value should be assigned using the most accurate measurements available. Curve number is selected from the SCS Engineering Division (1986) standard tables based on land use and land cover. Curve number is the most subjective of the parameters; therefore, careful attention should be given to selecting this value. Watershed slope can be determined from obtaining field measurements of elevation or reviewing contour maps and applying the relationships described by Van Haveren (1986). Drainage area is often obtained from delineated elevation maps and should be verified with field observations and measurements as needed.

Flow-paced sampling design showed some sensitivity to all nine input parameters (Table 3). Hydraulic length, showed the greatest sensitivity followed by runoff coefficient, drainage area, and 10 year, one hour precipitation amount. Flow-paced sampling interval was least sensitive to watershed slope, 10 year, 24 hour precipitation amount, and return period. Runoff coefficient is dependent on the precipitation return interval and general land use and topography (Chow et al., 1988). Runoff coefficient, like curve number, is subjective; therefore, careful attention should be given to selecting this parameter value. Data for the recurrence interval precipitation amounts (10 year, one hour; 100 year, one hour; and 10 year, 24 hour) in the United States has been summarized by Hershfield (1963). This data can facilitate selection of the recurrence interval precipitation amounts.

The magnitude of sensitivity indices was generally greater for time-interval compared to the flow-interval sampling (Tables 2 and 3). Sensitivity generally remained constant for each parameter over the three levels of tested acceptable error. Minor variances in sensitivity indices were noted between concentration/hydrograph relationships.

Application. The utility of this method can be illustrated with an example. Assume a need to sample water or collect data (e.g. based on a developed total maximum daily load (TMDL), research thrust, or a regulatory compliance audit) in a particular watershed. A sub-watershed of the Upper Big Walnut Creek watershed in Central Ohio will be considered for this example. The selected watershed is representative of a typical agricultural watershed in the region. Landuse classification in the 377.1 ha (931.83 ac) watershed is 89 percent agriculture (primarily a corn/soybean rotation), 10.4 percent woodlands, and 0.6 percent other. Land slopes are one to two percent. The watershed is comprised of three primary soils: Bennington (fine, illitic, mesic Aeric Epiaqualf), Pewamo (fine, mixed, mesic Typic Argiaquoll), and Cardington (fine, illitic, mesic Aquic Hapludalf) (SCS, 1969). Average annual precipitation for the area is approximately 1020 mm.

The first step is to collect the required information needed to develop a design hydrograph, which is a time of concentration, t_c, and a peak flow rate, q_p. The drainage length (2438.4 m or 8,000 ft) and average watershed slope (1.0 percent) can be obtained from field reconnaissance and topographic maps of the watershed. The curve number, (CN = 82), can be selected from SCS Engineering Division (1986) tables based on a hydrologic soil group C (moderately high runoff potential) classification with row crops and some residue in good condition. These values used with Equation 1 produce a time of concentration, t_c, of 157.4 minutes and a time to peak discharge of 173.1 minutes. The 10 year, one hour return precipitation (47.0 mm), 10 year, 24 hour precipitation (95.3 mm), and 100 year, one hour precipitation (67.3 mm) can be graphically determined from Hershfield (1963). Coefficients a (30.7), b (9.8), and c (0.82) can be determined graphically from Chen (1983). Using these values with Equation 2 and a two year return period, yields a return period precipitation of 37.1 mm with an average intensity of 14.2 mm hr^{-1}. Based on the rational method with

Table 4. Applied methodology results for a sub-watershed of the Upper Big Walnut Creek watershed located in north central Ohio.

Site 2 from Upper Big Walnut Creek study	
Watershed area (ha)	377.1
Watershed drainage length (m)	2438.4
Watershed slope (%)	1.0
Curve number	82.0
Runoff coefficient	0.36
10-yr, 1-hr return precipitation (mm)	47.0
10-yr, 24-hr return precipitation (mm)	95.3
100-yr, 1-hr return precipitation (mm)	67.3
Return period (yrs)	10.0
Design time of concentration (min)	157.4
Design peak discharge (m^{3}s^{-1})	4.6
Return period calculated precipitation (mm)	37.1
Calculated intensity (mm hr^{-1})	14.2

Estimated efficient sampling strategies

Expected error of 5.0%

	Positive correlation conc.	**Negative correlation conc.**	**Linear increases conc.**	**Linear decreases conc.**	**Positive skewed conc.**
Time-discrete (min)	147.5	88.3	167.1	216.1	265.0
Approx. No. of samples	6	10	6	5	4
Flow-discrete (mm vol. depth)	2.1	0.5	0.6	2.7	4.1
Approx. No. of samples	7	33	27	6	5

Expected error of 10%

	Positive correlation conc.	**Negative correlation conc.**	**Linear increases conc.**	**Linear decreases conc.**	**Positive skewed conc.**
Time-discrete (min)	160.7	147.0	197.6	264.6	319.8
Approx. No. of samples	6	6	5	4	3
Flow-discrete (mm vol. depth)	3.6	1.1	2.0	5.5	5.5
Approx. No. of samples	4	15	8	3	3

a runoff coefficient of 0.31 (from Chow et al., 1988; undeveloped, flat, cultivated land with a two-year return period), a drainage area of 377.1 ha (931.8 ac), and the calculated intensity (14.2 mm ha^{-1}), peak discharge, q_p, is 4.6 m^3 s^{-1}. The ordinates from the dimensionless unit hydrograph along with the calculated time to peak (173.1 min) and peak discharge (4.6 m^3 s^{-1}) amounts result in a design hydrograph.

The second step is to determine the hydrograph/concentration relationships of interest. If multiple pollutants are of interest, we recommend selecting the negatively correlated case. The negatively correlated hydrograph/concentration case was found to be the most conservative (providing the smallest time- or flow-paced interval) when compared to all other tested hydrograph/concentration relationships. The negatively correlated case will be used in this example. The third step is to calculate the total storm load. The total storm load can be calculated using Equation 3 and the negatively correlated hydrograph/concentration relationship. Once the total storm load is determined, the fourth step, testing for efficient time- and flow-paced intervals, can be completed. Results for acceptable errors of five percent and 10 percent are presented (Table 4).

In this example, the most efficient time-paced interval for sampling was 88-minute using a five percent acceptable error and 147 minute with a 10 percent acceptable error (Table 4). The most efficient flow-paced interval was 0.5 mm volumetric depth for a five percent acceptable error and 1.1 mm volumetric depth for a 10 percent error (Table 4). The number of expected samples using time-paced sampling was less than half the expected number using flow-paced sampling and the negatively correlated hydrograph/concentration relationship. This result may be a function of the watershed characteristics (slope, length, etc.) used in this example and may not be consistent with results from other watersheds. Increasing the acceptable error with time-paced sampling had minimal impact in reducing the number of predicted samples across all hydrograph/concentration relationships; however, increasing the acceptable error from five percent to 10 percent using flow-paced sampling reduced the expected number of samples for this two-year design event by at least half for all tested hydrograph/concentration relationships. Using a hydrograph/concentration relationship other than the negatively correlated case may provide fewer samples, but unless there is a considerable amount of confidence in the hydrograph/concentration relationship we recommend using the negatively correlated case.

The average annual runoff for this area is approximately 300 mm. Thus, the expected annual number of samples (approximately 600) using a five percent acceptable error and a flow-paced sampling approach from storm events using a flow-paced sampling approach could be estimated. Similar calculations could be completed for each of the hydrograph/concentration relationships. These types of estimates provide information needed to budget for laboratory supplies, time, and personnel. In addition, the results calculated from the field measurements can be reported and utilized with a high level of confidence in their accuracy.

Confidence in the efficient time- or flow-pacing interval is, in essence, confidence in the design hydrograph and concentration/hydrograph relationship. Unit hydrographs and the rational method have been used throughout the world for design projects in small rural basins and urban drainage subbasins (Linsley, 1986; Pilgrim, 1986). Design hydrographs in this study were based on a range of variables used to obtain the time to peak discharge and peak flow. Only hydrographs with single peaks were considered and the hydrograph/concentration relationships were simplified. Drainage areas for the dimensionless unit hydrograph were 3 to 2500 ha (9.8 to 8,202 ac). This range is representative of areas where the rational method is valid (Pilgrim and Cordery, 1993). Obtaining sampling strategies from the method outside the designed application range is possible; however, confidence with the design hydrograph would diminish. Efficiency in this study only considered accuracy with respect to the total storm load. Costs for sample analysis, equipment, and personnel, were not considered.

Laboratory and/or field testing of the method has not been completed. Field testing would be essentially impossible due to the need to collect samples at a small enough interval to assure that the total storm load is accurately measured (0.1 minute intervals in this study). In addition, forecasting when a significant event will occur is difficult and collecting data at a range of spatial scales for those events is cost prohibitive. Laboratory testing would be possible and may provide more confidence to the methodology; however, a scale issue arises due to the magnitude of generated peak flows that can be reproduced in a laboratory environment.

Summary and Conclusion

Selection of a water quality sampling strategy that results in a representative total storm load is essential for most water quality monitoring programs. A methodology was developed and presented to provide guidance in the selection of a discrete time- or flow-pacing interval for water quality sampling. The methodology utilized the dimensionless unit hydrograph and measured relationships of several pollutant concentrations to storm event hydrographs. A design hydrograph was developed from a calculated time of concentration and expected peak flow rate. A global sensitivity of the nine input parameters to the method was conducted. Time-paced sampling was primarily sensitive to variables used to determine the time of concentration (hydraulic length, watershed slope, and curve number). Flow-paced sampling showed some sensitivity to all nine input parameters. An example application was included to expound on the utility of the method. The application showed differences in the number of expected samples using both time- and flow-pacing to obtain a certain level of accuracy in load estimates. Application of this methodology to current or future projects requiring water quality loading data from small watersheds (less than 2500 ha; 6,178 ac) should enhance the usability of the data, provide more confidence in the storm event load estimates, and aid in the budgetary planning.

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