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COST-EFFECTIVE WATER QUALITY SAMPLING SCHEME FOR VARIABLE FLOW CANALS AT REMOTE SITES

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by

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EXECUTIVE SUMMARY

Constituent load computations for rivers, canals and streams in a watershed require representative constituent concentration and flow data. The design of cost-effective sampling schemes in water quality monitoring programs should consider the objective of sampling and the available resources. A literature review of worldwide sampling schemes is presented showing variation of efforts made to acquire cost-effective information with minimum uncertainty. Theoretical and applied load computation from grab, time-proportional and flow-proportional sampling schemes is addressed. Discrete and composite sampling are differentiated. A sampling scheme is presented to address cost-effective, flow-proportional sampling from variable-flow remote canals where the flow rate is not *a priori* known. In this scheme, historical weekly flow data are analyzed to develop high-flow and low-flow sampling trigger volumes. The median flow was used to estimate low-flow sampling trigger volume and the 5 percent exceedence probability flow was used for high-flow conditions. The flow-proportional water quality sampling scheme has resulted in a reduced cost of instrumentation and operation of remote sampling sites.

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INTRODUCTION

Inflow and outflow monitoring in an aquatic system is necessary for hydrologic and constituent mass balance. The periodic computation of mass balance is necessary for understanding sources and sinks and their respective magnitudes. Constituent loads are required to evaluate changes in historical constituent transport and to evaluate performance of mitigation projects. The process requires a monitoring system where inflow and outflows are measured and corresponding constituent concentration is estimated through a sampling strategy. The design, installation and operation of a monitoring system is a costly undertaking. The quality and cost of data acquired depends upon an optimal network design and carefully selected data quality objectives. The number and location of sampling sites, number and type of parameters to be sampled, and the continual availability of financial resources and skilled manpower have a direct bearing on the quality of information being gathered. Maher et al. (1993), in their paper on framework for designing sampling programs, stated that the aim of sampling programs is to collect useful information at the least cost. Oanh and Bengtsson (1997) incorporated error tolerance, variations in flow and concentration in designing representative and cost-effective sampling programs for industrial effluent from pulp and paper mills in Vietnam.

Manual grab sampling, automated time-proportional sampling and flow-proportional sampling are commonly used approaches for water quality sampling with various schemes adapted to site-specific situations. Sampling has always been challenging with respect to produce cost-effective information with minimum uncertainty.

Flow measurement schemes are relatively more developed than water quality sampling schemes for canals, streams and rivers. Flow rates and volumes passing through water control structures, such as weirs, culverts, spillways and pumps, are computed using widely accepted algorithms. The static parameters affecting flow through a structure, such as spillway gate width, weir crest length, culvert diameter and structure elevations are initialized. Dynamic parameters such as headwater, tailwater, gate openings and pump operations are constantly monitored. The quality of flow rate calculations depends on the accuracy of both static and dynamic parameters, calibrated equations of flow computation and quality control process. Flow through streams without flow control structures can be estimated with stage-discharge, slope-stage-discharge or velocity-area methods. Flow velocity through canals and streams is measured with flow-meters, ultrasonic transducers, floats and tracer solutions. Open-channel formulae are applied to compute discharge through canals, flumes, tunnels and partially filled pipes of regular geometry (Linsley and Franzini, 1979).

The South Florida Water Management District hydrologic and hydraulic system is comprised of lakes, reservoirs, constructed wetlands, canals, streams and rivers, where inflow, outflows, and in-stream flows are monitored. There are about 200 major and 2,000 minor flow control structures within the District. Table 1 summarizes the type of flow control structures and their associated monitoring requirements. With such vast network of remote flow control structures and canals, it becomes imperative to design flow-proportional sampling scheme that meet data collection objectives in the most cost-effective manner.

The intent of this paper is to present an effective flow-proportional water quality sampling scheme that resulted in a reduction in cost of instrumentation and operation of remote sampling sites. Theoretical and practical wide range experiences in water quality sampling are also presented.

SAMPLING METHODS AND CONSTITUENT LOAD ESTIMATION

Background

A constituent load is the mass of a specific element or compound that is carried by water passing from one location to another and depends on the concentration of the substance and the flow rate of the water. In canals and streams, flow rate and constituent concentration vary in three-dimensional space and time. Generally, various approaches are used to acquire estimates of flow rate and representative constituent concentration. Load computation can be represented by the following equation:

$$L_t = C_t V_t \qquad (1)$$

where L_t is constituent load for time t; C_t is representative constituent concentration for time t; and V_t is volume of flow for time t. In a flow event, there are four possible scenarios that could represent the temporal variation of concentration and flow rate:

1) Constant concentration (C) and constant flow rate (Q), expressed as follows:

   $C_t = C_i$ and $V_t = Q_i \times t$ where i is any instant during time t.

2) Variable concentration and variable flow rate:

$$C_t = \frac{\sum_{i=0}^{t} C_i Q_i \Delta t_i}{V_t} \qquad (2)$$

Δt_i is time between period i and i+1.

$$V_t = \sum_{i=0}^{t} Q_i \Delta t_i \qquad (3)$$

3) Constant concentration and variable flow rate.
4) Variable concentration and constant flow rate.

Figure 1 presents most of the possible concentration and flow rate relationships with time and the resulting constituent load as depicted by the following equations:

$$V_i = Q_i \Delta t \qquad (4)$$

where V_i is flow volume for sampling time (Δt) and Q_i is flow rate.

$$L_i = C_i V_i \qquad (5)$$

where L_i is load for sampling period (Δt).

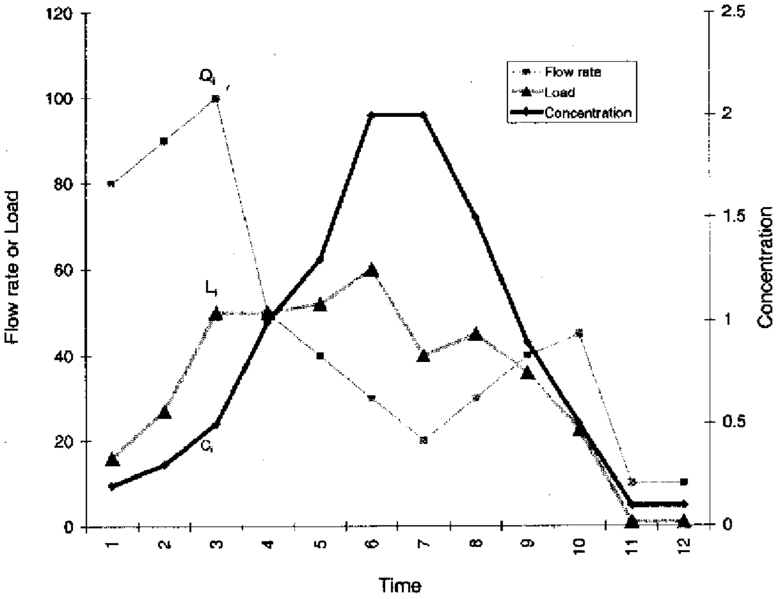
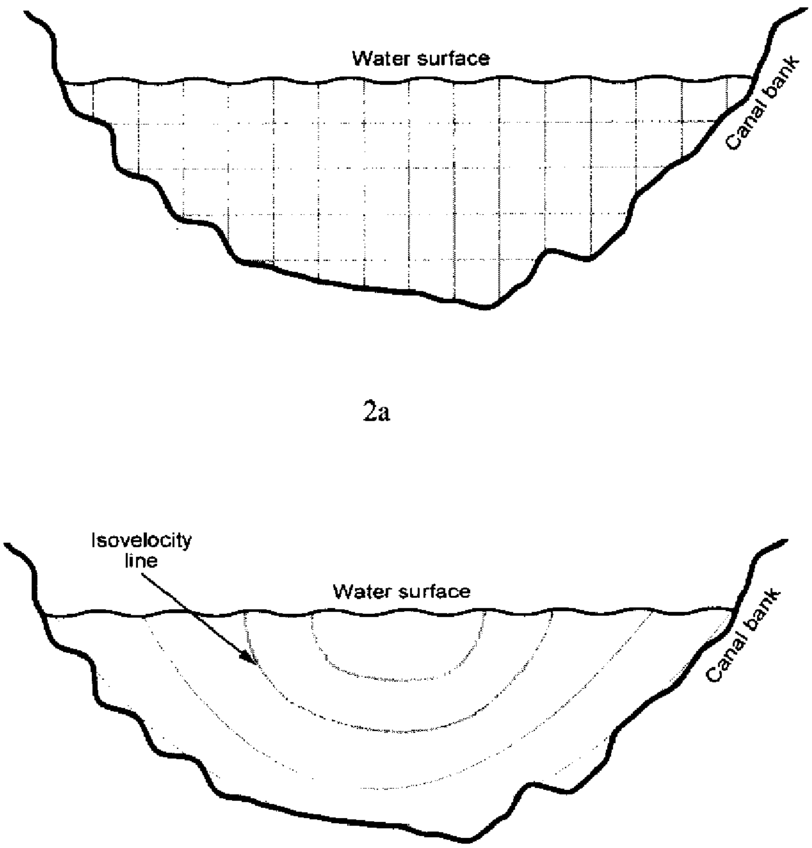


Figure 1. Concentration, flow and load relationships with time.

The true constituent load depends on accurate flow rate and concentration sampling. It is challenging and very expensive to acquire accurate flow rate and concentration sampling in rivers, canals and streams where both parameters vary in time and space. To appreciate the complexity of the issue, Figure 2a and Figure 2b depict the two-dimensional flow variation across an irregular, cross-section open channel. Concentration of constituents could vary spatially from grid to grid along the cross-section of monitoring at any instant. A highly non-uniform distribution of solids and BOD with depth was found in field observations of sewage samples (Marsalek, circa 1975). In a sewer cross-section, velocities vary spatially with higher velocities near the surface and the center; such velocity distributions are characteristics of open-channel flows (Shelley and Kirkpatrick, 1974). The spatial problem of true flow-proportional sampling at an instant in time is demonstrated by Figures 2a and 2b, where probably every grid has to be sampled both for flow rate and constituent concentration. Sampling points in a canal probably vary with sampling programs. Leitz (1999) studied the effect of sampling points on phosphorus and nitrogen concentrations in canals discharging to Biscayne Bay, Miami-Dade County, Florida. Part of the conclusions in this study was that except at one site, there was no statistical difference in total phosphorus concentration between depth-integrated samples and point grab sample at 1.64 ft (0.5 meter) depth.

Ebadian (2003) compared total Phosphorus (TP) and organic nitrogen (TKN) collected with different sampling schemes at the S-65E structure of the South Florida Water Management District. Twenty-seven months of concentration data from USGS Equal Width Incremental (EWI) spatially composited grab samples, USGS replicate samples, South Florida Water Management District grab samples and auto-sampler samples were statistically evaluated. Both significant and non-significant differences were reported from comparison of various combinations of methods. It was also concluded that flow conditions affected the comparability of the data.



2a

2b

Figure 2a,b. Canal cross-section, horizontal and vertical velocity variation.

Since sampling across the grid is not feasible for routine monitoring, attempts have been made to get representative samples with simplified schemes. Comparison was made between single-point auto-sampler sampling and the surface-water sampling protocols of the U.S. Geological Survey National Water-Quality Assessment (NAWQA) sampling protocols, which specify that sample be collected manually in equal-depth increments across a stream channel and composited for analysis (USGS, 1999). The result of paired sample analysis showed there was no significant difference between the two sampling methods for most dissolved constituents except calcium and organic carbon. Hilton et al. (1989) compared the effect of five spatial sampling strategies in lakes in the United Kingdom. After comparing spatial-integrated, depth-integrated, varying depth and edge-of-lake sampling locations, it was concluded that for national survey purposes, samples taken from the edge of the lake are the most cost-effective sampling strategies.

The temporal variation of both concentration and flow compounds the challenge of acquiring good load estimates. Various sampling schemes have been designed and implemented at different places to collect representative water quality samples. The commonly used water quality sampling schemes for controlled and uncontrolled flows are outlined below.

Grab Sampling

Grab sampling is an instant grab of a sample of water from a stationary or moving water regime, with the assumption that the constituent concentration is representative of the stationary water body or the flow passing through a cross-section. The frequency of sampling varies from project to project depending on the purpose of the study site, parameter of interest and available resources. Weekly, biweekly, monthly and quarterly grab samples are commonly used for various parameters. The inherent assumption in grab sampling is that concentration is constant for the time period under consideration for the spatial scale of interest. The product of the grab concentration and the flow volume during the period is the estimate of constituent load (equation 6).

$$L_t = C_g V_t \tag{6}$$

where L_t is constituent load for time t; C_g is grab sample concentration; and V_t is volume of flow for time t. Grab sampling is probably the most commonly applied sampling scheme in most cases. Spatial composite grab samples (USGS, 1999) or temporal composite grab samples are results of multiple grab aliquots producing the respective single sub-sample.

Time-proportional Discrete Sampling

Time-proportional discrete sampling is the process of taking aliquots of samples on fixed-time intervals and analyzing each aliquot separately. The load for each time interval can be computed using equation 7, provided that time-stamped flow data is available for each aliquot. Load can vary with sampling time interval or sampling event based on variation in concentration, flow or both.

$$L_i = C_{ti} \times V_i \tag{7}$$

where L_i is load for time interval i; C_{ti} is concentration of aliquot taken during time interval i; and V_i is volume of flow for time interval i. Total load (L_t) is computed as follows:

$$L_t = \sum_{i}^{t} L_i \tag{8}$$

High-resolution time-discrete sampling can provide "true" constituent load and temporal variation of concentration and flow, provided corresponding flow data are available. Figure 1 can be constructed from such a sampling method. The drawbacks are that many samples must be analyzed resulting in high cost. Also, the auto-sampler has to have flow-sensing capacity to not take a sample unless a minimum threshold of flow occurs. An advantage of this sampling scheme is that it is easier to program and operate time-activated auto-samplers, as the date of the last sampling event can be predetermined with most present-day samplers.

Time-proportional Discrete Composite Sampling

Time-proportional discrete composite sampling is the process of taking aliquots of samples on a predetermined, equal time interval and compositing at the end of the sampling process to analyze a single composite sample. There is the option to analyze each aliquot or discard some aliquots based on field quality control procedures. The representative concentration (C_t) is related to Figure 1, as follows:

$$C_t = \frac{\sum_{i=1}^{N} C_{ti}}{N} \tag{9}$$

where N is the number of time intervals or total number of aliquots taken. Load can vary with sample based on variation in concentration, variation in flow or both. An advantage is that it is easier to program and operate time-activated auto-samplers. The auto-sampler has to have flow-sensing capacity to not take a sample unless a minimum threshold of flow occurs.

Time-proportional Composite Sampling

Time-composite sampling is the process of taking aliquots of samples on a fixed time interval and instantly compositing in a single sample container from which one sub-sample is analyzed. Constituent load is computed using equation 1, provided total flow volume is also measured. As a result of mixing aliquots, the relationship of flow and concentration is not maintained. The magnitude of bias in load estimation by time composite scheme is shown in Shih et al. (1994). The primary advantage of time-composite sampling is the reduced analytic cost due to analysis of a single composite sample. A secondary advantage is that it is easier to program and operate time-activated auto-samplers as the date of the last sampling event can be predetermined. The auto-sampler has to have flow-sensing capacity to not take a sample unless a minimum threshold of flow occurs.

Flow-proportional Discrete Sampling

Flow-proportional discrete sampling is the process of taking aliquots of samples on a fixed flow volume interval (sampling trigger volume) and analyzing each aliquot separately. Load can vary with sample only based on variation in concentration. The load for each aliquot (L_i) can be computed as follows:

$$L_i = C_{fi} \Delta V \tag{10}$$

where C_{fi} is concentration of sampling aliquot i; ΔV is the sampling trigger volume or the volume of flow that passes through before each discrete sample is taken. Representative concentration (C_f) is computed with equation 12. Total flow volume (V_t) is computed as follows and N is the number of discrete samples:

$$V_t = N \times \Delta V \tag{11}$$

Flow-proportional discrete sampling with optimum sampling trigger volume can provide "true" constituent load and temporal variation of concentration and flow. Figure 1 can be constructed from such a sampling method in a case where the flow rate is *a priori* known. The major challenges are determining sampling trigger volume for variable-flow in remote canals where flow is not known *a priori*. Another disadvantage is that the number of samples to be chemically analyzed are many and costs can be high.

Flow-proportional Discrete Composite Sampling

Flow-proportional discrete composite sampling is the process of taking aliquots on a fixed flow volume interval (sampling trigger volume) and mixing the discrete samples to produce a composite sub-sample. Figure 4 depicts the relationship of flow rate, sampling trigger volume and sampling time for a case where the flow rate is *a priori* known. Aliquots are taken at the end of each sampling trigger volume and composited after the sample collection process is complete, to produce a single sub-sample that will be analyzed. Constituent load is computed using equation 1 and representative concentration (C_f) is expressed by the following equation.

$$C_f = \frac{\sum_{i=1}^{N} C_{fi}}{N} \qquad (12)$$

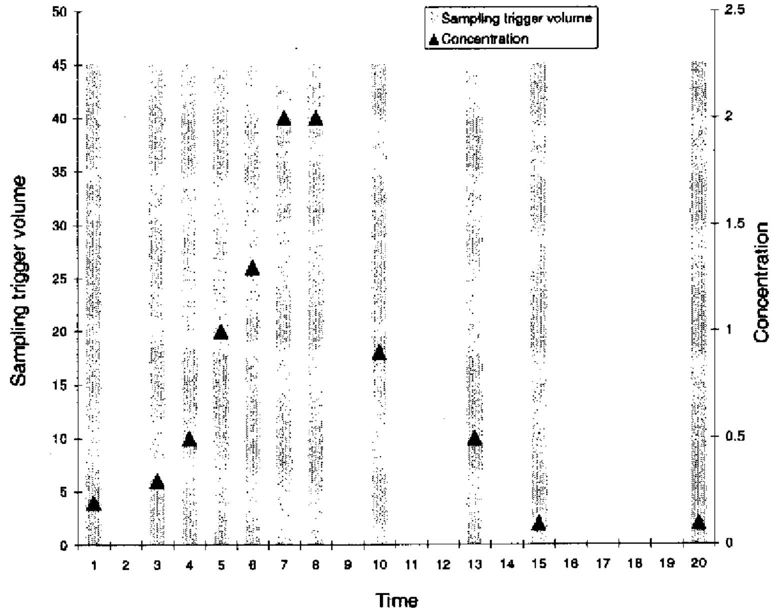


Figure 3. Flow-proportional discrete sampling.

The major challenge in determining sampling trigger volume for variable-flow, in remote canals is that the flow rate is *a priori* unknown for the sampling period. There is also the need to implement cost-effective sampling instrumentation and a sampling scheme for taking representative samples. The cost of sample analysis is reduced due to the analysis of a single sample for a sampling period. In this approach, there is always the option of analyzing discrete samples before producing a composite sub-sample. Also, during inspection of discrete samples for field quality control, one or more of the discrete samples can potentially be excluded from the composite sub-sample.

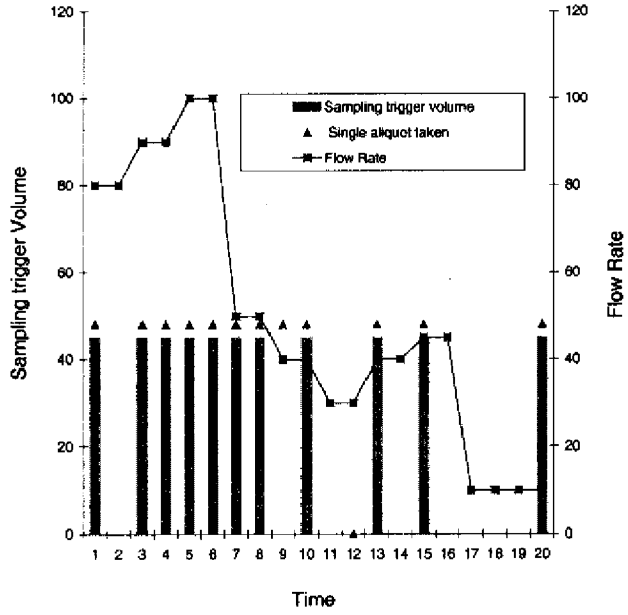


Figure 4. Flow-proportional discrete sampling and flow rate.

Flow-proportional Composite Sampling

Flow-proportional composite sampling is the process of taking aliquots on a fixed flow volume interval (sampling trigger volume) and instantly mixing the aliquots in a single container to produce a composite sample. There is no opportunity to analyze a single aliquot in the laboratory or exclude any aliquot. Constituent load is computed using equation 1, and single representative concentration (C_f) is generated from the composite sample. Figure 5 depicts the relationship of flow rate, sampling trigger volume and sampling time in cases where the flow rate is *a priori* known. Aliquots are taken at the end of each sampling trigger volume and are instantly composited to produce a single sample that would be analyzed.

LITERATURE REVIEW OF SAMPLING SCHEMES

A literature review indicated various methods of sampling from pressure conduits, open-channel, and subsurface drainage. In their study of phosphorus in drainage waters, Ulèn and Persson (1999) used an ISCO sampler controlled by a datalogger to collect flow-proportional samples. Flow over a V-notch weir was calculated every minute and accumulated to the volume of water that passed the weir. A sub-sample was taken when a sampling trigger volume of 2,344 gal (8,860 liters) passed through the weir. Ten sub-samples were composited to make a sample. In monitoring nitrate leaching from submerged drains in the Netherlands, de Vos (2001) concluded that a flow-proportional sampling scheme was required to obtain an accurate NO_3-N leaching measurements without prior knowledge of concentration and distribution in the soil. He designed a drainage flow-proportional sampling device that collected drainage in direct relation to a hydraulic head in the drainage ditch. He used a pair of reservoirs to measure sampling trigger volume, with one reservoir as a backup. An ISCO automatic sampler took 500 ml of sample each time the reservoir filled.

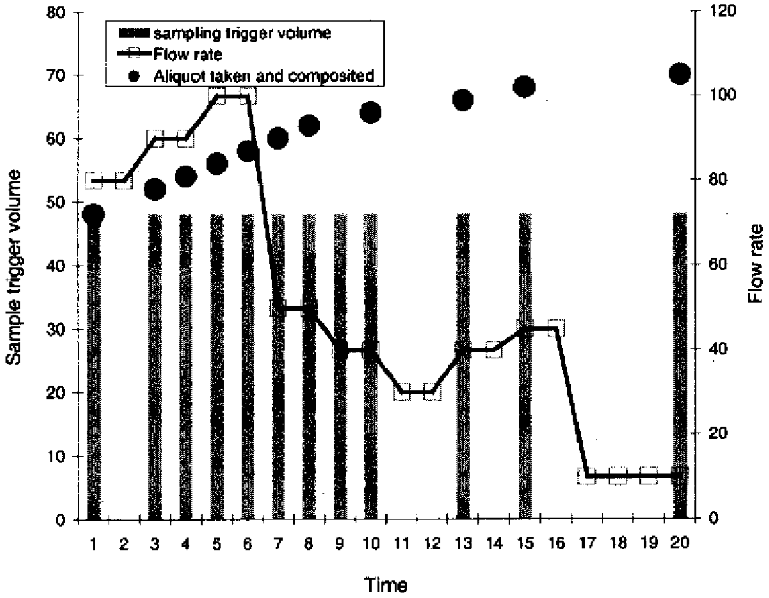


Figure 5. Flow-proportional composite sampling and flow rate.

Bottcher and Miller (1991) designed a flow-proportional composite sampler for use on small field plots. The mechanical system was composed of a rotating paddle wheel and a helical tube to collect flow-proportional samples and laboratory test results were presented. Braskerud et al. (2000), in their study of the performance of constructed wetlands in Norway used an average sampling trigger volume to take flow-proportional samples from inflows and outflows of a constructed wetland. Cuttle and Mason (1988) designed a flow-proportional water sampler for an experiment at a remote site in Great Britain. A combination of a V-notch weir and a sample chamber designed to hold proportional to the head on the weir was used. The sampling chamber was automatically drained to a sample collector every 30 minutes. The sampling time interval was the same, but the size of sample varied with flow rate. Holdsworth and Roberts (1982) designed a flow-proportional sampler for plot and lysimeter studies. A sample abstractor funnel intercepts the amount of sample proportional to the passing flow.

To address the problem of flow-proportional sampling from variable flow pipes and channels, Jennison (1972) devised two sampling schemes. In a variable pipe flow, a parallel plate capacitor was arranged as a manometer so that the air/water dielectric of the capacitor varied as the liquid level varied in the pipe. This capacitance analogue was converted to a voltage analogue, which, after amplification, drove a peristaltic pump that took a flow-proportional sample. For drains and channels that were not subject to high flow fluctuation, a discrete flow-proportional sample was taken every five minutes. Keffer (1975) compared the reliability of 11 commercially available wastewater sample collectors and determined an approximate overall failure rate of 16 percent.

Zannetti (1988) presented a sampling scheme for industrial effluent discharge into an estuary in the United Kingdom. The method employed an automatic sampler, a microcomputer and a flow measurement system. Sampling frequency was determined based on instantaneous flow into the estuary over an adjustable weir penstock. Oanh and Bengtsson (1997) presented cost-effective sampling studies for industrial effluent indicating that grab sample is sufficient when flow variation is $\leq$120 percent and concentration variations are $\leq$10 percent, for a systematic error of $\leq$13 percent. Time-composite sampling was recommended for concentration variations (2-82 percent) and flow variations of $\leq$90 percent with an error of $\leq$10 percent. Flow-proportional sampling was recommended for higher variations of flow and concentration and lower tolerance for errors.

Yaksich and Verhoff (1983), in developing a sampling strategy for river pollutant transport in western Ohio, recommended that approximately two to three of the largest events must be sampled for a yearly load estimate. Fifteen to 20 grab samples are recommended over each hydro-graph and 5 to 10 samples collected during steady-flow events. This sampling program is expected to yield load estimates with an error estimate of 10 to 20 percent.

Rekolainen et al. (1991) evaluated different sampling methods to estimate the annual phosphorus load from two agricultural basins in Finland. They reported best results with flow-proportional sampling of highest flows plus additional regular interval sampling outside peak flows. One of the adjustable parameters was the threshold value of flow for taking a flow-proportional sample. Tremwell et al. (1991) designed a geometrically incremental volume sampling method for ephemeral ditch pollutant sampling. In a comparison of discrete and intensive sampling for measuring loads of nitrogen and phosphorus from a river in Ireland, Stevens and Smith (1978) pointed out that it is possible to use river flow history to select sampling frequencies. Fredrikson (1969) designed a battery powered proportional stream-water sampler where the number of samples increased with flow rate, with one sample in 10 hours for low flow and increasing to a maximum of 20 samples for the peak flow.

Thrush and Leon (1993) developed an automatic stormwater sampling method to collect flow-proportional composite samples from drainage sewers. The average runoff volume is estimated from the rainfall that generates the average runoff. The magnitude of such rainfall is generated by various statistical analyses. The volume of runoff is computed as the product of rainfall depth, drainage area and runoff coefficient. Through a study, the optimum number of samples was determined to be 50, and the sampler container was 2.5 gal (9.5 liters). A single aliquot was 190 ml, and the sampling trigger volume was computed as follows:

$$\Delta V = \frac{V_{avg}}{N} \qquad (13)$$

where ΔV is sampling trigger volume (flow quantity interval between samples); V_{avg} is average runoff from the drainage area; and N is the number of samples to fill the sample container. From drainage areas where rainfall varies from season to season, they recommended that a seasonal average runoff be used in sampling trigger volume calculation and sampler programming.

Bhandari et al. (2001) designed a total auto-sampler system for sampling from the S5A pump station of the South Florida Water Management District. The S5A pump station has six pump units, and any number of pumps run during operation. The proposed sampling system is based on flow-proportional composite sampling, with proportional aliquots taken from each of the six pumps and representative samples taken from the discharge of each pump. The system has intake tubes, flow-meter pumps, aliquot metering pumps and two mixing tanks that are used as alternating sampling reservoirs.

CURRENT SAMPLING SCHEMES IN SOUTH FLORIDA

Water quality sampling schemes currently used by South Florida Water Management District and cooperating agencies include grab sampling, time-proportional discrete sampling, time-proportional discrete composite sampling, flow-proportional discrete composite sampling and flow-proportional composite sampling. Table 2 shows auto-sampler water quality monitoring sites with the monitoring equipment and the sampling method. There are 20 time-triggered and 65 flow-triggered auto-samplers. Figures 6a and 6b depict an auto-sampler and a water quality monitoring site.

Figure 6a. An auto-sampler.

Figure 6b. Water quality monitoring site.

Grab Sampling

The SFWMD (1999) comprehensive assurance plan provides details of a surface water sampling field procedure in the south Florida water quality monitoring system. The plan states that grab samples are collected at a depth of 1.64 ft (0.5 meters) or may vary based on the physical condition of the site or project requirements. Specific instructions on location of sampling are provided based on the mode of sampling, such as wading or using boats, and parameter type. Grab samples are also collected from an open marsh using helicopters with floats. In cases where grab samples do not meet sample collection criteria, an alternate sampling location is recommended with field documentation.

Time-proportional Discrete Composite Sampling

SFWMD (1999) states that discrete automatic samplers are programmed based on the specific project requirements. An example is provided where daily discrete samples are collected at a rate of 144-minute intervals and aliquot size of 80 ml, with a potential of picking a one-liter, discrete daily composite sample. Also, varying time intervals are used at various sites to trigger time-proportional sampling. Auto-samplers are activated at time intervals options of 90 minutes, three hours or three aliquots per day (Linda Crean, SFWMD, personal communication).

Flow-proportional Discrete Composite Sampling Scheme

The current, commonly used flow-proportional composite sampling scheme in the South Florida Water Management District canal water quality sampling is based on the scheme in Abtew et al. (1997). The major parameter of interest is total phosphorus. The scheme was developed for a monitoring system where flow across an open channel is measured with an Ultrasonic Velocity Meter (UVM) and at water control structures, with continuous monitoring of dynamic parameters required for flow computation. Continuous flow is calculated with a CR10 programmed with flow equations. When a sampling trigger volume passes through, a signal is sent to the automatic sampler to initiate sampling. Date, time and hour of sampling are stamped in the CR10 every time an aliquot is taken. The sampler has 24 one-liter bottles, each collecting eight aliquots of 100 ml. The total number of aliquots is 192. The sampling site is visited once a week, when a single composite sub-sample is generated by mixing.

The flow-proportional scheme had to address weekly flow variation, a maximum of 192 aliquots, weekly site visits, and a flow monitoring system and auto-sampler communication. The cumulative weekly flow volume (V_c), if *a priori* known, is expressed as a function of the number of samples or aliquots (N) collected during the week and the sampling trigger volume (V_s):

$$V_c = NV_s \quad (\text{for } N \leq 192) \tag{14}$$

The ideal sampling trigger volume for a 24-bottle and 8-aliquot-per-bottle auto-sampler system is a variable that changes with weekly cumulative flow volume and is expressed as follows:

$$V_{si} = \frac{V_{ci}}{24 \times 8} \quad (\text{for } 0 < V_{ci} \leq V_{cmax}) \tag{15}$$

where V_{si} is sampling trigger volume for week i, V_{ci} is the cumulative flow for week i and V_{cmax} is the maximum weekly flow through the canal. All aliqouts collected during the week are composited to generate one represenative sample with a flow-weighted concentration of C_f expressed by equation 12. Weekly constituent load is computed as a product of the total weekly flow volume and the composite concentration (equation 1).

In reality, the volume of weekly flow is not *a priori* known and the ideal sampling trigger volume can't be predetermined to program the auto-sampler. Flow rate changes temporally and from canal to canal. Existing flow record statistics were used to develop a simple and cost-effective sampling scheme. For each sampling site, seven days of cumulative flow were computed for the last 10 years. Although historical flow data may be available for more than 10 years, only the past 10 years data were used to minimize the effect of changes in land use and other activities that would change flow rate through the specific canal. Exceedence probabilities were computed for weeks with flow (Figure 7). Since no auto-sampling is done during weeks without flow, those weeks were excluded from analysis.

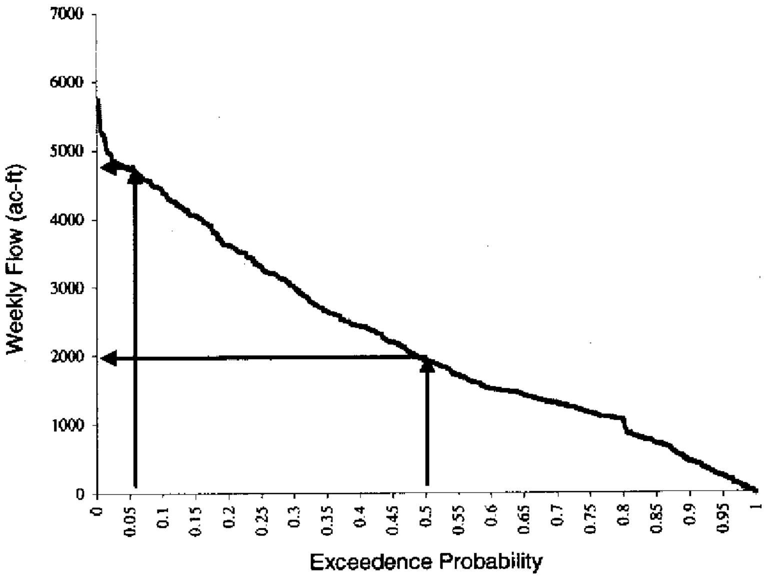


Figure 7. Weekly flow exceedence probability for G251 pump station in Stormwater Treatment Area 1 West.

This flow-proportional scheme recommends the use of two sampling trigger volumes, one for high-flow seasons and one for low-flow seasons. The 5 percent exceedence weekly flow volume is recommended to compute high-flow periods' sampling trigger volume, while the median weekly flow is recommended for low-flow periods' sampling trigger volume computation. The median weekly flow is preferred over weekly mean flow because the median is less affected by outliers or few extreme flows than the mean. Figure 7 shows the median and the 5 percent exceedence weekly flows for the G251 pump station located in the constructed wetland, Stormwater Treatment Area 1 West. As computed using equation 15, the high-flow sampling trigger volume is 24.65 ac-ft, and the low-flow sampling trigger volume is 10.05 ac-ft.

The CR10 scan time for flow-rate must be synchronized with the sampling system. The maximum scan time or flow volume information passed from the CR10 to the auto-sampler is expressed as follows:

$$T_{scan} = \frac{V_s}{Q \times 60} \tag{16}$$

where T_{scan} is CR10 flow scan time in minutes, V_s is sample trigger volume (ft^3) and Q is flow rate ($ft^3\ s^{-1}$). A smaller scan time minimizes the probability of missing a sampling event. The minimum sampling trigger volume is limited by the scan time as follows:

$$V_s \geq 60 \times T_{scan} \times Q \tag{17}$$

The CR10, after scanning flow monitoring parameters and computing flow rate, compares accumulating flow volume to the sampling trigger volume. If the accumulated flow volume is less than the sample trigger volume, the CR10 waits for the next scan. If the accumulated flow volume is greater or equal to the sample trigger volume, the CR10 sends a signal to the auto-sampler to activate sampling. If the sampling trigger volume is exceeded and the difference is less than a sample trigger volume, the CR10 adds the difference to the next flow scan output. If the difference is more than a sample trigger volume, the CR10 initiates an additional sampling event until the difference is lower than a sample trigger volume. An allowance of 5 percent fluctuation on the sampling trigger volume can provide flexibility to deal with scanning time lapse. A modified sampling trigger volume (V_{sm}) is given as follows:

$$V_{sm} = V_s \pm 0.05V_s \tag{18}$$

Simulation of Sampling Scheme

Simulation of the flow-proportional sampling scheme was performed using a computer program that imitates CR10 data logger and auto-sampler functions. Historical flow data were used to evaluate the sampling scheme performance on a weekly basis. Since available flow rate data was daily average, a uniform flow rate was assumed for the day. In the simulation, a CR10 scan time of two minutes was used, where flow volume was accumulated every two minutes and was compared to the sampling trigger volume. A high and low sampling trigger volume was used based on the previous week's flow rate. If flow was higher than the median flow, the high-flow sampling trigger volume was used. Otherwise, the low-flow sampling trigger volume was used. The simulation result produced a mean weekly aliquot number of 126, with standard deviation of 68. The maximum number of aliquots was 404 and the minimum was 1. All sampling bottles were filled before the end of the last day of sampling in 11.4 percent of the weeks. Figure 8 depicts two years of weekly flow distribution and the number of aliquots taken per week using high and low-flow sampling trigger volume for pump station G251 in Stormwater Treatment Area 1 West.

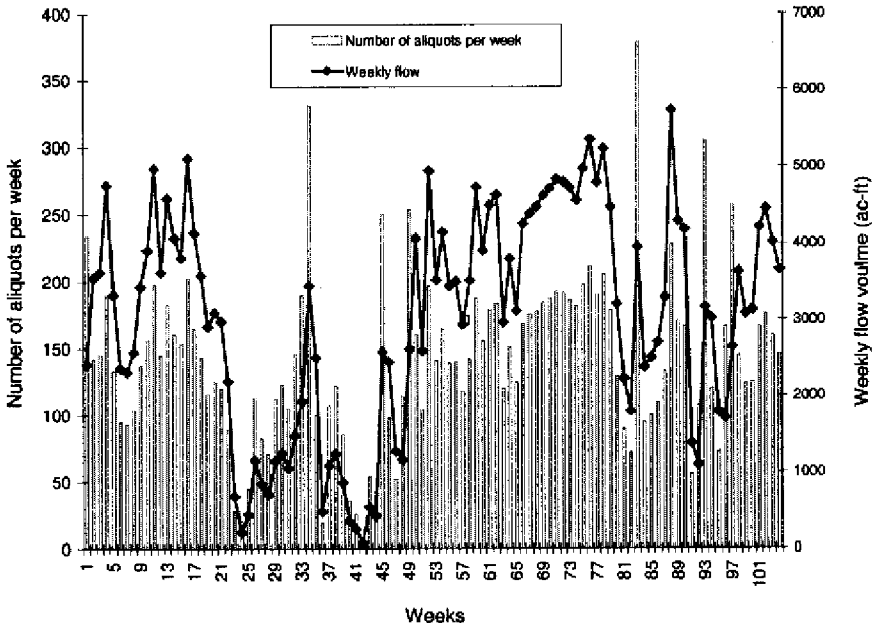


Figure 8. Weekly flows and simulated number of aliquots for two years for pump station G251 using high and low-flow sampling trigger volume.

A conservative approach for decreasing the percentage of weeks with overflows was to consistently use high-flow sampling trigger volume. A simulation for this case produced a mean weekly aliquot number of 90, with standard deviation of 56. The maximum number of aliquots was 228 and the minimum was 1. All sampling bottles were filled before the end of the last day of sampling in 3.3 percent of the weeks. Figure 9 depicts two years of weekly flow distribution and the number of aliquots taken per week, with the high-flow sampling trigger volume for pump station G251 in Stormwater Treatment Area 1 West. The weekly number of aliquots from high-flow sampling trigger volume for G251 from 1993 to 2003 is shown in Figure 10.

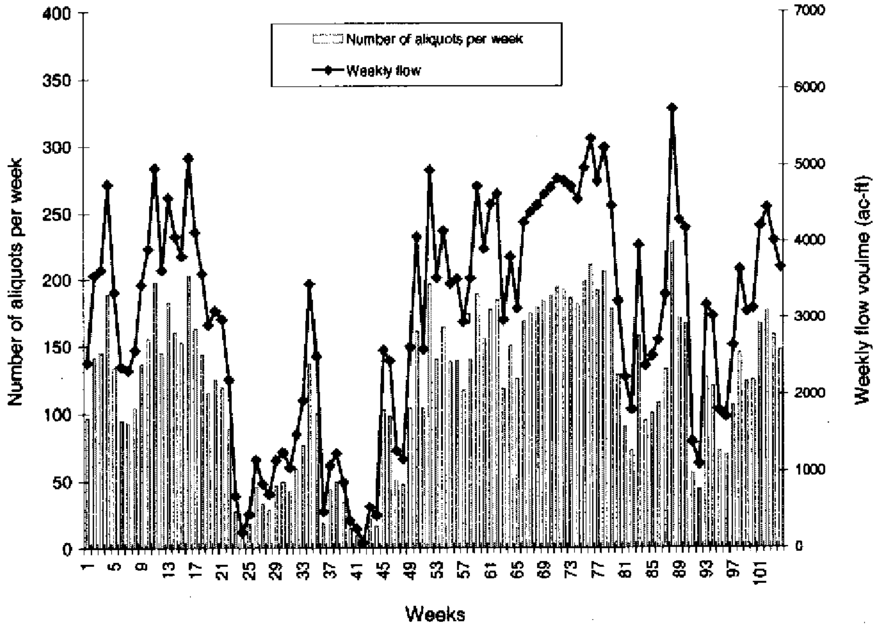


Figure 9. Weekly flows and simulated number of aliquots for two years for pump station G251 using high-flow sampling trigger volume.

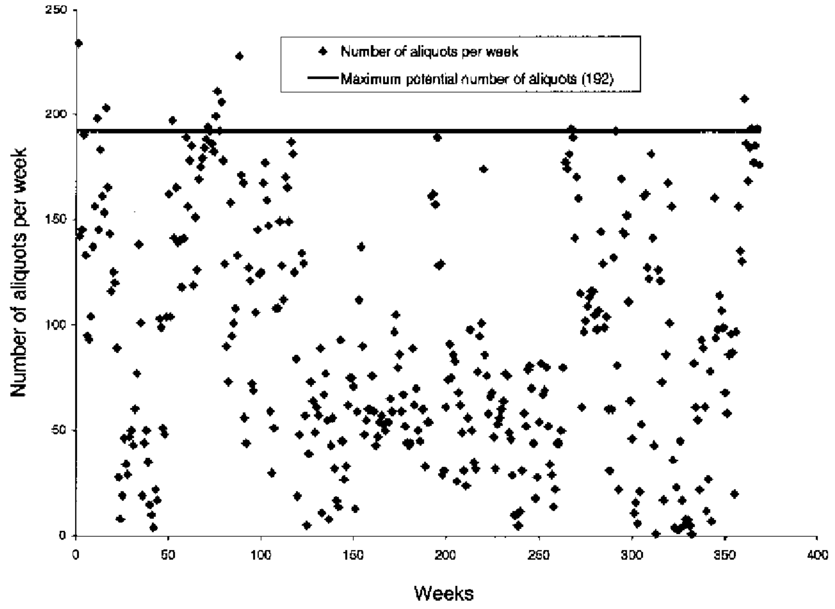


Figure 10. Weekly simulated number of aliquots for pump station G251 using high-flow sampling trigger volume (1993 to 2003).

Simulation results for high and low-flow sampling trigger volume for spillway structure S352 (HGS5) resulted in mean aliquots of 123 per week, with standard deviation of 92 aliquots. The maximum number of aliquots was 560 and a minimum of 1. The overflow rate was 15 percent. Figure 11 depicts two years of weekly flow distribution and number of aliquots taken per week using high and low-flow sampling trigger volume for spillway structure S352.

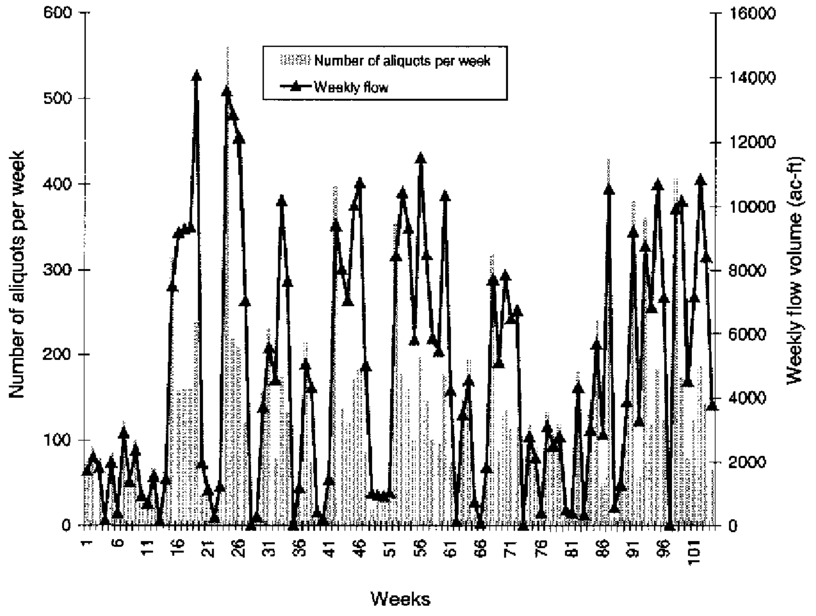


Figure 11. Weekly flows and simulated number of aliquots for two years for S352 using high and low-flow sampling trigger volume.

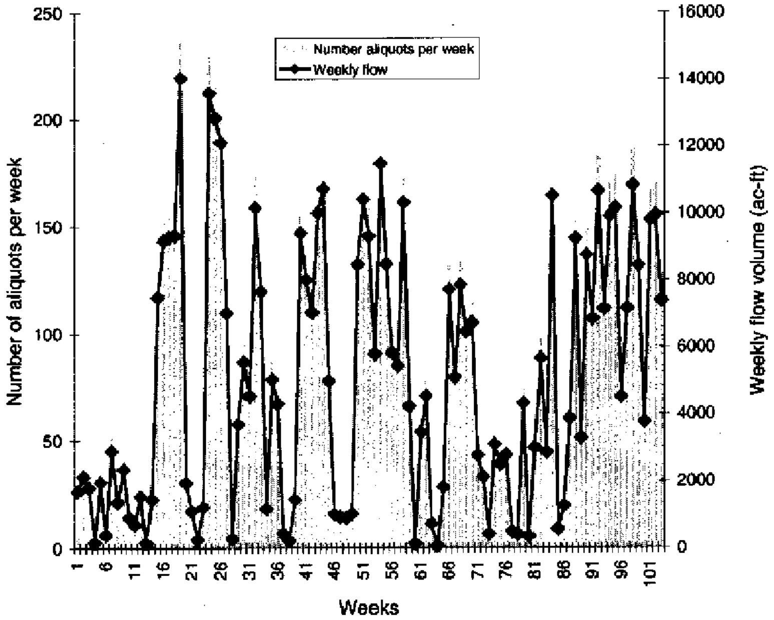


Figure 12. Weekly flows and simulated number of aliquots for two years for S352 using high-flow sampling trigger volume.

A simulation using only high-flow sampling trigger volume produced a mean weekly aliquot number of 86 with standard deviation of 64. The maximum number of aliquots was 237 and the minimum was 1. All sampling bottles were filled before the end of the last day of sampling in 4 percent of the weeks. Figure 12 depicts two years of weekly flow distribution and number of aliquots taken per week with the high-flow sampling trigger volume for S352. The weekly number of aliquots from high flow sampling trigger volume for S352 from 1991 to 2001 is shown in Figure 13.

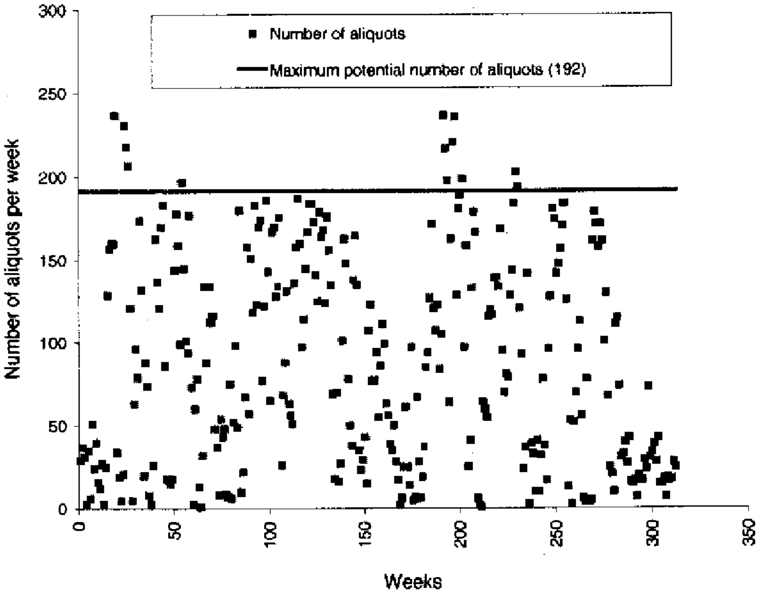


Figure 13. Weekly simulated number of aliquots for S352 using high-flow sampling trigger volume (1991 to 2001).

Flow-proportional Composite Sampling

Flow-proportional composite sampling is the process of taking water aliquots on a fixed flow volume interval (sampling trigger volume) and instantly mixing the aliquots in a single container to produce a composite sample. There is no opportunity for analyzing a single aliquot in the laboratory or excluding any aliquot. At the major pump stations, flow-proportional composite sampling is performed using a single, 5.3 gal (20 liter) refrigerated jug. Generally, samples are collected weekly (SFWMD, 1999). Sampling trigger volumes are set based on pump RPM (revolutions per minute) as an indirect measure of flow rate. Sampling trigger volume is computed based on a weekly sampling capacity of 189 aliquots for 100 ml or 378 aliquots for 50-ml aliquot size. Expected weekly flow is estimated as presented in the previous method. Constituent load is computed using equation 1, and single representative concentration (C_f) is generated from the composite sample. Figure 5 depicts the relationship of flow rate, sampling trigger volume and sampling time in a case where the flow rate is known *a priori*. Aliquots are taken at the end of each sampling trigger volume and are instantly composited to produce a single sample at the end of the week or the sampling period.

SUMMARY

Constituent load computations for rivers, canals and streams in a watershed require representative constituent concentration and flow data. The design of cost-effective sampling schemes in a water quality monitoring program should consider the objective of sampling and the available resources. A literature review of worldwide sampling schemes is presented showing variation of efforts made to acquire cost-effective information with minimum uncertainty. Theoretical and applied load computation from grab, time-proportional and flow-proportional sampling schemes is addressed. Discrete and composite sampling are differentiated. A sampling scheme is presented to address cost-effective flow-proportional sampling from variable-flow remote canals where the flow rate is not *a priori* known. In this scheme, historical weekly flow data are analyzed to develop high-flow and low-flow sampling trigger volumes. The median flow was used to estimate low-flow sampling trigger volume and the 5 percent exceedence probability flow was used for high-flow conditions. This flow-proportional water quality sampling scheme has resulted in a reduced cost of instrumentation and operation of remote sampling sites.

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Table 1. Flow control structures and monitoring requirements.

Structure	Type	Static Parameters	Monitored Parameters
CULVERTS	Gated Ungated Rectangular Square Round	Dimensions Shape Number of gates Upstream invert elev. Downstream invert elev.	Head water Tail water Gate opening Flash board operation
WEIRS	Ogee Trapezoidal Rectangular Triangular	Dimensions Shape Crest elevation	Head water Tail water
PUMPS	Variable Speed Constant Speed	Pump speed Number of pumps	Head water Tail water Engine speed Pump speed Number of pumps running
SPILLWAYS	Gated	Gate width Gate height Sill length Sill elevation Sill type Gate number	Head water Tail water Gate opening Bypass stage
OPEN CHANNEL	Open Channel	Cross-section	Head water stage Depth Velocity

Table 2. Water quality monitoring sites with auto-samplers, method of sample collection and equipment.

Project	Station	Project / Area Name	Frequency	Time (T) or Flow (F) proportional	Data Logger Type	Method of Collection	Auto-sampler	Refrigerated?	Collection Agency
ENP	S174	ENP	Weekly	T	MOSCAD	Discrete Composite	Sigma 900		Dade DERM
ENP	S178	ENP	Weekly	F	CR-10	Discrete Composite	Sigma 900		Dade DERM
ENP	S18C	ENP	Weekly	F	MOSCAD	Discrete Composite	Sigma 900		Dade DERM
ENP	S332DAS	ENP	Weekly	T	CR-10	Discrete Composite	Sigma 900		Dade DERM
ENRU	ENR002	STA1W	Weekly	F	CR-10	Discrete Composite	Sigma 800		Everglades Field Unit
ENRU	ENR305	STA1W	Weekly	T	CR-10	Discrete Composite	Sigma 800		Everglades Field Unit
ENRU	ENR305G	STA1W	Weekly	F	CR-10	Discrete Composite	Sigma 800		Everglades Field Unit
ENRU	ENR305N	STA1W	Weekly	F	CR-10	Discrete Composite	Sigma 800		Everglades Field Unit
ENRU	ENR306	STA1W	Weekly	T	CR-10	Discrete Composite	Sigma 800		Everglades Field Unit
ENRU	G253C	STA1W	Weekly	T	CR-10	Discrete Composite	Sigma 800		Everglades Field Unit
ENRU	G254D	STA1W	Weekly	T	CR-10	Discrete Composite	Sigma 800		Everglades Field Unit
ENRU	G255	STA1W	Weekly	F	CR-10	Discrete Composite	Sigma 800		Everglades Field Unit
ENRU	G256	STA1W	Weekly	T	CR-10	Discrete Composite	Sigma 800		Everglades Field Unit
ST5R	G343B	STA5	Weekly	F	CR-10	Discrete Composite	Sigma 900		Everglades Field Unit
ST5R	G343C	STA5	Weekly	F	CR-10	Discrete Composite	Sigma 900		Everglades Field Unit
ST5R	G343F	STA5	Weekly	F	CR-10	Discrete Composite	Sigma 900		Everglades Field Unit
ST5R	G343G	STA5	Weekly	F	CR-10	Discrete Composite	Sigma 900		Everglades Field Unit
ST5R	G349A	STA5	Weekly	F	CR-10	Discrete Composite	Sigma 900		Everglades Field Unit
ST5R	G350A	STA5	Weekly	F	CR-10	Discrete Composite	Sigma 900		Everglades Field Unit
SEMI	G409	EAA/Seminole Reservation	Weekly	T	None	Discrete Composite	Sigma 800		ELC Field Unit
SEMI	NFEED	EAA/Seminole Reservation	Weekly	T	None	Discrete Composite	Sigma 800		ELC Field Unit
SEMI	WWEIR	EAA/Seminole Reservation	Weekly	F	CR-10	Discrete Composite	Sigma 800		ELC Field Unit
SEMI	G404	EAA/Seminole Reservation	Weekly	F	MOSCAD	Discrete Composite	Sigma 800		ELC Field Unit
SEMI	G357	EAA/Seminole Reservation	Weekly	T	None	Discrete Composite	Sigma 800		ELC Field Unit
WQM	C23S48	Indian River Lagoon	Weekly	F	CR-10	Discrete Composite	Sigma 800		ELC Field Unit
WQM	C24S49	Indian River Lagoon	Weekly	F	CR-10	Discrete Composite	Sigma 900		ELC Field Unit
WQM	C25S50	Indian River Lagoon	Weekly	F	CR-10	Discrete Composite	Sigma 800		ELC Field Unit
WQM	C44S80	Indian River Lagoon	Weekly	T	None	Discrete Composite	Sigma 800		ELC Field Unit
WQM	GORDYRD	Indian River Lagoon	Weekly	F	CR-10	Discrete Composite	Sigma 800		ELC Field Unit
BRM	C40VMB	Brighton Resv	Weekly	F	CR-10	Discrete Composite	Sigma 900		Okee Field Unit
BRM	C41VMB	Brighton Resv	Weekly	F	CR-10	Discrete Composite	Sigma 900		Okee Field Unit
X	G207	Brighton Resv	Weekly	F	MOSCAD	Discrete Composite	Sigma 900		Okee Field Unit
X	G208	Brighton Resv	Weekly	F	MOSCAD	Discrete Composite	Sigma 900		Okee Field Unit
X	S2	Lake Okee	Event	F	CR-10 (RPMs)	Composite Jug	Sigma 900	Y	Okee Field Unit
X	S3	Lake Okee	Event	F	CR-10 (RPMs)	Composite Jug	Sigma 900	Y	Okee Field Unit
X	S4	Lake Okee	Weekly	F	CR-10 (RPMs)	Composite Jug	Sigma 900	Y	Okee Field Unit
X	S351	Lake Okee	Weekly	F	CR-10	Discrete Composite	Sigma 900		Okee Field Unit
X	S352	Lake Okee	Weekly	F	CR-10	Discrete Composite	Sigma 900		Okee Field Unit
X	S354	Lake Okee	Weekly	F	CR-10	Discrete Composite	Sigma 900		Okee Field Unit
X	S71	Brighton Resv	Weekly	F	MOSCAD	Discrete Composite	Sigma 900		Okee Field Unit
X	S72	Brighton Resv	Weekly	F	MOSCAD	Discrete Composite	Sigma 900		Okee Field Unit
LKR	S154	Lake Okee	Weekly	T	None	Discrete Composite	Sigma 900		Okee Field Unit
LKR	S191	Lake Okee	Weekly	T	None	Discrete Composite	Sigma 900		Okee Field Unit
LKR	S65	Lake Okee	Weekly	T	None	Discrete Composite	Sigma 900		Okee Field Unit
LKR	S65A	Lake Okee	Weekly	T	None	Discrete Composite	Sigma 900		Okee Field Unit
LKR	S65C	Lake Okee	Weekly	T	None	Discrete Composite	Sigma 900		Okee Field Unit
LKR	S65D	Lake Okee	Weekly	T	None	Discrete Composite	Sigma 900		Okee Field Unit
LKR	S65E	Lake Okee	Weekly	T	None	Discrete Composite	Sigma 900		Okee Field Unit
CAMB	S140	Non-Everglades Const	Weekly	F	MOSCAD	Discrete Composite	Sigma 900		Broward County DPEP
CAMB	S190	Non-Everglades Const	Weekly	F	MOSCAD	Discrete Composite	Sigma 900		ELC Field Unit
CAMB	S5AU	Upstream to S5A	Weekly	F	CR-10	Discrete Composite	Sigma 900		STA Field Unit
NECP	S9A	NON-EVERGLADES CONST	Weekly	T	MOSCAD	Discrete Composite	Sigma 900		Broward County DPEP
ST1W	G310	STA1W	Weekly	F	MOSCAD	Discrete Composite	Sigma 900		STA Field Unit
CAMB	G123	Non-Everglades Const	Weekly	T	CR-10	Discrete Composite	Sigma 900		Broward County DPEP
CAMB	G136	EAA/C139 Basin	Weekly	F	CR-10	Discrete Composite	Sigma 800		ELC Field Unit
CAMB	S150	EAA	Weekly	F	CR-10	Discrete Composite	Sigma 800		Broward County DPEP
CAMB	S5A	STA1W	Weekly	F	CR-10 (RPMs)	Composite Jug	ISCO	Y	STA Field Unit
CAMB	S6	STA2/EAA	Weekly	F	RACU (RPMs)	Composite Jug	ISCO	Y	STA Field Unit
CAMB	S7	EAA	Weekly	F	RACU (RPMs)	Composite Jug	Sigma 800	Y	Broward County DPEP
CAMB	S8	EAA	Weekly	F	CR-10 (RPMs)	Composite Jug	Sigma 800	Y	ELC Field Unit
CAMB	S9	Non-Everglades Const	Weekly	F	MOSCAD(RP	Discrete Composite	IA Series	Y	Broward County DPEP
CAMB	USSO	Seminole Resv	Weekly	F	CR-10	Discrete Composite	Sigma 900		ELC Field Unit
ST1W	ENR012	STA1W	Weekly	F	CR-10	Discrete Composite	Sigma 900		STA Field Unit
EAA	EBEACH	EAA	Weekly	F	CR-10	Discrete Composite	Sigma 900		ELC Field Unit
EAA	ESHORE	EAA	Weekly	F	CR-10	Discrete Composite	Sigma 900		ELC Field Unit
HOLY	G200	HOLY	Weekly	F	CR-10	Composite Jug	Sigma 900	Y	STA Field Unit
RTBG	G402A	HOLY	Weekly	F	MOSCAD	Discrete Composite	Sigma 900		STA Field Unit
RTBG	G402C	HOLY	Weekly	F	MOSCAD	Discrete Composite	Sigma 900		STA Field Unit

Project	Station	Project / Area Name	Frequency	Time (T) or Flow (F) proportional	Data Logger Type	Method of Collection	Auto-sampler	Refrigerated?	Collection Agency
STA2	G328	STA2	Weekly	F	MOSCAD	Discrete Composite	Sigma 900		STA Field Unit
STA2	G328R	EAA	Weekly	F	MOSCAD	Discrete Composite	Sigma 900		STA Field Unit
STA2	G335	STA2	Weekly	F	MOSCAD	Discrete Composite	Sigma 900		STA Field Unit
STA5	G342A	STA5	Weekly	F	CR-10	Discrete Composite	Sigma 900		STA Field Unit
STA5	G342B	STA5	Weekly	F	CR-10	Discrete Composite	Sigma 900		STA Field Unit
STA5	G342C	STA5	Weekly	F	CR-10	Discrete Composite	Sigma 900		STA Field Unit
STA5	G342D	STA5	Weekly	F	CR-10	Discrete Composite	Sigma 900		STA Field Unit
STA5	G344A	STA5	Weekly	F	CR-10	Discrete Composite	Sigma 900		STA Field Unit
STA5	G344B	STA5	Weekly	F	CR-10	Discrete Composite	Sigma 900		STA Field Unit
STA5	G344C	STA5	Weekly	F	CR-10	Discrete Composite	Sigma 900		STA Field Unit
STA5	G344D	STA5	Weekly	F	CR-10	Discrete Composite	Sigma 900		STA Field Unit
STA5	G349B	STA5	Weekly	F	CR-10	Discrete Composite	Sigma 900		STA Field Unit
STA5	G350B	STA5	Weekly	F	CR-10	Discrete Composite	Sigma 900		STA Field Unit
STA5	G406	STA5	Weekly	F	CR-10	Discrete Composite	Sigma 900		STA Field Unit
STA6	G354C	STA6	Weekly	F	CR-10	Discrete Composite	Sigma 900		STA Field Unit
STA6	G393B	STA6	Weekly	F	CR-10	Discrete Composite	Sigma 900		STA Field Unit
STA6	G600	STA6	Weekly	F	CR-10	Discrete Composite	Sigma 900		STA Field Unit