STORMWATER
PROGRAM

California State University, Sacramento
University of California, Davis (UCD)
California Department of Transportation (Caltrans)

QUANTIFYING REPRESENTATIVE SAMPLING USING A HYDROLOGIC ANALYSIS TOOL

Presented at:

Submitted on May 13, 2015 to StormCon for the 2015 conference August 2-6, 2015 in Austin, TX.

Authors:

Christian Carleton, PH, CPSWQ, CPESC, Office of Water Programs at California State University, Sacramento

Disclaimer:

This work reflects the author's opinions and does not represent official policy or endorsement by the California Department of Transportation, the California State University, or the University of California.

WATER PROGRAMS
Sacramento State

Research
Training
Public Education

QUANTIFYING REPRESENTATIVE SAMPLING USING A HYDROLOGIC ANALYSIS TOOL

ABSTRACT:

Representative sampling can be critical in accurately assessing BMP performance and watershed loading characteristics. However, there are very few tools available to assess the representativeness of sampling. The Hydrologic Analysis Tool (HAT) is a utility that was developed to assist with routine stormwater monitoring calculations and QA/QC, which includes qualitative and quantitative methods to assess monitoring data quality and sample representativeness. The three-part review process for sample representativeness that HAT is designed to assist with is presented. The review process starts with determining if the storm event meets project requirements and if the flow data quality is adequate. The second part of the review process uses rate and cumulative depth graphs to identify sample collection inconsistencies not easily discernable from typical data analysis methods. The review process culminates with calculating the percent capture, which provides a qualitative measure of the amount of runoff volume that is represented by the collected sample.

INTRODUCTION

Obtaining a representative water quality sample is critical for accurately assessing best management practice (BMP) performance and watershed loading characteristics. There are many factors that must be considered when deciding what constitutes a representative sample, all of which should be identified in the project's Quality Assurance Project Plan (QAPP; USEPA 2011) or similar document before monitoring begins. Some factors are relatively easy to obtain and check such as if the data were collected from the proper location or if the amount of rainfall met certain depth criteria. However, there are other factors that require additional analysis such as determining if a minimum runoff volume was achieved, a peak flow rate was obtained, or if the desired sample collection method occurred for a composite sample (e.g., flow- or time-weighted sampling). Unfortunately, there are very few tools available to help with the analysis of stormwater data and provide much of the information needed to assess the representativeness of the water quality sample.

The Hydrologic Analysis Tool (HAT) was developed by the Office of Water Programs (OWP) at California State University, Sacramento as a Microsoft Excel Add-in to help stormwater monitoring programs analyze collected storm time series data. HAT was specifically created to calculate basic hydrologic parameters from time series data to be used for research, compliance reporting, and project Quality Assurance/Quality Control (QA/QC) purposes. It accepts time series input files for incremental rainfall depth, volumetric runoff flow rates, and sample status (i.e., success or failure) for each sample collection attempt. Samples can either be individual grab samples or they may be part of a flow- or time-weighted sample collection.

Analyzing time series data for a storm event in HAT is initiated by first generating a preformatted Input Worksheet that is set up as a form. The Input Worksheet allows the user to enter information about the location where the data was collected, and provides a set of tables for the time series rainfall, runoff, and sample data which can either be imported or copied from a data logger file. Quality Control Graphs can be generated for the time series data to assist the user in identifying errors or missing time series data. After all of the data have been entered and checked, HAT then analyzes the data by first creating an Event Worksheet that functions as the data analysis worksheet and final report. All data is converted to standard units before being copied to the Event Worksheet where calculations are performed within the cells of the worksheet. This allows users and reviewers to follow exactly how the analyses are conducted and where the results come from. The formulas and data are locked and cannot be changed once in the Event Worksheet, but this format provides a window into the calculations, which allows users to track discrepancies in the results back through the calculation process to the original data.

This paper explains the various analyses and procedures that were designed into HAT to assist users with determining if a water quality sample from a single storm event is representative of the runoff observed at the monitoring location. Although the procedures and concepts discussed here can be done outside of HAT, the purpose for developing HAT was to standardize these basic hydrologic and QA/QC time series calculations, thereby allowing results to be compared between studies, minimizing calculation errors, and reducing the time and cost of performing such repetitive calculations. Furthermore, the automation of these elements in HAT enables project staff to focus on the objectives of the monitoring project instead of the calculation details.

FLOW DATA QUALITY

There are two primary purposes for collecting flow data as part of a water quality monitoring project. The first is when flow-weighted composite sampling is desired. This is the ideal method for obtaining a single composite sample that represents the event mean concentration (EMC). An autosampler uses the measured flow data to determine when to collect a sample from the runoff. It is important to have high quality, error-free flow data because any errors in the flow data translate into samples being collected at inappropriate times. If the sample collections do not follow a true flow-weighted scheme, then it can result in a composite sample that is not representative of the EMC.

The second purpose for collecting flow data as part of a water quality monitoring project is to calculate the storm loading for various constituents. For a storm event, the load value is calculated by multiplying the EMC by the runoff volume. Being able to accurately measure the flow is critical because any error in the runoff volume is directly translated to an error in the calculated load value. For example, if the runoff volume is overestimated by 27% due to errors with collecting the flow data, then any load values calculated using that runoff volume will also have the 27% error plus any error associated with the water quality analysis.

In order to help ensure high quality flow data, there are three general categories of QA/QC checks that can be done using the rainfall and runoff time series data. The first category is to determine if the event meets the project requirements as set forth in the QAPP. For rainfall data, these requirements may pertain to the storm's duration, depth, volume, or intensity. Furthermore, projects may have different requirements pertaining to the overall average intensity, instantaneous maximum intensity, or 1-hour maximum intensity. Project requirements for runoff data may be set based on flow duration, time to peak, peak flow rate, or total volume. These are all basic storm characteristics that HAT reports from the time series data.

The second category of flow data QA/QC checks is to look for errors in the data based on the physical constraints of the drainage area. For example, stormwater that is being monitored from a parking lot should only have runoff as a result of rainfall. If the flow data shows that runoff began before the rainfall, then either: 1) there is an error with the monitoring equipment and the data may be incorrect; or 2) there is flow not associated with the parking lot runoff, such as water from a broken irrigation pipe, that is being collected causing the sample to not be representative of the EMC. Other checks in this category include making sure that samples were collected when there was runoff, and that the runoff extends beyond the rainfall. HAT automatically performs and reports on these QA/QC checks when analyzing the time series data.

The third category of QA/QC checks is to use known relationships between the rainfall and runoff data to determine if there is a discrepancy between the two data sets that may indicate errors. Comparing the measured runoff volume with a volume predicted based on the rainfall depth is a good way to check for errors. Using the volumetric runoff coefficient (R_v) for the event is one way of doing this check. R_v is defined by Driscoll (1983) as the ratio of the drainage area's runoff volume (V_{runoff}) to rainfall volume ($V_{rainfall}$) as shown in Equation 1.

$$R_v = \frac{V_{runoff}}{V_{rainfall}}$$

Equation 1

An average Rv can be predicted using a relationship based on the drainage area's percent impervious (i). Equation 2 shows one such relationship, which is described in *Urban Runoff Quality Management*, Chapter 5 (WEF and ASCE 1998).

Equation 2

$$\bar{R}_v = 0.858i^3 - 0.78i^2 + 0.774i + 0.04$$

By checking if the R_v calculated from the storm event data is within an accepted range of the predicted average $\bar{R}_v$, it is possible to determine if a discrepancy in this simple volumetric relationship exists. For large discrepancies (greater than ± 20%), possible errors include monitoring equipment failures such as a malfunctioning rain gauge or erroneous flow data measurements. Another common cause for the discrepancy is an incorrectly reported drainage area size. While the measurement of the drainage area may be incorrect, this check is really intended to identify a change in the flow paths that may occur during the storm that could cause the sample to not be representative of the drainage area's runoff. This can be caused by overflow from an adjoining drainage or flows being redirected through tire ruts or cracks in the pavement.

The same type of check can be done using the time of concentration (T_c). T_c is the time that it takes for a drop of water to travel the longest path within the watershed to the outlet. The most common method used to estimate T_c is described by the National Resources Conservation Service (NRCS 2010). There are several ways to back calculate T_c based on the relationship between a hyetograph and a hydrograph. HAT uses the time difference between the center of mass of the hyetograph and the center of mass of the hydrograph to make this calculation. Determining if the T_c calculated from the event data is within an acceptable range of the estimated Tc can help identify possible errors in the data.

SAMPLE COLLECTION TIMING

Once the flow data has gone through the QA/QC process and the storm event meets the project's monitoring criteria, then the next step is to determine if the water quality sample was collected at an appropriate time so that it is representative of the runoff. This can be done both qualitatively using graphs and quantitatively through time series calculations.

When qualitatively assessing sample timing it is beneficial to graph the data in two ways: rates and cumulative depths. Both types of graphs are automatically generated by HAT when it analyzes the time series data. Rate graph contains both the rainfall hyetograph and runoff hydrographs as shown in Figures 1 and 2. The times that samples were collected are also plotted on the graph such that the points are placed on an imaginary horizontal line that separates the hyetograph from the hydrograph. While the plotted sample points have no relationship to either of the Y-axes in this graph, they do show how each sample collection time relates to the rainfall and runoff data.

For a grab sample, the rate graph provides a quick way to determine the timing of the sample with respect to the hydrograph. A typical requirement for a single grab sample is to collect it during the upper third of the rising limb. For multiple grab samples it is desirable to have one collected during the rising limb and the other during the receding limb of the hydrograph. The collection timing can be easily observed on the rate graph and the sample representativeness decided based on the requirements set forth in the QAPP.

For a multi-sample collection method typically used for a composite sample, such as time- or flow-weighted sampling, the spacing of the collection times should the focus of review. If the samples are evenly spaced horizontally on the rate graph, then they were collected using a time-weighted scheme as shown in Figure 1. However, if the samples are flow-weighted, then the spacing will not be even, but rather a pattern of more samples during times of higher flows and fewer samples during times of low flows as shown in Figure 2. Although it is nearly impossible to visually confirm a flow-weighed sample collection from the rate graph, it does provide a good indicator of flow-weighted sampling.

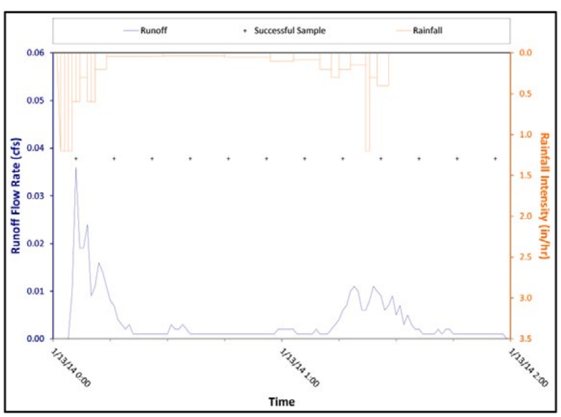

Figure 1. Rate graph showing time-weighted samples.

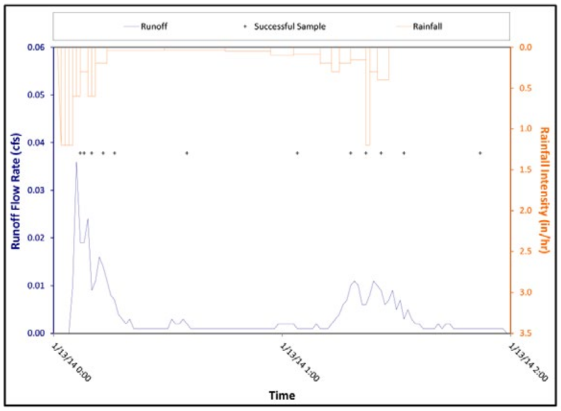

Figure 2. Rate graph showing flow-weighted samples.

The other beneficial way to graph data to qualitatively assess sample timing is to graph the data as cumulative depths, which results in rainfall and runoff mass curves as shown in Figures 3 and 4. Cumulative rainfall is easily obtained from the time series data, but for cumulative runoff the hydrograph must be divided by the drainage area size and then integrated. While more difficult to generate, this type of graph provides a way to visually determine if flow-weighted sample collection occurred. The cumulative runoff volume at which each sample was collected is plotted along an imaginary vertical line located on the right side of the graph. Plotting each sample like this shows how the samples were collected with respect to runoff depth. If the samples are spaced evenly as shown in Figure 4, then the same volume of flow passed between each collection time showing that they were collected using a flow-weighted method. However, if the samples tend to be clustered during periods of low flow where the runoff line flattens out, then it is a good indicator that they may be time-weighted as shown in Figure 3.

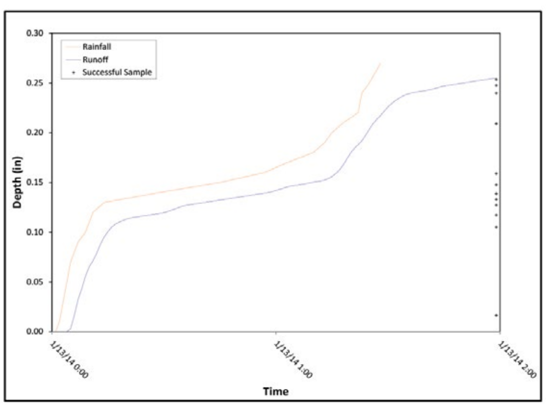

Figure 3. Cumulative depth graph showing time-weighted samples.

WATER PROGRAMS Sacramento State | Research Training Public Education

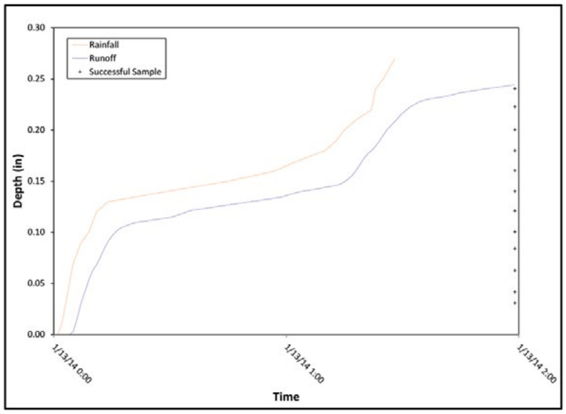

Figure 4. Cumulative depth graph showing flow-weighted samples.

Knowing how the samples were collected and understanding how each type should appear on the rate and cumulative depth graphs provides a quick and easy way to identify if an error occurred with the sampling. The graphs help identify when sample collection errors occurred and provide a good starting point for identifying the cause of sampling errors.

One common error that is often missed is when a flow-weighted sample is collected using an autosampler with a sample pacing that is too small. Sample pacing is the volume of runoff that must pass before a subsequent sample is collected. Figures 5 and 6 use the same sample time series data plotted on both a rate and cumulative depth graph. Based on the spacing of the samples in the rate graph shown in Figure 5, they appear to be flow-weighted because the samples are clustered around the peak of the hydrograph. However, when looking at the sample spacing on the cumulative depth graph shown in Figure 6, the samples appear to be time-weighted because they are clustered during periods of low flows.

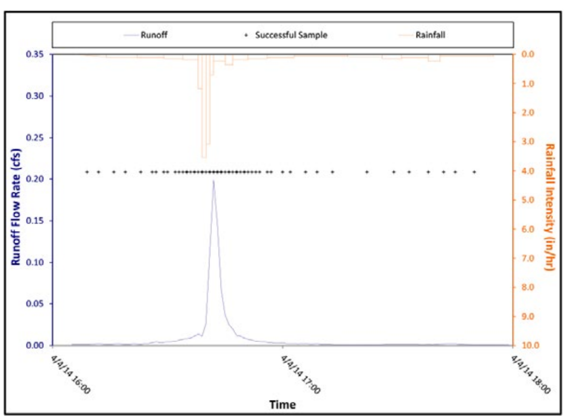

Figure 5. Rate graph showing flow-weighted sample data with a backup in the sampling queue.

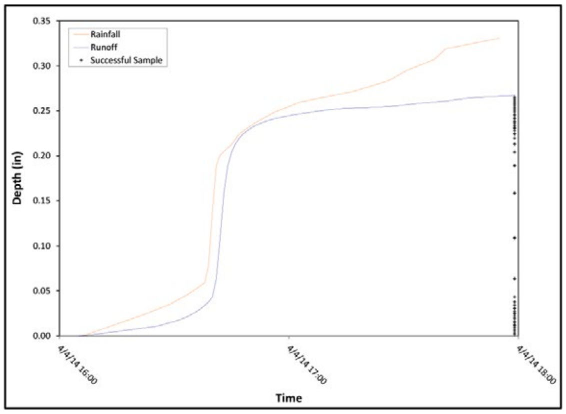

Figure 6. Cumulative depth graph showing flow-weighted sample data with a backup in the sampling queue.

This phenomenon occurs because most autosamplers run through a sampling routine during which the equipment purges the line of all water, rinses the line, purges it again, collects the sample, then purges the line one last time. Depending on the length of the sampling tube, this can take a few minutes to complete. During spikes in the runoff, it is possible that more than the pacing volume passes before the autosampler completes its routine. When this happens, it typically adds a trigger to the sampling queue, causing a backlog of samples the autosampler needs to collect. As long as the backlog exists, the sample collections are effectively time-weighted with spacing equal to the time it takes to cycle through the sampling routine. Even as the flow subsides, the autosampler will continue to collect one sample immediately after the next until it clears the sampling queue. A closer inspection of the sample spacing shown in Figure 5 reveals that the samples are evenly spaced during the period of high flow instead of displaying as a cluster that gets denser as the flow increases. Ultimately, such an error in sample collection timing results in the peaks being undersampled and in the receding limbs being oversampled. The QAPP must then be used to decide if the final composite sample adequately represents the EMC.

Sample spacing can also be determined quantitatively by using a uniformity index (UI). For sample spacing, the UI is the normalized variability of the spacing, either time or flow volume. The coefficient of variation (COV) can be used as the UI, and, as shown in Equation 3, is the ratio of the standard deviation (σ) to the mean (μ) of the data set.

$$UI = COV = \frac{\sigma}{\mu} \qquad \text{Equation 3}$$

One way to think about the COV is that it normalizes the standard deviation by dividing it by the mean. This allows for a comparison of the variability between data sets—even when the units or magnitude of the values within each data set are different. A small amount of variation in the data set results in a small COV, while a large amount of variation results in a large COV.

To test for time-weighted samples, the data set is comprised of all the time durations between each sequential sample. If the sample is properly time-weighted, then the spacing will be uniform with no variability and the UI will be zero. However, it is important to recognize that there will always be some variation in a real-world data set, so a uniformity threshold value can be used to determine when the UI is too large. If the UI is greater than the uniformity threshold it indicates excessive variation in the data set and therefore should not be considered evenly spaced. A trial-and-error process was used when developing HAT to determine that a uniformity threshold of 0.5 works well for determining if samples were collected using time- or flow-weighted sampling.

The same calculation can be done to check for flow-weighted sample collection by using the volume of water that passed between collection times as the data set.

PERCENT CAPTURE

Knowing how much of the storm runoff is represented by the collected sample is a useful metric for determining if the sample is representative of the EMC. This is referred to as the percent capture, and is particularly important for composite samples because it can vary depending upon when the sampling started, stopped, and if any of the sample collections failed. As with other sampling requirements, a project's percent capture requirement should be stated in the QAPP.

There are many different ways of calculating percent capture. For simplicity, some projects base it on time, such as comparing the duration between the first and last sample with the total event duration. Other projects may use the volume that passed between the first and last sample with the total runoff volume. Regardless of the method chosen, a project should always be consistent in the method used and the minimum percent capture value accepted.

The percent capture method developed for HAT is based on the assumption of a flow-weighted sampling scheme. The percent capture is the percentage of the volume that is represented in the sample (V_{rep}) compared to the total event runoff volume (V_{runoff}) as shown in Equation 4.

$$Percent\ Capture = \frac{V_{rep}}{V_{runoff}} \times 100$$

Equation 4

The denominator, V_{runoff}, is the area under the hydrograph that is one of the basic runoff parameters discussed as part of the flow data QA/QC. Mathematically, V_{runoff} is the integral of the hydrograph function *q(t)* with limits of integration that span the entire runoff event. For discrete time series data with n data points, the trapezoidal rule can be used, as shown in Equation 5.

$$V_{runoff} = \int_{t=0}^{t=n} q(t) = \sum_{t=0}^{n-1} \frac{q(t) + q(t+1)}{2}\big((t+1) - (t)\big)$$

Equation 5

The basic concept for calculating V_{rep} is shown in Figures 7 and 8 using a mass curve runoff hydrograph. Figure 7 shows the timing and placement of six flow-weighted samples collected from a theoretical storm event. Horizontal lines connecting the sample point with the Y-axis are provided to show that the samples are actually flow-weighted. When a sample is collected, it can be assumed to be representative of the runoff at that time. Traveling along the mass curve, the further away from the sample point the less it is representative of the runoff at that time. When collecting multiple samples, they are intentionally spaced out so that they provide coverage of the entire event and so that all flows are adequately represented by the collected samples. This is the purpose of the pacing volume in flow-weighted sampling. Therefore, based on the pacing, it can be assumed that there is a set volume of flow before and after the collection time that the sample is intended to represent. These representative volumes are the ΔVs for each of the six samples shown in Figure 8. For flow-based sampling each of the ΔVs are the same as the pacing volume.

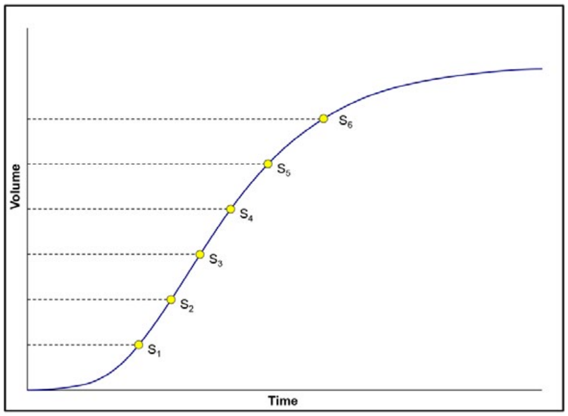

Figure 7. Flow-weighted samples on a mass curve hydrograph.

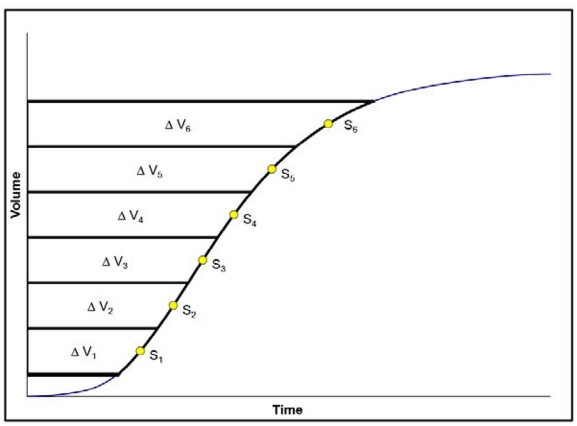

Figure 8. Representative volumes for flow-weighted samples.

Summing all of the ΔVs in Figure 8 gives a maximum runoff volume that is represented by the collected samples. However, sometimes an issue occurs with a particular sample that causes the collection to fail such as a clogged sample intake or a faulty pump. Figure 9 shows the same six samples as in Figure 7, but with two of them crossed out because they failed for some reason. This leaves samples S1, S2, S4, and S6 as the only samples that were successfully collected. In this case, the representative volumes for the three successful samples are the only ΔVs that are summed. Equation 6 shows this summation with m as the total number of successful samples and i as the successful sample number.

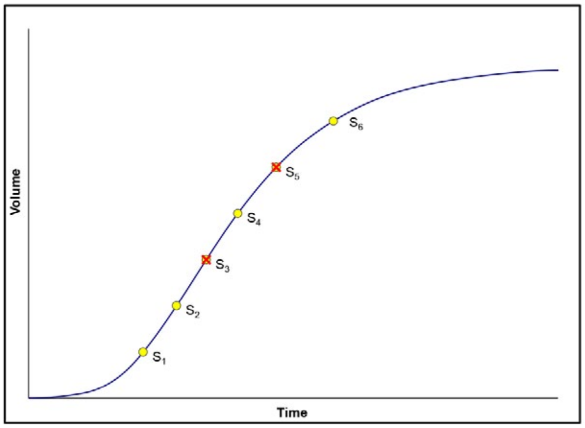

Figure 9. Flow-weighted samples with three failed collection attempts.

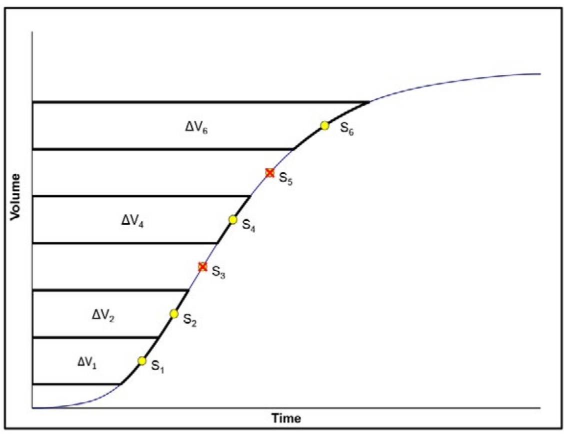

Figure 10. Representative volumes for the successful sample collection attempts.

$$V_{rep} = \sum_{i=1}^{m} \Delta V_i$$ Equation 6

Substituting Equations 5 and 6 into Equation 4 results in Equation 7, which is the percent capture equation used for a flow-weighted time series data.

$$Percent\ Capture = \frac{\sum_{i=1}^{m} \Delta V_i}{\sum_{t=0}^{n-1} \frac{q(t) + q(t+1)}{2}\left((t+1) - (t)\right)} \times 100$$ Equation 7

Although not currently part of HAT, similar approaches may be used for time-weighted sampling. It is important to recognize that a composite sample should always meet both percent capture requirements set forth in the QAPP and adequately follows the desired sample collection timing as previously discussed.

CONCLUSION

Having a QAPP or similar document that specifies project data quality objectives is critical to the long-term success of any monitoring program. A three-part review process of flow data quality, sample collection timing, and percent capture was discussed, and can be easily implemented by using HAT. The first part of the review process is to assess flow data quality by checking storm event parameters against project requirements, and by identifying data errors by leveraging physical constraints of the drainage area and known hydrologic relationships. The second part of the review process is to confirm that the sample collection timing followed project specifications either as properly timed grab samples or that composite samples follow the desired time- or flow-weighted sample collection method. The third part in the review process is to decide on a method for calculating the event percent capture for comparison against a QAPP specified minimum. Including a three-part review process such as this in a project's data quality objectives will help ensure quality monitoring data is produced for both research and regulatory compliance purposes.

ACKNOWLEDGEMENTS

The Office of Water Programs (OWP) developed HAT based in part on the California Department of Transportation's (Caltrans) Hydrologic Utility, Version 3, for which OWP wrote all new code that incorporated various tools previously developed by OWP staff to review and analyze hydrologic time series data. Funding for additional features in HAT was provided by the California State Water Resources Control Board (Water Board) Proposition 84 Stormwater Grant for the Implementation of the City of Sacramento's Low Impact Development (LID) Standards at California State University, Sacramento. Because the core functionality was funded by public agencies, HAT is freely available for use and download at www.owp.csus.edu with no implied or stated warranties.

The author would like to thank Dr. Ramzi Mahmood, Director of OWP, for the financial support to develop HAT as a free publicly available tool for use by the stormwater community. Many people have contributed to the data analysis methods used in HAT, with key support by Bhaskar Joshi of Caltrans as the Hydrologic Utility, Version 3 project manager, and Brian Currier of OWP for assistance in the development and review of the percent capture methodology. Also, a special appreciation goes to Lea Washington of OWP for her editorial review of this manuscript.

BIO

Christian Carleton has over 10 years of experience working in the stormwater field. He is currently a research engineer and hydrologist with the Office of Water Programs at California State University, Sacramento. He has a Bachelor of Science degree in Environmental Biology and Management and a Master of Science degree in Hydrologic Sciences both from the University of California, Davis, and a Master of Science in Civil Engineering from California State University, Sacramento. He is a certified Professional Hydrologist with the American Institute of Hydrology and a Certified Professional in Storm Water Quality and Certified Professional in Erosion and Sediment Control through EnviroCert International, Inc.

REFERENCES

Driscoll, Eugene D. 1983. Rainfall/Runoff Relationships from the NURP Urban Runoff Data Base. Presented paper at *Stormwater and Quality Models Users Group Meeting*, Montreal, Quebec, Sep 8-9.

Quality Management Tools–QA Project Plans. US Environmental Protection Agency (USEPA), Last Modified April 29, 2011. Accessed May 5, 2015. http://www.epa.gov/quality/qapps.html.

USDA-Natural Resources Conservation Service (NRCS). 2010. National Engineering Handbook, Part 630 Hydrology. US Department of Agriculture. Washington, DC.

Water Environment Federation (WEF) and American Society of Civil Engineers (ASCE). 1998. *Urban Runoff Quality Management, WEF Manual of Practice No. 23 and ASCE Manual and Report on Engineering Practice No. 87*. Alexandria, VA and Reston, VA: WEF and ASCE.