Technology for Increasing Efficiency and Monitoring of Stormwater BMPs and Graphical Method for Management of Stormwater BMPs

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Introduction

This document is intended to continue the conversation between P4 Infrastructure, Inc. and the Wisconsin DNR regarding the use of P4 sensor systems within stormwater infrastructure best management practices (BMPs) and how communities can best utilize measured data in their pursuit of MS4 and/or TMDL compliance.

P4 met (virtually) with WDNR on two separate occasions, May 28th and July 10th, 2020. This paper helps to summarize and provide further details of the information presented at those meetings and to provide the foundation for a formal letter of support or "green light" from WDNR for use of P4's technology.

After the July 10th meeting, the department provided P4 with a list of suggested items to include in this correspondence. P4 has outlined these in this introduction so that these items are addressed up front. More detailed information is provided in the following sections of the document.

Across the nation, and here in Wisconsin, local governments and the US EPA have approved MS4 Permits and Total Maximum Daily Load (TMDL) requirements on countless communities, counties, and drainage districts. To comply with the permits, non-point pollution reduction requirements, watersheds are delineated and appropriate best management practices (BMPs) are identified, designed, and implemented. Typically, design of BMPs is based upon commonly used computer software that will compute hydrology, hydraulics, and non-point pollution annual loads such as total suspended solids and phosphorus. Rainfall distributions and intensities, that are used in these analyses, are dictated by state and local ordinances. With each new BMP installed, documenting compliance is derived using these computer models. The actual performance of the BMP asset, whether it is a wet pond, permeable pavement system or a biofilter, is unknown. This information is important because if the BMP is over-performing, the owner of the asset should be able to receive those additional pollution reduction credits that are necessary to achieve permit compliance. On the other hand, if the asset is under-performing, maintenance and retrofits may be needed to improve the performance of the asset.

If owners of multiple BMP assets understand their real non-point pollution removal performance capabilities, future improvements and maintenance budgets can be modified based on actual system performance data and not theoretical models, perceived maintenance requirements, or unplanned asset implementations. Until recently, this type of tracking and measuring was unavailable to asset owners. Benefits that include data driven maintenance scheduling, reduced future infrastructure costs, and real-time compliance monitoring and reporting, can now be realized.

Stormwater infrastructure systems have service lives that span decades. Stormwater BMPs are no different and performance monitoring should have an objective to be continuous throughout the service life of an asset. The P4 sensor systems are intended to be installed and left in place for the entire service life of the stormwater BMP asset. P4 has been monitoring its liquid level measurement system for two years during two winters of freeze-thaw cycling and its liquid level sensor has performed flawlessly. In fact, it has been frozen many times during the past two winters and the sensor simply comes back to life after thaw. The P4 data acquisition systems have been designed to be modular and wireless communication "chips" are easily and economically replaced should migration from 4G/LTE cellular communication progress to 5G at a point in the future. P4's systems are battery powered and solar charged.

P4's sensor systems allow BMP infiltration and discharge rates to be continuously monitored over the asset's entire service life. Therefore, infiltration rates will be documented continuously and will define infiltration and discharge volume for every rain event encountered during the service life of the infrastructure asset. Infiltration and discharge rates over the service life can be reviewed at any time and extrapolation among limited numbers of data points is unnecessary. Asset owners will have a continuous history of infiltration and discharge rates.

There are many different types of stormwater best management practices considered as structural BMPs. These range from permeable pavement systems, to bioremediation systems, to wet detention ponds, to underground storage cisterns. The present document focuses on bioremediation and permeable pavement systems that contain underdrain and infiltration into the gallery subgrade. P4's systems include a component of real-time-control (RTC) that can be used to control discharge of a storage gallery. The outlet control is utilized to promote retention of water within BMPs for the maximum amount of time possible, limited only by required drawdown times. Holding water in BMPs using outlet control provides both quality and quantity improvements within the watershed. Volume of water passing through BMP systems with open underdrain versus closed underdrain is documented continuously and pollutant removal efficiency is adjusted accordingly. In other words, for every cubic foot of water exiting the BMP through infiltration when the underdrain is closed, 100% of the pollutant concentration is calculated as removed. For every cubic foot of water discharging through underdrain, when it is open, only 65% (35%) of the pollutant concentration is calculated as removed for TSS (TP).

The Wisconsin Department of Natural Resources (WDNR) technical standards and guidance for pollution removal efficiencies associated with stormwater BMPs are excellent and P4 Infrastructure does not propose changing the current technical standards in any way, nor does P4 recommend any changes to current practice with regard to Source Load and Management Modeling (SLAMM). BMP pollutant load removal efficiencies for suspended solids (TSS) and phosphorous (TP) outlined in WDNR technical standards are followed. P4 has not explicitly considered other pollutants present in stormwater runoff (*e.g. E.* coli). P4's procedures for considering pollutant loads in stormwater runoff volume are based upon how much water makes it into a stormwater BMP and whether that water infiltrates or is simply filtered and passed through. A baseline pollutant concentration in lbs/cf is defined by SLAMM and is based upon land use, source area, rainfall, runoff coefficients, etc. input into the model. Continuous volumetric measurements attained using P4's systems (based on collected water level readings) are multiplied by baseline pollutant concentrations to provide pollutant load and pollutant removal. Therefore, if a pollutant concentration in stormwater runoff is known (as assumed in current SLAMM), the runoff entering the BMP will be assumed to have that level of pollutant concentration and WDNR guidance for pollutant removal efficiency of the BMP is used to compute pollutant removed.

P4 has been monitoring permeable pavement sites in Cudahy, WI (three sites) and an underground storage cistern in Appleton, WI. Example calculations of stormwater volume captured using measured water level in the storage gallery and measured rainfall data are provided in the following. P4 has also provided examples of visualization tools to understand stormwater BMP pollutant removal effectiveness, compliance gaps and water quality credit trading opportunities.

Why INFIL-Tracker™ and Flow-RTC™ Systems?

P4 Infrastructure, Inc. has spent a lot of time speaking with consultants, DPW directors, and private asset owners over the past two years. Figure 1 includes the repeated questions heard in this two-year period. These are important questions facing asset owners everywhere and answers to them have significant impact on the perceived value of implementing stormwater BMPs, their long-term effectiveness and maintenance, and the economic justification for literally millions of dollars in spending on these infrastructure systems.

P4 developed the INFIL-Tracker and Flow-RTC systems to answer these questions and give stormwater BMP owners more cost-effective solutions in meeting MS4 permitting requirements and TMDL targets imposed by the US EPA. The P4 systems can also be used for data-driven maintenance intervention for these systems. P4 INFIL-Tracker and Flow-RTC include a rainfall measurement system (Rain-mX), a water level measurement system (INFIL-Tracker), and an optional smart valve system to optimize volume control and pollutant removal (Flow-RTC). Figure 2 provides a schematic of these systems and their installation.

These systems are installed using off-the-shelf rental equipment, require no special training, and installation is preferred to be done post-construction. Figure 2 shows installation of the INFIL-Tracker system for a permeable pavement done in Cudahy in January of 2020 with Cudahy DPW personnel. These systems are equally applicable to bioswales and other infiltration-type BMPs. P4 has a system called LIQUA-Level designed for underground cisterns and wet ponds.

Figure 3 demonstrates (in schematic fashion) the fundamental behavior of an infiltration type stormwater BMP with and without P4 systems. P4 fundamentally thinks of bioremediation and permeable pavement galleries as storage tanks. These tanks are supplied stormwater runoff through catchment area tributary to the BMP (illustrated schematically through the funnel in the figure). Figure 3 is essentially a side-by-side illustration of infiltration-type BMP performance with and without the Flow-RTC. The left side of the figure illustrates that water exits a storage gallery through infiltration and/or underdrain discharge, with corresponding pollutant credits given for that performance. The volume exiting through either of these is a function of site conditions like subgrade seepage rate, size, number, and location of underdrains.

When P4 considers these types of structural stormwater BMPs, the following questions come to mind. What happens if the amount of water assumed to be running off and funneled to the BMP does not reflect that assumed in the analytical models? What is used for rainfall? What are the runoff coefficients? How was the land use source area determined? What if you could determine, for a given rain event, the amount of water that actually makes it to the BMP? What if you could hold water in the BMP as long as you could to promote infiltration and increase settling time before letting the water exit through underdrain and do it without any risk of a system not draining? This is the value of real-time volumetric monitoring and outlet controls provided by the P4 systems.

The P4 systems are integral to Source Load and Management Modeling (SLAMM). The data from P4 systems are intended to be used to enhance SLAMM. SLAMM is often used in Wisconsin as the basis for TMDL and MS4 compliance. The basis for SLAMM is schematically illustrated in Figure 4. A SLAMM modeler provides input data that defines a tree diagram moving from land use to outfall. Land use defines the pollutant source and the source area defines the pollutant load after applying the parameter file information to the tree diagram (e.g. rain file, pollutant distribution file, runoff coefficient file, etc.). WinSLAMM computes total pollutant load and total stormwater volume generated by each land use and aggregates the calcs at Junctions (*e.g.* Junction 1). After this information is entered into the model, a baseline conditions (or no-controls) analysis is performed to estimate the amount of pollutant load and stormwater volume reaching the outfall. After the no-controls analysis, BMPs are added to the model. BMPs either retain, filter or infiltrate stormwater which reduces the amount of pollutant making it to the outfall. Adding a BMP DOES NOT change the amount of stormwater volume making it to Junction 1; however, it could (and usually does) change the volume at Junction 2.

The P4 systems augment SLAMM with measured data. Figure 5 illustrates an output summary for one of the P4 system sites in Cudahy, Wisconsin. It is a permeable pavement site designed with a single underdrain at the bottom of the aggregate storage gallery and an assumed subgrade seepage rate of 0.04 in/hr. The junction volumes are shown on the left in yellow and orange highlights. BMP performance (percent reduction from baseline values) is shown inside the red box. The figure illustrates the impact of infiltration rate moving from 0.04 in/hr to 2.5 in/hr. As more water infiltrates, pollutant reduction increases. There is significant improvement in pollutant reduction effectiveness with infiltration improvement. The P4 INFIL-Tracker and Flow-RTC systems are designed to optimize infiltration volume to the greatest extent allowed within the constraints of drawdown requirements and provide measured data for enhancement of SLAMM. If a monitored system illustrates that infiltration rate is greater than that assumed in the original SLAMM analysis, then SLAMM can be significantly improved for design of subsequent stormwater BMPs and there can be significant economic benefits realized. Furthermore, an asset owner may be able to take credit for additional pollutant removed as a result of this improved infiltration rate. This is an additional value of the P4 systems.

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Efficiency of Stormwater BMPs

Stormwater infrastructure BMPs are designed using state regulations and technical standards in conjunction with SLAMM software. As alluded to earlier, infiltration rate of subsurface soils is very important in SLAMM software. Wisconsin's technical standards for evaluating infiltration[1] provides three options for estimating infiltration rate at a site slated for future BMP installation. Option 1 recommends digging a soil pit to evaluate the types of soils present at the site. The engineer must then select a standard infiltration rate based on published test results in the literature corresponding to the *least* permeable layer discovered in the pit. Option 2 allows infiltration to be measured directly using a double-ring infiltrometer test. While better than Option 1, this option is only representative of the location/day/time/conditions present when the test was conducted. In other words, one set of double-ring tests define subgrade infiltration rate for the entire life of a BMP (10-20 years). Option 3 is essentially Option 1 with a correction factor (of less than 1) applied to the standard, published infiltration rates to account for compacted soil if efforts were not taken to mitigate such compaction during construction. These estimations can prove to be very conservative and inaccurate. For example, what if there is a sand seam in the subgrade just beyond the test pit that will eventually fall within the BMP footprint?

BMPs like permeable pavement and biofiltration basins serve as filters capturing pollutants from stormwater runoff passing through their surfaces and their underground media. These BMPs rely on both subgrade infiltration (also referred to in this document as subgrade seepage) and underdrain conveyance systems to drain their storage galleries after rain or other precipitation events. Typically, the underdrain is present to prevent overflows and to ensure the BMP is emptied/drained within a specified drawdown period (typically 48-72 hours).

Drawdown time is an important consideration when designing infiltration-type BMPs and can vary with jurisdiction. In Minnesota, for example, drawdown time is typically 48 hours, while it is 72 hours in Wisconsin. Each state or water jurisdiction may have similar or different drawdown times. There are several reasons infiltration-type BMPs must drain within an established time period including[2]: (1) wet-dry cycling of the storage gallery; (2) minimizing the opportunity for mosquito breeding; (3) promoting suitable habitat for vegetation (bioswales); (4) promoting aerobic conditions (bioswales); and (5) ensuring storage capacity is available for the next rain event.

Engineers must consider both pollutant removal efficiency and drawdown time when designing infiltration-type BMPs. Often, pollutant removal efficiency is sacrificed to mitigate risk of failure. If an infiltration-type BMP is constructed without an underdrain near the bottom of the storage gallery, there is a chance stormwater runoff will not drain within the specified drawdown period. If this happens, the BMP is considered failed and must be reconstructed with an underdrain to receive pollutant removal credits. This results in additional infrastructure spending and inefficiency.

While underdrains do not make up a large portion of the cost of a BMP (if they are installed during original construction), they do affect a BMP's ability to reduce pollutants driving up the cost per pound of pollutant removed. BMPs capable of infiltrating all stormwater passing through them remove 100% of pollutants carried by runoff. Stormwater filtered through a BMP, then discharged through an underdrain reduces only a portion of the pollutants carried by the runoff allowing some pollutants to escape the BMP and to enter the surface waters of the drainage system. Water discharged through permeable pavement underdrain is assumed to remove somewhere near 65% of total suspended solids (TSS) and 35% of total phosphorus (TP) – both significantly less than 100% achieved through a full infiltration system.

[1] https://dnr.wi.gov/topic/stormwater/documents/1002SiteEvalForInfiltr.pdf
[2] https://stormwater.pca.state.mn.us/index.php/Assessing_the_performance_of_infiltration

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The size (diameter), location and number of underdrains is important when designing a BMP. All three help to determine how quickly a BMP will empty after water enters the system. A large underdrain at the bottom of a storage gallery will provide an easy flow path for water to exit the BMP, limiting the ability for stormwater to be stored (ponded) in the gallery and/or infiltrate into the subgrade. Raising the underdrain to a higher elevation, shrinking the size, or reducing the number of underdrains used within the storage gallery all help to promote ponding and infiltration thereby increasing BMP pollutant removal efficiency. By doing this, however, there is increased risk that the BMP will not drain within the specified drawdown time. If underdrain is not installed within the cross-section of the BMP, observation wells are required to be installed to allow water level monitoring from the surface. State regulations require the observation wells be visited at least once per year at the drawdown time after a rain event of 0.5 inches or more to verify the storage gallery is draining effectively.

Software packages like WinSLAMM (www.winslamm.com) conveniently allow engineers to input all these properties to evaluate resulting BMP efficiencies. WinSLAMM was developed by PV & Associates to computerize the source loading and management modeling required to quantify the amount of pollutant captured by BMPs. It is an approved model in Delaware, Georgia, Minnesota, New York and Wisconsin and it is referenced by stormwater design manuals in 14 other states across the US.

WinSLAMM documentation[3] describes three mechanisms by which a BMP like permeable pavement can remove pollutants carried by stormwater. Stormwater is first filtered through the surface and bedding layers in the top portions of the pavement section removing larger-sized particles. The second pollutant removal mechanism is settling and can only occur if the stormwater is allowed to *pond* within a BMP. As water ponds inside a BMP, particles can begin to settle out at the bottom of the storage gallery. The third mechanism is through infiltration of stormwater directly into the subgrade beneath a BMP.

Ideally, all infiltration-type BMPs would infiltrate all water such that they achieve 100% pollutant removal credit for every drop of stormwater runoff entering these systems. This may or may not be feasible given the risks of failure outlined previously. The next best scenario would be to maximize infiltration to the greatest extent possible by sizing and locating underdrains within storage galleries such that stormwater is ponded for the full drawdown period after every rain event. To achieve the latter, existing design and construction methods would require engineers to retrofit BMPs with valves at underdrain outlets. Someone would then need to visit the site after rain events, monitor water levels and open or close valves accordingly within the drawdown time. The process just described would place a large and unpractical demand on limited staff devoted to stormwater management and would likely generate more cost in labor than is saved through increased pollutant removal efficiency.

Stormwater Volume Calculation

The INFIL-Tracker and Flow-RTC systems are founded on stormwater volumes entering and leaving the storage galleries measured with a liquid level device. Figure 6 illustrates water levels in a typical storage gallery over time with infiltration and underdrain discharge of stormwater from the gallery. The water volume is calculated through tracking water level in real-time and the plan area of the aggregate storage gallery. The volume of stormwater in the gallery varies over time and it varies with the water level in the gallery.

There are several interesting points to make regarding the water level variation over time. There are two fundamental discharge rates that can be seen in the time history. The first is a discharge rate that is a combination of discharge flow through underdrain and infiltration. The second discharge rate occurs when water level is below the

[3] http://winslamm.com/docs/WinSLAMM%20Model%20Algorithms%20v7.pdf

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invert of the underdrain. This discharge rate is flatter (slower) than the discharge through underdrain in combination with infiltration.

The time history behavior schematically shown in Figure 6 has been seen in a monitored permeable pavement storage gallery in Cudahy, Wisconsin. Figure 7 shows measured data from Van Norman Alley in Cudahy from January through end of March 2020. The bifurcation modeled in Figure 6 is illustrated in Figure 7 in the water level time history. It is interesting to note that the surface of the permeable pavement illustrated in the photo in Figure 7 appears to be plugged. Water is, however, clearly infiltrating through the surface of the pavement into the gallery.

Figure 8 illustrates how measured rainfall data is correlated with water levels from the INFIL-Tracker and Flow-RTC systems to define rain events and stormwater volume captured and discharged for a rain event(s). Although definitions of rain events can be altered for specific circumstances, P4 has defined a rain event as rainfall bounded by lack of rainfall for a minimum of 24 hours preceding and trailing the event. The rain event begins after a 24-hour period of no rain and ends following a 24-hour period of no rain. P4 correlates rainfall data measured via the P4 Rain-mX™ sensor system with the INFIL-Tracker™ sensor system. Water level time history within the rainfall event window is then used to measure stormwater storage volume during that rain event.

Illustration of the calculations used to compute water volume entering a storage gallery during rain events is given in Figure 9. Permeable pavement and bioremediation system storage galleries can have a variety of configurations. Two typical configurations considered by P4 in these calculations is shown in Figure 9. Gallery storage volumes corresponding to water levels measured during two hypothetical rain events at the Van Norman Alley are computed using a MathCAD™ worksheet. This is a simple computation illustrating how water level measurement can be used to compute stormwater volume in the gallery.

The P4 systems include browser-based dashboard viewing of sensor data. The P4 dashboard is shown in Figure 10. The upper image is the P4 sensor network viewed within an ESRI/ArcGIS™ environment. The central image is the sensor network for Cudahy, Wisconsin which consists of three permeable pavement sites instrumented with INFIL-Tracker™ devices and rainfall measurements in Cudahy at City Hall using a Rain-mX™ device. Device owners, and data subscribers to the P4 network, have the ability to download rainfall and sensor data. The CSV downloaded rainfall and sensor data for a permeable pavement storage gallery can be used in conjunction with Excel™ or another software package to compute stormwater storage volume during rainfall events.

The bottom image in Figure 10 illustrates the downloaded CSV data for the Van Norman Alley in Cudahy, Wisconsin. This data included two rainfall events as defined in Figure 8. These two events and the water level recorded is shown in the image. The two rainfall events resulted in 1.8 ft^3 (13.4 gallons) and 64.3 ft^3 (480.7 gallons) of stormwater storage for the two events. This indicates that these two events resulted in 66 ft^3 (494 gallons) of rainwater being captured in, and moved through, the Van Norman Alley permeable pavement gallery.

Increasing BMP Efficiency

A typical stormwater BMP installation with underdrain was outlined earlier in Figure 3. This BMP schematic includes a Rain-mX™ device for rainfall measurement and Flow-RTC™ that includes water level measurement and real-time control of gallery underdrain discharge.

BMP efficiency and pollutant removal efficiency can be thought of in a very simple way using the conceptual diagram shown in Figure 3. When it rains, water runs over land and turns into stormwater surface runoff. The surface runoff makes its way to the BMP (shown schematically by the funnel). The left side of the figure illustrates behavior common to most permeable pavement and bio-remediation storage galleries. When stormwater runoff entering the gallery is discharged through underdrain, suspended solids (TSS) and phosphorus (TP) is removed with 65% and 35%

efficiency, respectively. If the stormwater volume is infiltrated, TSS and TP efficiency is 100%. This implies that, if the volume of stormwater leaving the gallery through infiltration can be separated from the volume of stormwater leaving the gallery through underdrain, the efficiency of the BMP in removing TSS and TP can be measured and controlled.

The volume of stormwater in a BMP storage gallery is calculated as outlined earlier. When analyzing a BMP, engineers quantify the total volume of stormwater runoff, V_T, the portion of total volume infiltrated into subgrade, V_{inf}, the portion of total volume discharged through underdrain, V_U, and the portion of the total volume that will bypass the system altogether (*e.g.* overflow), V_B,

$$V_T = V_{inf} + V_U + V_B \quad (1)$$

The three potential paths for stormwater runoff have the following pollutant removal efficiencies:

1. enter the BMP and completely infiltrate into the ground beneath the surface providing 100% pollutant reduction
2. enter the BMP, partially infiltrate into the ground providing 100% pollutant reduction for this portion of rainfall infiltrated, and partially discharge the remaining through an underdrain where it is conveyed to surface waters providing a BMP-specific fraction (e.g. 35-65%) pollutant reduction for this portion
3. bypass the BMP providing 0% pollutant reduction for this portion. The BMP is sized such that V_B goes to zero for obvious reasons.

Flow-RTC™ allows control of the paths of stormwater movement out of the BMP storage gallery. The time history of stormwater volume without real-time control was schematically shown in Figure 6 and has been monitored in Cudahy, Wisconsin (Figure 7). The data from Cudahy, Wisconsin illustrates that the majority of stormwater migrating out of the storage gallery is being accomplished by underdrain discharge. There is, however, infiltration occurring as shown by the second discharge rate seen in the data. Real-time control added to the BMP as shown schematically in Figure 3 changes this fundamental behavior as shown schematically in Figure 11.

Rain events "charge" the storage gallery with stormwater runoff and this runoff volume can be held in the BMP storage gallery as long as guidelines allow using real-time control (RTC). For example, in Wisconsin, this storage duration can be 72 hours before the required drawdown period is exceeded. Thus, the autonomously controlled valve on the underdrain can be held closed for 72 hours and the volume of stormwater infiltrated can be quantified using the measured water level. Once the drawdown period limit is reached, the real-time control aspect to the system opens the valve and the volume of water discharged through combined underdrain and infiltration is quantified, again via the water level measurement. Once the water level reaches the invert of the underdrain pipe, the discharge returns to that of infiltration. At this point, however, the gallery is essentially empty.

The process described allows water level measurements and corresponding storage and discharged volumes of stormwater to be used to determine pollutant removal at 100% (infiltration) versus 65/35 (underdrain) for typical infiltration-based stormwater BMPs. The pollutant concentrations for land use assumed in SLAMM allow these volumes of stormwater discharge to be used to define pollutant removal amounts.

The pollutant concentrations in stormwater are a function of annual rainfall volume and land use. Pollutant concentrations for the Van Normal Alley in Cudahy, Wisconsin can be taken as 0.0126 lbs/cf for TSS and 0.000029 lbs/cf for TP. If one were to use the measured 66 ft^3 (494 gallons) of stormwater and the pollutant concentrations for its contributing land area, the BMP at Van Norman Alley could be said to remove 0.83 lbs of TSS and 0.0019 lbs of TP for these two rain events. The accumulation of pollutant for rain events continues all year and these pollutant removal amounts can be accumulated throughout the year. Annual pollutant removal is simply the aggregation of pollutant removal for all rain events during that year.

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An even more interesting scenario arises when the assumptions for infiltration rates used in the SLAMM analysis for the BMP deviate from measured data. As outlined earlier, an assumed infiltration rate of 0.04 in/hr used for initial modeling results in 5.6% reduction in filterable solids and 5.6% reduction in filterable phosphorus (Figure 5). If INFIL-Tracker monitoring shows that subgrade seepage is 2.5 in/hr, these pollutant reductions increase to 75.2% for filterable solids and 74.7% for filterable phosphorus. This is approximately 70% improvement in pollutant removal efficiency. It should be noted that the volume of stormwater moving through the gallery is also measured thereby providing improvement to the SLAMM analysis of the watershed (*i.e.* runoff coefficients can be altered to better reflect actual catchment area).

Relatively large intensity and duration rain events that occur with minimal separation in time (*e.g.* a 1 in/hr event lasting 1 hour followed by a 1.5 in/hr event lasting two hours the next day) have a relatively large volume of surface runoff generated in a “back-to-back” scenario. This outlines the “first flush” concept that implies that the second rain event in a closely spaced series of events does not have the same pollutant concentration as the first event. In other words, the first rain event flushes away most of the pollutant and there is no time for pollutant to accumulate on the surface by the time the second rain event occurs.

Figure 8 outlined a potential definition of rainfall event(s) and this definition was used to compute stormwater volume captured and migrated through a BMP. The continuous monitoring of rainfall and water level allows a BMP asset owner to define rainfall events throughout the life of the infrastructure system. These rainfall events have time/date stamps and sequences of these events can be defined and their intensity established. Therefore, the data acquired can be used to look at stormwater volume capture for each rain event. If a regulatory agency can provide recommendation on how “first flush” is defined, then asset owners can easily include this definition in the computation of stormwater volume and pollutant removal in the reporting of pollutant capture for a BMP. An asset owner will also have the ability to report stormwater volume capture and pollutant removal for each rain event that happens annually for a BMP. The first flush concept can be retroactively applied at the end of the year by looking at the history of rain events and their separation and asset owners can easily take credit for only those events that occur with proper separation. It should be emphasized, however, that the value in using the P4 systems is that these rain events and their corresponding stormwater volume captured can be measured and regulatory agencies will have data to help further understanding of what the first flush concept actually means and how to assess water quality impacted through stormwater runoff.

Maintenance of BMPs

Maintaining stormwater BMPs has historically been tricky business. If a bio-remediation system is being used, this system may have observation wells that need to be manually inspected after significant rain events to ensure that the system is being emptied within the required drawdown period. These systems also need to be visited periodically to ensure that no standing water or ponding is present at the BMP surface. A permeable pavement system is visually inspected on a periodic basis (*e.g.* semi-annually) to examine the pavement surface to assess its permeability. There are also relatively arbitrary semi-annual vacuum procedures recommended for permeable pavement surfaces to ensure functionality. These manual inspections by trained personnel, and costly maintenance interventions performed on ad-hoc bases, make the cost-effectiveness of stormwater BMPs highly uncertain to asset owners. Furthermore, the perceived added maintenance of these systems prevents widespread use of diversity in stormwater BMPs (*i.e.* “I have no idea what the real maintenance cost of distributed bioswales and permeable pavement parking lanes are going to be, so I am going to use a 5-acre wet detention pond and avoid these other BMPs”).

The value of the P4 systems in maintenance are significant. Remote and real-time water level monitoring in stormwater BMP assets allows manual site visits to be defined using data rather than arbitrary site visits. The ability to measure water level beneath a permeable pavement surface allows what appears to be a plugged surface (*e.g.* Figure 7)

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to be assessed as functional rather than arbitrarily executing a vacuum effort. This remote monitoring will facilitate understanding of when storage galleries are actually filling at slower rates over time and therefore, site visits can be scheduled when needed rather than on an arbitrarily fiscally wasteful schedule. A bioremediation asset owner can watch drawdown of a storage gallery remotely and conduct a site visit if drawdown is slow or not occurring. Furthermore, alerts can be sent to cell phones and computers (email) to alert asset owners' maintenance is needed.

Graphical Method for Management of Stormwater BMPs

The P4 systems and technology are also beneficial to management of stormwater BMPs (non-structural and structural) in pursuit of satisfying MS4 permitting and TMDL compliance. It is hoped that stormwater BMPs will become an enhanced part of modern stormwater infrastructure as there are significant benefits for improving surface water quality and mitigating flooding with their use. The challenge remains the ability of these systems to be successfully and economically integrated into communities.

MS4 permitting and TMDL compliance goals are often the motivation for stormwater management plans developed by communities. These plans are comprehensive studies of what type, how many, and where to place structural stormwater BMPs (*e.g.* bioswales, wet-detention, permeable pavement) and how and where and how often to conduct non-structural stormwater BMPs (*e.g.* street sweeping, catch-basin cleaning). Communities can receive stormwater management plans that recommend exceedingly costly stormwater management recommendations obfuscated by tabulated reporting of what really amounts to very complex systems.

P4 has developed BMP management tools that help communities understand what BMPs to implement, where to utilize BMPs within MS4s and TMDL watersheds, and most importantly, how to make these decisions with fiscal efficiency and responsibility. P4 has developed these tools using sunburst plotting that clearly illustrates pollutant removal, compliance gaps and potential pollutant credits generated within communities. The tools also give communities and private asset owners an ability to understand how reaches and subreaches within watersheds contribute toward compliance and how different alternatives for BMP construction contributed toward overall pollutant removal.

The P4 visualization tools for compliance can be discussed by starting with Figure 12. This figure illustrates sunburst plots for total suspended solids (TSS) pollutant load and removal. The Modeled TSS Load sunburst is a graphical depiction of pollutant loads resulting from SLAMM analysis of a community with two watershed reaches. Reach 1 has two subreaches and Reach 2 has one subreach. The circumferential length associated with a reach is the pollutant load in that reach. The top left sunburst in Figure 12 illustrates that Reach 1 and Reach 2 have similar pollutant loads in the community. The pollutant load contributed by Subreach 1 and Subreach 2 in Reach 1 is also shown in the sunburst and it is shown that Subreach 1 contributes greater pollutant load to Reach 1. This sunburst also illustrates that there are two BMPs in Subreach 3 (of Reach 2), one BMP in Subreach 1 (of Reach 1), and two BMPs in Subreach 2 (of Reach 1). The size of the BMP "pie" illustrates how much of the pollutant load in the Subreach is treated by the BMP.

Communities are given goals to meet with regard to pollutant removal. These goals result in gaps that need to be filled for compliance. These compliance gaps are at Reach levels in the community. The Modeled TSS Gap shown in Figure 12 (upper right sunburst) illustrates how the BMPs contribute to TMDL compliance and the TSS compliance gaps that are present for each reach in the community. If one were to look at the upper-right sunburst in Figure 12, one can see that two BMPs in Reach 2 are accomplishing roughly 50% of what is needed for compliance. A similar scenario is present for Reach 1. This very quickly suggests that the capital costs of constructing existing BMPs 1-5 in the community will need to be spent to reach TSS compliance goals.

These sunburst plots also give communities graphical demonstration of how P4 sensor systems (*e.g.* INFIL-Tracker, Flow-RTC) help reduce the gaps needed for compliance. Moving pollutant removal efficiencies from those

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dictated by underdrain discharge to discharge through infiltration has significant impact on meeting compliance goals as well as future expenditures to meet these goals. The Measured TSS Load sunburst (lower left sunburst in Figure 12) shows what can happen when BMP pollutant removal efficiencies are improved as a result of migrating to full infiltration of stormwater rather than discharge through underdrain. The size of the pie slices for BMPs 1 – 5 in this sunburst increases and the compliance gaps shown in the Measured TSS Gap (lower right sunburst in Figure 12) are reduced.

Figure 12 also includes tabulated effective costs to remove and close gaps in compliance for the community considered. The dollar amounts shown in these tables are based upon typical costs to remove a pound of suspended solids.

Figure 13 illustrates Modeled and Measured loads and compliance gaps for phosphorus pollutant in the same community considered previously. The value of phosphorus removed and the cost of closing gaps for phosphorus are shown in the tables. It should also be noted that the expense to remove phosphorus is greater than suspended solids.

Figure 14 illustrates how the sunburst plots can be “drilled into” by clicking on reach rings in the sunburst plot. This makes looking at more complicated numbers of reaches and subreaches in communities easier to visualize. The impact of sensors confirming infiltration in TP pollutant removal and closing compliance gaps can be seen in the stacked sunbursts (Modeled TP Gap and Measured TP Gap) on the right side of Figure 14.

The further value of the sensor and sunburst technology of P4 is shown in Figure 15. Communities are often met with Clean Water Act compliance requirements and have not fully addressed contributions of BMPs that are currently in place and owned by the community toward compliance goals. BMPs that are owned by private entities and those that do not have maintenance agreements in place are also often ignored in meeting compliance goals. P4 has developed its sensor technology to aid communities in taking account of these types of stormwater BMPs in meeting their Clean Water Act compliance goals. Stormwater BMPs owned by communities can be instrumented and their effectiveness can be immediately measured. Maintenance on these BMPs to bring them to functionality can then be addressed (if required) based upon the measured performance. Privately owned BMPs with uncertain maintenance history or lacking maintenance agreements can have P4 instrumentation serve as indicators of performance and can even serve as a remotely monitored demonstration of functionality (*i.e.* de-facto maintenance agreement with private entity).

If existing BMPs and privately owned BMPs are brought into the suite of BMPs communities use to meet Clean Water Act compliance, these can have a significant impact on the expense needed to close compliance gaps. If these systems and the existing systems (through instrumentation) are shown to be more efficient in pollutant removal, communities can actually achieve TMDL credits. Illustration of this is in Figure 15. The credits can also be shown at the reach level in the community (lower right sunburst in Figure 15). The ability to drill down into the sunburst and gain relative appreciation of BMP contribution and reach credits is shown in Figure 16.

The P4 viewing technology illustrated in the sunburst charts give communities a visual mechanism to: understand how their current stormwater BMP network contributes to TMDL compliance; display the impact of implementing P4 sensor technology on compliance; quantify the impact of BMPs not previously considered in meeting compliance on compliance goals; and document the path and source of credit trading in the community.

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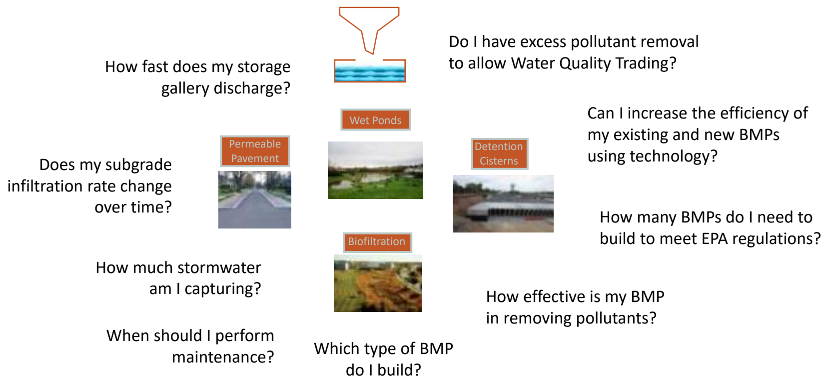

Figure 1. Questions Often Asked Regarding Stormwater BMPs

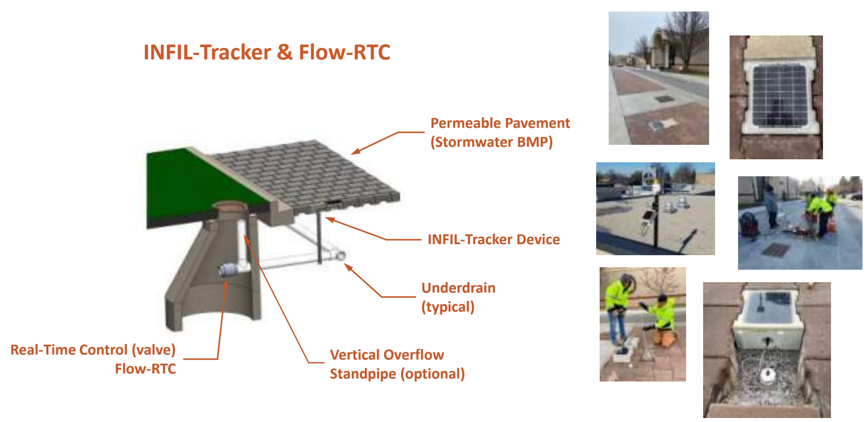

Figure 2. INFIL-Tracker and Flow-RTC Systems

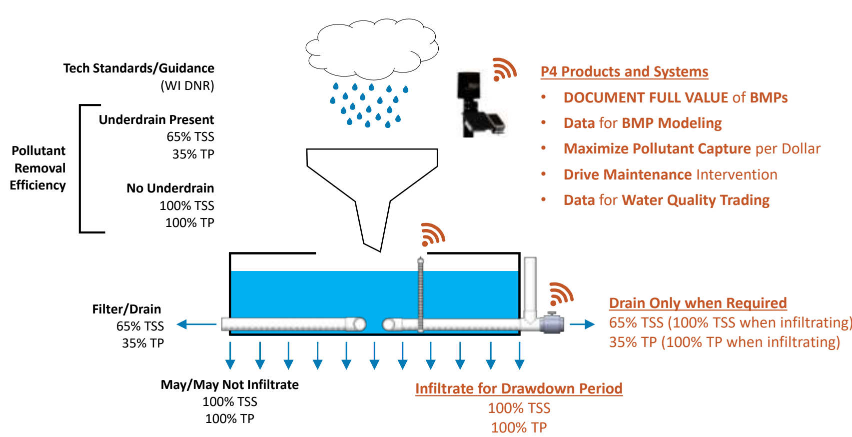

Figure 3. Infiltration and Underdrain-Based Structural Stormwater BMP

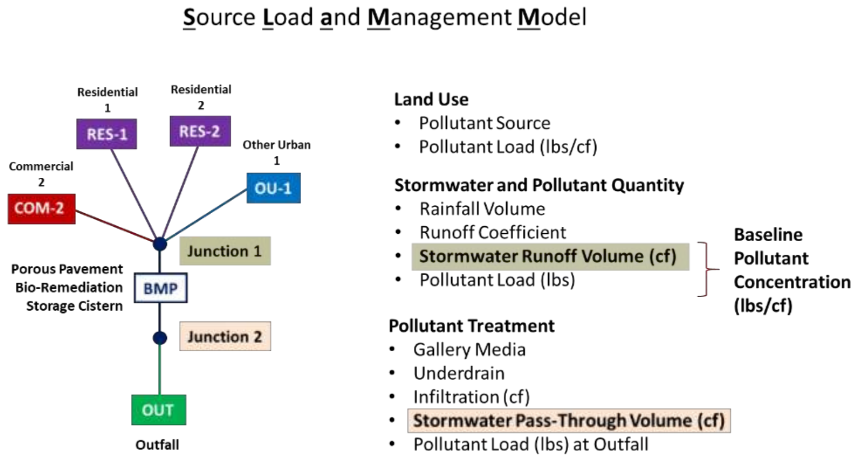

Figure 4. SLAMM Fundamentals

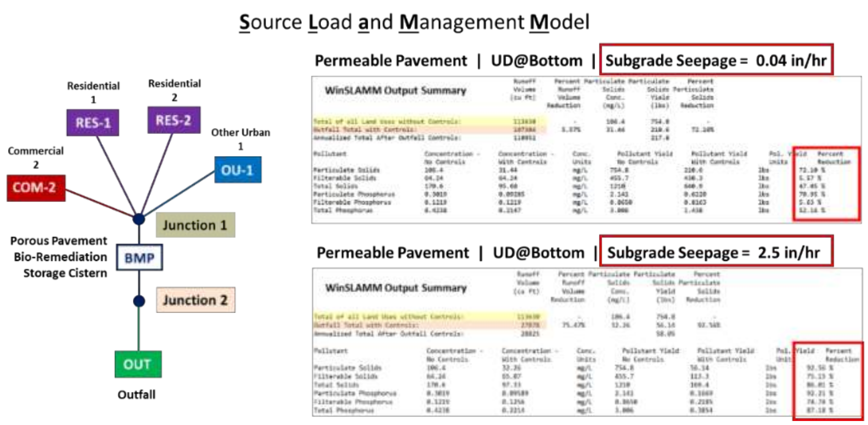

Figure 5. SLAMM Analysis Results Variability with Infiltration Rate

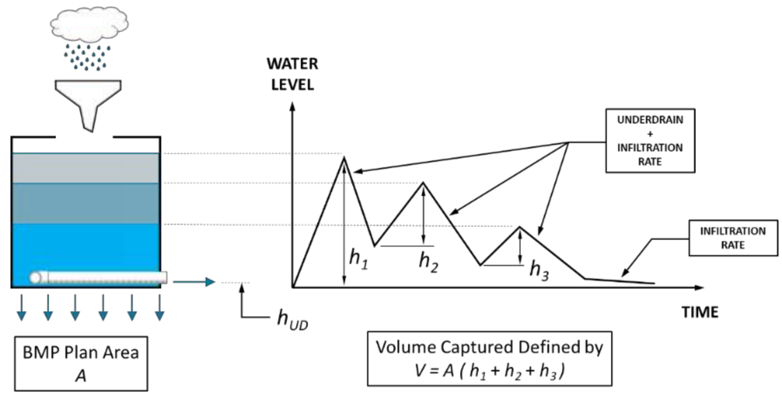

Figure 6. Water Level Time History, Stormwater Volume Capture, and Infiltration Rate

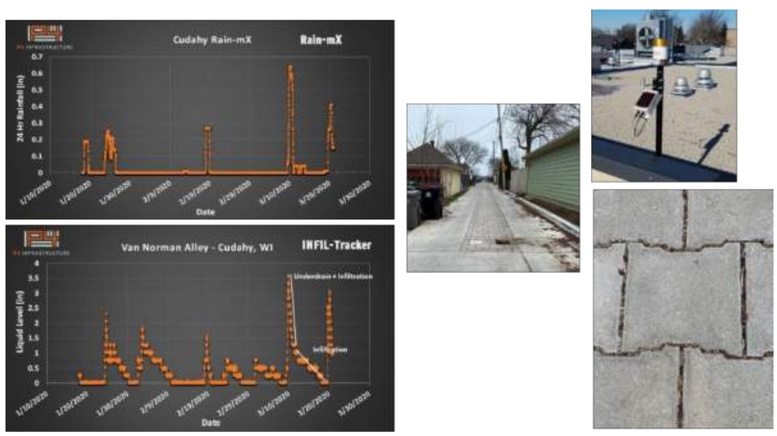

Figure 7. Measured Water Level Time History at Van Norman Alley, Cudahy, Wisconsin.

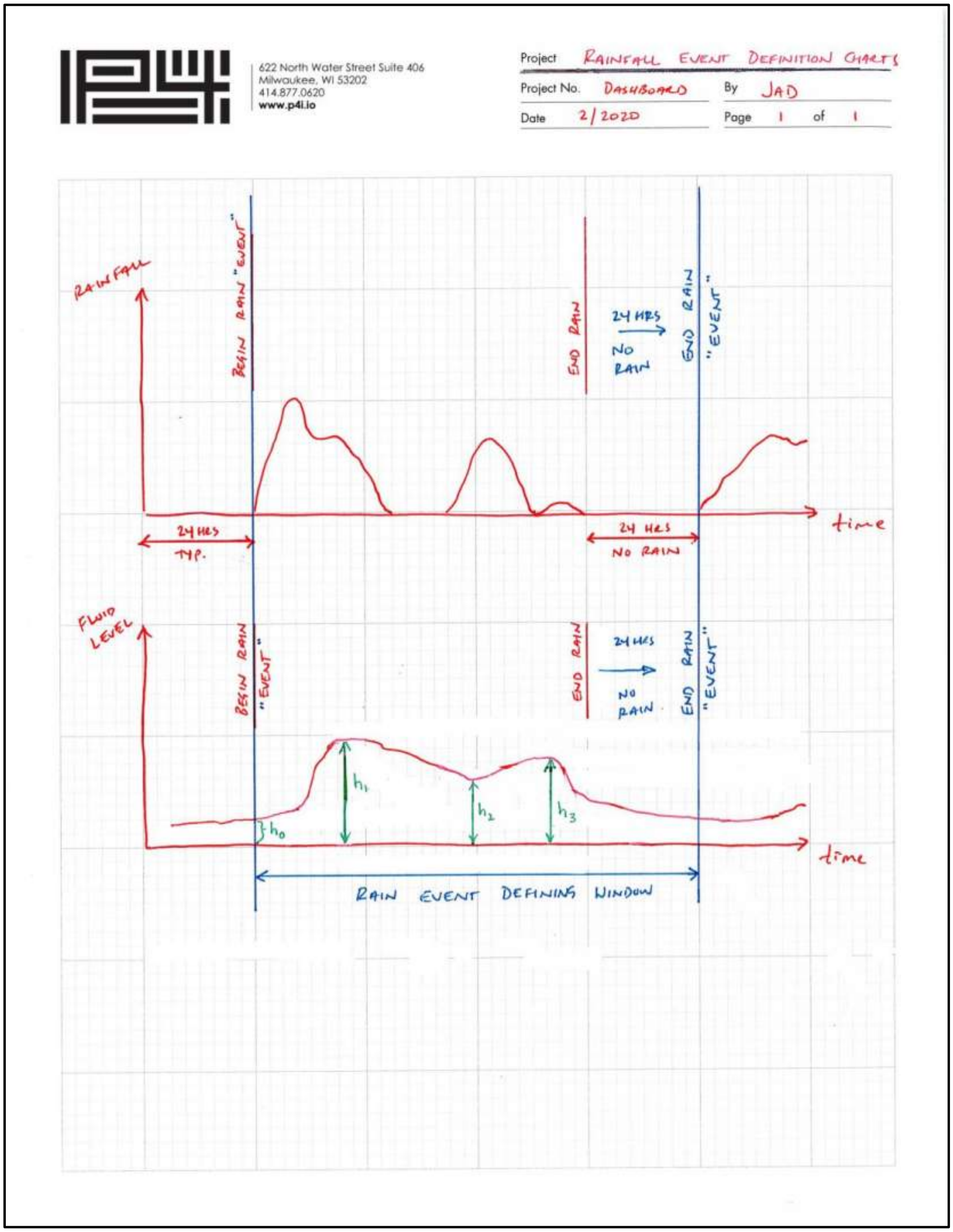

Figure 8. Rainfall Event Definition (other possibilities exist)

P4 INFRASTRUCTURE

INFIL-Tracker Dashboard Calculations

Total Maximum Daily Load (TMDL) Compliance Calcs

For a given site, the customer, or customer's civil engineering consultant, will provide the following site-specific information:

A_{WS} **acres** (watershed area draining to site)

- The watershed area may be comprised of several types of land use (e.g. some green space, some hardscape, some residential, some roof, etc.)
- Each land use has a prescribed runoff coefficient

V_{Runoff_design} **cubic feet** (annual volume of runoff)

- The annual runoff volume is currently based upon rainfall data collected at various locations throughout the US (typically at airports). The rainfall data used in WI is from General Mitchell, collected in 1969.

TSS **lbs** (total suspended solids)

- Pounds of TSS are based upon land use within the watershed area and runoff volume.

TSS_{conc} **lbs/cubic foot** (suspended solids concentration in runoff)

TP **lbs** (total phosphorus)

- Pounds of TP are based upon land use within the watershed area and runoff volume.

TP_{conc} **lbs/cubic foot** (phosphorus concentration in runoff)

w_1	**ft**	(width of lower storage gallery)
l_1	**ft**	(length of lower storage gallery)
d_1	**in**	(average depth of lower storage gallery)
n_1	**unitless**	(porosity of lower storage gallery)
w_2	**ft**	(width of upper storage gallery)
l_2	**ft**	(length of upper storage galler)
d_2	**in**	(average depth of upper storage gallery)
n_2	**unitless**	(porosity of upper storage gallery)

Figure 9. MathCAD Worksheet Computations for Stormwater BMP Volume Capture

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INFIL-Tracker Dashboard Calculations

Van Norman Alley Example - Rain Event 1

$A_{WS} := 0.438\ acre$

$V_{Runoff\_design} := 22678\ ft^3$

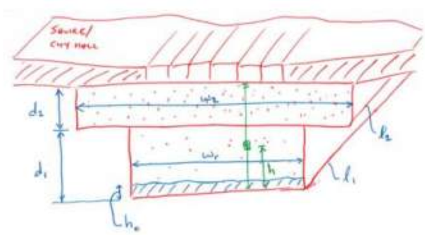
$TSS := 286\ lb$

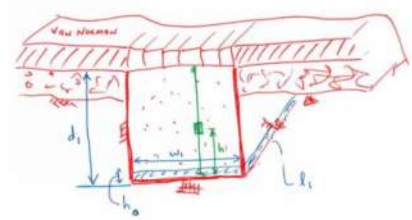
$TP := 0.654\ lb$

$$TSS_{conc} := \frac{TSS}{V_{Runoff\_design}} = 0.013\ \frac{lb}{ft^3}$$

$$TP_{conc} := \frac{TP}{V_{Runoff\_design}} = \left(2.884 \cdot 10^{-5}\right)\ \frac{lb}{ft^3}$$

Storage Gallery Dimensions/Properties





$w_1 := 4.1\ ft$ $\quad w_2 := 5\ ft$

$l_1 := 206.5\ ft$ $\quad l_2 := 206.5\ ft$

$d_1 := 46\ in$ $\quad d_2 := 12\ in$

$n_1 := 0.4$ $\quad n_2 := 0.4$

P4 INFIL-Tracker Measurements

$h_0 := 0.009035\ in$

$h_1 := 0.072283\ in$

$h_2 := 0\ in$

$h_3 := 0\ in$

Figure 9. (continued)

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If there is only one peak during the rain event:

for $h_0 \le d_1$ and $h_1 \le d_1$

$V_{captured} := (h_1 - h_0) \cdot w_1 \cdot l_1 \cdot n_1 = 1.785\ ft^3$

for $h_0 \le d_1$ and $h_1 > d_1$

$V_{captured} := (d_1 - h_0) \cdot w_1 \cdot l_1 \cdot n_1 + (h_1 - d_1) \cdot w_2 \cdot l_2 \cdot n_2 = -282.737\ ft^3$

for $h_0 > d_1$ and $h_1 > d_1$

$V_{captured} := (h_1 - h_0) \cdot w_2 \cdot l_2 \cdot n_2 = 2.177\ ft^3$

Figure 9. (continued)

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INFIL-Tracker Dashboard Calculations

Van Norman Alley Example - Rain Event 2

$A_{WS} := 0.438\ \mathbf{acre}$

$V_{Runoff\_design} := 22678\ \mathbf{ft^3}$

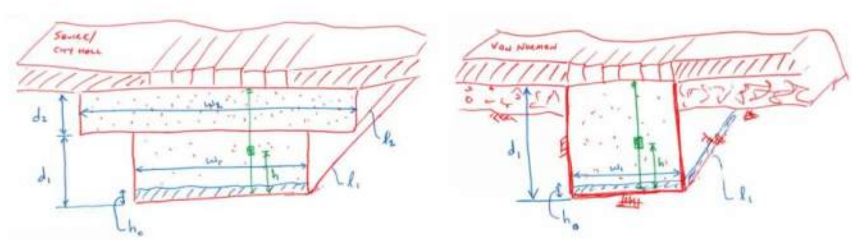
$TSS := 286\ \mathbf{lb}$

$TP := 0.654\ \mathbf{lb}$

$$TSS_{conc} := \frac{TSS}{V_{Runoff\_design}} = 0.013\ \frac{\mathbf{lb}}{\mathbf{ft^3}}$$

$$TP_{conc} := \frac{TP}{V_{Runoff\_design}} = \left(2.884 \cdot 10^{-5}\right)\ \frac{\mathbf{lb}}{\mathbf{ft^3}}$$

Storage Gallery Dimensions/Properties



P4 INFIL-Tracker Measurements

$w_1 := 4.1\ \mathbf{ft}$ $w_2 := 5\ \mathbf{ft}$

$l_1 := 206.5\ \mathbf{ft}$ $l_2 := 206.5\ \mathbf{ft}$

$d_1 := 46\ \mathbf{in}$ $d_2 := 12\ \mathbf{in}$

$n_1 := 0.4$ $n_2 := 0.4$

$h_0 := 0.036142\ \mathbf{in}$

$h_1 := 2.313065\ \mathbf{in}$

$h_2 := 0.67766\ \mathbf{in}$

$h_3 := 1.30110\ \mathbf{in}$

Created with PTC Mathcad Express. See www.mathcad.com for more information.

Figure 9. (continued)

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INFIL-Tracker Dashboard Calculations

If there is only one peak during the rain event:

for $h_0 \le d_1$ and $h_1 \le d_1$

$$V_{captured} := (h_1 - h_0) \cdot w_1 \cdot l_1 \cdot n_1 = 64.259\ ft^3$$

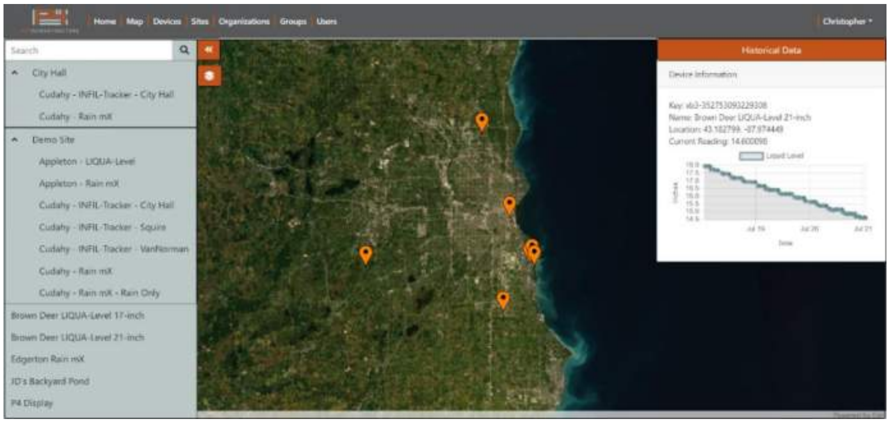
for $h_0 \le d_1$ and $h_1 > d_1$

$$V_{captured} := (d_1 - h_0) \cdot w_1 \cdot l_1 \cdot n_1 + (h_1 - d_1) \cdot w_2 \cdot l_2 \cdot n_2 = -206.382\ ft^3$$

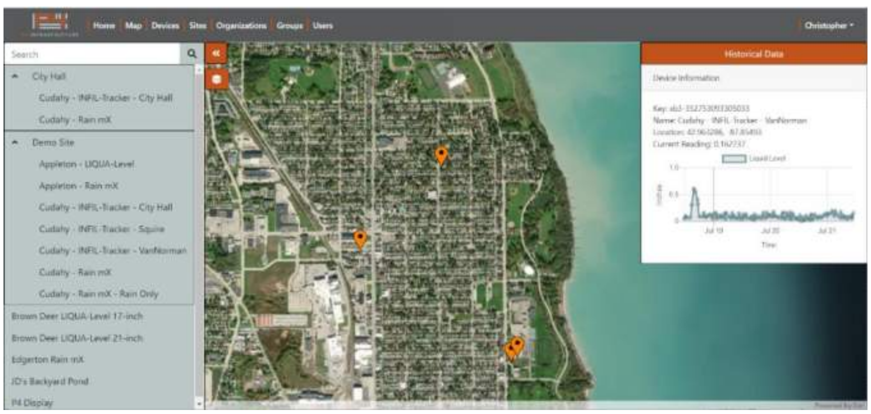
for $h_0 > d_1$ and $h_1 > d_1$

$$V_{captured} := (h_1 - h_0) \cdot w_2 \cdot l_2 \cdot n_2 = 78.364\ ft^3$$

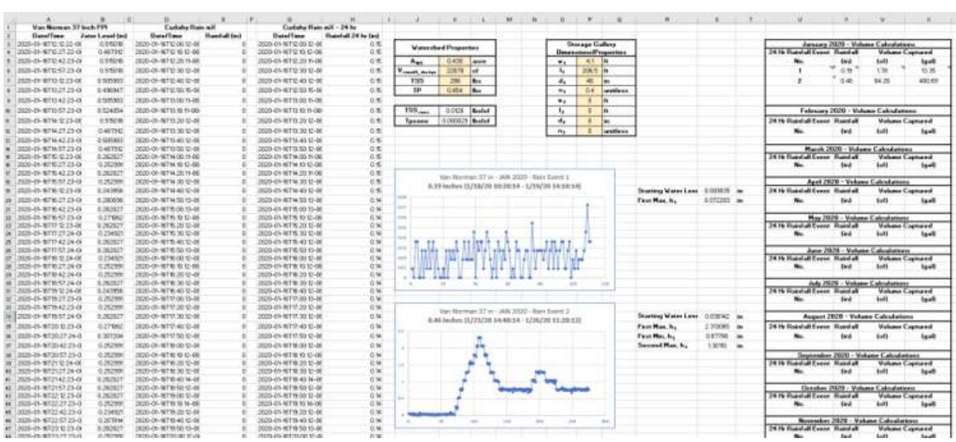
Figure 9. (continued)



(a) P4 Dashboard View of Wisconsin Sensor Network



(b) P4 Dashboard View of City of Cudahy, WI Sensor Network



(c) P4 CSV Downloaded Data and Excel Stormwater Volume Calculations

Figure 10. P4 Sensor Data used for Stormwater Volume Capture

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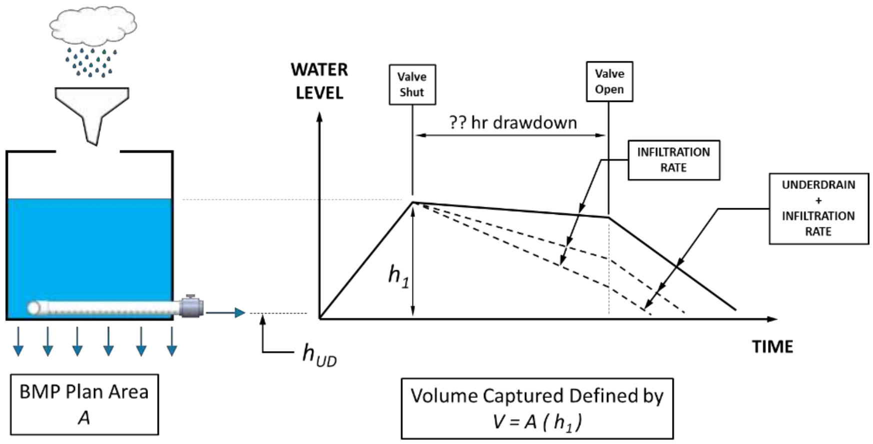
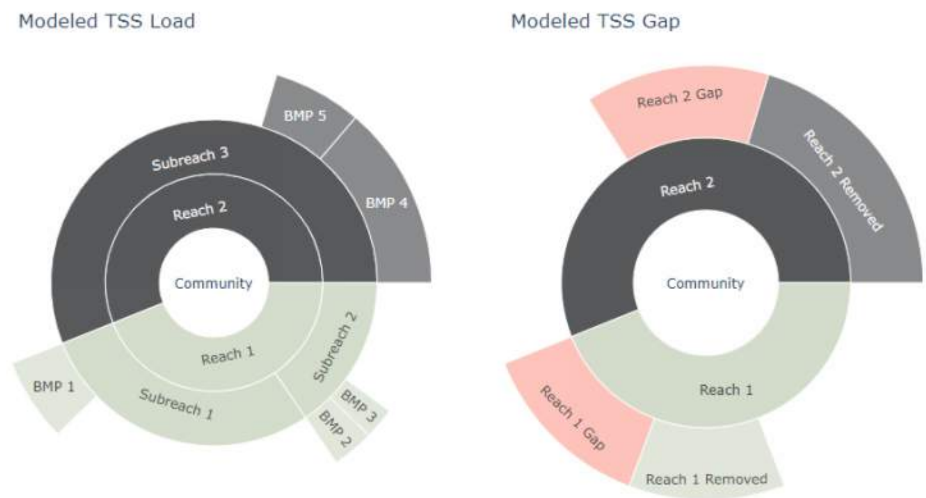


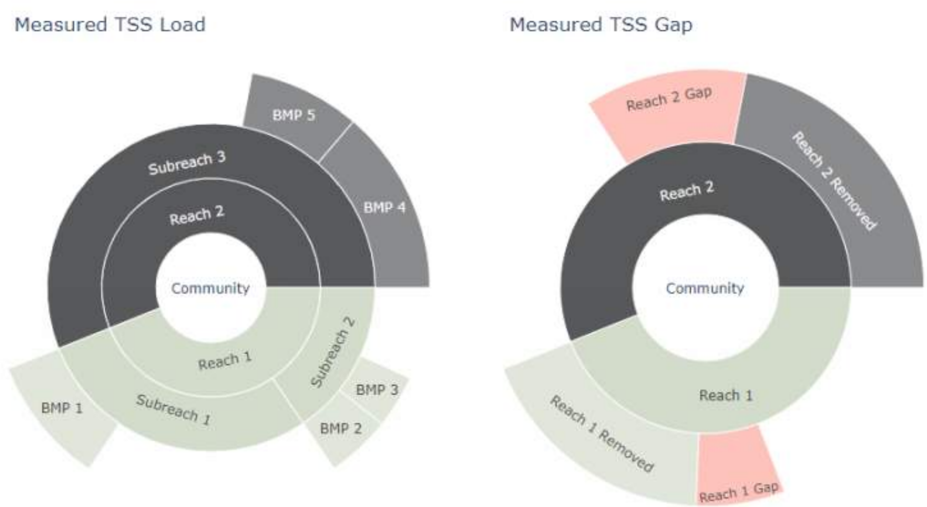
Figure 11. Water Level Time History, Stormwater Volume Capture, and Infiltration Rate with Real-Time-Control



Modeled TSS Cost Summary

TOGGLE COLUMNS

Label	Type	Effective Cost
Reach 1 Gap	Gap	$17,525
Reach 1 Removed	Value	$15,482
Reach 2 Gap	Gap	$18,280
Reach 2 Removed	Value	$27,036



Measured TSS Cost Summary

TOGGLE COLUMNS

Label	Type	Effective Cost
Reach 1 Gap	Gap	$8,788
Reach 1 Removed	Value	$24,220
Reach 2 Gap	Gap	$16,087
Reach 2 Removed	Value	$29,229

Figure 12. Sunburst Charts and Tabulated Data for Suspended Solids (TSS) TMDL Compliance

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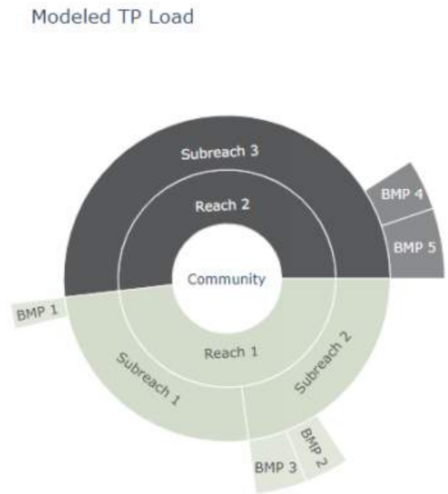

Modeled TP Cost Summary

TOGGLE COLUMNS

Label	Type	Effective Cost
Reach 1 Gap	Gap	$89,411
Reach 1 Removed	Value	$67,232
Reach 2 Gap	Gap	$141,430
Reach 2 Removed	Value	$67,232

Measured TP Cost Summary

TOGGLE COLUMNS

Label	Type	Effective Cost
Reach 1 Gap	Gap	$42,377
Reach 1 Removed	Value	$114,265
Reach 2 Gap	Gap	$141,430
Reach 2 Removed	Value	$67,232

Figure 13. Sunburst Charts and Tabulated Data for Phosphorous (TP) TMDL Compliance

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Modeled TP Cost Summary

Label	Type	Effective Cost
Reach 1 Gap	Gap	$89,411
Reach 1 Removed	Value	$67,232
Reach 2 Gap	Gap	$141,430
Reach 2 Removed	Value	$67,232

Measured TP Cost Summary

Label	Type	Effective Cost
Reach 1 Gap	Gap	$42,377
Reach 1 Removed	Value	$114,265
Reach 2 Gap	Gap	$141,430
Reach 2 Removed	Value	$67,232

Figure 14. Sunburst Charts and Tabulated Data for TP TMDL Compliance for Specific TMDL Reach

Label	Type	Effective Cost
Reach 1 Gap	Gap	$8,788
Reach 1 Removed	Value	$24,220
Reach 2 Gap	Gap	$16,087
Reach 2 Removed	Value	$29,229

Label	Type	Effective Cost
Reach 1 Gap	Gap	$8,788
Reach 1 Removed	Value	$24,220
Reach 2 Credit	Credit	$10,218
Reach 2 Removed	Value	$45,316

Figure 15. Sunburst Charts and Tabulated Data for Suspended Solids (TSS) TMDL Compliance with Added BMPs

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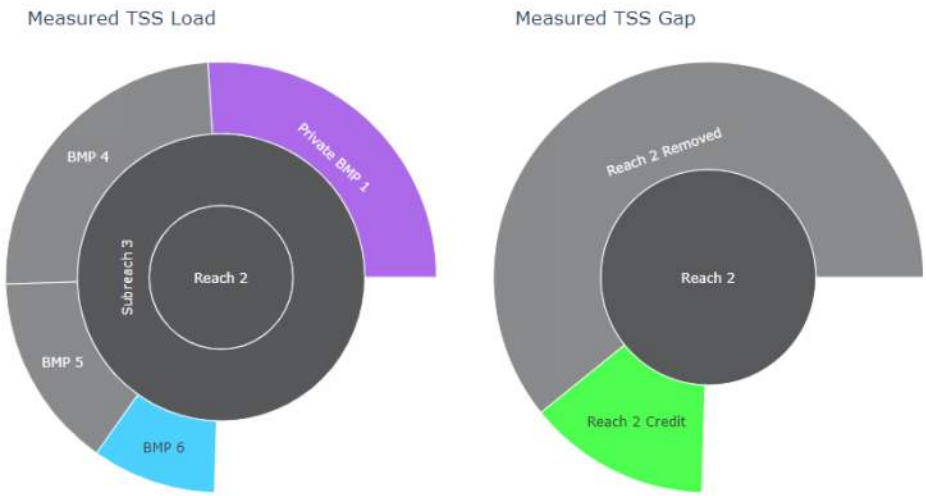

Measured TSS Cost Summary

TOGGLE COLUMNS

Label	Type	Effective Cost
Reach 1 Gap	Gap	$8,788
Reach 1 Removed	Value	$24,220
Reach 2 Credit	Credit	$10,218
Reach 2 Removed	Value	$45,316

Figure 16. Sunburst Charts and Tabulated Data for Suspended Solids (TSS) TMDL Compliance with Added BMPs in a Specific TMDL Reach