A Comparison of Methods and a Simple Empirical Solution to Quantifying Base Infiltration in Sewers

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ABSTRACT

This paper addresses three empirical prediction methods used to estimate the magnitude of Base Infiltration (BI) in 45 isolated sewer basins throughout the Orange County Sanitation District (OCSD) collection system: night-time "Wastewater Production", "Minimum Flow Factor", and a third empirical method employing the "Stevens-Schutzbach" equation. These empirical methods were tested against a chemical parameter verification method that involves regressing hourly concentrations of several common wastewater chemical analysis parameters (Chemical Oxygen Demand – COD, etc.) with hourly sewage flow rates. The chemical parameter method results were also compared to BI estimates based on potable water use records. In addition the Wastewater Production and Stevens-Schutzbach methods were evaluated by comparing the BI predictions to the sewer flows during the Northeast Power Blackout of 2003. Results indicate that the Stevens-Schutzbach equation provides a more accurate estimate of BI in basins yielding flows comprised of more than 20% BI.

KEYWORDS: Infiltration, Flow Monitoring, RDII, Sewer Capacity.

INTRODUCTION

In 1999, the Orange County Sanitation District (OCSD) established criteria upon which their 24 member cities would receive matching grant funds for rehabilitation work to reduce seasonal groundwater infiltration or Base Infiltration (BI) from offending areas of their 4500 mile collection system. In order to identify areas of high BI, OCSD identified isolated sewer shed areas or "basins" that approached or exceeded BI contributions of 30% of the total Average Daily Flow (ADF) from that basin. This roughly equates to values of BI that exceed the published standard of 500 gpd/idm (gallons per day/ inch-diameter-mile) (ASCE, 1982). OCSD sought a universally-accepted means of determining the magnitude of seasonal BI from specific basins to aid member cities and OCSD in qualifying applicants for the grant funds.

Historically, wastewater system managers have been interested in the magnitude of BI in their collection systems, because at a minimum, BI is considered a nuisance cost to treat, but in more severe cases it can actually rob a sewer's capacity to convey wastewater. More recently, the increasing use of hydraulic modeling has created the need for more accurate estimates of BI contributions from basins throughout the collection system. In the OCSD system, there appears to be a relationship between magnitude of BI in a basin and potential for that basin to generate high levels of Rainfall Dependent Inflow and Infiltration (RDII) (Mitchell, 2003 & 2005).

There is no clear-cut universally-accepted method by which to determine or otherwise verify the magnitude of BI from collection system basins. This paper will help clarify the most appropriate prediction method by presenting a comparison of various BI determination methods.

METHODOLOGY

Base Infiltration Estimation Methods

There are four common empirical prediction methods used by practitioners to estimate BI based exclusively on sewer flow data and daily (or diurnal) patterns derived from the flow data. All the methods are restricted to land use which is predominantly residential. The four methods are listed below. There is some uneasiness associated with the use of these prediction methods because there is not a practical way to verify the accuracy of the predictions. To evaluate the accuracy of these methods, this paper includes the fifth, sixth, and seventh methods as means to verify the accuracy of the predictions. The verification methods differ from the prediction methods because they include a third or independent element that can be used as "ground truth" or as a boundary condition.

Empirical Prediction Methods

1. Wastewater Production Method
2. Minimum Flow Factor Method
3. Stevens-Schutzbach Method
4. Fraction of Minimum Method

Verification Methods

5. Chemical Analysis Method
6. Potable Water Use Method
7. Dead-Low Flow Method

The following section discusses the first three of the empirical prediction methods, each of which bases it prediction on some function of Average Daily Flow (ADF) and Minimum Daily Flow (MDF). The fourth method is considered crude and is not evaluated here, since it simply assumes BI is a simple fraction of the MDF. In this paper, both ADF and MDF are quantities measured during dry weather during which the flow is not experiencing the immediate effect of rainfall.

Following the discussion of the three prediction methods, this paper compares the BI values predicted by each of the three methods using the data in a case study within the OCSD sewer service area. The empirically-derived BI values are then compared to BI values derived by the three verification methods; Chemical Analysis, Potable Water Use and Dead-Low Flow. The objective is to determine if one the prediction methods can be verified to a greater degree than the others. Each of the OCSD case study basins are isolated basins (no upstream flows to subtract) and are predominantly residential with some commercial land use interspersed.

Wastewater Production Method

The two components of dry weather flows, or ADF, are defined as domestic Wastewater Production (WWP) and Base-Infiltration (BI). This prediction method is considered the most commonly used method. It estimates the amount of flow that is attributed to domestic wastewater sources and derives BI by subtraction. The method is based on domestic water use studies wherein the minimum water use rate occurring in the early morning hours (typically 12:00 am to 6:00 am) is about 12% of the average daily water use rate (Mayer, 1999; Harping, 1997; University of Wisconsin-Madison, 1978). This observation leads to the conclusion that 88% of the daily WWP is equal to the difference between the average daily rate and the minimum rate (ADF – MDF). Then, if the total computed WWP is less than the actual ADF, BI is assumed to make up the difference

This assumption works well when travel time is not an issue. Potable water systems have no travel time and metered flow rate into a basin must equal the rate of water consumed in the basin. On the other hand, metered flow rates in sewers do not equal the rate of water use in the basin because of travel time or time of concentration. Flows are attenuated in gravity sewers causing an increase in minimum flow rates and a decrease in maximum flow rates. Attenuation reduces the accuracy of WWP predictions (and BI predictions) as basins increase in size (and travel times increase). Some practitioners modify the 88% value to achieve results more consistent with specific land use or basin size. Other issues that can affect this

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prediction method include residential areas with a high percentage of nighttime water use fixtures such as water softeners.

This can be restated to say that a factor, X, or 0.88 of the WWP equals the difference between ADF and MDF. Then, Base Infiltration (BI) is the flow that is left over after WWP is subtracted from ADF (See Figure 1). The green curve in Figure 1 depicts the actual daily dry weather flow pattern produced by a sewer basin throughout the day.

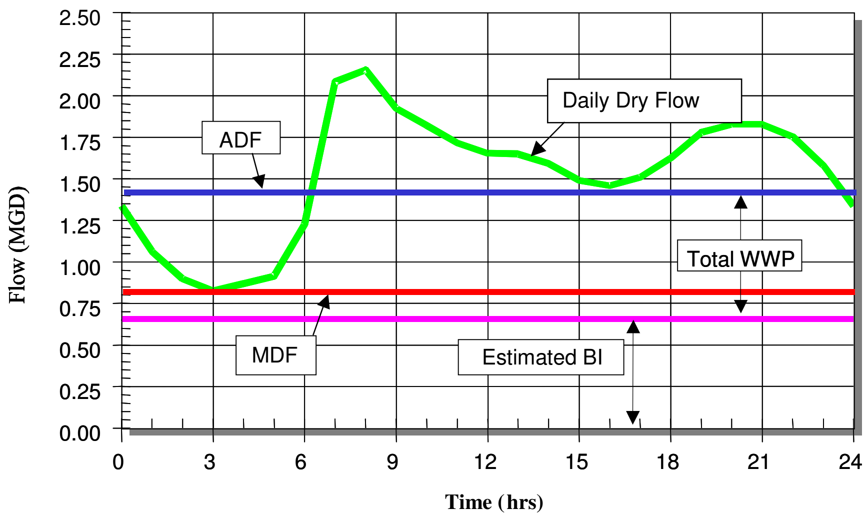

Figure 1 – Diurnal Dry Weather Flow Components used to Calculate BI.

The relationships used to estimate Base Infiltration (BI) are written in equations 1 and 2. Any consistent units of measure [e.g. million gallons/day (mgd) or liters/second (l/s)] can be used.

$$\mathbf{WWP = (ADF - MDF) / X} \quad (1)$$
$$\mathbf{BI = ADF - WWP} \quad (2)$$

Where,

BI = Base Infiltration
WWP = Daily Average Total Wastewater Production
ADF = Average Daily Flow rate
MDF = Minimum Daily Flow rate
X = fraction of WWP that accounts for non-zero nighttime wastewater production (0.88).

The accuracy of this method can be assessed by monitoring the difference between the ADF and MDF over the course of a year. As BI varies over the year, this method suggests that the difference between average and minimum flow should remain reasonably constant.

Minimum Flow Factor Method

This method uses the ADF to determine what the expected MDF would be for that size basin based on published minimum flow factors (ASCE, 1982). The Minimum Flow Factor (Min Factor) is defined as the fraction MDF/ADF. As expected, this factor becomes smaller with decreasing basin size as shown with the "Min Factor Curve" in Figure 2.

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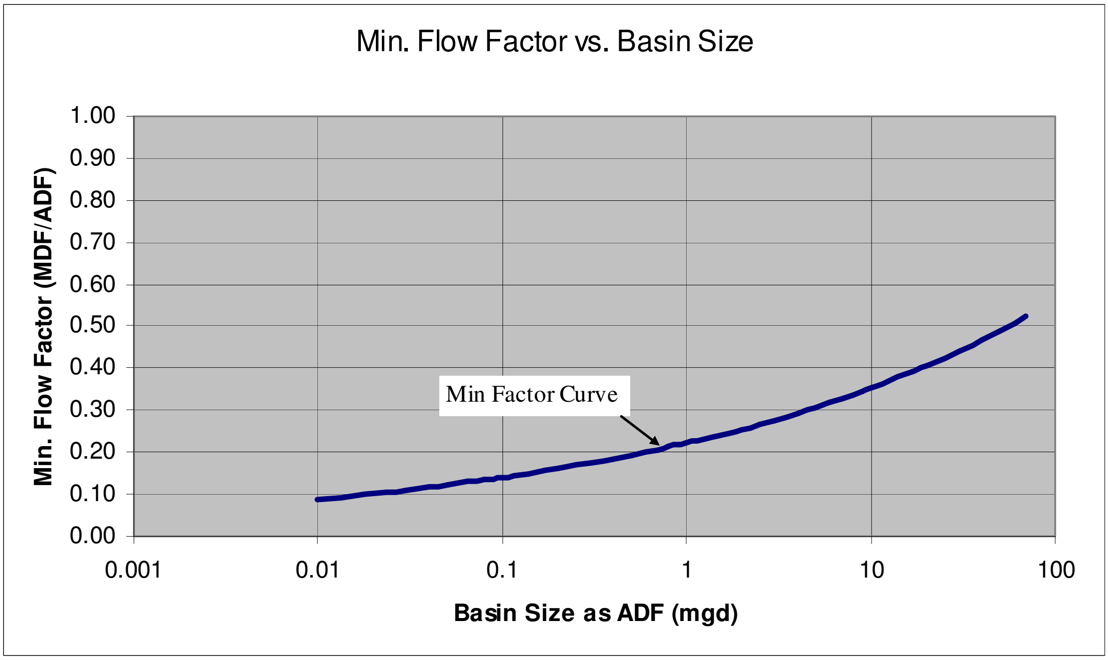

Figure 2 – Chart Showing Relationship of Basin Size vs. Expected Min Factor.

This relationship of basin size and the Min Factor can be closely approximated using equation 3 where the (ADF – BI) term can initially be set to ADF. Then BI can be computed by taking the difference between measured actual MDF and the MDF based on the Min Factor as shown in equation 4, which is rewritten as equation 5. For a more exact solution to BI, one or more iterations back through equations 3 and 5 should be done. For equation 3 to be valid, ADF and BI flows must be in units of mgd (ASCE, 1982).

$$\textbf{Min Factor} = 0.222\,(\text{ADF} - \text{BI})\ \hat{}\ 0.202 \quad (3)$$

$$\text{BI} = \text{MDF} - \text{Min Factor}\,(\text{ADF} - \text{BI}) \quad (4)$$

Which can be rewritten as:

$$\text{BI} = \frac{\text{MDF} - \text{Min Factor (ADF)}}{1 - \text{Min Factor}} \quad (5)$$

Stevens - Schutzbach Method

In 1999, Stevens and Schutzbach developed an empirical method to overcome apparent weaknesses in the Wastewater Production (WWP) method. It was observed that the WWP method appeared to overestimate BI from large basins (ADF >5 mgd) and underestimate BI from very small basins (ADF <0.1 mgd). The WWP method is strongly dependent on the minimum measured flow value, during which time it is often challenging for open channel flow meters to obtain accurate measurements of depth and velocity. In some small basins the BI estimate using the WWP method was observed to generate negative values.

In a search for a better prediction method, it was observed that there was a decent relationship between the value (ADF–MDF) and ADF, but that it was not constant as the Waste Water Production method would suggest. The attenuation in larger basins contributes to this non-linearity. The value (ADF–MDF) was plotted against ADF using data from approximately 2,000 basins nationwide and a fairly consistent relationship between (ADF–MDF) vs. ADF was observed. This relationship on a partial data set is shown in Figure 3. The x-axis in Figure 3 is plotted in log scale to allow the relationship at the lower ADF values

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to remain visible when plotted with very large ADF values. The regression equation is shown in its linear form.

Intuitively, the authors of this method believed it should include some factor that would change the prediction as a function of basin size and flow attenuation in a similar manner as the Min Flow Factor method while disallowing any negative values of BI. Practitioners often speculate about the existence of exfiltration in sewers and that a negative value of BI would validate the presence of exfiltration. However, the authors believe that any such exfiltration identified using flow data (notwithstanding an obvious overflow to the environment) is nearly always the result of weakness in the prediction method or poor measurement of minimum flow rates. The authors exercised mathematical license in selecting the factors in the equation.

The Stevens – Schutzbach equation has been used on thousands of sewer basins with realistic results based on feedback from consultants studying BI and other modelers. However, there has been a continuous search for sources of data that can verify the BI predictions.

A curve fitting technique was used generate the Stevens/Schutzbach (SS) equation shown in equation 6. The BI estimate produced by this equation appears to be more reliable with flow metering data from very low flow, very high flows and flow heavily influenced by pump stations. For equation 6 to be valid, units of mgd must be used for MDF and ADF values.

$$\mathbf{BI} = \frac{\mathbf{0.4\ (MDF)}}{\mathbf{1 - 0.6\ (MDF/ADF)\ \hat{}\ ADF^{0.7}}} \qquad (6)$$

Like equations 1 through 5, equation 6 is also dependent on average and minimum flows that occur in traditional residential flow patterns. However, like in the Min Factor method, equation 6 evaluates the relationship of the ratio of MDF/ADF vs. ADF (rather than the difference ADF–MDF vs. ADF as in the WWP method).

It was also observed that the best fit regression line (or curve as plotted on the Figure 3 Log plot) had a slope (0.317) that is far lower than the 0.88 default factor (equated to slope under zero BI conditions when relating ADF–MDF vs. ADF) used in the WWP method. This suggested either all of the evaluated basins were experiencing a significant amount of BI on average or the WWP method likely overstates BI using the default factor (X = 0.88).

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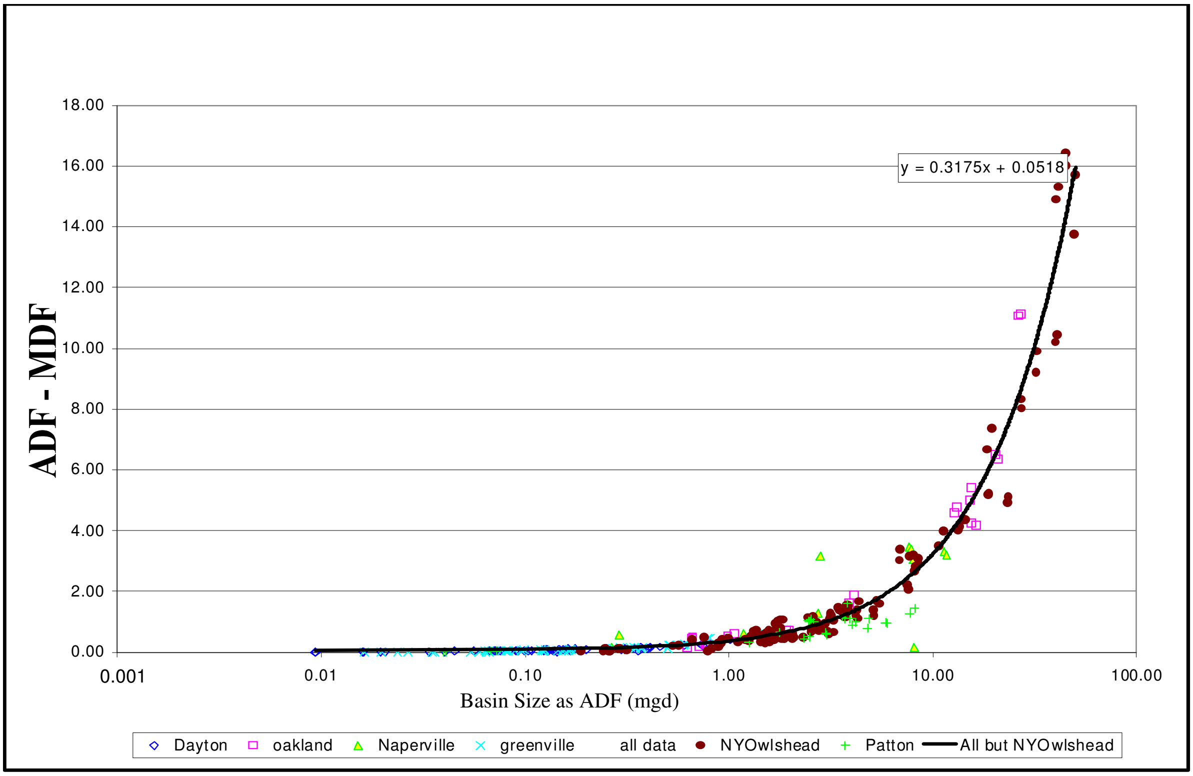

Figure 3 – Chart Showing Relationship of (ADF-MDF) vs. ADF.

Assuming there is consistent relationship between ADF and the ratio MDF/ADF when very little to no BI is present (as in the Min Factor method, see Figure 2), a wide scatter of data using this relationship would be expected in basins experiencing a measurable degree of BI. Figure 4 is plot of ADF vs. MDF/ADF for a sampling of the basins evaluated and confirms there is a significant departure from the Min Factor curve shown in Figure 2 (and re-plotted in Figure 4).

As discussed above, the format of equation 6 was designed to disallow negative values of BI (i.e. the lowest possible BI value is 0.4 times the measured MDF). Equation 6 was also configured to moderate the effect a high MDF has on estimated BI by applying an ADF exponent in the equation denominator. This effect of moderation is illustrated by setting a low BI constraint (10% of the ADF), and plotting the resulting curve based on inputting different ADF values and associated MDF/ADF ratios. Doing this with different magnitudes of BI results in various comparator "Min Curves" (see Figure 4). For example, the lower (low BI) Min Curve shown in Figure 4 was determined by setting BI to 10% of the ADF in equation 6, then the MDF/ADF ratio was calculated for each value of ADF (or basin size). Similarly, another Min Curve was generated using a moderate BI of 20% in Figure 4. The BI can be estimated from equation 6 for a vast array of basin sizes (ranging from 0.05 mgd up to more than 10.0 mgd).

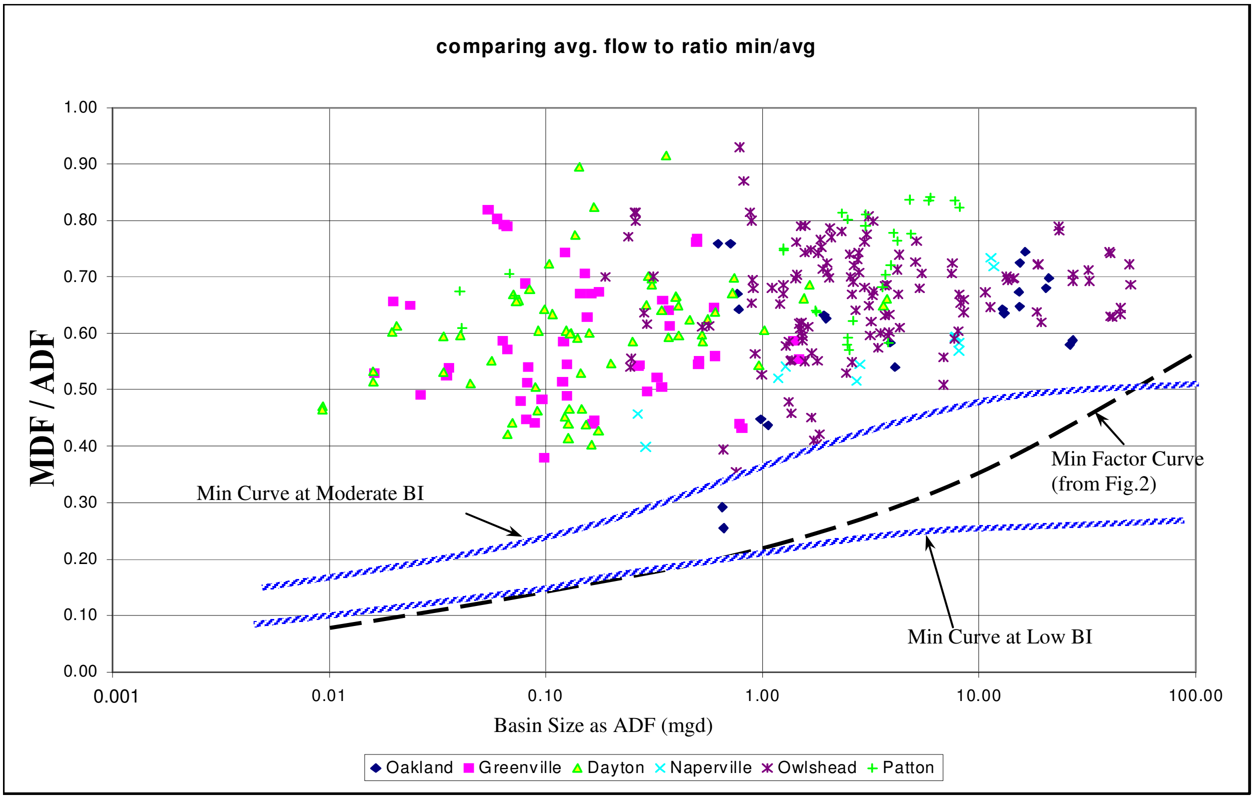

Figure 4 – Chart Showing Relationship of (MDF/ADF) vs. ADF and Variable Min Curve.

Comparing the SS and Wastewater Production Methods

Figure 5 plots the estimated BI for the nationwide data set of basins displayed by basin size (ADF). When compared to the SS method, the WWP method appears to generate several outlier BI estimates at ADF values greater than 5 mgd.

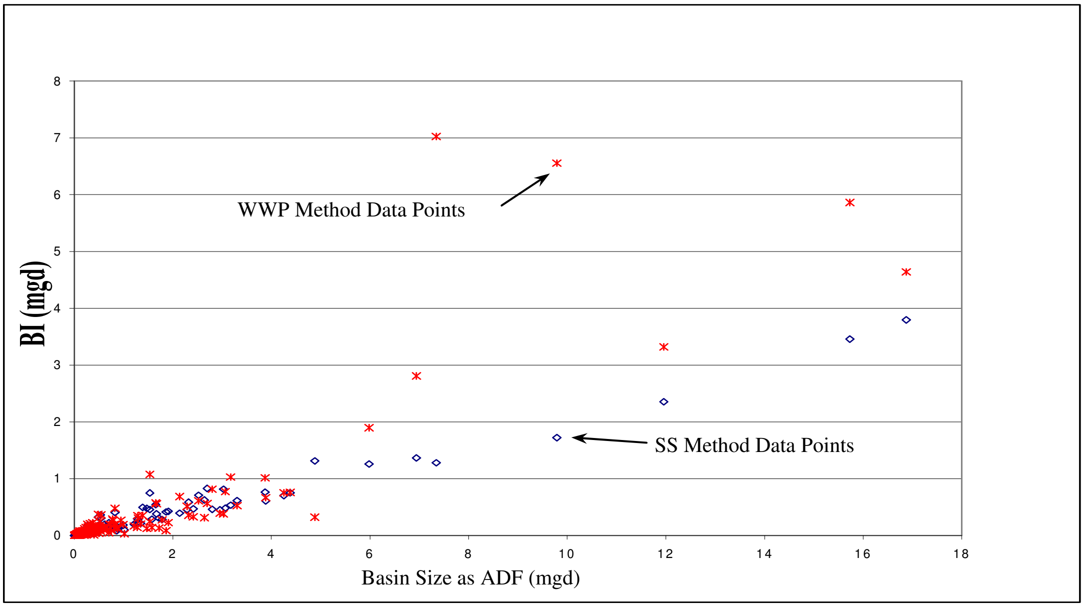

Figure 5- Chart Showing Relationship of WWP Method BI vs. SS Method BI.

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Case Study Basins in OCSD Service Area

To supplement the grant program discussed in the Introduction, OCSD conducted a long-term flow monitoring study from Spring 2002 through Spring 2005. This study covered approximately 75% of its service area in an effort to better understand the relative contributions of RDII from up to 138 basins. The basins ranged in size from 140 acres to 2600 acres (corresponding to flow ranges of 0.14 mgd to 5.0 mgd). Flow monitors associated with the top approximate 50% of the RDII-producing basins remained during the final season of the OCSD flow monitoring program (Winter 2004-2005), leaving 72 basins for evaluation. The OCSD service area experienced unusually heavy rainfall during this final season of the program with a season total rainfall of more than twice normal. RDII was largely observed at much higher flows with associated prolonged increases in MDF vales compared to previous seasons, suggesting the BI component of flows was also higher.

Of the 72 basins remaining in the final (heaviest) rain season, 45 were selected for rigorous evaluation of each of the above three BI empirical estimation methods. The 45 case study basins were chosen by eliminating those that were not hydraulically isolated (i.e. those requiring subtraction of an upstream flow meter, eliminating the potential for introduction of inaccuracies resulting from such flow subtractions), those producing ADF values less than 0.1 mgd, and those showing historically insignificant (i.e. less than 15% BI) since project inception with no increase into the recent heavy rain season.

The results of the BI determined for each of the 45 basins using each of the above three empirical BI estimation methods are shown in the graph as Figure 6. Note that the results of BI computed using chemical and potable water verification methods discussed later in this paper are also shown in Figure 6. The empirically derived BI values have been normalized in this chart by dividing computed BI flow rate by that basin's ADF to yield BI in units of %ADF. The chart is sorted according to average BI of the three empirical methods so as not to favor one over the other in the display. The BI estimates appear to trend reasonably well together, although some basins showed a much larger difference among the three methods while some basins showed very good agreement between the BI methods.

The Stevens-Schutzbach method appears to produce the lowest estimates of BI in the basins producing higher levels of BI while each of the three empirical methods tended to converge moving to basins producing lower levels of BI. In fact the Min Factor method appears to approach zero as calculated BI decreases below 15% indicating this method becomes very sensitive when BI is low.

This prompted a sensitivity analysis of the methods to the minimum flows recorded by the flow meters, particularly since the potential for error in flow measurement is more prominent (on a percent flow basis) during minimum flows (Mitchell and Stevens, 2005; Den Herder, 1995). Varying degrees of error were introduced to the MDF values using each of the three empirical BI estimating methods in evaluating a mid-size basin (ADF of 0.38 mgd) that produced moderate to high BI of about 40%. Figure 7 depicts the relationship between MDF error vs. error in calculated BI using each of the three empirical methods. This suggests that the Stevens-Schutzbach equation (the lower green curve in the figure) is better suited to basins that produce low MDF values or MDF values that are of lower confidence.

Figure 6 reveals that each of the three empirical methods yield similar BI estimates for some basins (e.g. the highest BI basin in Figure 6) while BI estimates among the three methods are significantly different in other basins (e.g. the fifth highest BI basin in Figure 6). By comparing basin size vs. degree of divergence in BI estimates among the three methods, a reasonable correlation is observed. Figure 8 depicts a plot of basin sizes vs. maximum divergence among the three methods. This chart indicates that the methods converge as basin size decreases below an ADF of 0.5 mgd. For basins with an ADF of 1.0 mgd or more, the three methods are divergent by generally around 15% to 20%.

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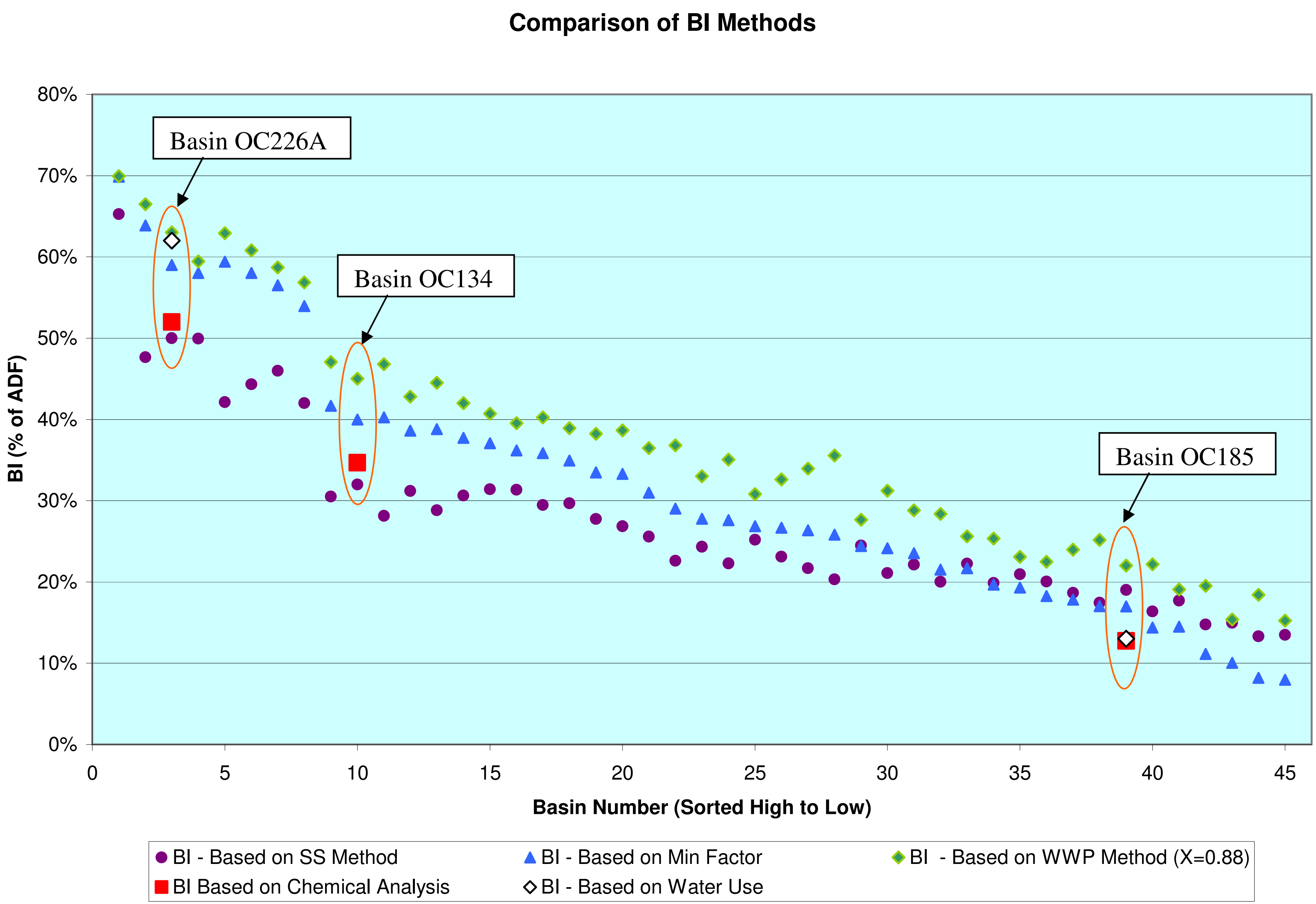


Figure 6 – Chart Comparing BI Methods in OCSD System Basins.

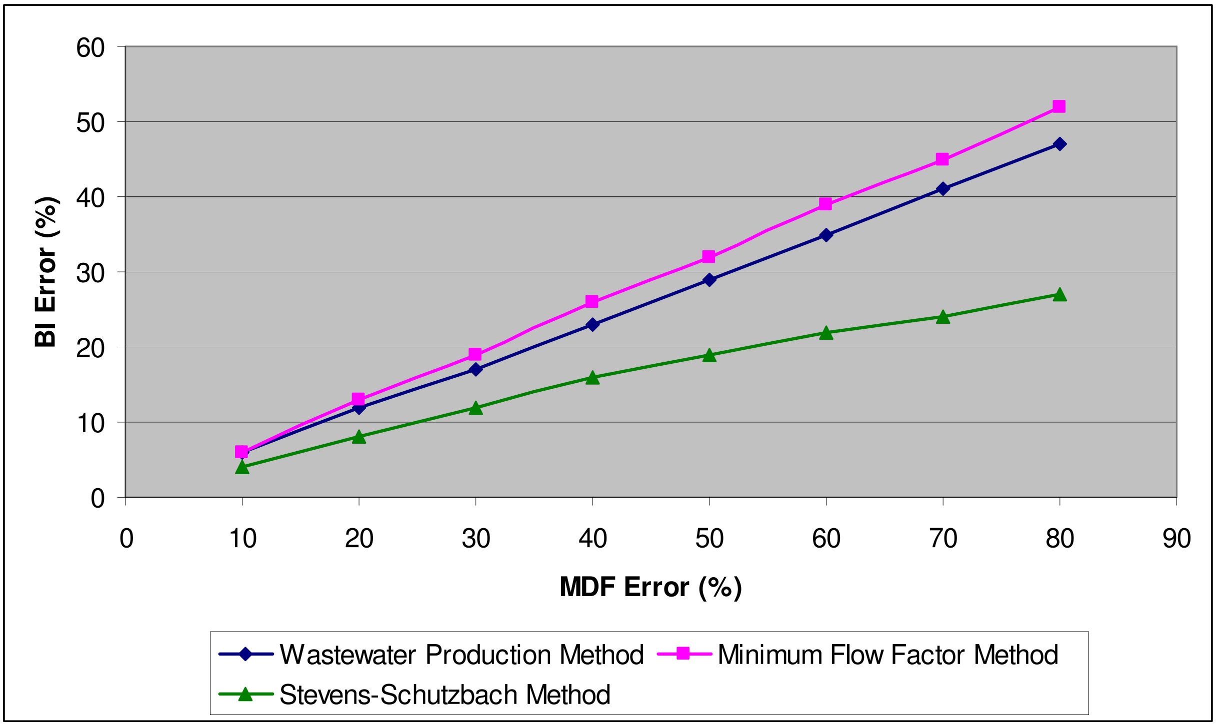


Figure 7 – Chart Showing Relationship of MDF Error vs. BI Resulting Error.

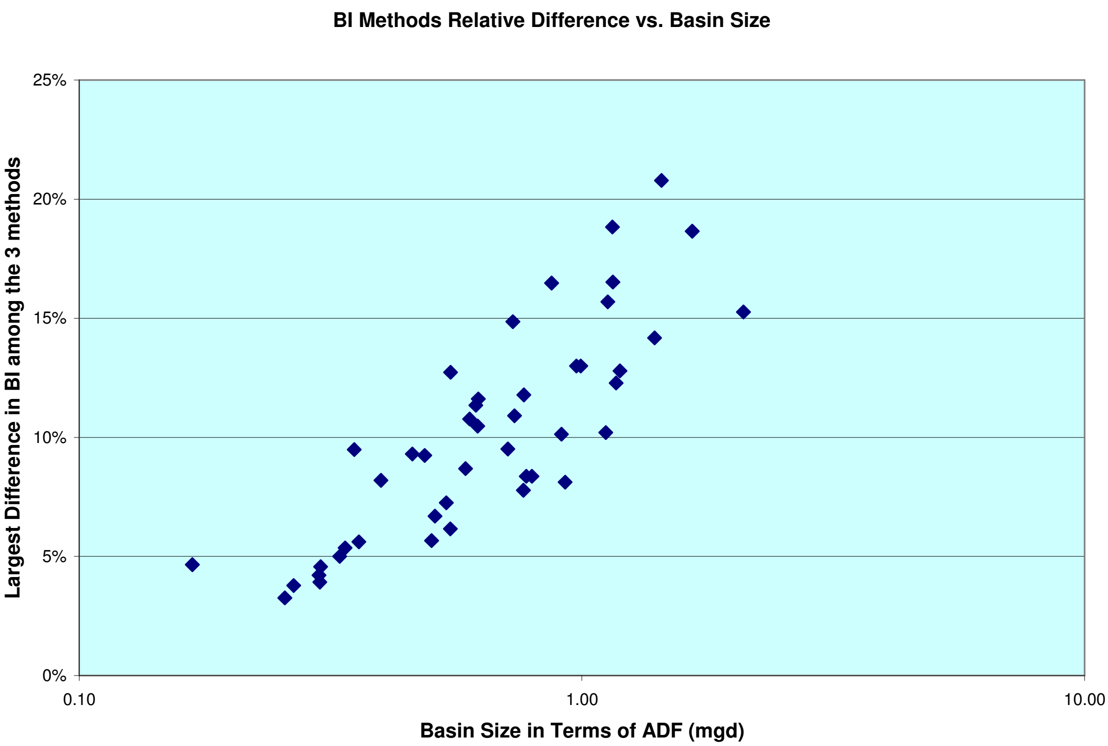
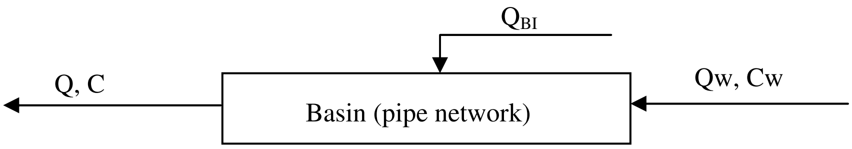


Figure 8 – Chart Showing Relationship of Basin Size and BI Method Agreement.

Chemical Analysis Method of Verifying BI

The above empirical method comparison provides relative performance among the methods. However, a verification method was needed to help determine which of the empirical methods produced BI estimates that were closest to actual BI. The primary method used for this verification relies on comparing typical wastewater parameter concentrations in selected basin outlets versus flow rate. This verification method relies on the assumption that, for a given fixed rate of infiltrating groundwater, the fraction of WWP out of the basin will be at its lowest during the minimum night-time flow period (i.e. when little wastewater is produced, leaving a higher fraction of groundwater in the sewer). Conversely, as WWP rises during the day, its fraction of the overall flow will increase. The simple mathematical model of this relationship is depicted below. Any consistent units of flow and concentration can be used in the following relationship.



Where,

C = wastewater parameter concentration out of basin
Q = ADF or flow rate as measured at basin outlet
Q_{BI} = BI or flow rate of infiltrating water
Qw = WWP or wastewater flow rate before dilution with infiltrating water
Cw = wastewater parameter concentration before dilution with infiltrating water

A mass balance of this model produces the relationship shown in equation 7.

$$\mathbf{Q = Cw\,(Q_{BI}) / (Cw - C)} \qquad (7)$$

By measuring values of Q and C directly and plotting, a regression curve can be generated using the solver functionality within Microsoft Excel©. This arrives at a best fit curve by simultaneously adjusting Cw and Q_{BI} in order to minimize the difference between measured values of Q and values of Q computed using equation 7.

Three of the case study basins were evaluated using this verification method. The chemical parameters used in this evaluation were Total Suspended Solids (TSS), Biochemical Oxygen Demand (BOD), Total Organic Carbon (TOC), and Chemical Oxygen Demand (COD). Plots of these parameters vs. flow rate (Q) for one of the three verification basins (OC134) are depicted in the series of graphs as Figure 9. In each case shown, a reasonably good regression coefficient is generated. The correlation coefficient for COD was lowest in this case.

The result of the above regression method allows the determination of total Q_{BI} (the y-intercept of the curve), assuming no other sources of nighttime clear water flows. The Q_{BI} (or BI) is then divided by ADF of that basin to yield BI in units of %ADF.

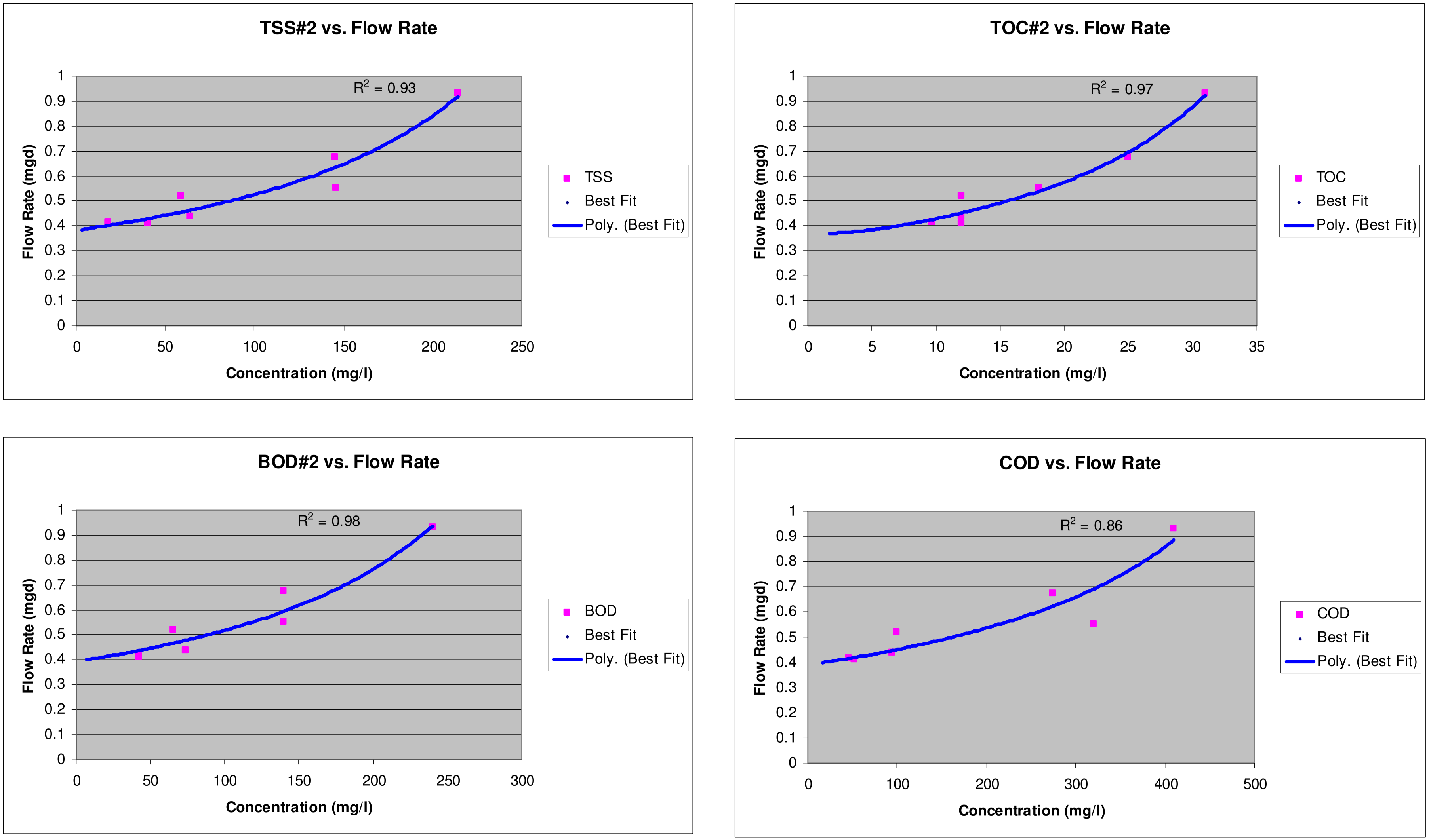


Figure 9 – Plots of Parameter Concentration vs. Flow Rate for Basin OC134 showing Best Fit Curve Regression to Equation 7.

Correction for Other Clear Water Sources

There are several possible additional sources of clear water flows that could occur continuously overnight in a residential basin. Those sources include water from recharge cycles from water softeners in hard water zones, leaking water mains, and leaking faucets. In the case of leaking water mains, this would likely be a consistent source and therefore would be appropriately included as overall BI. Leaking faucets would also likely be more continuous, but would result in high-biased computed BI values. Clear water contributions from leaking faucets were not evaluated in this document, although this source (as well as water main leakage) may be worthy of consideration in basins yielding high BI and unusually high per capita potable water usage rates. Clear water contributions from the water softener recharge sources are presented below.

The area in which this BI case study was conducted is considered to be in a hard water zone. Water softener market saturation in such areas is thought to be between 20% and 40% with an expectation of toward the higher percentage in more affluent areas (Pipes, 2002). Typical recharge volumes from water softeners range between 30 and 80 gallons per cycle about 2 times per week (volumes and rates depending on whether the unit is older and using a simple timer or more recent using a recharge monitor) (Friedman, 2007 and Christopherson, 2007).

Assuming an average of about 100 gallons per week per household of recharge water is produced and assuming 30% of households in this study area use water softeners, the adjusted average clear water production from this source is 4.2 gallons per day per household.

Recharge cycles typically occur overnight between 2:00 and 5:00 am. Based on the water use records from basin OC226A, there are about 1300 dwellings in this area. That means about 5,500 gallons of clear water are produced overnight between 2 and 5 am. OC226A is about 200 acres, so that is equivalent to 27.6 gallons/acre overnight. The overall wastewater flow from basin OC226A is about 44,000 gallons between 2:00 and 5:00 am (or about 9% of the ADF is during that time period), which is equal to 220 gallons/acre overnight. That means about 12.5% (27.6/220) of the flow overnight is likely from water softener recharge cycles.

Applying the same computations to basins OC134 and OC185, the portion of overnight flows that are potentially comprised of water softener recharge water is 18.4% and 47%, respectively. This illustrates that this source of clear water can be significant in basins yielding low BI as is the case in basin OC185.

The BI values (y-intercept) from the above discussed chemical analyses were adjusted downward based on these clear water flows from water softeners. The adjusted BI values for the three basins, using each of the chemical parameters, is shown in Figure 10 (and Figure 6).

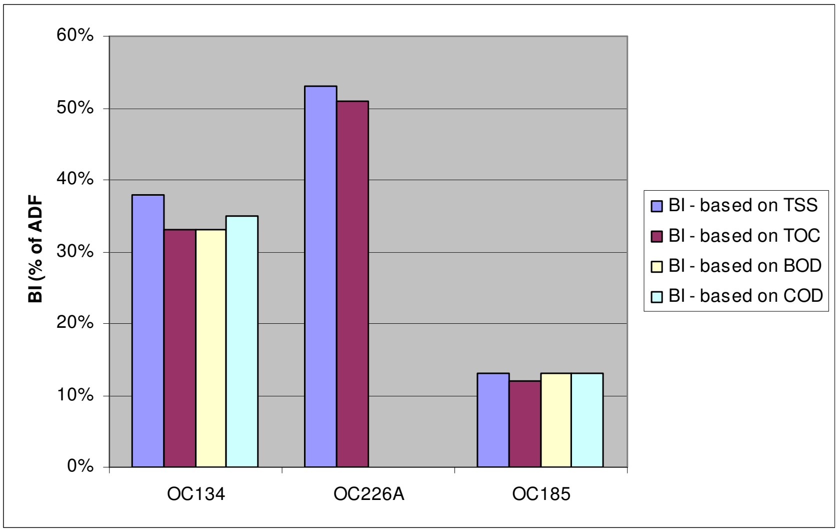


Figure 10 – BI Verification Results based on Chemical Parameter Regression Analysis.

The correlations between flow rate vs. BOD, as well flow rate vs. COD, in basin OC226A were very poor as shown in Figure 11. Yet, the correlations using TSS and TOC parameters were good with correlation coefficients of 0.97 and 0.82, respectively. This is one of the few basins located on the coastline, therefore producing BI that is likely predominantly comprised of highly saline water from the Pacific Ocean or Newport Bay. The BOD and COD indirectly measures waste constituent concentrations based on laboratory measured Oxygen demand. It is speculated that some constituents of the infiltrating salt water may have created some instability in measured Oxygen demand at the laboratory, but that has not been confirmed.

The BI verification results based on an average of the available results from each of the three test basins are posted on Figure 6 for reference. It appears that the verification values matched most closely to the Stevens-Schutzbach methods for the two basins yielding more than 30% BI. In the third basin producing much lower BI (13%), the chemical verification value was lower than all three empirical methods, but matched more closely to the Stevens-Schutzbach and Min Factor methods.

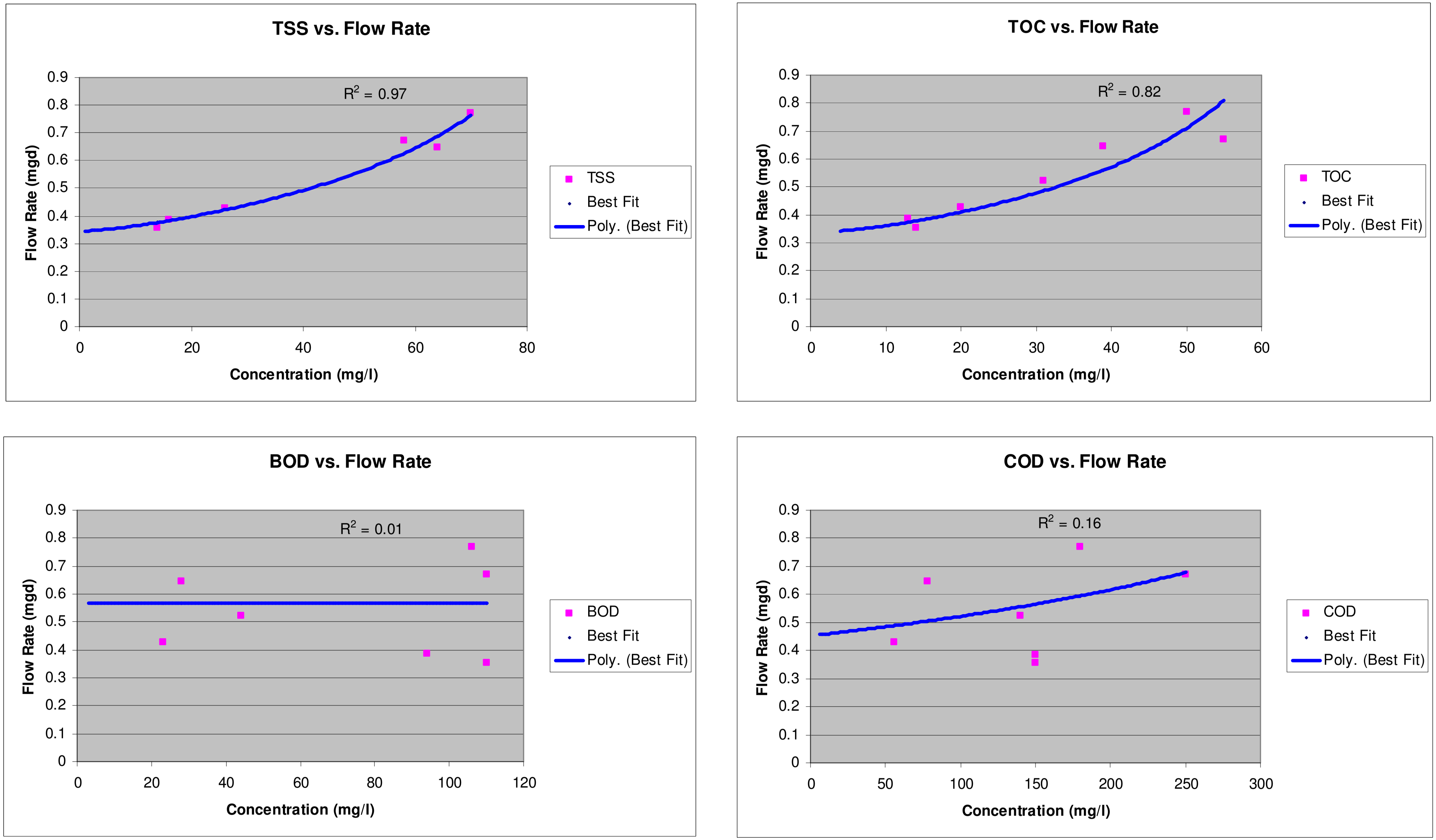


Figure 11 – Plots of Parameter Concentration vs. Flow Rate for Basin OC226A showing Best Fit Curve Regression to Equation 7.

Potable Water Use Method of Verifying BI

The source of wastewater produced and discharged into a sanitary sewer system is invariably a potable water source from a domestic water provider. Hence, it is possible to compare volumetric water use in a particular basin to wastewater delivered from that basin via the sewer system to determine if additional flows must be present from other sources such as BI.

This method of determining BI relies on three important assumptions: 1) potable water use is metered at each point of use and is reliable and accurate; 2) the only source of wastewater generation is from a metered potable water distribution system (i.e. no water wells or other un-accounted sources of water); and 3) the percentage of indoor water use (i.e. percent of water returned to the sewer as wastewater) can be reasonably estimated. Unfortunately, the last assumption regarding percentage of potable water returned to the sewer as wastewater varies widely in literature, from 40% to 85% (ASCE, 1982; Viessman & Hammer, 1985; Metcalf & Eddy, 1991). Data from two large cities proximate to the OCSD system in Southern California, Los Angeles and Santa Monica, reported potable water to sewage conversions of 47% and 69%, respectively (ASCE, 1982). Metcalf & Eddy reports that values from 60% to 85% can be expected in residential areas, with the lower values representing semi-arid regions of the southwestern U.S (Metcalf & Eddy, 1991).

Monthly water use data were collected from the highest and lowest BI-producing basins of the three case study test basins discussed above, OC226A and OC185, respectively. Water use data were collected for the period during which the chemical verification testing was conducted. Care was taken to exclude metered external uses including City sprinklers and fire hydrants. No known three-shift industrial operations exist in these basins. Complete water use data were not available for end-users in test basin OC134 due to non-existent or incomplete records from the four various size water agencies serving this basin area. The average daily water use rates for the two evaluated basins were computed from the monthly data and compared to the average daily wastewater flows measured in the sewer from each of the basins. The water used vs. wastewater generated is summarized in Table 1. Assuming a water-to-wastewater conversion factor of 60% (i.e. the low end of the Metcalf & Eddy estimate), the theoretical contribution from BI sources was determined and listed in Table 1 and compared to BI based on the chemical verification analyses from above.

Table 1 – Summary of Water Use and BI Estimates in Two Case Study Basins.

Basin	Average Daily Water Use (mgd)	Water Use To Sewer (mgd)	Metered Sewer ADF (mgd)	Difference as BI (mgd)	BI	BI from Chemical Verification
OC226A	0.353	0.212	0.550	0.338	62%	52%
OC185	0.507	0.304	0.350	0.046	13%	13%

The BI results from the water use analysis compare favorably to the BI estimated previously with the WWP method in the basin producing a high degree of BI (OC226A). However, the BI estimate from water use data in the lower BI basin, OC185, was much lower than previous empirical estimates. These water use-based BI results are plotted on Figure 6.

Dead- Low Flow Method

As shown in this paper, it is difficult to find a direct way to separate sewer flow into the components of wastewater and base infiltration. Probably the perfect, yet most difficult, way for measuring BI is the Dead-Low Flow (DLF) method. This method involves stopping all generation of wastewater in a basin and measuring what is left – the Dead-Low Flow. This method would clearly be unacceptable to dwellers in the basin so it is never done intentionally. The Northeast Power Blackout on 14 August 2003 provides us with an opportunity to directly measure base infiltration by finding basins in which all water service has ceased during the blackout. The DLF method may be clouded by the presence of elevated storage tanks and backup power will allow waste water production to continue during the blackout.

Several flow metering sites were discovered in Oakland County, Michigan in a community that had neither backup power nor elevated storage tanks. The community was connected to a highly-reliable potable water system that operated at a high pressure. Pressure regulators replaced elevated tanks as the pressure-control method. The sewer flow meters confirm that flow dropped very quickly after the power failure and remained at the DLF rate for several hours.

Figure 12 displays the hydrograph of meter site 4840, which measures flow from a basin that has neither elevated storage nor standby power on its potable water distribution system. The drop in flow can clearly be seen on 14 August 2003. The spike in flow late on the 15th is the result of a rain and an upstream wastewater pump station coming back online.

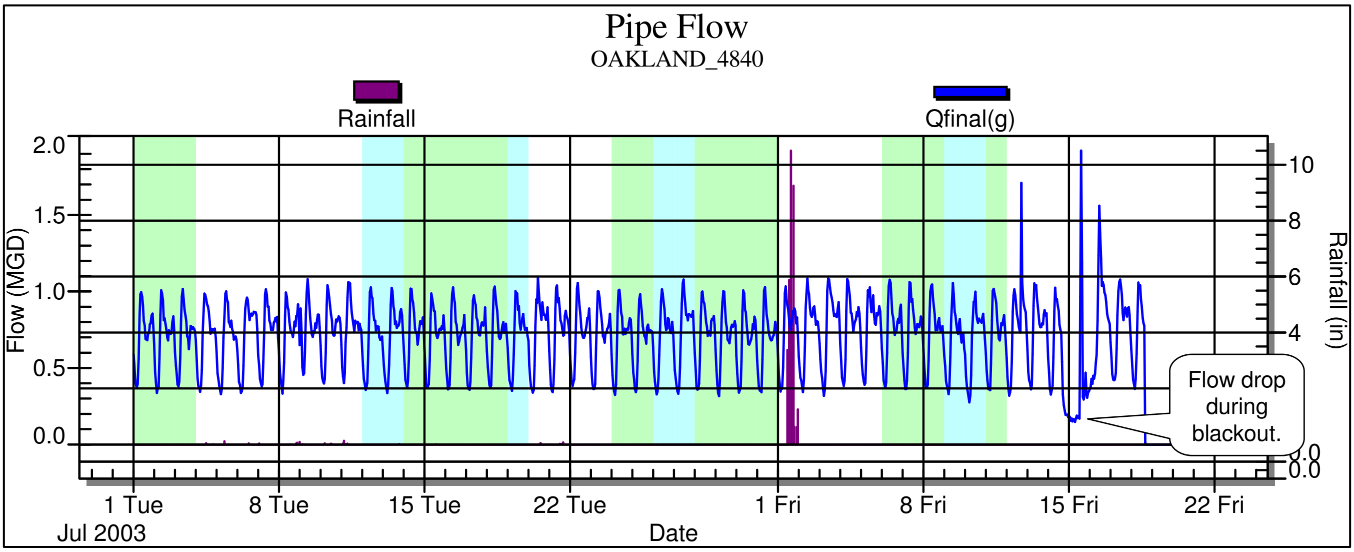


Figure 12 – Flow Drops on 15 August During the Northeast Power Blackout.

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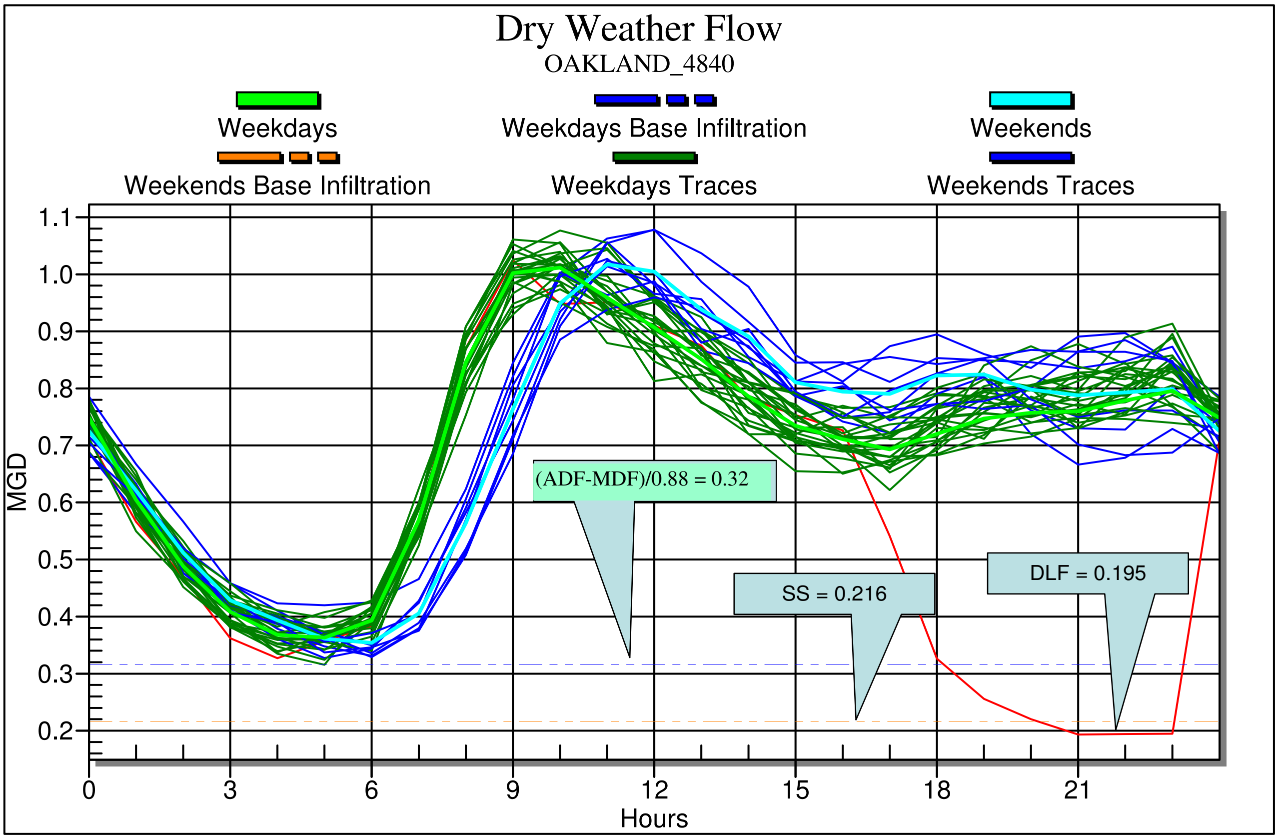
Figure 13 displays the weekday and weekend diurnal hydrographs for meter site 4840 along with the hydrograph of 14 August (shown in red) and the associated Dead-Low Flow (DLF) of 0.195 mgd. The Stevens-Schutzbach method predicts a Base Infiltration of 0.216 mgd, which is very close to the actual DLF. The WWP method predicts a base infiltration of 0.32 mgd using the common factor (**x**) of 0.88. Using of a factor of 0.70 in the WWP method produces a base infiltration that equals the Stevens-Schutzbach method of 0.216 mgd.

Figure 13 – Weekday Diurnal Hydrograph Showing the Flow Drop During the 15 August Power Blackout. The Dead-Low Flow (DLF) should be Base Infiltration.



DISCUSSION

Since the Wastewater Production (WWP) method appears to be the most widely used method of estimating BI, some additional discussion is warranted. This method consistently produced the highest BI estimates of all methods in all the case study basins, so an evaluation was done to determine if a more suitable factor (**x**) should be used in equation 1. In order to adjust the BI downward to match the chemical verification results for the two basins producing BI >40%, the wastewater production factor (**x**) would have to be reduced from the originally assumed 0.88 down to 0.69 and 0.75 for basins OC226A and OC138, respectively. The above Oakland County data suggests a value for (**x**) of 0.70 should be used.

The authors propose a factor in the range of 0.70 to 0.75 for (**x**) be adopted as a new default value for any BI studies conducted where the WWP method is to be used and BI is expected to be greater than 20%. Even though it appears that the WWP method can be adjusted this way to produce more accurate results, the authors recognize that a single value for (**x**) may not be realistic for all basin sizes for the same reason assuming a single value for a Min Factor is not realistic for all basin sizes (see Figure 2).

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SUMMARY AND CONCLUSIONS

Results to date allow the following conclusions to be made:

- The Stevens/ Schutzbach empirical method provides good estimates of BI in basins with BI flows of more than 20% and is also far more stable in such basins (i.e. less sensitive to errors in minimum night-time flow measurements). In very large basins (5 mgd or more), the Stevens-Schutzbach method is recommended since the alternative methods appear to produce unrealistically high estimates of BI. This method was also verified to be the most accurate using the DLF method and flow data during the Northeast Power Blackout.

- If the Wastewater Production method is to be used to estimate BI, a revised factor (**x**) of no more than 0.75 (rather than 0.88) should be used as a conservative default value in the associated equation in cases where BI is greater than 20% of the ADF for basin sizes ranging from 0.1 to 5.0 mgd. Caution is warranted in using this factor for basins outside of this size range. Caution is similarly warranted in using this method to compare/ rank vastly different size basins in terms of BI performance.

- When using the chemical verification method described herein to estimate BI, the BOD and COD parameters are not recommended for use in cases where the sewer system under evaluation is suspected of experiencing infiltration from saline or brackish environments. In addition, in hard water areas, corrections should be made for contributions from water softener recharging cycles.

- The Water Use Analysis method of estimating BI can produce reasonable BI estimates. However, extreme caution is warranted regarding the accuracy of such data and the exclusive reliance on this method. Also, appropriate fraction of water use returned to sewer would need to be chosen based on climate and land use.

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