Determining Base Infiltration in Sewers

A Comparison of Empirical Methods and Verification Results

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ABSTRACT

This paper addresses three empirical methods used to determine degree of Base Infiltration (BI) in 45 isolated sewer basins throughout the Orange County Sanitation District (OCSD) collection system. These include a common estimation method called night-time "Wastewater Production", a second method called "Minimum flow Factor", and a third empirical method called the "Stevens/ Schutzbach" equation. These empirical methods were tested against a chemical parameter verification method that involves regressing hourly parameter concentrations (Chemical Oxygen Demand – COD, etc.) with sewage flow rates.

Results to date indicate that the "Minimum flow Factor" method and a slightly modified version of the "Wastewater Production" method provide more accurate estimates of BI in basins yielding flows comprised of more than 25% BI. Alternatively, the "Stevens/ Schutzbach" empirical method provides good estimations of BI in basins yielding BI flows less than 25% and is also far more stable in such basins (i.e., less sensitive to errors in minimum night-time flow measurements).

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. The criteria were based in part on demonstrating that BI values exceeded benchmark values of about 12,000 gpd/idm (gallons per day/ inch-diameter-mile). This equates to BI from an isolated sewer shed area or "basin" that exceeds about 33% of the total Average Daily Flow (ADF) from that basin.

This created a strong need for a universally accepted means of determining degree 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 degree to which BI enters their collection systems in order to understand its impact. At a minimum, BI is considered a nuisance cost to treat, but in more severe cases it can actually substantially hinder the collection system's ability to convey wastewater in some basins.

More recently, the expanding interest in modeling the performance of collection systems over extended periods created the need for more accurate estimates of BI contributions from various collection system basins. In the OCSD system, there appears to be a relationship between degree 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 degree of BI from collection system basins. This paper will help clarify the most appropriate method by presenting a comparison of various BI determination methods.

BASE INFILTRATION ESTIMATION METHODS

There are four common methods used by practitioners to estimate BI based exclusively on sewer flow data and daily (or diurnal) patterns in areas of predominantly residential land use.

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

The following section discusses the first three of these methods, each of which involves evaluating Average Daily Flow (ADF) and Minimum Daily Flow (MDF). The fourth method is considered crude since it assumes BI is a simple fraction of the MDF; therefore this fourth method is not evaluated herein. In this paper, both ADF and MDF are quantities measured during dry weather during which the flow is not experiencing the immediate affect of rainfall.

It is important to recognize that some basins (including many in the OCSD service area) will be comprised of a considerable percentage of industrial and commercial land use zones that generate wastewater throughout the night and in irregular patterns. Consequently, in such areas, these estimation methods for calculating BI would be less accurate by overestimating BI.

Following the discussion of the three empirical methods, a comparison of empirically derived BI from three case study basins is made to BI values derived based on analyzing samples of common wastewater parameters [e.g. Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand-(COD)] from these basins. Each of the three case study basins are considered typical predominant residential land use (with some commercial zones). The three case study basins evaluated using this verification method were selected in typical primarily residential areas to minimize any potential skewing effect from industrial and commercial land uses as discussed above.

Wastewater Production Method

The two components of dry weather flows or ADF are defined as domestic Wastewater Production (WWP) and on-going infiltration from other sources (generally groundwater) or Base-Infiltration (BI).

This method 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 overall daily water use. (Mayer, 1999; Harping, 1997; University of Wisconsin-Madison, 1978) Some consultants use this observation as a basis to estimate that 0.88 of the total daily wastewater is produced during the day and 0.12 is produced at night. Some practitioners modify the 0.88 factor to achieve results more consistent with specific land use or basin size. This may include residential areas with a high percentage of nighttime water use fixtures such as water softeners. Then, if the MDF is higher than 0.12 of the ADF, BI is considered the culprit.

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).

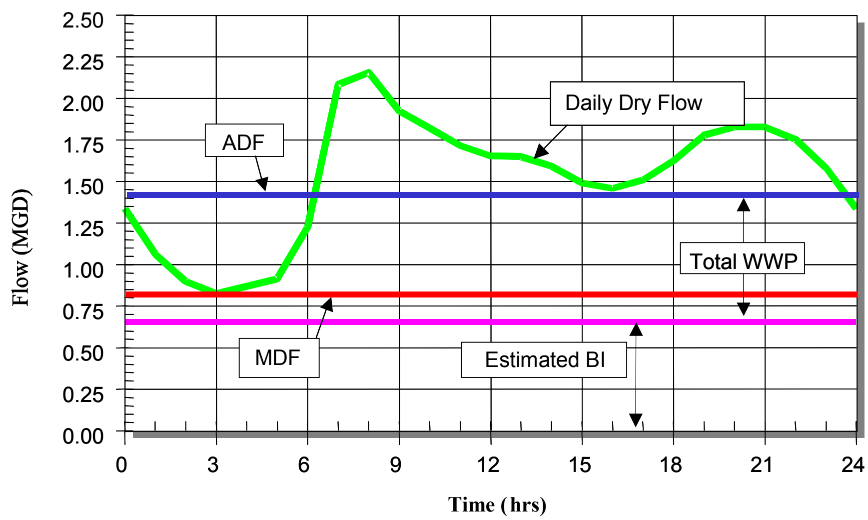


Figure 1 – Diurnal Dry Weather Flow Components used to Calculate BI

The relation used to estimate Base Infiltration (BI) is 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).

As BI varies over the year, the difference between average and minimum flow (and WWP) is expected to remain constant. This method of estimating appears to be reliable for residential neighborhoods with sewer basin sizes on the order of 10,000 to 100,000 lineal feet (lf) of sewer pipe.

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.

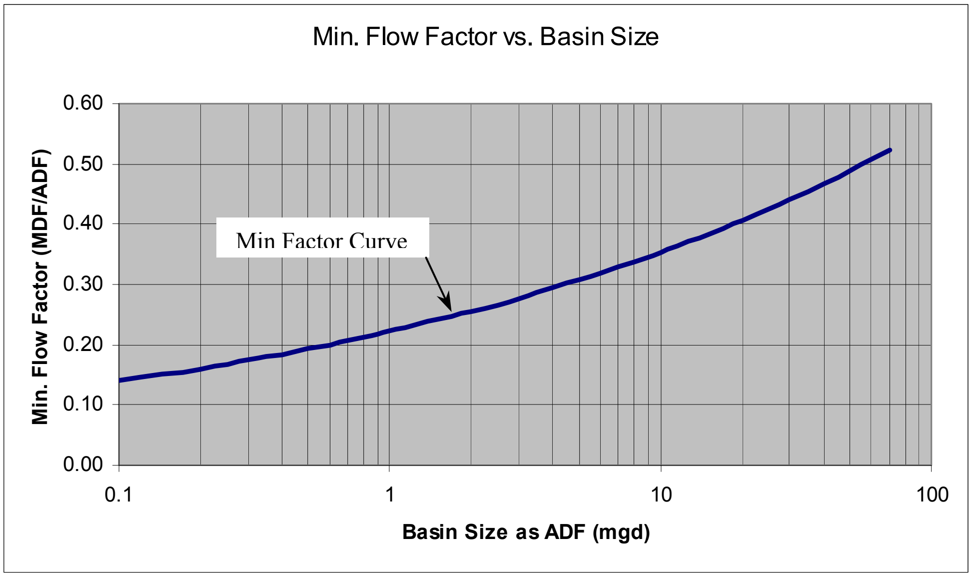


Figure 2 – Chart Showing Relationship of Basin Size vs. Expected Min Factor

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)

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

$$\textbf{BI} = \textbf{MDF} - \textbf{Min Factor}\,(\textbf{ADF} - \textbf{BI}) \qquad (4)$$

Which can be rewritten as:

$$\textbf{BI} = \frac{\textbf{MDF} - \textbf{Min Factor}\,(\textbf{ADF})}{1 - \textbf{Min Factor}} \qquad (5)$$

Stevens- Schutzbach Equation

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 in the depth and velocity regime with the greatest potential for measurement uncertainty. In some small basins the BI estimate using the WWP method was observed to generate negative values. The Stevens/Schutzbach (SS) equation uses a curve fitting technique to increase the reliability of the BI estimation at flow metering locations with very low or very high flows and in basins heavily influenced by pump station flow. Equation 6 is the empirically derived Stevens/Schutzbach equation that was used to estimate base infiltration in the OCSD basins. 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. MDF (rather than the difference ADF–MDF vs. ADF as in the WWP method).

ADS looked at ADF and MDF data from approximately 2,000 basins nationwide and noted a fairly consistent relationship between ADF–MDF vs. ADF as shown in Figure 3. This observation suggests that determining BI by measuring departure from the best fit curve to the lowest data points would be difficult to do in a precise manner (as in the WWP method).

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 the basins and confirms there is a significant departure from the Min Factor curve shown in Figure 2 (and re-plotted in Figure 4).

By regressing a curve to be below the lowest point in the large data set in Figure 4, setting a lower BI constraint of zero, and allowing the curve to adjust for different MDF/ADF ratios, various comparator "Min Curves" are generated (see Figure 4). This effectively disallows negative values of BI from being generated. The BI can be estimated from equation 6 for an apparent vast array of basin sizes (ranging from 0.05 mgd up to more than 10.0 mgd).

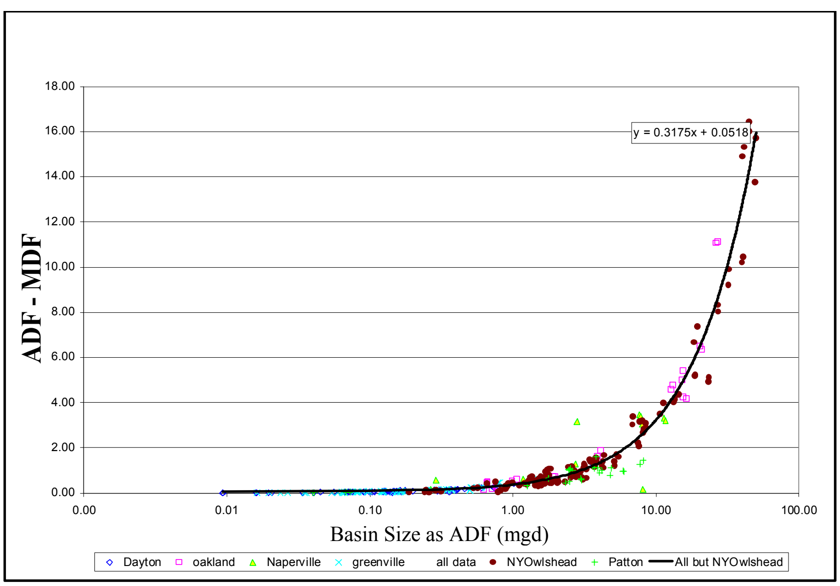


Figure 3 – Chart Showing Relationship of (ADF-MDF) vs. ADF

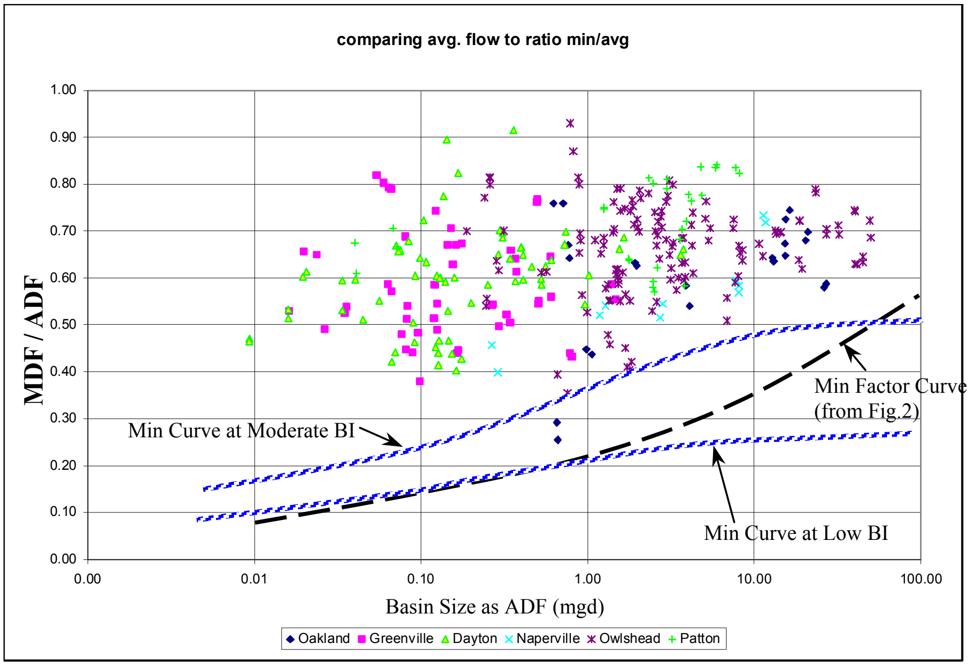


Figure 4 – Chart Showing Relationship of (MDF/ADF) vs. ADF and Variable Min Curve

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). It is seen that the SS Method in general produces a lower, more realistic and stable estimate of BI than does the Wastewater Production method at flows greater than 5 mgd.

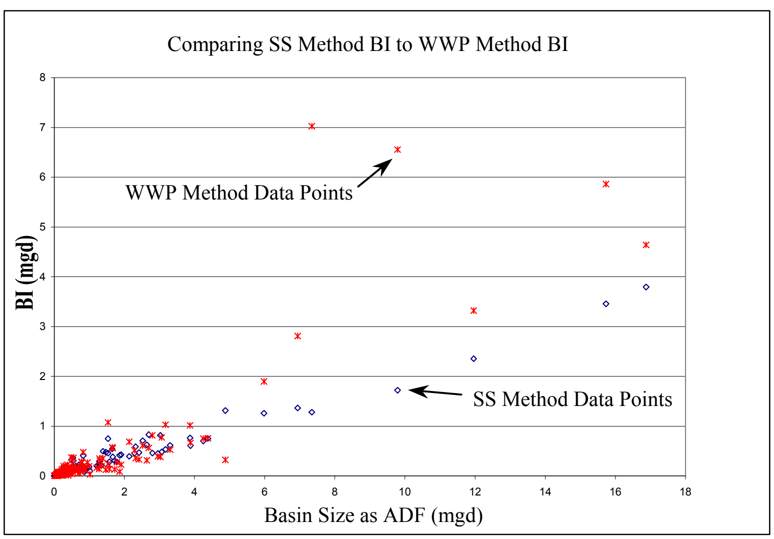


Figure 5 – Chart Showing Relationship of WWP Method BI vs. SS Method BI

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 sewer-shed areas or basins. The basins ranged in size from 20,000 lineal feet (lf) to 150,000 lf. The OCSD service area experienced unusually heavy rainfall during the final season (Winter 2004-2005) of the sewer flow study with a season total rainfall of more than twice normal. There were 72 remaining basins during this final wet weather season and RDII was largely sustained at much higher flows than observed in previous seasons exhibiting far less rainfall.

Of these 72 basins, 45 were selected for rigorous evaluation of each of the above three BI 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), 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 calculated BI for each of the 45 basins using each of the above three BI estimation methods are shown in the graph as Figure 6. The 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 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 be biased low in the basins producing higher levels of BI while the Min Factor and Wastewater Production methods appear to be biased low in the 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.

There appears to be a good correlation between increasing basin size and increasing divergence in BI estimates among the three methods. Figure 7 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%.

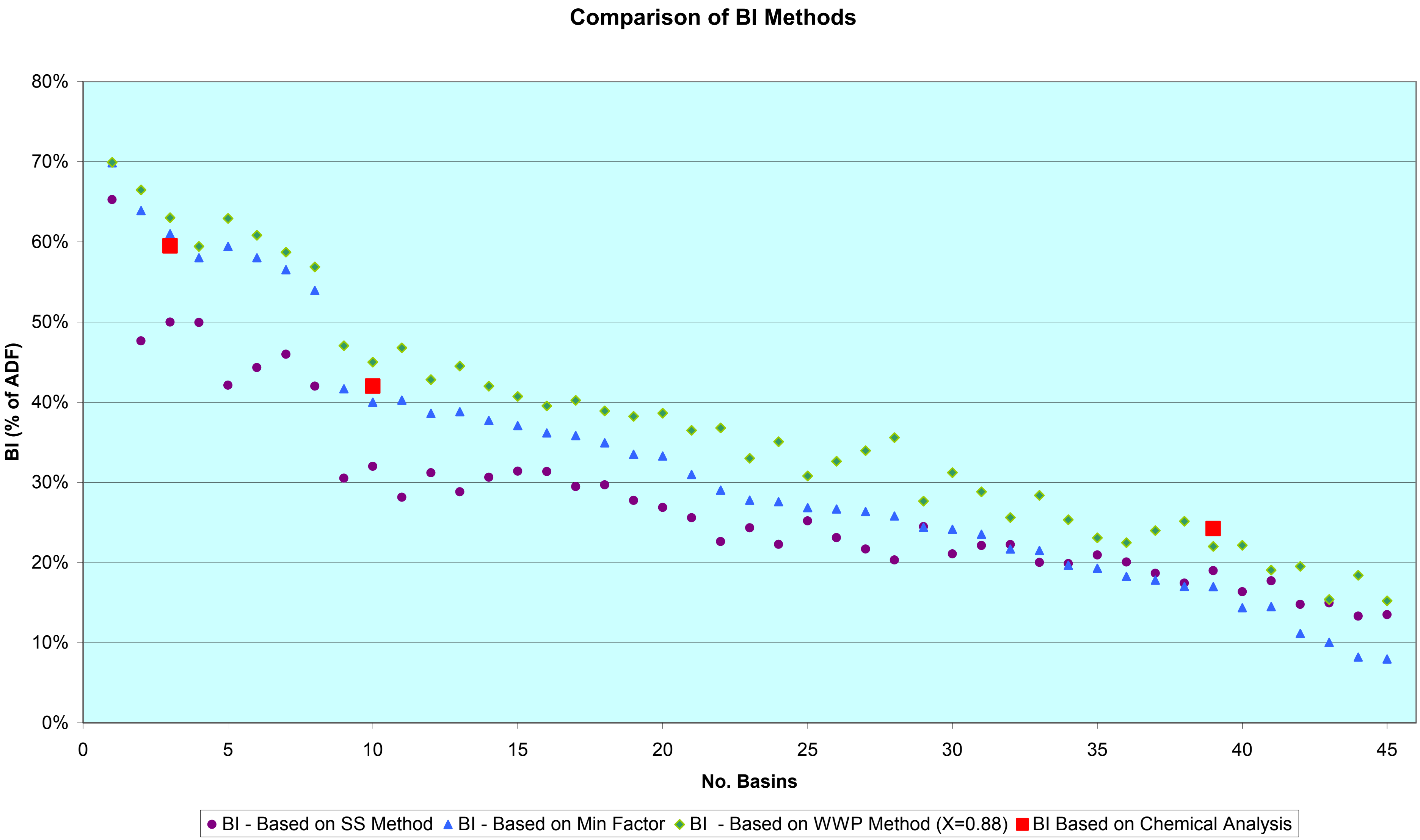


Figure 6 – Chart Comparing BI Methods in OCSD System Basins

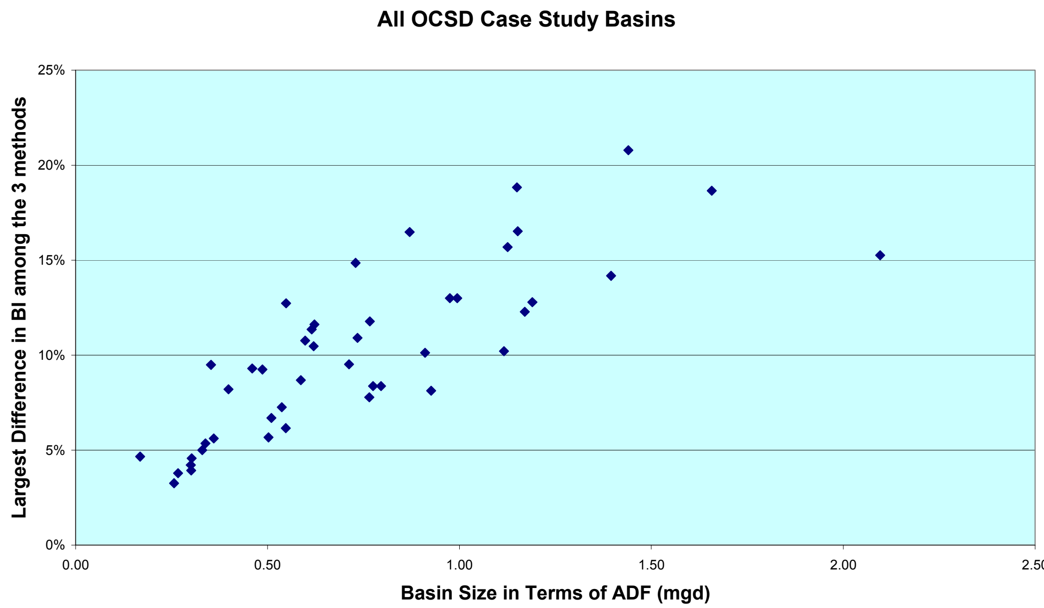
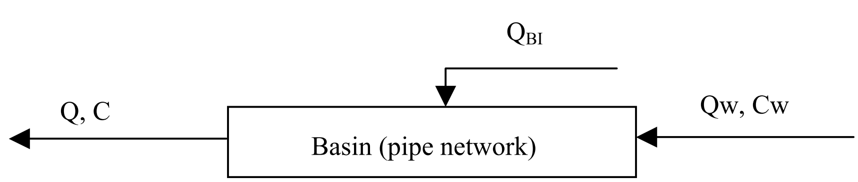


Figure 7 – Chart Showing Relationship of Basin Size and BI Method Agreement

Chemical Analysis Verification of BI

The above comparison provides relative performance among the methods. However, a verification method was needed to help determine which of the methods produced BI estimates that were closest to actual BI. The 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 theory that, for a given fixed intrusion rate of infiltrating groundwater, the percentage of actual wastewater 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 wastewater production 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 6.

$$\mathbf{Q = Cw\,(Q_{BI}) / (Cw - C)} \qquad \textbf{(6)}$$

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 minimizing the difference between measured values of Q and values of Q computed using equation 6.

Three 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 8. 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 BI (the y-intercept of the curve), which is then divided by ADF of that basin to yield BI in units of %ADF. The computed values of BI for each basin using each of the chemical parameters is shown in Figure 9.

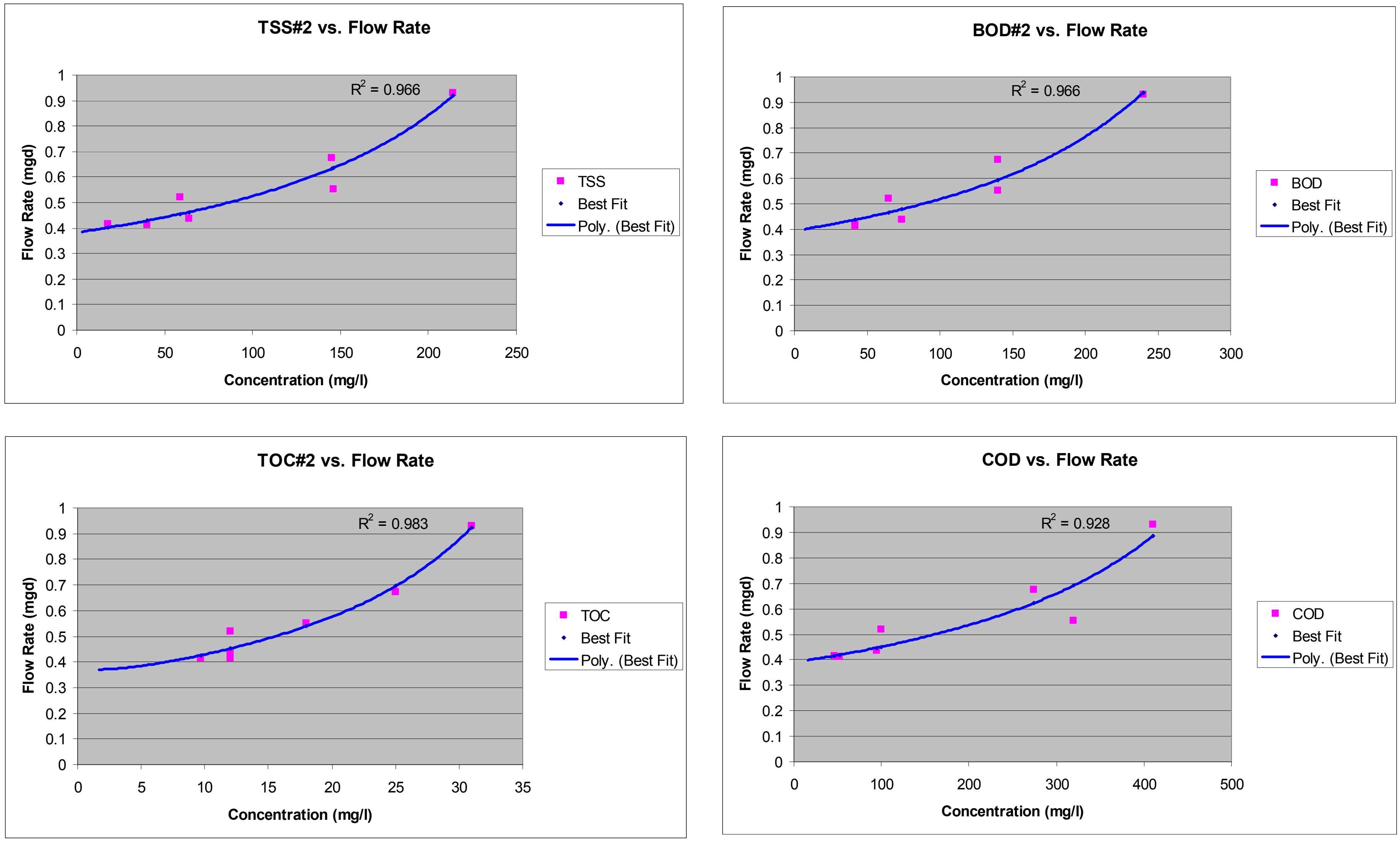


Figure 8 – Plots of Wastewater Parameter Concentration vs. Flow Rate for Basin OC134 showing Best Fit Curve Regression to Equation 6

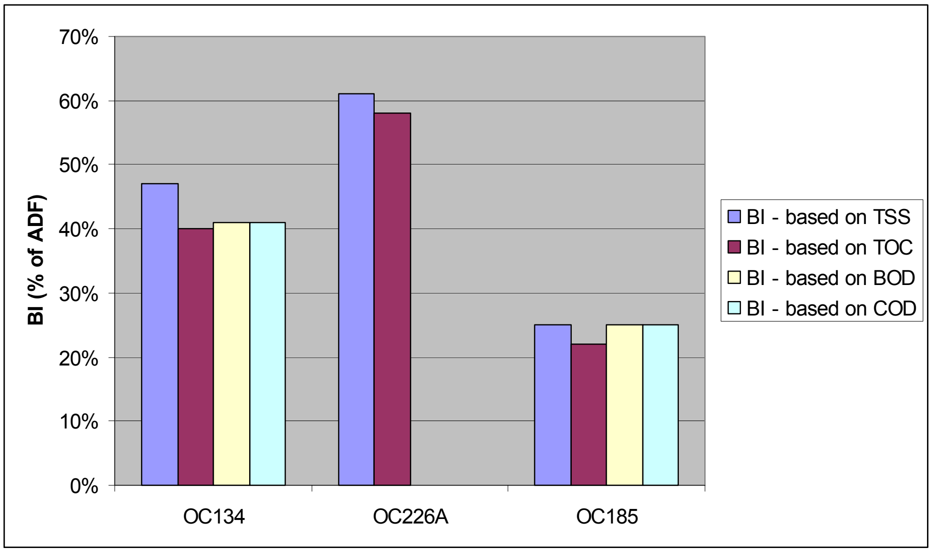


Figure 9 – BI Verification Results based on Chemical Parameter Regression Analysis

The relationship between flow rate and BOD as well as COD in basin OC226A was very poor as depicted in the COD plot in Figure 10. Yet, the correlations using TSS and TOC parameters were good at 0.98 and 0.91, respectively. This is one of the few basins that is 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 possible that some constituents of the infiltrating salt water may be creating some instability in measured Oxygen demand at the laboratory.

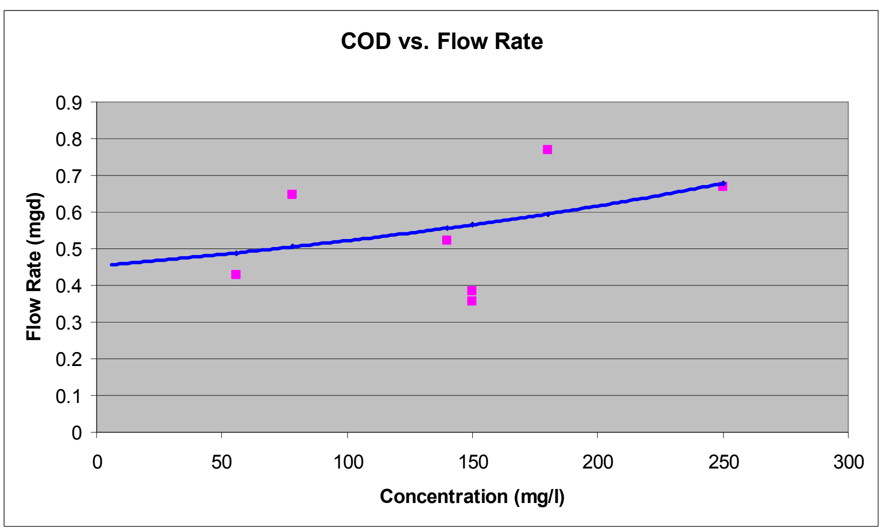


Figure 10 – Plot of COD Concentration vs. Flow Rate for Basin OC226A

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 Min Factor and Wastewater Production methods for the two basins yielding more than 40% BI. In the third basin producing much lower BI (24%), the chemical verification value matched more closely to the Stevens-Schutzbach and Wastewater Production methods.

Since the Wastewater Production method appeared to produce the highest BI estimates of all methods in all the case study basins, 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 to 0.84 from the 0.88 originally assumed. The authors propose that this factor be adopted for any BI studies conducted where this method is to be used and BI is expected to be greater than 25%.

SUMMARY AND CONCLUSIONS

Results to date indicate that the Min Factor method and a slightly modified version of the Wastewater Production method (i.e. reduce the wastewater factor, X, to 0.84 in equation 1) provide more accurate estimates of basin BI in basins yielding BI comprised of more than 25% of ADF. Alternatively, the Stevens/ Schutzbach empirical method provides good estimations of BI in basins yielding BI flows less than 25% and is also far more stable in such basins (i.e. less sensitive to errors in minimum night-time flow measurements). In medium sized basins (ADF of 1.0 to 2.0 mgd), the minimum flow factor method appears to produce reasonable yet conservative values of BI. 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. The data in this paper provide valuable calibration points to authors Stevens and Schutzbach and the SS equation may be revised for a better fit for medium sized basins with high BI.

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.

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