An Approach for Estimating Groundwater Infiltration Rates into Wastewater Collection Systems under Typical Year Conditions

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The performance of combined sewer systems is often assessed on the basis of a typical year approach. *Typical year* refers to a 1 y period for which system performance, often defined by overflow frequencies or volumes, is representative of the long term average. The use of the typical year is a modeling convenience which avoids the need to run multi-decade simulations to find the long term average.

In wastewater collection systems, flow is composed of dry weather flow (DWF) and wet weather flow. DWF can be separated into base wastewater flow (BWF) and groundwater infiltration (GWI). Flow hydrographs, especially during small storms, and total annual overflow volume can be significantly affected by DWF rates and volumes. GWI is a significant component of DWF. Estimation of GWI is critical for characterizing system performance with typical year simulations.

As endorsed by the *Modeling Guidelines* document for the City of Columbus, Ohio, long term wastewater treatment plant data can be used for estimating GWI. This chapter investigates the relationship of GWI and precipitation, and develops an approach to estimating GWI under typical year conditions using long term wastewater treatment plant (WWTP) effluent data and long term precipitation data, as part of the Sewer System Capacity Model (SSCM) Update 2006 Project, Columbus, Ohio. The estimation of typical

Zhang, L., F. Cheng, R. Herr, G. Barden, H. Kelly and E. Burgess. 2013. "An Approach for Estimating Groundwater Infiltration Rates into Wastewater Collection Systems under Typical Year Conditions." *Journal of Water Management Modeling*, R246-21. doi: 10.14796/JWMM.R246-21.

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year GWI rates is achieved by applying the approach to the typical year precipitation data provided by the City of Columbus, Ohio. The estimated typical year GWI is applied to simulate wastewater collection system performance under typical year conditions.

21.1 Introduction

The SSCM 2006 model is the City of Columbus's current version of the system wide sewer model developed using the PCSWMM modeling platform (CHI, 2011) with the USEPA's SWMM5 (Rossman, 2010) as the computational engine.

The model represents the collection and treatment system as of the year 2008. It covers a study area of approximately 256 000 acres (103 600 ha), with >23 000 sewer pipes. More than 100 flow monitors were installed to continuously monitor the system for 16 months from January 2008 to May 2009. Figure 21.1 shows the study area of the SSCM 2006 model.

Figure 21.1 Study area in Columbus.

One of the goals of the project is to develop a model under typical year conditions to evaluate the performance of the combined sewer system. *Typical year* refers to a 1 y period, for which system performance, often defined by overflow frequencies or volumes, is representative of the long term average. The SSCM 2006 model was calibrated for a continuous period from January 2008 to May 2009, which is relatively wet, especially so in 2008. When the model was validated using the year 2007, a relatively dry year, a large DWF difference was found between modeled data and observed data, which significantly affected overflow volume in the combined sewer system. In SWMM5, DWF includes BWF and GWI. Since BWF is relatively consistent from 2007 to 2008, the variation of GWI from wet year to dry year is the major reason for the DWF difference. This difference indicated that the accurate representation of GWI in the model is critical for evaluating the system performance. Developing GWI rates representative of the typical year conditions is necessary for accurate characterization of typical year DWF, and therefore necessary for accurate prediction of typical year system. Information about long term GWI variation is needed to develop GWI for the typical year condition to represent a long term average. Long term GWI data in the wastewater collection system is often difficult to retrieve. However, WWTPs often have influent and effluent data available over decades. WWTP data can therefore be used to extract GWI information, and this approach has been endorsed by the city's *Modeling Guidelines*. This chapter presents an analysis of long term GWI variation and its relationship with precipitation by utilizing long term WWTP effluent data.

21.2 Background

21.2.1 Wet Weather Wastewater Components

Wet weather flow in wastewater collection systems includes three major components: BWF, GWI, and rainfall derived infiltration and inflow (RDII). BWF is the residential, commercial, institutional, and industrial flow discharged to a sanitary sewer system for collection and treatment. GWI represents the infiltration of groundwater that enters the collection system through leaking pipes, pipe joints and manhole walls. BWF and GWI together comprise the DWF of wastewater collection system (Vallabhaneni et al., 2008).

High peak flow rate and volume in wet weather flow may cause a poor performance of sewer systems such as capacity related sewer overflows, basement backups, street flooding, and even serious operating problems at wastewater treatment facilities. RDII is the major component of peak wastewater flows in big storm events. GWI is of small magnitude relative to the high peak flow during storms, but it is a component existing through the entire storm

event period as illustrated in Figure 21.2. GWI can be a significant component of flow hydrographs, especially during small storms, and total annual overflow volume can be significantly affected by DWF rates and volumes. Accurately representing GWI can be critical for characterizing system performance in typical year simulations.

Figure 21.2 Components of wastewater flow during a precipitation event (Vallabhaneni et al., 2008).

21.2.2 GWI Simulation in SWMM5

GWI varies throughout a year. It is often higher when groundwater levels and soil moisture levels rise in a wet period, and lower after an extended dry period (Vallabhaneni et al., 2008). In SWMM5, baseline and baseline patterns are used to represent GWI and its variation. Baseline is a constant number at a given inflow loading node in a SWMM5 model. Baseline pattern represents the variation of GWI. The SWMM5 Time Pattern Editor provides monthly, daily, hourly and weekend patterns. In this study, the monthly pattern is used to represent the variation of GWI through a year. GWI is represented as a product of GWI baseline and monthly pattern of GWI for each inflow loading node.

21.2.3 Typical Year

The typical year approach is often used to evaluate system performance of combined sewer systems. Typical year refers to a 1 y period for which system performance, often defined by overflow frequencies or volumes, is representative of the long term average. A 1 y period of precipitation, referred to as typical year rainfall, is usually developed to meet certain statistical criteria to represent the long term average. The challenge in defining the typical year precipitation record is ensuring that it is representative of the long-term average for system performance conditions (often overflow frequencies and volumes), which is not necessarily the same as the long term average for precipitation conditions.

Another approach to evaluating system performance is continuous simulation, which requires multi-decade model runs to find the long term average. The use of the typical year approach is a modeling convenience which avoids the time consuming multi-decade simulations to find the long term average, especially for a large and complex sewer system.

Figure 21.3 Typical year rainfall data for Columbus.

In this study, typical year rainfall was provided by the Division of Sewerage and Drainage of the City of Columbus, Ohio. The typical year rainfall was

developed to represent long term average precipitation in the Columbus area based on a statistical analysis of approximately 60 y hourly precipitation data from a rain gauge located near Port Columbus International Airport (CMH). The typical year rainfall was based on a selected historical year (1981) which is close to the long term average for annual precipitation. The 1981 CMH precipitation data was adjusted to meet statistical criteria to represent the long term average for various other metrics, including annual rainfall depth, annual number of events, rainfall depth by calendar month, number of events by calendar month, and distribution of event sizes by calendar month (City of Columbus, 2005). Figure 21.3 above shows the typical year rainfall data provided by the city.

21.3 Approach

Development of GWI for a typical year to represent the long term average of system performance requires understanding of GWI variation in the long term. GWI varies temporally and spatially. It increases after an extended wet period when the ground water level is high, and decreases after an extended dry period when the ground level is lower (Vallabhaneni et al., 2008). GWI varies spatially with the elevation of ground water relative to the elevation of sewer pipes, and the integrity of the sewer pipes. To develop a typical year GWI to represent the long term average, temporal variation of GWI is of concern in this study. Spatial variation of GWI in the sewer system area is represented by the calibrated GWI in the system wide model when the model was extensively calibrated using >200 flow meters. Typical year GWI was estimated based on the calibrated GWI in the system wide model as discussed in section 3.1. Accordingly, the spatial variation of GWI under a typical year used is the same as in the calibrated system wide model, and it is not part of the analysis in this chapter.

Due to the difficulty of retrieving GWI directly from flow meter data, and the limited availability of long term flow meter data consistently throughout the entire system, WWTP data was used to quantify system GWI. The SSCM 2006 model includes the City's two WWTPs, Jackson Pike and South-erly. Effluent data at the two WWTPs from 2002 09 01 to 2011 08 31 was provided by the city's Division of Sewerage and Drainage. The 9 y WWTP effluent flow records were used to analyze long term GWI variation in the sewer system. To obtain the GWI information for the entire system, the effluent time series at the two WWTPs were added together to produce the wastewater flow rate time series of the entire system. Precipitation from the rain gauge located at CMH from 2002 09 01 to 2011 08 31 was used in analyzing GWI relationship with precipitation.

Dry days were selected using the reference of the CMH precipitation data and the effluent data at WWTPs. Figure 21.4 displays the sum of the two WWTPs' effluent data and precipitation data at CMH for the year 2006. The well depth data from USGS at the site of 400540082540400 FR-523 AT NGWA were also used as a reference to determine dry days. The well is located in Franklin County, Ohio. The well depth is 26.2 feet (8.0 m). Dry days were selected as the days with no precipitation, and at the local lowest points on wet well curves and the local lowest points on WWTP effluent curves.

Figure 21.4 Typical year rainfall data for Columbus.

WWTP GWI data for the entire system was obtained by subtracting BWF of the entire system from the effluent flow rate at WWTPs for the dry days. BWF was obtained from the calibrated system wide model for 2008–2009, assuming BWF was relatively constant through the years 2002–2011. The relationship of GWI and precipitation was analyzed using the WWTP GWI data of the entire system and CMH precipitation data in the period 2002 09 01–2011 08 31.

GWI simulation in SWMM5 consists of GWI baseline and baseline pattern. The approach presented in this chapter includes two parts for estimating baseline and baseline pattern: analysis of the rainfall and GWI relationship at an annual level to develop the GWI baseline in typical year conditions, and the analysis of the rainfall and GWI relationship at monthly level to develop the GWI baseline monthly pattern in typical year conditions.

21.3.1 Typical Year GWI Baseline

The calibrated system wide model represented GWI in the system for the calibration period of January 2008 to May 2009. DWF, including GWI and BWF, in the system wide model was calibrated to the driest period in 2008, which was June to September. The GWI monthly pattern specific for each year was calibrated in the system wide model to simulate the variation of GWI through that calibration period. The GWI monthly pattern specific for each year corresponds to the precipitation and GWI variation in that year. To utilize long term WWTP effluent data for developing the GWI baseline in typical year conditions, an assumption was made as shown in Equation 21.1. It assumed that the ratio of GWI baseline for typical year model to GWI baseline for the system wide model in the DWF calibrated period of June 2008 to September 2008 would be the same as the ratio of WWTP GWI under typical year condition to WWTP GWI in June 2008 to September 2008.

The calibrated GWI baseline in the system wide model and the WWTP GWI during the period June 2008 to September 2008 could be extracted from the calibrated system wide model and the WWTP effluent data. Therefore, to obtain the typical year model GWI baseline, only WWTP GWI under a typical year condition is required for estimation. The estimation was achieved by a regression analysis of the relationship of the yearly average WWTP GWI with the annual precipitation at CMH for the period of 2003 to 2011. Then the WWTP GWI under the typical year condition was estimated by applying the developed annual relationship to the typical year precipitation. Finally the typical year GWI baseline was calculated using Equation 21.1.

$$\frac{\text{Typical Year Model GWI Baseline}}{\text{Calibrated Model GWI Baseline in June - Sept 2008}} = \frac{\text{WWTP GWI in Typical Year}}{\text{WWTP GWI in June - Sept 2008}} \quad (21.1)$$

21.3.2 Typical Year GWI Monthly Pattern

The GWI monthly pattern under a typical year condition was estimated by developing monthly relationships between WWTP GWI and precipitation for each of the twelve calendar months using regression analysis. The typical year WWTP GWI average for each month was calculated using that month's relationship equation and the typical year precipitation data for that month. Then the WWTP monthly average GWI data were normalized to obtain GWI monthly patterns under typical year conditions.

Regression analysis of the monthly WWTP GWI on precipitation was performed for each month using the selected dry days. For each dry day, previous precipitation data affecting GWI on that dry day was calculated. To

explore how long a previous period of precipitation would affect dry day GWI level, five lengths of previous precipitation periods were analyzed respectively. Previous 15 d precipitation, previous 30 d precipitation, previous 60 d precipitation, previous 90 d precipitation, and previous 120 d precipitation were calculated for each selected dry day. Regression analysis of monthly GWI on previous precipitation for each of the five previous periods was performed for each of the twelve calendar months. The most significant relationship from the five regression equations corresponding to the five previous precipitation periods was selected as the relationship of monthly GWI and precipitation for each month.

21.4 Results

21.4.1 Results of Typical Year GWI Baseline

The result of the regression analysis for annual relationship of WWTP GWI and precipitation is shown in Figure 21.5.

Figure 21.5 Relationship between WWTP GWI and annual precipitation.

The scatter plot in Figure 21.5 demonstrated a strong linear relationship between the yearly average WWTP GWI and annual precipitation.

The regression equation is:

$$y = 1.7198x - 11.26 \quad (21.2)$$

where

y = yearly average WWTP GWI, and

x = annual precipitation at CMH rain gauge.

The regression results show that the adjusted R^2 is 0.78. It indicates that more than 78% of the variation of the yearly average WWTP GWI can be explained by the annual precipitation. The significant positive linear relationship means that the yearly average GWI would be higher at a wetter year with higher annual precipitation. The WWTP yearly GWI for typical year was calculated using Equation 21.2 with the annual precipitation of 37.56 in. (95.40 cm) from the typical year rainfall provided by the city's Division of Sewage and Drainage. The estimated WWTP GWI under typical year conditions was 53.34 MGD (201.91 ML/d). Average WWTP GWI in the period June 2008 to September 2008 was obtained by taking the average of WWTP GWI on the dry days during June 2008 to September 2008. The ratio was obtained by inserting those two values into the right side of Equation 21.1. The GWI baseline in the typical year model was obtained by multiplying the ratio to the GWI baseline numbers in the calibrated system wide model for the period 2008 to 2009.

21.4.2 Results of Typical Year GWI Monthly Pattern

Analysis of the monthly relationship of WWTP GWI to precipitation showed that the length of the previous period of precipitation affecting dry days GWI could be different for each of the twelve calendar months. Figure 21.6 opposite and Figure 21.7 below show the results of regression analysis of the monthly relationship of GWI with the five previous periods of precipitation for March and December respectively.

The most significant regression result for March is that of using the 15 d previous precipitation. The regression result shows an adjusted R^2 of 0.67. The regression equation for March is:

$$y = 17.92x + 59.014 \quad (21.3)$$

where

y = WWTP GWI on each dry day in March,

x = previous 15 d precipitation corresponding to each dry day
in March during 2002 09 01–2011 08 31.

The most significant regression result for December is that of using the 120 d previous precipitation. The regression result shows an adjusted R^2 of

0.76. The regression equation for December is:

$$y = 4.5595x + 1.0173 \tag{21.4}$$

where

- y = WWTP GWI on each dry day in December,
- x = previous 15 d precipitation corresponding to each dry day in December during 2002 09 01–2011 08 31.

Figure 21.6 March relationship between GWI at WWTPs and 15 d, 30 d, 60 d, 90 d, 120 d previous precipitation.

Figure 21.7 December relationship between GWI at WWTPs and 15 d, 30 d, 60 d, 90 d, 120 d previous precipitation.

Figure 21.8 opposite and below shows the monthly relationship of WWTP GWI and previous precipitation for the twelve calendar months identified as the most significant relationship of the five regression results using the five lengths of previous precipitation periods including 15 d, 30 d, 60 d, 90 d and 120 d.

The adjusted R^2 of the regression results of monthly relationships ranged from 0.36 to 0.76 (Figure 21.9 below). The average of the twelve adjusted R^2

values is 0.58. To obtain the dry days under typical year conditions, a typical year model without a GWI monthly pattern was run using typical year rain-fall. Dry days under typical year conditions were selected using typical year precipitation and the simulated flow rate results at the two WWTPs.

Figure 21.8 Monthly relationship between precipitation and GWI at WWTP.

Figure 21.8 Continued: monthly relationship between precipitation and GWI at WWTP.

Previous precipitation for each dry day in the typical year was calculated using the length of previous periods of the monthly relationships developed for each of the twelve calendar months. Then the WWTP GWI under typical year conditions was calculated for each dry day using the developed monthly relationship for each calendar month. The average monthly WWTP GWI under typical year conditions for each month was obtained.

Figure 21.9 R^2 of regression results of monthly relationship between GWI and precipitation.

The comparison with the monthly average of WWTP GWI from 2002 09 01 to 2011 08 31 was shown in Figure 21.10. The two curves in the figure have similar trends, which indicates that the developed typical year GWI pattern represents long term GWI monthly variation. The monthly GWI pattern of a typical year is shown in Figure 21.11. It was derived by normalizing the WWTP GWI under typical year conditions, which was used in the typical year model simulation for the sewer system for Columbus.

Figure 21.10 Typical year monthly GWI at WWTP.

Figure 21.11 Typical year GWI pattern.

21.5 Discussion

In Columbus, snow melting contributes to GWI in winter, typically in December, January, February and March. In this chapter, the snowmelt contribution of GWI was not differentiated from the rainfall contribution in winter for the analysis of the relationship between GWI and precipitation. This relationship was found to be significant both annually and monthly. For the monthly relationship, the length of previous precipitation affecting the GWI level in dry days varies. When the weather becomes colder, the lengths of previous precipitations affecting GWI level in dry days become longer. From October to February, the previous precipitation most significantly affecting GWI in dry days is 60 d or 120 d. From March to September, the previous precipitation most significantly affecting GWI in dry days is 15 d or 30 d, except in July when 60 d previous precipitation most significantly affecting dry weather GWI. The variation in the length of previous precipitations affecting GWI in dry days might be explained by the seasonal variation of vegetation coverage and the moisture content of soil which affect groundwater infiltration (Chow et al., 1988), as well as snow melting.

The relationship of precipitation and GWI was developed based on the precipitation data at the Port Columbus International Airport rain gauge, which may not fully represent the spatial variation of precipitation across the entire area. However, the relationship was developed for the GWI in the entire system by using nine years of precipitation in this study. The spatial variation within the system might be a less significant factor when the GWI in the entire system is concerned in the relationship with precipitation in a long-term period.

21.6 Conclusion

This study used long term WWTP effluent data and long term precipitation to analyze the relationship between GWI and precipitation. Significant positive linear relationships were found between GWI and precipitation both annually and monthly. The annual relationship showed that the adjusted R^2 of the regression result is 0.78, indicating that 78% of the variation of the yearly average WWTP GWI can be explained by the annual precipitation. The monthly relationships showed the adjusted R^2 of the regression results is in a range of 0.36 to 0.76, and at an average of 0.58. The length of the period for previous precipitation influencing GWI in dry days varies seasonally, with a relatively longer period for the wet season, and a relatively shorter period for the dry season. The regression results of the relationships between WWTP GWI and precipitation were applied to estimate GWI baseline and GWI monthly patterns under typical year conditions. The developed typical year GWI was used for the simulation of wastewater collection system performance under typical year conditions for Columbus, Ohio.

Acknowledgment

This study was supported by the SSCM 2006 Model Update Project for the City of Columbus.

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