Using System Identification to Model Near-Term Wet Weather Sewer Flow

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Abstract

Sanitary sewers often see an increased flowrate from wet weather, caused by inflow and infiltration (I/I). There are many modeling techniques used to simulate I/I that are used by industry professionals; however, many of these models fail to account for the differences between inflow and infiltration. Both react to moisture already in the environment in unique ways. This antecedent moisture is a result of both precipitation and temperature and is not readily modeled in the methods commonly used, yet it has critical effects on the increased flow from I/I.

System identification is a method of building a mathematical model of a dynamic system. This method is capable of modeling an adapted unit hydrograph called a Linear Transfer Function for multiple rain events that occur close together, as well as modeling the difference in I/I generation caused by seasonal changes. Unlike other methods, system identification requires few parameters and just two time series, temperature and precipitation, to accurately model the increased flowrate, as well as determine the effects that antecedent moisture has on I/I, and how it changes seasonally.

This paper looks at the use of system identification to model the flowrate into two different types of sewer systems, a combined sewer, and a separate storm and sanitary sewer. The two systems were located within the same area and managed by the Milwaukee Metropolitan Sewerage District (MMSD). The systems experience the same weather and rain events yet react in vastly different ways. This paper touches on the difference between the two systems.

Keywords: antecedent moisture, combined sewer system, infiltration, inflow, i/i, linear transfer function, modeling, residential environment, separate sewer system, system identification, unit hydrograph, urban environment

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Introduction and Background

Municipalities in the United States spend about 20 billion dollars a year on wastewater infrastructure system capital improvements with an estimated 271 billion dollars in needs over the next 25 years (American Society of Civil Engineers, 2017), yet the science behind predicting peak wastewater flowrates is outdated.

Most sanitary wastewater collection systems in the United States are designed to keep stormwater and groundwater out, yet stormwater still finds a way into the systems. Peak flows during wet weather can be multiple times higher than dry weather flows, which heavily impacts water infrastructure and water treatment facilities. Stormwater finds its way into sewer systems through small cracks, leaky joints, old connections to footing drains, and many other pathways. The current state-of-the-art in modeling wet weather flow in sewer systems is not very accurate or reliable (Singh, 1976). The purpose of this paper is to build and analyze a model using system identification to create a more accurate hydrograph that could be used for future predictions.

Sewers are difficult and expensive to monitor. Meters require time and money to install, maintain, and gather data. In many collection systems, the only long-term meter is at the wastewater treatment plant. Short term (several months to one or two years) is often the only available monitoring in most collection systems. Yet, engineers planning collection system improvements want the longest record possible in order to predict the long-term performance of any proposed infrastructure improvements. How do engineers create a long signal from a short one? One method that engineers use is by taking indicator signals that have a long record and relate them to sewer flow. There are many potential long-term indicator signals, including precipitation, temperature, stream flow, snowpack, soil temperature, evapotranspiration, groundwater level and others. With the use of system identification, a better idea of how those variables affect a system can be determined. Temperature is a common factor in most of the signals and is used as a surrogate for antecedent moisture.

Antecedent Moisture

How precipitation reacts depends on the water deficit. Was the system already dry or oversaturated? Is there surface water present to evaporate? Has ground water had time to settle, or is it above the normal levels? These conditions are summed together as antecedent moisture. Antecedent moisture is the preceding moisture condition of an environment. It is a complex representation of the relative wetness or dryness in the soil, also known as the soil moisture deficit. The wetness of the soil is impacted by many variables. Elevation, soil type, seasonal precipitation, impervious surfaces, temperature and more work together to define the state of the soil moisture deficit. At low temperatures, it is expected that there will be higher soil moisture content in the ground and less evapotranspiration and greater runoff will occur.

Many environments have different characteristics during spring, summer, fall and winter. In the spring, which experiences low average air temperatures, there is no soil moisture deficit. The soil cannot absorb any more moisture provided by additional rainfall or snow melt. The additional moisture pools on the surface or raises the water table. In the summer, which experiences high average air temperatures, there is high evapotranspiration which causes a soil moisture deficit. The soil moisture deficit increases the soil's capacity to absorb additional moisture from rainfall. The soil stores the additional water, making it less likely for water to pool on the surface or raise the water table until the moisture deficit is satisfied by a substantial amount of rainfall. Sustained high temperatures are associated with lowering the water table and increasing the soil moisture deficit.

In an urbanized environment the antecedent moisture has different characteristics. Urbanization coincides with imperviousness of an area. Streets, sidewalks, roofs, any impervious surface will cause greater amounts of runoff than in rural settings. Milwaukee County is 45 percent impervious with the highest percentage of impervious area found in the central city (City of Milwaukee's Office of Environmental Sustainability, 2015). The Jones Island Water Reclamation facility service area is the heavily urbanized center of the City of Milwaukee. The area is mostly impermeable, with little open land to absorb rain and runoff. The deficit is recharged slowly in urban environments and rainfall typically drains quicker (MMSD, 2020a).

Rain events are a major method of recharging a system and eliminating the soil deficit which saturates the soil. Once the soil is saturated, rainwater water pools can cause flooding. In a developed environment, water management practices use sewer systems to divert or convey the water away from the developed area. Many water management professionals prefer to let the precipitation soak into the soil and make its way to the groundwater to regain any volume lost to natural means, such as evaporation, or mechanical, such as drinking wells. Other methods of management include conveying the water to treatment facilities.

Combined and Separate Sewer Systems

There are two types of sewer systems used to convey stormwater and sanitary sewage: combined systems and separate systems. A combined system is simply one sewer line that combines both stormwater and sanitary sewage to be conveyed to a treatment facility. In this system, both wastewater and stormwater are treated together as they homogenize in the sewer line. These systems can be overwhelmed during heavy rain periods and may require a Combined

Sewer Overflow (CSO). A CSO is the discharging of excess wastewater directly to a waterbody instead of it being treated at a treatment facility. A CSO is ideally avoided.

Separate sewer systems use separate lines to convey wastewater to a treatment facility and stormwater directly to a waterbody. The wastewater is sent to a treatment facility to be treated before the cleaned effluent is sent to a waterbody. Although the sewer lines are separated, there is still often Inflow and Infiltration (I/I) that allows stormwater to enter the sanitary lines overtaxing sanitary sewer and treatment facilities capacity.

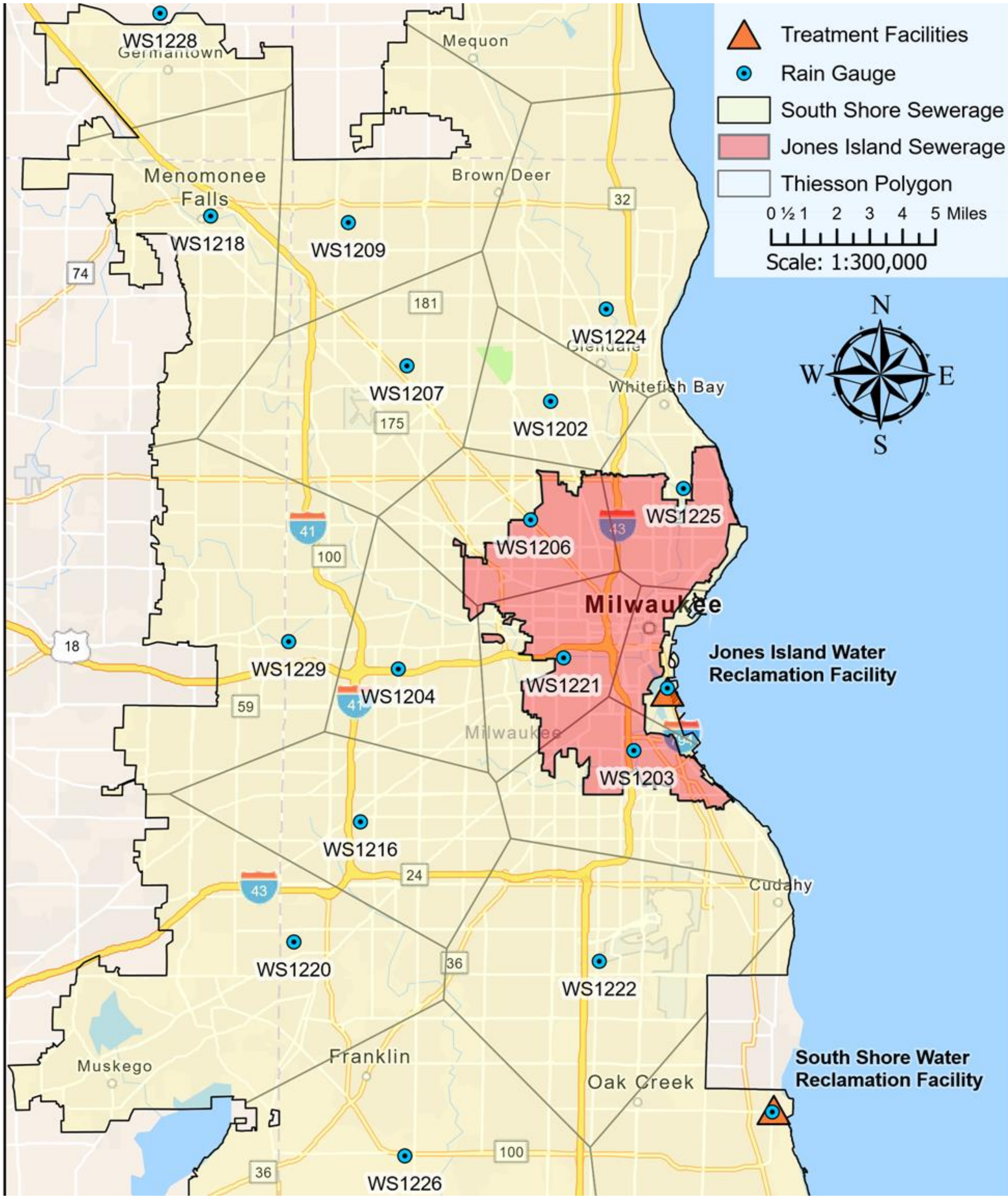
Milwaukee uses a combination of the two systems. The urban core of Milwaukee utilizes a combined sewer system, most of which is sent to Jones Island Water Reclamation Facility (JI) for treatment. To prevent unnecessary CSOs, combined sewage in excess of sewer capacity is diverted into the Inline Storage System, also known as the Deep Tunnel. The Deep Tunnel is able to store about 500 million gallons of wastewater and storm water that would otherwise overwhelm the treatment facilities (MMSD, 2020, May 18). Outer Milwaukee uses separate sewer systems that discharge stormwater directly to local waterbodies, such as Lake Michigan, the Milwaukee River, the Menomonee River and others. The sanitary sewage is mostly conveyed to the South Shore Water Reclamation Facility (SS). The Deep Tunnel also stores excess sanitary sewage from the separate sewer system.

The area serviced by Jones Island is small at less than 50 square miles, when compared to the area serviced by South Shore at greater than 600 square miles. The Jones Island sewer service area has a greater population density, which affects baseflow and daily variances, such as washday effects. As of 2018, the population density for the combined sewer area was 6,210 persons per square mile, while the towns and villages within the Milwaukee area that use the separate sewer system range from 520 to 4,400 persons per square mile (Open Data Network, 2020). The greatest distance that flow must travel is less than 8 miles to Jones Island, while some of the separate sewer system is nearly 30 miles away over land, longer when travelling through the sewer system. The flow to Jones Island would take minutes to an hour to reach the facility. The greater distance to South Shore means that some sewer flow will take hours or days to reach the facility.

The two treatment facilities do not strictly treat the two systems independently. Junctions and diversions are used throughout the entire MMSD area of operation (see Figure 1). These junctions allow engineers to manage the flow to the two water reclamation facilities and to the Deep Tunnel. During storm events, the Deep Tunnel may be used to prevent overflows. This stored water is then pumped to Jones Island or to South Shore for treatment. While some of the flow treated at Jones Island originates in the separate sewer system, its flow is dominated by the flow from the combined sewer system. Flow to South Shore is strictly from separate sewer areas, except for any Deep Tunnel pump-out to South Shore.

Figure 1

Map of Milwaukee Sewershed



Note. Areas of Milwaukee that are serviced by the Milwaukee Metropolitan Sewerage District. The county is split into areas measured by MMSD rain gauge stations and the different sewerages. Map created by author using ArcGIS Pro with available data from MMSD.

Inflow and Infiltration

Inflow and infiltration describe the clearwater that enters a sewer line. Clearwater is groundwater and stormwater that accumulates either below ground or on the surface and makes its way into a sewer line. This clearwater, which may not actually be clean or clear, is normally conveyed in stormwater sewers or left in the ground. A rainstorm drops a large amount of water on the surface. This water may take time to soak into the ground, and as a result, it pools on surfaces and then travels as runoff across the ground and collects at the lowest elevations. These low points are often collection points that divert the runoff into the storm sewer or combined sewer. However, sometimes the stormwater flows (inflows) into the sanitary lines through poorly sealed manholes, household drains for sump pumps, or other openings that allow runoff to flow in. Some water enters through cracks in the pipes, and pipe joints that are not seated well, among other means that are below ground.

When stormwater does soak into the ground, and reaches the groundwater, it causes the water table to rise above the level at which the sanitary sewer is buried. With the pipe submerged in groundwater, the groundwater can penetrate the sewer through the aforementioned defects. This stormwater that gets into sewer systems is referred to as infiltration. These two intrusions into the sewer system cause different reactions, but are difficult to separate, thus they are often grouped together, though there is a significant difference.

Inflow and infiltration reach a wastewater treatment facility at different speeds. The runoff from storms collects and inflows into the sewer system quickly. The inflow begins immediately, and the sudden increase of flow reaches the treatment facility in a rush. The Peak Inflow is the max flowrate from a storm event, and when recorded hourly, it is called the Peak Hourly Inflow. The infiltration from the rising groundwater has a later peak flow. Although the peak is later and not as high as the inflow, the peak infiltration flowrates last longer. These different flowrates are often referred to as fast and slow flowrates, or responses. Some systems may also have a medium or intermediate flowrate that describes runoff that takes longer to reach the system but not as long as infiltration to the groundwater.

Milwaukee uses both combined sewer and separate sewer systems. Because of the nature of these two systems, the treatment facilities for each system show very different flows during rain events. Jones Island, which treats the combined sewer areas, has a much higher inflow than South Shore and distributes more wastewater to the Deep Tunnel early during storms. The South Shore facility treats only separate sewer areas and collects sewage from a much greater area than the Jones Island facility and has a slower flowrate into the facility. There is more infiltration due to greater area, which can catch up to the inflow's faster speed. By studying these two facilities, it is possible to observe the impacts and differences in inflow and infiltration on the two types of sewer systems.

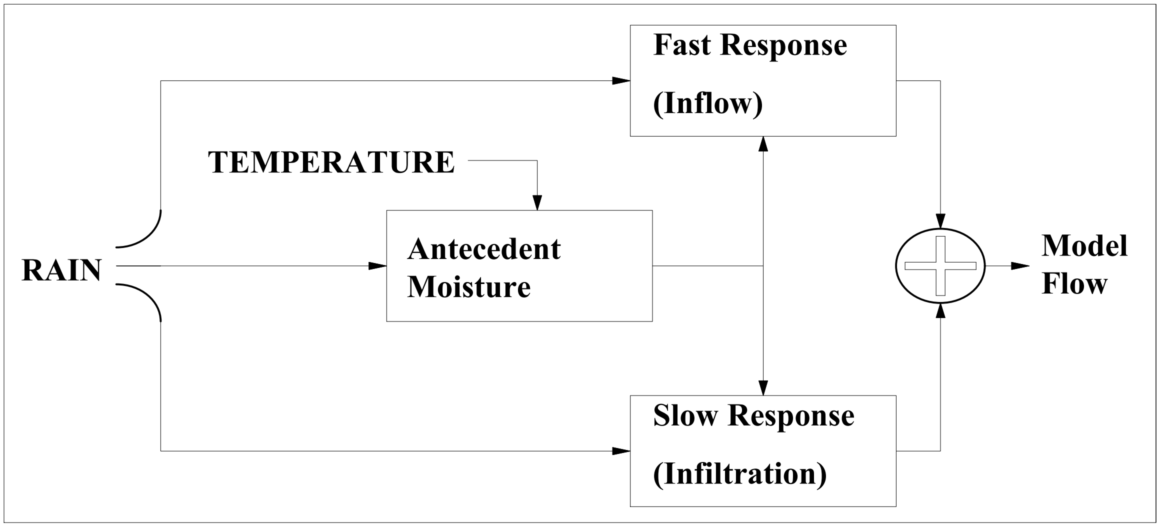
System Identification

Methods used to model unit hydrographs that are most used today rely on physical parameters such as precipitation measurements, and runoff calculations of soil types and perviousness. These models range in accuracy from 10 to 80 percent error (Hoffmeister, 2009). These methods are used to determine the resulting flow through a point, or into a place of interest such as a treatment facility. Based on these models, conveyance and treatment facilities are designed. Reliance on accurate models can mean the difference in designing a facility that is too small and overwhelmed by storm events, or over designing a facility that wastes money in its construction and costs more to operate. Designers and engineers rely on models to ensure the best possible design. Some models simulate single storm events, not considering the wetness of the system from previous storms. System identification models a continuous weather pattern and so builds on the past and current conditions of the environment.

System identification is a way to build mathematical models of a system with dynamic values, or values that depend on the current and past behavior of the system. To explain, Figure shows a simplified block diagram that describes how the model uses the inputs. The precipitation is dynamic, affecting the flowrate and the antecedent moisture. Throughout the day the temperature rises and then drops, but the diurnal temperature has less impact than the seasonal long-term trends. A higher current temperature has an effect on the current time step; there is greater evaporation and dryer conditions. However, the dryness within the system depends on past conditions and the daily average temperature that are a result of the seasonal trends. Using system identification, the effects that temperature has had on past conditions, together with the current conditions can be modeled. Rather than measuring each of the variables in antecedent moisture and creating an increasingly complicated formula, system identification simplifies these variables and provides a flexibility to the model. The model adapts to the changing environment adjusting the parameters for the appropriate situation, whether modeling inflow or infiltration. This method offers some insight into the system’s characteristic parameters, how the system reacts to an intense storm, whether more moisture is absorbed into environment, or if runoff accumulates suddenly.

Figure 2

Block Diagram of System Identification Model



Note. Adapted from "The Application of System Identification to Inflow and Infiltration Modeling and Design Storm Event Simulation for Sanitary Collection Systems," by T. Van Pelt and R. Czachorski, 2002, *WEFTEC 2002 Conference Proceedings*, Proceedings of the Water Environment Federation, p. 611. The diagram shows how the inputs of the model (RAIN, TEMPERATURE) alter the antecedent moisture, which adjusts the response flow.

This model uses a Fast Response and a Slow Response to model the inflow and infiltration, respectively. The two responses use the same environment; however, they react in vastly different ways. The responses are a result of the precipitation in the environment and are influenced by the antecedent moisture. The antecedent moisture is a multi-input nonlinear operator that is used to adjust the two responses. It is a result of the inputs of precipitation and temperature for the current and past timesteps. The Slow and Fast Responses are added together to create the model's total flow.

Linear Transfer Function Equation

The Linear Transfer Function --Equation (1)-- models an adaption of a linear unit hydrograph that describes the Flowrate (Q_t), which is affected by the current condition of the system as well as the previous timesteps' conditions:

$$\boldsymbol{Q_t = \frac{Conv.Factor \times Area\ Sewershed}{Time\ Step} \times (AC + RF_t) \times R_t + SF \times (Q_{t-1} - BF) + BF}, \qquad \textbf{(1)}$$

where

Q_t = flowrate,

AC = affine constant,

RF_t = response factor of current timestep,

R_t = rain depth of current timestep,

SF = shape factor of system,

Q_{t-1} = flowrate of previous timestep,

BF = baseflow into treatment facility during dry weather.

The Affine Constant (AC) describes the minimum amount that the current rainfall increases the flowrate. The Response Factor for the current timestep (RF_t) is the dynamic variable that describes the variable amount that current rainfall at time t increases the flowrate. The factor is affected by the temperature and antecedent moisture of previous timesteps. A larger ($AC+ RF_t$) yields a higher flowrate response to a given rain depth measurement. The AC and RF_t are combined and multiplied by the current timestep rain depth (R_t). This is the amount of the current rainfall that will contribute to the flowrate. By dividing the sewershed area by the timesteps, then converting to Million Gallons per Day (MGD), flows become comparable between the two sewersheds.

While the current rainfall adds to the flowrate, the transfer function will decay as the antecedent moisture in the system drains. The rate of decay is called the Shape Factor (SF) and controls the speed at which the transfer function decays (bounded by a range of 0-1). The SF is multiplied by the previous timestep's Flowrate (Q_{t-1}) less the Baseflow (BF). The BF is the minimum flowrate into the facility when no rain event has occurred and is typically made up of the normal sewage from county daily usage. The BF is removed from the Q_{t-1} as the transfer function's decay should asymptotically approach the BF of the system. The BF is then added back to bring the transfer function back to the appropriate flowrate it represents.

Antecedent Moisture Retention Equation

The Linear Transfer Function Equation is dynamically affected by the Response Factor for the current timestep (RF_t) which is described by the Antecedent Moisture Retention Equation, Equation (2):

$$\boldsymbol{RF_t = (TF_t) \times R_{t-1} + AMRF \times RF_{t-1},} \tag{2}$$

where

RF_t = response factor for current timestep,

TF_t = temperature factor of current timestep,

R_{t-1} = rain depth of previous timestep,

AMRF = antecedent moisture retention factor,

RF_{t-1} = response factor of previous timestep.

The RF_t is a result of the previous timestep's precipitation and the environment's antecedent moisture. The Temperature Factor for the current timestep (TF_t) quantifies how much the previous timestep rainfall increases the RF_t. When the TF_t is large, the previous timestep rainfall (R_{t-1}) produces a greater flowrate for the current timestep. The flowrate of the current timestep is added to the antecedent moisture of the system. The Antecedent Moisture Retention Factor (AMRF) is a decay factor (bounded by the range 1-0) that controls how fast the Response Factor (RF) decreases in time. This equation creates a mathematical description of the system with physical interpretation.

Exponentially Weighted Moving Average Temperature

Rather than using the current temperature, an exponentially weighted moving average of the temperature is used so that short-term daily and hourly temperature swings do not influence the system response:

$$\boldsymbol{EWMAT_t = \phi * EWMAT_{t-1} + (1-\phi) * T_t,} \quad \textbf{(3)}$$

where

$EWMAT_t$ = exponentially weighted moving average of current timestep,

ϕ = decay constant,

T_t = temperature of current timestep.

An exponentially weighted moving average ($EWMAT_t$) is used to prevent the current timestep's temperature from dominating the TF_t equation. In Equation 3, the $EWMAT_t$ of the sum of the previous step ($EWMAT_{t-1}$) is multiplied by the EWMA Decay Constant (ϕ) (bounded 0-1) and the current Temperature (T_t) is multiplied by 1 minus the Decay Constant. The $EWMAT_t$ is used in the temperature factor equation.

Temperature Factor

At cooler temperatures, the soil has less evapotranspiration, which makes it wetter in general, which means a greater amount of the rainfall is able to pool on the surface or percolate into the soil. This creates a larger TF_t, which is represented in:

$$\boldsymbol{TF_t = \left[\frac{Range}{1 + e^{(-k\{EWMAT_t - x_0\})}}\right] + Low\ TF - \frac{11}{12} Range,} \quad \textbf{(4)}$$

where

Range = the range of values between the high TF and low TF,

TF = temperature factor that correlates to ambient temperature,

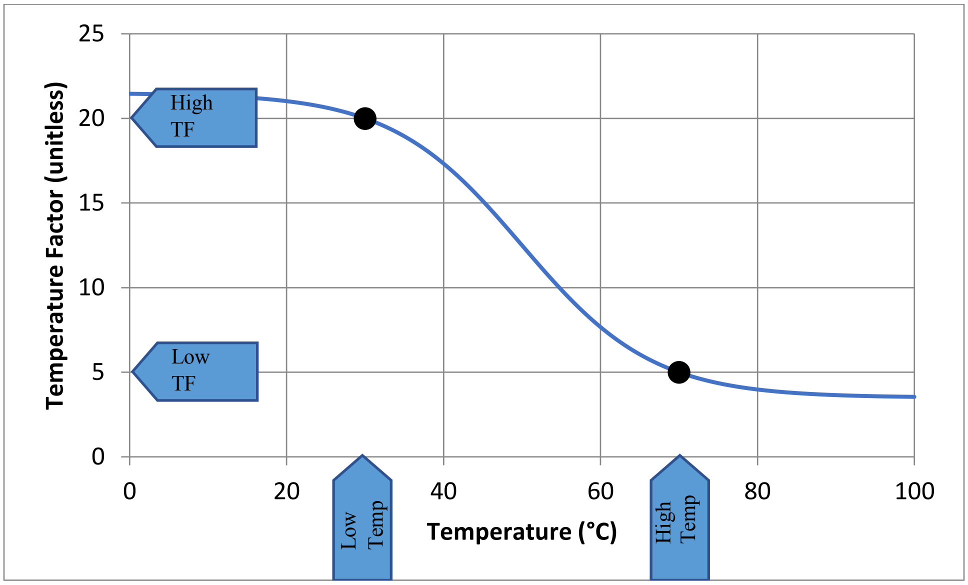
k = factoid range of temperature factors,

x_0 = average temperature.

The Temperature Factor (TF) is a logistic function that presents a sigmoid curve (S-shaped curve) which provides a unique TF for all temperatures. Figure is an example of the sigmoid curve. This equation also pushes the asymptotes of the high and low TF by 10% of the Range. This creates a more uniform distribution of TF between the specified temperatures. The average temperature (x_0) defines the middle of the function while the steepness parameter (k) provides the asymptotic boundaries for the Range of TF (Range), meaning the sigmoid will never become negative. When the $EWMAT_t$ is high, the bounds of the equation determine that the TF of subsequent $EWMAT_t$ will be similar.

Figure 3

Sigmoid Curve for Temperature Factor



Note. Adapted from R. Czachorski (personal communication, 2020). The figure shows a sigmoid curve, which represents the Temperature Factor that corresponds to the timestep's temperature. This example has a set factor of 20 for 30°C and 10 for 70°C. As temperature increases, the temperature factor decreases.

Calculating the Range of the Exponentially Weighted Moving Average Temperature

Equations (5), (6), and (7) are employed to calculate the range of the exponentially weighted moving average temperature:

Range = Range of TF:

$$\boldsymbol{Range = 1.2 * (Low\,TF - High\,TF);} \quad \textbf{(5)}$$

k = Factoid Range of T:

$$\boldsymbol{k = \left[\frac{4.7964}{Low\,T - High\,T}\right];} \quad \textbf{(6)}$$

x_0 = Average of T:

$$x_0 = \frac{Low\ T + High\ T}{2}. \qquad (7)$$

The Range provide the Sigmoid curve's maximum and minimum factor values. The Range is found with the difference of the TF for the high and low temperatures. The Range of the factors is assigned to temperature values (T). For this model, a high T of 70°C and a low T of 30°C were chosen. The TF for those temperatures is a variable that must be determined. The Range is determined by the constant 4.7964 divided by the difference in the chosen temperatures. The low temperature has a high TF, indicating that the antecedent moisture is evaporating less, and the soil is holding onto moisture without draining or absorbing as much. The use of the sigmoid function and adaption of the linear unit hydrograph to Linear Transfer Function was provided by VanPelt and Czachorski (2002).

The constant represents how weighted the $EWMAT_{t-1}$ is. A high ϕ represents an average that is controlled by the previous average, while a low ϕ means that the current temperature has a greater influence. This model used a high ϕ to ensure that the previous average was the controlling element.

Because this model adapts to the inputs of the environment, it is able to adjust to seasonal changes as well. The model does not rely on generalized seasonal inputs but changes according to the physical parameters of the environment. During cool spring temperatures, the model adjusts to how the soil does not absorb as much moisture, and in a warm fall, the model shows more absorption and a buildup of antecedent moisture. Unlike other models, the results will represent the seasonal environment, and not the general inputs.

Methodology

This study used historical precipitation measurements from rain gauges in Milwaukee County, Wisconsin, provided by the Milwaukee Municipal Sewage District (MMSD). These rain gauges were spread throughout the sewershed serviced by MMSD. The gauge data are from August 19 to October 9, 2018, which was a particularly rainy period for the area. To determine the cumulative rainfall for the entire sewerage district, the areas of each rain gauge were determined by the Thiessen Polygon method. The sewershed was then further broken up into combined sewer and separate sewer systems, as defined by MMSD. Each gauge area was divided by the total sewershed area. The gauge areas and the rain gauge measurements were then summed for the cumulative rainfall over Milwaukee County, and the two sewersheds. Each model used the relevant rainfall for its area as determined by the gauge locations and Thiessen polygons. The gauge data came with time and dates of the measurements, at hourly increments. With the timesteps known, historical temperature data were collected from cli-MATE Tool System at Midwestern Regional Climate Center website (Midwestern Regional Climate Center, 2020). The location for the temperature data was taken from General Mitchell International Airport.

Sewer flow data were also acquired from MMSD for both sewer systems. The data included flow directly to the facility, flow pumped from the Deep Tunnel to the facility, and flow from the facility to the Deep Tunnel. Flow into the Deep Tunnel is monitored at the many dropshafts throughout the system, as well as flow diverted back to the facilities. The metered data were combined to develop the observable flow into the facility. The flow into the Deep Tunnel goes through the facilities and must be taken out of the total flow so as to not count it twice. The system identification model was developed with the hourly gauge measurements, corresponding temperatures and observed flow into the facilities.

The Linear Transfer Function Model comes from an adaption of the Clark Instantaneous Unit Hydrograph Equation. The model itself is a Linear Instantaneous Unit Hydrograph, derived by system identification methods. The model was first developed by Dr. Robert Czachorski and Dr. Tobin Van Pelt (2002) who describe it as a Linear Transfer Function Model that is scaled by the Antecedent Moisture Retention Equation. A graph of the combined Fast and Slow Responses are combined to match the observed flowrate into the facilities.

When setting up the model in Microsoft Excel, a Fast and a Slow Response are developed to distinguish between inflow and infiltration. The previously mentioned equations need to be set up for both Fast and Slow Responses as the variables (SF, AC, AMRF, TF) will be different. The equations determine how each reacts. To calibrate the Jones Island model, a method of defining whether the time sequence is influenced by the Fast or Slow response is needed. For the Jones Island model, the calibrations were determined by the previous six timesteps (hours) of rain data. If there was a rain event in the previous six timesteps, then the model calibrated the Fast Response. When no rain event was present, the model calibrated the Slow Response. A South Shore model was made with the same method of calibration; however the characteristics of the system required a different method of calibration to be used, in which a cutoff flowrate was established. Flow less than the cutoff was classified as Slow Response, and flow greater than the cutoff became the Fast Response.

Model calibration minimized the sum square difference between the model and observed flows. Assumed variables were placed into the formulas in Microsoft Excel. The Excel tool Solver was used to adjust the variable values by minimizing the sum square difference for the model hourly flow and the observed hourly flow. The variables that were adjusted are the BF, SF, AC, AMRF, High TF, and Low TF. The base flow only affects the Slow Response. Solver was used to alter the variables until the sum square difference was minimized, and no further noticeable differences occurred from further uses of Solver.

Results

The results of the model are promising and show good accuracy. The Jones Island model and South Shore model showed vastly different results, which is expected as they are different types of sewer systems. The calibrated model parameters are listed in Table 1. The results for each response in both models were expected. The observed flow into both plants for the period of August 19 through October 7, 2018 are shown in Figure 4. The model results for Jones Island and South Shore are shown in Figure 5, Figure 6, Figure 7, and Figure 8.

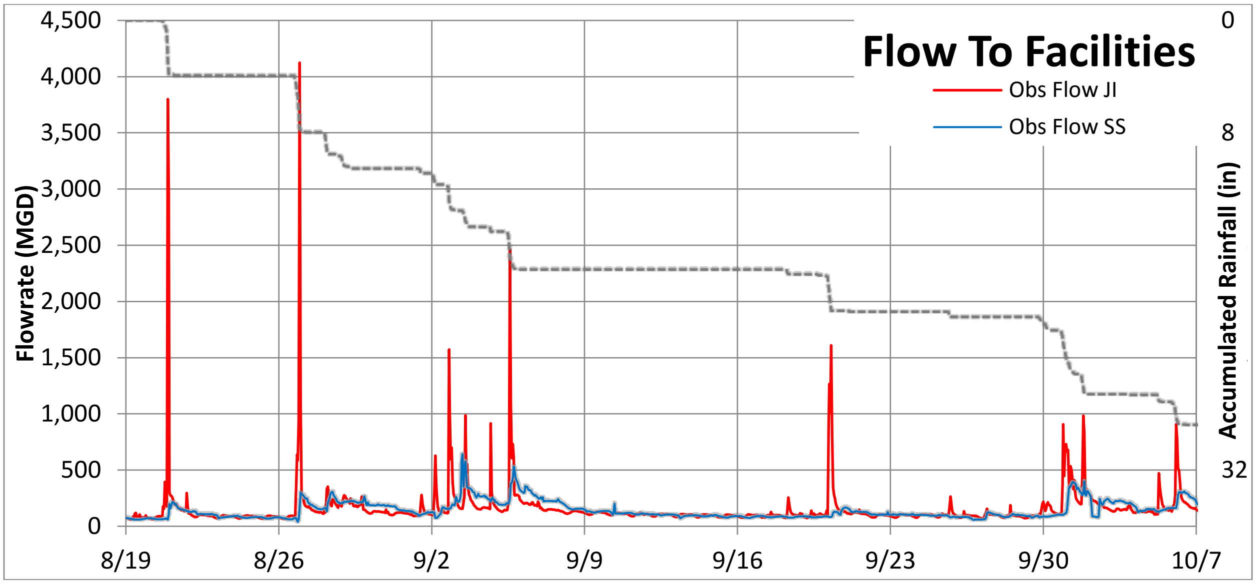
Table 1

Calibrated Model Parameters for the Jones Island and South Shore Models

Variables	Jones Island Model			South Shore Model		
	Slow Response		Fast Response	Slow Response		Fast Response
Area of Sewershed (mile^2) =	49			603		
Timestep (seconds) =	3600			3600		
CFS to MGD =	1.547			1.547		
Baseflow (MGD) =	87.00			55.00		
Shape Factor =	0.978	>	0.167	0.994	>	0.973
Affine constant =	4.97	<	529.41	2.70	<	55.61
Antecedent Moisture Retention Factor =	0.998	>	0.753	0.998	>	0.994
Temperature Factor $_{\text{High (30°C)}}$ =	45.00		598.06	257.45		115.72
Temperature Factor $_{\text{Low (70°C)}}$ =	4.06		597.81	1.71		9.13
Sum Square Error =	295,000		5,724,000	725,000		882,000

Figure 4

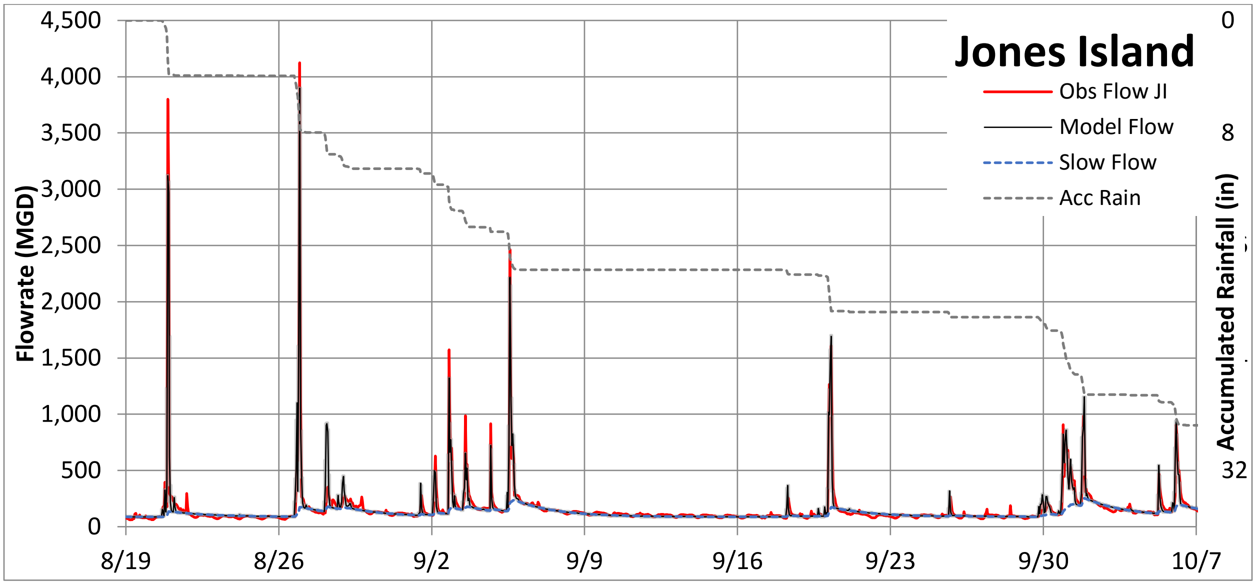
Observed Flow into Jones Island and South Shore Treatment Facilities



Note. Milwaukee County had several abnormal rain events from August 19 to October 7, 2018. Figure 4 depicts the observed flow to Jones Island Water Reclamation Facility and South Shore Water Reclamation Facility. Rain events are measured in inches per hour which indicate the intensity of the storm and are displayed as an accumulation to show the volume and intensity. Jones Island receives a far greater volume of water from the combined sewer system than South Shore. The flow to South Shore from the separate sewer system does not peak as high as Jones Island, but has a longer response to rainfall, indicating that there is a greater infiltration impact on the system.

Figure 5

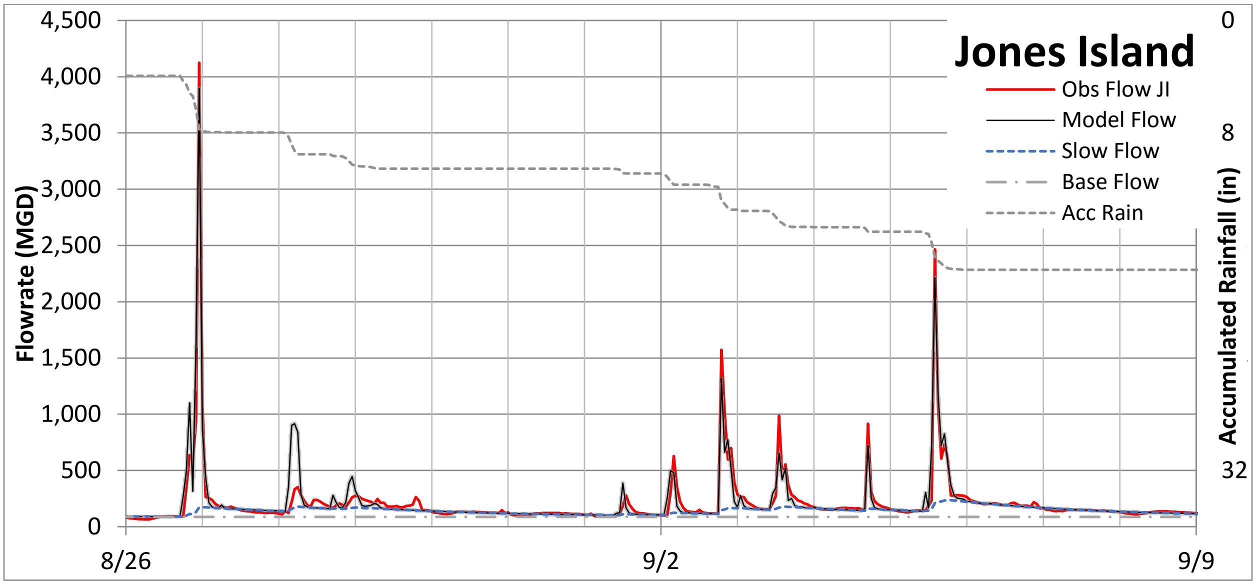
Comparison of Jones Island Model to Observed Flow to Jones Island



Note. Figure 5 shows the total model for Jones Island compared to the observed flow for the combined sewer system. The Fast Flow is the difference of the Slow Flow from the Model Flow. The Slow Flow is the Slow Response, representing infiltration in the sewer system. This system is affected most by inflow to the system during rain events.

Figure 6

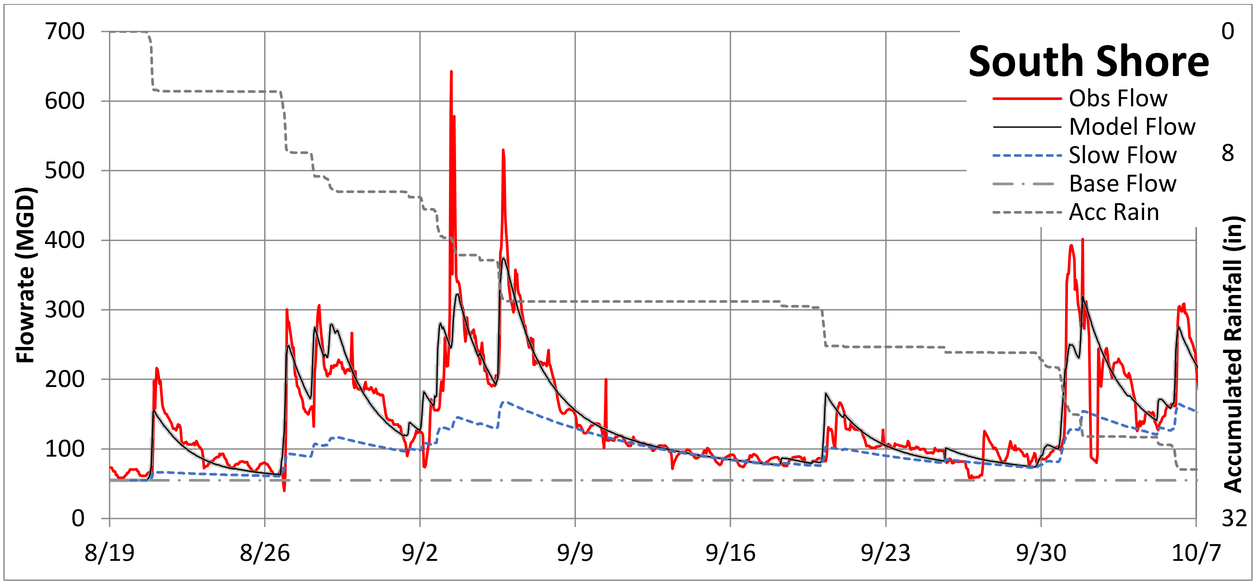
Two-Week Period of Jones Island Model



Note. Figure 6 shows a two-week representation of the model. The Slow Flow is the Slow Response, representing infiltration in the sewer system. This system is affected most by inflow to the system during rain events. With the Base Flow, or typical flow from daily use, the Slow Flow is shown to have a lasting effect on the system of about three days. The Model Flow Peaks are well defined and match the observed flow well, though the peaks fall short.

Figure 7

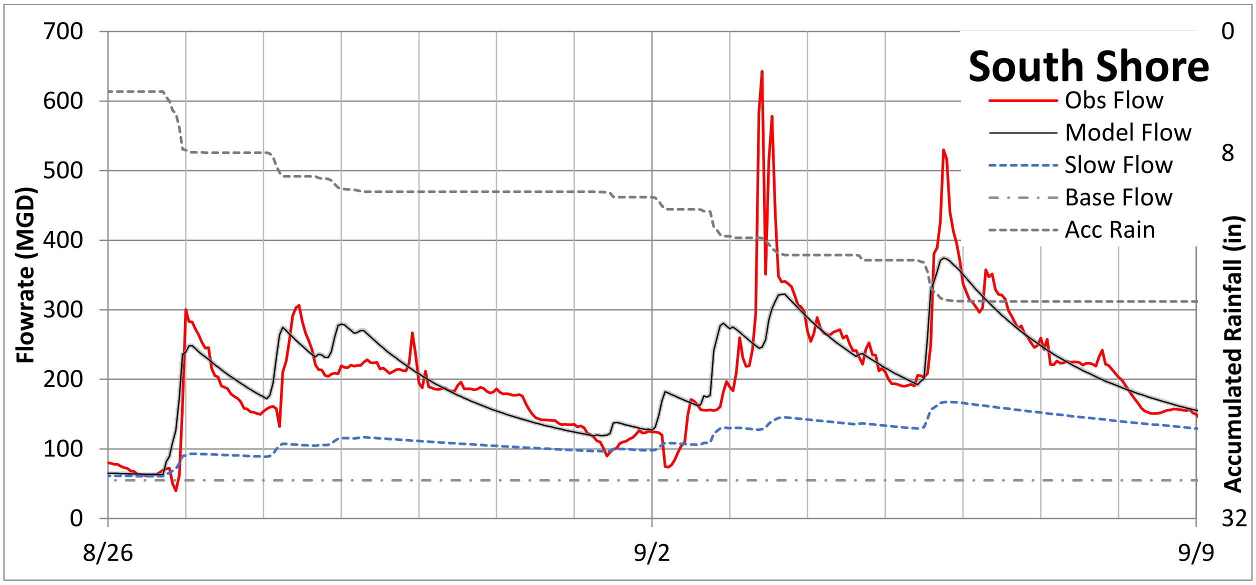
Comparison of South Shore Model to Observed Flow to South Shore Model



Note. Figure 7 shows the total model for South Shore compared to the observed flow for the separate sewer system. The flowrate to South Shore is significantly less than Jones Island.

Figure 8

Two-Week Period of South Shore Model



Note. Figure 8 shows a two-week representation of the model. The Slow Flow is the Slow Response, representing infiltration in the sewer system. This system is affected most by infiltration after a rain event. With the Base Flow graphed the Slow Flow is shown to have a lasting effect on the system. The Model Flow Peaks are less defined, and the peaks are missed by a significant amount.

Jones Island Model

The JI model represents a combined sewer system in a densely populated urban environment. From Figure 4, it was determined that the Slow Response lasted approximately three days, when the flow into the facility would return to baseflow. The Shape Factor was expected to be greater in the Slow Response, as the environment's ability to drain would have a greater impact on the infiltration than it would on the inflow. The Slow Response SF indicates that the infiltration is a gradual decline and lasts longer than the rain event duration. The Fast Response has a significantly smaller SF making a steep decline once the rain event ends.

The Affine Constant for the Jones Island model indicates that the combined sewer area responds strongly to rain events without regard to antecedent moisture conditions. The Fast

Response has an AC that is magnitudes larger than the Slow Response as the sewer system is designed to capture as much runoff as possible. The infiltration is a smaller percentage of the total rainfall. The system responds vigorously to any amount of rainfall in the area, then quickly returns to the baseflow.

There is less influence from antecedent moisture on this model. The urban environment does not absorb much moisture, and what it does absorb is drained within a short period (approximately three days). The AMRF has more impact on the Slow Response. The Fast Response has a strong relation to the TF, but little range to change with the season. The Slow Response is influenced more by the seasonal temperature change with a greater difference in the high and low TF.

The Jones Island model works well and fits the observed flow from the facility to a degree that is preferable over traditional models. The results show some insight into the environment of the Jones Island service area. The inflow factor of I/I is massive on a combined sewer system within an urban environment. The runoff also has an immediate effect on the system, increasing the flow greatly in a short time. The infiltration presents less impact on the combined systems total flow, but still has a lasting effect. The climate has a greater influence on the infiltration: more infiltration will occur during cold temperatures, and less during warm. The infiltration is small compared to the inflow from runoff, which is again, characteristic of an urban environment.

South Shore Model

The South Shore Model represents a separate sewer system servicing a large area with a combination of urban, residential, and some rural communities. This model was not as accurate at the Jones Island model, though it still shows promising results for a separate sewer system.

The baseflow is determined from early data, as the infiltration dominates the flow to the treatment facility and lasted longer than seven days. The Slow Response did not reduce to baseflow before a new rain event flooded the environment. The Slow Response is most affected by the SF, which explains the slow draining of the system area. The Fast Response also has a higher SF than the Jones Island model. This may be an indication of the size of the system area. Inflow takes time to reach the system, as well as traveling through it. The inflow also peaks later than the Jones Island model, again suspected to be due to the time the flow needs to travel through the system.

The affine constant was much smaller for both the Slow and Fast Responses than the Jones Island model. The immediate response to rain events is not as severe. The Fast Response has a gradual increase and decline, but the AC is still larger than the Slow Response. The small AC for the Slow Response makes the increase in flowrate gradual, taking hours to increase to the peak flowrate. The total flow is predominately from the Slow Response.

The antecedent moisture in the environment has a strong influence on both responses. The environment can react to the changing weather, generating more flow when multiple rain events occur within several days. The TF has less impact on the flowrate than Jones Island. Similarly, though, the Slow Response has a much greater range than the Fast. The Slow Response temperature range can exceed the Fast, meaning during cold weather it can produce more flow than the Fast. The Fast Response has limited range, making the response similar in warm or cold weather.

The South Shore model has a good fit from the model flow to the observed flow. The model lacks the definition that the Jones Island model has but models the accumulation of antecedent moisture satisfactorily. The infiltration for the separate sewer area is the dominating source for increased flow during wet weather. For the entire model, the Slow Response less the base flow makes up on average 51 percent of the Model Flow, while at the peaks, it makes up 31 percent. The Slow Response is the most impacted by the antecedent moisture in the environment.

Discussion

Parameter Calibration

The system identification model is able to adjust itself to the changing wetness in the environment as well as to seasonal changes, creating an appropriate hydrograph that represents the increased flow from wet weather. Separating the models by the type of sewer system allows an assessment of the different influences on each system. The variables that the model identifies further explain the environmental differences in the systems.

The parameters found through calibrating the model are specific to the MMSD service area, which encompasses almost all of Milwaukee County and extends into Racine, Waukesha, and Ozaukee Counties, and may be influenced by the fact that the period tested was abnormally wet. To find results more appropriate to the environment of Milwaukee, a longer period of time (an entire year or more) would need to be tested, and then verified against another time period. The Jones Island model had the best fit for the model flow to the observed flow. The Jones Island model and South Shore model produced parameters that differed greatly.

The calibrated parameters also appeared appropriate to what was expected. For a combined sewer system, it is expected that the Fast Response would have intense reactions to rain events. It should have a low SF and high AC. This is due to in part to the sewer being designed to capture as much runoff as possible, and the impervious nature of the environment. A small SF will mean the antecedent moisture takes less time to drain, resulting in a steeper decline on the transfer function. A larger SF will result in a longer less steep tail. The SF is related to the retention characteristics of the sewershed. For the combined sewer system that is in a largely impermeable urban area, it should have a smaller SF than the less urbanized separate sewer system, as most of the rainfall will become runoff rather than percolate into the ground. This runoff means the sewer system has a greater immediate flow resulting from a rain event. The AC represents this reaction. For a combined system, it is expected both variables would work together to define the intensity and suddenness of the peaks from inflow.

The environment has more influence on the flow in a separate sewer system. In this system, there is a greater SF for both responses. The environment will absorb moisture, allowing the antecedent moisture to build up in the soil. This build-up produces more infiltration into the sanitary sewer. In a separate sewer system, the inflow into the sanitary sewer is minimal. The sewer lines are not intended to collect stormwater. A less intense AC than the combined system is expected. Inflow still occurs, though it must travel greater distances and its path of flow is disrupted by lawns and open areas that can absorb or slow the flow. The smaller AC makes a smaller increase in flow with a later peak.

A high AMRF means that the system drains slowly, retains the moisture longer, and that the subsequent rainfalls will yield a higher flowrate. The AMRF is characterized by the soil types and the amount of imperviousness. In the combined sewer system, where there are greater amounts of impervious surfaces, the AMRF should be less than the separate sewer system. The resulting RF from the AMRF should be less intense. The separate sewer is more influenced by the antecedent moisture. The build-up of moisture in the more open environment takes longer to produce a peak flowrate and drains considerably slower. Consequent rain events produce greater amounts of flow, as the system is still saturated from the previous precipitation. The model is able to account for this increase in antecedent moisture, showing increased flows in later events.

Comparing the models for the two facilities in Figure and Figure , it can be seen that there were two large storm events on August 20 and August 28, 2018, that the facilities reacted much differently. Jones Island saw a huge increase flow from the Fast Response on the days, while South Shore had less intense increases. During the week of September 2, 2018, there were multiple small storms. Jones Island reacted to each storm and has well defined peak flows. South Shore was still experiencing an increased flow from the previous storms, resulting in a larger flowrate from these smaller storms. The soil moisture deficit during this period was minimized by the environment's ability to retain moisture, and the storms had a more direct impact on the flowrate into the treatment facility. The model's flexibility allows this to be modeled correctly.

The Temperature Factors are vastly different for the Slow and Fast Responses for Jones Island. The Slow Response has a greater range for the Temperature Factors, meaning that as the temperature changes in the environment, the TF will have greater effect on the system. In cold temperature, the model will respond with larger TF that produces a larger flowrate from the Slow Response. During warmer periods, the model will have a much smaller Slow Response from the TF. The Fast Response has a much greater reaction to the TF but has very little range. It will have a similar response in cold periods as warm. The large TF indicates that the Fast Response has a greater reaction to rain, working in conjunction with the large AC, to have a huge impact on the system flowrate. This is, again, likely due to the impervious nature of the environment. The South Shore model shows that the resulting flow from the Slow Response can also vary more than the Fast. This model's Slow Response can overcome the Fast Response during cooler temperature. During cool springs, precipitation will have a greater effect on the water table, creating more infiltration. This will cause longer lasting increased flowrates.

Model Discrepancies

There are several parts of this model that require further exploration. The model reveals many things about the Milwaukee sewer systems, but does not account for time delays, has difficulties hitting the peak flows, and cannot simulate operator intervention.

The flow from the combined sewers reaches Jones Island within the same hourlong timestep, meaning that peak rainfall will coincide with the peak flowrate into the treatment facility. This may be since the combined sewer area is small, when compared to the greater separate sewer area. For inner Milwaukee, which uses the combined sewer system, there is no need for time delay from the rain event to the flow to Jones Island.

South Shore Water Reclamation Facility treats water from a greater area that uses the separate sewer system. Peak rainfall and the coinciding peak flowrate to South Shore occur hours apart. The size of the sewershed makes offsetting the timestep difficult. Rain events that occur in the southern side of the separate sewer area have a much different time delay than events that occur in the northern side of the sewershed. An individual time delay needs to be determined for each rain gauge station. There are further complications to the delay from operator intervention.

When a large rain event occurs, MMSD operators may divert the sewer flow to the other treatment facility or to the Deep Tunnel. These diversions occur according to predetermined control policies and an operator's discretion. When an operator diverts the flow, it also offsets how long that flow will take to reach the treatment facility, or if it will reach it. This is especially true for diversions to the Deep Tunnel, which are added to the observed flowrate during the hour they occur, not the hour they get pumped out to the treatment plant. Some of the sewage that is diverted to the Deep tunnel would have arrived at the treatment plant many hours later, had it not been diverted. The diversions to the Deep Tunnel are spread throughout the system and are more proximate to the source of the flow. Determining the time delay becomes much more complicated and may need to be assessed by individual rain events. Because of the distance of the monitored areas to the facilities and operator intervention, the model cannot simulate the delay satisfactorily. Some parameters of the model for South Shore are complicated by the model trying to compensate for the time delay. In Figure , the model peaks before the observed flow. For some events, the difference in peaks is small – an hour apart and matching in a few events. Other events are off by a larger amount (several hours). In addition to the time delay, the interventions may prevent the model from accurately hitting the peak flowrates. The modeled flow predicts less flow to the facility than the observed data show. It is speculated that operator intervention causes this discrepancy.

The modeled peaks may be off for other unknown reasons. There are still parameters that are outside of this model's ability to calculate. The soil may not drain as expected in the model due to increased groundwater levels and the increased frequency of rain events during this period.

Conclusions

The use of system identification to create a model is an accurate method of modeling sewer flow. This paper documents the use of the method in a short and particularly wet period for two different types of sewer systems. The results show that the method is capable of modeling the two systems' increased flow from I/I during wet weather. Not only does it model the total flow but it is able to discern inflow and infiltration separately, which react distinctly to a rain event. This method is most impressive in its flexibility.

While this study did not focus on seasonal data, the results show that the model is flexible enough to describe the unique seasonal temperature differences. Many methods currently used neglect the seasonal differences in increased I/I flows. This model attains it flexibility by using the temperature and precipitation measurements to account for the antecedent moisture, representing the seasonal differences in the system. The antecedent moisture changes not only with long term temperature trends, but with the rain events as well, building up and draining. This allows the method to model multiple consecutive rain events accurately. Unlike other methods which typically only model a single rain event, the system identification method requires only limited data to create an accurate model.

Besides modeling the flow accurately, the model also provides some insight into how the system reacts to wet weather. For example, the South Shore model shows the flow from infiltration has a much greater effect on the flow during cooler weather than warmer weather. This insight can be beneficial to the engineers and operators of the sewer system in planning and designing and managing procedures.

Using system identification is a practical and practicable method of modeling the instantaneous flowrates for either a combined sewer system or a separate sewer system. In this study, the two systems experienced the same storm events, yet behaved in different manners. This method is capable of calibrating to the differences and producing an accurate model of the system and environment.

This method may be applicable to wastewater system operators who need to model their sewer system. It may be possible to use the model to predict incoming flow when antecedent moisture is predominant in the environment, potentially avoiding unnecessary CSOs. Treatment facilities can use the system identification method to predict long term increased flowrates based upon precipitation projections to allow time to prepare storage and treatment facilities for high flowrates. This method can be applied to a smaller section of the system, potentially identifying if the system is compromised, allowing more infiltration in than expected. Used in a smaller section, engineers and operators may be able to determine when and where to divert flow within the system, to stop that section from adding to the peak flowrate into the treatment facility.

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Civil Engineering

Capstone Report Approval Form

Master of Science in Engineering – MSCVE

Milwaukee School of Engineering

This capstone report, titled "Using System Identification to Model Near-Term Wet Weather Sewer Flow," submitted by the student Dennis Weiland, has been approved by the following committee:

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