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**Hydraulic Analysis and Performance Evaluation of Combined Trunk Sewers:
a Case Study of Baghdad City.**

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ABSTRACT

Sewer system plays an essential task in urban cities by protecting public health and the environment. The operation, maintenance, and rehabilitation of this network have to be sustainable and scientifically. For this purpose, it is crucial to support operators, decision makers and municipalities with performance evaluation procedure that is based on operational factors. In this paper, serviceability and performance indicator (PI) principles are employed to propose methodology comprising two enhanced PI curves that can be used to evaluate the individual sewers depending on operational factors such as flowing velocity and wastewater level in the sewers. To test this methodology; a case study of al-Rusafa in Baghdad city is studied in which two combined trunk sewers are serving (Zeblyn and ET-trunks). Hydraulic analysis for two scenarios (average and peak dry weather flows) is performed; afterward, performance evaluation showed a sub-index ranging from 0.5 (minimum level of performance) to one (excellent performance) which implicate that these two trunks, if well maintained will provide sufficient service to the catchment. By applying the serviceability and PI principles; a prioritizing tool is provided which help decision makers towards better management of the sewerage system.

Keywords: Hydraulic Analysis, Performance Indicators (PI), Sewer Systems, Operational Factors.

التحليل الهيدروليكي وتقييم أداء انابيب المجاري المشتركة: دراسة حالة لمدينة بغداد

الخلاصة

يلعب نظام الصرف الصحي مهمة لا غنى عنها في المدن الحضرية عن طريق حماية الصحة العامة والبيئة. يجب أن يكون تشغيل وصيانة وإعادة تأهيل هذه الشبكة بطريقة مستدامة وعلمية. ولهذا الغرض، من المهم دعم المشغلين وصناع القرار والبلديات بمنهجية تقييم أداء معتمدة على عوامل تشغيلية. في هذه البحث، يتم استخدام مبادئ مؤشر الخدمة ومؤشر الأداء (PI) لاقتراح منهجية تضم منحنيات PI يمكن استخدامها لتقييم انابيب المجاري اعتماداً على العوامل التشغيلية مثل سرعة التدفق ومستوى مياه الصرف الصحي في المجاري. من أجل اختبار هذه المنهجية؛ تمت دراسة حالة الرصافة في مدينة بغداد حيث ان الرصافة يخدمها خطي مجاري رئيسيين هما (زبلن و ET-trunks). تم إجراء تحليل هيدروليكي لحالتي جريان مختلفتين (متوسط وذروة تدفقات الطقس الجاف)؛ بعد ذلك، أظهر تقييم الأداء مؤشر فرعي يتراوح من 0.5 (مستوى الأداء الأدنى) إلى واحد (أداء ممتاز) مما يدل على أن هذين الخطين، إذا تمت عملية صيانتهم بصورة جيدة سيوفران الخدمة الكافية. من خلال تطبيق مبادئ الخدمة ومبادئ PI؛ تم توفير أداة يمكن استخدامها لتحديد الأولويات التي تساعد صانعي القرار على الإدارة الأفضل لنظام الصرف الصحي.

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الكلمات الرئيسية: التحليل الهيدروليكي ، مؤشرات الأداء (PI) ، أنظمة الصرف الصحي ، العوامل التشغيلية.

1. INTRODUCTION

The wastewater collection system is considered one of the most valuable assets as it is directly related to public health and the environment. This system (consisting mainly of sewers, man-holes and pumping stations) is intended to deliver the wastewater from generation points to the wastewater treatment plant (WWTP). To optimize the service, the system needs to maintain design functionality. However, the malfunctioning of this system can be attributed to many factors such as improper or inadequate operation, maintenance, and rehabilitation; aging, is one of the most important factors as it is directly related with population and/or catchment increase, **NEIWPC, 2003**. Prime functional goals of gravity sewers are to carry wet weather flow (WWF) without frequent surcharge or flooding and to achieve adequate self-cleansing during low-flow periods (e.g., dry weather flow periods (DWF)). Otherwise, solids buildup can retard and even block the flow and may foster a generation of hydrogen sulfide and methane, **Bizier, 2007**. Performance of the wastewater collection system can be defined as the ability of the network to convey the wastewater and stormwater without overload at the least environmental impact maintaining the structural integrity of the sewers.

Sewer network maintenance and rehabilitation are of two types; reactive (i.e., when equipment fails corrective maintenance is to be performed); and proactive (i.e., predictive/ preventive maintenance; before the occurrence of failure). The latter is the preferred type as it improves performance, and proven to be a more cost-effective approach. However, to perform an effective proactive maintenance/rehabilitation; prioritizing the sewers is required. This can be accomplished through monitoring of the system and developing tools that objectively evaluate the performance of the individual sewers, **Fenner, 2000**.

Performance indicators (PIs) quantitatively measure the efficiency of the sewer system, providing an understanding of the system's functionality and the usefulness of the operation and maintenance programs. Application of performance indicators for the wastewater collection system could provide many benefits. Examples are: help the operators by providing a tool for proactive management used for prioritizing sewer candidates for rehabilitation; benchmarking technique to compare the sewers under study with other systems (or internal comparison within the system); help decision makers to perform efficiently and monitor the effectiveness of their decisions; assist in strategic planning, **Alegre, et al., 2013** and **Matos, et al., 2003**.

Bennis, et al., 2003 introduced a methodology to evaluate the hydraulic performance of the sewers; considering the surcharge that happens in an individual sewer, and the effect of backwater flow from this pipe on promoting upstream sewers surcharge. In an attempt to exploit PIs in the wastewater collection system; **Cardoso, et al., 2004** developed two performance curves for wastewater level and flowing velocity (V). These two curves can be considered more generalized and can be modified according to the local codes. Later, **Tabesh and Madani, 2006** proposed more detailed performance curves for both velocity (V) and wastewater depth inside the pipe relative to the pipe's diameter (y/D). For instance, the wastewater depth inside the pipe divided into sections each with a specific performance level.

Nonetheless, this curve neglected the surcharge and flooding events. Velocity curves proposed by **Cardoso, et al., 2004** and **Tabesh and Madani, 2006** showed a similar behavior as the same concepts are adopted. However, Tabesh velocity curve is less conservative (i.e., if the two curves are used to evaluate the same network; Tabesh method will give higher performance level).



This study aims to propose an enhanced hydraulic performance evaluation methodology entailing detailed, adjustable PI curves. Moreover, apply this methodology for a case study in Rusafa side of Baghdad city.

2. METHODS

2.1 Case Study Description and Data Collection

The sewerage system of the East Bank of Baghdad City (Rusafa Side) is studied. Two major trunks shown in Fig. 1, serves Rusafa; the first trunk is called Zeblin starting at Al-Shaab district and ending at the third expansion Rustamiya WWTP; serving more than 2.5 million inhabitants in a densely populated area, collecting wastewater which is mostly generated from residential and commercial areas. The diameter of this sewer ranged from 1.8 to 3 meters. The second trunk is called ET-trunk; this trunk is smaller in diameter (ranging from 0.75 to 2.4 m) serving more than one million people and large commercial areas bounded by Tigris river and Qanat al-Jaish, **Alsaqqar, et al., 2017**, and **Jbbar, 2018**. Data is collected from Baghdad Mayoralty (BM) and used to build a GIS-based hydraulic model. In this paper, each trunk is divided into several reaches (ET-trunk consists of five reaches, while Zeblin trunk has six reaches).

The data collected regarding ET-trunk is showing that some of the sewers are having negative slopes (the upstream man-hole invert level is lower than downstream man-hole invert level).

2.2 Hydraulic Simulation

To perform the sewage flow assessment, hydraulic analysis has been carried out using SewerCAD® software; a useful software from the Haestad method; widely used in the design and analysis of the sewer networks, **Walski, et al., 2007**. For convenience, two scenarios of flow had been considered here, average dry weather flow (avg. DWF) and peak dry weather flow (peak DWF). The estimation of avg. DWF was done depending on the population forecast assuming a wastewater generation of 240 (liters/capita/day). The famous peaking factor given by Eq. (1) is used, **GLUMRB, 2014**. Where PF is the peaking factor (peak DWF/avg. DWF), and p is the population (in thousands).

$$PF = \frac{18 + \sqrt{p}}{4 + \sqrt{p}} \quad (1)$$

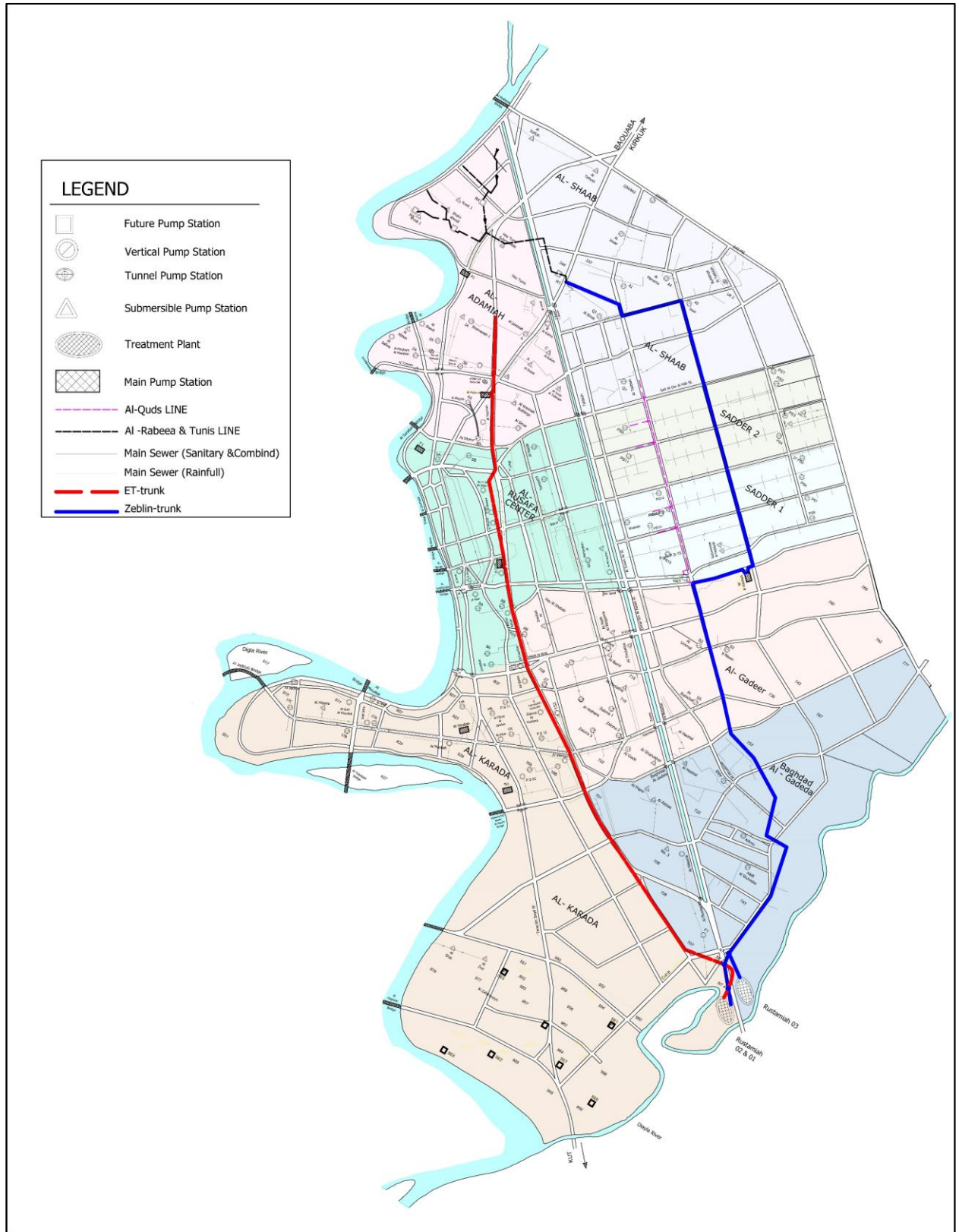


Figure 1. Rusafa sewerage system map (BM, 2018).

2.3 Building PI Curves

The first PI curve is for wastewater level (i.e., hydraulic gradient line H.G.L) shown in **Fig. 2**, where y-axis shows performance indicator scores, and it is separated into five levels ranging from zero to one. In which (0, 0.25, 0.5, 0.75, and 1) representing (null, unsatisfactory, minimum, acceptable and excellent service level), respectively. While x-axis shows wastewater level in the sewer, taking the invert level as an arbitrary level.

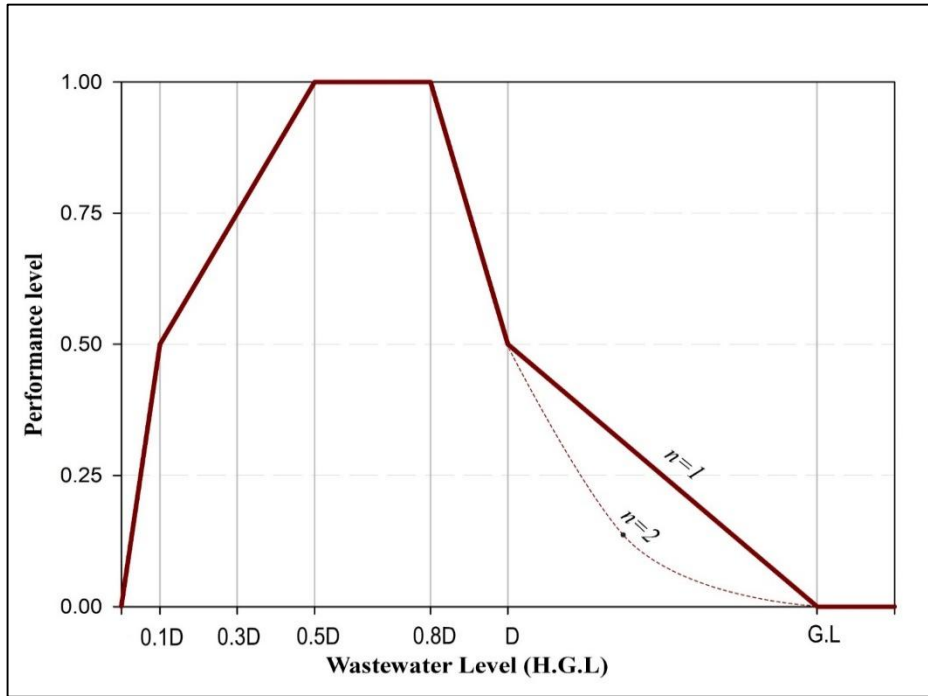


Figure 2. wastewater level performance curve

To justify and for more illustration on **Fig. 2**, **Table 1** is showing in more details on how the PI values are determined.

Table 1. Water level curve interpretation.

y/D	PI score	Explanations
0	0	No flow; no service
0.1	0.5	Minimum acceptable level of service is attained when the flow level at 10% of the diameter ⁽¹⁾
0.3	0.75	Some codes consider y/D ratio of 0.3 is acceptable and permit flatter design slope if this ratio is sustained ⁽²⁾
0.5-0.8	1	Best performance is to be expected at this region ⁽³⁾
1	0.5	Surcharge risk presents; service is at the lowest level ⁽¹⁾
(1):Tabesh and Madani, 2006; (2):GLUMRB, 2014; (3):Walski, et al., 2007		

As mentioned earlier, Tabesh’ curve of wastewater depth lacks the details when the wastewater level exceeds the diameter of the sewer (the surcharge and flooding effect). In **Fig. 2**, Bennis’ Eq. (2) is utilized for calculating the performance in surcharged sewers: in which modification over the risk factor (n) can be done to highlight strategic importance given to the flood or surcharge of a pipe. For instance, if the sewer under evaluation serving high-density



residential/commercial area, the consequence of flooding will be catastrophic, therefore n should take a value of 2 or 3.

$$PI_i = PI_{max} + (PI_{min} - PI_{max}) \left[1 - \left(1 - \frac{H_i^{us}}{G_i} \right)^n \right] \tag{2}$$

Where: PI_i is the performance level varying from PI_{min} to PI_{max} ; H_i^{us} is the height of surcharge in the manhole located directly upstream from sewer i measured from the sewer crown; G_i is the depth at which the pipe is buried, measured from the ground surface to the sewer crown. In this study, PI_{min} and PI_{max} are set to be 0 and 0.5, respectively. When the $H_i^{us} = 0$, PI_i will be equal to $PI_{max} = 0.5$ (full flowing sewer); while when $H_i^{us} = G_i$, PI_i will be equal to $PI_{min} = 0$ (flooding occur). n is set to be 2 because the case study for a trunks sewer serving the huge residential / commercial areas. Subsequently, Eq. (2) becomes:

$$PI_i = 0.5 \left[1 + \left(\frac{H_i^{us}}{G_i} \right)^2 \right] - \frac{H_i^{us}}{G_i} \tag{3}$$

The second PI curve is for the velocity of flow inside the pipe, shown in **Fig. 3**. This curve is agreed to that proposed **Cardoso, et al., 2004**; nonetheless, it is more detailed and more conservative. **Table 2** is showing in details how the PI values are determined.

Table 2. Velocity PI curve interpretation (**Cardoso, et al., 2004**).

Velocity	PI score	Explanations
$\leq 0.8 V_{min}$	0	This led to solid deposition. A tolerance of 20% is given below V_{min} .
V_{min}	0.25	V_{min} is considered the unsatisfactory level of service.
$1.5 V_{min} - 0.75 V_{max}$	1	Optimum performance is attained. Good scouring Velocity without risking the sewer structural integrity.
V_{max}	0.75	The performance acceptable (higher velocities may cause mechanical problems such as corrosion).
$\geq 1.2 V_{max}$	0	Serious structural damage may happen if V_{max} is exceeded (20% tolerance)

It should be noted that, in this study, V_{min} and V_{max} are set to be 0.6 and 2.4 m/s, respectively, **McGhee and Steel, 1991**. To evaluate the hydraulic performance of the entire network or a subnetwork; a weighting function is applied to summarize the pipe performance index as follows, **Tabesh and Madani, 2006**:

$$PI_{Net} = \frac{\sum_{i=1}^N V_i PI_i}{\sum_{i=1}^N V_i} \tag{4}$$

$$V_i = \frac{\pi D_i^2 L_i}{4} \tag{5}$$

Where PI_{Net} is the network or subnetwork performance index, N is the number of pipes in the network or subnetwork. PI_i , D_i and L_i are the performance index, diameter and length of pipe i , respectively.

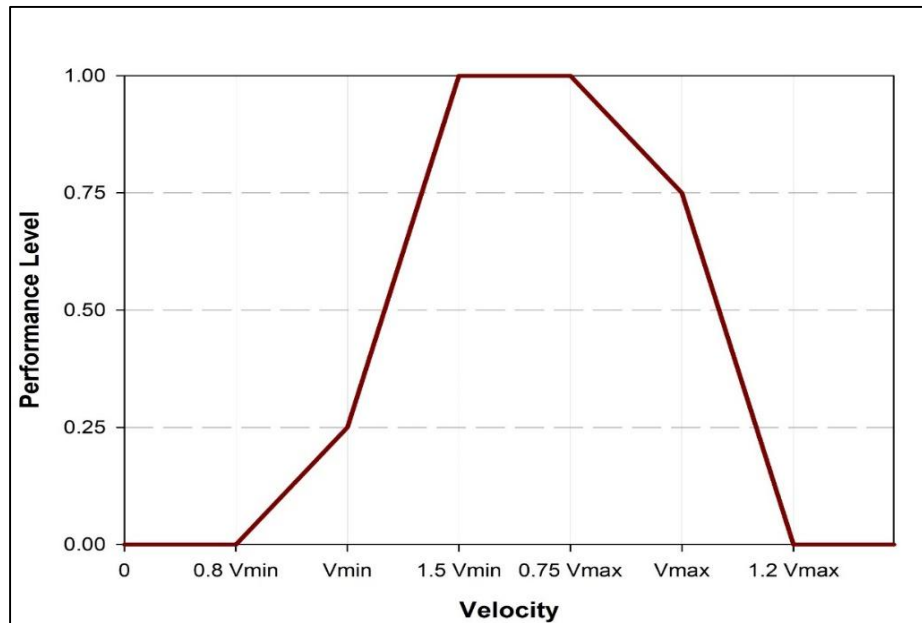


Figure 3. Velocity performance curve.

3. RESULTS AND DISCUSSION

3.1 Hydraulic Simulation

Two scenarios are used in which only the flow varies. The first scenario is for average dry weather flow (i.e., the flow that happens in the dry period). The second is the peak hourly dry weather flow which could occur in the rush hours of the service.

Table 3 is showing the hydraulic simulation result of ET-trunk; in which, the hydraulic gradient line (H.G.L) is fluctuating due to several factors including frequent diameter changes resulted from incorrect repairs (e.g., replacing a collapsed sewer with smaller/larger sewer resulting in a constriction/expansion). Also, in Reach-2 some pipes are showing a negative slope; these slopes are causing significant problems in terms of surcharge and flooding in both, Reach-1 and Reach-2.

Besides, Zeblin trunk hydraulic simulation summarized in **Table 4** is showing y/d values of less than 0.8 along the trunk reaches; this indicates that Zeblin trunk is adequate to transfer the present DWF discharges while the flow velocity (V) values are shown to be high enough for most of the cases.

3.2 Performance Evaluation

Applying the performance indicator curves given in **Fig. 2** and **Fig. 3**. The performance of the ET-trunks is summarized in **Fig. 4**. In Reach-1, the performance is nearly excellent except for H.G.L in peak DWF in which the surcharge effect reduced the performance to a below acceptable value (i.e., below 0.75). This surcharge is induced from the surcharge effect in Reach-2 which is a result of inadequate (or negative) slopes and poor repairs (i.e., sur-charge caused by backing up due to sur-charge/flooding in the downstream sections). Reaches 3,4 and 5 are showing perfect performance for the anticipated flow. If rehabilitation is intended for this trunk, attention should mostly on Reach-2.



Table 3. Results of hydraulic simulation of ET-Trunk.

Reach	Reach limits	D (m)	Length (km)	Avg. DWF		Peak DWF	
				y/D	V (m/s)	y/D	V (m/s)
Reach-1	ET139-ET110	0.75-1.1	1.65	0.54	0.956	1.27*	1.125
Reach-2	ET110-ET93	1-1.6	1.7	0.96*	0.702	1.34**	0.894
Reach-3	ET93-ET73	1.3-1.6	3.18	0.43	1.09	0.57	1.263
Reach-4	ET73-ET37	1.85-2.15	6.28	0.46	1.01	0.6	1.13
Reach-5	ET37-ET1	2.3	7.29	0.56	0.97	0.7	1.04

*: partially surcharged; **: fully surcharged

Table 4. Results of hydraulic simulation of Zeblin Trunk

Reach	Reach limits	D (m)	Length (km)	Avg. DWF		Peak DWF	
				y/D	V (m/s)	y/D	V (m/s)
Reach-1	TH60-TH40	1.8	3.38	0.24	0.827	0.34	1
Reach-2	TH40-TH29	2.4	2.05	0.31	0.907	0.39	1.03
Reach-3	TH29-TH1	3	5.06	0.4	1.03	0.48	1.135
Reach-4	NT71-NT50	3	4.18	0.57	1.18	0.7	1.248
Reach-5	NT50-NT25	3	4.52	0.62	1.327	0.75	1.403
Reach-6	NT25-NT1	3	5.06	0.65	1.37	0.76	1.414

The same method is tested for Zeblin trunk sewer; results are shown in **Fig. 5**. In this chart, it is clear that Zeblin trunk is having better performance than ET-trunk. The first two reaches are having relatively low flow (more specifically, y/D range is 0.24-0.31) which is why the performance is lower than the last four sections.

It is worth mentioning that in almost all reaches of the two trunks, performance scores for velocity and H.G.L are analogous, and it can be compared to the hydraulic simulation results. Overall, neglecting the sediment accumulation and other problems present in the sewers; the two trunks showed relatively good performance (except Reach-2 of ET-trunk). This may be not quite realistic as the authors assumed the sediment accumulation is null and the wall condition thought to be the same as the for new pipes. However, this is a perfect indicator that these trunks are adequate if they are maintained well.

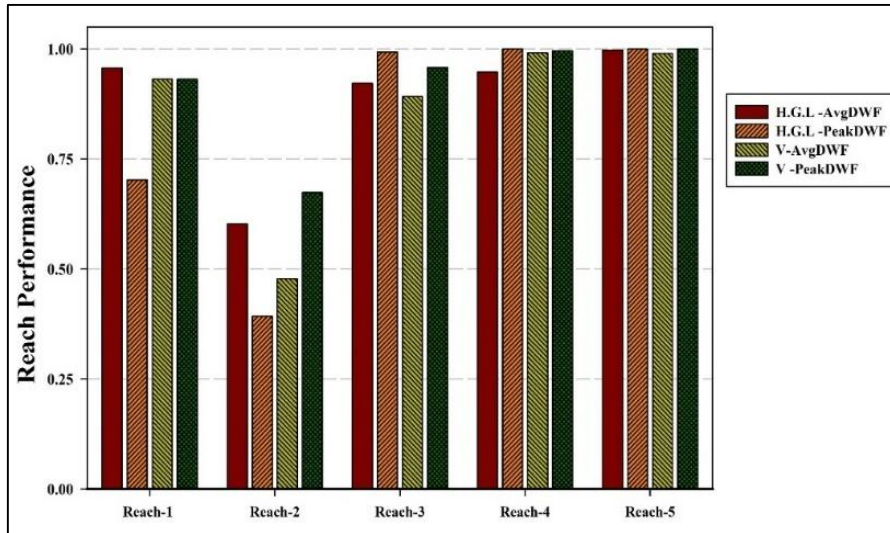


Figure 4. Performance under Average and Peak DWF of ET-trunk.

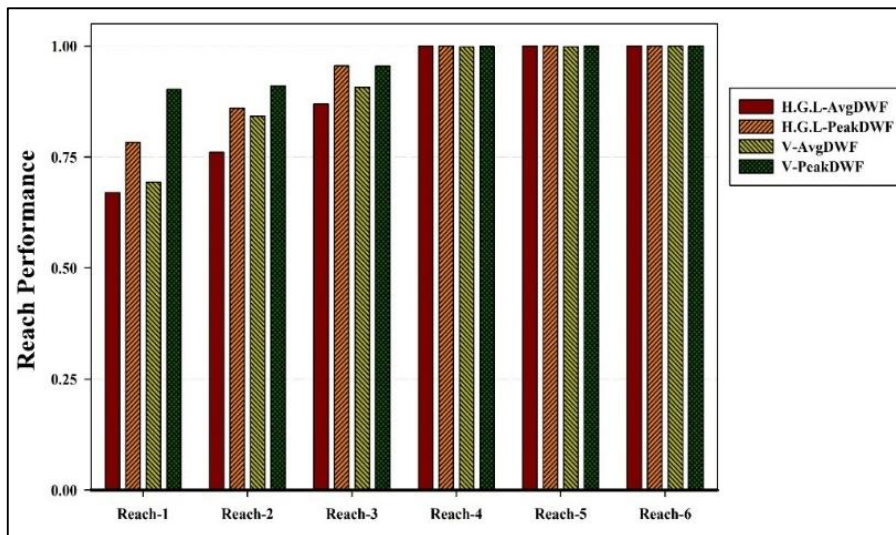


Figure 5. Performance under Average and Peak DWF of Zeblin-trunk.

4. CONCLUSIONS

The following conclusions are made based on the investigations above:

1. The performance evaluation of the sewer network is a practically useful concept and could be used for prioritizing the sewer for rehabilitation. A methodology for sewer performance evaluation based on performance indicator principles is developed, tested for two case studies showing that the result of the two curves is matching in most of the cases.
2. It must be distinguished that the surcharge/flooding of the sewer could be either due to the inadequacy (e.g., under-sizing the sewer or providing flatter slopes) or may be caused by a downstream problem that can induce the surcharge in the upstream sections.



5. RECOMMENDATIONS

For improved management of the sewerage system, municipalities are recommended to use a wide range of PIs; these can include environmental, operational, and social indicators.

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