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Assessment of Inflow and Infiltration in Sewers: Case Study of Antalya, Türkiye

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ABSTRACT

Unwanted inflow and infiltration (I/I) of rainfall and groundwater into urban sewer systems are a critical issue for sustainable water management. This study examines the data from the two largest and most representative wastewater treatment plants (WWTPs) in central Antalya, Lara and Hurma, which both have large service areas and diverse hydrological conditions and infrastructural characteristics. By analysing data from 2016–2019, the study explored various standards and methods, including empirical equations, to quantify I/I levels. Results indicate that I/I contributed between 40.4% and 94.3% to wastewater flow during the period. Additionally, I/I was calculated as 0.8 and 1.3 m^3/day-ha for Lara and Hurma WWTPs, respectively. Overall, the findings not only demonstrate the deficiency of existing collection systems in Antalya but also show the strategic value of applying comparative I/I assessment methods to develop a framework that can support more resilient wastewater management strategies in fast urbanizing regions worldwide.

1 | Introduction

Efficiently treating wastewater from communities is fundamental for ensuring a healthy and sustainable lifestyle. Within this framework, sewerage networks and wastewater treatment facilities emerge as pivotal municipal service sectors crucial for public health. By ensuring that wastewater reaches treatment facilities, sewerage networks also play a vital role in preventing environmental pollution, mitigating the uncontrolled dispersion of this highly contaminating source. In essence, the development and dependable operation of sewerage networks are paramount.

The escalation of inflow and infiltration (I/I) in sewage systems can lead to significant alterations in wastewater pollution parameters, resulting in challenges such as decreased treatment efficacy and, predominantly, increased operating costs. While I/I are typically factored into the design of wastewater treatment plants (WWTPs), unanticipated and undesired infiltration still occurs due to uncontrollable circumstances. Various methods are commonly employed in the literature to estimate theoretical infiltration flow. These include assuming a certain percentage of the average annual domestic wastewater generated as infiltration flow, adopting a specific value of infiltration flow per unit area served by the sewerage network and assigning a certain value of infiltration flow per unit length and diameter of the sewerage network. I/I have been documented within the range of 0.2–28 m^3/day-ha and 0.01–1 m^3/day-mm-km (Metcalf and Eddy 2003). Similarly, values range from 200–28 000 L/day-ha to 94–9400 L/day-cm-km (Qasim 1998). Istanbul Water and Sewerage Administration in Türkiye typically assumes I/I between 0.1 and 0.2 L/s-ha (IWWA 2017). Some examples of

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Summary

- Compares multiple empirical methods for inflow and infiltration (I/I) assessment.
- Evaluates I/I using long-term flow data from two major WWTPs in Antalya.
- Estimated I/I contributions ranged from 40.4% to 94.3% of wastewater flow.
- EPA-based estimates were benchmarked against empirical assessment methods.
- Provides a practical framework for sustainable sewer system management.

quantitative I/I assessments found in the literature include the period 1991–2007: I/I contributed to untreated bypasses and overflows amounting to a total of 2.2–10.8 million m^3 in Ontario, Canada (Hey et al. 2016).

An increase in I/I poses a heightened risk of hydraulic overload within wastewater networks. This uptick in I/I levels can lead to localized flooding or sanitary sewer overflows, negatively impacting the performance and efficiency of WWTPs, as well as affecting energy consumption, maintenance needs and public health (Beheshti et al. 2015). In addition, I/I water contributes to pollution transport through weirs and increased emissions from WWTPs (Vråle 1993, 2011). It is imperative to thoroughly analyse the extent of I/I. In this regard, a study was undertaken to assess I/I in 45 isolated sewer basins across the Orange County Sanitation District (Mitchell et al. 2007). Various empirical methods, including wastewater production (WPM), Stevens–Schutzbach (SS), minimum flow factor and base infiltration (BI), were utilized to evaluate I/I. Mitchell et al. (2007) also demonstrated that the SS method provides more accurate estimates of BI, particularly in high-infiltration basins, whereas the WPM tends to overestimate unless properly corrected. Their findings emphasize the importance of carefully selecting and calibrating the method to obtain reliable I/I estimates. Additionally, the findings were corroborated through a chemical parameter verification method involving regression analysis of hourly concentrations of wastewater chemical analysis parameters such as chemical oxygen demand (COD), total nitrogen (TN) and total phosphorus (TP). Furthermore, a methodology was developed to identify instances of stream and spring capture, which were found to have comparable impacts to I/I, particularly concerning increased clean baseflow to combined sewers and WWTPs (Broadhead 2014).

Researchers conducted a case study focusing on WWTPs in various cities in Sweden, utilizing flow data from 2011 to 2012 (Gerly et al. 2016). By employing average daily flow (ADF) measurements, they explored simple methodologies to quantify the effect of high flows attributed to I/I. Their findings underscored the significant impact of I/I-induced high flows on removal rates at WWTPs and on effluent loadings.

To quantitatively assess the infiltration, traditional monitoring methodologies are based on volume balances (WEF and ASCE 1994; Weiß et al. 2002). Studies suggest the use of natural tracers for mass balance methods to define infiltration (Kracht et al. 2007; Bares et al. 2009). However, the simplest approach uses minimum night-time flow (Houhou et al. 2010). Inflow is usually monitored based on volume balances (Staufer et al. 2012). A straightforward and economical approach has been devised to assess I/I and sewer overflow in sewer systems using conductivity data (Zhang et al. 2018). This method enables the separate estimation of rainfall-induced I/I. Despite the presence of several case studies, there remains a dearth of literature that comprehensively addresses I/I concerns.

Besides studies in Europe and North America, I/I have recently been studied in other regions of the world. For example, in Kuantan, Malaysia, Yap and Ngien (2017) studied the sewerage and reported considerable I/I contributions as evidence of a need for improved management strategies for rapidly urbanizing tropical areas. In Portugal, Bentes et al. (2022) evaluated inflow quantification in an urban sewer network, where only 15% of the flows reaching the WWTP was considered domestic, while the other 85% were I/I flows, largely due to infiltration or rainwater inflow. Zeydalinejad et al. (2024) compiled a comprehensive review of groundwater infiltration (GWI) to sewer networks and found this to be an increasing threat to urban sustainability, emphasizing the need for integrated assessments and mitigation forms. Furthermore, newer research similarly advances the integration of hydraulic modelling and management approaches to enhance overall sewer system performance to reduce excess I/I. Recent research encompasses advanced modelling and solver refinement (Koşucu et al. 2022), economically prudent pressure management strategies (Koşucu and Demirel 2024) and dynamic stormwater–infiltration interactions (Çırağ et al. 2025). These studies work together to illuminate the collaborative opportunities between hydraulic and sustainable drainage approaches.

Although several empirical methods are available for estimating I/I, no universally accepted method exists, and their applicability may vary depending on sewer system characteristics and data availability. Therefore, comparing different methods is essential to evaluate their consistency and applicability under different conditions. In brief, the primary objective of this study is to calculate I/I utilizing different methodologies outlined in existing literature and standards, employing wastewater flow data from varying periods. The results obtained through empirical equations will be compared with previous literature findings. Additionally, the data from different WWTPs were used to evaluate I/I. Because no universally accepted method exists, especially in Türkiye, where research on I/I estimation is limited and its impacts on WWTPs are still unclear. This study seeks to provide clarity by comparing various I/I determination approaches and evaluating their outcomes against empirical equations and findings from previous studies.

2 | Materials and Methods

2.1 | Location of the Case Study

Antalya is located on the Mediterranean coast in the southwest of Türkiye, perched atop a cliff overlooking the sea and surrounded by the Taurus Mountains. Its climate is typically

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Mediterranean, featuring scorching, arid summers where temperatures often soar into the 40°C range during July and August, though mid-30°C temperatures are more common. Winters are relatively mild and rainy. With approximately 300 sunny days annually and sea temperatures never dropping below 15°C, reaching around 28°C in the summer, Antalya draws significant tourism (Balsari and Werner 2008). The city receives an average of 1050 mm of rainfall annually, with nearly three-quarters of this amount concentrated in the winter months—November, December, January and February along with long-term rainfall data from 1923 to 2019. Antalya also experiences significant seasonal rainfall variation, with January and December seeing the highest amounts, approximately 240 and 250 mm, respectively. In stark contrast, the summer months of June, July and August are notably dry, with almost no rainfall in July and August. Spring and autumn bring moderate rainfall, with a notable increase in October and November. Overall, Antalya's climate is characterized by a Mediterranean pattern, featuring wet winters and dry summers.

As of 2019, it boasts a population of 2 511 700 and a coastline stretching 657 km, adorned with beaches, ports and ancient ruins (ASAT 2019). Antalya is one of the most attractive cities with a 2.5 million population and hosts nearly 10–15 million foreign tourists every year (ASAT 2019). In 2008 alone, Antalya Airport welcomed 8 880 000 tourists between 1 January and 30 November. The city's economy thrives on a blend of tourism, agriculture, commerce and light industry. Antalya comprises 19 distinct districts and houses 39 WWTPs, ranging in capacity from 400 to 210 000 m^3/day (ASAT 2019). The city's sewerage system spans a total length of 900 km, with older sections built as combined systems and newer sections as separated systems (ASAT 2019).

Despite Antalya's significance as one of Türkiye's foremost cities, there has been a notable absence of comprehensive studies on wastewater and stormwater collection systems; this has prompted only limited research efforts (Tan et al. 2021). Within this context, an investigation was undertaken, focusing on two major WWTPs situated in central Antalya. Figure 1 illustrates

FIGURE 1 | Locations of the evaluated WWTPs in central Antalya.

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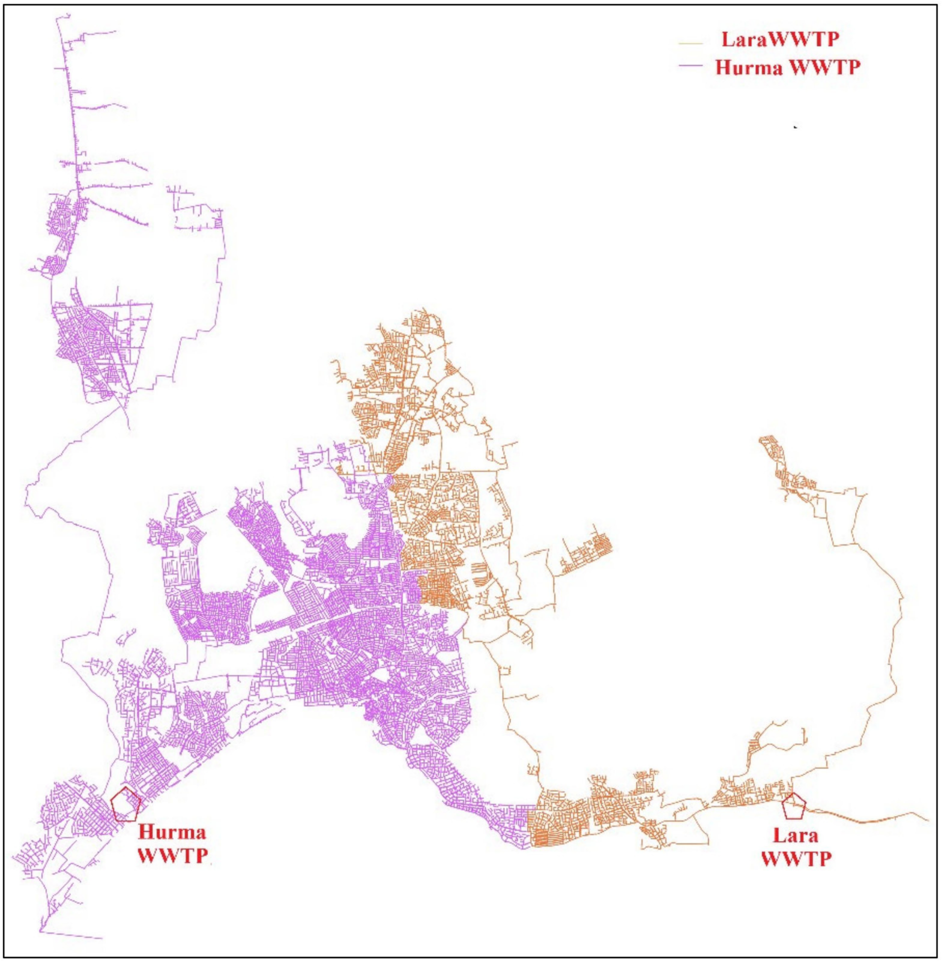

FIGURE 2 | Wastewater collection systems for Hurma and Lara WWTPs.

the locations of these plants as evaluated in the study. Both facilities employ the five-stage Bardenpho process following initial pretreatment (Karatay et al. 2017). During periods of excessive flow reaching the plants, surpassing the capacity of the biological units, particularly during instances of rainfall-induced inflow, the surplus wastewater is directed solely through the pretreatment units and discharged into the deep sea, with only the flow rate matching the design capacity allocated to the biological units. This operational strategy ensures the ongoing biochemical processes within the plants operate at optimal efficiency (Karatay et al. 2017).

As previously mentioned, Antalya's sewerage system operates predominantly as a combined system but also includes sections functioning as separate systems. According to the Antalya Water and Sewerage Administration (ASAT), rainwater from combined systems is entirely directed to the WWTPs. However, even within the separate system, infiltration rates are notably high, and a significant number of misconnections persist (Balsari and Werner 2008). Figure 2 illustrates the sewerage networks servicing the Lara and Hurma WWTPs. The service area of the Hurma Wastewater Collection System spans 82 849.9 ha, while that of the Lara system covers 53 315.6 ha. Construction of the Lara wastewater collection network commenced in the early 2000s. Additionally, the Hurma network gathers wastewater from the western and northern sectors of Antalya's city centre, whereas the Lara network collects wastewater from the eastern region and conveys it to the plant. Regarding groundwater conditions, the elevation of groundwater is lower in the service area of the Lara WWTP compared with that of the Hurma WWTP, which serves the western part of the city.

Tables 1 and 2 present the specific attributes of pipes that impact the occurrence and scale of I/I. As of 2019, the cumulative lengths of sewer pipes in the Hurma and Lara WWTP service regions had reached approximately 1580.5 and 593.8 km, respectively. The majority of pipes in both WWTPs have a diameter of 200 mm. Additionally, there exists a considerable number of pipes whose types are not precisely identified. This substantial issue accounts for an estimated percentage of approximately 10% and 15% for Lara and Hurma, respectively.

2.2 | Determination of I/I

The I/I affecting wastewater flow within the sewer system can arise from various sources, including GWI, rain-induced I/I and BI. GWI refers to the volume of groundwater that permeates into the sewer system through compromised pipes, pipe joints, connections or manholes. It is noteworthy that under adverse conditions, the quantity of GWI into deteriorated pipes can surpass 50% of the total wastewater volume.

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TABLE 1 | Pipe characteristics for Hurma WWTP.

Pipe diameter (mm)	Pipe type and length (m)							Total
	Concrete	Steel	HDPE	Corrugated	PE	PVC	N/I[a]	
N/I[a]	—	—	148.2	112.3	—	—	24 314.7	24 575.2
110	—	—	224.6	—	—	—	—	224.6
150	—	—	719.7	257.8	—	53.8	—	1031.4
200	745 198.8	—	113 164.1	172 664.8	6840.3	5271.8	208 005.4	1 251 145.1
225	—	6.5	—	—	—	892.7	—	899.3
300	—	—	—	—	—	3.6	—	3.6
400	40 387.8	550.1	8148.1	3598.1	1011.4	—	—	53 695.4
500	14 945.5	—	1304.4	2206.6	31.9	1302.4	—	19 790.8
600	10 935.6	129.7	1619.9	1503.5	—	—	76.3	14 265.1
700	226.3	—			—	—	—	226.3
800	17 517.8	562.9	3664.9	200.2	—	—	—	21 945.9
1000	19 998.3	—	2179.3	57.1	—	—	—	22 234.6
1200	24 261.8	4301.2	13 675.5	733.7	—	—	332.7	43 305.1
1400	1217.3	—	—	—	—	—	—	1217.3
1600	4959.7	—	559.1	—	—	—	—	5518.7
2000	12 334.7	—		—	—	—	—	12 334.7
Total	959 701.6	6179.2	165 020.4	198 039.0	10 750.9	7524.4	232 796.1	1 580 521.2

[a]Pipe types are not precisely identified.

TABLE 2 | Pipe characteristics for Lara WWTP.

Pipe diameter (mm)	Pipe type and length (m)					Total
	Concrete	Steel	HDPE	Corrugated	N/I[a]	
N/I[a]	—	—	—	146.2	3466.9	3613.1
100	—	—	—	28.6	—	28.6
150	—	—	44.1	63.4	—	107.5
200	128 057.6	—	63 722.4	189 983.6	56 578.5	438 342.1
300	24 038.6	—	—	15 371.7	1404.2	47 266.1
400	11 923.4	—	—	287.6	—	13 590.9
500	7533.2	—	178.1	883.	—	8594.6
600	6120.4	—	307.7	3438.1	—	9866.2
800	17 828.1	123.8	8535.3	1367.6	—	27 854.8
1000	5796.3	—	8040.8	534.1	—	14 371.1
1200	805.7	—	1861.3	—	—	2666.9
1400	8768.5	—	—	—	—	8768.5
1600	13 513.1	—	2759.1	—	—	16 272.2
1800	—	—	737.3	—	—	737.33
2000	1797.9	—	—	—	—	1797.9
Total	226 182.6	123.8	94 017.8	212 104.0	61 449.5	593 877.8

[a]Pipe types are not precisely identified.

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GWI is accounted for during periods of elevated groundwater levels, typically occurring in the spring months (March–May). Infiltration measurements are typically conducted during periods of high groundwater levels, often coinciding with dry weather conditions. In this study, 'dry weather conditions' refer to the absence of rainfall events, not necessarily to low groundwater levels. In fact, seasonal high groundwater (e.g., after snowmelt) may coincide with such dry periods, increasing the potential for infiltration. Additionally, the minimum nightly flow is considered when assessing infiltration (Franz 2006).

Base or constant infiltration is determined by assessing the minimum night-time flow, theoretical dry weather flow and wastewater flow, which closely resembles GWI. Globally, the extent of I/I varies significantly, driven by the intricate nature of sewer systems and the multitude of factors influencing their magnitude. Substantial discrepancies are anticipated among WWTPs and municipalities, attributable to diverse factors including the state of sewer infrastructure, intensity of rainfall, soil conditions and groundwater levels. This issue is poised to escalate with the projected increase in severe precipitation events in the future (Haghighatafshar 2014). Table 3 illustrates the estimated average contribution of I/I to sewer systems based on various quantification methods.

2.3 | Methodology

The GWI, one of the components of I/I, is associated with extraneous water entering the sewer system through defects in pipes and manholes (Environmental Protection Agency [EPA] 2014). It cannot be measured directly, but it is usually estimated by using a variety of empirical methods with measured wastewater flow data. Given Antalya's status as one of the world's most appealing regions, there are minimal industrial or commercial night-time flows, aligning GWI closely with BI in this study. Furthermore, inflow is distinct from infiltration and is typically measured during wet weather conditions (EPA 2007). It encompasses water other than sanitary flow entering the sewer system from various sources, such as roof leaders, cellar drains, yard drains, area drains, wet areas, cross connections between storm sewers and sanitary sewers, catch basins, cooling towers, stormwater surface run-off (including leaking manhole covers), street wash-water or drainage. Wastewater flows exhibit continuous variations based on the time of day and time of year. Various terms are commonly employed to describe these flow fluctuations, each with its significance, as briefly outlined in Table 4.

TABLE 3 | Estimated contribution of I/I to wastewater flow (Hey et al. 2016).

Country	I/I share (%)
Germany	35
Netherlands	38
Norway	67
Austria	25–50
Sweden	50
United Kingdom	45
Scotland	60
Ireland	10–75
Switzerland	35–65
Canada	8
Czech Republic	45
United States	55–65

There are empirical methods recommended in the literature which involve evaluating ADF and minimum daily flow (MDF) for the estimation of the GWI in sewers. The three most common methods, wastewater production method (WPM), minimum flow factor method (MF) and SS method, are given in Table 5 (Mitchell et al. 2007). The order in which these methods are presented corresponds to the historical aspect on which they were developed, starting with the MF and WPM in the 1970s, followed by the SS method in the 1990s. The more recent methods also take into account or address the shortcomings of the more traditional ones (Kevin et al. 2020). According to Table 5,

TABLE 4 | Terminology for the calculation of the I/I.

Term	Definition
Average daily flow (ADF), $Q_{av,d}$	The average of the daily volumes to occur for a continuous 365 days.
Groundwater infiltration (GWI or BI)	During the ADWF flow period, average the low night-time flows (midnight to 6 AM) per day for the same time period, minus significant industrial or commercial flows.
Average daily dry weather flow (ADWF), $Q_{av,dry}$	The average daily flow without precipitation (0 rainfall) for a continuous 12 months.
Average daily wet weather flow (AWWF), $Q_{av,wet}$	The average daily flow during a period of rainfall for a continuous 12 months.
Maximum daily flow (MDF), $Q_{max,d}$	The largest volume of flow that occurs within a 1-day period for a continuous 12 months.
Minimum daily dry weather flow (MiDWF), $Q_{min,d}$	The lowest volume of flow without precipitation (0 rainfall) occurs within a 1-day period for a continuous 12 months.

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TABLE 5 | Empirical methods for the estimation of GWI.

Method	Formula	Note	References
Minimum flow factor method (MF)	$MF = 0.222 \cdot (ADWF - GWI)^{0.202}$ $GWI = MiDWF - MF \cdot (ADWF - GWI)$ $GWI = \frac{MiDWF - MF \cdot ADWF}{1 - MF}$	The unit of measure is million gallons per day (mgd)	ASCE (1982)
Wastewater production method (WPM)	$WPM = (ADWF - MiDWF) / 0.88$ $GWI = ADWF - WPM$	The unit of measure is litres/s (L/s)	Mitchell et al. (2007)
Stevens–Schutzbach method (SS)	$GWI = \frac{0.4 \cdot ADWF}{1 - 0.6 \cdot \left(\frac{MiDWF}{ADWF}\right)^{ADWF^{0.7}}}$	The unit of measure is million gallons per day (mgd)	Stevens and Schutzbach (1998)

MF refers to the minimum flow factor, which compares the lowest observed daily flow with the corresponding ADF. It can be calculated through one or more iterations using the equations provided in method MF. This approach also illustrates how flow monitor data can be applied to estimate GWI in sewers. However, it does not provide guidance on selecting one method over another (Kevin et al. 2020).

By using these three empirical methods, GWI was found, and by calculating with empirical equations, the total amount of I/I was estimated as the total I/I should be equal to the summation of GWI and rain-dependent I/I. EPA recommended that the rain-dependent I/I may be found by considering data from wet weather conditions (EPA 2014). Thus, I/I was found by subtracting the GWI from the AWWF and the total amount of I/I was found by using daily wastewater flow data for 3 years between 2016 and 2019.

This study was focused on WWTPs in the same city, based on the analysis of ADF measurements from the wastewater flow data from 2016 to 2019 as a case study. Dry weather flow refers to periods without rainfall and with zero inflow or at most a rainfall intensity of 0.3 mm (Staufer et al. 2012). The ADWF ($Q_{av,dry}$) and MiDWF ($Q_{min,d}$) were also found by considering the daily wastewater flow data within the days in each year between 2016 and 2019 when there is no rainfall event recorded higher than 0.3 mm. During dry weather, inflow is expected to be zero. However, for the rain-dependent parameters such as AWWF ($Q_{av,wet}$), it was calculated from the daily wastewater flow in each year in between 2016 and 2019 only if the rainfall event exceeded 0.3 mm.

Additionally, these results were compared with the recommendation given by EPA (EPA 2014) for GWI estimation. Because the EPA recommends this approach, it can be estimated from wastewater influent flow data measured during dry weather periods under high groundwater conditions. GWI can also be calculated using minimum night-time flows by subtracting industrial or commercial night-time flows. For this purpose, hourly wastewater flow was used in the year 2019. Furthermore, several parameters influence the occurrence and magnitude of I/I such as the construction of the sewer trench, sewer pipe material, workmanship, age of the sewer system, maintenance procedure and connected impermeable surfaces (Gerly et al. 2016; EPA 2007). For a better understanding, the I/I was recalculated by considering the pipe characteristics for both Hurma and Lara WWTP as illustrated in Tables 1 and 2, respectively.

3 | Results and Discussion

In this study, assuming that most of the flows originate from groundwater, the infiltration rate was quantified by averaging night-time flows on dry weather days, following the approach of Gerly et al. (2016). Dry weather flow conditions were defined as periods without rainfall and with zero inflow, or with a maximum rainfall intensity of 0.3 mm, similar to the definition given by Staufer et al. (2012). Thus, dry weather is defined as when it has been at least 3 days without a rain event in the study. For the determination of GWI, it is also calculated by using minimum night-time flows by subtracting industrial or commercial night-time flows as recommended by EPA (2014). During seasonal high groundwater periods, infiltration reaches its peak. The infiltration rate can then be quantified by averaging night-time flows (midnight to 6 AM) over several days, during dry weather conditions. The night-time GWI was found from the hourly wastewater flow in the year 2019 for both Lara and Hurma. An example illustration was given in Figure 3 for the determination of minimum hourly night flow measurement and GWI for Lara WWTP data. Minimum daily dry weather flow (MiDWF) was represented with a red line in this figure.

By using EPA's (2014) recommendation, both Hurma and Lara's GWI was found 69 487.2 and 37 440.0 m^3/day for 2019, respectively. Considering the service area of the WWTPs, the total I/I was also calculated as 1.3 and 0.8 m^3/day-ha for Hurma and Lara, respectively, in the same year. The I/I can be reported with different units such as in litres per person per day, in litres per millimetre of pipe diameter per kilometre length per day according to the number of inhabitants connected, the size of the sewer system or as the ratio of peak wet weather flows to average dry weather flow (Metcalf and Eddy 2003; Qasim 1998). Metcalf and Eddy (2003) stated that the amount of infiltration may vary widely with a range between 10 and 1000 L/day-mm-km. EPA (2014) also suggested a threshold infiltration rate of 140 L/day-mm-km. Calculated I/I values were reported with different units as in the literature by using information summarized in Tables 1 and 2 with data obtained from ASAT.

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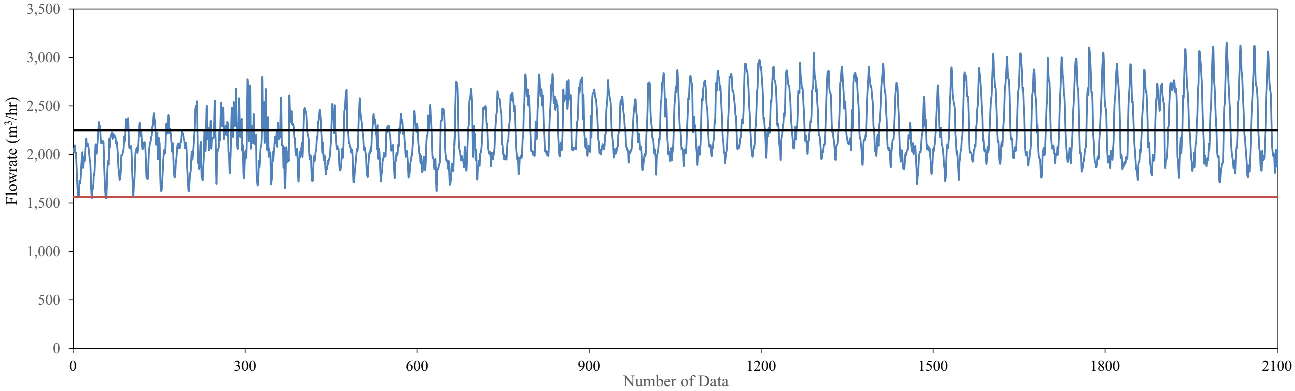

FIGURE 3 | Minimum hourly night-time flow measurements for Lara WWTP (red line is minimum flow, and black line is average flow).

TABLE 6 | The I/I result for Hurma and Lara based on EPA (2014) recommendation.

Unit	Hurma WWTP	Lara WWTP	References	Reference range
m^3/day-ha	1.3	0.8	Metcalf and Eddy (2003)	0.2–28
L/day-ha	1343.5	798.1	Qasim (1998)	200–28 000
m^3/day-mm-km	0.25	0.21	Metcalf and Eddy (2003)	0.01–1
L/day-cm-km	2473.0	2121.0	Qasim (1998)	94–9400

Table 6 summarizes the reference ranges and the I/I values calculated for the Hurma and Lara WWTPs according to EPA (2014) recommendations. The estimated I/I values based on the service area were 1.3 m^3/day-ha (1343.5 L/day-ha) for Hurma and 0.8 m^3/day-ha (798.1 L/day-ha) for Lara, which are well within the reference ranges reported by Metcalf and Eddy (2003) (0.2–28 m^3/day-ha) and Qasim (1998) (200–28 000 L/day-ha). Furthermore, the I/I values also calculated using pipe-based parameters were 0.25 m^3/day-mm-km for Hurma and 0.21 m^3/day-mm-km for Lara, which fall within the reference range (0.01–1 m^3/day-mm-km) proposed by Metcalf and Eddy (2003). When expressed in L/day-cm-km, the calculated I/I values were 2473 for Hurma and 2121 for Lara, both falling comfortably within Qasim's (1998) reference interval of 94–9400 L/day-cm-km. Overall, these findings demonstrate that both service area-based and pipe-based I/I estimates remain well within the literature reference ranges, indicating that the I/I levels in the Hurma and Lara WWTP service regions are consistent with acceptable limits.

Moreover, when the dry and wet parameters were analysed, they had a proportional change between 2016 and 2019, even though the increase for 2019 was slightly higher for Hurma WWTP. On the other hand, these parameters constantly increased between 2016 and 2019, and they reached an approximate value of 70 000 m^3/day for both average dry and wet parameters. Similarly, Hurma also took the value of 175 544.0 and 185 520.6 m^3/day for average dry and wet flowrates, respectively.

After GWI was calculated using the equations in Table 5, the I/I results were summarized in Tables 7 and 8 for the Hurma and Lara WWTPs, respectively. The estimated contribution of I/I to wastewater flow ranged between 40.4% and 94.3% during 2016–2019, depending on the method used. For the Lara WWTP, although both dry and wet weather flow parameters increased between 2016 and 2019, the I/I ratios did not change consistently over the same period. In contrast, for the Hurma WWTP, the flow parameters and the I/I ratios exhibited varying trends, indicating that their changes were not uniform in direction or magnitude.

According to the SS method, the ratio of GWI to I/I was determined in the range of 61.8%–74.1% for Hurma and 64.6%–98.9% for Lara WWTPs, while the estimated contribution of I/I to annual wastewater flow (AF) was calculated to range from 52.6% to 61.6% and 40.4% to 59.3%, respectively. Using the WPM, the GWI/I/I ratio was found to be 72.9%–85.1% for Hurma and 56.4%–78.2% for Lara, with the I/I/AF ratio ranging from 85.0% to 94.3% and 64.0% to 86.2%, respectively. Similar ranges were also obtained from the MF method, which showed strong resemblance to the WPM. These results cover the period 2016–2019. Due to the lack of hourly measurement data, GWI could be estimated according to EPA's (2014) method only for 2019. With the exception of EPA's method, the WPM and MF methods tended to overestimate GWI compared with the SS method in the Hurma WWTP. In contrast, for Lara WWTP, the WPM consistently produced lower percentages than the SS method. This outcome is also consistent with the findings of Kevin et al. (2020), who reported that the WPM and MF methods tend to overestimate GWI in larger basins due to flow attenuation, while the SS method accounts for this factor and provides more accurate estimates.

Considering the results for 2019, similarly, the WPM and MF methods overestimated the ratios of the I/I and AF from 62.5% to 85% and 69.6% to 80.7% for Hurma and Lara WWTPs, respectively. Even though EPA (2014) gave a close estimation of the SS method for Hurma as an approximate value of 59%, it was in the range of 47.2%–60.8% for Lara. In brief, the calculated

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TABLE 7 | The I/I results for Hurma WWTP by using different methods.

Year	Dry parameters	Flowrate (m^3/day)	Wet parameters	Flowrate (m^3/day)	Annual flow parameters	Flowrate (m^3/day)	SS method GWI/I/I (%)	SS method I/I/AF (%)	WP method GWI/I/I (%)	WP method I/I/AF (%)	MF method GWI/I/I (%)	MF method I/I/AF (%)	EPA (2014) GWI/I/I (%)	EPA (2014) I/I/AF (%)
2016	$Q_{max,dry}$	217 108.0	$Q_{max,wet}$	312 328.0	$Q_{max,d}$	312 328.0	71.8	54.3	83.3	91.9	80.3	78.0		
	$Q_{av,dry}$	158 042.6	$Q_{av,wet}$	182 906.4	$Q_{av,d}$	162 118.6								
	$Q_{min,dry}$	128 140.0	$Q_{min,wet}$	134 490.0	$Q_{min,d}$	128 140.0								
2017	$Q_{max,dry}$	190 409.0	$Q_{max,wet}$	349 108.0	$Q_{max,d}$	349 108.0	74.1	52.6	85.1	91.6	82.6	78.3		
	$Q_{av,dry}$	159 774.2	$Q_{av,wet}$	182 143.7	$Q_{av,d}$	164 125.5								
	$Q_{min,dry}$	131 856.0	$Q_{min,wet}$	141 014.0	$Q_{min,d}$	131 856.0								
2018	$Q_{max,dry}$	239 784.0	$Q_{max,wet}$	385 689.0	$Q_{max,d}$	385 689.0	66.1	58.4	79.0	94.3	75.0	79.1		
	$Q_{av,dry}$	162 793.1	$Q_{av,wet}$	196 184.6	$Q_{av,d}$	168 739.6								
	$Q_{min,dry}$	130 197.0	$Q_{min,wet}$	127 520.0	$Q_{min,d}$	127 520.0								
2019	$Q_{max,dry}$	260 766.0	$Q_{max,wet}$	396 165.0	$Q_{max,d}$	396 165.0	64.0	59.2	74.9	85.0	65.8	62.5	63.7	58.8
	$Q_{av,dry}$	175 544.0	$Q_{av,wet}$	215 124.9	$Q_{av,d}$	185 520.6								
	$Q_{min,dry}$	124 933.0	$Q_{min,wet}$	121 279.0	$Q_{min,d}$	121 279.0								

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TABLE 8 | The I/I results for Lara WWTP by using different method.

Year	Dry parameters	Flowrate (m^3/day)	Wet parameters	Flowrate (m^3/day)	Annual flow parameters	Flowrate (m^3/day)	SS method		WP method		MF method		EPA (2014)	
							GWI/I/I (%)	I/I/AF (%)	GWI/I/I (%)	I/I/AF (%)	GWI/I/I (%)	I/I/AF (%)	GWI/I/I (%)	I/I/AF (%)
2016	$Q_{max,dry}$	73933.0	$Q_{max,wet}$	68000.0	$Q_{max,d}$	73933.0	98.9	40.4	63.5	64.0	99.1	49.5		
	$Q_{av,dry}$	50182.5	$Q_{av,wet}$	50410.5	$Q_{av,d}$	50220.0								
	$Q_{min,dry}$	34092.0	$Q_{min,wet}$	38453.0	$Q_{min,d}$	34092.0								
2017	$Q_{max,dry}$	66280.0	$Q_{max,wet}$	83830.0	$Q_{max,d}$	83830.0	81.2	48.4	73.9	83.1	87.5	72.9		
	$Q_{av,dry}$	54162.8	$Q_{av,wet}$	59182.0	$Q_{av,d}$	55139.2								
	$Q_{min,dry}$	42381.0	$Q_{min,wet}$	42414.0	$Q_{min,d}$	42381.0								
2018	$Q_{max,dry}$	81297.0	$Q_{max,wet}$	93692.0	$Q_{max,d}$	93692.0	83.0	47.5	78.2	86.2	89.8	78.6		
	$Q_{av,dry}$	61302.2	$Q_{av,wet}$	66311.9	$Q_{av,d}$	62194.3								
	$Q_{min,dry}$	50150.0	$Q_{min,wet}$	49898.0	$Q_{min,d}$	49898.0								
2019	$Q_{max,dry}$	87545.0	$Q_{max,wet}$	93234.0	$Q_{max,d}$	93234.0	83.0	47.2	72.7	80.7	88.4	69.6	86.8	60.8
	$Q_{av,dry}$	69475.9	$Q_{av,wet}$	75185.9	$Q_{av,d}$	70915.2								
	$Q_{min,dry}$	53703.0	$Q_{min,wet}$	60320.0	$Q_{min,d}$	53703.0								

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ratios regarding I/I were distributed over larger ranges for Lara WWTP as illustrated in Tables 7 and 8. These results are quite compatible with the results of the estimated contribution of the I/I to wastewater flow recommended by Hey et al. (2016).

4 | Conclusion

An increase in I/I within sewage systems leads to significant alterations in the pollutant parameters of wastewater, resulting in challenges such as decreased treatment effectiveness and, notably, increased operational costs. Despite the primary consideration of I/I during the design of WWTPs, unforeseen infiltration persists due to uncontrollable circumstances. In the case of Antalya, a region characterized by predominantly touristic land use, practitioners commonly employ three empirical methods and recommendations from the EPA to estimate GWI and total I/I solely based on sewer flow data and daily (or diurnal) patterns. The study presented herein yields the following outcomes:

- Technical issues such as uncontrolled measurements, unidentified pipe types, numerous misconnections and an inadequate wastewater collection system contribute significantly to the notably high levels of I/I.
- The estimated I/I contribution to wastewater flow ranged from 40.4% to 94.3% during the period of 2016–2019 using various methodologies. For the Lara WWTP, while dry and wet weather flow parameters increased between 2016 and 2019, the ratios of I/I did not uniformly change over the same period. For the Hurma WWTP, similar behaviours were observed in both flow parameters and I/I ratios.
- Analysis of the I/I estimate according to EPA (2014) guidelines revealed that calculations based on the service area (m^3/day-ha or L/day-ha) were slightly more consistent with the literature reference ranges compared with those based on pipe characteristics (m^3/day-mm-km or L/day-cm-km). Nevertheless, both estimation approaches produced values that remained well within acceptable limits, indicating that the sewer collection systems serving the Hurma and Lara WWTP service regions generally perform efficiently without signs of excessive leakage or infiltration.
- Different empirical methods yielded varying results during the period of 2016–2019. Due to the lack of hourly measurement data, EPA estimates for GWI were available only for 2019. The WPM and MF methods tended to overestimate GWI compared with the SS method, likely due to unaccounted basin size. In 2019, the EPA and SS methods proved more suitable for the Hurma and Lara WWTPs, which are located in densely touristic areas.
- In 2019, the estimated contributions of I/I to daily average wastewater flow were approximately 59% for Hurma and ranged from 47.2% to 60.8% for Lara WWTPs. This study recommends maintaining this ratio within the range of 55%–60% for the region.

Future efforts should focus on developing comprehensive master plans for the city or region to mitigate I/I in the wastewater collection system. Improvement of measurement systems and the collection of hourly data for both flow rates and wastewater constituents are imperative for effective planning and management.

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Ethics Statement

This article does not contain any studies with human participants or animals performed by any of the authors.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data are available on request due to privacy/ethical restrictions.

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