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Analysis of the Sensitivity of the Main Sewage Pipe in Karbala City Center to Heavy Rainfall Events

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Abstract.

The sewerage network is one of the main pillars of urban infrastructure. However, it faces increasing challenges due to the aging of its components, the rapid pace of urbanization, climate change, and high consumption rates. Rainwater runoff and seepage (RDII) are among the most significant problems negatively impacting the efficiency of these networks, contributing significantly to sewage overflows and their consequent serious environmental and health impacts. The current research focused on analyzing the sensitivity of the main sewerage pipeline in the center of Karbala, Iraq. This city of global religious and tourist importance receives millions of pilgrims annually in a short period of time, placing high pressure on the sewerage network. To achieve this, recorded discharge and rainfall data were analyzed using Sanitary Sewer Overflow Analysis and Planning (SSOAP), along with a comprehensive flow simulation using the Personal Computer Storm Water Management Model (PCSWMM) to evaluate the hydraulic performance of the pipeline under heavy rain conditions and identify potential areas of vulnerability. The analysis results showed that rainfall intensities ranging from 20 mm/h to 24 mm/h represent the upper limit of a pipe's capacity where the 25 mm/h rainfall signifies the failure threshold for the existing pipeline.

Keywords: Sewer, Rain, Infiltration, Inflow, Capacity

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1. Introduction

The sewerage network is a vital component of urban infrastructure, playing a key role in collecting and transporting wastewater generated by residential, commercial, industrial, and health-related activities through pipelines to treatment and final disposal sites. Therefore, ensuring the efficiency and sustainability of these networks is crucial to reducing the problems and undesirable consequences that may arise during their operation[1], [2], [3]. In recent decades, intertwined factors such as increasing consumption rates, accelerating urbanization, and climate change have exacerbated the pressure on drainage systems. Recent literature indicates that extreme weather events cause increased rates of short-term, heavy rainfall, which directly impacts the networks' capacity to absorb and process water[4], [5], [6], [7]. Many urban networks are aging and prone to problems during construction and subsequent operation, such as cracks, joints, and faulty connections. This increases their susceptibility to complications under operating pressure. Rainfall-Derived Infiltration and Inflow (RDII) are among the most significant factors that lead to increased loads and network saturation. RDII is defined as the portion of rainwater that infiltrates or flows into the sewer system. This can occur directly through manhole openings and faults during rainfall, or be delayed as gradual infiltration from saturated soil. The amount of RDII is affected by multiple factors such as soil quality, network condition and age, rainfall intensity, and land use patterns, making estimation and prediction more complex. Sudden increases in flows can cause flooding and congestion within the network, resulting in pollution and health risks, as well as increased pressure on treatment plants and higher operating costs. Infiltration or surface water may also carry waste that impedes the efficiency of pumps and pipelines at lift stations[8], [9], [10]. The risk of urban flooding increases significantly when high flows coincide with sudden demographic changes, as is the case in the city of Karbala, which receives millions of visitors annually during major religious events. Such an event increases the pressure on the drainage system and makes its study particularly important. The city of Karbala attracts millions of pilgrims in a short period of no more than two weeks. The cumulative number of visitors during this short period exceeds 21 million, equivalent to more than forty times the city's permanent population[11]. This sudden increase in population density poses a serious challenge to the wastewater infrastructure, due to the sharp increase in wastewater generation. This phenomenon becomes more serious when it coincides with the rainy season, as the accumulation of population and climatic influxes places additional pressure on the network, increasing the likelihood of sewage flooding and the resulting environmental and health risks, as witnessed in previous years[12]. Accordingly, it becomes necessary to study rainfall-induced discharges (RDII) in the central Karbala sewer network, with the aim of assessing their impact on the network's operational capacity and identifying mitigation strategies and future solutions. To achieve this, researchers have developed several methodologies for measuring RDII and analyzing its results[13], [14], [15]. SSOAP (Sanitary Sewer Overflow Analysis and Planning) is an important tool in this field. It allows for the examination of temporal data related to sewer discharges, weather conditions, and it rainfall to differentiate flows under dry and wet conditions, and enables the accurate identification and separation of RDII. The program is based on the Modular Unit Overflow (SUH) diagram methodology, which assumes that RDII in sewers responds to rainfall in a manner similar to stormwater runoff in a watershed. The RTK method, the most common, relies on three triangular diagrams to represent the different stages of RDII. These diagrams are calibrated within the program to determine appropriate RTK coefficients that can be used in subsequent analyses of other drainage networks. SSOAP has been widely used in previous studies and has contributed to providing relatively accurate and reliable estimates[13], [16], [17], [18], [19]. Additionally, the Personal Computer Storm Water Management Model (PCSWMM) is an advanced tool for modeling urban sewerage networks and managing stormwater systems. It builds on the Storm Water Management Model (SWMM) platform and adds a more intuitive interface and advanced features that improve operational efficiency. One of its most notable features is its integration with GIS data, which enhances spatial representation accuracy and ease of data management[20], [21], [22], [23], [24]. PCSWMM allows for a variety of network analyses under different flow and rainfall scenarios, with the user entering RTK parameters and precipitation data to accurately represent RDII within the model. Examining network behavior and performance under the influence of RDII using tools such as SSOAP and PCSWMM is a key step to understanding vulnerability and risk mechanisms, and developing sustainable strategies to address operational challenges associated with demographic and climate change.

This research aims to analyze the sensitivity of the main sewage pipeline in the center of Karbala to heavy rainfall events, with the aim of evaluating its performance and determining its maximum capacity.

2. Study Area

The case study location is situated in the core of Karbala city, Iraq, approximately 100 km southwest of the capital, Baghdad. The city features a separated sewer system. Encompassing 1,270 hectares and serving approximately 200,000 citizens Fig. 1. The wastewater is transported via a conveyor pipe consisting of two main lines (Line 1 and Line 2) that meet at the P2 lift station Fig. 2. This lift station pumps wastewater to the third line, which heads to the city's old treatment plant. The first line (Line 1) starts from the Saadia lift station and reaches the P2 station, while the second line (Line 2) starts from the Hayabi lift station and meets the first line at the P2 station. This arrangement contributes to regulating the flow of wastewater and efficiently delivering it from the various collection points to the final treatment plant. The diameters of the main sanitary sewage system in the research region vary from 600 mm to 1800 mm, including sizes of 800 mm, 1000 mm, 1400 mm, and 1500 mm. The total length of the pipeline network, which consists of three transmission lines, is approximately 7.8 km, and this network includes approximately 98 inspection holes (manholes) distributed along its route. The region is significant due to its sacred religious shrines, attracting millions of pilgrims during annual gatherings, which places the sewer network under critical strain to accommodate the sudden surge in sewage volume. Last year, the city welcomed around 21 million pilgrims within a span of fewer than two weeks. This figure is roughly 40 times the city's entire population, and the density of these numbers in the city center places the sewage system in a precarious state. The concurrence of major religious events with the rainy season poses a risk, as the network is susceptible to a sudden surge in sewage produced by pilgrims, in addition to the influx of rainwater entering the system. Certain segments of this network are antiquated, originating from the 1970s, rendering it susceptible to leakage and other deficiencies, compounded by the existence of arbitrary connection points between the stormwater and sanitary sewer systems. Consequently, Analyzing and measuring the performance of the main wastewater pipeline during periods of heavy rainfall is an essential step in understanding the pipeline's capacity and its ability to handle changing loads under varying rainfall conditions. This analysis helps evaluate the operational efficiency of the infrastructure and ensure its readiness to handle heavy rainfall without exceeding its capacity limits.

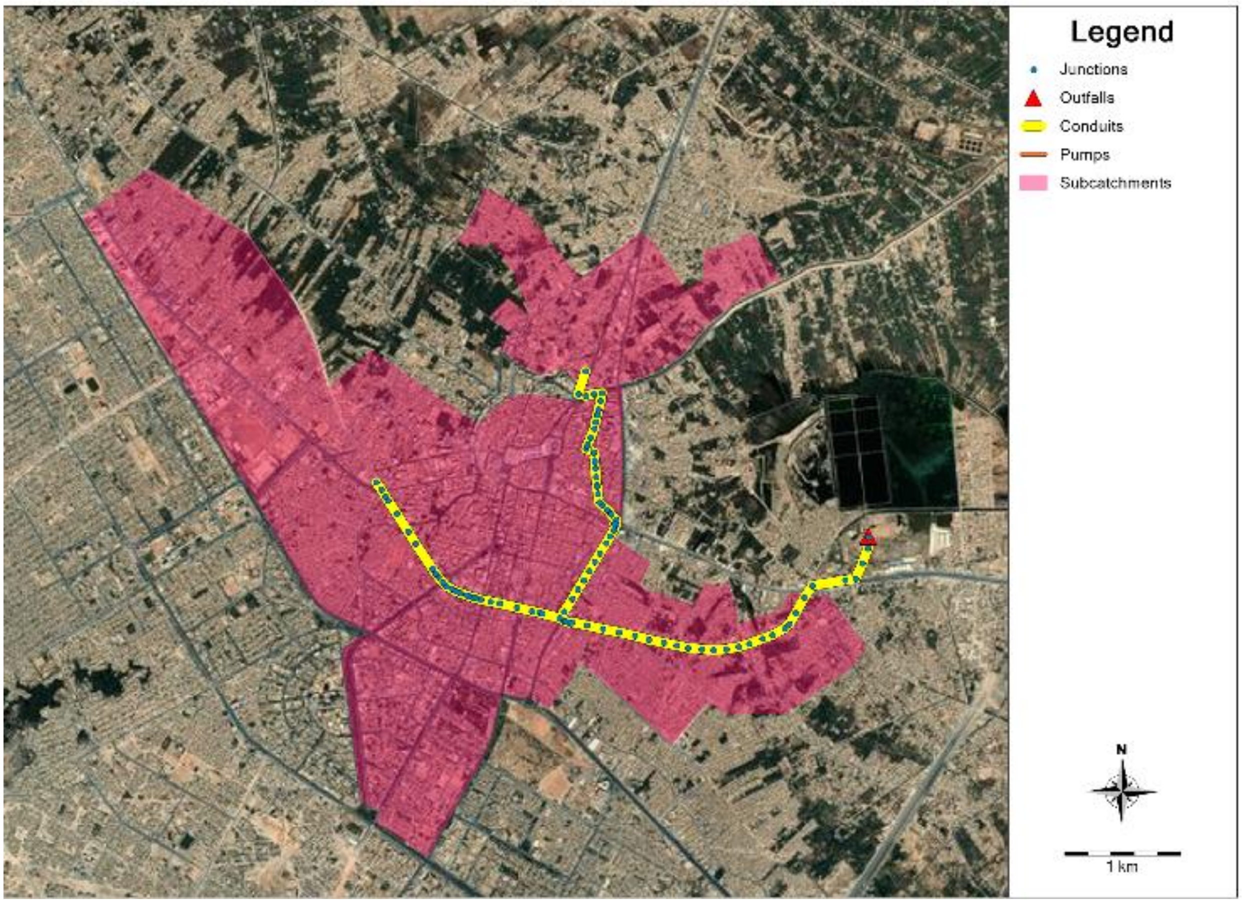

Figure 1. Study area, center of Karbala, Iraq.

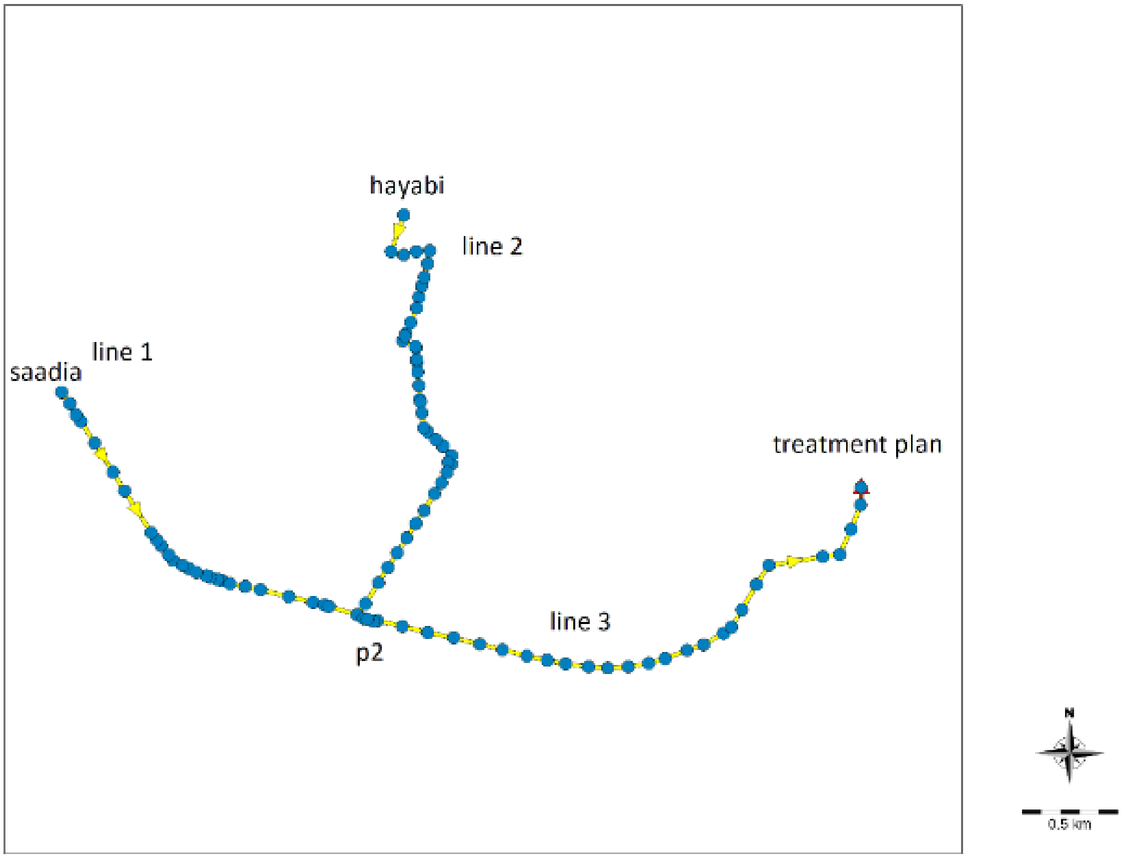

Figure 2. Main pipelines.

3. Data collection

Data were obtained from various agencies and institutions in Karbala, with historical information on rainfall events and flow being limited. Flow data in the primary sewage pipeline to the city center is recorded via a flow meter at the main lift station (P2) in fig. 3, which elevates the sewage to the disposal site. Due to the area's ongoing development and the scarcity of historical data, the analytical approach relies on the stability of the network's physical components to yield consistent and pertinent conclusions. Data were collected over a period of 10 months, encompassing both the rainy season and the typical dry season. In what location is the region's climate predominantly arid throughout the year.

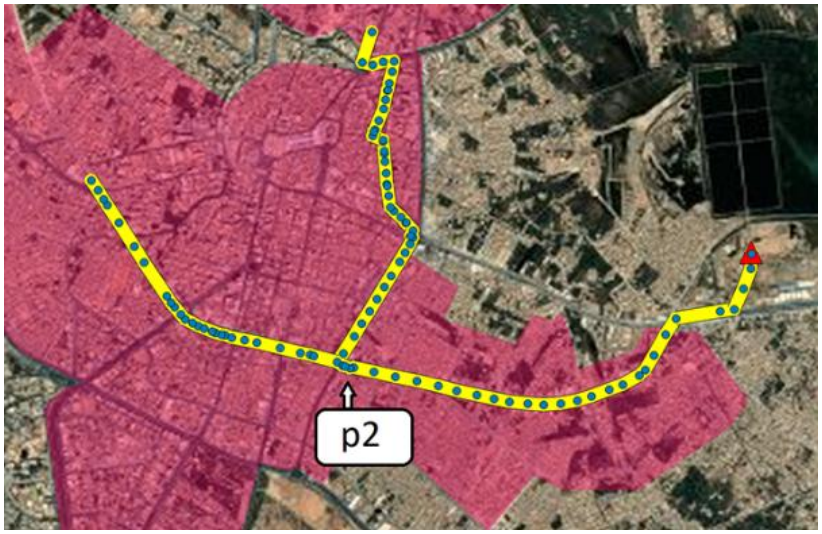

Figure 3. P2 Location (pump station).

Five precipitation occurrences were documented during the rainy season (2023-2024), utilizing data from the Meteorological Department in Karbala. The depths of the rainfall events were 6.4 mm, 12 mm, 16.75 mm, 19.5 mm, and 25.5 mm (Table. 1).

Table 1. Recorded rainfall events.

time	15/11/2023	20/11/2023	11/2/2024	24/3/2024	3/5/2024
0	0	2	0	0	0
1	0	3	1	0	0
2	0	4	2	0	1.5
3	0	5.5	2	0	2.5
4	0	4	3	0	4.5
5	0	4	3.5	0	5
6	0.5	2	2	0	4
7	2	1	2	0	2
8	3	0	1.25	0	0
9	0.9	0	0	0	0
10	0	0	0	0	0
11	0	0	0	0	0
12	0	0	0	0	0
13	0	0	0	0	0
14	0	0	0	0	0
15	0	0	0	0	0
16	0	0	0	1	0
17	0	0	0	3.5	0
18	0	0	0	3.5	0
19	0	0	0	3	0
20	0	0	0	1	0
21	0	0	0	0	0
22	0	0	0	0	0
23	0	0	0	0	0
Total depth (mm)	6.4	25.5	16.75	12	19.5

Data regarding the primary pipeline, pipe sizes, manholes, and elevations were gathered with the support of the Karbala Sanitary Directorate.

Additional data, including maps, spatial areas, demographic distributions, land uses, and GIS, were acquired with the assistance of the Karbala Governorate.

4. SSOAP and PCSWMM

The Sanitary Sewer Overflow Analysis and Planning (SSOAP) Toolbox is software used in this study due to its ability to analyze and separate the rainfall-derived infiltration and inflow (RDII). SSOAP uses the synthetic unit hydrograph (SUH) approach for predicting RDII. Specifically, the approach that employs the RTK method to characterize the RDII response to a rainfall event. The RTK method is based on fitting up to three triangular unit hydrographs to an observed RDII hydrograph to estimate the fast, medium, and slow RDII responses Fig. 4.

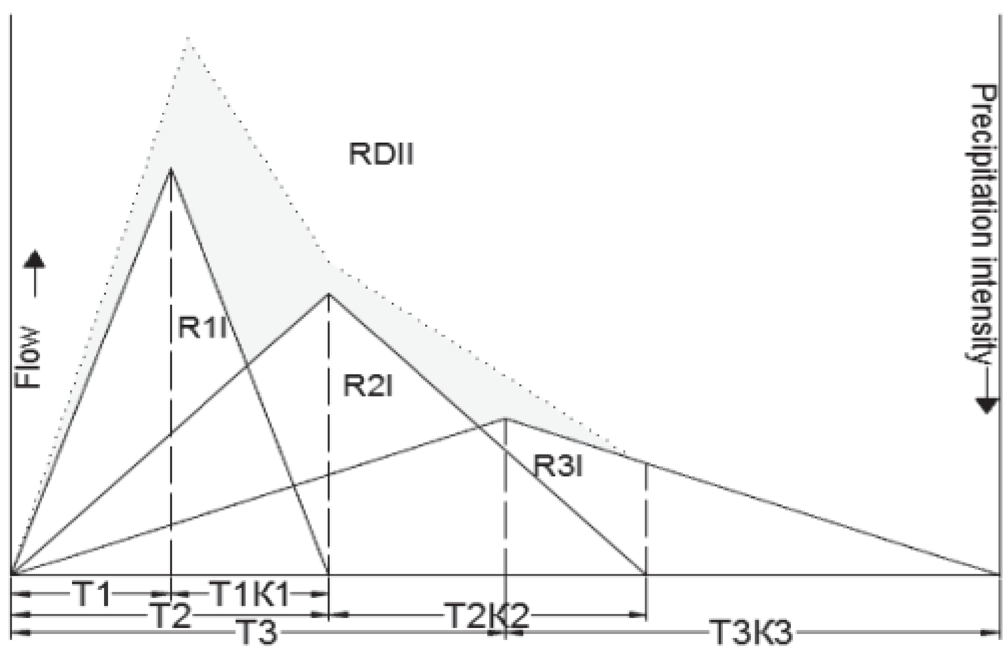

Figure 4. The RTK method elements.

The R parameter is the fraction of rainfall volume entering the sewer system as RDII, T is the time to peak, and K is the ratio of time of recession to T. The total R value is divided into three sub-values called R1, R2, and R3, such that

$R = R1 + R2 + R3$

These three values represent the fraction of total rainfall that enters the sewer network within each of the short, medium, and long-term hydrographs.

R1: Represents the portion of rainfall that is rapidly diverted to the network, expressed as the short-term response. If the R1 value is high, it means that the flow is mainly caused by direct water inflow through cover openings or loose connections.

R2: Represents the fraction of rainfall that arrives over an average period and expresses average velocity infiltration; usually associated with water percolating through soil or lateral connections.

R3: Represents the portion of rain that arrives after a longer period and indicates slow infiltration; this portion usually reflects water seepage from cracked pipes or from deeper soil layers[16].

Upon inputting all relevant data concerning the study area, including areas and pipe lengths, alongside the recorded flow and rainfall data for five events during the study period, the program delineates the dry flow and quantifies the wet flow. Additionally, for each event, the volume of infiltrated rain is simulated and can be estimated.

To validate the results and assess the operation of the primary pipeline, the data and outcomes from SSOAP are imported into the PCSWMM program for simulation.

PCSWMM (PC Stormwater Management Model) is a software application utilized for modeling stormwater systems and studying the dynamics of urban drainage systems. It is founded on the Storm Water Management Model (SWMM) created by the U.S. Environmental Protection Agency (EPA).

The PCSWMM model was developed to simulate the flow in the main sewer pipeline in the study area using realistic data including engineering network information, discharge and rainfall data. The development process included drawing the pipe and manhole network based on available topographical plans and network maps (fig. 5 and fig. 6). Hydraulic properties such as pipe lengths, diameters, inlet and outlet levels. For hydrological factors, the study area was divided into a number of sub-catchments based on the nature of the sewer network branches, with the characteristics of each sub catchment determined, such as area and population. Rainfall data were entered as temporal inputs in the form of rain events or time series, in addition to entering the RTK data generated by the SSOAP program to prepare the program to calculate the RDII.

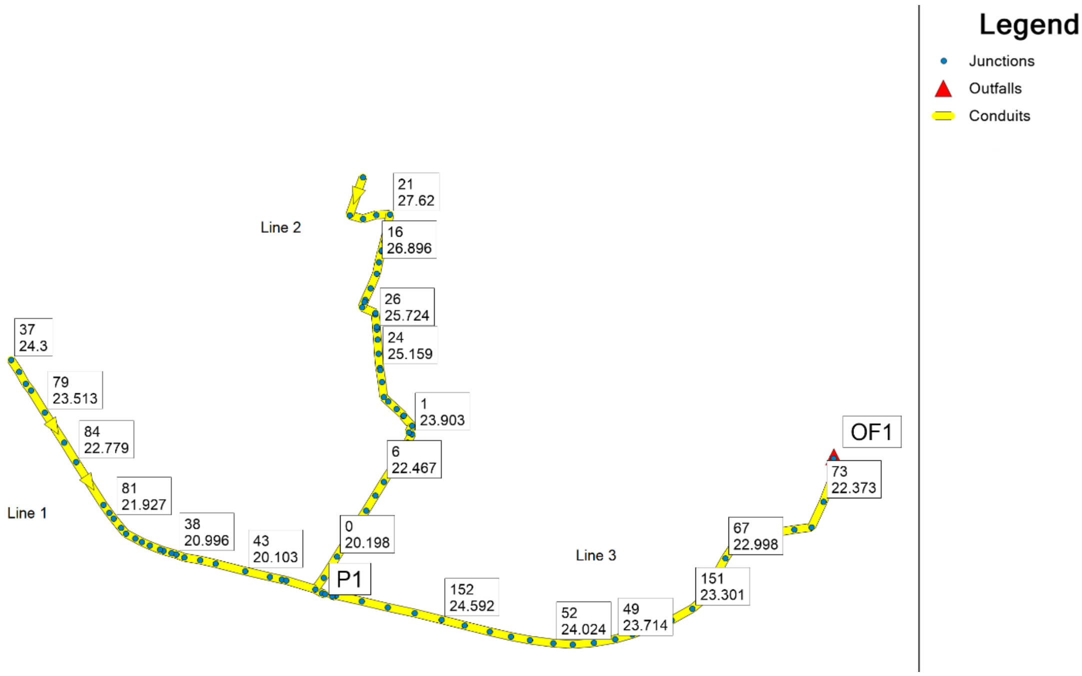

Figure 5. Main pipeline junctions and elevations.

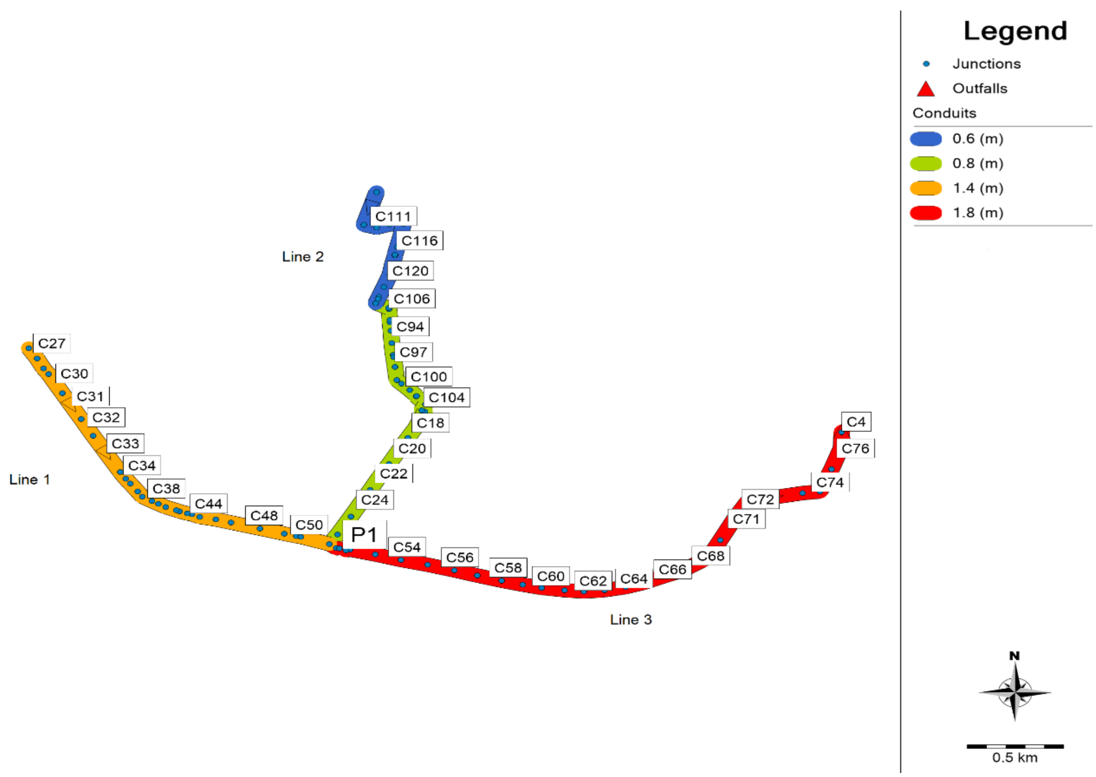

Figure 6. Main pipeline diameter.

5. Results and discussion

5.1.Dry weather flow analysis

During this study, flow data for the study area were collected over a ten-month period, covering most seasons and representing various flow patterns. These data were analyzed using SSOAP software to determine the hydraulic characteristics of the system during dry flow conditions. As Fig. 7 shows, the flow curve at lift station P2 exhibits a distinct daily pattern associated with human activities during daylight hours. The average daily flow volume at this station was approximately 94,000 cubic meters. The operating efficiency of the lift station pumps is estimated to be approximately 80%, according to the Karbala Sanitary Directorate. P2 pumping station relies on a system consisting of six main pumps, three of which are screw type and three of which are submersible type, with the aim of ensuring operational flexibility and providing operational alternatives that guarantee the continuity and efficiency of the station's operation under various discharge conditions.

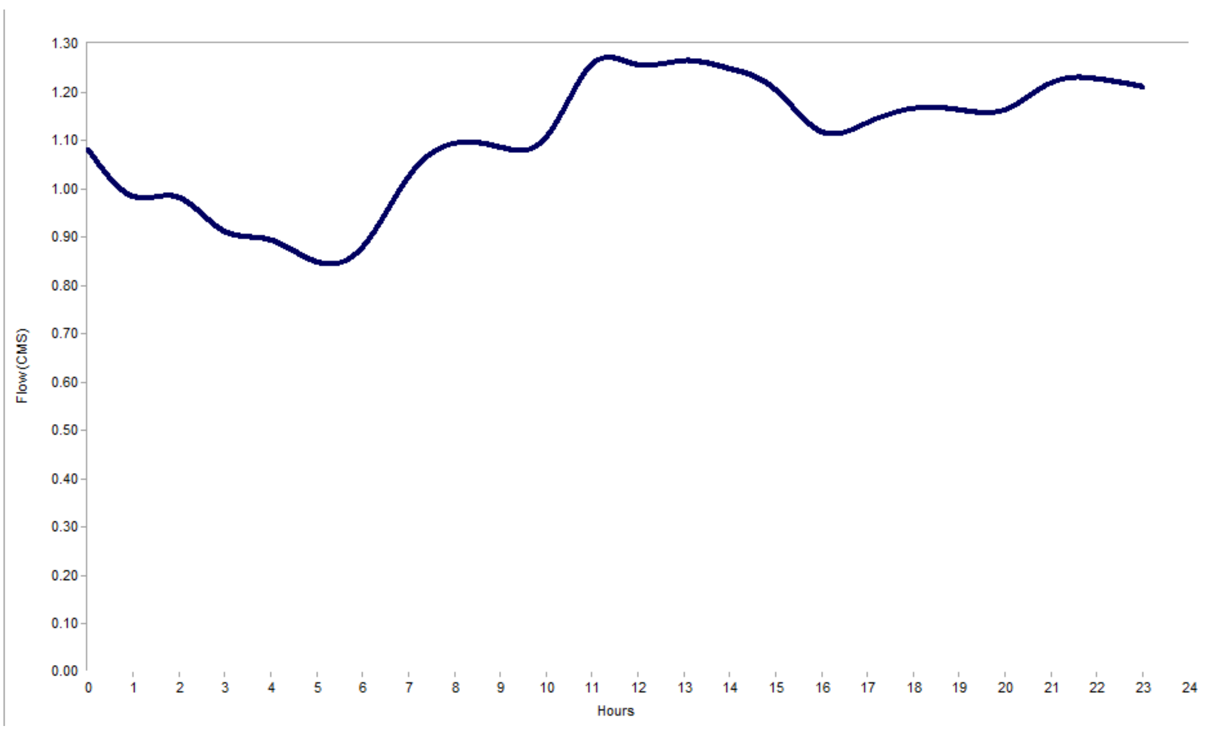

Figure 7. Dry weather flow obtained by SSOAP.

Dry weather flow was simulated using the PCSWMM program, using assumptions based on population water consumption rates, population estimates in different areas, and data from pumping stations. The simulation results showed high agreement with field readings recorded at pumping station P2, as shown in Fig. 8, demonstrating the hydraulic model's accurate representation of actual hourly dry weather flow conditions in the network.

The results of the dry flow analysis showed that the conveying pipe did not face any problems in conveying the daily sewage discharges, as the flow was stable and normal throughout the day. The highest occupancy rate of the pipe's maximum capacity reached 49%, in line 2 at the point of its intersection with line 1(pipe c26), as shown in Fig. 9.

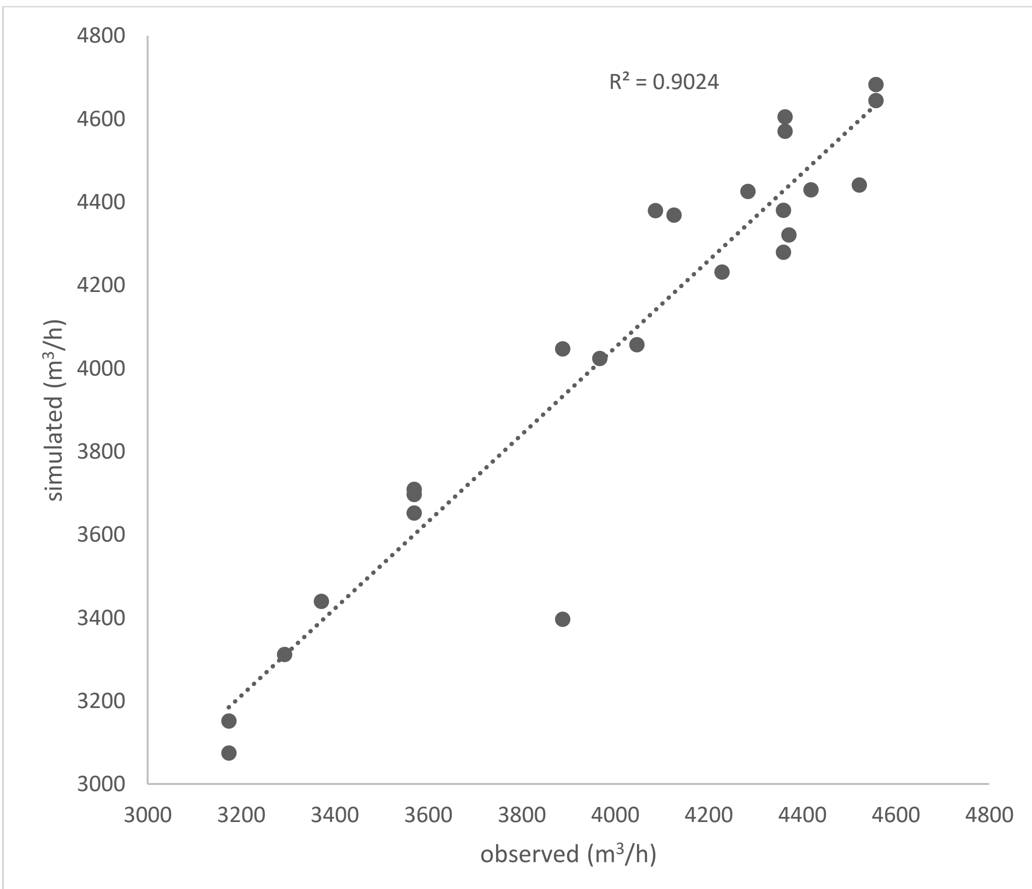

Figure 8. Dry weather flow, simulated vs observed.

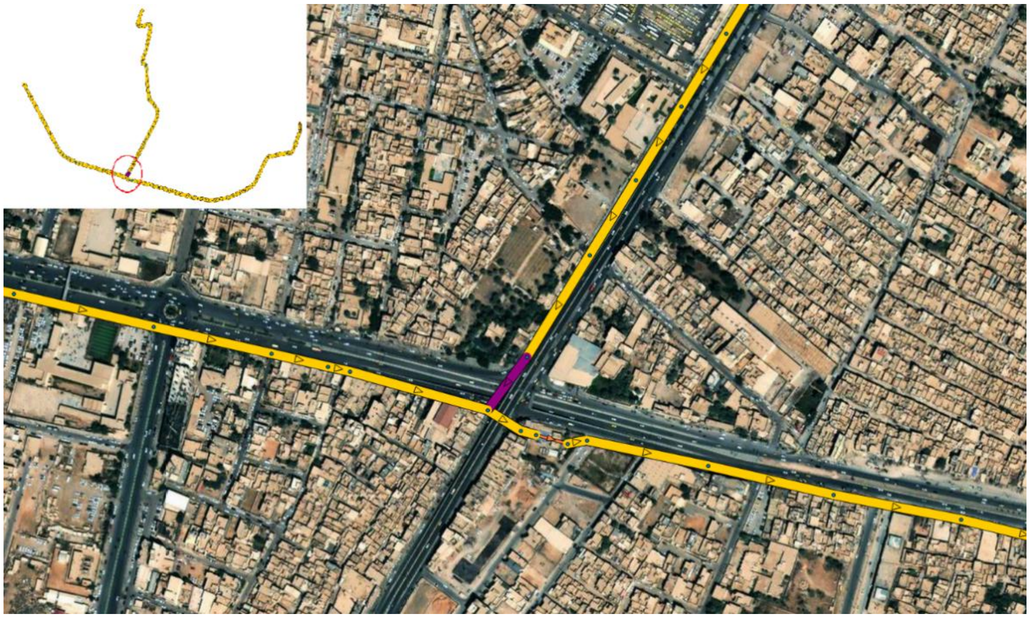

Figure 9. Dry weather flow 49 % capacity pipe C26.

After successfully completing the dry flow simulation in the main pipe, it is possible to input the RTK parameter values derived in the previous analysis phases and then perform a wet flow analysis. This analysis allows studying the pipe's performance under rainfall conditions and evaluating the hydraulic response under rainfall flows.

5.2.Wet weather flow and RDII

The Sanitary Sewer Overflow Analysis and Planning Toolbox (SSOAP) software was used to calibrate the sewer network hydrological model and determine the RTK coefficients (R = surface runoff, T = delay time, K = shape constant). Hourly flow data recorded at the monitoring station over a ten-month period, including five rainfall events, were entered. To validate the calibration, one rainfall event was isolated and not used in the initial calibration set. The model was calibrated by adjusting the shape of the resulting hydrographs to match field runoff readings using the optimization algorithm available in the software (Fig. 10). Where the yellow line represents the simulated RDII and the red line represents the observed RII

After the calibration was completed, the RTK coefficients were extracted, as shown in the following table. These coefficients represent the dynamic characteristics of the rainfall network response within

the study area. The fifth rainfall event (16.75 mm) will be used to verify the simulation results that were conducted by PCSWMM.

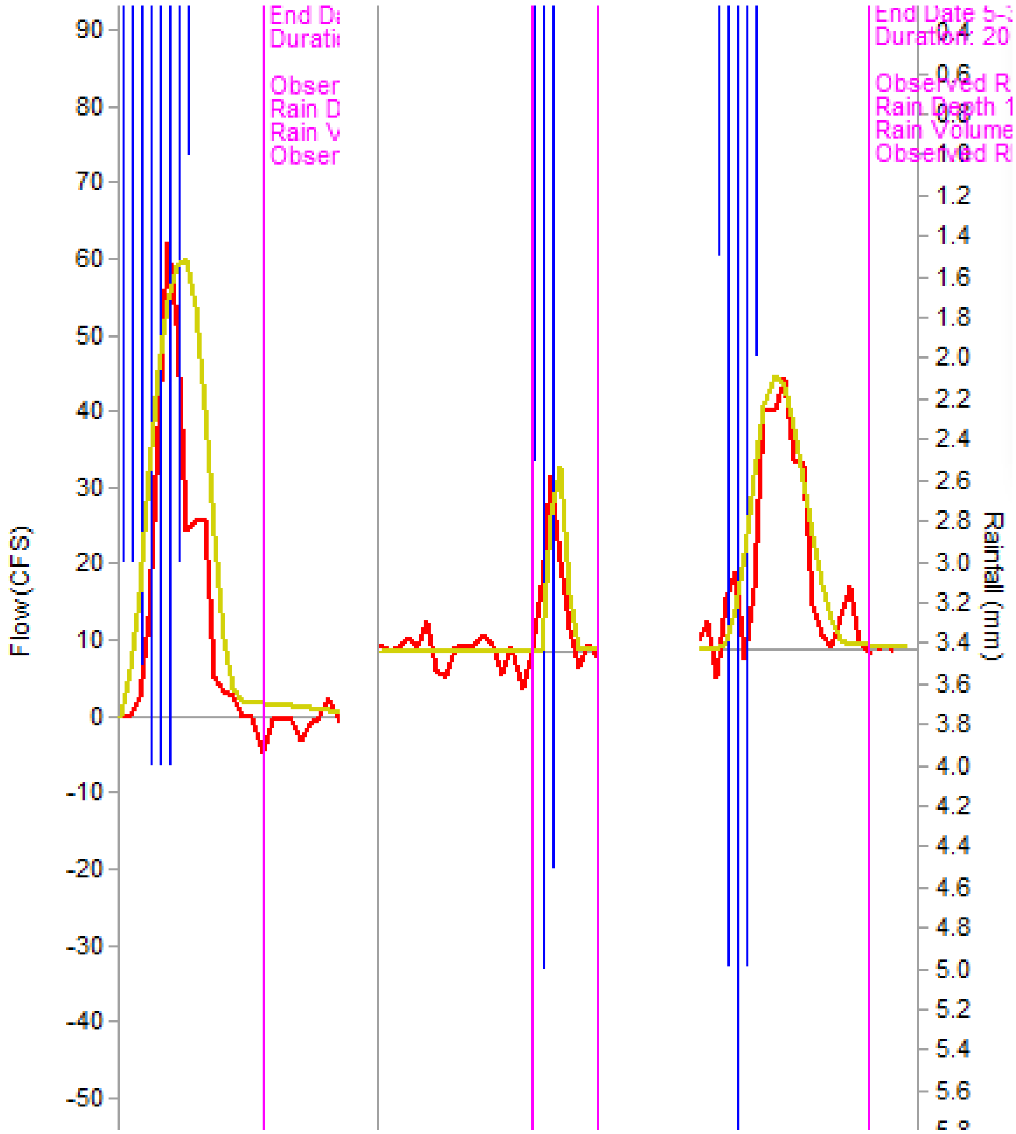

Figure 10. RDII hydrographs calibration in SSOAP.

Table 2. RTK values obtained from SSOAP.

Depth (mm)	**R1**	**R2**	**R3**	**R (total)**	**T1**	**T2**	**T3**	**K1**	**K2**	**K3**
6.4	0.001	0.009	0.002	0.012	1.5	3.5	5	2	2	4
25.2	0.002	0.12	0.01	0.132	1	3	5	0.5	1	4
12	0.002	0.035	0.002	0.039	0.5	2	5	2	2	3
19.6	0.003	0.075	0.0035	0.0815	2	4	5	1.5	1.5	4

Fig. 11 illustrates the correlation between rainfall depth and overall R value. A linear relationship is evident within the depth range of recorded rainfall events, enabling a reasonable deduction of the value of R within this range. At increased depths of rainfall, the value of R is anticipated to diminish due to the restricted capacity of the pipes and the saturation of the soil with water, which decreases the proportion of water entering the network despite an escalation in rainfall volume. Consequently, the linear relationship

fails to effectively estimate the value of R during severe rainfall events, Therefore, the polynomial equation representing the relationship curve will be adopted to calculate the value of the R ratio for the assumed heavy rainfall in this research, due to its more logical representation in cases of heavy rainfall, since the increase in the total R ratio is not directly proportional to the increase in the total depth of the rainfall event, which more accurately reflects the realistic behavior of heavy rainfall.

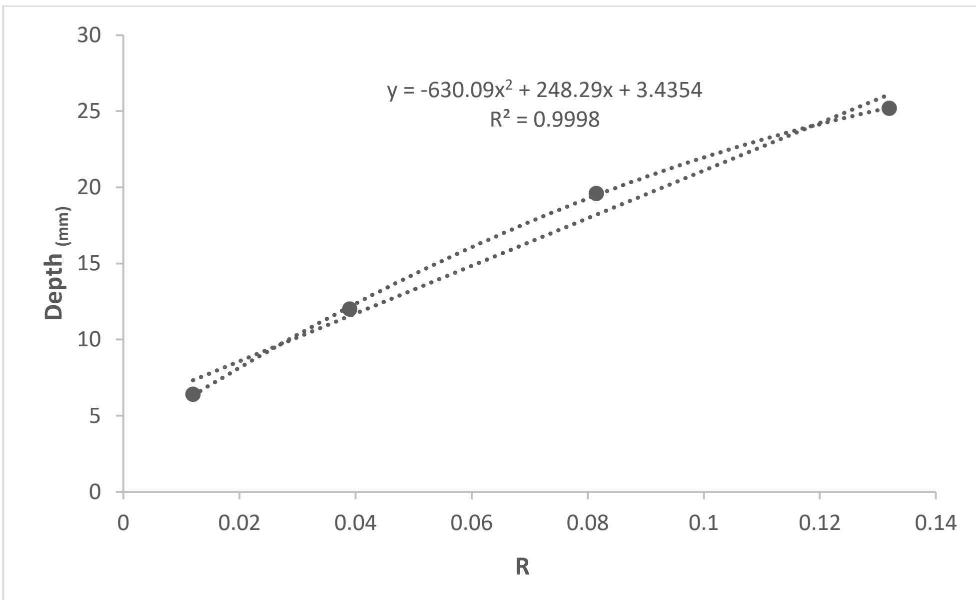

Figure 11. The relationship between rainfall depth and R.

From the prior relationship (Fig. 11) and at the intensity of the fifth rainfall event (16.75mm), the estimated value of R was derived (R = 0.064), followed by a simulation conducted using PCSWMM.

The estimated hourly flow closely aligned with the recorded measurements (Fig. 12), indicating that the PCSWMM model effectively simulated the rainfall event. Consequently, the flow dynamics and the volume of RDII can be assessed at varying rainfall depths for analytical and decision-making purposes.

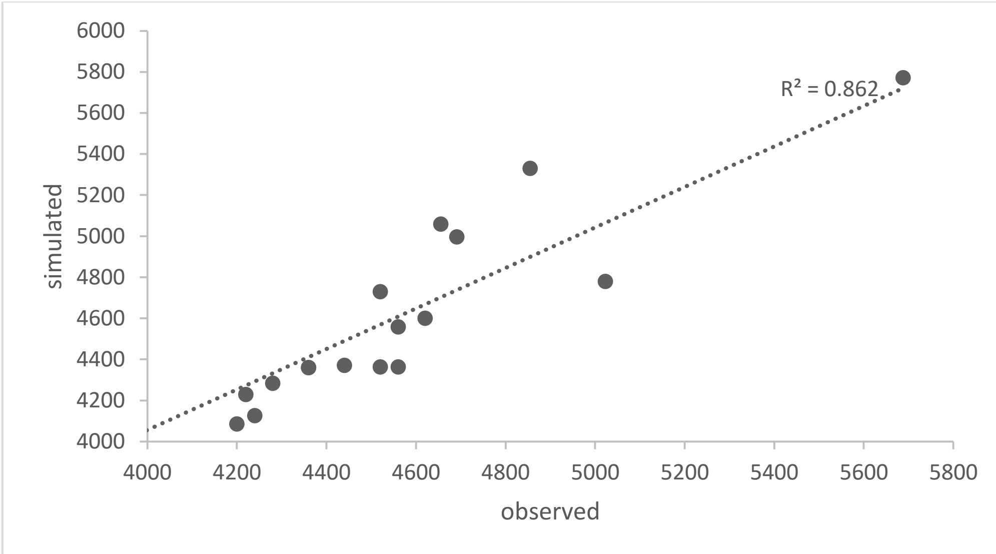

Figure 12. PCSWMM model validation (at P2).

Table 3. Model summary.

Regression Statistics	
Multiple R	0.928437955
R Square	0.861997036
Adjusted R Square	0.855724174
Standard Error	203.1143237
Observations	24

Table 4. The coefficients estimation.

ANOVA					
	df	***SS***	***MS***	***F***	***Significance F***
Regression	1	5669191.7	5669192	137.42	6.22244E-11
Residual	22	907619.4264	41255.43		
Total	23	6576811.126			

	Coefficients	**Standard Error**	**t Stat**	**P-value**	**Lower 95%**	**Upper 95%**	**Lower 95.0%**	**Upper 95.0%**
Intercept	496.8	327.37	1.51	0.143	-182.124	1175.72	-182.12	1175.726
X Variable 1	0.87	0.074	11.72	0.06E-9	0.719	1.02	0.719	1.028639

6. Hydraulic evaluation under the influence of high intensity rainfall

After completing the RTK parameter extraction process using SSOAP, creating the full hydrological and hydraulic model, and verifying the success of the simulation by comparing the results with field readings, moving on to the stage of evaluating the sensitivity and capacity of the main wastewater pipeline in the study area To predict the performance of the network under potential future rainfall conditions, six different rainfall intensities were used, representing scenarios with varying return times up to 100 years. These intensities were generated based on hydrological design data used in the region and were fed into the model to test the network's ability to discharge the resulting flow without flooding or exceeding the pipe's capacity. These rainfall events will be simulated using PCSWMM software, with the temporal distribution of the rainfall event being introduced so that it generates flow synchronous with the peak flow periods in the conveying pipe.

Table 5. Experimental rainfall intensities.

number	Rainfall intensity (mm/h)	Duration (h)
1	10	1
2	15	1
3	20	1
4	25	1
5	30	1
6	40	1

The R values were extracted for each rainfall intensity based on the previously deduced relationship shown in Fig.11 .The values were as shown in the following table.

Table 6. R (The percentage of rainwater entering the sewers)

Rainfall event depth (mm)	R %
10	2.85
15	5.4
20	8.51
25	12.92
30	19.7
40	19.7

The simulation process was conducted using the PCSWMM program after entering all data related to the drainage network and rainfall characteristics. The results were as follows:

Simulation results for the first two rainfall events (10 and 15 mm/h) under the assumed rainfall intensity scenarios indicate that the network is capable of handling the generated flow without any problems related to filling or overflowing of manholes or pipes. The results showed that sewage levels within the network remained below the maximum capacity, and no critical pressure or flow exceedances were recorded Fig. 13, Fig. 14 and Fig. 15.

The results provide a positive indication of the system's performance under normal rainfall conditions or those with short return periods.

Figure 13. The pipe during the 10 (mm/h) and 15(mm/h) events shows no surcharge and no capacity problem.

At 10 mm/h event the max capacity reached in the pipe was 55 % in line 2 while at 15 mm/h event the max capacity was 62%

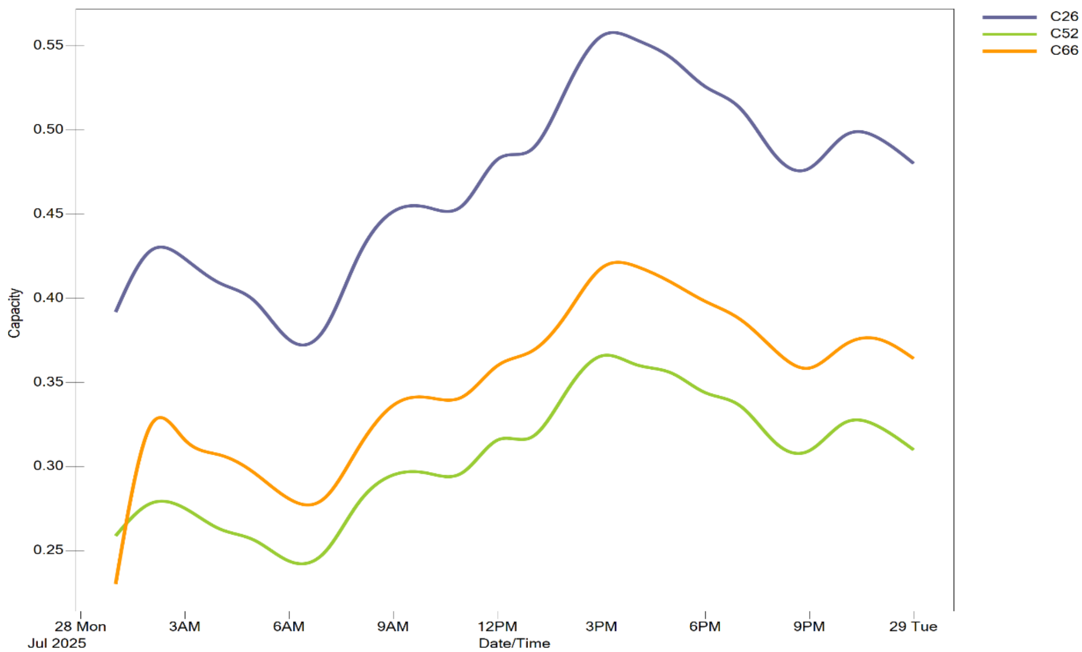

Figure 14. Capacity of the critical pipe on each line during the day under 10 (mm/h) rain event.

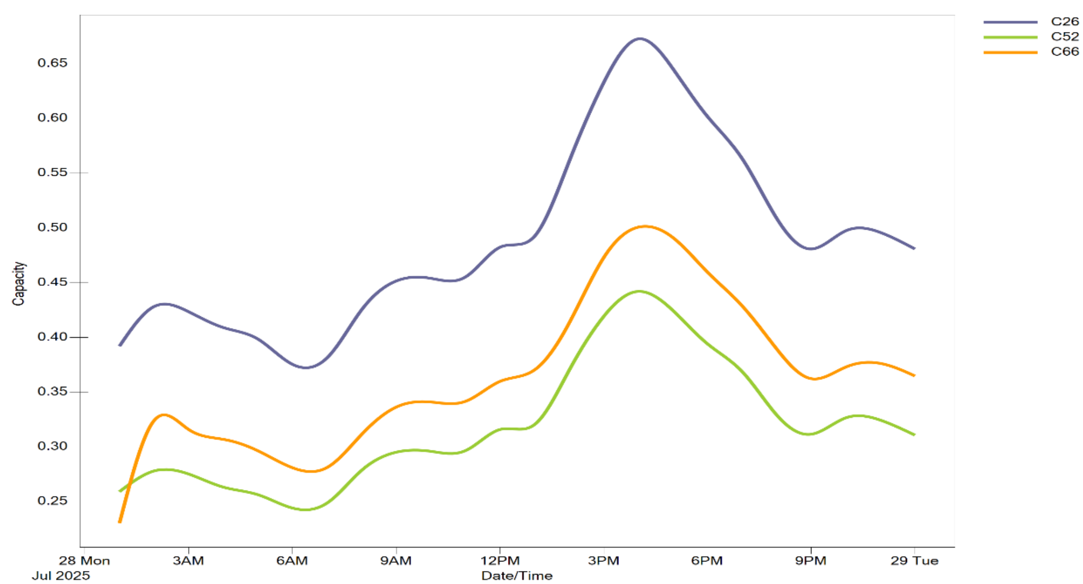

Figure 15. Capacity of the critical pipe on each line during the day under 15 (mm/h) rain event.

During the simulation of the third rainfall event, which had an intensity of 20 mm/h, preliminary signs of the network's hydraulic function being compromised began to surface. high flow depths were recorded in multiple sections, with certain pipelines attaining their full capacity (100%). Nonetheless, no actual flooding was documented in the manholes or on the surface under this scenario.

The significant issues were localized in a particular segment of the network, namely Line 2, at the final pipe preceding the intersection with Line 1 adjacent to the P2 lift station. Data indicated that this portion functioned at full capacity, rendering it a potentially crucial site of impact in the case of increased rainfall intensity. This pipe (C26) is considered the bottleneck of the pipe system, as it is constantly exposed to higher hydraulic pressures than the rest of the sections, making it the weakest link in absorbing flows during periods of rainfall and heavy precipitation Fig. 16 and Fig. 17.

Figure 16. C26 pipe reaching 100 % capacity during 20 mm/h rain event.

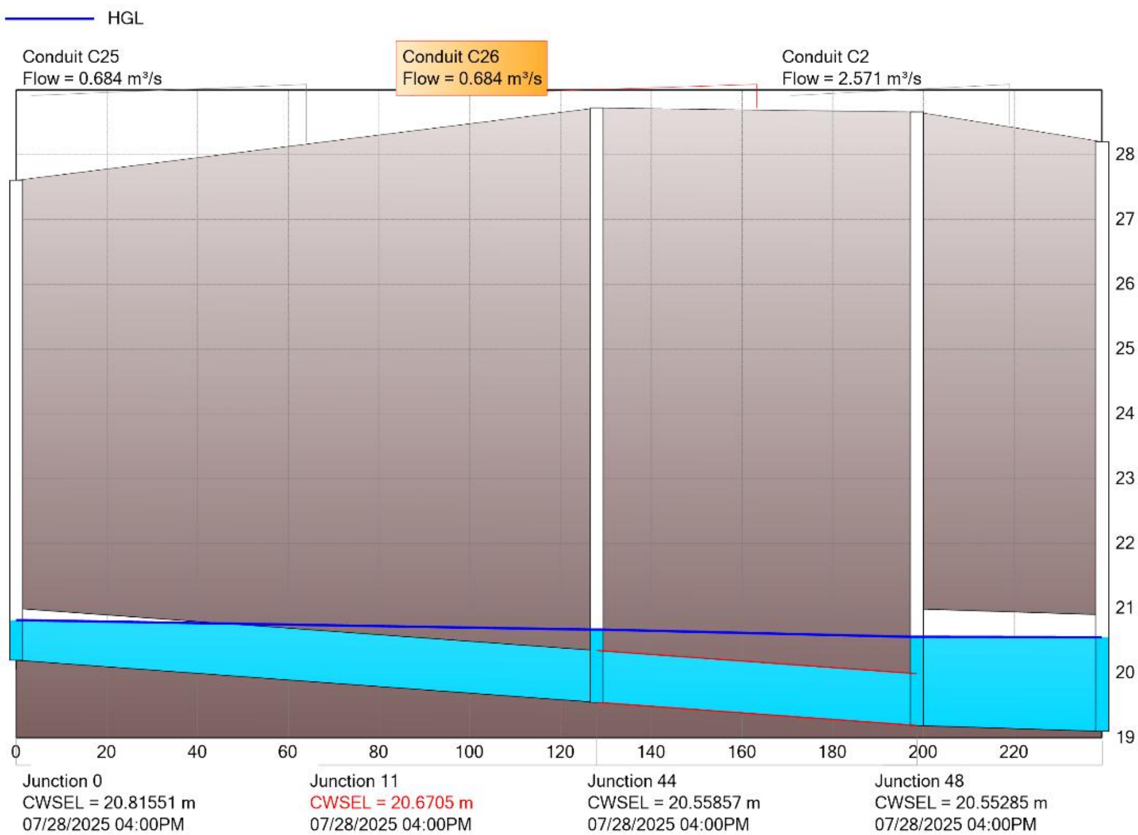

Figure 17 C 26 pipe profile during peak flow.

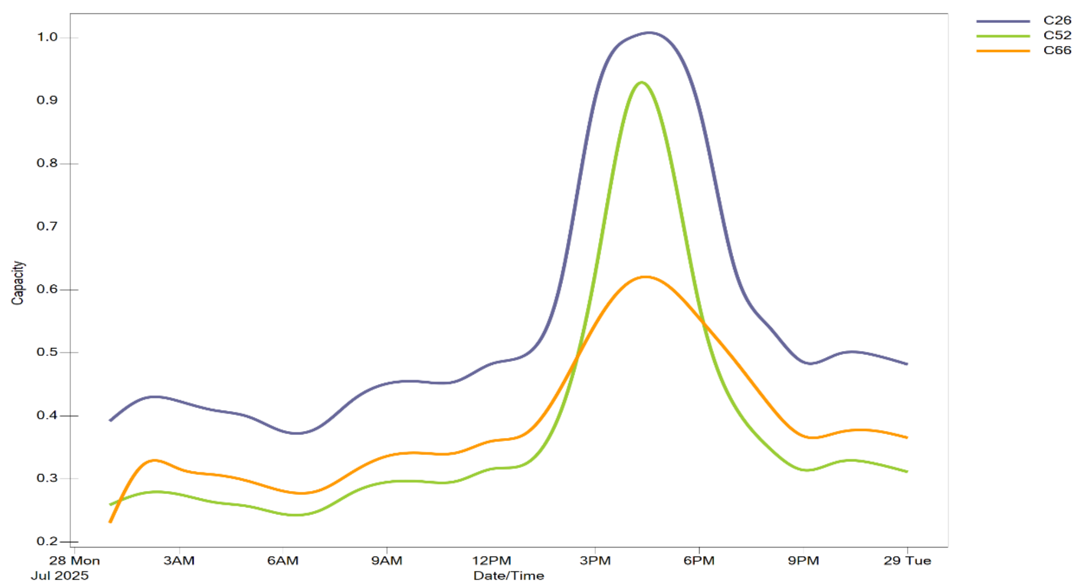

Figure 18. Capacity of critical pipe sections during the day under 20 (mm/h) rain event.

Simulation results for rainfall intensities ranging from 20 mm/h to 24 mm/h exhibited a pattern analogous to that of 20 mm/h rainfall, characterized by heightened vulnerability and suboptimal hydraulic performance. Intense flow persisted, and the lengths of segments attaining their full capacity (100%) expanded. This range of rainfall intensity represents the upper limit of a pipe's capacity to discharge without causing flooding, revealing its limited capacity under extreme rainfall conditions. Thus, a pipe's performance within this range is a direct indicator of its maximum hydraulic capacity and reflects its ability to handle rainfall-generated flows without compromising system function.

At 25 mm/h, the model documented the initial occurrence of flooding, corresponding with the network reaching capacity and failing to accommodate the ensuing flow. The results reveal that 25 mm/h signifies the failure threshold for the existing pipeline, where the design capacity is surpassed and operational issues start to manifest. The results of the hydraulic analysis showed that the two nodes (47) and (92) represent the main suffocation points within the carrier's pipe path, as they together formed the most sensitive foci of the floods Fig. 19. The simulation data indicated that these two nodes contributed to the largest part of the volume of surplus wastewater, which reflects their sensitivity to increase in the upcoming sewage volumes and makes them critical points in the pipeline path. The results also showed that the lines (1) and (2) reached their maximum capacity after the rainy event, and this hydraulic suffocation continued in the two pipes for nearly four hours, indicating the slow discharge of the accumulated water in the network. Fig. 20 and Fig. 21 explain this temporal behavior after the rainy event.

Figure 19. Flooding places (25 mm/h rainfall event).

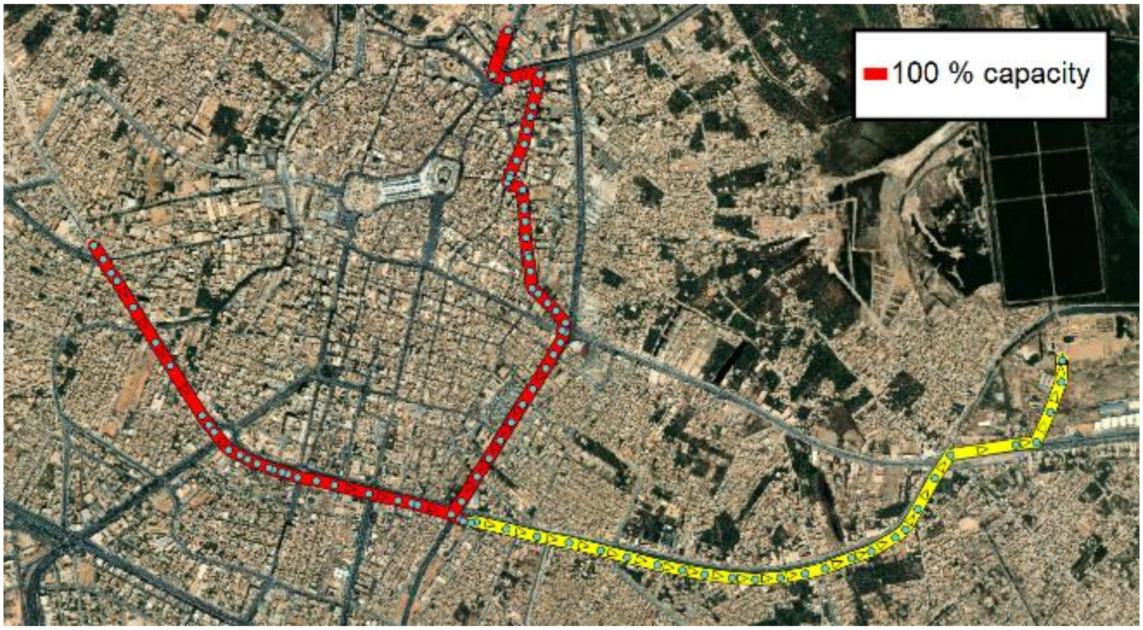

Figure 20. Pipe capacity situation under 25 mm/h rainfall event.

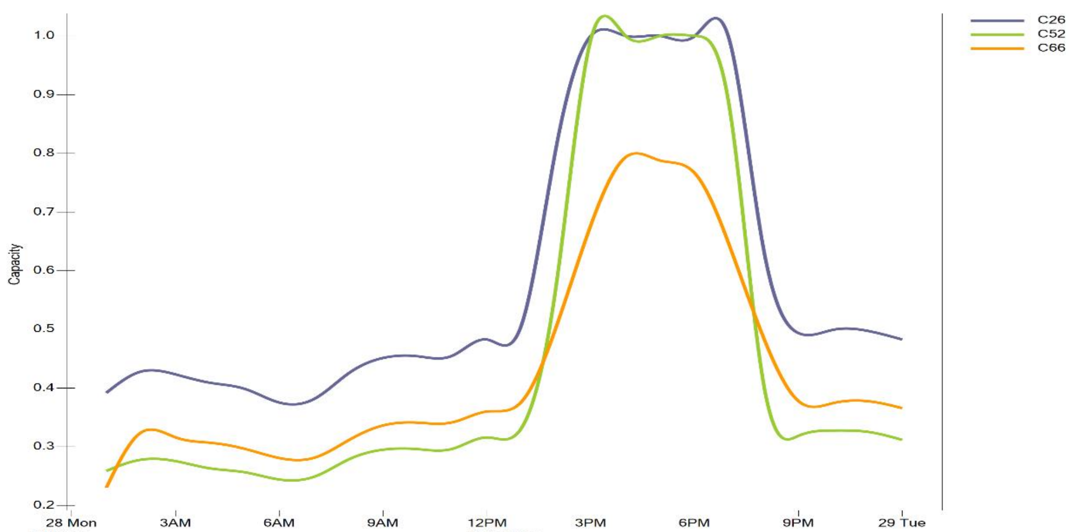

Figure 21 Capacity of all pipe sections during the day under 25 (mm/h) rain event.

When simulating rainfall intensities of 30 mm and 40 mm, the hydraulic condition of the network significantly worsened, with an increase in the number of manholes flooding and an expansion of the affected areas. A significant increase in the volume of wastewater flowing to the surface was also recorded due to the inability of pipes and manholes to accommodate the increasing amounts of wastewater and rainwater.

These results demonstrate that the current network rapidly loses operational efficiency as the intensity of the rainstorm increases, indicating limited capacity to cope with extreme rainfall events. Despite the increase in the number of nodes that witnessed floods, nodes (47) and (92) were the most influenced and sensitive to the high flood, as they were found responsible for the vast percentage of surplus wastewater volumes in the carrier pipe (Fig.22 and Fig. 23).

Figure 22. Flooding places (30 mm/h rainfall event).

Figure 23. Flooding places (40 mm/h rainfall event).

The results also indicated that the pipes in the two lines (1) and (2) reached their maximum capacity, and this situation lasted for more than four hours in the case of the rainy event (30 mm/h), and for more than five hours in the case of the rainy event (40 mm/h), as shown in Fig. 24 and Fig. 25.

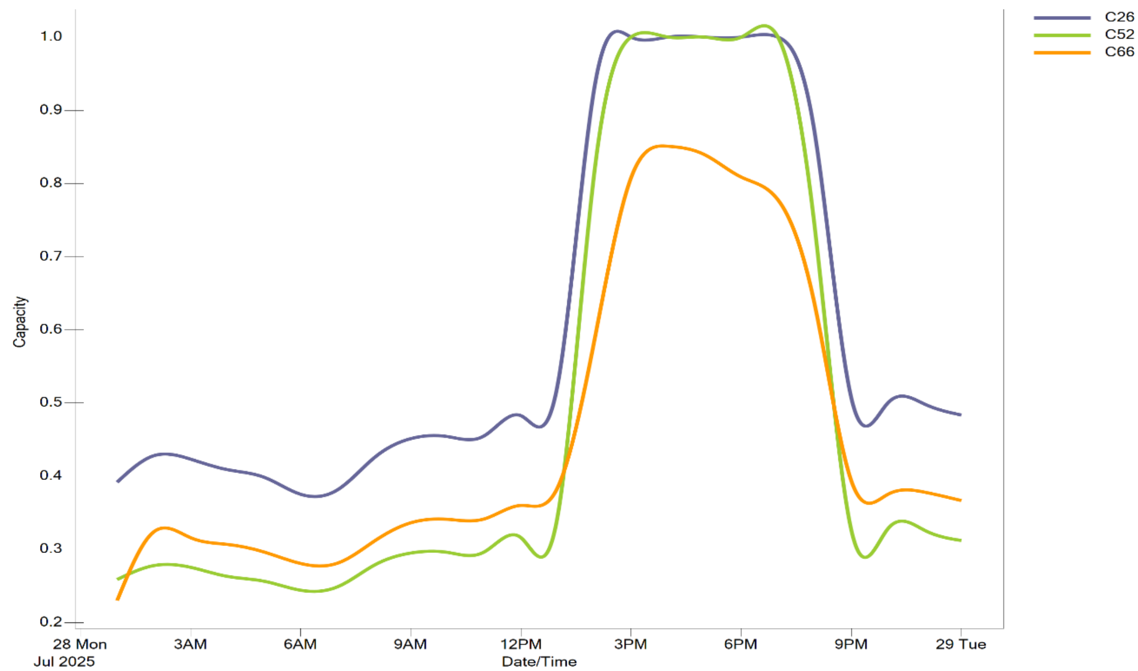

Figure 24 Capacity of all pipe sections during the day under 30 (mm/h) rain event.

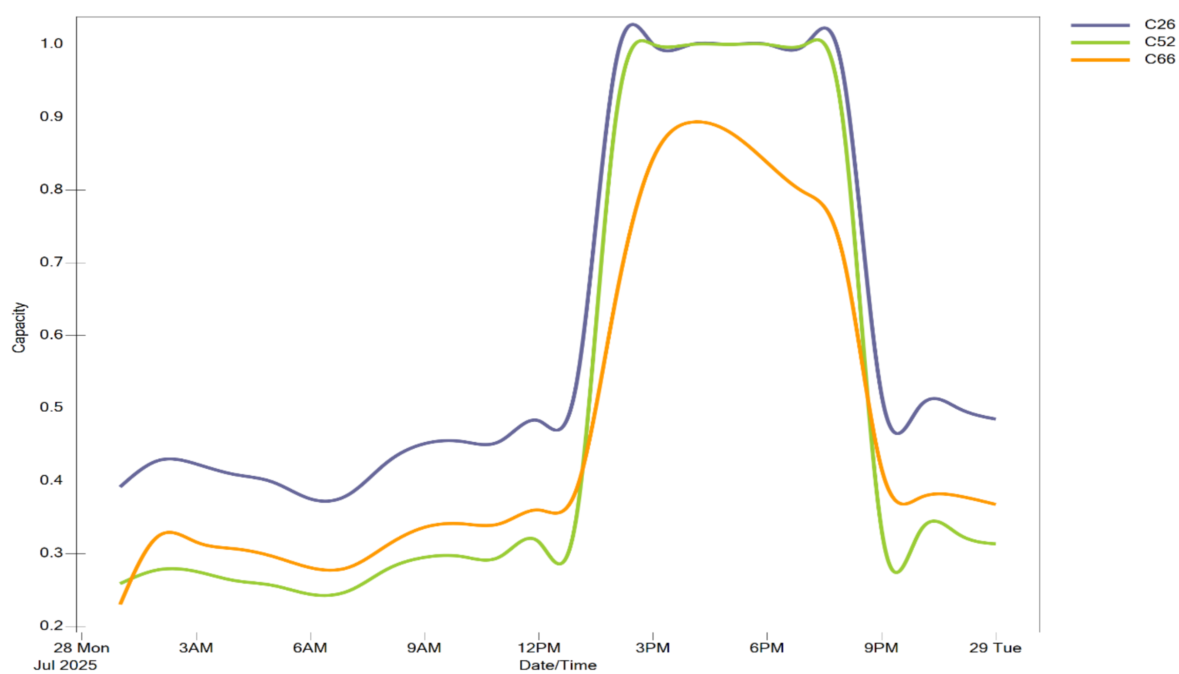

Figure 25 Capacity of all pipe sections during the day under 40 (mm/h) rain event.

The following table shows a summary of the cases of surcharge and floods and their volumes in the nodes and pipes within the carrier line. The data shows that the volume of surplus wastewater increased significantly from 1660 m^3 in the case of the rainy event (25 mm/h) to 25567 m^3 in the event of the event (30 mm/h) and then to 46906 m^3 in the event of the event (40 mm/h). It can be noted that a gradual increase in the number of nodes that witnessed floods of 9 qualities in the event (25 mm/h) to 14 in the event (30 mm/h) and then to 18 in the event (40 mm/h).

Table 7 Surcharge and overflow statistics for the main conveyance line.

Rainfall intensity (mm/h)	Flood volume (m^3)	No of flooded nodes	No of surcharged nodes	No of surcharged pipes
10	0	0	0	0
15	0	0	0	0
20	0	0	2	16
25	1660	9	71	71
30	25567	14	71	71
40	46906	18	72	82

7. Conclusion

Based on the analysis of the results extracted from the current research, the following can be concluded:

- The model used in the simulation by PCSWMM, with the help of RTK elements extracted from SSOAP, has proven its efficiency in representing both dry and wet flow with acceptable accuracy, which makes it able to predict hydraulic behavior under the influence of other heavy rain events that fall outside the range of recorded data.
- Simulation results indicate that rainfall intensity between 20 and 24 mm/h represents the hydraulic threshold at which the pipe reaches its maximum capacity. Exceeding this threshold leads to flooding due to the pipe's inability to discharge the additional flow.
- When rainfall intensity exceeds 24 mm/h, the pipe begins to flood. Simulations showed that at 25 mm/h, the excess discharge volume reached approximately 1660 m^3, increasing to nearly 15-fold at 30 mm/h, and then jumping to approximately 28-fold at 40 mm/h. This reflects the high sensitivity of the hydraulic system to increased rainfall intensity after exceeding the critical threshold.
- The results showed that Pipe C26, located on Line 2 near its intersection with Line 1, is the most sensitive to increased discharge volumes, making it the network's main weak point. Node 47 on Line 2 and Node 92 on Line 1 were also found to be the most vulnerable to flooding due to increased discharge volumes, necessitating a focus on these locations in future treatment and improvement plans.

- The results of the assessment of the pipe's capacity under the influence of rain highlight the importance of this study, particularly as the rainy season coincides with the religious gatherings season for millions of pilgrims in Karbala city after five years, and this synchronization will continue for years to come. The additional pressure resulting from the significant increase in hydraulic loads during these periods reduces the network's capacity to absorb rainwater, increasing the likelihood of flooding.
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Declaration of generative AI and AI-assisted technologies in the writing process

-None

Disclosures

The authors have no conflicts of interest to declare in relation to this manuscript.

Abbreviations

The following abbreviations are used in this manuscript:

SSOAP	Sanitary Sewer Overflow Analysis and Planning
PCSWMM	Personal Computer Storm Water Management Model
RDII	Rainfall-Derived Infiltration and Inflow
GIS	Geographic Information System

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تحليل حساسية أنبوب الصرف الصحي الرئيسي في مركز مدينة كربلاء لأحداث الأمطار الغزيرة

الخلاصة: تُعدّ شبكة الصرف الصحي إحدى الركائز الأساسية للبنية التحتية الحضرية. إلا أنها تواجه تحديات متزايدة نتيجة لتقادم مكوناتها، والتوسع العمراني السريع، وتغير المناخ، وارتفاع معدلات الاستهلاك. ويُعدّ تسرب مياه الأمطار من أبرز المشكلات التي تؤثر سلبًا على كفاءة هذه الشبكات، مما يُسهم بشكل كبير في فيضانات مياه الصرف الصحي وما يترتب عليها من آثار بيئية وصحية خطيرة. ركّز البحث الحالي على تحليل حساسية خط أنابيب الصرف الصحي الرئيسي في قلب مدينة كربلاء بالعراق. تستقبل هذه المدينة ذات الأهمية الدينية والسياحية العالمية ملايين الحجاج سنويًا في فترة وجيزة، مما يُشكّل ضغطًا كبيرًا على شبكة الصرف الصحي. ولتحقيق ذلك، تم تحليل بيانات التصريف وهطول الأمطار المسجلة باستخدام برنامج تحليل وتخطيط فيضانات الصرف الصحي (SSOAP)، بالإضافة إلى محاكاة شاملة للجريان باستخدام نموذج إدارة مياه الأمطار الحاسوبي الشخصي (PCSWMM)لتقييم الأداء الهيدروليكي لخط الأنابيب في ظل ظروف الأمطار الغزيرة وتحديد مناطق الضعف المحتملة. أظهرت نتائج التحليل أن شدة هطول الأمطار التي تتراوح من 20ملم/ساعة إلى 24ملم/ساعة تمثل الحد الأعلى لسعة الأنبوب، حيث يشير هطول الأمطار بمعدل 25 ملم/ساعة إلى عتبة الفشل لخط الأنابيب الحالي.

الكلمات المفتاحية: الصرف الصحي، مياه الأمطار، التسرب، التدفق الداخلي، السعة.