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Research Article

Evaluation of the Capacity of Main Sewage Pipeline in The Center of Karbala City Under the Impact of The Rainfall Derived Infiltration and Inflow (RDII)

Ali N. Ghulam[1]*, Basim K. Nile[2], Jabbar H. Al-Baidhani[3]

[1]University of Kerbala, Kerbala, Iraq
* **Corresponding Author Email:** ali.nasir@s.uokerbala.edu.iq - **ORCID:** 0000-0002-5245-7851

[2]University of Kerbala, Kerbala, Iraq
Email: basimnile@yahoo.com - **ORCID**: 0000-0002-5245-7852

[3]University of Al-Nahrain, Baghdad, Iraq
Email: jabbaralbaidhani@yahoo.com - **ORCID:** 0000-0002-5245-7853

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Abstract:

The sanitary sewer network is one of the most important pillars of infrastructure and is affected by many variables today. The aging of the network, increasing urbanization, climate change and high consumption all lead to a continuous challenge to the operation and efficiency of the network. One of the most important problems facing sewage networks is the Rainfall Derived Infiltration and Inflow (RDII), which is one of the main causes of sewer overflows with the negative repercussions it causes to health and the environment. The current research focused on evaluating the effect of the RDII on the capacity of the main sewage pipe in the center of Karbala city in Iraq, that receives millions of pilgrims annually during a short period of time during which the sewage network is under high consumption pressure. recorded data of discharge and rainfall were analyzed using the SSOAP and PCSWMM software. The analysis results showed that high levels of RDII entered the network during a rainfall depth of 25 mm, which led to an increase in maximum hourly discharge to 86%, an increase in total daily discharge to 21.5% and the capacity of the main pipe in the critical area reached 91%.

1. Introduction

The sanitary sewer network is considered one of the most important parts of the infrastructure of cities, as it transports sewage generated from residential, commercial, industrial and health facilities through pipes to treatment and disposal sites. Therefore, maintaining the effectiveness and sustainability of the network is essential to avoid problems and inconvenient consequences that occur during its operation [1,2,3]. In recent years, increased consumption, urbanization and climate change have expanded pressure on these networks. Studies indicate that climate extremes lead to increased incidence of heavy rains and high intensity rain of short duration, which directly affect the performance of sewage networks, their capacity and treatment efficiency[4-8]. With the old age of these networks in most cities and the problems that exist in them during their implementation and after operation in terms of fractures, cracks, openings and faulty fitting and connections, this increases their sensitivity and exposure to problems that occur due to operating pressure. One of the most important reasons that lead to congestion and flooding in the sewage network is the Rainfall derived infiltration and inflow (RDII)[9], [10]. Where (RDII) can be defined as the part of a rainstorm that enters the sewer network. This is done in two parts: either directly into the network through manhole openings, fractures and other defects, which happens quickly during the rainfall event, or it enters later in the form of infiltration from the saturated soil into the network, which is slower and takes a longer time and continues even after the rainfall event ends[11]. The amount of precipitation entering the network depends on many factors such as the type of soil, the condition of the network, its age, rainfall intensity, type of land use and other factors that makes it difficult to determine and estimate the amount of RDII. This sudden increase in flow may lead to congestion in the network or flooding of manholes, which causes pollution and damages the health of people[12].

The sewerage system becomes under critical pressure resulting from this sudden increase in the flow where it affects the capacity of treatment plant and increases the cost of the treatment process in addition to that, the incoming water, whether from the ground surface or from the soil, may carry debris that may negatively affect the network pipes and pumps in the lifting stations[13]. The chances of network flooding increase significantly when the network flow is affected by a sudden large change in population, as is the case in the study area of this research. The city of Karbala is one of the most important cities in Iraq and it is a destination for millions of pilgrims annually to perform religious rituals. Millions of pilgrims gather in Karbala during a short period time of no more than two weeks. The total number of pilgrims arriving in the city during this short period exceeds 21 million, which is more than 40 times the total population of the city[14]. This sudden and large increase in population leads to a significant increase in the amount of wastewater generated and poses a major challenge to the wastewater network and the rest of the sewerage system. In addition, the timing of this gathering may coincide with the rainy season, putting more load to the sewer network that leads to flooding in the sewage network and threatens the health of the population, as happened in previous years[15]. Therefore, it is necessary to study the RDII in sanitary sewer network in the center of Karbala city in order to try to understand the extent of its impact on the network capacity and to clarify the vision to avoid problems and pave the way for future solutions. Researchers have used many methods to study RDII to estimate its quantity and impact [16-18]. One of the tools used is Sanitary Sewer Overflow Analysis and Planning (SSOAP), which is a computer software that can analyze recorded data to estimate the amount of RDII. This software receives data of sewer shed areas, discharges and rainfall as inputs over time and analyzes them, allowing the separation and finding of dry weather flow and wet weather flow, as well as the possibility of separation and estimating of RDII. SSOAP tool is characterized by a simple interface with ease of use and dealing with data. SSOAP uses the synthetic unit hydrograph method (SUH) which presupposes that RDII in sewer responding to rainfall is similar to stormwater runoff in a watershed[17,19]. One of the most commonly used (SUH) methods for determining the RDII is the RTK method, which uses three triangular unit hydrographs to represent the stages and parts of the RDII. These unit hydrographs are calibrated visually within the software to achieve a close representation to RDII and finding the RTK elements that can be used in other relevant sewer network analyzing software. SSOAP has been used by many researchers in the past, the results have been useful and reasonably accurate[9], [16]. Analyzing the behavior and performance of the network under the influence of the RDII is a necessary step to understand its amount and mechanism of its impact and to identify the areas of weakness and danger. PCSWMM software is considered one of the important tools in this field, where PCSWMM is a modeling software that analyzes and manages urban storm water and wastewater networks, it uses SWMM modeling but with more user-friendly experience and more features and tools that makes it more efficient and easier to use. One major advantage to PCSWMM compared to SWMM that it integrates with GIS data makes it more convenient and saves time[20], [21,22]. By employing PCSWMM, the sewer network can be analyzed under different conditions and RDII can be represented by entering the RTK elements and rainfall data into the program.

The aim of this research is to evaluate the effect of the RDII on the capacity of the main sewer pipeline carrying sewage inside the center of Karbala city and try to determine a relationship between of rainfall event depth and the amount of RDII in the sewer system.

Case study area

The case study area is the center of Karbala city in Iraq, which contains separated sewer system Covering an area of 1270 hectares and serves more than (200,000) citizens. The diameters of the main sanitary sewer pipeline in the study area range from 600, 800, 1000, 1400, 1500, and 1800mm. The region is of great importance as it contains sacred religious shrines and receives millions of pilgrims to the shrines during the annual gatherings period, which makes the performance of the sewer network in this region in critical condition trying to cover the sudden increased volumes of generated sewage. Last year, the city received more than 21 million pilgrims in a period of less than two weeks. This number is approximately 40 times the total population of the city, and the concentration of these numbers in the city center puts the sewerage system in a critical condition. The coincidence of these religious occasions with the rainy season is dangerous, as the network is exposed to a sudden increase in sewage generated by pilgrims, as well as the volume of rainwater flowing into the network. Some parts of this network are old and date back to the 1970s, which makes them vulnerable to leakage and other defects, in addition to the presence of some random connection points between the rainstorm and sanitary sewer networks. Therefore, studying the performance of the main sewer pipeline under the impact of RDII is necessary to understand its behavior and evaluate its capacity during different rainstorm conditions.

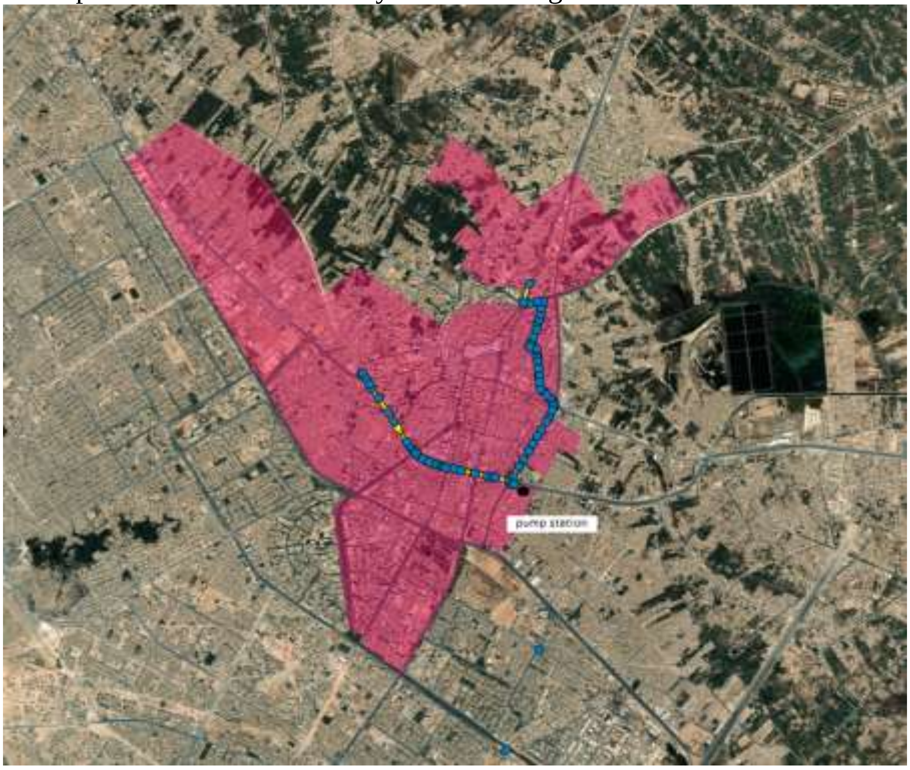

Figure 1. *study area, center of Karbala, Iraq*

2. Data collection

The flow data in the main sewage pipeline to the city center is recorded using a flow meter at the main lift station that lifts the sewage to the disposal site Fig (1). Given that the area is under continuous development and there is not much historical data available, the analysis method depends on the stability of the physical elements of the network to give consistent and relevant results. Data were recorded for 10 months, including the rainy season and normal dry season. Where The climate of the region is dry most of the year.

Five rainfall events were recorded during the rainy season, with the help of information from the Meteorological Department in Karbala. the rainfall events depths were 6.4 mm, 12 mm, 16.8 mm, 19.6 mm and 25.2 mm.

Data of the main pipeline, pipe diameters, manholes, and elevations were collected with the assistance of the Karbala sanitary Directorate.

Other data like maps, areas, population distributions, land uses and GIS were collected with the help of the Karbala Governorate.

SSOAP and PCSWMM analysis

Sanitary Sewer Overflow Analysis and Planning (SSOAP) Toolbox is a 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 (Fig 2) to estimate the fast, medium, and slow RDII responses. 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 RDII volumes of three-unit hydrographs are designated as R1, R2, and R3. A high R1 value indicates that the RDII is primarily inflow driven

After entering all data related to the study area in terms of areas and pipe lengths, as well as the recorded data for flow and rainfall during the study period, the program separates the dry flow and determines the wet flow, and for each event, the amount of the infiltrated rain are simulated and can be estimated.

This allows the possibility of finding a relationship between the depth of the rainfall event and the amount of RDII, which would enable the prediction of the amount of RDII for the depths of other rainfall events that did not occur. In order to verify the results obtained and to analyze the performance of the main pipeline, the data and results obtained from SSOAP are taken to

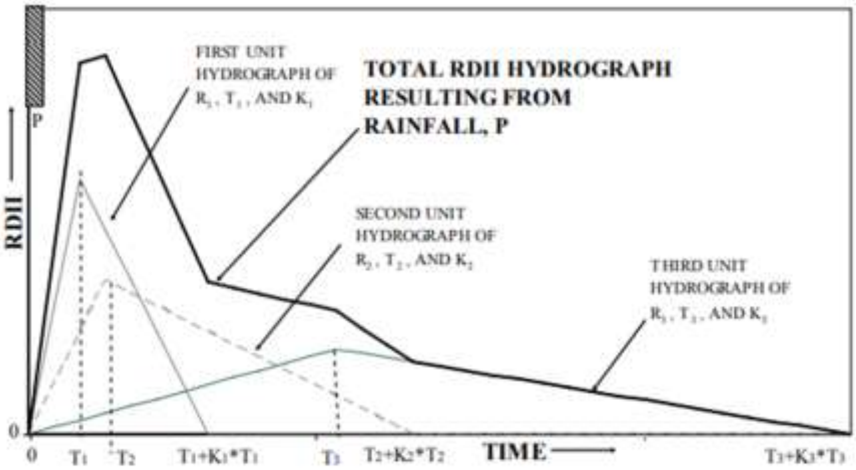

Figure 2. *the RTK method elements*

the PCSWMM software and simulation is conducted.

PCSWMM (PC Stormwater Management Model) is a software application used for modeling stormwater systems and analyzing the behavior of urban drainage systems. It is based on the SWMM (Storm Water Management Model) developed by the U.S. Environmental Protection Agency (EPA)

Utilizing PCSWMM, the flow in the main pipeline is simulated for rain events days and its impact is evaluated and compared to the normal daily flow. Moreover, the results of the relationship between the total R (R1+R2+R3) and the depth of rainfall events are verified using PCSWMM software simulation

3. Results and discussion

Dry weather flow analysis

Base dry weather flow was determined by using SSOAP toolbox analyzing the recorded dry weather flow data of 10 months the average flow is shown in (Fig 3)

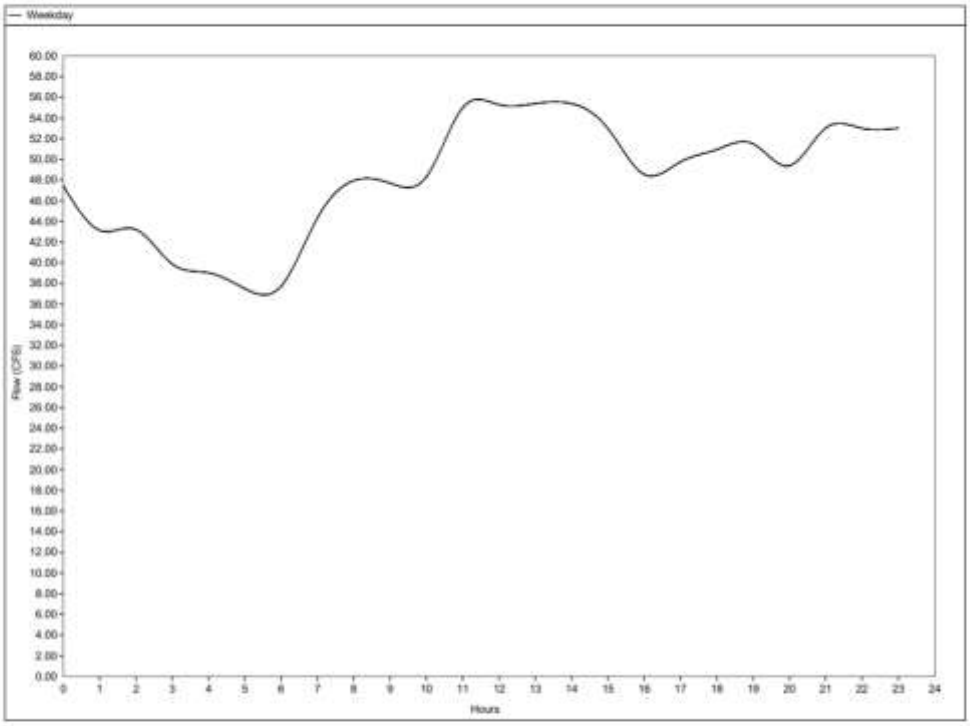

Figure 3. *base dry weather flow obtained by SSOAP*

The daily flow volume in the pump station were about 120 000 m^3 which is more than 70% greater than what was recorded at the same station 10 years ago, this increase demonstrates the need to study the capacity of the main pipelines due to population growth and increased consumption over time.The dry flow is simulated in PCSWMM where the model can receive rainfall data and RTK values obtained from SSOAP to simulate rainstorm events.

Wet weather flow and RDII

After separating the dry weather flow hydrograph, the amount of RDII for each rainfall event is found by subtracting the wet weather flow hydrograph from the dry one and finding a new hydrograph that simulates this process, through which the values of RTK are determined (Fig 4).

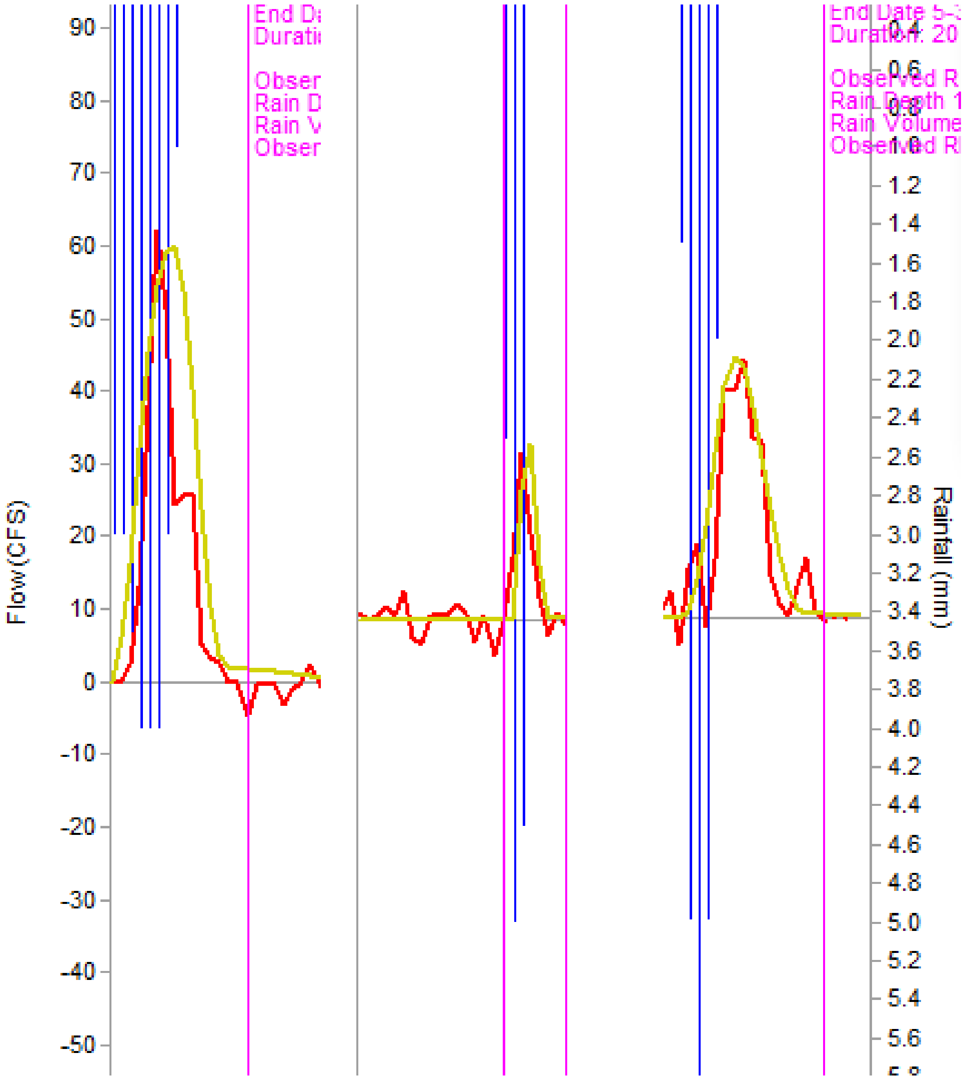

Figure 4. *RDII hydrographs calibration in SSOAP*

Table 1. *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

Where the yellow line represents the simulated RDII and the red line represents the observed RII

The table below shows the RTK values obtained from SSOAP for four of the five most recent rainfall events that occurred during the study period. RTK values can be used to form a relationship between the total amount of RDII (R) and the depth of the rainfall event. The fifth rainfall event (16.8mm) will be used to verify the results of the prediction of total R value that have been estimated by that relationship as well as verifying the simulation results that conducted by PCSWMM.

Due to the large study area associated with a single flow measurement unit, it is difficult to determine the flow phases, but in all rain events there was a sudden increase in flow and then a rapid decline in flow to return to normal base flow. This indicates that the main factor for the increase is the direct inflow to the network, and it can be attributed to several factors, the most important of which is the nature of the residential building structures in the area, as these buildings contain flat roofs and some of them have drainage of rainwater collected on them connected to sanitary sewer and not the stormwater network. Another factor is the opening of manhole covers by residents during heavy rains, which leads to an increase in the entry of rainwater into the sewer network. In addition to the presence of random connections at some points between the two networks (sewage and stormwater) at some points, besides other factors such as the old age of some parts of the network.

Fig 5. shows the relationship between the depth of rainfall and total R value. It can be observed that there is a linear relationship within the depth range of recorded rainfall events, which allows us to reasonably deduce the value of R that falls within this range. However, at greater depths of rainfall, it is expected that the value of the R will decrease due to the limited capacity of the pipes and the saturation of the soil with water, which reduces the percentage of water entering the network even with an increase in the amount of rainfall. Therefore, the linear relationship does not succeed in estimating the value of the R for heavy rainfall events accurately but can be initially used to assess the sewer main pipe capacity.

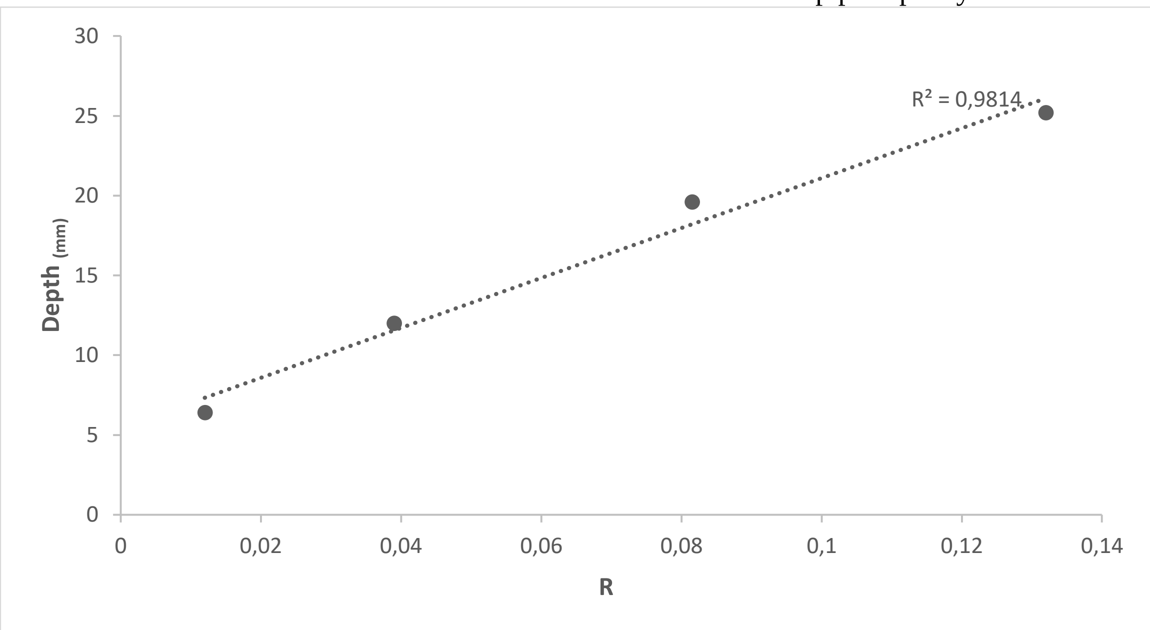

Figure 5. *The relationship between rainfall depth and R*

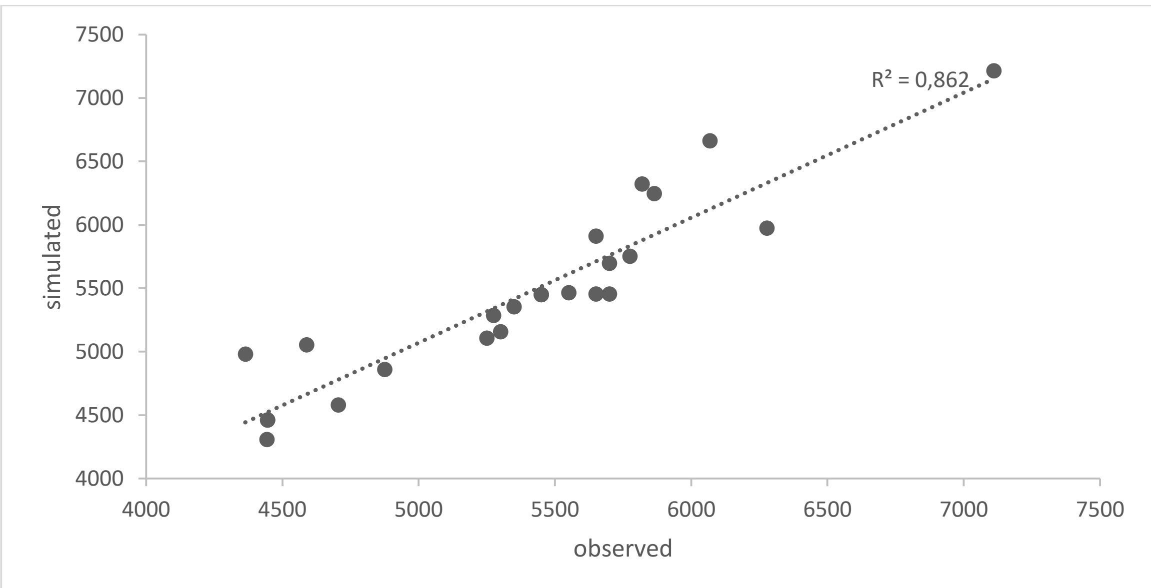

Figure 6. *PCSWMM model validation*

***Table 2**. model summary*

Regression Statistics	
Multiple R	0.928437955
R Square	0.861997036
Adjusted R Square	0.855724174
Standard Error	253.8929047
Observations	24

***Table 3.** the coefficients estimation*

ANOVA					
	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	8858112.03	8858112.03	137.4168662	6.22244E-11
Residual	22	1418155.355	64461.60705		
Total	23	10276267.39			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	621.00	409.21	1.51	0.14	-227.65	1469.65	-227.65	1469.65
simulated	0.8740	0.0745	11.7224	6.22E-11	0.7193	1.0286	0.7193	1.02866

Through the previous relationship and at the depth of the fifth rain (16.8mm), the estimated value of the R was extracted and then a simulation was made using the PCSWMM, where the estimated hourly flow was close to the recorded readings (Fig 6), as the model in PCSWMM succeeded in simulating the rain event, and thus the flow behavior and the amount of RDII can be estimated at different rainfall depths for the purpose of study and decision-making.

Hydraulic evaluation

The simulation of the flow in the network was carried out using PCSWMM, which allows the entry of the RTK values obtained from the SSOAP toolbox. The simulation was carried out for each rainfall event with its RTK values, and the results showed that the network was able to accommodate all rainfall events without flooding or filling. But it gave an excellent idea of the impact on the main pipeline performance during these rain events. (Fig 7) shows the extent of the impact of each rainfall event on the total daily volume of wastewater compared to the total daily volume of the normal dry flow.

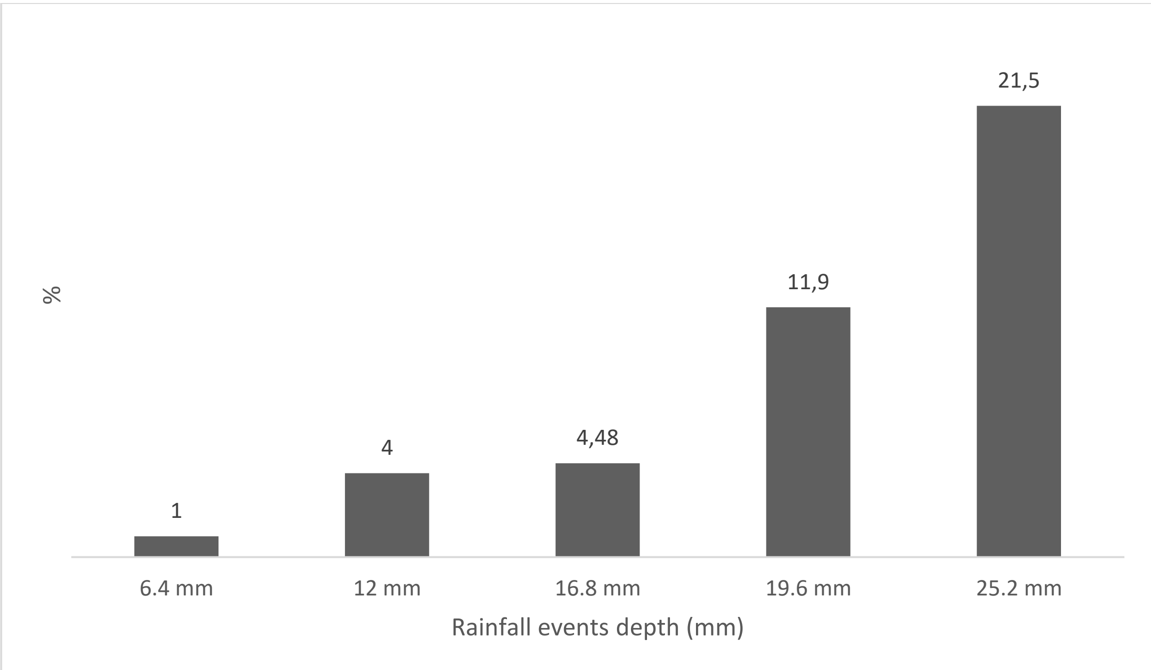

***Figure** 7. the increase in total daily volume of wastewater due to RDII (%)*

Rain events of depths (6, 12 and 16.8 mm) resulted in a slight increase in the total volume of wastewater. While, at a rainfall depth of 25 mm, the total volume of wastewater increased by 21.5 %. This is a large and significant percentage that could affect the main pipeline and treatment plant and its capacity, especially if the rainfall event coincides with days of religious gatherings of millions of people, where the daily volume of wastewater will be already increased under the influence of the large numbers of people.

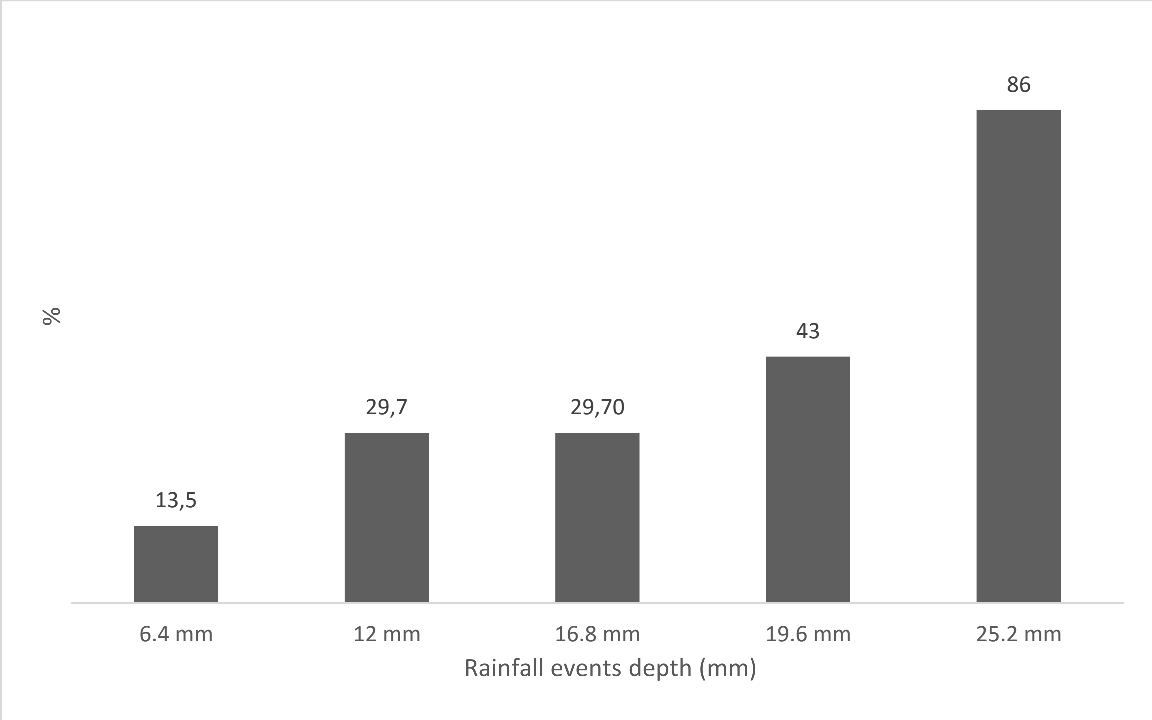

Figure 8. *the increase in maximum hourly flow (%)*

Figure 9. *C_{24}, C_{25}, C_{26} pipe's location*

Table 4. Hydraulic information of C1 pipe

Rainfall depth (mm)	Max capacity	Min capacity	Max dept (m)	Min dept (m)	Max flow m^3/s	Min flow m^3/s
DWF	0.56	0.43	0.44	0.36	0.37	0.26
6.4	0.61	0.43	0.47	0.36	0.42	0.26
12	0.68	0.43	0.51	0.36	0.48	0.26
16.8	0.68	0.46	0.51	0.36	0.48	0.28
19.6	0.74	0.43	0.55	0.36	0.53	0.26
25.2	0.91	0.47	0.68	0.38	0.69	0.29

Fig 8. shows the effect of a rain events on the maximum hourly flow during the day. This shows the effect of the rain event on the capacity of critical areas within the main pipe line and the extent to which the depths of rain events affect the performance of the pipe. It is clear that all rainfall events had a significant effect on the maximum hourly flow, but the magnitude of this effect jumps at (25.2mm) event of rainfall, where the increase in discharge is close to double compared to the normal daily maximum flow, which puts a lot of pressure on the main pipe, and at greater depths of rainfall it may lead to capacity problems and possibly flooding, taking into account the circumstances that occur in the annual mass gatherings in the city, where the coincidence of these two events will be critical.

The performance analysis of the main sewer pipeline was done using the PCSWMM using the RTK values resulting from the SSOAP analysis for all rainfall events. The table below shows the capacity, maximum discharge and flow depth during the day of the rainfall event for the critical part of the network (pipe C_{26}, diameter = 800mm) (Fig 9).

The results show that the performance of the main pipe was barely enough to withstand the rain events that occurred without overflowing or flooding, as the highest flow rate reached 91% of the pipe capacity at the largest rain event (25.2mm) compared to the normal daily flow that reaches 56% of the pipe capacity.

Considering these results, if the annual religious mass gathering event coincides with the rainy season and rainfall occurs at a depth of approximately 25mm or more, then the congestion of the main sanitary sewer pipe in this critical area and its flooding are certain to occur.

The performance in the other parts of the main pipe line were significantly better and sufficient to withstand all the recorded rainfall events but the significant increase in discharge due to rain indicates the need to evaluate the performance of the pipe for greater depths and intensity of rain, as well as taking into consideration the increase that occurs in the annual religious gatherings in the city, because the coincidence of these events may lead to failure of the pipe and the network.

4. Conclusion

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

- The amount of RDII entering the sewage network is high at a depth of rainfall of 25 mm or more, which poses a risk to the network’s capacity, indicating the necessity of studying the capacity of the main sewer pipeline under a depth of rainfall greater than that which occurred during the monitoring period of the study. the relationship between R and the depth of rainfall concluded in the study can be initially used for that.
- The PCSWMM software succeeded in simulating the flow in the main pipeline during rainfall events using RTK elements extracted from SSOAP, which allows the possibility of studying the flow behavior in the pipe under the influence of more rain depths.
- Rainfall events of 25 mm or more poses a significant risk to the capacity of the main pipe, as the 25 mm rainfall event led to a near-doubling of the maximum hourly flow, while the total daily volume of sewage has increased by more than 21%.
- The main pipe in its critical area during the 25mm rainfall event reached 91% of its capacity, which warns the risk of flooding in the event of heavy rain or during the times of religious gatherings.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper
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- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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