Mitigating the Volume of Inflow and Infiltration Entering the Sewage Network during the Storm of the Trunk Sewage Line (A Case Study in Karbala-Iraq)

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Abstract. Managing rainwater in light of climate variability is one of the most difficult problems facing urban areas in the world. Heavy rainfall contributes to increased infiltration of rainwater and effluent (RDII) into the sewage systems, which leads to system overflow and thus increased environmental pollution. This study aims at reducing the volume of surface runoff and thus reducing the volume of inflow and infiltration that enters the sewage network during the storm of the main sewage line of Karbala city. To investigate the extent to which the proposed solution would mitigate floods in the study area, the rainwater Management Model [SWMM] used data density for hourly precipitation from 2016 - 2019. The results indicate that the size of the flood was reduced to more than 75%, while the flood time decreased from 38 hours to 8 hours. The overload limit was reduced from 25 manholes to 5 manholes reduced (80%), and the excess duration were reduced by 55%. Total sanitary sewer overflow (SSO) 95 m$^3$ and area flooding 633 m$^2$. This analysis is expected to provide a comprehensive solution to mitigate sewage flooding during a storm and provide support to decision-makers to reduce environmental and health problems during heavy rains.

Keywords. Mitigation, Flooding, Trunk line, Open channel, SWMM

1. Introduction
One of the main causes of flooding of the sewage network is rainwater whose intensity exceeds the design standards [1, 2]. About 80% of overflows from the sewage network are caused by rain [3]. Land-use change and urbanization are closely related to the increasing flood volume due to the transformation of lands into impervious areas, which increases surface runoff and reducing the time required to reach peak volume of water and increasing drainage volume and peak discharge [4]. Besides, the progress of urbanization with a high intensity of rain increases flood risks in developing countries that do not have the necessary measures [5- 6- 7]. Furthermore, the increase in urbanization increased the volume of surface flow tenfold, as flooding that can occur every 100 years can increase by 30% [8-9-10]. Sewage flow (SSO) occurs when the amount of rain entering the system exceeds the design capacity, when the sewage network is filled with rain water, the sedimentation ponds are unable to absorb the pumping volume resulting in the SSO being close to the pumping stations [11]. Several studies have been conducted to reduce and mitigate storm network flooding and thus reduce sewage network flooding. [12, 13, 14] Used water sensitive urban planning techniques to reduce flooding. SWMM was used in [15] to assess a decrease in the level of flood dumping due to the existence of storage tanks of 70 m$^3$ / s during continuous rainfall events over five years. The
simulation results showed that the discharge was reduced by 14% to 20%. [16] stated that the recently used pipe jacking system could be deployed more than 20m below the earth's surface. They used numerical analyses to determine how to minimize friction between pipe and ground by filling the tail-void with lubricants. [17] used Pipe Jacking System to mount the mainline of the modern wastewater treatment plant on Vistula River road, Czajka, Warsaw. The pipe depth was 4.5m underground, diameter 3000 mm. HOBAŞ also designed a pipe-jacking project in Singapore, which was highly feasible for heavily populated areas. Research conducted in [18] uses SWMM to assess the impact on the efficiency of wastewater systems in China of the new solutions. In this work, the floods in the study area could be reduced similarly by 81.62% by increasing the pipe diameter by changing the size of the sewage hole. [19] presented a study to upgrade the efficiency of the storm network to reduce its flooding by using a filter to capture sediments associated with the storm. [20] presented a study for wastewater flood mitigation, conventional exchange solutions, and low-impact development measures. Traditional solutions include expanding sewers and building tanks outside the pipeline. The development solutions include green infrastructure at low costs, and the latter has been found suitable with low rainfall intensity. The traditional answer is to solve the problem of high flood rate. A new solution was proposed in this study to reduce the flooding of the sewage network by raising and increasing the efficiency and capacity of the storm network by replacing the current rain-catching basin with an open channel system along the street. The city has been divided into ten parts based on the importance and location of the flow count. It is suggested to use the open canal system in the three positions at the top of the sewage network. When simulating the proposal with Model SWMM, it was observed that the flood was reduced to 75% in all parts of the system. Flood time has also been reduced by 55%, and this result is very satisfactory. Additionally, the cost is also lowered compared to the proposal of replacing the pipe diameter. This study differed from previous studies by developing a radical solution at the lowest price. It does not address such a local solution, and it can be applied without affecting the existing infrastructure and services. This study aims at limiting and reducing sewage network flooding by raising the efficiency of the storm network.

2. The study area
Karbala is an Iraqi city about 100 km southwest of the capital, Baghdad, known for its religious and agricultural characteristics. Karbala is one of the richest cities in Iraq, as it benefits from religious tourism and agriculture. This city is served by three sewage lines of 64 km long with 522 intersections to collect sewage. The system also includes 32 km of pipes with 512 connections in the existing main line so that the wastewater can manage the rainwater. The network system is separate, not a combined approach. Gravity pipes account for 99% of the sanitary systems, while siphon and pressurized pipes account for up to 0.6% and 0.4% of the system, respectively (Directorate of Karbala sewerage, 2020). The network is owned by the Directorate of Sewerage in Karbala, responsible for the sewer network tasks. The Directorate's duties include the maintenance, replacement, and expansion of the region's sewer network. Karbala city on the map of Iraq is shown in Figure (1).

![Figure 1. Map of Karbala city in Iraq.](image-url)
3. Methodology
A storm water management model SWMM5 was used to evaluate the hydraulic performance of the sewage network before and after using flood mitigation methods. One of the best urban rainfall runoff programs to simulate hydrological processes in an environment is SWMM. Sanitary Sewer Overflow Analysis and planning (SSOAP) software was used to determine the volume of inflow and infiltration entering the sewer network.

3.1. Data collection
Hourly precipitation data that was provided by the General Authority for Climate and Seismic Monitoring for the Karbala Center monitoring station from 2016 to 2019 was used. The geographic information systems program restricted the rain catchments. The catchments area is about 2134.145 ha, and it consists of 47 sub-catchments. The parameter details like area, width, imperviousness rate and average slope were derived from these sub-catchments. Elevation for each sub-catchment ranges from 24 m to more than 36 m [6]. Rainwater drainage performance was analyzed in the Storm Management Model for a 10-year return time. Flow routing includes constant dynamic and cinematic wave options. The emotional wave model was used for flow routing and Green-Ampt for infiltration for this study. Wastewater flows monitoring device data obtained from the General Directorate of Sewerage for the years 2016 to 2019 with an interval of one hour. Sewer shed data which includes the area of the area served by the sewage network, from which parks and other facilities are subtracted from the Geographic Information Systems (G.I.S.) in addition to data on the physical properties of the sewage network Department of Karbala Sewerage Directorate. Furthermore, data on the physical properties of the sewage network are subtracted from the (G.I.S.).

3.2. The proposed mitigation mechanism
After analyzing the trunk line of the sewage network for center Karbala and finding the volume of inflow and infiltration in the SSOAP program, then evaluating the network and determining the amount and location of the flood in the SWMM program. It was found that the network failed to absorb the amount of rainwater at a density of 24.5mm/h with a volume of 105mm. Figure 2 illustrates the network analysis and evaluation before using a mitigation scenario. Flooding in manholes was divided into five stages, as follows:

- **The first stage** (without flooding) [0 to 0.001 cms].
- **Stage 2** [very light flooding] [0.01 to 0.02 cms].
- **Stage 3** [medium flooding] [0.02 to 0.03 cms].
- **Stage 4** [high flooding] [0.03 to 0.05 cms].
- **Stage 5** [very high flooding] [greater than 0.1 cms].

The figure 2 shows the network analysis and identifies the flood sites and the percentage of each.

![Figure 2. Shows flood areas and percentages in the sewage network during heavy rains.](image-url)
To mitigate and reduce sewage network flooding in urban areas caused by heavy rainwater, it is proposed to raise the efficiency of the storm network by increasing its capacity. The network efficiency has to be increased by increasing catch basin capacity. It can be implemented at a lower cost compared to replacing the pipe with a higher diameter.

3.2.1. An example. In this example we can see that there are footnotes after each author name and only 5 addresses; the 6th footnote might say, for example, ‘Author to whom any correspondence should be addressed.’ In addition, acknowledgment of grants or funding, temporary addresses etc might also be indicated by footnotes.

3.2.2. Increase catch basin capacity (inlet). Catch basin: it is an ergonomically designed structure to catch rainwater. Rainwater is transported from the streets to the rain network via underground pipelines. It is manufactured from regular concrete, whether it is precast or site poured, and some are made of HDPE and G.R.P. fiberglass. Open channels can be used instead to absorb the volume of heavy rain. The open channels technique has been applied in rainy countries such as Malaysia, Iran, and others, and it has proven successful. Open channels will be used instead of the current catch basin to increase the capacity and reduce sewage flooding in areas regularly exposed to flooding. The channel's dimensions that are used are 1 meter deep, 0.75 meters wide, and a length equal to the street. The open channel was designed based on Darcy's equation.

\[ Q = \frac{1}{n} A R^{2/3} S^{1/2} \]  

Where; \( Q \) = discharge, m³/s, \( V \) = velocity, m/s, \( n \) = Manning’s roughness coefficient, \( R \) = hydraulic radius = \( A/P \), \( m \), \( P \) = wetted perimeter, \( m \), and \( S \) = channel slope, m/m.

They will be used in the sub-sanitation area most affected by the rain. The cost of constructing the canal is (400$), 500,000 dinars per meter of length. Figure 3 shows the shape of the proposed channel.

![Figure 3. Shape of the open channel.](image)

Three open channel scenarios were used for three subs sewershed at the top of the network. Figure (4) shows the locations of the open channel in G.I.S.
Figure 4. Shows the locations of the open channels in G.I.s.

4. Results and discussion

4.1. Model calibration and validation

To validate all input parameters in the model and to estimate model parameters, validation is performed on the data. Using two titration methods, one of which is the trial and error method has been used to calibrate the simulation model of sewage drainage network of the study area. Nash-Sutcliffe coefficient of efficiency (ENS) method. The model was calibrated for a rainfall event in February and was validated for the March event. It is noted in both calibrations how strong the correlation is between the observed data and the simulated data, where the correlation coefficient for both events was 95% and 94% respectively, which is a very satisfactory result. Figures (5) and (6) show the calibration result for both events.

To consider the fluctuations between the observed and simulated data, the ENS coefficient was used. The ENS coefficient can be extracted according to the equation ENS parameter;

\[
E_{NS} = 1 - \left( \sum_{i=1}^{N} \frac{Q_{obs}^i - Q_{simul}^i}{\sum_{i=1}^{N} Q_{obs}^i} \right)^2
\] (2)

Figure 5. Model calibration result for the 22 February event.

Figure 6. Model calibration result for the 26 March to 29th event.
Where; Qobs refer to Observed flow, Q simu refers to simulated flow, N= Number of monitoring'. ENS is useful for showing hydraulic flow accuracy (Coutu et al., 2012). The closer the ENS 1 value, the more accurate the results, indicating the extent to with Figure (7) and (8) illustrate the consequence of variation in the observed data and the simulated data.

**Figure 7.** Result of the hydraulic calibration of the March event.

**Figure 8.** Result of the hydraulic calibration of the February event.

Calibration results are very acceptable, Table 1, and this makes the simulation ideal with an error rate near zero. 

\[
\text{Error} = \frac{1}{n} \sum_{i=1}^{n} (Q_{obs} - Q_{simu})
\]

Where; Qobs refer to Observed flow, Q simu refers to simulated flow, n=number of monitoring.

| Event       | $R^2$ | ENS | %Error  |
|-------------|-------|-----|---------|
| 22/2/2016   | 0.95  | 0.9 | 0.00321 |
| 26-28/3/2016| 0.946 | 0.89| 0.00424 |

4.2. Evaluation of hydraulic performance after using a mitigation scenario

The proposed scenario aims at limiting and reducing sewage network flooding by raising the efficiency of the storm network. The proposed method is evaluated using a stormwater management model (SWMM). Figure 9 illustrates the simulation results before using an open channels scenario for flood mitigation. Figure 10 illustrates the simulation results after using it. Three open channels were used in the upper part of the network because it is the most affected areas due to the rain due to its low levels.

**Figures 9.** Schematic diagram before using the catch basin (open channel).
Figures 10. Schematic diagram after using the catch basin (open channel).

Figures (9 and 10) show the difference in sewage network behavior before and after implementing the RDII reduction scenario. 41% of the manholes were not exposed to floods (stage 1), 39% of the manholes were exposed to light floods significantly (step 2), 15% of manholes had moderate floods (stage 3), 3% of manholes had high floods (stage 4), and 2% of manholes had very high floods. Below is a presentation of the rest of the sewage areas in the first and second lines, in which the flood volume decreased after applying the scenarios at the top of the network. Figure (11) shows the sewage network's behavior after implementing the RDII downsizing scenario. On the top side of the system.

Figure 11. Shows flood areas and percentages in the sewage network during heavy rains after using the mitigation scenario.
Figure 11 shows when using the mitigation scenario at the top of the network, one can notice the reduction in flood volume in all parts of the network. Detailed hydraulic modelling was performed with open channel systems of rain collectors. It is evident that the volume of SSO is reduced by 81%. Reduced overload limit from 25 manholes to 5 manholes (80%), and overloading duration reduced by 55% total SSO 95 m$^3$ and area flooding 633 m$^2$. It was also noted that the manholes that continued to flood were anchor points between the branch line and the mainline. This analysis is expected to provide a comprehensive solution to mitigate sewage flooding during a storm and provide support to decision-makers to reduce environmental and health problems during heavy rains, Table 2.

Table 2. Volume and area SSOs before and after using open channel for manholes.

| Manhole No. and type | Rainfall total=105mm | Rainfall total=105mm |
|----------------------|----------------------|----------------------|
|                      | Intensity= 24.5mm/h  | Intensity= 24.5mm/h  |
|                      | before using open   | after using open     |
|                      | channel | | | | |
|                      | m | m$^3$ | m$^2$ | hour | m | m$^3$ | m$^2$ | hour |
| 14401-CS | 12.5 | 22 | 146 | 28 | 11.5 | 20 | 133 | 6 |
| 14399-CS | 14.5 | 28.5 | 226 | 28 | | | | |
| 14398-CS | 17 | 30 | 230 | 24 | | | | |
| 14413-CD | 15.5 | 26 | 300 | 24 | | | | |
| 14414-CD | 9.7 | 16.29 | 42 | 24 | | | | |
| 14415-CD | 9.5 | 16.36 | 110.6 | 24 | | | | |
| 14416-CD | 9.8 | 16.5 | 96.2 | 24 | | | | |
| 14417-CD | 14.8 | 26.2 | 43.5 | 24 | | | | |
| 14418-CD | 15.8 | 27.9 | 186 | 28 | 6.5 | 18.5 | 135 | 6 |
| 14419-CD | 12.65 | 22.15 | 217 | 31 | | | | |
| 14472-CD | 8 | 14.77 | 32 | 24 | | | | |
| 14457-CD | 13.3 | 22 | 148 | 24 | 11 | 17 | 111 | 5 |
| 14452-CD | 8.9 | 15.6 | 37 | 21 | | | | |
| 14485-CD | 10 | 17.6 | 117.3 | 23 | | | | |
| 14486-CD | 14.4 | 25.37 | 169.13 | 26 | | | | |
| 14488-CD | 14.8 | 24.7 | 171.3 | 26 | 12 | 22 | 148 | 6 |
| 14489-CD | 6.8 | 12 | 80 | 24 | | | | |
| 14597-CD | 8.2 | 14.5 | 96.70 | 27 | | | | |
| 14604-CD | 13.2 | 22 | 148 | 24 | | | | |
| 14603-CD | 15 | 25 | 166.6 | 22 | | | | |
| 14612-CD | 16.3 | 28.8 | 192 | 28 | | | | |
| 14624-CD | 13.3 | 22.2 | 148.8 | 26 | | | | |
| 14632-CD | 11.4 | 20 | 133.3 | 32 | 8.5 | 18 | 125 | 8 |
| 14637-CD | 6 | 10.7 | 71.3 | 24 | | | | |
| 14556-CD | 8.5 | 15 | 160 | 32 | | | | |
| Total SSO | 510 | 3400 | 95 | 633.3 | | | | |

5. Conclusion

The purpose of this study is to reduce the amount of rain that enters the sewage network and causes it to flood, using a new scenario that has not been dealt with locally. It is an open channels scenario. The rainwater management model was used for the hydraulic evaluation of the sewage network before and after using the mitigation scenario. The proposed plan reduced the flood volume to 81% and the flood time to 55%, the volume of the SSO became 95 m$^3$ and the flooded area surveyed 633m$^2$. It was also noted that the manholes that continued to flood were anchor points between the branch line and the mainline. This analysis is expected to provide a comprehensive solution to mitigate sewage flooding during a storm and provide support to decision-makers to reduce environmental and health problems during heavy rains. It can benefit from the open canal in areas that suffer continuous flood, especially those that are catchment areas with low levels. This canal draws the largest amount of rainwater. This channel draws the largest amount of rainwater and thus reduces surface runoff and rainwater entering the storm network.
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Appendix (Tables A1 to A2 and Figures A1 to A9)

**Figure A1.** Time of water flooding in a selected manholes before and after mitigation.

**Figure A2.** Volume of water flooding in a selected manholes before and after mitigation.

**Figure A3.** Model calibration result.
Figure A4. Model calibration result.

Figure A5. Profile after used open channel 1.

Figure A6. Profile for open channel 1.
Figure A7. Profile for open channel 2.

Figure A8. Profile for open channel 3.

Table A1. Analysis of dry weather for weekdays and weekends, including GWI for each sub-sewershed.

| Sub sewershed | Area (ha) | DWF cms weekdays | Max | Average | Min | DWF cms weekend | Max | Average | Min | GWI cms |
|---------------|-----------|------------------|-----|---------|----|-----------------|-----|---------|----|---------|
| A             | 46        | 0.057            | 0.068 | 0.046  | 0.013 |
| HU            | 96        | 0.064            | 0.069 | 0.048  | 0.026 |
| M             | 80        | 0.059            | 0.065 | 0.049  | 0.033 |
| G             | 201       | 0.09             | 0.096 | 0.0575 | 0.019 |
| M1            | 260       | 0.13             | 0.134 | 0.1    | 0.074 |
| J             | 199       | 0.157            | 0.17  | 0.104  | 0.038 |
| B             | 157       | 0.26             | 0.28  | 0.19   | 0.096 |
| SE            | 166       | 0.07             | 0.08  | 0.053  | 0.026 |
| ME            | 280       | 0.197            | 0.22  | 0.136  | 0.053 |
| D (downstream)| 1110      | 0.56             | 0.59  | 0.44   | 0.29  |

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Figure A9. Flow-time relation.

Table A2. R, values and inflow/infiltation for each sub-sewershed for the selected events.

| Sub sewershed | R1     | R2     | R3     | R total (rain inter sewer) | Inflow/infiltation mm |
|---------------|--------|--------|--------|---------------------------|-----------------------|
| A             | 0.015  | 0.01   | 0.01   | 0.035                     | 3.7                   |
| HU            | 0.013  | 0.001  | 0.0011 | 0.034                     | 5.14                  |
| M             | 0.02   | 0.01   | 0.01   | 0.04                      | 9.8                   |
| G             | 0.01   | 0.005  | 0.005  | 0.038                     | 4                     |
| M1            | 0.01   | 0.007  | 0.0093 | 0.0293                    | 2.77                  |
| J             | 0.02   | 0.013  | 0.02   | 0.053                     | 5.57                  |
| B             | 0.05   | 0.1    | 0.02   | 0.08                      | 8.4                   |
| SE            | 0.01   | 0.016  | 0.01   | 0.036                     | 3.87                  |
| ME            | 0.015  | 0.01   | 0.01   | 0.035                     | 3.68                  |
| D             | 0.02   | 0.014  | 0.014  | 0.048                     | 5.04                  |