A sewer overflow mitigation during festival and rainfall periods: case study of Karbala

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Abstract

The objective of the present study to assess the performance of a suggested sewer line by using pipe jacking system (PJS) in order to enhance the sewage capacity and mitigate sewer flooding of historic pilgrimage city of Karbala, Iraq. The storm water management model (SWMM5) was used for this purpose. The simulation of exiting sewer system reveals that sewer discharge during peak pilgrimage period is more than 200% of the capacity of existing sewer line. Installation of SLL having a diameter of 2.5 m at a depth ranging between 12 and 22 m by PJS can reduce water depth in sewer pipe by 78%. The reduction of water depth at sewer pipe can reduce sewer overflow up to 70%, if the system is installed and managed properly. The methodology proposed in the paper can be applied in any location having similar problem with necessary modifications.

Keywords Pipe jacking system · Sewer overflow management · Sewage flooding · Floating population

Abbreviations

SWMM5	Storm water management model 5
SOs	Sewer overflows
C	Celsius
SSL	Suggested sewer line
PJS	Pipe jacking system

Introduction

Sewage flooding is a major problem in festival or pilgrimage cities where sudden influx of visitors and tourists during festival or pilgrimage periods put tremendous pressure on sewerage system and causes sewer overflow (Sharpley and Sundaram 2005; Shinde 2012; VandeWalle et al. 2012; Vijayanand 2012). Inundation of land and road with sewer due to sewer overflow causes sanitary and health problems as well as distress and hardship to urban populations. In many cases, the excess sewer is drained into storm networks

or to natural water outlets, which eventually cause urban pollution and ecological imbalance in the long run.

Various technical measures have been proposed to adopt or mitigate sewer overflow during extreme events such as larger floating population and extreme rainfall events (Aziz et al. 2011; Abdellatif et al. 2014). The most often used measures include use of tanker trucks, the direct link between sewage and stormwater networks by small pumps, sewage discharge directly into nearby water bodies to alleviate the sewer overflow. Leandro et al. (2009) and Sun et al. (2011) mentioned that technical measures usually prescribed to mitigate sewer overflow and sewage quality are not suitable for many cities, particularly for festival cities which experience huge influx of floating population (Stein and Partner 2015; Vazquez-Prokopec et al. 2010). This is especially true for old and historic cities, where sewer network often cannot be rebuilt due to number of reasons including heritage of the area, security matters, narrow streets, frequent the visits during a year, the old sewer networks, etc.

Pipe jacking system (PJS) is often proposed in such situation. In PJS, works are done underground and only the manholes are used to appear on the surface. Therefore, it could be a good solution of the problems usually faced in old historic cities and in poor soil. Zhen et al. (2014) used steel pipe jacking method to mitigate the sewer overflow in Shanghai, China. Their study provided a reference for effective design and construction of steel pipe jacking. The pipe jacking method has also been used in Japan to installed

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pipeline more than 20 m below the earth's surface (Senda et al. 2013; Llopart-Mascaró et al. 2014). It has been used in Warsaw, Poland to install sewer network.

Karbala, Iraq is the most important center of the world for Shit Muslim. Millions of people visit Karbala city during pilgrimage period. The sewer system of Karbala was built in 1970, with a capacity to handle the sewage of 436,500 populations. Population of the city has increased over the last four decades. The number of pilgrims is also increased with the increase in economic ability and mobility of people. Consequently, sewer system of Karbala often fails to handle the amount of sewer produced by large population. Sewer overflow occurs when the peak flow exceeds 10 times of the carrying capacity of sewer pipes of the city (Obaid et al. 2014a, b; Ying and Sansalone 2010; Zeferino et al. 2012). In such situation, the sewer water spills through gullies or manholes, causing flooding and environmental pollution. Changes in rainfall patterns, particularly those are related to global warming induced climate change such as, increase intensity of rainfall, have aggravated the situation. However, the sewer system of Karbala could not be upgraded with time to handle the pressure of increased population due to its historic nature and structure as well as the public sentiment to preserve the old historic religious structure of the city.

The objective of the present study is to assess the performance of a proposed sewer network installed by PJS in enhancing the sewage capacity of the historic pilgrimage city of Karbala. Various models have been proposed and successfully applied to assess the performance of existing or proposed sewer network. Among those storm water management model (SWMM5) (Rossman 2010; Maalel and Huber 1984) is the most popular one. SWMM is developed by coupling runoff model with a two-dimensional surface flow model (Leandro et al. 2009; Sun et al. 2011). It allows different control options to simulate sewerage discharge under different scenarios. It also allows easy operation for efficient simulate of complex sewer system. Huber (2003) studied the patterns of generating wastewater in London using SWMM, and reported that SWMM has the ability to simulate both the total volume of sewer runoff and peak discharge rate efficiently. Yoo (2005) reported that the potential information produced by SWMM can be used to support decision making in order to develop better wastewater drainage system. In the present study, SWMM is used to simulate the sewer network in order to assess the efficiency of sewer network installed by PJS.

Methods and materials

PJS only needs to dig few manholes in the surface. Even the distance of manholes can be very far (up to 1000 m) compared to normal sewer network. This system can be used

to construct pipe tunnels up to 3000 mm in diameter and construct both long (maximum length: 1000 m) and short lines. The minimum diameter of pipe in PJS is limited to person entry pipes as it requires people working inside the jacking pipe. Therefore, a minimum diameter of 1075 mm is recommended for the pipe installed by PJS. On the other hand, there is no upper limitation of jacked pipe diameter. The largest pipe can be nearly 3.7 m in diameter (Roe 1995). Cohesive soils are considered most suitable for PJS. However, pipe jacking is also possible in non-cohesive soil, if necessary precaution measures are taken, which includes using earth pressure balance machines to counterbalance the ground pressure, and using closed-face machines (Roe 1995). Due to above advantages, PJS is considered as most suitable for installing sewer network for Karbala city.

A model was developed using SWMM5 to simulated sewer discharge with varying population and rainfall. The additional discharges caused by floating population were considered as a direct flow. Manning equation (Eq. 1) was used to express the relationship between flow rate (Q), cross-sectional area (A), hydraulic radius (R), and slope (S) in all conduits (Gauckler 1867; Steel et al. 1985; Blansett 2011),

$$Q = V * A = (1/n) * AR^{(2/3)} * S^{(1/2)} \quad (1)$$

where Q =flow rate, (m^3/s); V =velocity, (m/s); A =flow area, (m^2); n =Manning's Roughness Coefficient; R =hydraulic radius, (m); S =pipe slope, (m/m).

Description of the study area

Karbala with an area of 5034 km^2 , is a city in Iraq, located about 100 km (62 mile), (Latitude: 32° 36' 51" N, Longitude: 044° 01' 29" E) southwest of Baghdad. It is made up of two districts, "Old Karbala"—the religious center, and "New Karbala"—the residential district containing Islamic schools and government buildings. The city center of Karbala has the old sewer system and the narrow streets, and therefore, redesign of sewer is very difficult. It has an estimated population of 436,500 in the city center (City Population 2013). During pilgrimage days, the population increases to more than 4 million (Jafria 2013). The Karbala in the map of Iraq is shown in Fig. 1a.

The toposheets, collected from Directorate of planning of Kabala city, was used to prepare the base map. Several features such as settlements, roads, water bodies, vegetation and industrial areas were digitized and corresponding maps are generated. Total 64 urban sub-catchments are found in the toposheets. The boundary of those sub-catchments was delineated using GIS for preparing the base map of sub-catchments of the city as shown in Fig. 1b. Sewer system requires a variety of appurtenances to insure proper

Fig. 1 **a** Map of Karbala city in Iraq (on the left) and **b** base Map of Karbala, 2006 (on the right)

operation. These include manholes, inlets, inverted siphons, pumping stations, etc. Figure 2a shows the map of the sewer networks and wastewater treatment plants in the city center of Karbala. Six main sewer lines are used in the city center of Karbala to carry on the sewage to wastewater treatment plant as shown in Fig. 2b.

Karbala is located in semi-arid region of Iraq. The climate of the city is characterized by cold winter and prolonged dry season. It experiences a hot desert climate with extremely

hot and dry summer and cool winter. Most of the rainfall is received between November and April; however, rainfall is not high in any month. The monthly distribution of rainfall in Karbala city is shown in Fig. 3. The distribution of precipitation shows that the maximum rainfall is close to 22.5. (World Weather Information Service- Karbala 2014; Hussein et al. 2015). Detail description of SSL having a length of 13,594.6 m is given in Table 1. The descriptions of manholes are given in Table 2.

Fig. 2 **a** The sewer networks in the city center of Karbala (on the left) and **b** the six main sewer lines in the city center of Karbala (on the right)

Fig. 3 The seasonal variation of climate in Karbala city (1980–2013)

Table 1 Details of the suggested sewer line (SSL)

PIPE	From manhole	To manhole	Distance (m)	Internal diameter (mm)	External diameter (mm)	Slope%	Manning roughness
P-1	J-12	J-13	297.6	2100	2500	0.17856	0.012
P-2	J-13	J-14	218	2100	2500	0.1308	0.012
P-3	J-14	J-15	250	2100	2500	0.15	0.012
P-4	J-15	J-1	421	2100	2500	0.2526	0.012
P-5	J-1	J-2	634	2100	2500	0.3804	0.012
P-6	J-2	J-3	615	2100	2500	0.369	0.012
P-7	J-3	J-J	557	2100	2500	0.3342	0.012
P-8	J-12	J-11	262	2100	2500	0.1572	0.012
P-9	J-11	J-10	363	2100	2500	0.2178	0.012
P-10	J-10	J-9	253	2100	2500	0.1518	0.012
P-11	J-9	J-8	1046	2100	2500	0.6276	0.012
P-12	J-8	J-7	617	2100	2500	0.3702	0.012
P-13	J-7	J-6	601	2100	2500	0.3606	0.012
P-14	J-6	J-5	534	2100	2500	0.3204	0.012
P-15	J-5	J-4	425	2100	2500	0.255	0.012
P-16	J-4	J-J	589	2100	2500	0.3534	0.012
P-17	J-J	J-16	765	2100	2500	0.459	0.012
P-18	J-16	J-17	444	2100	2500	0.2664	0.012
P-19	J-17	J-18	932	2100	2500	0.5592	0.012
P-20	J-18	J-19	750	2100	2500	0.45	0.012
P-21	J-19	J-20	907	2100	2500	0.5442	0.012
P-22	J-20	J-21	856	2100	2500	0.5136	0.012
P-23	J-21	J-22	364	2100	2500	0.2184	0.012
P-24	J-22	PJ-STATION	894	2100	2500	0.5364	0.012

Results and discussions

The city center of Karbala is well covered by sewer network. Only some outlying areas of the center as well as nearby agricultural areas are still out of sewer network. Both storm and sewer networks of the city are more than

half century old. During pilgrimage, stormwater networks are intentionally connected to the sewer network randomly in some places to carry 20% of sewerage. During sewer overflow, huge sewerage enters into stormwater network, which causes overflow in stormwater network. The situation deteriorates during rainfall. Capacity of stormwater network is insufficient in some places and therefore, it

Table 2 Details of the manholes of the suggested sewer line (SSL)

Manhole name	Manhole depth (M)	Invert elevation	Ground elevation
J-J	13.3	14.34	27.64
J-1	11.71	18.75	30.46
J-2	9.5	18.37	27.87
J-3	10	18	28
J-4	12.1	14.69	26.79
J-5	12	14.95	26.95
J-6	10.6	15.27	25.87
J-7	9.3	15.63	24.93
J-8	10	16	26
J-9	12.74	18.93	31.67
J-10	10.8	19.08	29.88
J-11	11	19.3	30.3
J-12	10.8	19.46	30.26
J-13	11	19.28	30.28
J-14	11.1	19.15	30.25
J-15	11.5	19	30.5
J-16	12.3	13.88	26.18
J-17	19.3	13.62	32.92
J-18	20.1	13.07	33.17
J-19	16.4	12.8	29.2
J-20	16.6	12.26	28.86
J-21	17	11.72	28.72
J-22	17.3	11.51	28.81
PJ-STATION	19.7	10.97	30.67

overflows even during normal period (when no floating population), if heavy rainfall occurs.

The total permanent resident of the Karbala city center (395,411) is shown in Fig. 4a. It shows that the population in the area varies between less than 305 people and closed to forty thousand people during normal days. The total number of cumulative population in the days from 10 to 21 of the month of Safar is approximately 20 million due to the influx pilgrims (Arbaeen visit). The distribution of these 20 million populations in Karbala city is shown in Fig. 4b. The figure illustrates that population for each sub-catchment of the city center of Karbala ranging from 616 people to about 12 million people during twelve pilgrimage days of the Safar month.

Following the directives of the directory of water supply of Karbala city, the per capita per day water consumption for permanent resident is considered between 200 and 400 L. The water consumption at each sub-catchment of the Karbala city center for the normal days is shown in Fig. 5a. On the other hand, the water consumption for each sub-catchment of the Karbala city during the 12 pilgrimage days is shown in Fig. 5b. Following the directives of the directory of water supply of Karbala city, the per capita per day water consumption for floating population was considered between 100 and 200 L. The figure shows that water consumption in the study area by floating population varies from sub-catchment to sub-catchment, between less than 31 m³/day to about 1508,625 m³/day. High water consumption is estimated around the center of pilgrimage.

The sewer discharge from each sub-catchment of the Karbala city center (m³/d/Sub-area) was estimated considering that per capita per day sewer delivery is from 160 to 320 L. On the other hand, the per capita per day sewer discharge by

Fig. 4 **a** Distribution of permanent population; and **b** during 12 pilgrimage days (Arbaeen visit) of Karbala city

Fig. 5 **a** Water consumption at each sub-catchment of Karbala city center ($\text{m}^3/\text{day}/\text{sub-area}$) during normal, and **b** during pilgrimage days

Fig. 6 **a** The sewer discharge from each sub-catchment of Karbala city center ($\text{m}^3/\text{d}/\text{sub-area}$) during normal; and **b** pilgrimage days

floating population was considered about from 80 to 160 L as proposed by Directorate of sewerage of Karbala. The sub-catchment wise distribution of sewerage discharge during normal and pilgrimage days are shown Fig. 6a, b, respectively. The figures show that the spatial distribution of sewer discharge follows the same pattern of water consumption. Proposed sewer line for Karbala city to be installed using PJS is shown in Fig. 7. SWMM model was used to simulate the sewer overflow changes with the installed sewer line. Amount of sewer overflow as well as the times and locations overflow before and after installation of sewer line is used for comparison.

The results of average and maximum sewer discharge for suggested sewer line (SSL) are shown in Table 3a and b.

Fig. 7 Suggested sewer line (SSL) of the Karbala city center by PJS

Table 3 (a) Average and (b) Maximum sewer discharge for SSL

<i>Average sewer discharge for SSL</i>	
Pipe diameter, d_0	2100 mm
Manning roughness, n	0.012
Pressure slop, S_0	0.06
Percent of full depth (100%)	50%
Flow, q	2.3006 CMS
Velocity, v	1.3284 m/s
Velocity head, h_v	0.0900 m
Flow area	1.7318 m ²
Wetted perimeter	3.2987 m
Hydraulic radius	0.5250 m
Top width, T	2.10 m
Froude number, F	0.47
Shear stress (tractive force), τ	6.1778 N/m ²
<i>Maximum sewer discharge for SSL</i>	
Pipe diameter, d_0	2100 mm
Manning roughness, n	0.012
Pressure slop, S_0	0.06
Percent of full depth (100%)	100%
Flow, q	4.6011 CMS
Velocity, v	1.3284 m/s
Velocity head, h_v	0.0900 m
Flow area	3.4636 m ²
Wetted perimeter	6.5973 m
Hydraulic radius	0.5250 m
Top width, T	0.0 m
Froude number, F	0.47
Shear stress (tractive force), τ	12.3556 N/m ²

Besides that Table 3a and b shows that the maximum discharge SSL is 4.6011 m³/s, and the velocity is 1.3284 m/s. The standard ratio of actual to maximum discharge is (q/Q) 0.5. The point of intersection on the left hand scale is found 0.56. Using this value, the depth of sewer flow in SSL is obtained as 1176 mm (0.56×2011). Similarly, the ratio of actual to maximum velocity (v/V) is obtained as 0.84. The minimum velocity in the pipe when it is carrying a flow of 2.3006 m³/s is thus be 1.12608 m/s (0.85×1.3284).

The wastewater level in the SSL obtained using SWMM5 during the normal days is shown in Fig. 8a. The wastewater level in the SSL during the pilgrimage days (3th January) is shown in Fig. 8b. It should be noted that partial-flow diagram gives only approximate results, particularly for high velocities. The discrepancies between computed and actual flow conditions may be caused by wave formation, surface

resistance, and other factors. It can be found from the analysis that velocities below 78% of the total depth decreased.

There are three main pump stations in the pilgrimage zones (Bab Baghdad, Alsadia and P2 stations) to lift the sewage from the city center into the old water treatment plant. By applying SSL, all of these pump stations have to remove. The inlets of these pump stations have to connect directly into SSL. In the downstream of SSL, there is a pump station should be constructed, which is lifting the sewage from LINE-1, LINE-2 and LINE-3, and therefore, the sewage is supposed to go to a new water treatment plant. Consequently, the maintenance process will be easier after removing the pump stations in the pilgrimage zones.

Sewer flooding before and after installation of SSL is shown in Fig. 9. The figures show that SSL will contribute up to 55% reduction of the rash in the average sewer discharges values while mitigates the peak sewage flows by 74% during the pilgrimage periods. The percentage of mitigation of flood has been estimated and checked by running of SWMM5 after installed SSL and removed all pump stations in the city center of Karbala. It was estimated by the model that sewer water depth is less than 70% in SSL during the critical period. Therefore, no sewer overflow in downstream areas during pilgrimage period. However, the results show that sewer overflow might happen in sub-pipes. The internal networks are required rehabilitate for complete mitigation sewer overflow in the city.

Conclusions

Performance of suggested sewer line by PJS has been assessed in Karbala city of Iraq, one of the most important holy cities of the world in order to mitigate the problem of sewer overflow. The study suggests that PJS can be a suitable approach for installation of sewer line in old heritage and densely populated areas for mitigation sewer overflow. It has been found that installation of new sewer line using PJS can reduce the sewer flooding up to 78% in Karbala city, if properly installed and managed. The rest amount of excess sewerage can be managed through rehabilitation or slight modifications of the existing sewer system. It is expected that the case study presented in this paper can be replicated in other cities experience huge floating population for modeling of sewer discharge and mitigation of sewer related problems.

Fig. 8 a Wastewater level in SSL during the normal day, b Wastewater level in SSL during pilgrimage day (3rd January)

Fig. 9 Sewer system flooding before SSL (on the left) and after installed SSL (on the right)

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Compliance with ethical standards

Conflict of interest The authors declare that they have no competing interests.

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