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# A simulation-based assessment of a prospective sewer master plan*

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**Abstract.** Towards achieving its strategic goal of zero waste waters released untreated to the environment and zero effluent to be released unutilized to the environment, Kuwait has developed a new sewer master plan. The prospective master plan is a major infrastructural project that includes building new waste water treatment plants and pumping and lifting stations nationwide. This paper reports the findings of a simulation-based assessment of effluent flows of treated waters' distribution. Simulation models were created due to the complexity of waste water networks, stochastic behavior of water consumption and seasonality.The daily flow rates data and capacities for all waste water treatment facilities and pumping stations were collected and fitted into statistical distributions to be later incorporated into the simulation models. The existing waste water network was modeled first. Upon validation, another simulation model was created for the prospective waste water treatment plan of 2050. The simulation showed that the prospective waste water network of 2050 will be able to handle the capacity of the sewage water inflows efficiently, expect for Al-Sulaibiy a plant that will reach its upgraded capacity the earliest followed by Umm Al-Hayman WWTP. Additionally, parts of the treated effluent network need to be upgraded to accommodate future demand.Simulation assisted in predicting overall flow efficiencies, estimate capacities, analyze and balance effluent water flows and assess overall performance measures. The results were validated at a 95 percent confidence level.

**Keywords:** discrete event simulation, waste treatment planning, waste water, infrastructure, sanitation, effluent

## 1 Introduction

Kuwait is a small country that occupies a land area of 17818 km2 located on the Arabian (Persian) Gulf peninsula of the Middle East. Kuwait has a population of 2,818,042 as of 2011[28]. Kuwait commenced its first waste water treatment plant in late 1950's[18]. This was a solution against dumping untreated sewage water to the sea. Since early 90's, Kuwait ranks fifth place worldwide in water sanitation services[22]. This is due the upgrading of all secondary treatment waste water plants to tertiary effluent quality in 1984[16]. In 2005, Kuwait celebrated the commencement of the largest waste water treatment and reclamation plant worldwide[14]. The facility uses Reverse Osmosis (RO) to treat municipal waste waters to potable quality but for non-potable use. Alone, the RO facility recycles around 64% of the entire sewage of the country. Today, it is the strategic goal for the sanitary division at the Kuwait Ministry of Public Works (MPW) to reach the so called zero release level. That is zero waste waters released untreated to the environment and zero effluent to be released unutilized to the environment as well[14]. To be able to reach this strategic goal while coping with population growth, the MPW has developed an expansion to the current sewer infrastructure system that should launch in 2045. In this paper, we assess the performance of the newly developed sewer master plan projected in 2045 with respect to amounts of treated and untreated municipal waste waters.

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All major and minor pumping stations (PS) national-wide were analyszed with respect to capacities and production. Special emphasis was directed towards Al-Sulaibiya waste water treatment and reclamation plant as it is the largest facility worldwide that applies Reverse Osmosis and Ultra Filtration membrane water purification. Simulation models were adopted due to the complexity of waste water networks and stochastic behavior of water consumption. The daily flow rate records collected at each pumping station was fitted into statistical distributions to be later incorporated into the simulation models. We first built a simulation of the as-is system.The results were validated to represent reality at a 95 percent confidence level.Accordingly, a simulation model for the prospective 2045 plan was built. Forecasted population increase and future water consumptions were included to foresee how the new sanitary infrastructure will perform in the future after 2045. The analysis showed that the network will be capable of handling input waste water but requires upgrade to distribute treated effluent. The Simulation turned to be an excellent tool to estimate efficiencies and bottlenecks to minimize amounts of untreated sewage water dumped into the sea for such a large infrastructure project.

## 2 Background

In the area of wastewater treatment, discrete-event simulation has been applied repeatedly to estimate capacities, analyze and balance effluent water flows and improve overall performance measures[2, 3, 7, 17, 19, 24, 27]. Ceric[4] have used discrete event simulation to model a solid-waste processing system which is to be installed in Zagreb, Croatia. Researchers have exploited simulation to develop simplified mathematical models to anticipate the behavior of current and prospective wastewater Treatment Plant (WWTP) discussed in their study[21, 23]. In Glen et al.[9], a discrete-event simulation model was created using General-Purpose Simulation System (GPSS) to investigation of the batch operation of a poultry processing wastewater treatment plant. Hasanlou et al.[11] have used simulation-based prediction models to acquire an applicable operation over industrial treatment plants. Huang et al.[12] have applied simulation on higher level to assess potential dynamic evolution of environmental systems caused by various strategies. In addition, Ferrer et al.[6], presents a software tool to design, simulate and optimize WWTP. The program is called DESASS (DEsign and Simulation of Activated Sludge Systems). In similar studies, the simulations were carried out using gProms software which is capable of accommodating rain and storm weather data files[20]. Hubert et al.[13] simulation modeling combined the with machine learning and optimization techniques to improve wastewater flow efficiencies for on-site treatment in the food and beverage industry. Aleisa et al.[1] have conducted two discrete-event simulation studies to model the activities of a residential wastewater treatment facility to prepare it to accept additional wastewaters through tanker trucks. The first simulation study modeled the wastewater treatment facility to ensure its ability to handle the added capacity arriving through the pit, while the second study simulates various managerial strategies to handle the traffic, testing and unload procedures of tank trucks arriving to the facility.

## 3 Wastewater treatment plants in Kuwait

Currently, four WWTPs serve the urban and suburban areas of Kuwait; these are Sulaibiya, Al-Jahra, Riqqa, and Umm Al Hayman (see Tab . 1). In addition,the wastewater network consists of twelve main PSs, locally referred to as “A” stations by MPW personnel. Similarly, secondary pumping is referred to as “P” PSs. “S” stations are screwing and lifting stations. These are always connected to “A” stations and thus have the same flow rate. The daily flow rates data, capacities (in cubic meters) and location for each main PS, for the years 2009 and 2010 are provided in Tab. 2. The locations for the main PSs A are shown in Fig. 1.

### 3.1 Sulaibiya wastewater treatment and reclamation plant

Al-Sulaibiya wastewater treatment and reclamation plant is the largest facility worldwide that applies Reverse Osmosis (RO) and Ultra Filtration (UF) membrane water purification[10]. The facility was constructed

Table 1: WWTP' Capacities and Locations

| WWTP | Al Riqqa | Al Jahra | Um Al-Hayman | Sulaibiya |
|---|---|---|---|---|
| Constructed | 1982 | 1982 | 2001 | 2002 |
| Initial Capacity | 85,000 | 65,000 | 27,000 | 425,000 |
| Expanded Capacity m3/d | 180,000 | - | - | 600,000 |
| Current inflow m3/d | 170,000 | 100,000 | 16,000 | 450,000 |
| Tertiary treated water m3/d | 166,000 | 98,000 | 15,680 | - |
| RO water treated m3/d | - | - | - | 320,000 |
| Location North | 29° 9'8.42"N | 29°19'36.29"N | 28°52'19.95"N | 29°15'57.94"N |
| Location South | 48° 4'0.08"E | 47°43'50.31"E | 48°12'47.37"E | 47°43'40.80"E |

Table 2: Main PSs for the current wastewater network

| PS | | Capacity ($m^3$/day) | Average Flow ($m^3$/day) | Location | |
|---|---|---|---|---|---|
| | | | | North | East |
| ZONE (1) | A3 | 172,800 | 58319 | 29°22'0.06"N | 48° 0'38.87"E |
| | A4 | 69,120 | 19171 | 29°23'0.95"N | 47°59'40.65"E |
| | A6 | 172,800 | 123988 | 29°21'37.20"N | 47°57'37.59"E |
| | A7 | 288,000 | 148067 | 29°20'52.43"N | 47°56'31.82"E |
| | A8 | 17,420 | 3550 | 29°19'59.01"N | 47°54'25.19"E |
| | A9 | 211,200 | 72764 | 29°17'55.39"N | 47°55'34.81"E |
| | A12 | 126,000 | 90483 | 29°17'10.76"N | 47°55'38.11"E |
| ZONE (2) | A14 | 176,400 | 138187 | 29° 7'37.37"N | 48° 8'2.23"E |
| | A15 | 328,320 | 211887 | 29° 7'56.39"N | 48° 7'34.41"E |
| | A18 | 100,800 | 55615 | 29°21'4.95"N | 47°41'27.82"E |
| | A19 | 208,000 | 35375 | 29°18'36.34"N | 47°50'2.19"E |
| | A20 | 48,080 | 12984 | 28°54'36.23"N | 48°13'4.14"E |


Fig. 1: The location of main wastewater PSs around Kuwait City

with an initial capacity of 425,000 $m^3$/d (cubic meters per day) to treat domestic wastewaters to potable quality. Just after few years of operation, the facility accepts over 500,000 $m^3$/d. It is recycling around 64% of the entire sewage of the country alone. Future plans are directed towards expanding the capacity to 600,000 $m^3$/d. Al-SulaibiyaWWTP receives wastewaters through a 25 km-long main feeder pipeline that conveys a pre-treated flow from the ArdiyaPS. The Ardiya station does the receiving, initial screening, degreasing, odor removal, and flow regulation. Al-SulaibiyaWWTP is connected with seven main pumping "A" stations. Also, Sulaibiya is receiving sewage water directly from additional two PSs: A12 and A9 (see Fig. 2). Al-Sulaibiya effluent is pumped to nearby produce farms in Al-Abdily (North), and Al-Wafra (South).

Fig. 3 shows that at 2010 Al-SulaibiyaWWTP have already reached its maximum capacity. A sharp drop has occurred when one of the secondary PSs (Mishrif) failed in August 2009. Mishrif station is part of the

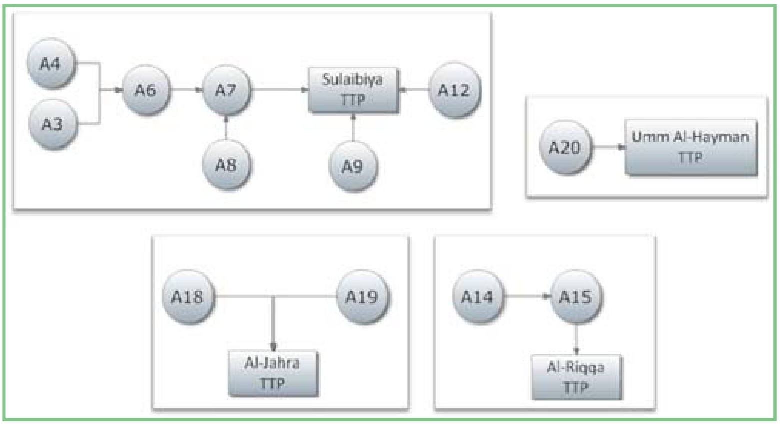


Fig. 2: Pictorial flow chart of current connections of wastewater main PSs

Hawalli residential district which is partially connected to Al-SulaibiyaWWTP. Prior to its malfunction in August 2009, Mishrif station pumped around 200,000 $m^3$/d to SulaibiyaWWTP and Al Riqqa plant. Tank trucks continued to transport some of the sewage generated to a pit connected to the 12thPS of Sulaibiya. However, authorities indicate that the amount of wastewater transported is around 25,000 $m^3$/d while the vast majority of waste generated is currently dumped into the sea. That is due to the fact that huge amounts of wastewaters needed to be withdrawn from the facility prior any maintenance or repair operations[25].

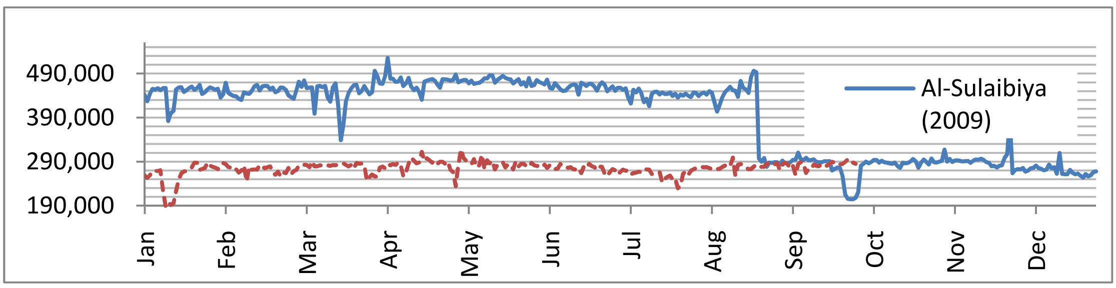


Fig. 3: Daily record for the flow-rate in cubic meters for Al-SulaibiyaWWTP2009-2010

### 3.2 Al-Jahra WWTP

Al JahraWWTPreceives water from two PSs: A18 and A19. Treated water is used for landscape irrigation only such as the landscapes of:Kuwait Airport, Kuwait Airways headquarters, and highways. Overloading Al-JahraWWTP affected the tertiary treated effluent quality[8]. The Biological treatment and technology was upgraded later on to meet the national standards by both the MPWand the Ministry of Health (MOH)[14]. The capacity was also reduced in August 2010 due to the Mishrif secondary PS (see Fig. 4).

### 3.3 Al-Riqqa WWTP

Al- Riqqa WWT Preceives water from A14 and A1. Al Riqqa effluent is utilized in Ahmadi and Ardiya landscapes. Mild fluctuations in Riqqa and Umm Al-Hyman flowrates are due to spring and winter rain seasons. As shown in Fig. 5 a sharp drop occurs in End of November 2009 due to a major power failure.

### 3.4 Umm Al-Hayman WWTP

Umm Al-Hyman WWTPis connected to nearby residential communities that are closer to the coastal areas[1]. It receives wastewaters from a single main PS that is A20 and from a sewage pit that receives wastew-

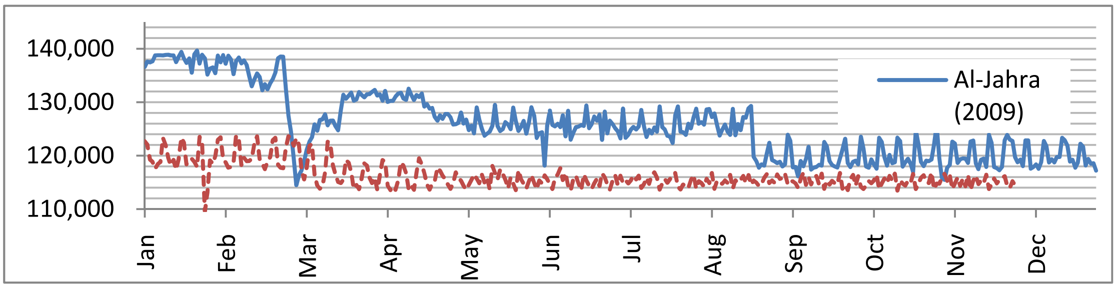


Fig. 4: Daily record for the flow-rate in cubic meters for Al-JahraWWTP2009-2010

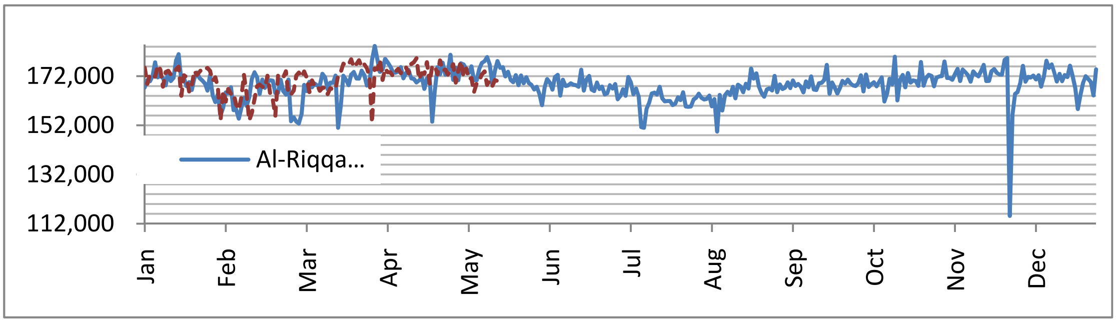


Fig. 5: Daily record for the flow-rate in cubic meters for Al-RiqqaWWTP2009-2010

ater via trucks[1, 26]. The pit designed was established in 2010, hence flow data form Fig. 6 is not available for the first semi of the 2010. Part of Umm Al-Hayman effluent is pumpedto irrigate golf courses and gardens.

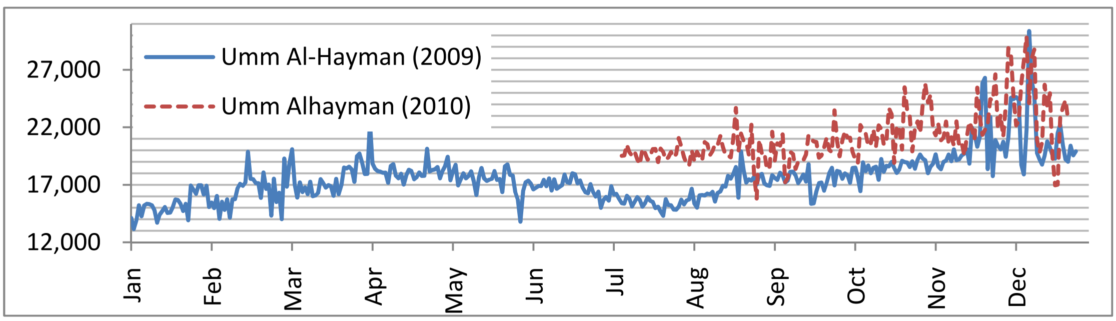


Fig. 6: Daily record for the flow-rate in cubic meters for Umm Al-Hayman2009-2010

## 4 The simulation model for the current wastewater network

The current wastewater network was modeled and simulated for validation purposes. The daily flowrate records collected at each PS was fitted into statistical distributions to be later incorporated into the simulation models. The Data fitting results are provided in Tab . 3. In the simulation models, entities were discretized to an equivalent of 1,000 m3. Each simulation replication consisted of 365 days. Ten replications were used to maintain the error to below five percent. The simulation study was built according to the following effluent flows:

- Al-Sulaibiya: 83% of treated water through RO produces water is of potable quality, 15% untreated water, and 2% sludge.

Table 3: Statistical Distributions for PSs

| Station | Distribution | Station | Distribution |
|---|---|---|---|
| A3 | NORM (5.83e+004, 3.59e+003) Square Error: 0.030145 | A12 | NORM (9.05e+004, 1.24e+004) Square Error: 0.148262 |
| A4 | NORM (1.92e+004, 1.89e+003) Square Error: 0.016721 | A14 | NORM (1.38e+005, 3.77e+003) Square Error: 0.007789 |
| A6 | 9.45e+004 + WEIB(3.18e+004, 4.14) Square Error: 0.008776 | A15 | NORM (2.12e+005, 8.6e+003) Square Error: 0.005994 |
| A6 Overflow | 3.38e+004 + 2.51e+ 004 * BETA(2.17, 2.12) | A15 Overflow | 4.74e+004 + 8.58e+ 004 * BETA(9.88, 22.4) |
| A7 | 1.2e+005 + 5.38e+ 004 * BETA(6.79, 6.44) Square Error: 0.006670 | A18 | 5.44e+004 + ERLA(314, 4) |
| A7 Overflow | NORM (2.05e+004, 4.55e+003) Square Error: 0.003297 | A19 | 3.31e+004 + 3.78e+ 003 * BETA(15.6, 10) Square Error: 0.011357 |
| A8 | NORM(3.55e+003, 440) Square Error: 0.009516 | Jahra overflow | NORM(2.54e+004, 2.91e+003) Square Error: 0.065338 |
| A9 | .58e+004 + 6.03e+ 004 * BETA(17.3, 10.9) Square Error: 0.041131 | A20 | 1.08e+004 + WEIB(2.41e+003, 1.91) Square Error: 0.003456 |

- Al-Jahra:of the tertiary water treated effluent, 45.83% goes to Jahra bird reserve, 4.3% is used in irrigation inside Jahra area, 1.43% goes to private companies in Jahra, 1% is transferred into sludge, and 0.11% is used in irrigation inside the plant itself, and the rest of the treated water is disposed into the sea.
- Al-Riqqa: Most of its effluent is pumped to Ardiya Data Monitoring Center (DMC), 11.7% goes to Ahmadi irrigation and the remaining 1% consists of sludge.
- Umm Al-Hayman: 14.15% of effluent goes to nearby golf course, 9.43% to landscape irrigation, 7.07% to landscapes within Umm Al-Hayman WWTP, 1% constitutes produced sludge, and the rest is disposed to the desert.

## 5 Validation of the current simulation network

Statistical model validation provides evidence whether or not the model is a legitimate representation of reality[15]. A 95% confidence levels is typical in simulation validation practices. The equality of the real and simulated population variances were tested first. According to result of the equality of variances test, the proper formula for testing the equality of the real and simulated population is selected and applied. Four replications were conducted for an entire year. Tab. 4 shows the results of the validation.

Let $\bar{x}_i$, $s_i$ and $n_i$ indicates mean, standard deviation and sample size of sample $i$ respectively. Similarly, let $\sigma_i^2$, $\sigma_i$ and $\mu_i$ indicate the variance, standard deviation and mean of population respectively. For instance, for the Sulaibiya plant: $\bar{x}_{1,\text{actual Sulaibiya}} = 300623$, $\bar{x}_{2,\text{model sulaibiya}} = 311219$. $s_{1,\text{actual Sulaibiya}} = 50949$, $s_{2,\text{model Sulaibiya}} = 590$. Then,

$$-91320 \leq \mu_1 - \mu_2 \leq 70126 \ \text{m}^3/\text{day}. \quad (1)$$

This result indicates that the means of these two populations statistically the same at a 95% confidence level. In other words, the simulation is a valid representation of the real system. Tab . 4 summarizes the validation result for the rest of the plants. The P-values result in failing to reject the equality of the actual and simulated systems' population means.

Table 4: Statistical Comparison between actual and simulated flow rates

| Plant | Al-Sulaibiya | | Umm Al-Hayman | | Al Riqqa | | Al-Jahra | |
|---|---|---|---|---|---|---|---|---|
| Criteria | Actual | Simulation | Actual | Simulation | Actual | Simulation | Actual | Simulation |
| Average | 300623 | 311219 | 17572 | 19997 | 168776 | 181000 | 116199 | 116350 |
| Standard deviation | 50949 | 590 | 1632 | 79 | 2583 | nil | 1824 | 384 |
| Test- statistic | −0.42 | | 2.9 | | −2.9 | | −0.15 | |
| P-value | 0.704 | | 0.062 | | 0.062 | | 0.893 | |
| Confidence interval | (−91320, 70126) | | (−5084, 232) | | (−5084, 232) | | (−3431,3130) | |
| Conclusion | Fail to reject | | Fail to reject | | Fail to reject | | Fail to reject | |

## 6 Modeling the prospective sewer master plan

The new wastewater treatment master plan is supposed to commence in 2045. It will eliminate all treatment plants and major PSs that are located in residential areas. In addition, the main PSs will be reduced from twelve main to five major ones to simplify the network hence its maintenance. Therefore, the sewage water will flow through a maximum of two PSs thereof. Other changes also include:

1. The Sulaibiya WWTP will be connected to two major PSs. These are Mishref and Riggae stations. Riggae PS will replace the current A3, A4, A6, A7, A8, A9, and A12 PSs in Kuwait City. While Mishref PS which already exists, will be upgraded to serve the east part of Kuwait City and Hawalli governorates. Those two PSs will pump to Ardeya first, then, it will pump the sewage waters into SulaibyaWWTP.
2. The SulaibyaWWTP will be upgraded to increase its designed capacity but most likely towards the end of the project. Finally, the plant will pump the treated effluent into the DMC. The DMC will monitor and control the distributing the treated effluent into destinations such as Abdali, Al-Wafra, Sulaibiya Farms, Al-Jahra birds reserve, and many other places.
3. Al-JahraWWTP will be demolished and replaced by a new plant called KabdWWTP. KabdWWTP will receive sewage water from one majorPS:Al-Jahra PS. Kabd too will be connected to a DMC as well. See Fig. 7.
4. Umm Al-Hayman capacity will be increased. A new PS called Egaela will be installed to replace A14 and A15. Main station A20 will remain as is.
5. A new treatment plant will be constructed at Al-Khiran. This plant will serve the south coastal areas of Kuwait. Authorities claim that Khiran is expected to develop a new residential community. KhiranWWT-Pis designed to serve this community and will receive the sewage water from localized small pumping and lifting stations. Tab . 5 shows the designed capacity, expected average flow, and the geographic location of the futures ewer master plan elements.

Table 5: Capacities, expected flows and locations of prospective treatment plants and PSs

| Treatment Plant | Capacity ($m^3$/day) | Expected average flow ($m^3$/day) | Location North | Location East |
|---|---|---|---|---|
| SulaibiyaWWTP | 600,000 | 930,797 | 29°14’48.51”N | 47°42’53.39”E |
| KabdWWTP | 360,000 | 239,545 | 29°12’24.16”N | 47°43’7.97”E |
| Umm Al-Hayman WWTP | 450,000 | 383,885 | 28°52’22.89”N | 48°12’36.64”E |
| KhiranWWTP | 27,000 | - | 28°39’36.15”N | 48°22’59.13”E |
| PS | Capacity ($m^3$/day) | Expected average flow ($m^3$/day) | Location North | Location North |
| Mishref PS | 340,000 | 360,500 | 29°16’10.46”N | 48° 4’56.70”E |
| Reggae PS | 777,600 | 641,307 | 29°18’33.65”N | 47°55’11.14”E |
| Jahra PS | 375,000 | 239,545 | 29°19’42.19”N | 47°44’8.32”E |
| Egaela PS | 360,000 | 436,487 | 29° 9’40.72”N | 48° 6’30.31”E |
| A20 PS | 48,080 | 26,747 | 28°54’36.09”N | 48°13’3.88”E |

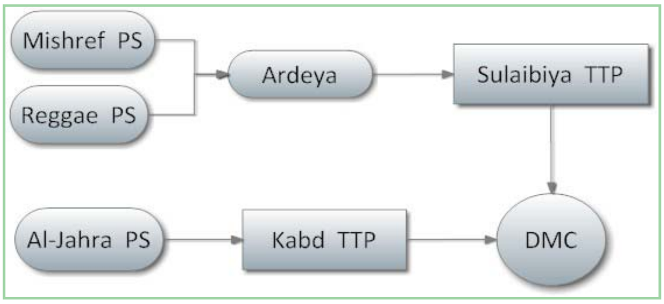


Fig. 7: Pictorial representation of major PSs that will connect to Kabd and Sulabiaya

The validated simulation model of the current wastewater network is used as basis for building the prospective sewer master plan. Forecasted inflows anticipated due to increased population and commencement of the Khiranresidential community is incorporated.Ten replications were conducted each of the length 365 days.

## 7 Analysis on the future wastewater network

The simulation shows that the prospective wastewater networkwill be able to handle the capacity of the water inflow. However, parts of the treated effluent need to be upgraded to accommodate future demand. The following are further results of the study:

1. Umm Al-Hayman will be able to distribute only 77% of its effluent the created outflow network will not be able to handle the access effluent.
2. Similarly only 70% of Sulaibiya effluent will not be utilized for produce irregation. Its best to use Sulabia effluent to re-injectnearby brackish groundwater reservoirs.
3. Only 86% of Kabdtreated effluent will be distributed and utilized.
4. Al-SulaibiyaWWTP will reach its upgraded capacity the earliest. Umm Al- Hayman will follow. See Fig. 8.
5. The simulation study also indicates that by 2050 around 380,0000 $m^3$ of sewage water might be dumped untreated into the sea if SulaibiyaWWTP was not upgraded on the time scheduled.
6. As for the major PSs, if Sulaibiya was not upgraded on time, then Mishref and EgaelaPSs are both expected to dump untreated sewage water into the sea (see Figs. 1 and 10). While Reggae, Jahra, and A20 PSs are expected to work safely within their designed capacity.
7. The planfor utilizing the existing and future sludge that is a byproduct of all WWTPs is still unknown. However, there is an inclination toward working with international consultants to study the feasibility of generating electricity from the sludge produced from WWTP[5]. This issue needs to be emphasis for future research.

## 8 Conclusions

This study has applied discrete-event simulation to assess the performance of a prospective sewermaster plan to commence by 2050 for the stateof Kuwait. In the study we collected daily flow rate records for each wastewater treatment plant, pumping, lifting and screwing stations. The flow rates were fitted into statistical distributions to be later incorporated into the simulation models.In the simulation models, entities were discretized to an equivalent of 1,000 m3. Each simulation replication consisted of 365 days. Ten replications were used to maintain the error to below five percent. The current wastewater network was created first.The validated simulation model of the current wastewater network is used as basis for building the prospective sewer master plan.Statistical model validation was conducted provide evidence that the simulation model is a legitimate representation of reality. Analysis on the simulation model for the future master plan incorporated

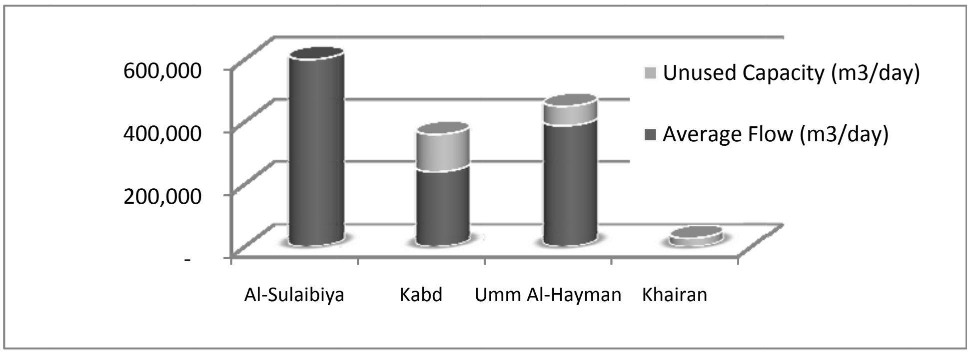


Fig. 8: Treated effluent rates of from proposed sewer master plan by 2054

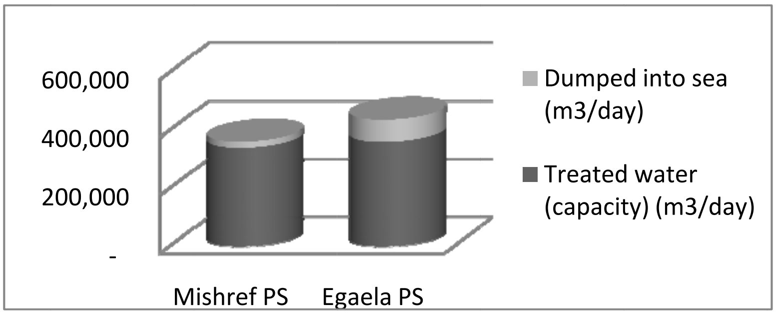


Fig. 9: PTreated effluent rates of from Mishrif and EgaelaPSs from the proposed master plan by 2054

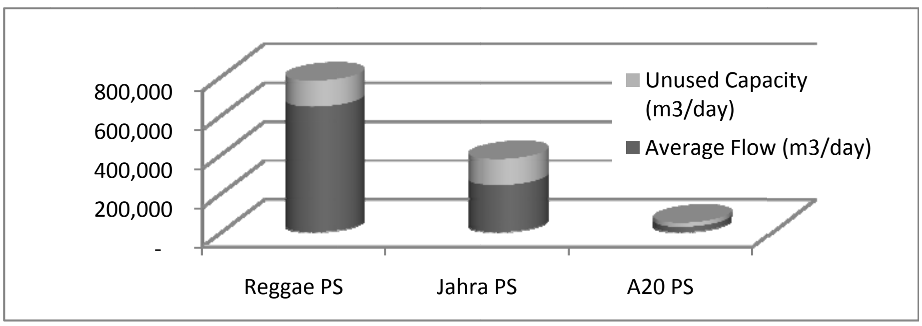


Fig. 10: Treated effluent rates of from Reggae, Jahra and A20PSs from the proposed master plan by 2054

forecasted inflows anticipated due to increased population and commencement of new residential communities. Results indicate that the future sewer master plan will efficiently handle incoming flow, expect for Al-SulaibiyaWWTP will reach its upgraded capacity the earliest followed by Umm Al-HaymanWWTP. The simulation study also predicts that if capacity increase didn't take place by 2050, around 380,0000 m3 of sewage water will be possibly be dumped untreated into the sea by Mishref and Egaela pumping stations. In addition, by year 2045 and beyond, the pipelines network for Sulaibiya effluent outflow will only be able to handle around70%. Hence, RO potable quality effluent will not be utilized for produce nor landscape irrigation. It is our recommendation that either the outflow network gets upgraded or better re-injects treated water to brackish groundwater aquifers that are very close to the plant. In all cases, an associated plan must be created to utilize the sludge which is produced as a byproduct from all wastewater plants. Future research is directed toward this direction. Simulation turned to be a valuable tool for anticipating future performance especially for such a major infrastructural project.

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