Design flow factors using socioeconomic based synthetic wastewater hydrographs for small communities

Haitham Yousri Elnakar

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Design Flow Factors using Socioeconomic Based Synthetic Wastewater Hydrographs for Small Communities

BY

Haitham Yousri Elsayed Elnakar

A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science in Environmental Engineering

Under the Supervision of:

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The American University in Cairo

Summer 2012
Acknowledgement

In the name of Allah, The Most Gracious and The Most Merciful

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Abstract

Reliable estimation of sewage flow rates is essential for the proper design of sewers, pumping stations, and treatment plants. The widely used design peaking factors for sewerage systems are usually related to the population served or the average sewage flow rate ignoring the difference between communities having same population but different socio-economic conditions and water use practice. In this study, a simulation model is developed to generate synthetic wastewater flow hydrographs resulting from a community with specific socio-economic conditions. The synthetic hydrographs are developed while retaining their commonly observed random behavior. The socioeconomic characteristics of a community are accounted for by the composition of the community and its social categories, the water use pattern of every category during the various daily activities (weekday and weekend), and the water use facilities (fixtures and appliances) available to the community. The model utilizes different water use patterns by every social group for every appliance during the different day types e.g. weekday and weekend. The use patterns account for the stochastic nature of use in terms of number of uses, duration of use and times of use in the day. Randomly generated hydrographs are generated for weekdays and weekends. The daily sewer hydrographs are transformed by hydraulic routing through the sump --pump to daily pumped flow hydrographs conveying wastewater to the treatment plant. One year of generated record of both hydrographs is statistically analyzed to derive two sets of flow factor curves to be used for the design of sewers, and the various components of the treatment plant. The flow factors are given in terms of the duration when the flow factor is sustained and the probability that the flow is not-.

The proposed model was applied to a small community with certain socio-economic conditions and population and the resulting design peaking factors were obtained and compared to flow factors derived from a limited measurement program of the wastewater hydrographs generated by the community. The results indicate the usefulness of the proposed model in predicting probable flow hydrographs from selected communities with specific socio-economic setting and population. A parametric study is carried out to investigate the effect of the community population, class and socio-economic conditions on the design flow factors.
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Chapter 1: Introduction

1.1 Introduction
Design of sewerage systems in small communities such as small rural villages and resorts have received less vigilance in comparison to larger sewerage systems. The sewage from the domestic use of water appliances and fixtures in small communities is characterized by extreme fluctuations. The efficient management of sewage flow requires a realistic acquaintance with its characteristics. Thorough characterization data of these flows are necessary not only to enhance the progress of the design of sewer networks, wastewater treatment and disposal systems, but also to facilitate the development and application of water conservation and waste load reduction strategies. Prediction of wastewater flow rates and its variation are both important at the stage of designing wastewater treatment plants (WWTPs) and during their operation.

Flow into the sewers of small communities results from the quasi-random usage of a range of home appliances (with frequency of use being related to the time of day and living and work style of the residents), each with its own characteristics. At the outfall, the observed flow in the sewer is normally continuous and tends to have repetitive diurnal patterns, although it is still subject to variability. As the sewer network becomes larger, flows from the different branches join and tend to even out the flow variation. Therefore, flow variability decreases as the population increases. Sewage discharges from small communities flowing in the trunk sewer are highly variable, and there are uncertainties in the values of the maximum and average hourly and daily-sustained flows.

Wastewater from kitchens, bathrooms, laundries and toilets ends up in the sewer network, pumping stations and finally the treatment plant. All these elements should be designed to handle their critical design flows. For sewers and pumping stations, instantaneous or peak hourly flows are critical whereas for the various units of the treatment plant other flows that would be sustained for different residence times are critical to their design.

Design codes for different localities usually include formulas to compute critical design flows using average unit flow of wastewater generated from a community and an appropriate peaking factor. These codes usually refer to a system capacity based on the average unit
sewage flow related to the level of water use in the community which might vary based on the nature of the community (urban, rural, arid climate with limited water resources or temperate climate, etc.). Peaking factors suggested usually by design codes are related to the population or daily flow rate without considering the socioeconomic status and the water use behavior of the community.

1.2 Thesis Objectives
The objective of this thesis is to estimate design flow factors for sewerage systems of small arid communities accounting for its specific socioeconomic characteristics. The required design flow factors shall apply to the various components of the sewerage system of the small community. Small communities usually have populations in the range of 1,000 to 20,000 and are served by a sewer network, a single pumping station and discharge pipe, and a wastewater treatment plant. Two flow factors will be developed; namely sewer flow factors and pumped flow factors. The design sewer flow factors shall apply to the various sewers of the sewerage system and wastewater treatment plants that may receive and handle its influent sewage by gravity. The design pumped flow factors shall apply to the pressurized sewers of the sewerage system and the wastewater treatment plants that may receive and handle its influent through pumping station. These design flow factors shall account for their sustained durations and probabilities of non exceedance.

1.3 The Approach in General
The design flow factors for the sewerage system will be developed in two steps: i) the development of a record synthetic domestic sewage hydrographs from the community under study, and ii) the statistical analysis of the record to derive the design flow factors.

A model will be developed to generate the sewage hydrographs resulting from the community at the various locations of the sewerage system. The model shall account for the water-use pattern of each social category forming the community. The water-use pattern shall reflect variability on hourly basis, with the various days of the week, and the season of the year. Measurement of typical sewage hydrographs from small communities with known
social composition, and socio-economic status will be carried out and used to calibrate and verify the hydrographs generation model.

The model will be used to generate a yearly record of the probable sewage hydrographs that might be collected from the community. The record will be statistically analyzed to derive the design flow factors accounting for the various durations of flow sustainability and probability of non-exceedance. These design flow factors will be compared with the existing design basis.

1.4 Thesis Organization
This Thesis is composed of six chapters. In addition to this Chapter, the introduction, the remaining five Chapters are organized as follows:

Chapter 2: Introduces a review of the available literature. It intertwines the different subjects discussed in this thesis. In this chapter, literature will be reviewed with comments, observations and clarifications related to the objective of this thesis.

Chapter 3: Contains the model development, and this is the core part of the thesis. It contains the development of design flow factors algorithm from the level of socioeconomic use of water fixtures and appliances till the level of design flow factors.

Chapter 4: Presents one case study for Dyar Al Rabawa compound in Sharm Alshaikh, Egypt. Actual measurements will be compared with the results from the model.

Chapter 5: Presents a parametric study of a typical composition of people for different populations and lifestyles and their effect on the design flow factors.

Chapter 6: Summarizes the study, followed by the main conclusions. Furthermore, recommendations for future study are suggested.
Chapter 2: Background and Literature Review

2.1 Introduction
The presented literature review in this chapter covers the research areas related to the objective of this thesis. The current thesis research focuses on the estimation of flow factors based on sustained flows estimated using socioeconomic based domestic wastewater hydrographs at different probabilities of non-exceedance. Estimation of flow factors has attracted environmental and sanitary engineers. The reliable estimation of flow factors has several impacts on the design of sewerage systems. The efficient engineering judgment in designing sewerage systems needs a reliable support system that may be formulas, graphs and/or experience. Over years, environmental and sanitary engineers tried to utilize the data collected at different collecting points such as intermediate sewage pump stations, wastewater treatment plants and manholes and interpret them in to formulas and graphs that can be used then in the design of sewerage systems. The gap observed was the lack of characterization of the communities for which these data was collected. In the coming sections, literature will be reviewed with comments, observations and clarifications related to the objective of this thesis.

2.2 The need for small sewerage system
The need to design a small sewerage system may appear in several cases. The design of such small sewerage systems arises in localities where it is not possible or economically infeasible to be connected to a larger sewerage system and then be treated at its wastewater treatment plant [1]. The impossibility to connect to a larger sewerage system may be the case when the topography of the community prevents such connection like islands or communities in high altitudes. The infeasibility may also be due to the large distance between communities. This case may also arise where the local regulations of cities do not allow some places like gated compounds or touristic areas to connect their sewer systems to the main sewer system of the city.
2.3 Characteristics small sewerage systems
Small capacity WWTPs are seriously affected by flow rate variation. Small communities will generally feed WWTPs with highly accentuated peaks and minimums \[^{[1]}\]. Butler and Graham (1995) indicated that these flows are generally intermittent, of relatively short durations and are hydraulically non-steady \[^{[2]}\].

As the sewer system size decreases, the captured variations tends to increase because of the lack of damping effects that characterize the larger systems as a result of the longer travel time of flow and in-sewer storage. The size of the collection system and the population density affects the degree of variation in the sewer systems. Flow sources from complexes of residential buildings, where nearly no flow is measured during part of the time, exhibit larger variations \[^{[1]}\].

Daily and weekly variations in small residential communities are often caused by commercial sources \[^{[1]}\]. The commercial contribution can be assumed to be incorporated in the per capita domestic wastewater flows if only limited commercial development exist \[^{[1]}\].

The seasonal variations also have impacts on the sewerage systems of small communities. In small communities, high levels of ground water that may be existed during the winter season; for example, may lead to multiple treatment units to be existed during that season of the year \[^{[1]}\].

2.4 Common formulas used in estimating flow factors
Sewer segments are usually designed to convey the peak (highest) flow they may receive during the lifetime of the sewerage system; i.e. during a critical design instance. For sanitary sewers, most design codes require sewers to flow partially full under such peak flows. Moreover, sewers are checked against settling conditions during instances of low flow. In summary, the design of sewers is largely determined based on the predicted future peak and low flows.

Peak and low flows are estimated as multiples of an average wastewater flow and flow variation factors. Several equations have been developed to estimate flow factors. Table (1) summarizes some of the equations that estimate flow factors. These formulae relate the flow
factors to the population served or to the generated average flow without consideration to the socio-economic status of the community. The socio-economic status significantly affects the water-use pattern of the various individuals forming the community. These water use patterns are the cause of the occurrence of coincident or distributed flows.

**Table 1:** Flow factors formulae

<table>
<thead>
<tr>
<th>Method</th>
<th>Sustained Duration</th>
<th>Peaking Factor Formula</th>
<th>Conditions of application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Babbit and Baumann 1985 [3]</td>
<td>Peak Instantaneous</td>
<td>$\frac{5}{p^{0.2}}$</td>
<td>$1 \leq P \leq 1000, P \text{ in thousands}$</td>
</tr>
<tr>
<td>Harmon 1918 [4],</td>
<td>Peak 1 – hour</td>
<td>$1 + \frac{14}{4 + \sqrt{P}}$</td>
<td>$1 \leq P \leq 1000, P \text{ in thousands}$</td>
</tr>
<tr>
<td>Egyptian code of Practice 169/1997 [5]</td>
<td>Minimum 1 – hour</td>
<td>$0.2 \frac{1}{P^{0.5}}$</td>
<td>$P \text{ in thousands}$</td>
</tr>
<tr>
<td>Munksgaard &amp; Young 1980 [6]</td>
<td>Extreme Annual Peak 4 hours</td>
<td>$\frac{2.97}{Q_m^{0.0907}}$</td>
<td>$Q_m, \text{ in } m^3/sec$</td>
</tr>
<tr>
<td></td>
<td>Extreme Annual Peak 8 hours</td>
<td>$\frac{2.9}{Q_m^{0.0902}}$</td>
<td>$Q_m, \text{ in } m^3/sec$</td>
</tr>
<tr>
<td></td>
<td>Extreme Annual Peak day</td>
<td>$\frac{1.75}{Q_m^{0.036}}$</td>
<td>$Q_m, \text{ in } m^3/sec$</td>
</tr>
<tr>
<td>Egyptian code of Practice 169/1997 [5]</td>
<td>Peak day</td>
<td>1.5-1.8</td>
<td>-</td>
</tr>
</tbody>
</table>

**2.5 Sewer sociology**

Sewer sociology is defined as “The science of society social institutions, and social relationships viewed through the eyes of sewer, specifically: the systematic study of the development, structure, interaction, and collective sewer use of organized groups of human beings [7].
The lifestyle of the served population directly affects the time and amplitude of peak or minimum flows over the day. Hydraulic loading on sewerage systems depends on large number of social variables such as habits, needs and behavioral aspects of humans. Statistical techniques can be utilized to quantify and interpret such social variables. Hydrographs monitoring for sewered communities over long periods exhibit differences between weekdays, weekends, special events, for different land uses, and lifestyle.

2.6 Wastewater generation based on community classes
The Egyptian code of practice for the design of sewers gives different classifications of the generated per capita wastewater based on the technique of water supply and the lifestyle as illustrated in Table (2).

Table 2: Different classifications of the generated per capita wastewater in Egypt

<table>
<thead>
<tr>
<th>Area classification</th>
<th>Average daily wastewater (L/capita/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-piped supply</td>
<td>20</td>
</tr>
<tr>
<td>Public Stand post</td>
<td>30</td>
</tr>
<tr>
<td>Yard Taps</td>
<td>40</td>
</tr>
<tr>
<td>House Connections</td>
<td></td>
</tr>
<tr>
<td>Low Class community</td>
<td>50</td>
</tr>
<tr>
<td>Middle Class community</td>
<td>100</td>
</tr>
<tr>
<td>High Class community</td>
<td>200</td>
</tr>
</tbody>
</table>

Geyer and Lentz presented an approach for estimating flows and flow variations. They developed a relation between the average per capita waste water flow rates and average assessed property valuation, and the relation was plotted in a linear relation with coefficient of correlation equal to 84.6%, as given by Equation (1).

\[ U = 0.017 + 0.0016W \]  

Where: \( U \) is the average per capita sewage flow rate in gallons per minute, and \( W \) is the average assessed valuation of the property in thousands of dollars.
In addition, they presented the daily peaking factors for different communities at different probabilities without defining the socioeconomic characteristics of these communities\textsuperscript{[10]}, as shown in Figure (1).

![Figure 1: Daily peaking factors for different communities at different probabilities\textsuperscript{[10]].](image)

**2.7 Wastewater treatment plants design- sustained flow considerations**

Design of wastewater treatment plants (WWTPs) is usually made based on a nominal plant flow capacity with an allowance for peaking flows. The optimum design of the various components of the WWTP should be designed based on critical design flow for each component. These design flows should be based on the relevant flow factors that account for their acceptable limits of behaviour. The expected sustained flows that persist for various time durations (2 hours or longer) are on equal importance with the expected peak flows, especially in the design of wastewater treatment facilities\textsuperscript{[11]}. The individual plant units are affected by different flow and load variations that require different peaking factors\textsuperscript{[12]}.

In order to meet new wastewater treatment objectives like “Best Practicable Technology” (BPT) and Best Available Treatment (BAT), regulatory agencies, engineers and operating
personnel must modify the traditional practices of determining the flow and waste constituent load variations\textsuperscript{[12]}. During peak flow and load periods, potential loss of treatment efficiency may occur. Wastewater treatment plants should be designed to perform effectively and to provide the desired effluent quality measures during the peak flows\textsuperscript{[12]}. The final settling tank, for example, is affected highly if not designed properly to preserve the desired amount of biological solids during peak loads\textsuperscript{[12]}. Washing out of solids due to peak flows will reduce the treatment efficiency for several days until new biological solids are formed and sufficiently accumulated\textsuperscript{[12]}. Pumps, grit chambers, grinders and screens should be designed to accommodate the extreme peak flow rates. No specific sustained duration was given by Young, Cleasby and Baumann for the extreme peak flow rates that should be used in designing such preliminary treatment units. Primary clarifiers can be designed using 4-hr sustained flow rates. Final clarifiers can be designed using 4-hr sustained flow rates or higher extreme peaks to prevent solids loss from the activated sludge systems\textsuperscript{[12]}.

Although equalization tanks have been stated to have a significant improvement to the biological treatment systems through equalizing the peak hourly flow periods, pilot scales and plant scale’ test data do not fully support this claim especially in the peak month and peak week flow and loads. The retention time at these peaks is decreased and the blending becomes ineffective\textsuperscript{[13],[14]}.

### 2.8 Probabilistic determination of flows

The probability of non exceedance is an important factor that should be considered in the estimation of the design flow factors. Gaines suggested that the engineering judgment should expect probabilities based on the function of sewers and the controlling agency permits\textsuperscript{[15]}. Zhang, Buchberger and van Zyl developed a theoretical peaking factor equation for water and domestic wastewater using Poisson rectangular pulse model, as given by Equation (2)\textsuperscript{[16]}. This equation relates the peaking flow factor with the number of homes of the community and percentile of Gumbel distribution.

\[
\begin{align*}
pF(N | p) &= \frac{N \lambda \tau \alpha}{N \lambda \tau + \xi_p} \\
&= \psi_p \left( 1 + \frac{\xi_p}{\psi_p \sqrt{\frac{1 + \Theta^2}{\psi^2 \rho N}}} \right)
\end{align*}
\]

(2)
Where:

<table>
<thead>
<tr>
<th>Term</th>
<th>Meaning</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\psi^* = \lambda^*/\lambda$</td>
<td>Dimensionless peak hourly demand factor</td>
<td>2.500</td>
</tr>
<tr>
<td>$\rho = \lambda \tau$</td>
<td>Daily average utilization factor for a single family home</td>
<td>0.045</td>
</tr>
<tr>
<td>$\Theta_4$</td>
<td>Coefficient of variation of PRP indoor water demand pulse</td>
<td>0.550</td>
</tr>
<tr>
<td>$N$</td>
<td>Number of homes in the neighborhood</td>
<td>varies</td>
</tr>
</tbody>
</table>

And the percentile of Gumbel distribution is given by Equation (3):

$$\xi_p = -\frac{\sqrt{6}}{\pi} \left[ 0.5772 + \ln \left( \frac{1}{p} \right) \right]$$

(3)

They compared the results obtained by the rectangular pulse model at percentile 99.9 to some empirical methods like the Babbitt and Baumann and Harmon formulas at different population figures. The results from the rectangular pulse model gave values lower than those of Babbitt and Baumann equation, and higher than those of Harmon equation\(^\text{[16]}\).

Some reliable design decisions should be taken by the designer of sewerage systems. Designers should be able to weigh the amount of uncertainty that should be taken into consideration while designing a certain component of a sewerage system. This design decision should not, for example, allow the wastewater to flow back into the basement of buildings after some years of community development\(^\text{[15]}\). The role of confidence limits and the sustained duration over which the peaking factors are calculated is based on the function of the sewerage unit under consideration\(^\text{[15]}\).

2.9 Use of appliances and the generated hydrographs

There are different percentiles of water use of the domestic water fixtures and appliances. The use of each appliance may vary based on socioeconomic factors, place of study, climatic
and seasonal conditions or traditions and religion. Table 3 gives typical water use percentiles in various countries \[17\].

**Table 3: Water use in Various Countries**\[17\]

<table>
<thead>
<tr>
<th>Water Usages</th>
<th>UK (%)</th>
<th>Germany (%)</th>
<th>USA (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toilet</td>
<td>28.2</td>
<td>29</td>
<td>28</td>
</tr>
<tr>
<td>Kitchen sink</td>
<td>14.0</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Bath/ Shower/Hand basin</td>
<td>28.2</td>
<td>37</td>
<td>20</td>
</tr>
<tr>
<td>Laundry</td>
<td>12.0</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td>Other (Garden tap, etc.)</td>
<td>17.6</td>
<td>19</td>
<td>42</td>
</tr>
</tbody>
</table>

Butler and Graham developed a model to predict wastewater hydrographs for dry weather flow conditions that account for the wastewater inflow and the routing in the sewer network \[2\]. They presented the term “Expected Flow” as the product of the number of appliances connected to a node, the average dwelling occupancy, and the sum of the product of the probability of using an appliance, the discharge of the appliance and the fraction of appliances upstream from the node at a time for all appliances \[2\]. The probability of using an appliance was assumed to be the product of the time of use of a certain appliance and its frequency of use \[2\]. The model developed by Butler and Graham utilized the data collected by Butler that were collected in the form of the frequency of use of water closets, wash basins, sinks, baths, showers and washing machines and the discharge characteristics of these appliances in terms of duration of use and volume \[8\]. These data were collected as average values with a range for all user types without classifying the user types in terms of male or female, work style, age, and others \[8\].
Chapter 3: Model Development

3.1 Introduction
A simulation model is developed to generate daily dry-weather wastewater hydrographs resulting from a certain small arid community. The community is divided into various categories; each with a similar water use pattern. The water use pattern for each category will be assumed to vary from a weekday, a weekend, a holiday or a special event. The water use pattern will account for the stochastic use of fixtures and appliances by members of the same category, day-to-day use by the same person, and the generated wastewater flow for the same type of fixture. The model can generate the synthetic hydrograph at different locations (nodes) in the sewerage system by considering the fraction of the community population existing upstream of the node. For small communities, the effect of hydrograph shift and distortion due to storage and travel time will be assumed negligible due to the small size of the community and its sewerage network. The following sections elaborate on the model development which will be applied to generate a synthetic record of generated wastewater from the community under consideration and accounting for its socio-economic status.

3.2 Model assumptions
The model is based on the following assumptions:

1- People living in homogeneous 'neighbourhood' with similar lifestyle generally exhibit same water use tendencies that reflect on the wastewater generation.

2- There is a general repetitiveness in the wastewater hydrograph patterns during weekdays, weekends, and special events, and the water-use patterns in these days differ according to the working style of the members of the community. However, the repetitive pattern shall also include randomness to reflect the human behaviour.

3- The damping effects that characterize the larger systems due to the longer travel time of flow and in-sewer storage are neglected.

4- The hydrographs include only domestic sewage excluding storm water which is the case for arid desert communities or for communities with separate wastewater collection systems.
3.3 Community composition

A community is composed of a number of social categories (k); each with a similar water-use pattern: working men, working women, stay-at-home women, students and school children, stay-at-home children and senior citizens. It is assumed that the community is predominantly residential with small commercial and educational facilities that will not alter the generated wastewater hydrograph. The number of persons in any category \( L \) (\( L=1, 2... k \)) is estimated as a fraction of the total community population with a specific water use pattern (\( L_1, L_2, L_3... k \)). There are different water-use patterns for each social category \( L \) depending on the type of day (d): weekday, weekend, holiday or special event. The number of people (\( N_{L,d} \)) with the same pattern is a fraction of the total population (P), as shown in Equation (4).

\[
N_{L,d} = C_{L,d} P
\]  

(4)

Where: \( N_{L,d} \) = the number of people within the social category \( L \) with the same pattern during day type (d) either weekend or weekday; \( P \) = the total population contributing to the node under consideration; and \( C_{L,d} \) = fraction of the population in category \( L \) on day (d).

3.4 Water use pattern for each fixture/appliance

The generated wastewater hydrograph on a typical day (d) from an individual of category (L) of the community is assumed to be the sum of component discharges resulting from the person’s use of the various fixtures and appliances at home during the day. The water use pattern of a certain fixture or appliance (F/P) is characterized by the number of uses, the times of its use during the day, and the duration of use, as shown in Figure (2). Such water use pattern of a certain F/P can be monitored for each category and day of use for a community with a certain socioeconomic status.

**Figure 2:** Water use pattern of fixture or appliance for a person from social category (L) on day (d)
Figure 2 shows the water-use pattern of a person of social category (L) who uses on the average the given \( i^{\text{th}} \) F/P with a frequency \( n_{L,i} \) equal to five times on a certain day type (d). The times \( t_1, t_2, t_3, t_4, \text{ and } t_5 \) are the most common times for the person to start use of the \( i^{\text{th}} \) F/P for a duration of \( \Delta t \). Obviously, the human behaviour is not repetitive in the form of identical daily cycles; therefore the above variables will be treated as random variables. The start of the times of use (\( t_i \)) are considered as normally distributed random variables with mean values \( t_i \) and standard deviations \( \sigma_i \) that reflects the variation in the behaviour of the category L-person on a day type- d, as shown Figure 3.

\[ p(t) = \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{t-\mu}{\sigma}\right)^2} \]  

(5)

Where: \( \mu \) is the time (\( t_i \)) at which the F/P is most likely to be used by an individual of category (L); and \( \sigma_i \) is the standard deviation for the \( i^{\text{th}} \) use.

Figure 3 shows the probability density \( p(t) \) that the person starts his/her use No. i of the F/P at the shown time of the day. The time of occurrence of the \( i^{\text{th}} \) use is assumed to have the probability density function (PDF) given by Equation 5.

The probability that the person (L) starts to use the fixture/appliance during the period from (\( t_i \)) to (\( t_i + \Delta t \)) is given by the area under the PDF curve corresponding to that duration. The
same PDF curve of Figure 3 can be interpreted as the fraction \( N_t/N_L \) of the category-L individuals that might be using the F/P at the particular time \( t_i \) during the period \( \Delta t \).

To proceed with the simulation of the hourly uses of F/P by the L-individual the simulation period (typically a day) is divided into time increments, \( \Delta T_s \). The probability \( (t) \) that an L-person uses the F/P at any time of the day, \( t \), during the period \( \Delta T \) equals the probability density \( p(t) \) times the period \( \Delta T \), as shown in Equation (6).

\[
 f(t) = \Delta T \cdot \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{1}{2} \left( \frac{t - \mu}{\sigma} \right)^2}
 \]  

(6)

Figure 4 shows the probability function \( f(t) \) of the time to start use of the F/P under consideration for the four uses per day. During certain times of the day several uses are likely to overlap.

![Figure 4: Normal probability density function of the time of uses of F/P.](image)

The probability of use of the F/P at any time \( t \) will be adjusted such that the area under the final probability distribution is equal to 1, as seen from Equation 7. The probability of using the F/P \( f_u(t) \) is the union of probabilities of the overlapping uses. The probability distribution \( f_u(t) \) of Figure 5 is derived from the superposition of probability distributions of \( r_{L,i} \) uses and is calculated using Equation (7) for each time step. However, the probability of use will apply to the \( r \) uses.

\[
 f_u(t) = \left[ \sum_{y=1}^{r} f_y(t) - \sum_{y=1}^{r} \sum_{z=y+1}^{r} f_y(t) f_z(t) + r \prod_{y=1}^{r} f_y(t) \right] / r_{L,i}
 \]  

(7)
Figure 5: Probability of use of an F/P by an L-person starting at time t during ΔT

The probability “histogram” depicted in Figure 5 gives the probability f(t) of use of an F/P by an L-person at time t during ΔT. The probability P(n_L) of L-users (n_L) to be using the F/P simultaneously at time t from the entire population of L-persons (N_L) follows a binomial probability distribution and can be computed from Equation 8.

$$P_{nL} = \frac{N_L}{n_! (N_L-n) !} f_u(t)^n (1 - f_u(t))^{N_L-n}$$  \hspace{1cm} (8)

The mean expected number and standard deviation of people $E(n)_{d,L,i,t}$ who start using simultaneously the (F/P) at time t of day type (d) is also given by the binomial distribution as shown in Equation (9) for the mean and Equation (10) for the standard deviation.

$$E(n)_{d,L,i,t} = N_L * P_{nL}$$  \hspace{1cm} (9)

$$\sigma_n = \sqrt{N_L * f_u(t) * (1 - f_u(t))}$$  \hspace{1cm} (10)

3.5 Wastewater generated when using an appliance and at nodes

Equation 6 gives the expected number of L-persons (n_L) out of the total number of L-persons (N_L) of category (L) who might start using appliance (i) during a time increment ΔT at a certain time (t) of a day type (d).

The use of (F/P) by the entire category L during the day of type- d as given by Equation 6 can now be linked to the wastewater flow generated from the (F/P)_i. Certain fixtures generate flow with random amounts that would last for random durations (Δt)_u, e.g. showers and sink faucets or taps. The volume and duration of use (Δt)_u varies from an individual to another and
from one use to another for the same person. On the other hand, some appliances generate fixed volumes for nearly fixed durations (e.g. the flush tank and washing machines).

To account for the various sources of variability in the generation of wastewater from the community, the number of uses \( r_{L,i} \) of an appliance \( i \), the generated wastewater volume of the fixture or appliance \( V_i \), and the duration of use \( \Delta t_u \) will all be dealt with as normally distributed random variables. Each variable has its mean and standard deviation as will be discussed in section 3.6.

The duration and volume of waste generated by an appliance \( i \) by a user profile \( L \), \( V_{l,L} \), is expressed by a random value that represent the normal probability of water use of a certain appliance. The expected number of people \( E(n)_{d,L,i,t} \) times the number of uses \( r_{i,L} \) times the volume of single use \( V_{l,L} \) over the duration of single use \( \Delta t_u \) gives the discharge \( Q_{L,i,t} \),

\[
Q_{L,i,t} = E(n)_{L,i,t} \ r_{L,i} \ \frac{V_{l,L}}{\Delta t_u} = E(n)_{L,i,t} \ r_{L,i} \ q_{L,i}
\]  

(11)

The unit wastewater discharge generated during each \( \Delta t \) at time \( t \) of the day \( d \) by category \( L \) when using a single appliance \( i \), will be summed up to account for all other appliances \( i=1,2,...,j \) and community categories \( L=1,2,...,k \), Equation.(12).

\[
Q_{d,t} = \sum_{i=1}^{j} \sum_{L=1}^{k} Q_{L,i,t}
\]  

(12)

3.6 Model default values

3.6.1 Types of appliances and fixtures and day and user types

Five types of appliances and fixtures \( i \) are assumed to prevail in all types of residential communities namely water closet (WC \( i_1 \)), washroom basin or lavatory (\( i_2 \)), shower (\( i_3 \)), kitchen sink (\( i_4 \)), and washing machine (\( i_5 \)). Two day types \( d \) are considered namely weekday (WD) and weekend (WE). Although holidays and special events may have different water use patterns, yet they may not change the statistical pattern of the hydrographs due to their limited occurrence. For the regular weekdays, six main social categories forming most of the communities are assumed based on the working and
educational styles. These categories are morning workers (L₁), afternoon workers (L₂), working women (L₃), stay home Women (L₄), school children (L₅) and stay home children (L₆). During weekends, certain social categories which have different water use patterns during the weekdays may have similar use patterns during weekends. The user types (L) are reduced to men or children (L₁) and women (L₂) because of the water-use practises observed over the weekend.

3.6.2 Durations, volumes and frequencies of the use of F/P use

Over the period 2010-2012, several field surveys were conducted for 14 communities in Egypt and Saudi Arabia with different socioeconomic characteristics. These field surveys give some knowledge and allow for reasonable assumptions to the water use characteristics for different social classes. The assumed data along with published literature values are the bases for tables 4, 5, 6, 7, 8, 9, 10 and 11 which characterize the use of fixture and units by the class of the community and their discharge characteristics. It should be noted that morning workers (L₁), afternoon workers (L₂), school children (L₅) and stay home children (L₆) will be dealt as men or children (L₁) during weekend modelling, and working women (L₃) and stay home Women (L₄) will be dealt as Women (L₂) for weekend modelling.

3.6.3 Synthetic water use patterns

3.6.3.1 Weekdays

The synthesized water use probability patterns for the six main social categories forming the most communities are graphed in Figures 6, 7, and 8 for the three appliances (WC, wash basins, showers), respectively. The times of use, frequency of use per day are set to reflect the use of facilities on working day by them. The use of the kitchen sink and washing machines are assigned to both the stay-home and working women, but with different use patterns as shown in Figures 9 and 10.

3.6.3.2 Weekends

The water use patterns for the various social categories are assumed to reflect that these days are non-working ones. The water use patterns, as shown in Figures 11, 12, 13, 14 and 15, reflect the human activities of the family members during these days and are much related to the cultural and religious factors.
Table 4: Mean and standard deviation of the volume of a single use of a water appliance or fixture

<table>
<thead>
<tr>
<th>Appliance or Fixture</th>
<th>High class community</th>
<th>Middle class community</th>
<th>Low class community</th>
<th>Ref. (8) Butler 1991</th>
<th>Ref. (18) BS 8301: 1985</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (L)</td>
<td>STDEV (L)</td>
<td>Mean (L)</td>
<td>STDEV (L)</td>
<td>Mean (L)</td>
</tr>
<tr>
<td>WC (i₁)</td>
<td>10</td>
<td>4</td>
<td>10</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>Basin (i₂)</td>
<td>8</td>
<td>3</td>
<td>5</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Shower (i₃)</td>
<td>120</td>
<td>50</td>
<td>60</td>
<td>10</td>
<td>30</td>
</tr>
<tr>
<td>Sink (i₄)</td>
<td>15</td>
<td>10</td>
<td>12</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>Washing Machine (i₅)</td>
<td>25</td>
<td>10</td>
<td>25</td>
<td>5</td>
<td>15</td>
</tr>
</tbody>
</table>

Table 5: Mean and standard deviation of the duration of use of a single use of a water appliance or fixture

<table>
<thead>
<tr>
<th>Appliance or Fixture</th>
<th>High class community</th>
<th>Middle class community</th>
<th>Low class community</th>
<th>Ref. (8) Butler 1991</th>
<th>Ref. (18) BS 8301: 1985</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (SEC)</td>
<td>STDEV (SEC)</td>
<td>Mean (SEC)</td>
<td>STDEV (SEC)</td>
<td>Mean (SEC)</td>
</tr>
<tr>
<td>WC (i₁)</td>
<td>10</td>
<td>5</td>
<td>10</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>Basin (i₂)</td>
<td>120</td>
<td>60</td>
<td>90</td>
<td>30</td>
<td>60</td>
</tr>
<tr>
<td>Shower (i₃)</td>
<td>600</td>
<td>200</td>
<td>300</td>
<td>150</td>
<td>200</td>
</tr>
<tr>
<td>Sink (i₄)</td>
<td>180</td>
<td>120</td>
<td>130</td>
<td>60</td>
<td>90</td>
</tr>
<tr>
<td>Washing Machine (i₅)</td>
<td>1000</td>
<td>600</td>
<td>1000</td>
<td>600</td>
<td>800</td>
</tr>
</tbody>
</table>
Table 6: Frequency of use of appliances for High Class individuals during weekdays

<table>
<thead>
<tr>
<th>Appliance or Fixture</th>
<th>Frequency of uses/day ( r )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Morning Workers (L₁)</td>
</tr>
<tr>
<td>WC (i₁)</td>
<td>Mean</td>
</tr>
<tr>
<td></td>
<td>5</td>
</tr>
<tr>
<td>Basin (i₂)</td>
<td>7</td>
</tr>
<tr>
<td>Shower (i₃)</td>
<td>1</td>
</tr>
<tr>
<td>Sink (i₄)</td>
<td>X</td>
</tr>
<tr>
<td>Washing Machine (i₅)</td>
<td>X</td>
</tr>
</tbody>
</table>

Table 7: Frequency of use of appliances for High Class individuals during weekends

<table>
<thead>
<tr>
<th>Appliance or Fixture</th>
<th>Frequency of uses/day ( r )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Morning Workers (L₁)</td>
</tr>
<tr>
<td>WC (i₁)</td>
<td>Mean</td>
</tr>
<tr>
<td></td>
<td>7</td>
</tr>
<tr>
<td>Basin (i₂)</td>
<td>9</td>
</tr>
<tr>
<td>Shower (i₃)</td>
<td>1</td>
</tr>
<tr>
<td>Sink (i₄)</td>
<td>X</td>
</tr>
<tr>
<td>Washing Machine (i₅)</td>
<td>X</td>
</tr>
</tbody>
</table>
Table 8: Frequency of use of appliances for Middle Class individuals during weekdays

<table>
<thead>
<tr>
<th>Appliance or Fixture</th>
<th>Morning Workers (L₁)</th>
<th>After Noon Workers (L₂)</th>
<th>Stay Home Women (L₃)</th>
<th>Working women (L₄)</th>
<th>Stay home children (L₅)</th>
<th>School children (L₆)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean STDEV</td>
<td>Mean STDEV</td>
<td>Mean STDEV</td>
<td>Mean STDEV</td>
<td>Mean STDEV</td>
<td>Mean STDEV</td>
</tr>
<tr>
<td>WC (i₁)</td>
<td>5 2</td>
<td>5 2</td>
<td>7 2</td>
<td>5 2</td>
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</tr>
<tr>
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<tr>
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<td>0.5 0.25</td>
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<td>0.5 0.25</td>
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<tr>
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Table 9: Frequency of use of appliances for Middle Class individuals during weekends

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</tr>
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<td>Shower (i₃)</td>
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<tr>
<td>Sink (i₄)</td>
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Table 10: Frequency of use of appliances for Low Class individuals during weekdays

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<th>STDEV</th>
<th>Mean</th>
<th>STDEV</th>
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<td>7</td>
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Table 11: Frequency of use of appliances for Low Class individuals during weekends

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<th>STDEV</th>
<th>Mean</th>
<th>STDEV</th>
<th>Mean</th>
<th>STDEV</th>
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<td>2</td>
<td>7</td>
<td>2</td>
<td>7</td>
<td>2</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Basin (i₂)</td>
<td></td>
<td>7</td>
<td>2</td>
<td>7</td>
<td>2</td>
<td>7</td>
<td>2</td>
<td>7</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Shower (i₃)</td>
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<td>0.1</td>
<td>1</td>
<td>0.1</td>
<td>0.15</td>
<td>0.1</td>
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<td>0.1</td>
<td>1</td>
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<tr>
<td>Sink (i₄)</td>
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<td>X</td>
<td>X</td>
<td>X</td>
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<td>2</td>
<td>5</td>
<td>1</td>
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<td>Washing Machine (i₅)</td>
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<td>X</td>
<td>X</td>
<td>X</td>
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</table>
Figure 6: Probability distribution of using WC for different user types (L) during weekdays

Figure 7: Probability distribution of using Washroom Basin for different user types (L) at weekday

Figure 8: Probability distribution of using Shower for different user types (L) at weekday
Figure 9: Probability distribution of using Sink for different user types (L) at weekday

Figure 10: Probability distribution of using Washing Machine for different user types (L) during weekday

Figure 11: Probability distribution of using WC for different user types (L) during weekend
Figure 12: Probability distribution of using Washroom Basin for different user types (L) during weekend

Figure 13: Probability distribution of using Shower for different user types (L) at weekend

Figure 14: Probability distribution of using Sink for different user types (L) during weekend
3.7 Simulation of random variables to generate wastewater hydrographs

A simulation is useful only if it closely mirrors real-world outcomes. The steps required to simulate the random variables in order to generate wastewater hydrographs are presented below based on the previous sections.

3.7.1 Description of the possible outcomes and model setup

The purpose of the model is to generate two sets of hydrographs; namely sewer flow hydrographs and pumped flow hydrographs. These two sets can be used then to generate sewer and pumped flow factors. These hydrographs are daily generated record of wastewater flow rates versus time of the day. The time step of the model that divides the time scale or X-axis should be selected in a way that allows the designer to capture the extreme peaks at certain instants. However, this is based on the computer capabilities and the judgement of the designer. The model time step that will be used over this thesis is 5 minutes.

3.7.2 Linking outcomes to random variables

To simulate sewer flow hydrographs, the components that contribute to form flow hydrographs; namely the number of uses ($r_{L,i}$) of an appliance (i), the generated wastewater volume of the fixture or appliance ($V_i$), and the duration of use ($\Delta t$) will be dealt with as normally distributed random variables each with a mean and a standard deviation. Each use of an appliance or fixture will have its selected time of use $t_i$ which is the most likely time to

Figure 15: Probability distribution of using Washing Machine Basin for different user types (L) during weekend
start that use. There will be a number of uses \( r_{L,i} \) with their assumed \( t_i \). The number of uses, the timing for each use, and the standard deviation that characterizes the variation in \( t_i \) will all depend on the user type (L) and varies with the type of day (d).

Equation (7) is then used at each time step to superimpose probability distributions of \( r_{L,i} \) and get the probability of using a certain appliance \( i \) by a certain user type (L). For the obtained probability from Equation (7) and the number of people in a certain user type (L), the mean expected number of L-persons \( n_L \) out of the total number of L-persons \( N_L \) of category (L) who might start using appliance \( i \) during a time increment \( \Delta T \) at a certain time \( t \) of a day type (d) can be obtained using Equation (9) along with its standard deviation using Equation (10).

As stated before, since the quantities of the generated wastewater volume of the fixture or appliance \( V_i \), and the duration of use \( \Delta t \) are not generally constant, these quantities will be dealt with as normally distributed random variables. As the two distributions have non-zero mean then the form used by David Hinkley 1969 can be used \[19\]. In the absence of correlation \( \text{cor} \ (V_{Li}, \ \Delta t) = 0 \), the probability density function of the ratio \( q_{L,i} = Z = X/Y \) which is the division of the two normal variables \( V_{Li} = X = N(\mu_X, \sigma_X^2) \) and \( \Delta t = Y = N(\mu_Y, \sigma_Y^2) \) is given by Equation (13).

\[
p_Z(z) = \frac{b(z) \cdot c(z)}{a^2(z)} \frac{1}{\sqrt{2\pi} \sigma_x \sigma_y} \left[ 2\Phi \left( \frac{b(z)}{a(z)} \right) - 1 \right] + \frac{1}{a^2(z) \cdot \pi \sigma_x \sigma_y} e^{-\frac{1}{2} \left( \frac{\mu_X^2}{\sigma_X^2} + \frac{\mu_Y^2}{\sigma_Y^2} \right)}
\]

(13)

Where:

\[
\alpha(z) = \sqrt{\frac{1}{\sigma_x^2} z^2 + \frac{1}{\sigma_y^2}}
\]

\[
b(z) = \frac{\mu_x}{\sigma_x^2} z + \frac{\mu_y}{\sigma_y^2}
\]

\[
c(z) = e^{\frac{1}{2} \frac{\mu_Y^2}{\sigma_Y^2} \Phi(z)} - \frac{1}{2} \left( \frac{\mu_X^2}{\sigma_X^2} + \frac{\mu_Y^2}{\sigma_Y^2} \right)
\]

\[
\Phi(z) = \int_{-\infty}^{z} \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2} u^2} du
\]
For each time step ($\Delta T$) and a certain user type (L) who starts using certain type of appliance (i), the corresponding random discharge can be obtained. During each time step ($\Delta T$), the expected value $E(Q_{i,t})$ of discharge for all user types who start using a certain appliance is the sum of random discharges which is equal to the sum of their expectations, Equation (14).

$$\sum_{i=1}^{k} E(Q_{i,t}) = E(Q_{L_1,t} + Q_{L_2,t} + \cdots + Q_{K,t}) = E(Q_{L_1,t}) + E(Q_{L_2,t}) + \cdots + E(Q_{K,t})$$ \hspace{1cm} (14)

And the variance is the sum of variance of each random variable, Equation (15)

$$VAR(\sum_{i=1}^{k} Q_{i,t}) = \left[ \sum_{y=1}^{k} VAR(Q_{L_y,t}) - \sum_{y=1}^{k} \sum_{z=y+1}^{k} E(Q_{L_y,t})E(Q_{L_z,t}) + k \prod_{y=1}^{k} E(Q_{L_y,t}) \right]$$ \hspace{1cm} (15)

With the same concept in Equations 14, and 15 during each time step ($\Delta T$), the expected value $E(Q_t)$ of discharge for all user types who start using all appliances is the sum of random discharges which is equal to the sum of their expectations, as mentioned before in Equation 9.

### 3.7.3 Generation of random numbers

When it comes to choosing a means to select random numbers (Step 2 above), several options exist. Tables of random numbers (often found in the appendices of statistics texts) are one option. A random number generators module can be found in Microsoft Excel. This work uses the MS. Excel associated with @Risk simulation Add Ins. Any random number between (0, 1) can be chosen, and based on the random number, the simulated outcome can be observed.

### 3.7.4 Simulation runs-Synthetic Daily Hydrographs

The development of the design flow factors for the sewerage system will consist of two steps: i) the development of synthetic domestic sewage hydrographs from the community under study, and ii) the statistical analysis of the generated hydrographs to derive the design flow factors.

The simulation model will be applied to generate one year record of sewage hydrographs resulting from the community at the various locations of the sewerage system. The model shall account for the water-use pattern of each social category forming the community. The
water-use pattern shall reflect variability on hourly basis, with the various days of the week, and the season of the year. The daily sewage hydrographs generated will not be identical as several key parameters are considered random variables with specified mean values and standard deviations,

The simulation model will be applied repeatedly to generate a record of one year daily wastewater hydrographs generated from the served population. The simulation runs will be carried out to generate 313 random weekdays and 52 random weekends to form a full year of record. For intermediate nodes (or junctions) of the sewerage system, the population existing upstream of the node is used to generate the node hydrograph. For the final sewer discharging the collected wastewater into the sump of the pumping station and then conveyed by the force main to the treatment plant the population used is the entire population of the community. The design of any sewer will be based on the critical discharge such sewer will be subject to. These critical design discharges will be estimated using statistically derived flow factors from the record of service of the sewer which is assumed to be multiples of the synthetically derived yearly record.

3.7.5 Analyses of the simulated outcomes and reporting the results

The simulation outcome is a set of sewer hydrographs with mean and standard deviation. Although, the model can predict a certain hydrograph at a certain probability, this hydrograph does not correspond to a typical day, but it is an envelope to all hydrographs that are equal to or less than the defined probability.

3.7.6 Derivation of simulated pumped flow hydrographs from simulated sewer flow hydrographs

A Small community, due to its limited areal extent, is typically served by one pumping station to discharge the wastewater collected by the gravity sewer network to the treatment plant. The capacity of pumps, the hydraulic design of the sump, and the operation of the pumping station accentuate the inflow hydrograph reaching the treatment plant. Therefore, the estimated flows usually given by the design codes for sewer flow may not be readily applicable to the design of the individual components of the treatment plant. The outflow of
the pumping station should be equally analysed and predicted. Figure 16 shows a schematic view of the In/out flow of a pump station that pumps sewage to a wastewater treatment plant (WWTP).

**Figure 16**: Schematic view of the In/out flow of a pump station that pumped sewage to a wastewater treatment plant WWTP.

The maximum instantaneous flow recorded over the sewer hydrographs will be used to design and choose the pump(s) capacity ($Q_p$) and the sump dimensions. The minimum storage volume is calculated using Equation (16). The time of starts per hour ($T$) will be assumed to be from (4-6) starts per hour for small to medium size motors.

$$\text{Min. Storage volume} = V = \frac{Q_p \times T}{4}$$  \hspace{1cm} (16)

The simulation model includes an algorithm to generate pumped flow hydrographs from the synthetic sewer inflow hydrograph using storage routing through the sump and the pump capacity and its operating rules. For each day of the sewer set of hydrographs and for the designed storage volume, the area under the sewer hydrograph from the start of each day is calculated and counted as one pulse of PUMP-ON. The pump then will operate till the storage volume becomes near empty then turns off and the pump is PUMP-OFF, and the area under the hydrograph is then summed up over time till the storage volume is equal to the pre-
designed value and the PUMP-ON. A new set of pumped flow hydrographs is now ready to be statistically analysed to derive pumped flow factors.

Using the model described earlier and the model default values for low class community, Figures 17 and 18 show the sewer hydrograph and the pumped flow pulses for one day at the outfall of the final sewer of a 1000 capita low class community, respectively. These graphs show the difference between the continuous oscillating sewer flow and the “surge-like” pumped flow.

**Figure 17:** Sewer flow generated from a 1000 capita of low class community with an average flow 62 m3/day.

**Figure 18:** Pumped flow pulses generated from a 1000 capita of low class community with an average flow 62 m3/day
3.8 Statistical analyses of sewer and pumped flow hydrographs to get flow factors

Sewer flow varies with hour of the day, while the total daily flow varies with day of the year. The hydraulic design of sewers, pumping stations, and the various components of the wastewater treatment is based on design or critical values of the discharges these elements will be subject to.

For sewers conveying peak flows with short durations should be handled by the sewer under consideration while satisfying the set performance parameters. Design codes usually specify for sewers that the “highest” discharge does not fill the sewer section beyond an acceptable limit. The codes may also set limits on the maximum non-destructive permissible velocity and the minimum non-settling velocity. Many designers define the design peak discharge for sewers to be the highest instantaneous flow that the sewer may be required to convey. Other designers may use the peak hourly flow as the critical design value, on the basis that higher instantaneous values that would last periods less than one hour may not seriously violate the set performance parameters for the sewer. In-sewer storage is assumed to handle sub-hourly variations and can justify basing the design on the hourly rather than the instantaneous flow.

Similarly for each component of the wastewater treatment there is a critical or design for its hydraulic design. For certain components, the design flow could be peak instantaneous one such as the inlet screens and inlet pumps. For other units, the residence time may be long and surges or short-duration discharges may not affect the performance of the unit. The design flow of these units is the highest sustained flow these units will experience for the specified duration $T_d$.

An equally important attribute of the design peak flow of a sewer or unit is the definition of “peak”. Such definition should be clearly defined when the wastewater flow records are analysed to establish the peak or “highest” flow. The highest flow of a record with one month in length is different from the highest value for a one year-length record. A better approach would be to define a peak flow by the per cent time it will not be exceeded. Theoretically the peak or highest flow is the one that will not be exceeded 100 per cent of the time. However, establishing such value is neither practical nor needed. For some units of the sewerage system if the actual flow exceeds the design value very rarely and such exceedance does lead to intolerable effects, then the design may be based on non-exceedance
probability of less than 100 per cent. The allowable degree of exceedance depends on the consequences of such exceedance and the economic impact of using flows with lower non-exceedance probability.

The studies on flow variation and design codes usually specify factors that relate the peak design flows to the average flows by the use of peaking factors.

Two peaking factors will be used to capture flow variations: $P_{hr-t-avghr}$ to account for hourly variation within a given day, and $P_{i-avg}$ to account for the variation of the daily flow within the record. Both factors may be combined to give peak flow factor ($P_{max/min.t}$) as:

$$P_{max/min.t} = (P_{max/min hr-t-avghr}) (P_{i-avg})$$

(17)

The $P_{max/min hr-t-avghr}$ is defined as:

$$P_{max/min hr-t-avghr} = \left( \frac{Q_{max/min hr-t}}{Q_{avg-1hr}} \right)$$

(18)

Where $(Q_{max/min hr-t})$ = the average flow during a duration $(t)$ hours when the sustained flow $Q$ is either maximum or minimum. For every day of the synthetic record $Q_{max/min hr-t}$ is calculated for all durations $t = (1, 2, \ldots, 24)$; $Q_{avg-1hr}$ = the average hourly flow for that day of synthetic record.

The peaking factor given by Equation 17 is calculated for every day of the record and for every duration $t$. For every duration $(t)$, there will be peaking factors equal to the number of days $(N)$ for which hourly-flow record is available. All $(N)$ peaking factors $P_{max/min hr-t-avghr}$ for the same $(t)$ are sorted in a descending order. A factor with a rank $(m)$ in the record is assigned a probability $(p)$ of not being exceeded: $p = (m-0.5)/N$.

The $P_{i-avg}$ is the factor that accounts for variation of daily flow $(Q_i)$ during day $(i)$ of the record with respect to the average daily flow $(Q_{avg-daily})$ of the record $(N)$ as in Equation 19.

$$P_{i-avg} = \left( \frac{Q_{i}}{Q_{avg-daily}} \right)$$

(19)
The \((N)\) values of the daily peaking factor \((P_{i-\text{avg \, d}})\) are sorted in a descending order. A factor with a rank \((m)\) in the record is assigned a probability \((p)\) of not being exceeded: \(p = (m-0.5)/N\).

Normal probability distribution is assumed to apply to the three-flow variation factors given by Equations (14-16). Then, the cumulative probability distribution (CPD) factor will plot as a straight line if the CPD is plotted on graph with normal probability- linear scales, as shown in Figure (19). The fitted straight line is subsequently used to predict the extreme events of probabilities non-exceedance of any percentage.

![Cumulative Normal Probability Ratio of Maximum 1 hr Sewer Flow Rate to Average Daily Sewage Flow Rate on all Length of Record](image)

**Figure 19:** Probability of non-exceedance of peak 1 hour flow factor \((P_{\text{max-1hr-avghr}})\) for sewage flows
Chapter 4: Case Study

4.1 Introduction

The model developed in chapter (3) to predict design flow factors using synthetic wastewater hydrographs is applied for a case study: Dyar Al Rabwa (DAR) which is located in Sharm Al Sheikh – South Sinai- Egypt. The community has an area of about 97,500 m² (23 acres) with 950 capita. The community is mostly composed of villas and under construction hotel. Dyar Al Rabwa is a predominately middle to high class homogeneous residential compound, and its residents are mostly Egyptians with very few foreigners. No commercial, industrial or recreational sources of wastewater presently exist at DAR compound. The wastewater hydrographs generated by the community were measured in the period from 23rd of June till the 7th of July 2011. The number of runs used in the simulation is 312 for model weekdays and 52 to model weekends that summed up to form a year of synthesized record.

4.2 DAR sewerage system and measurements’ program

The sewer system is a combined sewer system although it rarely rains. Gravity sewers collect the wastewater to a pumping station that discharges via a small force main to a wastewater treatment plant serving this compound. The pumping station has one-duty submersible pumps with a capacity of 32 m³/hr.

Due to the difficulty of measuring gravity flow in the partially flowing full incoming sewer, the sewage flows pumped to the treatment plant were measured instead by the station flow meter, i.e. the pumped flow hydrograph was measured. The measured flows were also confirmed by a portable ultrasonic flow meter that was mounted on the discharge pipe of the pumping station. Figure 20 shows the portable ultrasonic flow meter that was mounted on the discharge pipe of the DAR pumping station. The incoming sewer hydrograph was derived by the hydraulic routing of the measured pumped flow hydrograph and utilizing the actual sump and pump capacities. Tracking of the water level variation in the sump was also used to verify the incoming sewer flow hydrograph. Figure 21 shows the level indicator to track the water level variation of in the sump of the pump station at DAR.
Figure 20: Portable ultrasonic flow meter mounted on the discharge pipe of DAR pumping station.

Figure 21: Level indicator to track the water level variation of the incoming sewer flow in the sump of the pump station

4.3 Sewer flow and pumped flow for DAR

Figure (22) shows a typical sewer flow hydrograph discharging into the sump of DAR pumping station. It indicates that peak flow occurred near 9:00 pm on that day, and significantly lower flows took place late at night.
Since the actual pumping capacity is 32 cubic meters per hour which is slightly higher than the peak flow of 30 m$^3$/hr and even much higher than the zero low night flow, then the pumping station will operate intermittently with cycles of on- and off-periods. The intermittent flow and “surge-like” operation of DAR pumping station, as shown in Figure (23), is the result of the fixed speed pump in relation to random inflow sewage hydrograph from the trunk sewer.

**Figure 22:** Sewer flow generated from the 1000 capita DAR for a day with an average flow 200 m$^3$/day

**Figure 23:** Pumped flow pulses generated from the 1000 capita DAR for a day with an average flow 200 m$^3$/day
4.4 Community composition
DAR has a total population $P$ of 950 capita. At this time of the year, the community consists of five social categories ($k=5$) with similar water use patterns, as shown in Figure 24. The community is composed of 300 morning working professionals who will be dealt as morning workers ($L_1$), 150 of afternoon working professionals who will be dealt as afternoon workers ($L_2$), 250 of stay home women ($L_3$), 50 of working women ($L_4$), and 200 of stay home children ($L_5$) because of the summer vacation.

Figure 24: Social categories of DAR

4.5 Durations, volumes and frequencies of use
Volumes and durations of single use for the various social categories ($L$) of DAR are shown in Table (12). Also, frequencies of use for the various social categories ($L$) of DAR are shown in Tables (13, 14) for weekdays and weekends respectively.

Table 12: Mean and standard deviation of the volume and duration of a single use of a water appliance or fixture at DAR

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<th>Volume of Single Use</th>
<th>Duration of Single Use</th>
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<tbody>
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<td>Mean (L)</td>
<td>STDEV (L)</td>
</tr>
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<td>10</td>
<td>3.5</td>
</tr>
<tr>
<td>Basin ($i_2$)</td>
<td>6.5</td>
<td>2</td>
</tr>
<tr>
<td>Shower ($i_3$)</td>
<td>90</td>
<td>30</td>
</tr>
<tr>
<td>Sink ($i_4$)</td>
<td>13.5</td>
<td>7.5</td>
</tr>
<tr>
<td>Washing Machine ($i_5$)</td>
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<td>7.5</td>
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</table>
### Table 13: Frequency of use of appliances for DAR individuals during weekday

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<th>Frequency of uses/day (r)</th>
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<td></td>
<td>Mean</td>
</tr>
<tr>
<td>WC (i₁)</td>
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</tr>
<tr>
<td>Basin (i₂)</td>
<td>6</td>
</tr>
<tr>
<td>Shower (i₃)</td>
<td>0.75</td>
</tr>
<tr>
<td>Sink (i₄)</td>
<td>0</td>
</tr>
<tr>
<td>Washing Machine (i₅)</td>
<td>0</td>
</tr>
</tbody>
</table>

### Table 14: Frequency of use of appliances for DAR individuals during weekend

<table>
<thead>
<tr>
<th>Appliance or Fixture</th>
<th>Frequency of uses/day (r)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Morning working professionals (L₁)</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
</tr>
<tr>
<td>WC (i₁)</td>
<td>7</td>
</tr>
<tr>
<td>Basin (i₂)</td>
<td>8</td>
</tr>
<tr>
<td>Shower (i₃)</td>
<td>1</td>
</tr>
<tr>
<td>Sink (i₄)</td>
<td>0</td>
</tr>
<tr>
<td>Washing Machine (i₅)</td>
<td>0</td>
</tr>
</tbody>
</table>
4.6 Synthetic water use patterns
The synthesized water use probability patterns for the five main social categories forming DAR are graphed in Figures 25, 26, and 27 for three appliances (WC, wash basins, showers) respectively during weekday. The times of use, frequency of use per day are set to reflect the use of facilities on working day by them. The use of the kitchen sink and washing machines are assigned to both the stay-home and working women, but with different use patterns as shown in Figures 28 and 29.

The water use patterns for the various social categories during weekends are assumed to reflect that these days are non-working ones. The water use patterns, as shown in Figures 30, 31, 32, 33 and 34, reflect the human activities of the family members during these days and are much related to the cultural and religious factors existing at DAR.

![Figure 25: Probability distribution of using WC for different user types (L) of DAR at weekday](image)

![Figure 26: Probability distribution of using Washroom Basin for different user types (L) of DAR at weekday](image)
Figure 27: Probability distribution of using Shower for different user types (L) of DAR at weekday

Figure 28: Probability distribution of using Kitchen Sink for different user types (L) of DAR at weekday

Figure 29: Probability distribution of using Washing Machine for different user types (L) of DAR at weekday
**Figure 30:** Probability distribution of using WC for different user types (L) of DAR at weekend

**Figure 31:** Probability distribution of using Washroom Basin for different user types (L) of DAR at weekend

**Figure 32:** Probability distribution of using Shower for different user types (L) of DAR at weekend
Figure 33: Probability distribution of using kitchen Sink for different user types (L) of DAR at weekend

Figure 34: Probability distribution of using Washing Machine for different user types (L) of DAR at weekend

4.7 Measured and predicted hydrographs
Wastewater hydrographs generated from the entire DAR community during weekdays were derived by the model for different probability of non-exceedance as shown in Figure 35. A comparison between the measured hydrographs and those synthesized by the model for weekdays is shown in Figure 36. The predicted wastewater discharges are within the same range of those measured. The deviations may be attributed to the assumed water use patterns and to what extent they resemble the actual use patterns for the community during the period of the measuring program. Figure 37 compares the synthesized and measured weekend
wastewater hydrographs for DAR. It is to be noted that a better agreement can be observed for the weekend.

**Figure 35:** Envelope hydrographs for different probabilities of non-exceedance for weekday

**Figure 36:** Actual hydrographs versus model envelope probability hydrographs for weekday
Figure 37: Measured hydrographs versus model envelope probability hydrographs for weekend

4.8 Probabilistic sewer and pumped flow factors at the downstream of DAR
The sewer and pumped flow factors for selected probabilities for DAR are shown in Figures 38 and 39 respectively. In Figure 38, the 99% 1- hr sustained peak flow factor is 3 which means that the trunk sewer, pump station, or treatment plant will receive this value or less at probability equal to 99 %. On the other hand, the 99% 1- hr sustained low flow factor in Figure (38) is 0.4 which means that the trunk sewer, pump station, or treatment plant will receive this value or more at probability equal to 99%.

The pumped flow factor in Figure 39 is higher than the sewer flow factors in Figure 38 by 0.75. This reveals that the design of the pump station is oversized. The pumped and sewer flow factors tends to be the same as the sustained duration increases.
Figure 38: Probabilistic design sewer flow factors generated at the downstream of DAR at weekday

Figure 39: Probabilistic design pumped flow factors generated at the downstream of DAR at weekday

For the given population of DAR 950 capita, the Babbit and Baumann formula gives 5 for instantaneous flow factor which is higher than the model instantaneous flow factor for sewer and pumped flow factors in Figures 38 and 39, respectively. In addition, the Harmon formula gives 3.75 for 1 hour sustained flow factor which is also higher than the model 1-hour flow factor for all cases mentioned in Figures 38 and 39. The minimum 1-hour flow factor mentioned in Egyptian code of practice 169/1997 gives 0.2 which is smaller than 0.4 estimated from the model. Although these formulas are widely accepted, these formulas give very conservative results when compared with the actual modeled results from DAR.
Chapter 5: Parametric Study

5.1 Introduction
The following sections present the results of a parametric study for the simulation model developed in chapter three with the stated model default values. Three socio-economic conditions are studied and are represented by the daily per capita wastewater flow and its associated life style (water use pattern). The contributions of the various members of the community to the generated hydrograph are presented for the three community class-levels. The contributions of wastewater generated by the various appliances and fixtures are also investigated for the three community classes. The parametric study also investigates the effect the community population on the generated hydrographs and sewer and pumped flow factors.

5.2 Community composition and its effect on the community wastewater hydrographs

5.2.1 Community composition
The base community composition for the parametric study is shown in Figure (40). The community is assumed to consist of working-men in a morning shift (L1), working-men in night shift (L2), stay-home women (L3), working women (L4), school children (L5), and stay-home children.

Figure 40: The base community composition of the parametric study.
An appropriate water use pattern is assumed for each of the social categories of Figure 40 for weekdays. For weekends, two water use patterns are assumed to apply for the six categories: men/children pattern ($L_1$, $L_2$, $L_5$, and $L_6$), and women ($L_3$ and $L_4$). Water use patterns are set to vary for the three socio-economic levels: low, middle, and high.

5.2.2 Contribution of community members to the final wastewater hydrograph

5.2.2.1 Low-class community

The simulation model is applied to a small low-class community (population of 1000 capita). Figure 41 shows the final weekday expected (average) hydrograph for the community and the contributions of the six user types of the low class community. In Figure 41, the average per capita generated wastewater flows are 54.5 for morning workers ($L_1$), afternoon workers ($L_2$), and school children ($L_6$). For stay home children ($L_5$), the average per capita generated wastewater flows are 74.5, as shown in Figure 41. For stay home women ($L_3$) and working women ($L_4$), the per capita generated waste water flows are 117 and 77, respectively, as shown in Figure 41. The overall average per capita waste water flows for the 1000 capita low class community at weekday is 77.

![Figure 41: Contributions of the various community members to the final weekday hydrograph for a 1000 capita low-class community](image)

Figure 41 shows the expected (average) final weekend hydrograph for the 1000 capita low-class community and the contributions of the six user types. In Figure 42, the average per capita generated wastewater flows are 100 for morning workers ($L_1$), afternoon workers ($L_2$),
stay home children (L₅) and school children (L₆). For stay home women (L₃) and working women (L₄), the per capita generated waste water flow is 117, as shown in Figure 42. The overall average per capita wastewater flow for the 1000 capita low class community during weekends is 105.

Figure 42: Contributions of the various community members to the final weekend hydrograph for a 1000 capita low-class community

5.2.2.2 Middle-class community

Figure 43 shows the expected (average) final weekday hydrograph for the 1000 capita middle-class community and the contributions of the six user types. In Figure 43, the average per capita generated wastewater flow is 105 for morning workers (L₁), afternoon workers (L₂), and school children (L₆). For stay home children (L₅), the average per capita generated wastewater flow is 141, as shown in Figure 43. For stay home women (L₃) and working women (L₄), the per capita generated waste water flows are 225 and 159, respectively, as shown in Figure 43. The overall average per capita waste water flow for the 1000 capita middle class community during weekdays is 140.

For the same middle class community, the contributions of the community members to the expected weekend hydrograph are shown in Figure 44. In Figure 44, the average per capita generated wastewater flow is 165 for morning workers (L₁), afternoon workers (L₂), stay
home children (L₅) and school children (L₆). For stay home women (L₃) and working women (L₄), the per capita generated waste water flow is 225, as shown in Figure 44. The overall average per capita wastewater flows for the 1000 capita middle class community during weekend is 185 L/capita/day.

Figure 43: Contributions of the various community members to the final weekday hydrograph for a 1000 capita middle-class community.

Figure 44: The contribution of community composition on the hydrographs generated at the downstream of middle class community for 1000 Capita at weekend
### 5.2.2.3 High-class community

For the 1000 capita high class community, the contributions of the six user types to the expected (average) weekday hydrograph is shown in Figure 45. In Figure 45, the average per capita generated wastewater flow is 226 litre/day for the morning workers (L₁), afternoon workers (L₂), and school children (L₆). For stay home children (L₅), the average per capita generated wastewater flow is 262, as shown in Figure 45. For stay home women (L₃) and working women (L₄), the per capita generated waste water flow is 377 and 289, respectively, as shown in Figure 45. The overall average per capita wastewater flow for the 1000 capita high class community at weekday is 269 litre/day.

![Figure 45](image_url)

**Figure 45:** Contributions of the various community members to the final weekday hydrograph for a 1000 capita high-class community.

For the high-class 1000 capita community, Figure 46 shows the expected (average) hydrograph for a weekend and the contributions of the various members of the community. In Figure 46, the average per capita generated wastewater flow is 262 for morning workers (L₁), afternoon workers (L₂), stay home children (L₅) and schoolchildren (L₆). For stay home women (L₃) and working women (L₄), the per capita generated waste water flow is 377, as shown in Figure 46. The overall average per capita waste water flows for the 1000 capita high class community at weekend are 300 litre/day.
Figure 46: Contributions of the various community members to the final weekend hydrograph for a 1000 capita high-class community.

5.3 Contributions of wastewater generated by the various appliances and fixtures.

5.3.1 Low-class community
Figures 47 and 48 show the expected weekday and weekend hydrographs for 1000 capita low-class community and the contributions of the five main appliances and fixtures. For the assumed frequency of use and water volumes per use, it can be seen that the black water generated from the WC represents the highest contribution throughout the day while washing activities for the low class community. This may be used as a measure in setting the water management strategies especially the feasibility of separating black water from grey water for low class community. Unlike weekdays, the shower use during weekend tends to increase before noon because of the Friday prayer.
Figure 47: Wastewater flows generated during a weekday by the various appliances and fixtures for a 1000 capita low-class community.

Figure 48: Wastewater flows generated during a weekend by the various appliances and fixtures for a 1000 capita low-class community.

5.3.2 Middle-class community
For a middle-class community with a population of 1000 capita, Figure 49 shows the flow contribution of each of the five appliances for an average weekday. The frequency of and water volumes per use of the middle class community are higher than the values for the low class one.
Figure 49: Wastewater flows generated during a weekday by the various appliances and fixtures for a 1000 capita middle-class community

For an average weekend, Figure 50 shows the flow contributions of each of the five appliances for the middle-class community. Similar to low class community, the shower use activities increases before noon in contrast with weekdays because of the Friday prayer. Two peaks are observed one before noon and the other nearly at 3:00 pm due to the life style and water use pattern of the middle class community during the weekend.

Figure 50: Wastewater flows generated during a weekend by the various appliances and fixtures for a 1000 capita middle-class community
### 5.3.3 High-class community

For the 1000 capita high-class community, Figure 51 shows the flow contributions of each of the five appliances for an average weekday. It can be seen that the proportions of the wastewater generated by the various appliances and fixtures are different from the low and middle class communities. There is an increase in water use and the resulting generated wastewater by uses that generate wastewater with low-organic content. The generated hydrograph and its contributions can give guidance as to the variations of wastewater strength during the various hours of the day.

![Wastewater flows generated during a weekday by the various appliances and fixtures for a 1000 capita high-class community](image)

*Figure 51: Wastewater flows generated during a weekday by the various appliances and fixtures for a 1000 capita high-class community*

Figure 52 shows the wastewater hydrograph and the contributions of the various appliances and fixtures resulting from a high-class 1000 capita community. Similar to the middle class community, two peaks are observed one before noon and the other nearly at 3:00 pm due to the religious traditions of Friday prayer during this day. In addition the unit wastewater flows generated are much higher than the low and middle class communities.
Figure 52: Wastewater flows generated during a weekend by the various appliances and fixtures for a 1000 capita high-class community

5.4 Probabilistic envelope hydrographs of weekdays and weekends for communities with various classes

The envelope hydrographs define the extreme values of the generated random discharge values at the different times of the day. It is worth mentioning that any hydrograph with a certain probability is not likely to occur with its real time sequence as shown on any day, but the hydrograph shows the values at the different times of the day with the defined probability.

5.4.1 Low-class community

For low class communities, Figure 53 shows the probabilistic weekday hydrographs at different probability of non exceedance. The 50% is the mean hydrographs generated by the entire community.
Figure 53: Probabilistic envelope weekday hydrographs for 1000 capita low class community.

Figure 54 shows the probabilistic weekend hydrographs generated by the 1000 capita low-class community. It can be seen that the different water use patterns during the weekend change the times of peak and low flow during the day from the corresponding weekday hydrographs.

Figure 54: Probabilistic envelope weekend hydrographs for 1000 capita low class community.

5.4.2 Middle-class community

For middle class communities, Figure 55 gives the probabilistic hydrographs at different probability of non exceedance for 1000 capita at weekday. The 50% is the mean hydrographs generated at the outfall of the community.
Figure 55: Probabilistic envelope weekday hydrographs for 1000 capita middle-class community

For middle class communities, Figure 56 gives the probabilistic hydrographs at different probability of non exceedance for 1000 capita at weekend. The 50% is the mean hydrographs generated at the outfall of the community.

Figure 56: Probabilistic envelope weekend hydrographs for 1000 capita Middle-class community
5.4.3 High-class community

Figures 57 and 58 show the synthesized weekday and weekend hydrographs at different probability of non exceedance for a 1000 capita high-class community. It shows the much higher early morning peak flow as compared to the middle and low class communities.

**Figure 57**: Probabilistic envelope weekday hydrographs for 1000 capita high-class community

**Figure 58**: Probabilistic envelope weekend hydrographs for 1000 capita high-class community
5.5 Sewer and pumped flow factors for communities with different socio-economic classes

5.5.1 Low-class community

Figure 59 gives the peak flow factor \( P_{\text{max,t}} \) of the pumped (P) and sewer (S) flow hydrographs for a 99 % probability of non-exceedance and the minimum flow factor \( P_{\text{min,t}} \) of the pumped (P) and sewer (S) flow hydrographs for a 99 % probability of exceedance for the 1000 capita low-class community.

![Graph showing flow factors over duration](image)

**Figure 59:** Design sewer (S) and pumped (P) flow factors at 99% probability of non-exceedance (peak) and exceedance (min.) for the 1000 capita low-class community

The sewer flow factors (S) are used for the design of sewers and usually for peak one hour of sustained flow which is equal to 4.2 in Figure 59. This flow is what is usually referred to as peak hourly flow. The flow factors based on the pumped (P) sewage hydrograph to the treatment plant are used for the design of the various components of the wastewater treatment plant. The instantaneous flow factor which is equal to 5.2 in Figure 59 for the pumped sewage hydrograph is the basis for sizing the inlet works of the plant. This flow factor is mainly determined by the selected pump capacity. It will increase if the pump capacity is sized for a future population. For eight hour duration, the pump will operate and stop for numerous cycles, the average pumping flow approaches the incoming sewer flow.
5.5.2 Middle-class community

Figure 60 gives the peak flow factor $P_{\text{max,t}}$ of the pumped (P) and sewer (S) flow hydrographs for a 99% probability of non-exceedance and the minimum flow factor $P_{\text{min,t}}$ of the pumped (P) and sewer (S) flow hydrographs for a 99% probability of exceedance for the 1000 capita middle-class community.

![Graph showing peak and minimum flow factors for middle-class community](image)

**Figure 60**: Design sewer (S) and pumped (P) flow factors at 99% probability of non-exceedance (peak) and exceedance (min.) for the 1000 capita middle-class community

It can be seen that the instantaneous ($t=0$) peak factor for sewer (S) flows decreased to 3.5 from 4.5 for the low class community. The higher wastewater flows for the middle class community damped the hourly variations, but it did not decrease the magnitude of the hourly flows because the peak factors will be multiplied by the higher average unit per capita wastewater flows for the middle class.

5.5.3 High-class community

Figure 61 gives the peak flow factor $P_{\text{max,t}}$ of the pumped (P) and sewer (S) flow hydrographs for a 99% probability of non-exceedance and the minimum flow factor $P_{\text{min,t}}$ of the pumped (P) and sewer (S) flow hydrographs for a 99% probability of exceedance for the 1000 capita high-class community.
Figure 61: Design sewer (S) and pumped (P) flow factors at 99% probability of non exceedance (Peak) and exceedance (min.) for the 1000 capita high-class community

It can be seen that the instantaneous (t=0) peak factor for sewer (S) flows decreased to 3.2 from 4.5 for the middle-class community. The higher wastewater flows for the high-class community further damped slightly the hourly variations, but it did not decrease the magnitude of the hourly flows because the peak factors will be multiplied by the higher average unit per capita wastewater flows for the higher class.

5.6 Effect of level of probability on the sewer flow factors for the different community classes

5.6.1 Low-class community

Figure 62 shows the various sewer flow factor-duration curves for different levels of probability (99, 95, 90, 80, 70, 60, and 50%) for the 1000 capita low class community. It shows that the peak flow factor decreases from 4.5 to 4 if a lower probability of non-exceedance of 95% is used instead of the 99% probability.
Figure 62: Sewer flow factors-duration-probability of non-exceedance curves for the 1000 capita low-class community

5.6.2 Middle-class population

Figure 63 shows the various sewer flow factor-duration curves for different levels of probability (99, 95, 90, 80, 70, 60, and 50%) for the 1000 capita middle-class community. It shows that the peak flow factor decreases from 3.5 to 3.25 if a lower probability of non-exceedance of 95% is used instead of the 99% probability. The change in the flow factor is less for the middle-class than for the low class community.

Figure 63: Sewer flow factors-duration-probability of non-exceedance curves for the 1000 capita middle-class community
5.6.3 High-class community

Figure 64 shows the various flow factor-duration curves for different levels of probability (99, 95, 90, 80, 70, 60, and 50%) for the 1000 capita middle-class community. It shows that the peak flow factor decreases from 3.25 to 2.9 if a lower probability of non-exceedance of 95 % is used instead of the 99 % probability.

![Figure 64: Sewer flow factors-duration-probability of non-exceedance curves for the 1000 capita high-class community](image)

5.7 Effect of level of probability on the pumped flow factors for the different community classes

This section gives a probabilistic framework for the design of pressurized sewers or the wastewater treatment plants that receive its sewage through pressurized sewer lines. It is the role of the designer to choose the appropriate probability to the case at hand.

5.7.1 Low-class community

Figure 65 shows the various pumped flow factor-duration curves for different levels of probability of non-exceedance (99, 95, 90, 80, 70, 60, and 50%) for the 1000 capita low class community. It shows that the peak flow factor for a duration of 8-hours decreases from 2.75 to 2.4 if a lower probability of non-exceedance of 95 % is used instead of the 99 % probability. This 8-hour flow factor may be the basis of design of an activated sludge
aeration tank. It is clear that the allowable tolerance in the hydraulic loading on a plant component can affect the sizing of the unit.

**Figure 65**: Pumped flow factor-duration-probability of non-exceedance curves for the 1000 capita low-class community

### 5.7.2 Middle-class community

Figure 66 shows the various pumped flow factor-duration curves for different levels of probability of (99, 95, 90, 80, 70, 60, and 50%) for the 1000 capita middle-class community. It shows that the peak flow factor for a duration of 8-hours decreases from 2.25 to 2.1 if a lower probability of non-exceedance of 95% is used instead of the 99% probability. It can be seen that the decrease in the peak factor is smaller for the middle class community than that of the low-class one.

**Figure 66**: Pumped flow factor-duration-probability of non-exceedance curves for the 1000 capita middle-class community
5.7.3 High-class community

Figure 67 shows the various pumped flow factor-duration curves for different levels of probability (99, 95, 90, 80, 70, 60, and 50%) for the 1000 capita high-class community. It shows that the peak flow factor for a duration of 8-hours decreases from 1.9 to 1.8 if a lower probability of non-exceedance of 95% is used instead of the 99% probability. It can be seen that the decrease in the peak factor is even smaller for the high class community than that of the middle-class one.

![Graph showing pumped flow factor-duration-probability curves for 1000 capita high-class community](image)

Figure 67: Pumped flow factor-duration-probability of non-exceedance curves for the 1000 capita high-class community

5.8 Effect of community class on the sewer and pumped flow factor-duration-probability curves

Figures 68 and 69 show the sewer and pumped flow factor-duration curves at 99% probability of non-exceedance for the 3 community classes. Both Figures show that the low class communities have the highest peak flow factors. In addition, the low class communities have the lowest minimum flow factors. This confirms the reported inverse relation between the flow factors and the average flow generated from the community.
Figure 68: Sewer flow factors (S)-duration curves for different community classes at 99% probability

Figure 69: Pumped flow factors (P)-duration curves for different community classes at 99% probability of non exceedance
5.9 Model sewer and pumped peaking flow factors versus factors estimated by common formulas
In this section, the values from two widely used population based formulas which are used to calculate instantaneous flow factors and one hour sustained flow factors will be compared with the model instantaneous and one hour flow factors for the three class levels communities. In addition, values from discharge based formulas to calculate one day sustained flow factors for different per capita wastewater that represent the different classes stated earlier will be compared with the same sustained duration flow factors of the model.

5.9.1 Comparison based on a low-class community
For a low-class community, Figure 70 shows the model’s instantaneous sewer and pumped peaking flow factors for 99% probability of non-exceedance compared with the instantaneous peaking factors estimated using Babbit and Baumann. The Babbit and Baumann gives nearly similar results to the instantaneous model’ pumped flow factors till a population of 10,000 capita, then the estimated values using this formula becomes higher. The instantaneous sewer flow factors are less than values of both the formula and the model instantaneous pumped flow factors for all populations of low class community.

![Figure 70: 99% probability of non-exceedance for model sewer and pumped instantaneous peaking flow factors and instantaneous peaking factors estimated using Babbit and Baumann for low class community.](image-url)

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For low class community, Figure 71 shows the model’s one hour sewer and pumped peaking flow factors for 99% probability of non-exceedance compared with 1-hour peaking factors estimated using Harmon formula. The Harmon formula tends to be conservative for all populations more than 2000 capita while for population less than 2000 capita the model predicts higher values.

Figure 71: 99% probability of non exceedance for model sewer and pumped 1-hour peaking flow factors and 1- hour peaking flow factors estimated using Harmon for low class community

For low class community, Figure 72 shows the model’s one-hour sewer and pumped minimum flow factors for 99% probability of exceedance compared with 1-hour minimum factors estimated using Egyptian code of practice 169/1997 formula. The Egyptian code of practice 169/1997 formula tends to be conservative and gives lower values than the model minimum one hour flow factors for all populations. The sewer and pumped minimum flow factors tends to be the same at 99 % probability of exceedance. This may be because the times of no sewer flow are associated with times of Off-Pump periods during night. In addition, the minimum flow factors values increases with the increase of population.
Figure 72: 99% probability of exceedance for model sewer and pumped minimum 1-hour flow factors and 1-hour flow factors estimated using Egyptian code of practice 169/1997 for low class community.

For low class community, Figure 73 shows the model’s 1-day sewer and pumped peaking flow factors for 99% probability of non-exceedance compared with average 1-day peaking factor mentioned in the Egyptian code of practice 169/1997. The interpretation of the results reveals that values given in the Egyptian code of practice 169/1997 are higher than the derived values for all populations. The values of the model are around one because the assumed community does not have sources that will lead to significant variations in daily flow such as educational institute, office buildings, commercial centres, schools, hospitals and others. In addition, the water use patterns incorporated in the model vary with the day of the week, but do not reflect seasonal changes. The model’s one-day sewer and pumped peaking flow factors for 99% probability of non-exceedance are the same at this sustained duration.

Figure 73: 99% probability of non-exceedance for model’s sewer and pumped peaking flow factors and 1 day peaking factors mentioned in the Egyptian code of practice 169/1997 for low class community.
5.9.2 Comparison based on a middle-class community

For middle class communities, Figure 74 shows the model’s instantaneous sewer and pumped peaking flow factors for 99% probability of non-exceedance compared with the instantaneous peaking factors estimated using Babbit and Baumann. The Babbit and Baumann gives higher results than the instantaneous model’ pumped-flow factors till 7,000 capita of middle class community, then the estimated values using this formula becomes lower than the model’s pumped flow factors. The instantaneous sewer flow factors are less than values of both the formula and the model instantaneous pumped flow factors for all populations of middle class communities.

Figure 74: 99% probability of non exceedance for model’ sewer and pumped peaking flow factors and instantaneous peaking factors estimated using Babbit and Baumann for middle class community.

For middle class communities, Figure 75 shows the model’s one-hour sewer and pumped peaking flow factors for 99% probability of non-exceedance compared with 1-hour peaking factors estimated using Harmon formula. The Harmon formula tends to be conservative for all populations of the middle class community.
Figure 75: 99% probability of non exceedance for model’ sewer and pumped peaking flow factors and 1 hour peaking factors estimated using Harmon for middle class community.

For middle class communities, Figure 76 shows the model’s one-hour sewer and pumped minimum flow factors for 99% probability of exceedance compared with one-hour minimum factors estimated using Egyptian code of practice 169/1997 formula. The Egyptian code of practice 169/1997 formula tends to be conservative and gives lower values than the model minimum one hour flow factors for all populations. The sewer and pumped minimum flow factors also tends to be the same at 99 % probability of exceedance. This may be because the times of no sewer flow are associated with times of Off-Pump periods during night. The minimum 1-hour flow factors for middle class community give higher values than those estimated for low class community. In addition the minimum flow factors values increases with the increase of population. This may be associated with the notion that the minimum flow factors increase with the increase of average flow.

Figure 76: 99% probability of exceedance for model sewer and pumped minimum 1-hour flow factors and 1- hour flow factors estimated using Egyptian code of practice 169/1997 for middle class community
For middle class communities, Figure 77 shows the model’s one-day sewer and pumped peaking flow factors for 99% probability of non-exceedance compared with average 1-day peaking factor mentioned in the Egyptian code of practice 169/1997. The interpretation of the results reveals that values mentioned in the Egyptian code of practice 169/1997 are higher than the derived values for all populations similar to the previous case of low-class community with the same clarification for the difference in factors.

**Figure 77**: 99% probability of non-exceedance for model’ sewer and pumped peaking flow factors and 1 day peaking factors mentioned in the Egyptian code of practice 169/1997 for middle class community.

### 5.9.3 Comparison based on a high-class community

Figure 78 shows the model’s instantaneous sewer and pumped peaking flow factors based on a high-class community for 99% probability of non-exceedance compared with the instantaneous peaking factors estimated using Babbit and Baumann. The Babbit and Baumann gives higher results than the instantaneous model’ pumped flow factors for high-class communities with population less than 13,000 capita. For larger populations, the estimated factors using this formula become lower than the model’s pumped flow factors. The instantaneous sewer flow factors are less than values of both the formula and the model instantaneous pumped flow factors for all populations of high class community.
Figure 78: 99% probability of non exceedance for model’ sewer and pumped peaking flow factors and instantaneous peaking factors estimated using Babbit and Baumann for high class community.

For high-class communities, Figure 79 shows the model’s one-hour sewer and pumped peaking flow factors for 99% probability of non-exceedance compared with one-hour peaking factors estimated using Harmon formula. The Harmon formula tends to be conservative for all populations of the high class community.

Figure 79: 99% probability of non exceedance for model’ sewer and pumped peaking flow factors and 1 hour peaking factors estimated using Harmon for high class community.
For high-class communities, Figure 80 shows the model’s one-hour sewer and pumped minimum flow factors for 99% probability of exceedance compared with one-hour minimum factors estimated using Egyptian code of practice 169/1997 formula. The Egyptian code of practice 169/1997 formula tends to be conservative and gives lower values than the model minimum one-hour flow factors for all populations. The sewer and pumped minimum flow factors also tend to be the same at 99% probability of exceedance. This may be because the times of no sewer flow are associated with times of Off-Pump periods during night. The minimum 1-hour flow factors for high class community give higher values than those estimated for low and middle class community. In addition the minimum flow factors values increases with the increase of population. This may also be associated with the notion that the minimum flow factors increase with the increase of average flow.

Figure 80: 99% probability of exceedance for model sewer and pumped minimum 1-hour flow factors and 1-hour flow factors estimated using Egyptian code of practice 169/1997 for high class community

For high class communities, Figure 81 shows the model’s one-day sewer and pumped peaking flow factors for 99% probability of non-exceedance compared with average 1-day peaking factor mentioned in the Egyptian code of practice 169/1997. The Figure shows that the factors in this case deviate more from the values estimated by Egyptian code of practice 169/1997 for all populations. The 1-day flow factors of the model are around one as the assumed community does not have sources that will cause significant variations in daily flow such as educational institute, office buildings, commercial centres, schools, hospitals and
others. In addition, the assumed water use patterns do not sufficiently account for the possible seasonal variations.

**Figure 81**: 99% probability of non exceedance for model’ sewer and pumped peaking flow factors and 1 day peaking factors mentioned in the Egyptian code of practice 169/1997 for high class community.

### 5.9.4 Interpretation of the results of the comparison between the estimated flow factors using model and formulae

The results of the comparison show that the instantaneous flow factors estimated by Babbit and Baumann formula are generally close to the model values based on a low-class community, while it gives higher values for small populations and lower values for larger populations than the model instantaneous pumped flow factors for middle and high class communities. Harmon formula that estimates one hour flow factors generally gives (higher) conservative flow factors than the model’s sewer and pumped flow factors.

For all classes, the model’s one -day sewer and pumped peaking flow factors for 99% probability of non-exceedance approach a value of one. The assumed communities are predominantly residential with no other commercial and educational uses that usually introduce noticeable daily variations. Moreover, the assumed water-use patterns are not varied for the different seasons.

Not all of these formulas have a clearly defined probability of non-exceedance associated with them. In addition, these formulas lack the description of the socio-economic conditions
for the communities that were used for their development and the communities they are intended for. Furthermore, the distinction between the sewer flow factors and the pumped flow factors and their range of applicability had not been taken into consideration.

This study deals with sewage results from homogeneous small residential arid communities during typical weekdays and weekends. As a result, the variation from day to day is minimal and tends to be the same because of the lack of such sources that cause variation like the seasonal variations and the existence of schools, companies,..., etc. The variation from hour to hour in small network of a small community tends to increase as the sewer network becomes smaller in size because of the lack of damping effects from longer flow times found in larger systems. The lack of damping effect in the smaller network makes it clear to observe the variations due to the socioeconomic characteristics of the small community. The times of the peaks and minimums at weekdays and weekends are closely related to the socioeconomic characteristics of the small residential community. During weekdays, two peak times can be observed; one at the walk up time between 07:00 AM to 09:00 AM and the other the back home time between 4:00 PM and 06:00 PM. During weekends, a major peak time occurs before noon because of the shower activities related to the Friday prayer with another peak related to the lunch activity afternoon. The variations due to the diurnal activities during seasonal changes and special events can be observed similarly using the same steps used to generate wastewater flow hydrographs for weekdays and weekends. These variations have a direct impact on the flow factors either peak or minimum. The peak flow factors estimated for homogeneous residential small communities tend to be higher than those estimated for larger communities and using empirical methods because of the concentrated socioeconomic activities at some times of the day. The minimum flow factors tend to be lower than those estimated for larger communities and using empirical methods because of the long times of no flow at night due to inactivity and inexistence of infiltration flow due to the aridity nature of the community.
Chapter 6: Conclusions

6.1 Summary and Conclusions
The developed model can generate synthetic domestic wastewater hourly flow hydrographs based on the specific socioeconomic characteristics of small arid communities. The hourly hydrographs are generated for weekdays and weekends. The synthetic hydrographs are developed while retaining their commonly observed random behavior. The socioeconomic characteristics of a community are accounted for by the composition of the community of its social categories, the water use pattern of every category during the various daily activities (weekday and weekend), and the water use facilities (fixtures and appliances) available to the community. The model utilizes different water use patterns by every social group for every appliance during the different types of days. The use patterns account for the stochastic nature of use in terms of number of uses, duration of the use and times of use in the day. Randomly generated hydrographs are generated for weekdays and weekends along with synthetic hydrographs of non-exceedance. The contribution of user profiles and appliances to the outfall hydrograph may be a good way to further understand the sewer sociology. The appliances contribution can be used in the wastewater management strategies especially in studying the feasibility of separating black and grey water. In addition, the flows from these appliances can be associated with organic and chemical loading to estimate the loadings on the wastewater treatment plant based on the actual sources.

The synthetic hydrographs have been used to generate probability based peak and low flow factors to be used in the design of sewerage systems, pumping facilities, and treatment plants. For small communities the sizing and operation of the pumping station accentuate the sewer hydraulic and results in a pulse-like pumped flow hydrograph that should be the basis for the design of the treatment plant. Therefore, two sets of peaking flow factors are derived: sewer flow factors to be used in the design of the sewer network and pumped flow factors to be used in the design of the various components of the wastewater treatment plants.

The flow factors derived by the model are given for different flow durations. The use of the widely used instantaneous or hourly peaking factors in both sewers and the components of the wastewater treatment plant may not ideal. For sewers such factor may be justified as a
design basis. Pumps, screens, and grit chambers should be designed based on the extreme instantaneous peaking factor. Other components of the wastewater treatment plant (WWTP) may tolerate short- duration higher flows that would last less time than the residence time of the component. Therefore, an average flow that is sustained for a selected duration can be the basis for the hydraulic design of such component.

The flow factors derived by the model are given for different levels of their probability of non-exceedance. The designer may opt to design the sewers or the various WWTP components using an appropriate probability of non-exceedance to optimize on the size of the units. The main criterion for selecting the probability would be the consequences of subjecting the treatment unit to a higher flow and the possibility of the entire plant not meeting its effluent standards. The available budget and the needed level of service of the components of the sewerage system may also govern the selection of the appropriate probability.

In addition to estimating certain probability, different plant components should be designed according to their critical peak and minimum conditions.

The developed model has proven capable of synthesizing daily wastewater hydrographs that account for the possible use of the fixtures and appliances by the various members of the community under consideration. The use of different water use patterns for the various members of the community, and the variation of the water use pattern for the same person between the days of the week, and the seasons of the year has proven efficient in synthesizing hydrographs that resembles the measured ones. The water use pattern is expressed in terms of frequency of use, timing of individual uses, and duration of use of any fixture or appliance and reflects the lifestyle and water use practice of the community members. This concept has made possible to account for the socio-economic conditions and cultural and religious behavior of the various members of the community. The comparison of the synthetic hydrographs for the case study of the 1000 capita community has shown the potential of the simulation model.

The simulation model can segregate the hourly contributions of the various appliances to the entire community hydrograph. A relevant useful application is to use these component
hydrographs combined with a wastewater quality algorithm to generate constituent pollutograph graphs from each appliance and fixture. Such component pollutograph graphs can aid in simulating the consequences of separating grey and black water in a sewerage system.

### 6.2 Recommendations for further research

The following are recommendations for further future research to enhance the results achieved in the current thesis:

- A social study can be made to survey the water use practice or patterns (timing, durations of use, frequency of use) of fixtures and appliances at home by the various social categories of the community: adults (men, women, working professionals, day or night shifts), and children (at schools, higher institutes). For every social category, various water use patterns need to be established for different days of the week (weekday, weekend), special events and holidays, and for the different seasons of the year. The water use patterns reflect the socio-economic and cultural conditions of a community. Design codes used to design a sewerage system for a community should be based on the social composition of the community and the water use patterns of its members.

- The sources of wastewater other than the wastewater generated from homes need to be investigated similarly. These sources include educational facilities (schools, institutes, and universities), office establishments, commercial centres, hospitals). Water use patterns for those present, working at, or visiting these facilities need to be surveyed in a similar way to the home activities.

- The effect of travel time and in-sewer storage on the synthetic hydrographs and their routing effect are needed to extend the applicability of the model to larger communities.

- For larger communities, several pumping stations may exist and the flow factors for pumped flow should be adjusted accordingly.

- Studies should be made on the effect of using certain flow factors on the design of the different components of treatment plant. Each component of the sewerage system has its acceptable limits of behavior. Flow factors based on sustained durations may modify the designs of wastewater treatment plants to more sustainable and economically feasible designs.
References


