Modelling Kuwait Water System Using Simulink

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1. Table of Contents

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2. Abstract

The Gulf Region, and Kuwait specially, in general are facing a great challenge in meeting water demand for its current and prospect population. Kuwait's water supply depends mainly on non-conventional water sources, such as seawater desalination. The desalination plants have been proven over the years to supply sufficient amount of fresh water; however, large residential buildings have forced the Government of Kuwait to lead a public campaign asking the general public to ration water usage. In some cases, this have stressed the pipeline network and increased the occurrence of water leaks due to faulty equipment in some of these oversized residential buildings. For this reason, the technology has been developed to hopefully eliminate loss and waste of water without intrusive hardware installation and without invasive changes to the pipeline network.

The water system behavior and the pipeline connection in Kuwait residential buildings have been investigated with variation in connection and variation in components. The monitoring was done manually in order to check the changes in water behavior. The affection of several parameters on the system's water volume and pressure are considered in order to monitor the operation of the pump. A base model is designed followed by the exploration of a realistic model that includes variation commonly found in the system.

The functional simulation has been developed demonstrating the basic water flow throughout a typical Kuwaiti residence. The four major load types: sink, toilet, shower, and clothes washer. Also, the pump and tank applications used in the simulation which they match the actual pump and tank configuration.

The simulation can provide the basis for future diagnostic efforts. The final result of the water system shows us the healthy water system. For further developing, it would be modeling various leeks throughout the system.

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3. Introduction

Kuwait has a desert climate characterized by a long, dry, hot summer, with temperatures reaching more than 45°C with frequent sandstorms, and a cooler winter, with temperatures sometimes even falling below 4°C. The rainy season extends from October to May. Over an area of about 100 km^2 annual rainfall is less than 100 mm, in the remaining part it varies between 100 and 300 mm. The long-term average annual rainfall for the whole country was about 176 mm, giving slightly more than 3.1 km^3. In recent years rainfall has decreased to an average of between 106 and 134 mm/year.

Kuwait relies on water desalination as a primary source of fresh water for drinking and domestic purposes. The first desalination plant was established in 1953 with a total capacity of 4,545 m^3/day. In 1994 there were 6 desalination plants with a maximum capacity of 950,000 m^3/day. The quantity of desalinated water produced in 1993 was 231 million m^3. Fresh water is obtained by mixing distilled water with low salinity groundwater (with a proportion of 8% groundwater) in order to get water suitable for drinking according to the official standards.

The quantity of wastewater produced was 119 million m^3 in 1994. About 103 million m^3 was treated and of this 52 million m^3 has been reused, while the remaining part was directed to the sea. [17]

Research is necessary to understand dynamics of the water distribution system. The research presented is an in-depth examination of the water behavior in each component throughout the water system and the operation of the pump. In order to better understand the system dynamics, a computer based model is developed to simulate the system and better test the diagnostic methods. The goal of exploring the model development step-by-step is to make this method applicable to any water system.

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4. Basic Premises and Test Platform Description

4.1. Kuwait Water System

Active water system is the perfect platform to conduct tests and data in order to succeed in modeling this specific water distribution system. The system being studied and modeled is a Kuwait residential water distribution system. This system receives water from the Ministry of Electricity and Water (MEW) of Kuwait through the main line to supply all water network system through the house. The supplied water is measured by a volume measuring water meter connected in series with the main line. The components of this system are located in a storage room usually in the basement, or sometimes on the roof. However, Kuwait differs from other countries with a sealed, anti-bacterial water tank located on the roof used to store water. This tank varies from 1000 to 2000 gallons which makes it huge enough to act as a low pass filter. A float ball valve is located inside the tank to control the amount of water entering it. This tank stands upright with a ¾-1 HP hydraulic pressure boosting pump connected in series with the tank via piping. The water is pumped into water filter and water heater. The toilets, faucets and showers are zoned throughout the house lagged with several isolation valves by three-pipe connection: hot water, cold water, and reversed hot water. Draining water from any of these parameters drops the pressure in pipes, which controls the energizing and de-energizing of the main pump between specified thresholds. The water connection is not really completed unless the hot water is circulated using 1/25 HP pump. This pump keeps cycling hot water in the pipes that provides hot water through the sink and shower, for example, to make sure the water stays hot regardless of any draining.

4.2. Overview of the Kuwaiti Residential Water System

The Kuwaiti residential water system features a unique infrastructure that allows for interesting and impactful diagnostic opportunities. The arid climate puts harsh demands on the pipelines and water storage tanks. Similarly, the sandy environment dictates robust filtering solutions. In contrast to the situation in the United States, each residential building in Kuwait has its own large water storage tank, usually located on the roof. This tank may be fed by either of two main water pipelines, the "Main Line" or the "Private Line". The Main Line is a one-inch diameter pipe that is used by the Ministry of Electricity and Water (MEW) during normal operating conditions, while the Private Line is a two-inch diameter pipe that can be filled by tankers when the MEW needs to cut the water supply for any given reason.

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The discussion in this report will focus on the flow of water after it arrives at the residence. In order to realize opportunities for leak detection and other non-intrusive diagnostics, it is first essential to understand how water starts at the home's water meter and ends up at the faucet. In the first section, each of the various components in the typical household water system will be described. Next, the approach to modelling this system is discussed, specifically focusing on how usage events such as running a faucet or flushing a toilet can be represented using probability distributions and common usage patterns. Finally, we'll present a functional water flow simulation constructed using MATLAB® and Simulink® of a Kuwaiti home that will provide the basis for future diagnostic efforts.

A high-level schematic of a typical Kuwaiti household is provided in Fig. 1. The water first encounters a GWF-manufactured cold water meter, provided by the MEW and connected in series with the Main Line. Next, a ¾-HP pump is used to maintain the water level of a large (1000-gallon) storage tank located on the roof. After the tank, water passes through a filtering system, and then cold water is distributed throughout the house. A parallel water loop is heated by a Bradford White standing water heater and is maintained by a small 1/25-HP circulator pump. Each of these components will be discussed in more detail in the following sections. The setup that is shown in Fig. 1 is actually notional and not necessarily as approved by the MEW in Kuwait. Additionally, please note that the system configuration described represents a notional model intended for study and may not be approved by the MEW. The simulation through this research can be applicable to several of configurations. We will focus on

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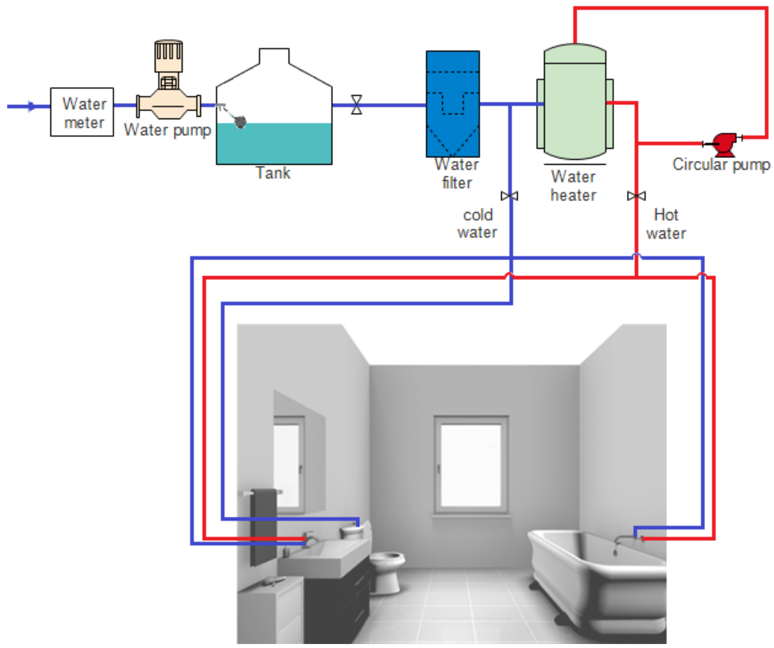

Fig. 1a. Schematic of a typical Kuwaiti residential water system. The 3D picture's source is in [1]

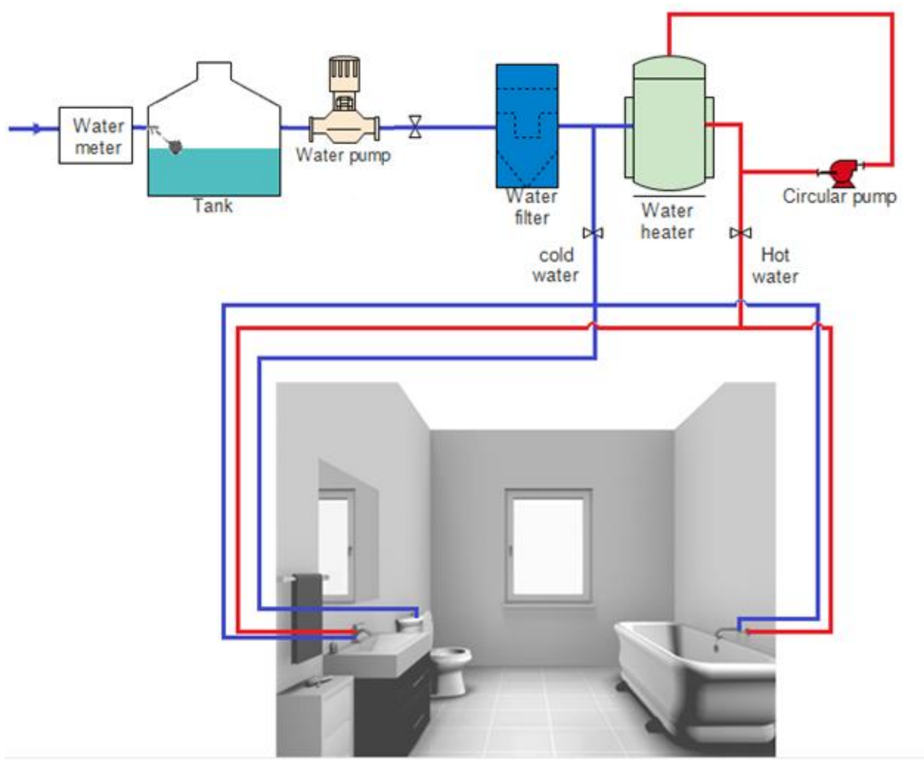

Fig. 2b. The allowed household water system by the MEW. The #D picture's source is in [1]

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4.2.1. Water Meter

A typical water meter is shown in Fig. 3. The water meter, manufactured by GWF and provided by the MEW, is used to measure the total volume of water consumed by each residence. Operation is very similar to devices in the United States. A measuring chamber is located inside the water meter. As water flows through the chamber, it moves a disc inside the chamber in a circular motion. The movement of the disc is translated to a small spinner at the top of the chamber that is magnetically coupled to the meter's register. The flowing water creates pulses in the register that advance the numbers of the odometer.

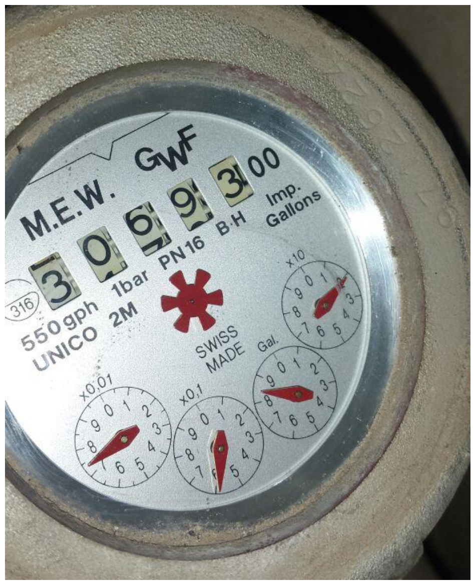

Fig. 3. Water meter provided to each residence by the Ministry of Electricity and Water, usually manufactured by GWF.

Kuwaiti residential water meters are calibrated to Imperial gallons where 1 Imperial gallon = 1.2 US gallons [2] (apart from this particular section on water meter readings, assume all volumetric units in US gallons). The odometer has two stationary zeros at the end, which are place holders for the 10-gallon unit, which is registered by five small needles that move around the dial. As can be seen in Fig. 3, the meters are capable of reading 550 gallons per hour.

To gain a better understanding of water consumption patterns in a Kuwaiti residence, water meter readings were recorded for two weeks as a preparation. This has been done with the help of Dr. Sami Habib in Kuwait University. These results are presented in Table 1. It is interesting to note that daily water consumption spiked to beyond 1000 gallons on the Thursday of each week recorded. This may be connected to the fact that the Kuwaiti "weekend" is on Friday/Saturday rather than Saturday/Sunday. Additionally, we notice a wide range of consumption rates, varying from as low as 254 gallons per day to

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as high as 1,811 gallons per day. As a rule of thumb, 80-100 gallons/day is typical for one person [2]; this is confirmed by the median daily water consumption, which is 476 gallons/day. The consumption of water was recorded in spring, and these readings may quietly varies in summer and winter. The size of the household and the number of residence can possibly affect the records.

Date	Day	Meter Reading [Imperial Gal]	Daily Consumption [Imperial Gal]
24-Mar-2015	Tue	4511838	382
25-Mar-2015	Wed	4512220	390
26-Mar-2015	Thu	4512610	1811
27-Mar-2015	Fri	4514421	470
28-Mar-2015	Sat	4514891	451
29-Mar-2015	Sun	4515341	487
30-Mar-2015	Mon	4515829	702
31-Mar-2015	Tue	4516530	679
1-Apr-2015	Wed	4517209	318
2-Apr-2015	Thu	4517527	1393
3-Apr-2015	Fri	4518919	256
4-Apr-2015	Sat	4519175	254
5-Apr-2015	Sun	4519428	931
6-Apr-2015	Mon	4520359	482
7-Apr-2015	Tue	4520841	-
MEDIAN			476

Table 1: Water meter readings at a typical Kuwaiti residence over a two-week period.

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4.2.2. Storage Tank Pump

Following the water meter, the water flows directly into a pump used to maintain the water level of the tank. A common pump model used is the Grundfos-Manufactured MQ3-35, pictured in Fig. 4. These types of pumps are specifically designed for residential use and can be found in many homes in the United States. The Grundfos-Manufactured pump is a low-noise water supply system consisting of a pump, motor, pressure tank, and controller combined into one compact unit. It is suitable for both indoor and outdoor use.

The pump starts when the water level in the tank drops below a certain set point. The internal, built-in, non-return valve prevents backflow during priming and operation. The pump incorporates over-temperature and dry-running protection as well as a control panel. The built-in pressure tank reduces the number of starts and stops in case of leakage during installation. The maximum flow rate of the pump is 22 gallons per minute and the maximum inlet pressure is 40 psi. It has a discharge range of 15 – 49 psi. [3]

Fig. 4. Grundfos MQ3-35 3/4-HP pressure-boosting pump used to maintain the water level of the storage tank. [3] source is in [3]

A quick note about pump/tank configuration: As previously described, utilizing a single pump to maintain water level in the tank is nearly universal. Due to the typical size of Kuwaiti homes, locating the tank on the roof generally provides a sufficient head pressure to water flowing inside the residence. In some cases, there may be an additional pump located after the tank inside the home to further increase the water pressure. For the purposes of our model, we will only consider the first pump located before the storage tank.

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4.2.3. Water Storage Tank

Water is stored on the roof of each residential building in a large anti-bacterial tank, such as the one pictured in Fig. 5. These tanks typically hold 3,000 to 5,000 gallons of water, depending on the size of the house and number of residents. Due to the hot climate in Kuwait, especially during summer, the storage tanks are heavily insulated so that cold water is readily available.

Fig. 5. Water storage tank typically holds 3,000 – 5,000 gallons of water and is located on the roof. The source is in [4].

The water level inside the tank is maintained by a simple ball float valve, such as the ones pictured in Fig. 6. When the tank is full of water, the ball floats to the surface and closes the valve. When the water level drops below a certain set point, the valve opens allowing water to refill the tank.

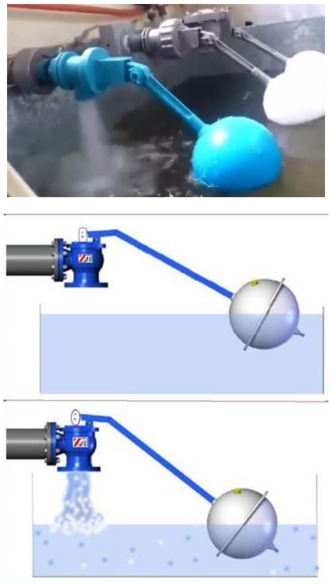

Fig. 6. Three ball float valves filling tank (top, image's source is in [5]) and diagram of float valve operation (bottom, image's source is in [6].

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4.2.4. Water Filter

Following the tank, the next stage of the water system is the filtering system, such as the ones pictured in Fig. 7. As can be seen in the figure, the filtering system usually comes with its own tank (or sometimes two, depending on consumption requirements). The filter is often called the water "softener," because it cleans the water by removing certain minerals, and more importantly, sand. Water softening works on the principle of ion exchange. The softener contains resin beads, which are charged with sodium ions. When water passes through the resin, the hard minerals change places with the sodium ions on the beads. [7]

Fig. 7. Examples of water filtering systems.

To install the filter correctly, an accurate measure of daily consumption is required; this can be obtained using the water meter, as previously described. It is also necessary to know the "hardness" of the water. Hardness is a measure of the calcium and magnesium present in the water. It is usually expressed either in parts per million or, more commonly, in grains per gallon, where 1 grain per gallon = 17.1 parts per million. [7]

4.2.5. Water Heater and Circulation Pump

Once filtered, the cold water is distributed around the house as required, while a parallel pipe network is used to deliver the hot water. In order for hot water to be readily available, a small pump is

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used in conjunction with the water heater to continually circulate the water from the various loads back to the heater.

Bradford White standing water heaters, such as the ones pictured in Fig. 8, are widely used in Kuwait. A common model for the pump is the Grundfos-Manufactured 1/25-HP circulator pump, shown in Fig. 9. Despite its relatively small size, it is capable of pumping up to 16 gallons per minute [8] and is usually sufficient for even large houses.

Fig. 8. Bradford White standing water heaters commonly found in Kuwaiti homes.

Fig. 9. Grundfos-Manufactured 1/25-HP pump used to circulate hot water.

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4.3. Modeling of Water Usage Events

In order to identify opportunities for leak detection, it is necessary to establish a basic understanding of typical water usage throughout the residence. In particular, it is essential to know the frequency and duration of runs by the pump discussed in section 0, as this is likely to be the target of non-intrusive monitoring techniques. For instance, we may find that a healthy water system results in predictable pump run statistics that are altered under the effects of a leak.

In order to draw accurate conclusions, it is first necessary to establish a baseline understanding of the expected pump operation under healthy conditions. This requires accurate models of water usage events, such as running a faucet or flushing a toilet. As demonstrated by the two-week record of water meter readings, the amount of water consumed on a daily basis can vary significantly. Therefore, a purely deterministic approach to load frequency is not sufficient. Instead, we utilize a combination of probability and assumptions about common usage patterns to signal usage events. This variability results in a more truthful depiction of water flow throughout the residence.

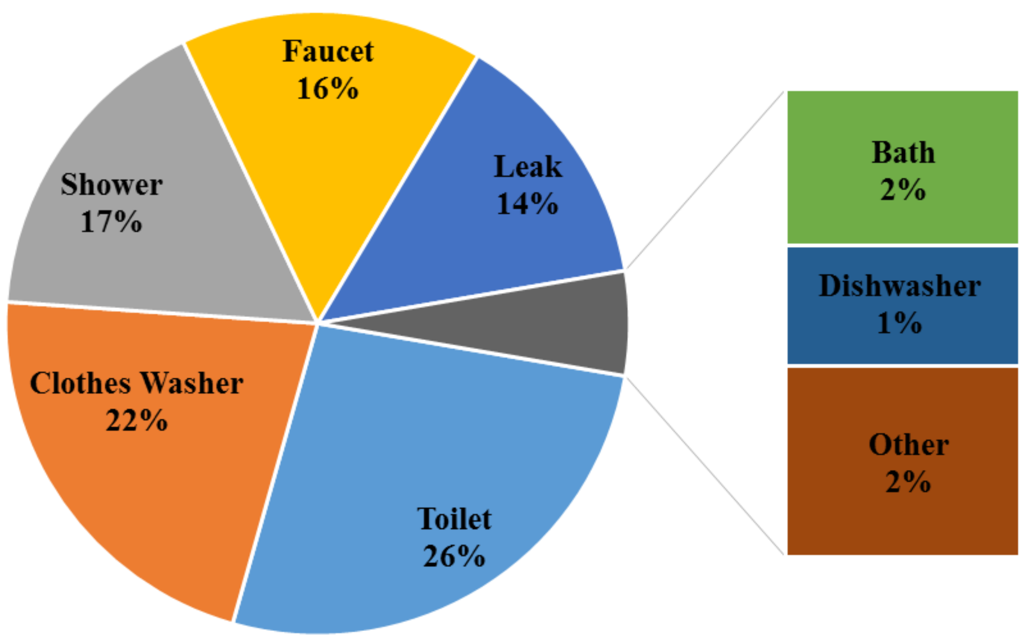

Fig. 10. Breakdown of typical indoor water consumption. The source is in [9].

Home Water Works, a project of the Alliance for Water Efficiency, provides a typical breakdown of indoor water consumption, summarized in Fig. 1 Fig. 9. For the simulation, the focus will be on the four primary culprits: toilet, clothes washer, shower, and faucet. Together, these account for 81% of total

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indoor water consumption [9]. Additionally, note the striking percentage of home water leaks: 14%, which is comparable to both the shower and the faucet, providing further evidence of the potential impact of water monitoring and leak detection.

4.3.1. The Poisson Distribution

As we develop a model for each of the four primary usage events, we will rely heavily on the Poisson distribution. The Poisson distribution is a discrete probability distribution that expresses the probability of a given number of events (x) occurring in a fixed interval of time (or space), when the average number of events (λ) is known [10]. This probability is given by

$$P(x;\lambda) = e^{-\lambda}\frac{\lambda^x}{x!} \tag{3.1}$$

For a Poisson process, the average number of events (expected value) and the variance are the same (both represented by λ).

Many events can be modeled using the Poisson distribution; in [11], it is shown that toilet flushing is one excellent example. In the following sections, we will utilize the Poisson distribution, assumptions about lifestyle patterns, and known usage statistics to determine both the frequency and duration of each usage event.

A quick note about the usage values that will be presented throughout these sections: the statistics are provided by the Alliance for Water Efficiency and were compiled using data collected in the United States, typically for a family of four. We will assume the same family size for our Kuwaiti home simulation. While usage statistics from Kuwait would have been ideal, this information is not readily available. Despite this, the numbers we have used are sufficient in establishing a baseline model for indoor water consumption; additionally, the model is flexible and can be easily updated with more accurate usage data in the future.

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4.3.2. Modeling Toilet Usage Events

As previously mentioned, toilet flushing follows a basic Poisson distribution. The average person flushes 5 times per day [12]. To increase the fidelity of our simulation, we recognize that this average rate will not be constant throughout the day. For example, during normal working hours, the flush rate will likely be lower than during the evening, when most household members are home and awake. To account for these differences in expected value, we utilize three separate averages: daytime, evening, and night.

After 1992, all toilets manufactured in the United States are required to consume no more than 1.6 gallons per flush [12]; these are known as Ultra Low Flush (ULF) toilets, and we will assume they are used in Kuwaiti homes as well. However, this detail *does* warrant further investigation in the future—toilets made from 1980 – 1992 typically consume 3.5 gallons, and toilets prior to 1980 can consume as much as 5 – 7 gallons per flush[12].

Table 2 summarizes the key parameters for toilet flushing and the values used for the simulation. Note that the lambda values are presented as hourly rates for the *entire* household, i.e. for four family members. These values are also consistent with the rate previously given: since one person is expected to flush 5 times per day, we expect the household to flush 20 times per day. If we sum the three lambda values presented in the following table (0.5, 0.75, and 1.25 flushes per hour) and multiply by the time period (8 hours), we obtain the expected value of 20 flushes.

Parameter	Value	Description
λ_n	0.5 flushes/hour	average frequency at night, 12am – 8am
λ_d	0.75 flushes/hour	average frequency at day, 8am – 4pm
λ_e	1.25 flushes/hour	average frequency at evening, 4pm – 12am
t	2 min	usage time (time for tank to refill)
$\dot{V}$	0.8 gal/min	volumetric flow rate
V	1.6 gal	total volume consumption per usage

Table 2: Model parameters for toilet flushing.

4.3.3. Modeling Sink Usage Events

An average household of four uses 30 gallons of water per day from the various faucets located inside the home [13]. The aerator on the nozzle restricts the flow rate from the faucet—common values range from 0.5 – 1.5 gallons per minute [13]. For simplicity, we will assume a flowrate of 1 gallon per minute for all sink usage in the household.

The model for sink usage is in two parts. The first is related to toilet usage: we assume that every time a toilet is flushed, a sink runs one minute later. As discussed in the previous section, we expect 20 flushes per day for a family of four. At a flow rate of 1 gallon per minute and assuming a 1-minute usage time, this accounts for 20 gallons of water per day.

The second part of the model uses a Poisson distribution to account for any other sink usage throughout the day, such as before a meal or after gardening. To be consistent with the average household daily consumption, this "random" usage should make up an additional 10 gallons. Once again assuming a flow rate of 1 gallon per minute and a 1-minute usage time, we calculate an expected value of 0.42 sink uses per hour in addition to the faucet runs following toilet flushes. All sink parameters are shown in Table 3.

Parameter	Value	Description
λ	0.42 uses/hour	average frequency for additional sink use
t	1 min	usage time (time faucet is running)
$\dot{V}$	1 gal/min	volumetric flow rate
V	1 gal	total volume consumption per usage

Table 3: Model parameters for sink usage.

4.3.4. Modeling Shower Usage Events

To predict shower usage frequency, we again rely on the Poisson distribution. We assume that each person takes one shower per day, for a total of four showers for a typical household. However, we confine the distribution to two separate time periods, one at morning and one at night. Additionally, each time period is given its own lambda value—it may be more likely for showers to occur in the morning, for instance. As with the flushes, we can sum the two lambda values (1.25 and 0.75 showers per hour) and multiply by the time period (2 hours) to obtain the expected value of 4 showers.

Similar to the toilet restrictions enacted in 1992, showerheads in the United States are currently restricted to a maximum flow rate of 2.5 gallons per minute, with some nozzles limiting the flow rate to as low as 0.75 gallons per minute. The average American shower lasts 8 minutes at a flow rate of 2.1 gallons per minute. [14] These two values are used in the simulation, although once again, further

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investigation into actual Kuwaiti standards is needed. Showerheads manufactured prior to 1980 often exceed 5 gallons per minute [14], which would certainly impact usage statistics. The key parameters for the shower are presented in Table 4.

Parameter	**Value**	**Description**
λ_m	1.25 showers/hour	average frequency at morning, 5am – 7am
λ_n	0.75 showers/hour	average frequency at night, 9pm – 11pm
t	8 min	usage time (time shower is on)
$\dot{V}$	2.1 gal/min	volumetric flow rate
V	16.8 gal	total volume consumption per usage

Table 4: Model parameters for shower usage.

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4.3.5. Modeling Clothes Washer Usage Events

The clothes washer is the second-leading water consumption device in the household, behind the toilet. This is largely due to the typical vertical axis design: a large amount of water is required to suspend the clothes while the agitator churns. One load of laundry in a standard washer consumes roughly 45 gallons of water. [15] The flow rate of washers is typically 3 gallons per minute [16], resulting in a usage time of 15 minutes. New high-efficiency washers use considerably less water—usually 15 – 30 gallons [15]—but due to the expensive nature of appliances, many homes still utilize standard machines.

The average four-person household does over 300 loads of laundry per year [15]. Assuming that the washer is only run during the day and evening time periods, we are left with 112 hours per week and 5,824 hours per year. Using the Poisson distribution one final time, this results in a lambda value of 0.052 washer runs per hour. All washer parameters are presented in Table 5.

Parameter	**Value**	**Description**
λ	0.052 runs/hour	average frequency, 8am – 12am
t	15 min	usage time (time washer is running)
$\dot{V}$	3 gal/min	volumetric flow rate
V	45 gal	total volume consumption per usage

Table 5: Model parameters for clothes washer usage.

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4.4. Simulating Water Flow

The water flow simulation was constructed using MATLAB® and Simulink®. Six components were considered in the simulation: the pump described in section 0, the storage tank of section 4.2.3, and the four loads modeled in section 4.3. The water filtering and heating systems were not included in this baseline simulation. A high-level diagram illustrating the major simulation components is presented in Fig. 10, and the actual Simulink block diagram is shown in Fig. 11.

Basic operation of the simulation is as follows: First, "control signals" for each load type are used to trigger a water usage event (toilet flushing, shower turning on, etc.). These usage events deplete the water in the storage tank located on the roof of the house. A pump is used to maintain the water level in the tank.

The simulation runs on a time step of minutes, chosen due to the typical time duration of the various load types (washer runs for 15 min, shower runs for 8 min, etc.). This timescale provides enough resolution to clearly capture load starts and stops, but it is not prohibitive computationally. The following sections describe the various aspects of the simulation in more detail.

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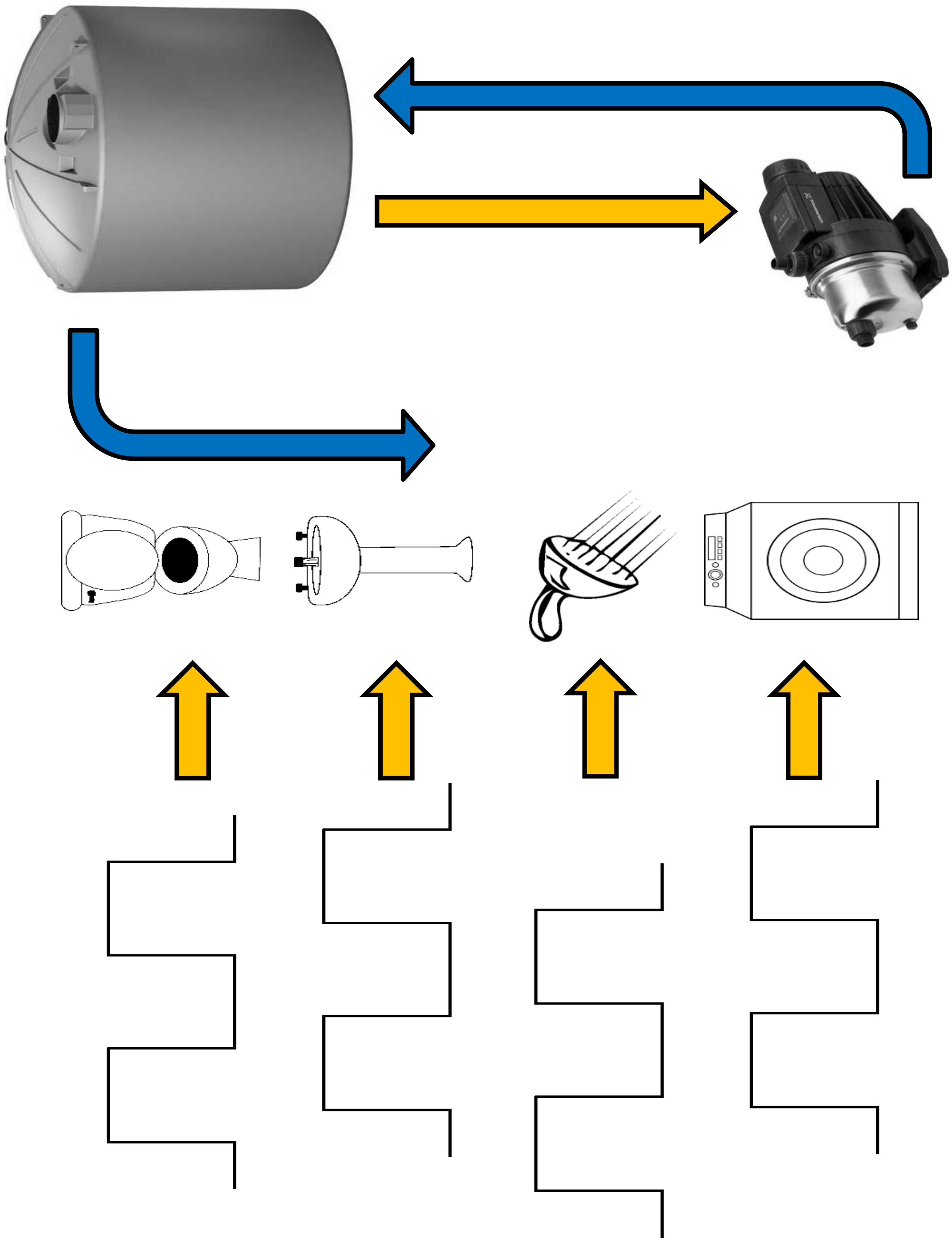

Fig. 11. Pictorial diagram of simulation. Control signals for each load type set the frequency and duration of each water usage event. As these events drain water from the tank, the pump turns on and off to maintain water level.

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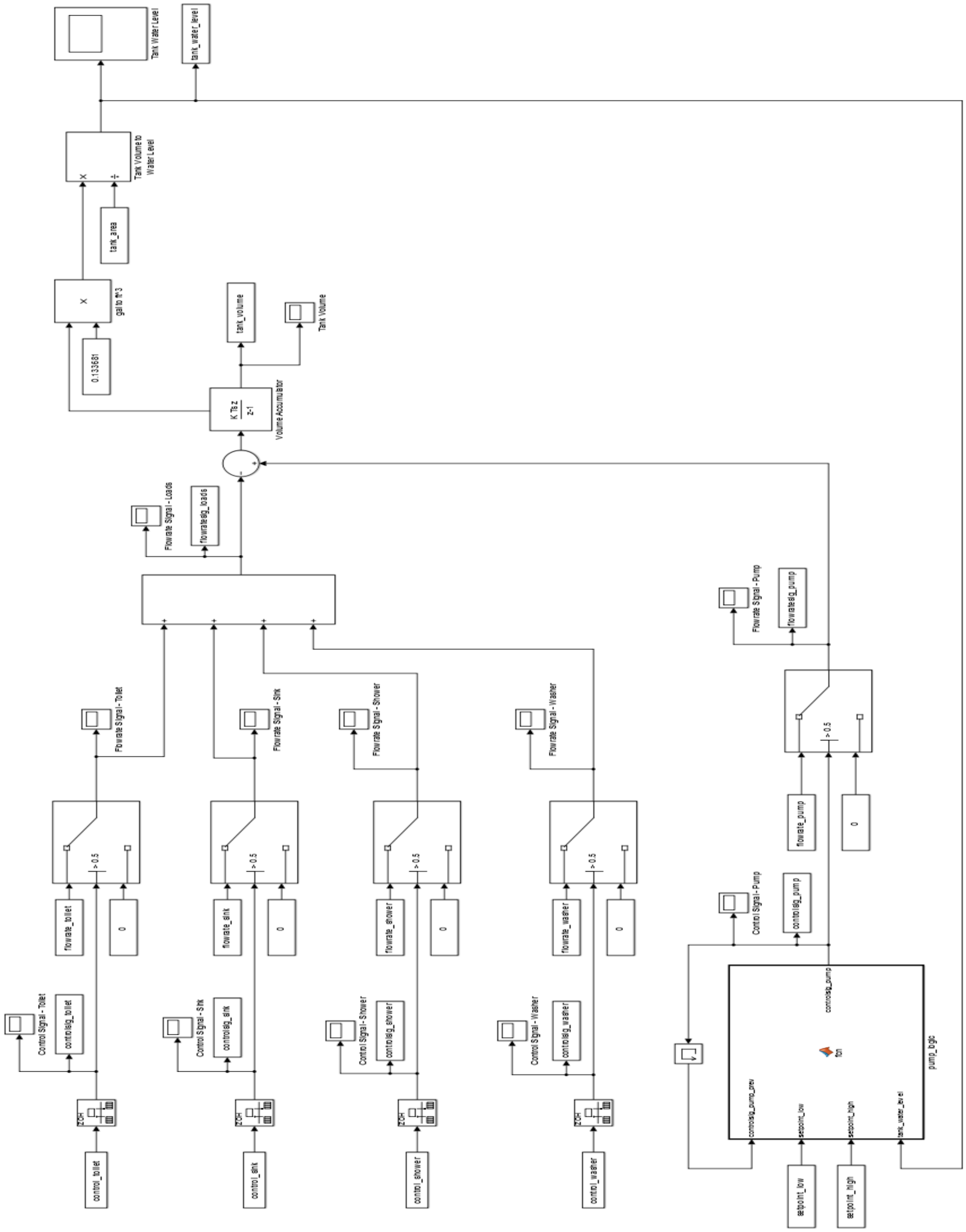

Fig. 12. Simulink block diagram.

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4.4.1. Generating Control Signals

The controls for each load type (toilet, sink, shower, and washer) are created beforehand by means of “prep” functions. These controls consist of a vector of ones and zeros corresponding to a vector of time steps that determine the frequency and duration of each water usage event. The models discussed in the previous sections are used to create these vectors. Simulink then reads the vectors and performs a zero-order hold to construct a square wave that is “high” when the load should be running and “low” when the load should be off.

Fig. 12 shows an example control signal for each load type during one day, from 8pm – 12am (1200 – 1440 minutes). Note the agreement with the frequency and duration dictated by the models. We expect an average of 20 flushes per day, and the Poisson distribution produced 6 flushes during a 4-hour time period, which is reasonable. The toilet stays on for 2 minutes after each flush, which is the time set for the tank to refill.

Following each flush, we notice a sink usage one minute later. There are also two additional sink runs—once again, this is reasonable, since we expect an additional 10 sink runs per day along with those corresponding to flushes. All sink runs have a duration of 1 minute.

The time window shown in the figure includes the night-time shower period, which lasts from 9pm – 11pm. We see two shower occurrences, each lasting 8 minutes. Finally, we see one run of the clothes washer. Due to the lower rate of washer usage, we only expect approximately one run per day, and it happened to occur during the selected time window. The washer run lasts for 15 minutes, as set by the model.

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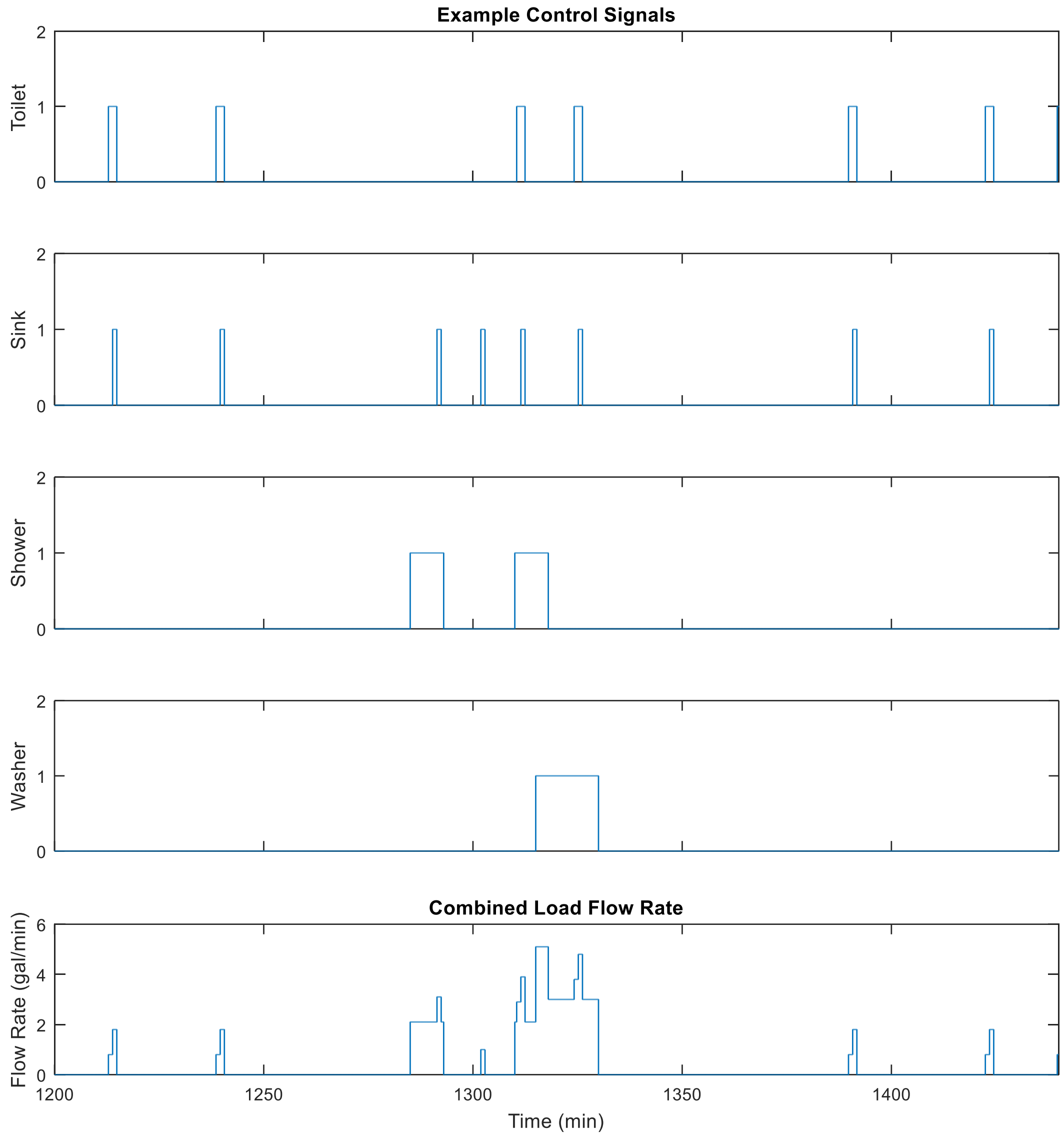

Fig. 13. Example control signals for each load type and combined load flow rate during one day, from 8pm – 12am.

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4.4.2. Determining Tank Water Level

The square-wave control signals are used to activate a switch for each load type, as shown in the Simulink block diagram of Fig. 11. This switch turns the individual flow rate for each load on or off. The load flow rates are then summed at each time step, producing a combined load flow rate, shown in the last plot of Fig. 12. Notice how the load flow rate increases when loads are turned on and goes to zero when all loads are off.

Once the combined load flow rate is calculated, it is *subtracted* from the pump flow rate, which replenishes the water in the storage tank. This "net" flow rate is then integrated to obtain the volume of the tank. Finally, the current water level is simply the volume of the tank divided by the cross-sectional area of the tank.

A note about the steady-state flow rate assumption for each of the loads: it can be seen that the dynamics for the various loads are generally on the order of a few seconds, which is much faster than the duration of the loads. Furthermore, the loads deplete water from a massive storage tank (3,000 – 5,000 gallons), as described in section 4.2.3. This tank acts like a low-pass filter—any errors in volume accumulation due to load flow rate dynamics is negligible for the purposes of this simulation.

4.4.3. Controlling the Pump

As described in section 4.2.3, the water level in the storage tank is controlled using a ball float valve. For the simulation, the pump logic is contained in the MATLAB® function block shown in Fig. 11, which takes the current water level as an input and produces the pump control signal. This control signal is handled like the signals for the loads—a switch reads the signal and turns the pump flow rate on or off. The flow rate for the simulation is set at 20 gallons per minute to match the description of the pump in section 0.

Operation of the pump is simple: When the water level is above the high set point (currently set to 8 feet) the pump is off and the control signal is zero. When the water level falls below the low set point (currently set to 5 feet) the pump kicks on, switching the signal to one. When the water is between set points, the pump retains its previous state, causing it to refill the tank only after the water has dropped below the low set point.

Fig. 13 shows a plot of the pump flow rate and water level corresponding to the loads shown in Fig. 12. As expected, the water level decreases as the various loads are turned on until it falls below the low set point. Then, the pump kicks on, restoring the water level to the high set point.

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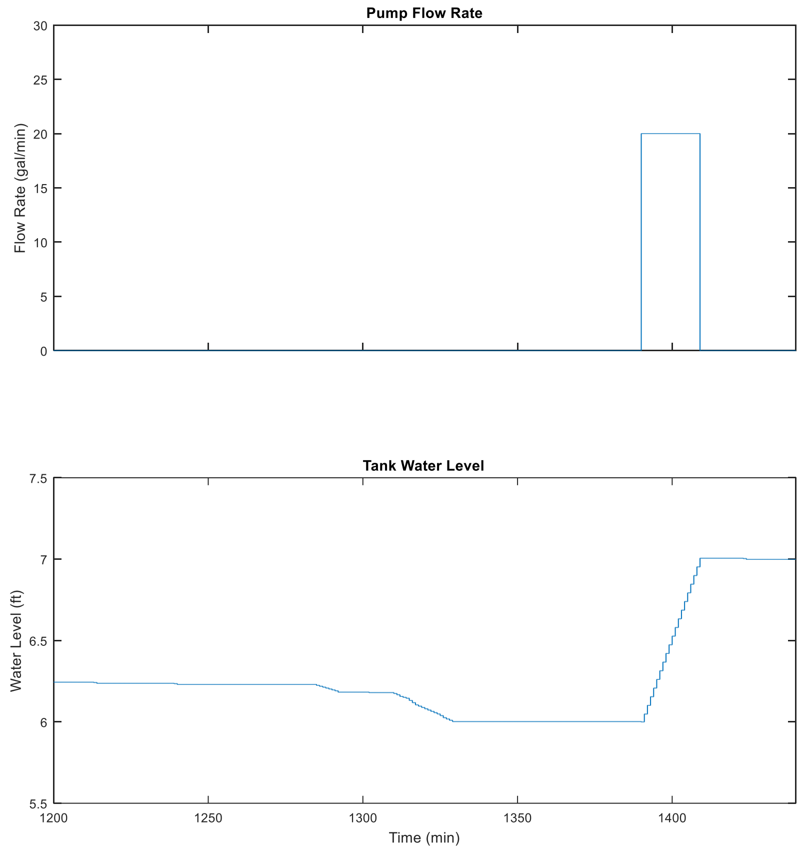

Fig. 14. Pump flow rate and tank water level corresponding to the loads in Fig. 13.

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5. Conclusion

We have developed a functional simulation demonstrating basic water flow throughout a typical Kuwaiti residence. The four major load types accounting for 81% of residential water usage [9] were included in the model: toilet, washer, shower, and sink. Load frequencies were determined using the Poisson distribution in tandem with common usage patterns. Appliance information and energy regulations were used to set load durations and flow rates. The pump and tank logic used in the simulation match actual pump and tank configuration in the vast majority of homes in Kuwait.

This model will provide the basis for future diagnostic efforts. The simulation in its current state shows us a picture of a healthy water system. The next step is to model various leaks and search for discrepancies and changes in pump operation and load flow signature. These results will allow us to recognize similar patterns when diagnosing actual water systems in Kuwait.

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