Modeling and Simulation of a Wastewater Pumping Plant

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Abstract: Modeling wastewater pumping plants is rarely addressed in the literature. Standard component models as found in fluid simulation tool libraries are too complex, due to their projected generality, to be used for these applications. Lack of models results in a burden on engineers who have to test their control scenarios on real implemented systems. This may lead to unexpected delays and painful costs. In this work, easily manageable component-oriented models are derived and applied to the modeling and simulation of a real wastewater pumping system. The model derived in this paper is implemented in Modelica, and it helps better understanding the system dynamics. Thereby, a tool is provided for evaluating the performance of possible control schemes.

1 INTRODUCTION

Daily amounts of about 15000 m^3 of partially treated wastewater are pumped through the new terminal pumping station (NTPS) located at northern Gaza to the new wastewater treatment plant (WWTP). Once the construction of a new treatment plant is completed, the pumping rate will reach an average of 35000 m^3 per day. The transmission pipe has 7.6 km length, 80 cm diameter and 26 m static head. At the present phase a group of ponds near the pumping station are used to buffer and partially treat the wastewater collected from northern Gaza (Werner et al., 2006). Operators of the pumping station manually control the intake amount of these ponds and allow it to be pumped to the wastewater treatment plant. The manual operation should be replaced by an automation system. To this end, models for evaluating different control schemes are necessary. These models should allow efficient simulation of the overall system over long time horizons, to validate the system behavior especially under abnormal conditions like e.g. power outages which are quite common in Gaza.

The pumping station is equipped with 5 booster pumps from ABS. Each pump has a power rating of 315 kW and an expected head of 38 m. It has a pumping capacity of 360 kg/s while running safely at a maximum speed of 1300 rpm. The suction chamber of the booster pumps has a capacity of 500 m^3 and equipped with a level transmitter which is used to control the operation of the booster pumps (Abdelati and Rabah, 2007).

In (Abdelati et al., 2011) a model of the wastewater recovery system was developed. The work presented here, continues the project by presenting a component-oriented model of the wastewater pumping plant. The control scheme of the pumping process will be detailed in Section 2 and modeled in Section 3. The simulation results will be presented in Section 4 and finally in Section 5, concluding remarks will be given.

2 FUNCTIONAL DESCRIPTION

The new terminal pumping station (cf. process flow diagram in Figure 1) transports wastewater from the northern part of Gaza city to the new wastewater treatment plant for Northern Gaza. It basically consists of a screen station and a pump station (Palestinian Water Authority, 2004).

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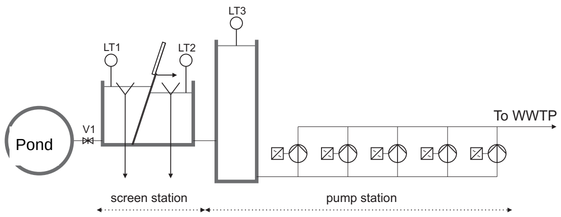

Figure 1: New terminal pumping station (NTPS).

2.1 Screen Station

The screen chamber receives the wastewater from the pond by gravity force. The manual valve (V1) allows setting the intake flow rate. The screen separates coarse material out of wastewater. The coarse material is loaded into a conveyor system. The rack screen and the conveyor starts at a signal due to difference in levels of level transmitters (LT1) and (LT2) located in front of and behind the screen respectively. They run during a preset time to leave at pause position.

If the outtake of the screen fails to compensate the intake, wastewater starts to accumulate in the screen chamber. Overflow occurs if accumulation reaches a specific level (1.6 m). The overflow is collected in a dedicated pond where it is recharged to the main pond by a minor process that is not addressed in this paper.

2.2 Pump Station

This station pumps the wastewater from the suction chamber to the new wastewater treatment plant. The bottom of the suction chamber is placed 2.3 m below the bottom of the screen chamber. The booster pumps are controlled and operated by a signal from level transmitter (LT3). Due to efficiency concerns, pumps are not allowed to run at speeds below one third their nominal speeds. The first pump in operation starts at level L6. When one pump is in operation, a flow of about 120-360 kg/sec (corresponding to 33-100% rotational speed) will be pumped using the frequency converter to keep a preset value of the level (L5) in the suction chamber. The first pump stops at level L1.

If the first pump operates at 100% capacity and the level increases, the second pump starts at level L7. When two pumps are in operation, a flow of about 360-720 kg/s (corresponding to 50-100% rotational speed) will be pumped using the frequency converters to keep a preset value of the level (L5) in the suction chamber. Each pump in operation will pump 180-360 kg/s equal. The second pump stops at level L3.

If two pumps operate at 100% and the level increases up to level L8, the third pump starts. When three pumps are in operation, a flow of about 720-1000 kg/s (corresponding to 66-100% rotational speeds) will be pumped using the frequency converters to keep a preset value of the level (L5) in the suction chamber. Each pump in operation will pump 240-333 kg/s. The third pump stops at level L3.

If three pumps operate at 100% and the level increases up to level L9 the forth pump starts. When four pumps are in operation, a flow of about 1000-1200 kg/s (corresponding to 75-100% rotational speeds) will be pumped using the frequency converters to keep a preset value of the level (L5) in the suction chamber. Each pump in operation will pump 250-300 kg/s. The forth pump stops at level L4. It should be noted that the previous flow rates are predicted values. Actual quantities depend on the resulting dynamic head which is almost proportional to the square value of the flow rate as will be highlighted in the simulations. A maximum of four pumps can be concurrently operated leaving the fifth one as standby unit. Typical values for the level setting are summarized in Table 1.

Table1: Level threshold settings.

Level No	*Activity*	*Setting(m)*
L1	Stop level P1	1.2
L2	Stop level P2	1.4
L3	Stop level P3	1.6
L4	Stop level P4	1.7
L5	**Set point level**	**1.8**
L6	Start level P1	1.8
L7	Start level P2	1.9
L8	Start level P3	2.1
L9	Start level P14	2.3
L10	High Level Alarm	2.500

3 MODEL DERIVATION

For the modeling of large fluid systems, standard component models as found in simulation tool libraries (Elmquist et al., 2003) are very complex (Link et al., 2009). The generic concept behind these models makes them widely applicable for different systems. However, this also leads to a complex parameterization and large simulation overhead. In the presented project, it is not intended to build a sophisticated model for detailed investigations rather to conclude with a manageable working model. The desired simulation model is required to provide better understanding of the pumping process dynamics. Moreover, it is intended to be tool for testing and improving proposed control schemes. To this end, we used the modeling and simulation environment Dymola which is based on the component-oriented modeling language Modelica (Tiller, 2004).

In (Abdelati et al., 2011) a water recovery system has been modeled using the same approach. The system included source/sink, pipes, pumps and other components. The water network components are interconnected through a liquid connector, where conservation of mass flow is assumed. The pressure of the liquid (wastewater in our case) at the connector is referred by p and the mass flow rate is referred by q. In the following subsections the new components necessary to build the system model will be derived.

3.1 Screening Process

The screening process may be decomposed to the following components: two buffering chambers (one after the inlet and one before the outlet), a Bar screen crossing between the buffer chambers, and a screen controller. This is illustrated in Figure 2.

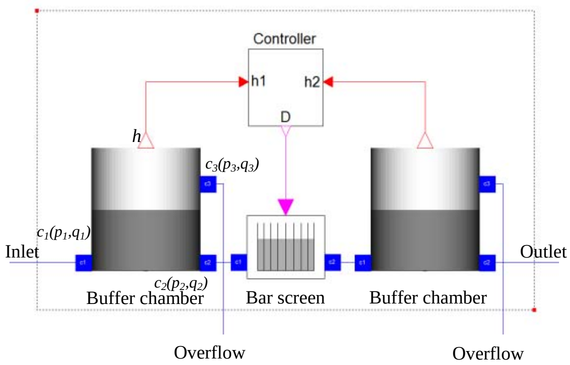

Figure 2: Screening process.

The buffer chamber model has two water connectors at its base and a third one located at the overflow level h_{of} measured from the chamber's base. Another connector of type real output is added to deliver the liquid height (h) to the screen controller.

The pressure at the base connectors c_1 and c_2 is given by:

$$p_1 = p_2 = \rho g h \tag{1}$$

where ρ is the wastewater density, g is the acceleration due to gravity, and h is the wastewater level in the chamber. The pressure at the overflow connector c_3 is discontinuous at the threshold height h_{of} (equals 1.6 m in our case) as follows:

$$p_3 = \begin{cases} 0, & h \leq h_{of} \\ \rho g (h - h_{of}), & h > h_{of} \end{cases} \tag{2}$$

The wastewater level is related to the mass flow rate in the ports as follows:

$$\frac{dh}{dt} = \frac{q_1 + q_2 + q_3}{\rho A} \tag{3}$$

where A is the cross sectional area of the chamber.

The bar screen is the interface located between the two buffering champers. The wastewater flow across this section may be visualized as shown in Figure 3.

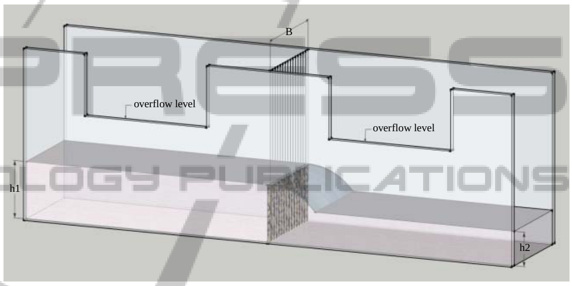

Figure 3: Bar screen visualization.

At a given time, the screen collects an amount of coarse material causing a friction resistance to the water flow. This results in a difference in the wastewater levels across the screen. The waste water flow has two components; the first one (q_a) for which the flow crosses the screen facing atmospheric pressure (from h_2 to h_1). The other remaining component is referred by (q_b) as illustrated in Figure 4.

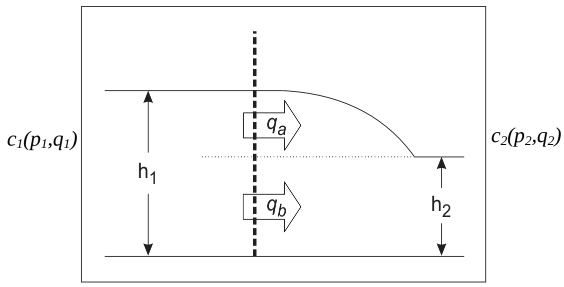

Figure 4: Decomposing the flow across the screen.

The values of these components may be derived from the Bernoulli equation. Under the assumption that the screen area is much less than the area of the inlet buffer base, the following results are obtained:

$$q_a = \frac{2}{3} GB\rho\sqrt{2g}\,(h_1 - h_2)^{3/2} \quad (4)$$

$$q_b = GB\rho\sqrt{2g}\,h_2(h_1 - h_2)^{1/2} \quad (5)$$

where B is the screen width and G is a transparency coefficient that represents the screen conductivity ranging between one and zero. At a given time instant it is related to the amount of the coarse material accumulated on the screen. Therefore, it is a function of the total mass flow (Q) across the screen and a function of the wastewater quality. In analogy with charging a capacitor, we model G as

$$G = e^{-Q/Q_0} \quad (6)$$

where Q_0 is a factor that reflects the wastewater quality. In simulations, we treated it as a constant equal to 864000, forcing G to be about 1 % after working for five hours at the maximum mass flow rate.

The total mass flow since $t = t_0$ and the connectors' signals are related as follows:

$$p_1 = \rho g h_1 \quad (7)$$

$$p_2 = \rho g h_2 \quad (8)$$

$$q_1 = q_2 = q_a + q_b \quad (9)$$

$$\frac{\mathrm{d}}{\mathrm{d}t} Q = q_1;\ Q(t_0) = 0 \quad (10)$$

where $Q(t_0)$ is the initial value. When the screen is triggered by a digital signal (D) to discharge accumulated coarse material, at $t = t_0$, Q is re-initialized by 0. The bar screen module is graphically represented as illustrated in Figure 5.

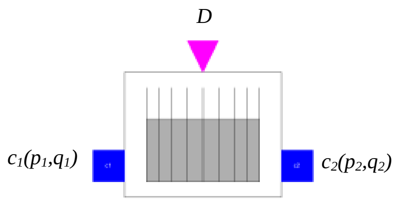

Figure 5: Bar screen icon.

The screen controller senses the amount of accumulated coarse material by means of the wastewater levels in the buffer champers. The controller activates the discharge signal (D) whenever $h_1 - h_2 > h_t$ where h_t is a preset value taken 20 cm in the simulations.

3.2 Pumping Process

This process contains a suction chamber, booster pumps and a controller as illustrated in Figure 6.

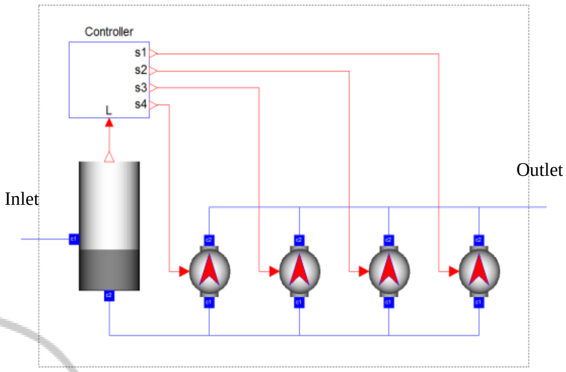

Figure 6: Pumping process.

The suction chamber model is governed by the following equations:

$$p_1 = \begin{cases} 0, & L \leq 2.3 \\ \rho g(L - 2.3), & L > 2.3 \end{cases} \quad (11)$$

$$p_2 = \rho g L \quad (12)$$

$$\frac{dL}{dt} = \frac{q_1 + q_2}{\rho A} \quad (13)$$

The level signal (L) is measured relative to the chamber's bottom, which is located 2.3 m below the inlet connector.

A liner head-flow characteristic around the nominal operating point is used for the booster pumps (Abdelati et al., 2011) as follows:

$$q_1 = \frac{s}{s_n}\left[q_n - a\left(\frac{p_2 - p_1}{\rho g} - h_n\right)\right] \quad (14)$$

where a is the slope of the flow-versus-head curve at the nominal operating point (h_n, q_n), s is the respective pump's speed, and s_n is the nominal speed. The specific data for the installed pumps are: $a = 8.3\ kg/s/m$, $h_n = 38m$, $q_n = 360kg/s$, and $s_n = 1300\ rpm$.

In order to implement the control scheme specified in Section 2.1, the calculation of the speed vector, **s**= $(s_1, s_2, s_3, s_4)^{\mathrm{T}}$, according to the level signal (L) is decomposed as shown in Figure 7.

The controller has a PID module with limited output, anti-windup compensation and set point weighting (Astrom and Hagglund, 1995). Its output specifies the required pumping capacity, which has a minimum of 0 when all pumps are off and a maximum of 4·1300 when 4 booster pumps run at their full speed.

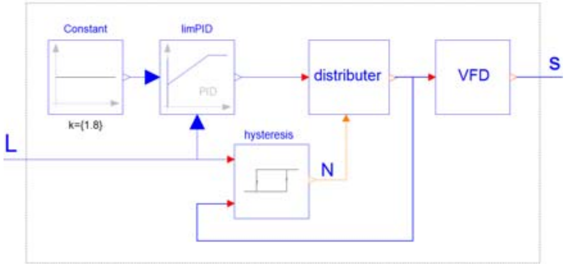

Figure 7: Pumping process controller.

The hysteresis module decides on enabling or disabling each pump and calculates the number of enabled pumps (*N*). The implementation of this module will be described later. The distributer divides the PID output value by this number and assigns the result to the enabled pumps taking into account that the result has a saturation value of 1300 rpm. The hysteresis module is a sequential circuit which uses the state of pumps (enabled/disabled), their assigned speed, and the wastewater level to calculate their next states. Then it calculates the number of enabled pumps and delivers it to the distributer module. The state equation of a pump is simply the characteristic equation of an RS flip flop which is set whenever wastewater level exceeds the set level of the pump and reset whenever the level drops below the stop level or its speed drops below its minimum allowed speed. The minimum speed limits of pumps are 433, 650, 866, and 975 rpm, respectively. This ensures exempting a pump whose load share can be carried by the other running pumps.

The Variable Frequency Drives (VFD) module is modeled by a first-order block with a time constant of 5 s resulting in an acceleration time of about half a minute to move forward or backward between zero speed and rated speed states.

3.3 Complementary Modules

Encapsulating the screening and pumping processes into two stand alone modules, the system model will be as illustrated in Figure 8.

Connectors of the overflow pond and the sink pond are located above the surfaces of the ponds. Therefore, they have the atmospheric pressure value which is our reference ($p = 0$). On the other hand, the connector of the source pond is located at the bottom of the pond. The wastewater level in the source pond may vary along the year depending on the collected sewage. However, the pond is so huge that its level is safely considered as constant on weekly or even monthly bases. Consequently, the pressure at the source pond connector is treated as constant. This constant is taken as the value found during the month of June which is about 0.25 bar.

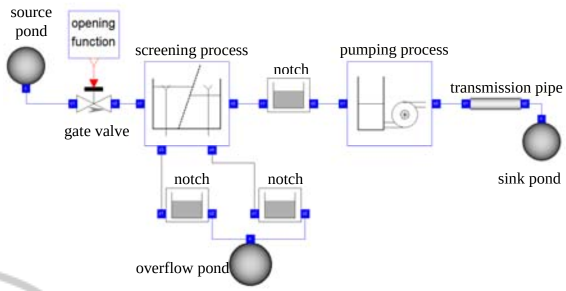

Figure 8: System model.

The gate valve is adjusted manually to control the daily transmitted wastewater and indirectly decide on the pumping capacity. If the inlet wastewater rate exceeds the feasible pumping capacity, then the automation system should signal a high level alarm prior to overflow. The operator in turn, should react immediately by decreasing the gate valve opening and vice versa. Operator interaction is expected to be on weakly bases in case pumping is done all the day. A linear relation between flow and pressure drop is used for the valve model. The control signal of the valve is named $opening$ and its value ranges from 0 at full closure to 1 at full opening. The nominal hydraulic conductance of a valve, k, is defined as the ratio of nominal flow to nominal pressure drop at full opening. Assuming linear pressure drop, then the flow is governed by the following equation:

$$q_1 = opening \cdot k \cdot (p_1 - p_2) \tag{15}$$

The Bernoulli equation is used to derive the model of notches. Since they always have inlet pressure greater than or equal to the corresponding outlet pressure, their equation reduces to

$$q_1 = \frac{B}{g}\sqrt{\frac{2}{\rho}}\left[\frac{2}{3}(p_1 - p_2)^{3/2} + p_2(p_1 - p_2)^{1/2}\right] \tag{16}$$

where B is the width of the notch.

The transmission pipe is modeled according to the Hazen-Williams equation (Brater at al., 1996). The resulting model is

$$p_1 - p_2 = \frac{10.67gl}{C^{1.85}\rho^{0.85}d^{4.87}}q_1^{1.85} + \rho g H \tag{17}$$

where d is the diameter, l is the length, H is the static head, and C is the roughness coefficient of the pipe. This coefficient is about 140 for most pipes as it does not depend so much on the roughness of the material itself, but on the roughness of the bacterial slime layer which grows on the pipe wall.

3.4 The Implementation Procedure

This subsection describes briefly how the models were implemented in Modelica using the Dymola tool (Dynasim, 2009). The first step was implementing the liquid connector (*c*). Its icon is represented by a small blue square and it is defined as follows:

```
connector c
  Modelica.SIunits.Pressure p;
  flowModelica.SIunits.MassFlowRate q;
end c;
```

Then, the components necessary to build the top level module are implemented one by one. For example, the suction chamber has two liquid connectors (*c1* and *c2*) in addition to an output connector (*L*) of type real. Being governed by Eq. 11, 12, and 13, its Modelica code will be as shown in Figure 9.

```
model SuctionChamber
  constant Real g=Modelica.Constants.g_n;
  parameter Modelica.SIunits.Density rho=1200 "liquid density";
  parameter Modelica.SIunits.Area A=125 "base area";
  parameter Modelica.SIunits.Length L_0=0 "initial height";
  Modelica.SIunits.Length L(start=L_0,min=0) "hight";
  Connectors.c c1 "inlet";
  Connectors.c c2 "outlet";
  Connectors.OutPort Level;
equation
  c1.p =if L>2.3 then rho*g*(L-2.3) else 0;
  c2.p = rho*g*L;
  der(L)=(c1.q+c2.q)/rho/A;
  Level.signal[1]=L;
end SuctionChamber;

connector MyPackage.Components.Connectors.c
  Modelica.SIunits.Pressure p;
  flow Modelica.SIunits.MassFlowRate q;
end c;

connector MyPackage.Components.Connectors.OutPort
  "Connector with output signals of type Real"
  parameter Integer n=1 "Dimension of signal vector";
  replaceable type SignalType = Real "type of signal";
  output SignalType signal[n] "Real output signals";
end OutPort;
```

Figure 9: Modelica code of the suction chamber.

Only the equations section along with the necessary parameters and constants need to be written by the programmer. The instantiations of connectors are simply done by dragging-and-dropping in the graphical interface of Dymola. Moreover, the tool allows drawing a graphical icon to represent the component. It also generates code for graphically interconnected components that build a higher level module. For example, Figure 10 illustrates the Modelica code that corresponds to the screening process shown in Figure 2.

```
model ScreeningProcess
  Connectors.c inlet;
  Connectors.c outlet;
  Connectors.c overflow1;
  Connectors.c overflow2;
  BufferChamber bufferChamber1;
  BufferChamber bufferChamber2;
  BarScreen barScreen;
  ScreenController screenController;
equation
  connect(inlet, bufferChamber1.c1);
  connect(bufferChamber1.c2, barScreen.c1);
  connect(barScreen.c2, bufferChamber2.c1);
  connect(bufferChamber2.c2, outlet);
  connect(bufferChamber1.c3, overflow1);
  connect(bufferChamber2.c3, overflow2);
  connect(bufferChamber1.h, screenController.L1);
  connect(bufferChamber2.h, screenController.L2);
  connect(screenController.Discharge, barScreen.Discharge);
end ScreeningProcess;
```

Figure 10: Code generated by the graphical tool.

A good modeling methodology starts by implementing simple models, which can be easily verified by intuition. It continues with models of increasing complexity until reaching the top-level module. At each stage, created components are connected to form system models whose simulation results can be compared to expectations from the *mind* model. If they agree, the model is verified. Otherwise, the mathematical model is revised or the mind model is adjusted through gaining new physical insight (Jensen, 2003).

4 SIMULATION RESULTS

The aim of simulations is to validate the consistency of the derived model and to investigate the behavior of the system under unfavorable scenarios. Power failure, excess flow, and operator inattentiveness may lead to overflow. The implemented control algorithm is widely used in pumping stations and claims to minimize the number of restarts of pumps and the number of running pumps given a desired daily flow. The running period and the number of restarts have direct impact on the depreciation of pumps and their power consumption. Deriving a formula for the cost function, which also includes overflow cost and operator satisfaction (utility), is intended to be done in a future work. The scope of this paper is to create a working model and simulate normal and unfavorable running conditions leaving the evaluation and improvement of the control algorithm to a complementary work. To this end, the opening signal of the gate valve and the availability of electric power are assigned the functions shown in Figure 11. The opening signal function represents possible flows along the year. The failure of electric power supply during the time period [3600 s, 4800 s] is intended to investigate overflow behavior during a relatively high flow period. The failure is implemented by suppressing the controllers' outputs during the failure period.

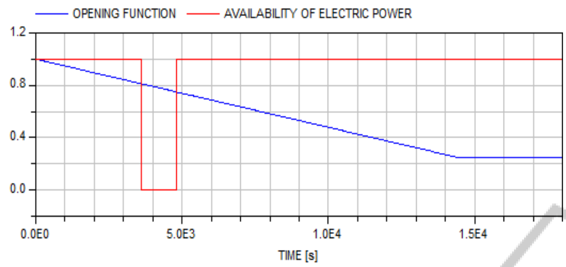

Figure 11: Simulation Scenario.

Simulation results which lie within our interest are shown in Figure 12. As expected, they are consistent with real world data observed in the plant. In Figure 12.a, the waste water levels in the screen chambers are depicted. Shortly after the power failure, the levels in the chambers reach the level of the overflow notches (1.6 m) and eventually cause flood to the overflow pond as shown in Figure 12.b. In the same figure, the inlet and transmitted flows are depicted. It is worth to highlight the value of the outlet flow when the pumps run at their full capacity. It is about 380, 720, 982, and 1186 kg/s while the number of pumps equals 1, 2, 3, and 4, respectively. Figure 12.c illustrates the time instances when the screen discharge signal is enabled. This happens whenever the level difference in the screen chambers reaches 0.2 m. The wastewater level in the suction chamber is depicted in Figure 12.d. Apart from the starting and the power failure periods, the level in the suction chamber is almost equal to the reference value which is 1.8 m. The overshoot is expected as it is necessary to trigger the starting of the pumps. The load share of these pumps is shown in Figure 12.e. Running pumps always have equal shares, as desired, and it is notable that sudden increase in the pump speeds occurs at screen cleaning instants.

Keeping the wastewater level in the suction chamber around the reference value implies adjusting the outlet flow to meet the inlet flow. However, this does not insure running the plant in the most efficient way. One should develop a controller which maximizes a proper performance measure while keeping the level within allowable domain. A good performance measure could be the pumping efficiency which is the ratio of the outlet flow to the consumed power.

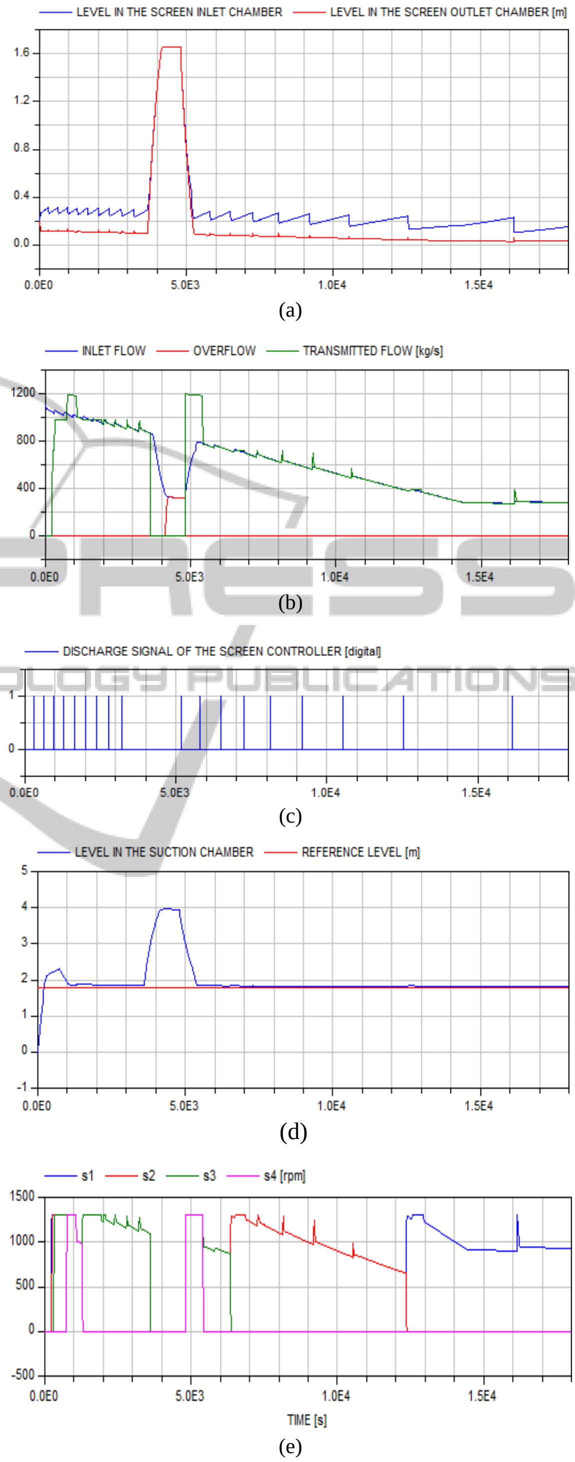

Figure 12: Simulation output results.

5 SUMMARY AND OUTLOOK

This work presents an easily manageable model for a wastewater pumping station in northern Gaza. The resultant model provides a practical tool for examining the system control under different running conditions, such as pump failure and changing flow rates. This simulation model assists in adjusting the control reference points and parameters to cope with regular and undesired situations. The simulated control algorithm is widely used in pumping stations and it is believed that it works to minimize maintenance and running costs by minimizing the number of running pumps and limiting the number of their restarts for a certain inlet rate.

At the present phase, the ponds of the old treatment plant serve as a buffer for the wastewater before being pumped via the NTPS to the new treatment plant. This buffering stage will not be available by the completion of the project as the old plant will be removed and incoming wastewater is planned to be transmitted directly to the new treatment plant. Only one small size pond will be left for collecting emergency overflows at the pumping station. As a result, the real challenge of the control problem is not the present phase where a fixed daily amount of wastewater needed to be transported. In the final phase, the pump station must handle instantaneous variation of the wastewater flow. Accidental overflow will result in an additional re-pumping cost and undesired environmental consequences. Therefore, an estimate of the daily diurnal flow pattern is necessary to examine the plant controller under daily variation of wastewater flow.

In a future work, we plan to model the daily diurnal flow pattern and formulate a quantitative performance measures for running the system. This will enable us to develop a criterion for optimal control of pumping stations. We will employ simulations over long time horizons to respect special conditions found in Gaza but also many other developing areas. For example, frequent failure in the main electric power supply is common in Gaza city nowadays and requires intensive operator supervision. Moreover, power produced by the standby generators is much more expensive than the power of the main supply. This is a point normally not considered in deriving the control laws. Models implementing functions to derive the total cost of operation similar to models presented in (Felgner et al., 2011) combined with predictive – simulation based – hybrid control schemes as in (Sonntag et al., 2009) are expected to be of great value under these conditions.

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