MODELING, SIMULATION AND CONTROL OF A WATER RECOVERY AND IRRIGATION SYSTEM

Mohamed Abdelati
Electrical Engineering Department, IUG, Gaza, Palestine

Felix Felgner, Georg Frey
Chair of Automation, Saarland University, Saarbrücken, Germany

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Abstract: For the modeling and simulation of large water recovery and irrigation systems, standard component models as found in simulation tool libraries are too complex. In this work, simple models are derived and applied for the modeling and simulation of a real system. In this system, water for irrigation will be collected by recovery wells around the wastewater treatment plant infiltration basins located in northern Gaza. There will be 27 recovery wells to collect the water in a reservoir before being distributed for irrigation via 10 booster pumps. During summer time, the system is expected to recover and distribute about 50885 m^3 daily. The model derived in this paper using Modelica helps better understanding the system dynamics and provides a tool for evaluating the performance of possible control schemes.

1 INTRODUCTION

Daily amounts of about 15000 m^3 of partially treated wastewater are infiltrated through allocated basins in northern Gaza. Once the construction of a new treatment plant is completed, the infiltrated water will reach an average of 35000 m^3 per day. This infiltrated water is not suitable for domestic use and eventually will contaminate the aquifer of all over northern Gaza (Werner, 2006). However, this water is suitable for irrigation and is recommended to be utilized due to the scarce water recourses of Gaza. Consequently, the Palestinian Water Authority (PWA) with technical assistance from specialists proposed the construction of 27 recovery wells around the infiltration basins. Pumps of 56 kW will be used in these wells and recovered water will be collected in a 8000 m^3 reservoir before being distributed for irrigation via 10 booster pumps, each with a rating of 350 kW (Ziara, 2010). Recovery pumps have an expected head of 90 m and a pumping capacity of 170 m^3/hr at that head, while booster pumps have an expected head of 115 m and a pumping capacity of 750 m^3/hr at that operating point. Figure 1 illustrates the layout of the waste water treatment plant in northern Gaza.

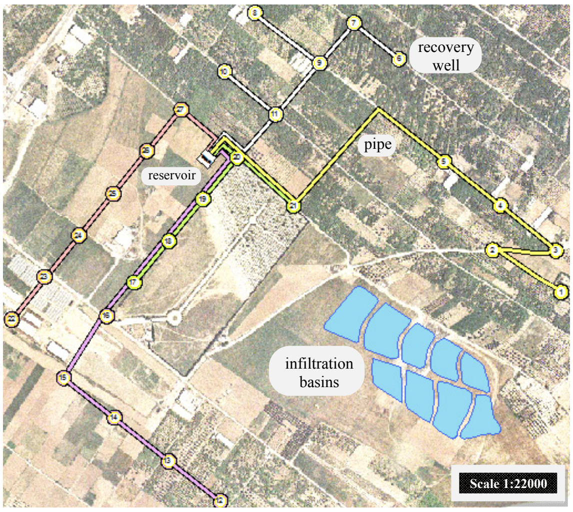

Figure 1: The recovery wells and collection pipes.

The presented work is part of a project which aims to design a control system for the infiltrated wastewater recovery. To this end, first a simulation model is designed based on the physical properties of the process. This model, using the component-

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oriented modeling language Modelica (Tiller, 2004), is then used to design and validate proposed automation strategies.

The paper is organized as follows: Section 2 describes the recovery process and the irrigation scheme. In Section 3, the modeling is described and in Section 4, some simulation results of the proposed control scheme are presented. Finally, Section 5 concludes with summary and outlook on future work.

2 RECOVERY PROCESS AND IRRIGATION SCHEME

Hydrology specialists have studied the aquifer characteristics and the process of water infiltration and decided on the number, capacity, and location of wells so as to siege the pollution plume within standard limits. The whole amount of infiltrated water within one year will be recovered along the year depending on the demand patterns of the crops. At least 10% extra should be abstracted to ensure capturing of all infiltrated quantity. Due to security conditions at northern Gaza, pumping is only allowed during day time and should be adjusted monthly with a maximum of 12 hrs in summer and 8 hrs in winter. The expected quantity of recovered water, the number of running wells, and the duration of daily operation are summarized in Table 1. The beneficiary agricultural area is about 15 km^2. It has been split into six zones of approximately equal sizes. Each zone will be served for one day every week and receive the same amount of extracted water. This irrigation pattern is recommended by agriculture specialists after studying the soil and types of crops.

Table1: Recovery process data.

Month	*Recovered* (m^3/day)	*Number of wells*	*Duration* (hrs/day)
Jan.	33081	19	8
Feb.	35816	21	8
Mar.	34995	21	8
Apr.	34204	20	10
May	46622	23	11
June	**50885**	25	12
July	50136	25	12
Aug.	49073	24	12
Sept.	40290	20	11
Oct.	30187	18	9
Nov.	31484	19	8
Dec.	33146	20	8
Average	**39160**	21	10

3 MODEL DERIVATION

Modelica is an object-oriented language developed by the Modelica Association. Its standard library contains a *fluid* package which provides components for 1-dimensional thermo-fluid flow in networks of pipes. All components are implemented such that they can be used for an incompressible or compressible medium, a single or a multiple substance medium with one or more phases (Elmqvist, 2003). Although it provides a user friendly way to model water networks, we preferred to build our own library. The reasons behind our approach are:

1. The fluid library is a general purpose tool, associated with an overhead that is manageable in systems with small number of component instances (Link, 2009). However, as the number of instances increases, the resultant number of equations may lead to problems in simulation. Simplifying the components to deal with the basic dynamics of our application allows generating models with much less equations.
2. Implementing the fluid components provides more insight on the physical process and allows better capabilities in resolving possible programming and simulating problems.
3. It is not intended to end up with a complex model for detailed hydraulic investigations rather than to conclude with a manageable working model which is well suited to test control methodologies in large scale water networks. It is analogues to the load flow analysis on power systems where simple models are used for electrical equipment and loads.

The system under study contains instances of key components which are tank, source/sink, pipe, fixed speed pump, variable speed booster pump, valve, end users, and some instruments. Developing a model in Modelica starts by defining the connectors (ports), then building the components, and finally creating necessary instances of these components and interconnecting them properly.

Water network components are interconnected through a water connector where conservation of mass flow is assumed. The water connector (*c*) is defined as:

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

where q is the mass flow rate of water into the connector and p is the water pressure at that connector. The pressure is measured relative to the atmospheric pressure, which is assumed to be constant in our work. Finishing the definition of the water port, the system components are then addressed in the following subsections.

3.1 Water Tank

The tank has two water connectors; one is positioned at the top for filling while the other is located at the bottom for draining as illustrated in Figure 2. A third connector of type *real output* is added to deliver the water level information (L) to the controller.

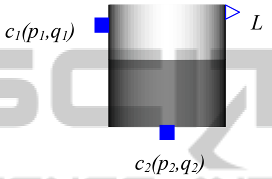

Figure 2: Water tank icon.

The pressure at the outlet port is given by:

$$p_2 = \rho g L \tag{1}$$

where ρ is the water density, g is the acceleration due to gravity, and L is the water level in the tank.

At the inlet port, a velocity head pressure is assumed according to:

$$p_1 = k q_1^2 \tag{2}$$

where k is a constant that may be determined experimentally. In simulations, k is set to 0.07 Pa·s^2/kg^2 so as to allow about one bar pressure at full capacity.

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

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

where A is the cross sectional area of the tank. Finally, the signal at the "level" port is assigned the value of L.

3.2 Boundary Source/sink

The model for source and sink has one water port as shown in Figure 3. It is assumed that the absolute pressure at the water source/sink is the same as the nominal ambient pressure. Hence, a source/sink is simply modeled by the equation $p = 0$.

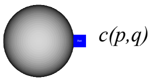

Figure 3: Water source/sink icon.

3.3 Pipes

A pipe has two water ports as illustrated in Figure 4. All pipes have circular cross section and each one is characterized by its diameter d and length l.

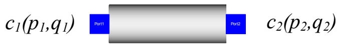

Figure 4: Water pipe icon.

Pipes are modeled according to the Hazen–Williams equation:

$$V = 0.849 C R^{0.63} S^{0.54} \tag{4}$$

where V is the water velocity, C is the roughness coefficient, R is the *hydraulic radius*, and S is the head loss per length of the pipe (Brater, 1996). The value of C can vary from around 100 to 150. For PVC pipes used in our network, a value of 140 is adopted.

Substituting $S = \Delta p/(\rho g l)$, $V = q/(\rho \pi (d/2)^2)$, and $R = d/4$ in the Hazen-Williams equation and manipulating gives the dynamic pressure drop as:

$$\Delta p = \frac{10.67 g l}{C^{1.85} \rho^{0.85} d^{4.87}} q^{1.85} \tag{5}$$

Let the static head of the pipe equal "*HEAD*" then the pressure deference between the pipe ports is given by:

$$p_1 - p_2 = \frac{10.67 g l}{C^{1.85} \rho^{0.85} d^{4.87}} q_1^{1.85} + \rho g HEAD \tag{6}$$

3.4 Recovery Pumps

A recovery pump is a fixed-speed pump which has two water ports and one Boolean input port (u) for on/off control as illustrated in Figure 5.

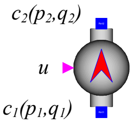

Figure 5: Water recovery pump.

Pumps have head-versus-flow characteristics similar to the curve illustrated in Figure 6.

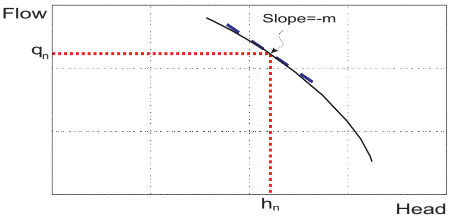

Figure 6: Typical pump flow characteristic.

It may be linearized around its nominal operating point (h_n, q_n) at which the slope of the curve is $(-m)$. This implies that the water flow rate near the nominal operating point is approximately given by:

$$q = q_n - m(h - h_n) \tag{7}$$

If simulation is expected to encounter operating points which are too far away from the nominal one, then the curve may be approximated by a polynomial equation. A check valve is installed at each pump preventing reverse flow when a pump is shutdown (u = false). Substituting $h = \frac{p_2 - p_1}{\rho g}$ and $q = q_1$ results in

$$q_1 = \begin{cases} q_n - m\left(\frac{p_2 - p_1}{\rho g} - h_n\right) : & u = \text{true} \\ 0 \qquad\qquad\qquad\qquad : & u = \text{false} \end{cases} \tag{8}$$

At the nominal operating point (90 m, 47 kg/s), the value of m for the currently selected pump is found to be 1.04 kg/s/m.

In order to simplify modeling the recovery network, a recovery well module consisting of a boundary source, a vertical pipe, and a recovery pump is encapsulated. This module is graphically represented as illustrated in Figure 7.

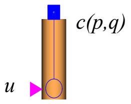

Figure 7: Recovery well icon.

3.5 Booster Pumps

A booster pump is similar to a recovery pump but it has a real signal input (s) for speed control as illustrated in Figure 8.

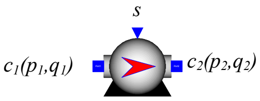

Figure 8: Booster pump.

Currently investigated boosters are of model type NK 150-315 from Grundfos (Grundfos, online). This type has a flow-head slope of -2.78 kg/s/m at our nominal operating point (115 m, 208 kg/s). As booster pumps have a rated speed (s_n) of 2900 rpm, the flow at a certain speed (s) is given by:

$$q_1 = \frac{s}{s_n}\left[q_n - m\left(\frac{p_2 - p_1}{\rho g} - h_n\right)\right] \tag{9}$$

3.6 Valve

The valve model is used here to facilitate the total user demand of water flow. Therefore, it has a linear relation between flow and pressure drop. The model valve has two water ports and one real input port for opening control as illustrated in Figure 9. The control signal is named "*opening*" and its value ranges from 0 at full closure to 1 at full opening.

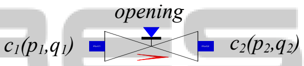

Figure 9: Water valve.

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:

$$q_1 = opening \cdot k \cdot (p_1 - p_2) \tag{10}$$

3.7 Users' Demand

There are variations in irrigation demand during the year as well as during the day. In what follows, modeling users' demand during the peak month of June is explained as an example. The irrigation plan, which is already illustrated in Table 1, specifies daily recovery and distribution of 50885 m^3 of water during June. The variation in distribution during the day has been determined based on the number and size of farms as well as the irrigation preference by farmers. The number and sizes of farms in each of the six irrigation zones has been determined. In addition, a questionnaire to farmers has shown that farmers prefer to irrigate in the morning hours. Therefore, it is assumed that all farmers start irrigation once the pumping process starts in the morning (7 am) and end at various times depending on the farm size. The minimum irrigation period for the smallest farm size of less than 1500 m^2 is 4 hours. This is achieved by allocating proper subscription capacity for each farm. The irrigation period increases by one hour for each 1500 m^2 increase in the farm size until reaching the maximum of 12 hours for farms larger than 12000 m^2 where irrigation ends at 7 pm. Table 2 illustrates demand calculations carried for one of the irrigation zones.

Table 2: Irrigation demand calculations for zone F.

farm class	No. of Farms	Period (hr)	Area (m^2)	Demand (m^3/day)	Demand (m^3/hr)
< 1.5	5	4.0	7300	152.7	38.2
1.5 - 3.0	35	5.0	95000	1987.7	397.5
3.0 - 4.5	65	6.0	289400	6055.1	1009.2
4.5-6.0	34	7.0	213500	4467.1	638.2
6.0-7.5	19	8.0	153400	3209.6	401.2
7.5-9.0	17	9.0	165800	3469.1	385.5
9.0-10.5	13	10.0	150100	3140.6	314.1
10.5-12	11	11.0	147000	3075.7	279.6
>12	49	12.0	1210500	25327.4	2110.6
total			2432000	50885.0	5574.0

During the first 4 working hours (from 7 to 11 am), the demand has a peak of 5574 m^3/hr (1548.3 kg/s). During the next hour (form 11 to 12 am), demand will be reduced by 38.2 m^3/hr and in the consecutive hour, it will be reduced by 397.5 m^3/hr and so on. Using this approach, the demand values along the day are computed for each irrigation zone and the results are normalized to their maximum value (1548.3 kg/s) as listed in Table 3.

Table 3: Relative demand values for irrigation zones.

Time	A	B	C	D	E	F
07:00 - 11:00	0.8152	0.8831	0.8489	0.8830	0.9237	1.0000
11:00 - 12:00	0.8137	0.8826	0.8479	0.8780	0.9232	0.9970
12:00 - 13:00	0.8063	0.8709	0.8353	0.8637	0.9156	0.9579
13:00 - 14:00	0.7987	0.8326	0.8110	0.8392	0.8632	0.8389
14:00 - 15:00	0.7777	0.8008	0.7791	0.8082	0.8049	0.7512
15:00 - 16:00	0.7570	0.7255	0.7489	0.7336	0.7189	0.6881
16:00 - 17:00	0.7427	0.6678	0.7272	0.6949	0.6506	0.6199
17:00 - 18:00	0.7216	0.6226	0.6827	0.6384	0.5414	0.5582
18:00 - 19:00	0.6883	0.5804	0.6785	0.5978	0.4915	0.4977

Sharp transitions are smoothed by a first-order low pass filter whose time constant is 3 minutes to generate more realistic transitions in the demand function. This function is used to specify the opening of the users' valve. Designers of the irrigation network specified the nominal head at farmers tab to be 2.5 bar. Therefore, in simulations it is assumed that the valve has a nominal flow of 1548.3 kg/s and a nominal pressure drop of 2.5 bar. This implies that the hydraulic conductance of the valve is 0.061932 kg/s/Pa.

3.8 Instruments

The flow and pressure meters are modeled as ideal devices. They just tap the required physical quantities and provide them through connectors of type real.

4 SIMULATION RESULTS

The system is built in Dymola and fed by wells' depths and pipes' data as illustrated in Figure 10. Different control schemes and various running scenarios are examined to validate the model. Selected results are presented in this section to provide an overview of the system dynamics.

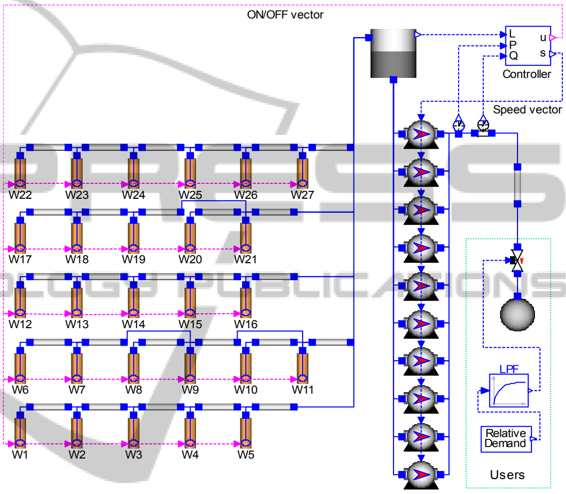

Figure 10: Top level model of the system.

The control variables are the water level of the tank (L) and the water flow rate at the distribution pipe (Q). The tank has a capacity of 8000 m^3 and has a height of 5m. The reference value of L is set to 4.9 m. This tolerates possible overshoots up to 2% of the height before occurrence of overflow. Meanwhile, it utilizes about 98% of storage capacity to handle possible daily demand variations. The reference value of the flow is the expected water demand. In regular conditions, the controller will be able to manage water distribution as planned. However, in certain circumstances, the behavior of farmers may not be as scheduled. This has a direct impact on the pressure at the distribution network. The controller should use the pressure signal (P) at the output of the booster pumps as an interlock variable. The controller should protect the distribution network from over-pressure conditions by keeping the signal P less than the threshold value specified by the hydraulic system designers (11 bar in our case). On the other hand, if farmers require more water than scheduled while having some idle pumping resources, resultant decrease in the pressure may be used by the controller to increase the pumping rate. However, this has an impact on the aggregated amount of extracted water. Due to this consequence, it has been decided to ignore low pressure events so as to encourage farmers to obey the planned irrigation schedule.

The filling process controller is based on a PID controller with limited output, anti-windup compensation and set point weighting as illustrated in Figure 11 (Astrom, 1995). This PID controller is available in the Modelica standard library. The controller is tuned and its output is limited to the range [0, 25]. The analog output is quantized taking into account a sufficient hysteresis value (0.4) to prevent possible oscillations. The resultant number specifies the required number of running wells. One should mention that this number is limited to 25 in order to leave 2 wells as standby.

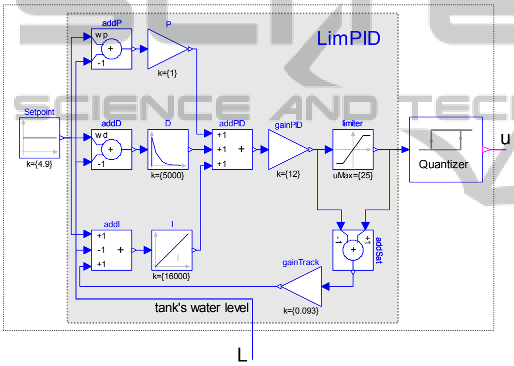

Figure 11: Filling process controller.

On the other hand, the distribution process has 10 speed-controlled boosters and the maximum capacity is limited to 8, leaving 2 as standby. The simulated controller of this process is shown in Figure 12.

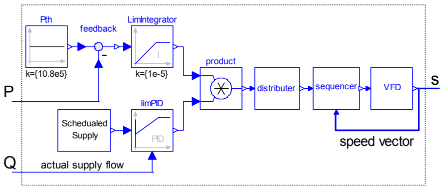

Figure 12: Distribution process controller.

The lower part of the controller has a PID module with limited output, anti-windup compensation and set point weighting. Its output specifies the required pumping capacity which has a minimum of 0 when all pumps are off and a maximum of 8·2900 when 8 booster pumps run at their full speed. The upper part has an integrator with a limited output [0,1]. In regular cases, the error signal is positive and the integrator saturates to unity value. Once the pressure exceeds the specified threshold ($P_{th} \approx 98\%$ of the maximum permissible pressure), the integrator output starts to decrease and eventually saturates to 0. This gives a measure for the persistence of the pressure to exceed the threshold value. The result of this integrator is multiplied with the output of the Limited PID module to generate the recommended pumping capacity. The *distributer* module uses this value to generate the reference speeds for the boosters. In order to maximize efficiency, only one booster pump may be assigned a partial load while all others that share the pumping load must be assigned the rated speed. The *sequencer* block regulates the starting and shutting operations of the boosters. In order to protect the hydraulic system from water hummer effects and also to protect the power system from electrical surges, booster pumps are allowed to enter or leave operation only one after another. Having a feedback from the Variable Frequency Drives (VFD) of the motors, the sequencer is able to manage that task. The VFD 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.

The most important simulation outputs are shown in Figure 13. The tank's water level (L) is depicted in Figure 13a. As intended, the tank starts at full state in the morning and the controller returned it back to that state at the end of day. The number of running pumps, which is shown in Figure 13b, demonstrates how pumps are called for running when the error signal (deviation from the tank full state) and its derivative is high in the morning. Later in the afternoon, supplied water is less than collected water, and thus the water level in the tank starts to increase. Consequently, the controller decreases the number of running pumps. Figure 13c shows the demanded flow, the scheduled supply flow, and the supplied flow (Q). The test data is designed to explore the controller behavior when there is a large mismatch between demand and scheduled supply. During the first half of the day, there is excessive demand and the controller supplies the planned quantity. In contrast, during the second half of the day, demand is much less than the scheduled supply. The controller delivers excess flow to the extent that pressure (P) at the network does not exceed the safe limit as illustrated in Figure 13d. Finally, Figure 13e shows how 6 booster pumps share the pumping load of that day. At any given time, the controller adjusts the speed of only one booster pump. Other boosters are either off or at their rated speed.

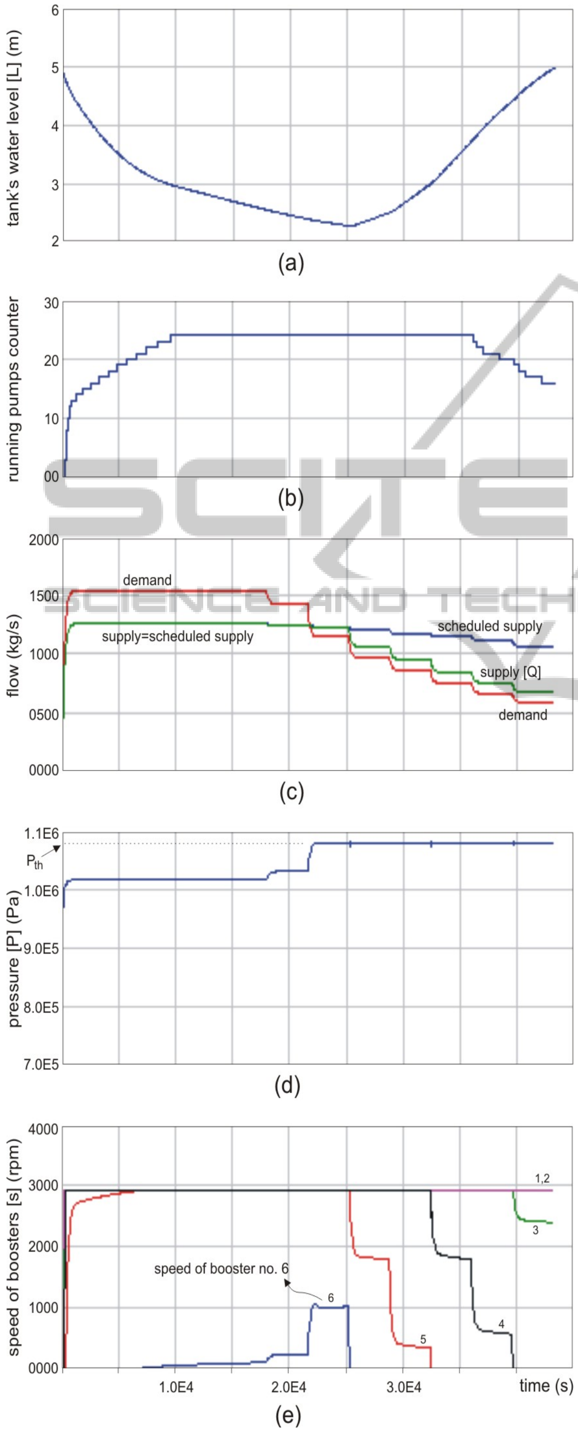

Figure 13: Major simulation outputs.

5 SUMMARY AND OUTLOOK

This work presents the design of an easily manageable model of the water reuse system in northern Gaza. The resultant model provides a novel tool for testing the performance of the system under different operation scenarios and control schemes. It also helps in understanding the dynamics of the system and enables designing and tuning a stable and robust controller for the system. It is our aim in a future work to elaborate on the control problem and derive a cost function for running the system. In other words, we plan to develop a practical criterion for optimal performance of the system and study the influence of uncertainties in users' demand.

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