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Leakage reduction in water supply system through the adjustment of its hydraulic efficiency

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ABSTRACT

The present paper provides a pilot example for water networks managers and operators intending to adjust the hydraulic condition of a pressurized water system to operations conditions with the objective to improve its efficiency. For this aim, a hydraulic modeling methodology has been applied and combined with site inspection, and field measurements. The selected water system operates under particular topographic and operational conditions and suffers from major problems making the system unable to deliver water with the designed volume to the regional reservoir. The system is studied under both steady and unsteady conditions. The study shows benefits of the proposed methodology in terms of water loss reduction which allows enhancing the hydraulic performance of the system. Consequently, the adjustment of a water system to fit with the real operations conditions has improved the hydraulic reliability and efficiency of the system.

The novelty of this paper is two-fold. First, it gathers field measurements and hydraulic modeling. Second, it forecasts and measures the efficiency of proposed rehabilitation works by checking the performance of the water system. Therefore, the paper results can be useful to researchers in hydraulics who need an identification of relevant studies, as well as to practitioners interested in understanding the available methods, techniques and tools and their applicability level in real case studies.

Keywords: Pressurized system, Water hammer, measurements, leakage, hydraulic modeling, rehabilitation

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1. INTRODUCTION

Problems of water networks in Lebanon are related to the poor management and control of water resources which result in a high volume of leakage in the most of water networks (Abdulrazzak M. And Kobeissi, 2002).

The present paper focuses on improving efficiency in a pipeline by recalibrating the hydraulic conditions of the water system in a way to fit with the current operations constraints. The ultimate goal of this paper is to rehabilitate the water system in order to feed suitable pressure and flow to the regional reservoir and the localities supplied directly from the pipeline.

The present paper discusses three main tasks: site inspection, field measurements, and hydraulic transient modeling. It focuses on hydraulic transient modeling of the water system with the objective to assess hydraulically the operating condition of the water system in order to identify leakages, illegal connections, dis-functioning of the pipeline and/or fittings and recommends modifications and rehabilitation on lift line.

After calibration, optimal design has been determined for the model through a design satisfying constraints and considering future requirements.

The paper is divided into sub sections; section 2deals with the methodology of the study and presents the water system, site inspections, field measurements, hydraulic transient model, constraints and parameters. Section 3 discusses the analysis of results of the case study. The paper is concluded in section 4.

2. METHODOLOGY

The proposed methodology consisted of (i) collecting data related to the pumping station and pipeline; (ii) making site inspection and assessment of the pumping station and the pipeline; (iii) counting the housing units and population and estimating the water demand of the localities supplied from that water system; (iv) performing flow and pressure measurements at different locations on the pipeline; (v) and performing a water transient modeling of the system under its current and recommended operation conditions.

2.1 Water system description

The studied water system constitutes the main water source for the area of Tyr (South Lebanon) and its surrounding localities where water is originated from Ras El Ain springs (Badawi1997, and Bakalowiczet al .2002) located in the southern coastal zone of Lebanon 3km from Tyre city. Near those springs a pump station equipped with water treatment plant was built during the last decades (CDR, 2007). Ras El Ain pumps station includes four pipelines that supply water for the area of Tyr and the surrounding localities. In this paper, we focus our study on Ras El Ain Saddîqîne water system which provides water for the 3000 m^{3}Saddîqîneregional reservoir (387mabove mean sea level) as well serves a number of localities directly with water from the pipeline. According to the South Lebanon Water Establishment (SLWE), water does not reach Saddîqîne reservoir.

The pumping system is of 3 sets of pumping mounted in parallel; each set is made of 2 identical pumps in series. Currently there is 1 set is operative. It should be noted that all pumps are identical and they are Flowserve VTP 14 EJH, rated duty point: 180 m3/h @225 m. The Pump speed 1480 rpm, efficiency: 80.9%.

The initial anti-hammer protection system is of bladder surge vessel, with 2000 liters and with an operation pressure of 50 Bars. The protection system is currently out of service.

To supply the anticipated rapid growth of the area it will be necessary to optimize Ras El ain water supply system. SLWE planned to evaluate the steady state and transient hydraulic of the preferred pipeline, pump station and reservoir combination, and to improve the overall reliability and efficiency of Ras El Ain network system.

2.2 Site inspection

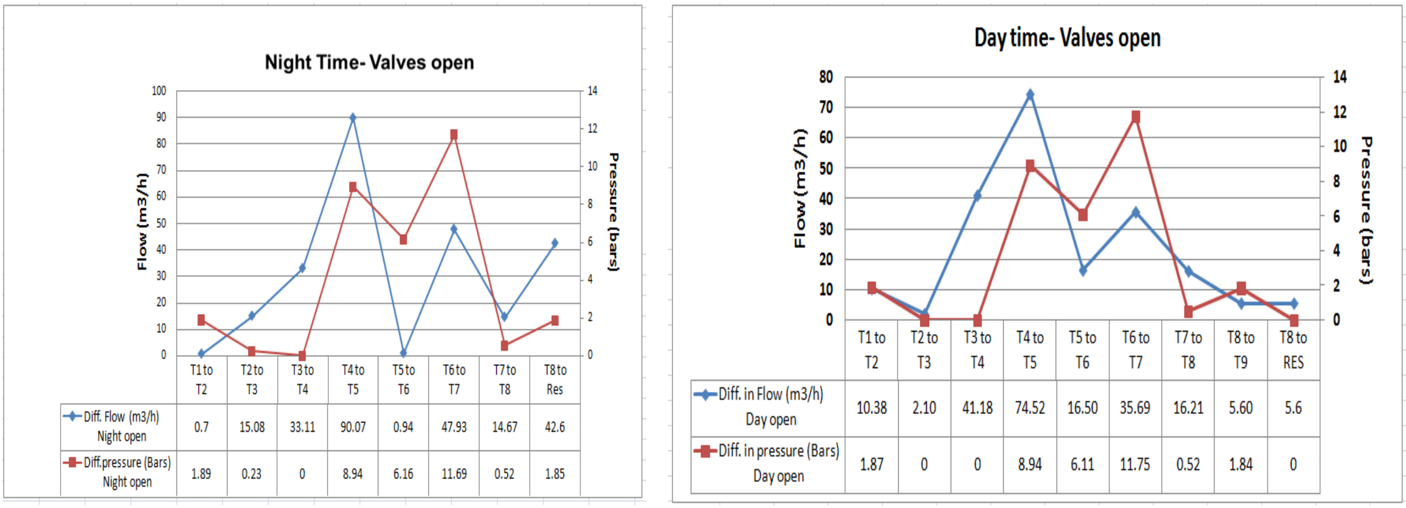
Site investigations were conducted along the pipeline routing in order to assess its physical condition and collect data on the nature of the equipment and their specifications.

Further to the site investigation, a number of accessories as air valves, washouts, and valves were identified as not implemented and/or not found on the pipeline as the as built drawings. Also, some fittings are in bad condition and they are not in operation.

The missing accessories could have severe impact on the normal functioning of the hydraulic system. That impact appears clearly in terms of leakage at joints or bursts. This conclusion is confirmed by the high number of leakage and repairs as it was seen during the site investigation.

2.3 Field measurements

Figure 1.Pipeline alignment, trenches and branches locations



	T1 to T2	T2 to T3	T3 to T4	T4 to T5	T5 to T6	T6 to T7	T7 to T8	T8 to Res
Diff. Flow (m3/h) Night open	0.7	15.08	33.11	90.07	0.94	47.93	14.67	42.6
Diff.pressure (Bars) Night open	1.89	0.23	0	8.94	6.16	11.69	0.52	1.85

	T1 to T2	T2 to T3	T3 to T4	T4 to T5	T5 to T6	T6 to T7	T7 to T8	T8 to T9	T8 to RES
Diff. in Flow (m3/h) Day open	10.38	2.10	41.18	74.52	16.50	35.69	16.21	5.60	5.6
Diff. in pressure (Bars) Day open	1.87	0	0	8.94	6.11	11.75	0.52	1.84	0

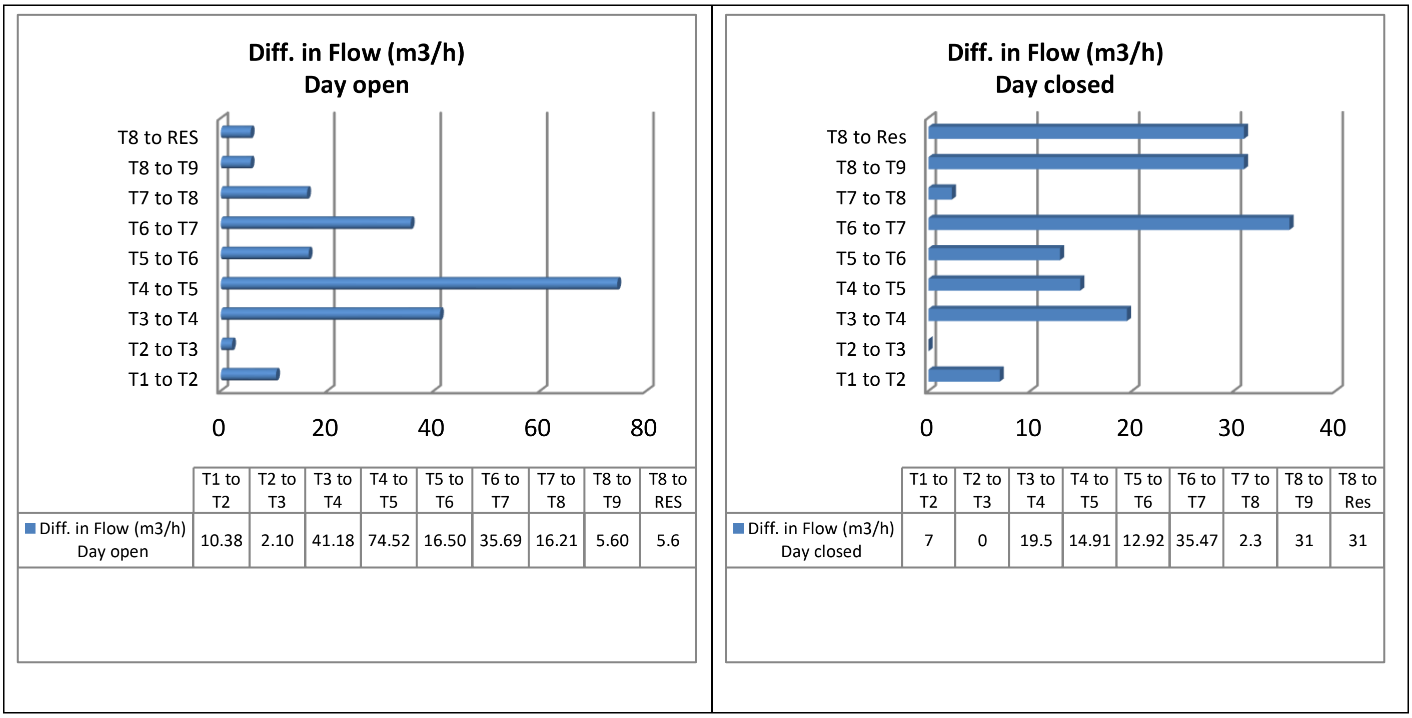
Figure 2. Loss in flows and pressure in pipeline sections in day and night times

In absence of complete data, shop drawings, and information over illicit connections, in situ pressure and flow measurements have been the right tool to calibrate and validate the developed model. Pressure and flow measurements were conducted at some selected locations along the lift line where the pipeline is divided into 9 sections (from S1 to S9). Sections are identified according to locations of legal connections, locations of observed leakages, locations of direct branches, and type and importance of the road where trenches will be performed in a way to avoid excavations on main roads to minimize the impact of these works on traffic. Nine sites of trenches (*Ti=1..to..9*)in addition to the pumping station site location were selected to carry out measurements of pressure and flow.

Measurements of pressure and flow were performed while the pumps worked normally and continuously during 8 hours and records were made of the flow and pressure at the ten locations. Measurements were done under variables conditions of operations: (i) under normal conditions in night time and all valves controlling the flow into the branches are open; (ii) under normal conditions in day time and all valves controlling the flows into the branches are open; and (iii) under extreme conditions in day time and all valves controlling the flows into the branches are closed.

The results of flows measurements whether in night or day time (Figure 2) show that most of drops in flows are between trench T3 and trench T8 (From S3 to S8) which represents 70% of the pumped flow (*270 m3/h*)to Saddiqine reservoir. That drop in flow can be explained by the fact that three lateral connections are open on the pipeline between trench T3 and trench T8 and too many leakages have been identified at pipes joints mostly between trench T3 and trench T4. The figure shows also that the loss in pressure is localized between trench T4 and trench T7.

The results of measurements indicate that when the valves are open, only 56 m^3/h arrive to the reservoir of Saddîqîne. This means that only 21% of the pumped water arrives to the reservoir.



	T1 to T2	T2 to T3	T3 to T4	T4 to T5	T5 to T6	T6 to T7	T7 to T8	T8 to T9	T8 to RES
■ Diff. in Flow (m3/h) Day open	10.38	2.10	41.18	74.52	16.50	35.69	16.21	5.60	5.6

	T1 to T2	T2 to T3	T3 to T4	T4 to T5	T5 to T6	T6 to T7	T7 to T8	T8 to T9	T8 to Res
■ Diff. in Flow (m3/h) Day closed	7	0	19.5	14.91	12.92	35.47	2.3	31	31

Figure 3. Results of difference in flows on each pipeline section, open valves condition versus closed valves condition – Day time.

The comparison of measurements under open valves condition with closed valves conditions during day time shows clearly that the measured flows begins to increase at trench T5 under closed valve condition and keep on increase till the flow value reaches around 51% of the pumped flows. Also a slight increase in pressure under closed valves condition could be identified.

The proposed repair works will allow, at best case, to savethe following flows in each pipe section: S1, S2, S3, S4, S5,S6, S7, S8, and S9 a respectively saving of 3%, 3%, 7%, 6%, 5%, 13%, 1%, and 11% of the pumped flow is targeted. Note here that these savings are calculated on the basis of a pumped flow of about 270m3/h.

To define all needed rehabilitation works and to explain the origin of the leaks at the pipes joints, a hydraulic modeling of the system with a surge analysis were made, using the measured flows, and pressure valves, in day time and under open valves condition.

2.4 HYDRAULIC MODELING

The methodology of modeling followed in the present study to fulfill its objective is described in the following:(i) Preparation of a computer model which represents closely the existing system to be studied, with provision for amendment to incorporate additional surge suppression/relief equipment; (ii) Computation of steady flow and pressure regimes to determine achievable flow rates for extremes of static and friction conditions, this being essential prior to investigation of unsteady conditions; (iv) Execution of computer simulations of upset conditions, deemed by appraisal as most severe, to determine the maximum and minimum surge pressures which are then compared with the system rating; and (v) Determination of appropriate surge alleviation techniques and sufficient computer simulations to optimize and verify the proposed modifications and methods of protection.

2.4.1 Model data collection

The hydraulic modeling was performed using the minimum required data to ensure a model describing well the system hydraulically, physically under the current operating conditions.

2.4.2 Model constraints

The main constraints are related to allowable pressures in both cases positive and negative.The maximum allowable incidental pressure (MAIP) for ductile iron pipeline is dictated by the pressure limit PMA (Allowable Maximum Operating Pressure) of installed flanged fittings, the allowable limits are specified in ISO2531 –EN545 2006.

Table 1. Allowable pressures as per ISO2531/ EN 545/ 2006 for DN350 Ductile iron system.

Allowable Limit for DN350 mm	Push-in Pipes & Fittings	Flanged fittings
Allowable operating pressure steady PFA	45 bar	25bar
Maximum pressure including surge PMA	54 bar	30 bar

Although ductile iron is designed to withstand a negative pressure of -5 m, sub atmospheric (negative) pressures should not normally be allowed to form in a potable water pipeline as this may cause suction of flanges gaskets, intrusion of contaminants resistance. The minimum allowable pressure is generally limited to +0.2 bar above pipeline crest.

However, this particular force is exposed to dewatering at idle pumps in view of the illicit connections, the minimum pressure of 0.0 m will be exceptionally accepted.

2.4.3 Surge model

In the present study to evaluate the water hammer and its control equipment used the simulation model by Hytran software (Version: v3.8.7-4); one of powerful tools for analyzing complex system of pumps and a network of pipes when moving from one steady state to another unsteady state. The computer program Hytran (Hydraulic Transients) developed by Hytran Solutions is a transient analysis program used to assess the magnitude and extent of transient events within water and sewage system such as pressure surges and sub-atmospheric pressures. Program can handle both steady state and transient applications.

Hytran software uses the method of characteristics(Wylie and Streeter V.L. 1987). The collected in situ measurements have been used for assessing the findings of the computer model and its closeness to the effective system. However, it was possible to develop a computer model reflecting with good approximation the effective system (the model is illustrated in Figure 2)

Calibration of the hydraulic model has been done using results of flow and pressure measurements campaign which identified water losses from unseen leakage and illicit connections. Water losses at each pipe section were assessed to accuracy calibrate the hydraulic model (Pipe sections: Losses (**T3 to T4**) =19.5 m3/h; Losses (**T4 to T5**) = 4.91 m3/h; Losses (**T5 to T6**) =12.9 m3/h; Losses (**T6 to T7**) =35.47 m3/h; Losses (**T7 to T8)** **=**2.3 m3/h; Losses (**T8 to RES)** **=**31 m3/h).

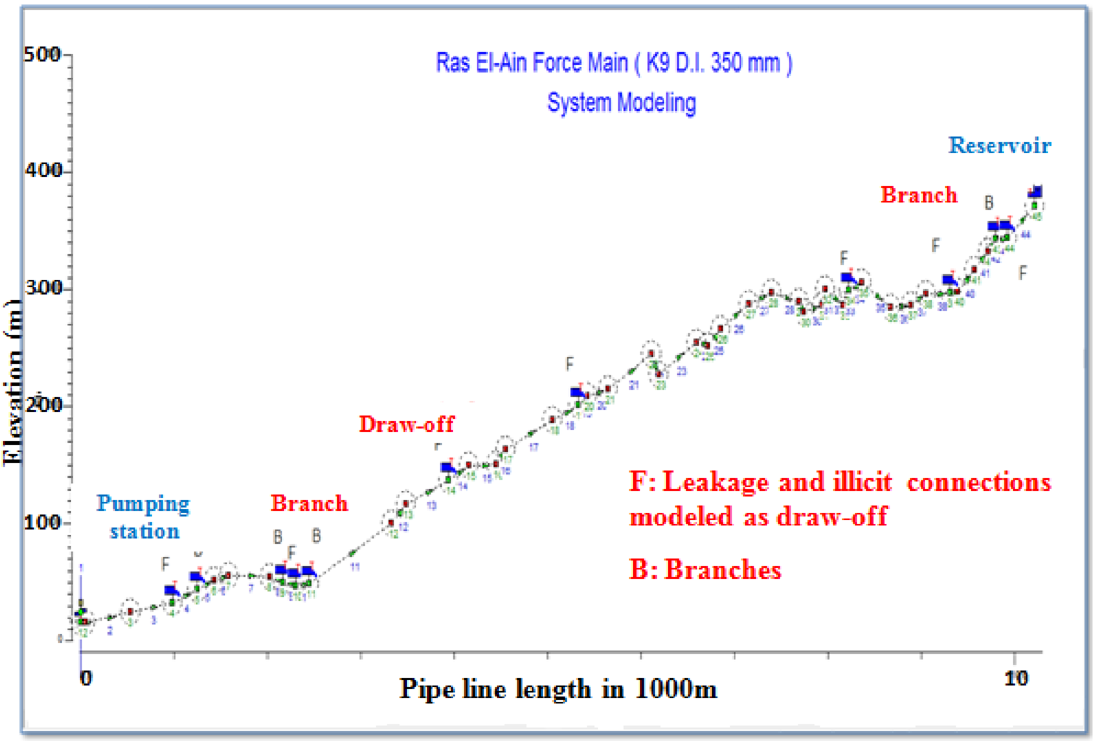


Figure 4.Ras El Ain System Modeling, inline branches, illicit connections and leakage are modeled as draw-off valves

1. Existing methods for solving water hammer equations include graphical method, arithmetic method, algebraic method, method of characteristics. The used method of Hytran software to solve equations is water hammer characteristic method. Using

characteristic method at first partial differential equations converts to the ordinary differential equations and then solves the finite element method (Ehtesham Manesh J. 2010).

2. Main water hammer equations are a combination of the following equations:
3. The momentum equation in calculating the water hammer (Akbari, Gh., And Fasihi, F. 2011.):

$$\frac{dV}{dt} + V \cdot \frac{\partial V}{\partial x} + \frac{1}{\rho} \cdot \frac{\partial P}{\partial x} + g \cdot \frac{\partial z}{\partial x} + \frac{f|V|V}{2D} A = 0 \quad \text{(Eq. 1)}$$

4. Where v steady flow velocity, p water pressure, f roughness coefficient, D diameter, ρ density of the fluid (water) and g is the gravitational acceleration.
5. The continuity equation in calculating the hammer:

$$a^2 \frac{\partial V}{\partial z} + \frac{1}{\rho} \cdot \frac{dP}{dt} = 0 \quad \text{(Eq. 2)}$$

Where "a" is the wave velocity (Streeter V.L. and Benjamin W. 1987).

The findings of the model under steady state approximately agree with "in situ" measurements, the HGL (*Hydraulic grade line*) limits as per computer model are shown in Table 2 along with the pressure plotted under steady state in different locations. Difference between the calculated and measured pressure can be explained by the imprecision in plotting the elevation and sometimes due to illicit connections not considered in the model.

Table 2.Pressures in computer model versus pressures measured in situ

Location	**Plotted pressure (bars) in model**	**Measured in situ (bars)**
Exit of P.S.	37.70	38.00
T6 5329 from P.S.	18.37	18.07
T9 9789 from P.S.	3.69	3.66

3. RESULTS AND DISCUSSION

Hydraulic modeling of the system with a surge analysis were made, using the measured flows, and pressure valves, in day time and under open valves condition with the aim to check the hydraulic performance and effectiveness of the system after rehabilitation.

3.1 Modeling the existing condition

The most severe water hammer conditions are generally caused whether by power failure to the pump motor sets or by uncontrolled startup. At the beginning all computer runs for following scenarios are performed without any control devices mounted on the pipeline with the aim to determine the nature and extent of the transient. Two scenarios were studied; they are as follow: (i) Scenario A: Startup without protection; (ii) Scenario B: Power failure without protection.

Scenario A: Scenario of startup without protection

The scenario of the Pumps in duty is 1 set (2 pumps)and the startup drive is ignored. The active protection is none and the pipeline is supposed to be water filled. The results of simulation presented in Figure 5 show that upon startup of pump the resulted pressure spikes up to +431 m at the discharge of pumping station before lining gradually with the operating steady pressure of +380 m, the plotted pressure remains within the limit PMA (54 bar, Table 2) of push-in pipes providing that pipeline does not include any flanged fitting of DN350 mm mainly over its the first run.

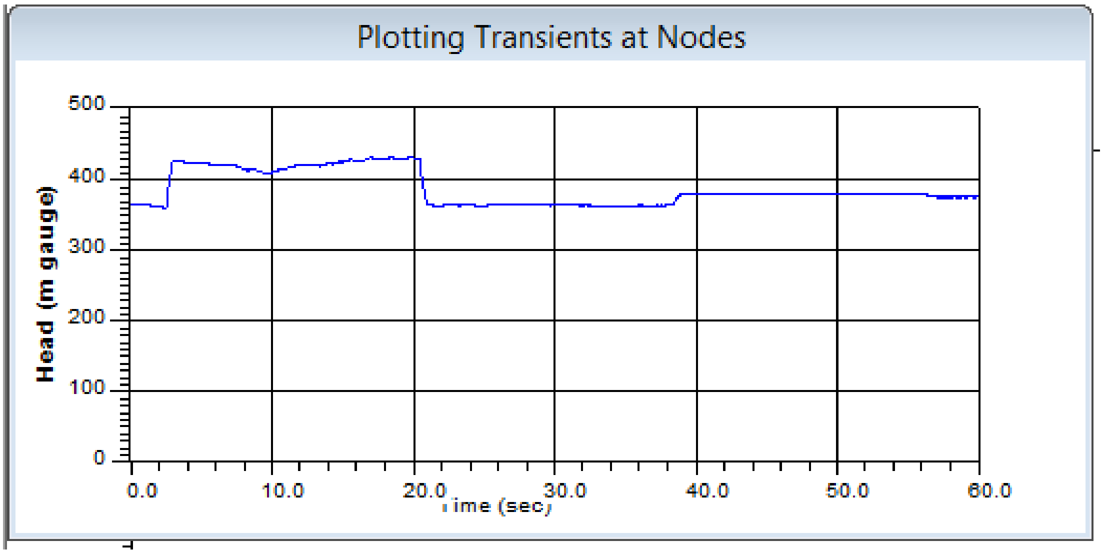


Figure 5.Simulation of startup without protection, pressure at the discharge of PS

Scenario B: Scenario of power failure without protection

Always pumps in duty are 1set (2 pumps).Pumps starts running at closed branches before proceeding with opening of inline branches, the event of power failure to pump occurs afterward without any active surge. The results of simulation presented on figure 6 illustrate the pressure envelopes over the entire alignment.

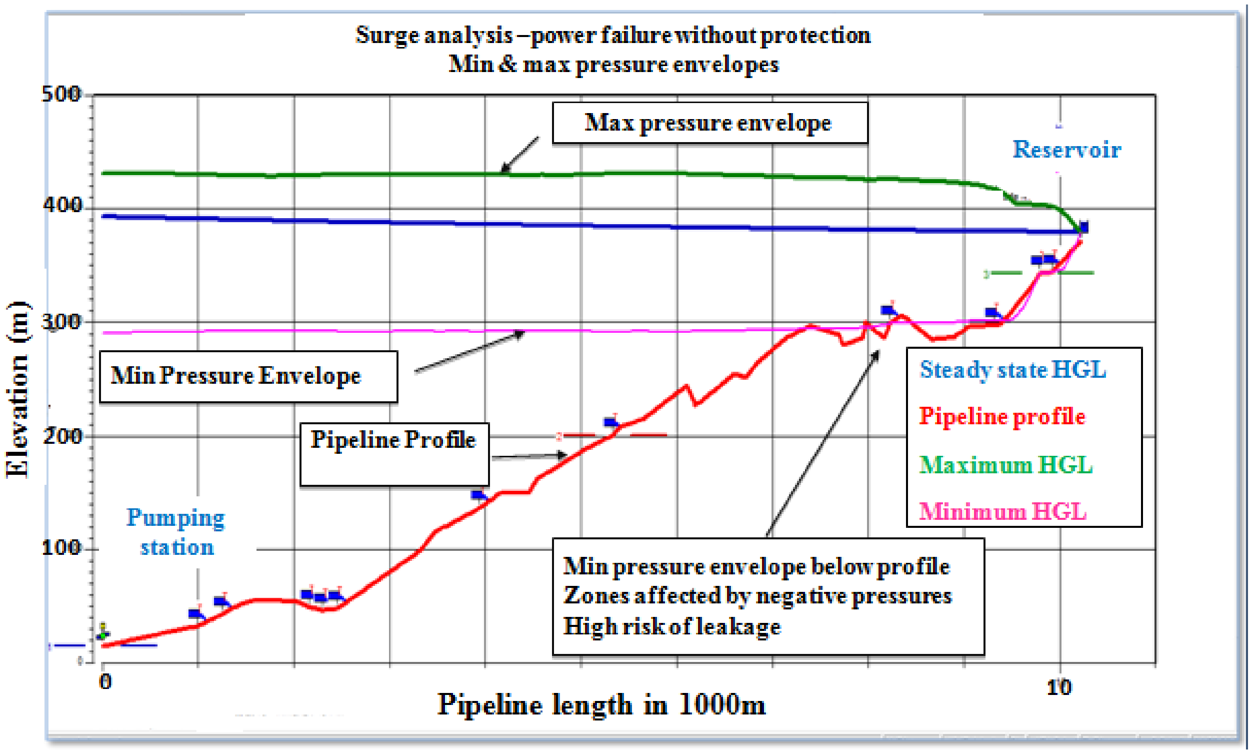


Figure 6. Simulation of power failure without protection, Pressure envelopes

Figure 6 shows that a power failure leads to damaging negative pressure(Down-surge) wave affecting upper sections posing thereby high risk of gaskets failure, leakage and contaminants intrusion over the section running from station 7+335 (From the pumping station) up to reservoir. In addition, the simulation shows the backflow causes a moderate pressure (Upsurge "positive pressure") spike of +415 at the discharge side of pumping station. The plotted pressure remains within the limit PMA of the system providing that the first run of pipeline is not fitted with any flanged ends of DN350 mm. Protection is highly required to prevent development of harmful negative pressure causing suction of gaskets, recurrent leakage and intrusion of contaminants. Two options were studied:

(i) Option1: Restoring the existing system;
(ii) AndOption2: Upgrading the entire hydraulic system.

3.1 Restoration of the existing system

The first option of modeling was based on the objective to restore the hydraulic capacity of the system.

3.1.1 Review of steady state and extent of risks

Dewatering of pipeline at idle pumps

With the particularity of inline branches and illicit connections, the pipeline is subjected to emptying upon shutdown of pumps. In presence of insufficient or defected air control valves, this event will be associated with development of cavitations mainly over the upper stretches of pipelines and posing thereby high risk of recurrent gaskets failure.

Pressure limit of the system

It can be easily noticed that the designer has intentionally avoided the installation of convenient chambers of washouts and air valves in order to avoid installing flanged pieces of DN350 mm that could undermine the pressure rating of the system.

The system is currently operating at 38 bar at its onset whereas the design practices used to limit the continuous operating pressure PFA of DN350 mm ductile iron systems to 25 bar in view of the flanged pieces.

Low pressure allowances have been taken at the design stage to account for a likely expansion of the pumping capacity. Even under current status, water hammer may result in pressure nearing critical limit of installed NRV and valves.

3.1.2 Recommendations regarding steady state

Measures to be taken irrelevant of the surge protection:

- Installation of additional air valves at summits in addition to convenient number of washouts (air valves are intended to cope with dewatering of pipeline).
- All Tees for additional manholes should be "flanged branch on double socketed tee" so as not to affect the pressure limit of the system by inserting any flanged end of DN350 mm, proposed dimension will be 350*350*DN80.
- All air valves are highly required to be of kinetic type, rapid filling 3F anti-shock, existing air valves should be replaced accordingly.
- All repairs should be performed by using slip coupler "Express Type" in view of its high performance versus standard repair couplings
- Installation of inline mechanical water meters to control the illicit connections and vandalism.

3.1.3 Recommendations regarding unsteady state

Preventative measures are highly required to control the air exhaust under startup event by installing particular type of rapid filling air valves averting thereby any likely induced water hammer. The optimum anti-hammer provision for this particular pipeline proved to be inline surge vessel (1000 L) strictly of bladder type backed by inline check valve (DN300), the alternative of mounting the surge vessel at the pumping station has been discarded in view of the likely pipe dewatering of pipeline at idle pumps that will result in bladder destroying.

In the instance of maintaining existing operative pump, a pressure relief valve discharging into atmosphere should be installed at the pumping station in order to relief the pressure spike associated with startup operation, this valve will be removed in case of changing pipe material into higher pressure classes.

3.1.4 Forecasting the performance and effectiveness of system within option 1

The following simulation aims at checking performance and effectiveness of the recommended surge control measures under power failure scenario.

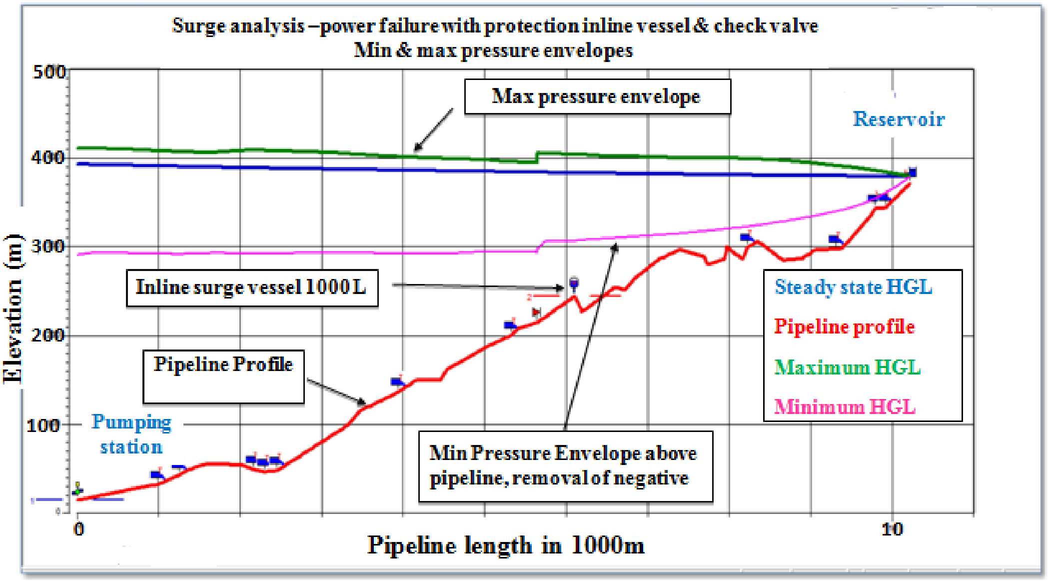


Figure 7.Simulation of power failure with protection (surge vessel +NRV), pressure envelopes and removal of negative pressures

The results of simulation presented in Figure 7 confirmed the efficiency of the designed surge protection in completely removing the negative pressure, the minimum pressure envelope lies above pipeline profile whereas the pressure at the discharge of pumping station is mitigated to +400 m.

3.2 Upgrading the entire system

The development of the current option was based on the objective to restore and to expand the capacity of the water system. The proposed new water system requires installing the following (See appendix A.1.4.):

- Pumping units: Additional pumping units will be needed to increase the conveyed flow to Sâddîquine reservoir. The number of pumps: 4+2 units, Type: multistage (deep well version).
- Air control,
- Leakage and Illicit draw-off control
- Control requirements.
- Surge protection requirements: The protection system set was designed to fit ultimate condition of 6 operative pumps.
    - Inline Surge vessel:2 units of bladder type surge vessel, each of minimum capacity of 1000 liters, to be installed in series at summit station 6+107, vertical or horizontal installation.
    - Inline check valve: Intended to provide a backup protection for the pumping station in case of poor maintenance on installed surge vessel.

3.1.1 Forecasting of the performance and effectiveness of system within option 2

The results of simulation of power failure presented in Figure 8 confirmed the efficacy of designed surge protection in completely removing the negative pressure, the minimum pressure envelope lies above pipeline profile with (lowest pressure +7 m) whereas the overpressure at the discharge of pumping station peaks to maximum of +430 m which is below the permissible limit PMA of push-in DN350.

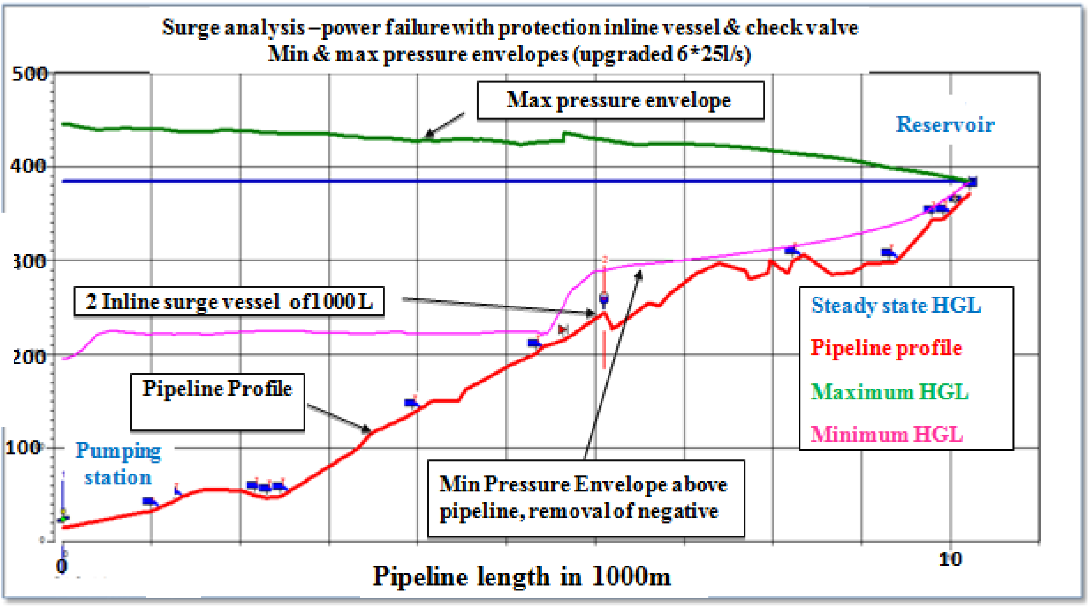


Figure 8.Simulation of power failure with protection (surge vessel +NRV), pressure envelopes and removal of negative pressures

Increasing the flow capacity of the system

As mentioned before the upgrading of the water system is based on raising the flow capacity of the system by adding new pumps. This requires reviewing the pipe material and pressure ratings. Several scenarios of operative pumps were studied (See table 3). It should be noted that the delimitation of pressure classes shall fit both steady and unsteady operation conditions; with the aim to develop the highest possible pressure on the pipeline the worst steady state is modeled by assuming 9 pumps operating against closed inline connections, delimitation of pressure classes for this case is illustrated on Figure 9. High pressures require replacing a part of the ductile iron pipe with a steel pipe.

Table 3. Extent of steel pipeline according to number of operative pumps and fatigue impact

Number of operating PumpsEach 25l/s *410 m	Operating pressure At station discharge	Length of steel Section PFAof D.I set to45 bar (K9 pipes -push-in joints)	Length of steel section PFA of D.I. derated to 40 bar(fatigue effect)
4 units	408 m	0 m	0 m
5 units	420 m	0 m	500 m
6 units	434 m	0 m	1000 m

The extent of the steel section (See appendix A.1.2.)at pipeline start will depend on the flow rate to be conveyed but also on the magnitude of fatigue through the life span of pipeline (cycles of starts and power failures). *Warning: No flanged ends of DN350 mm shall fit the first run of 4500 m.*

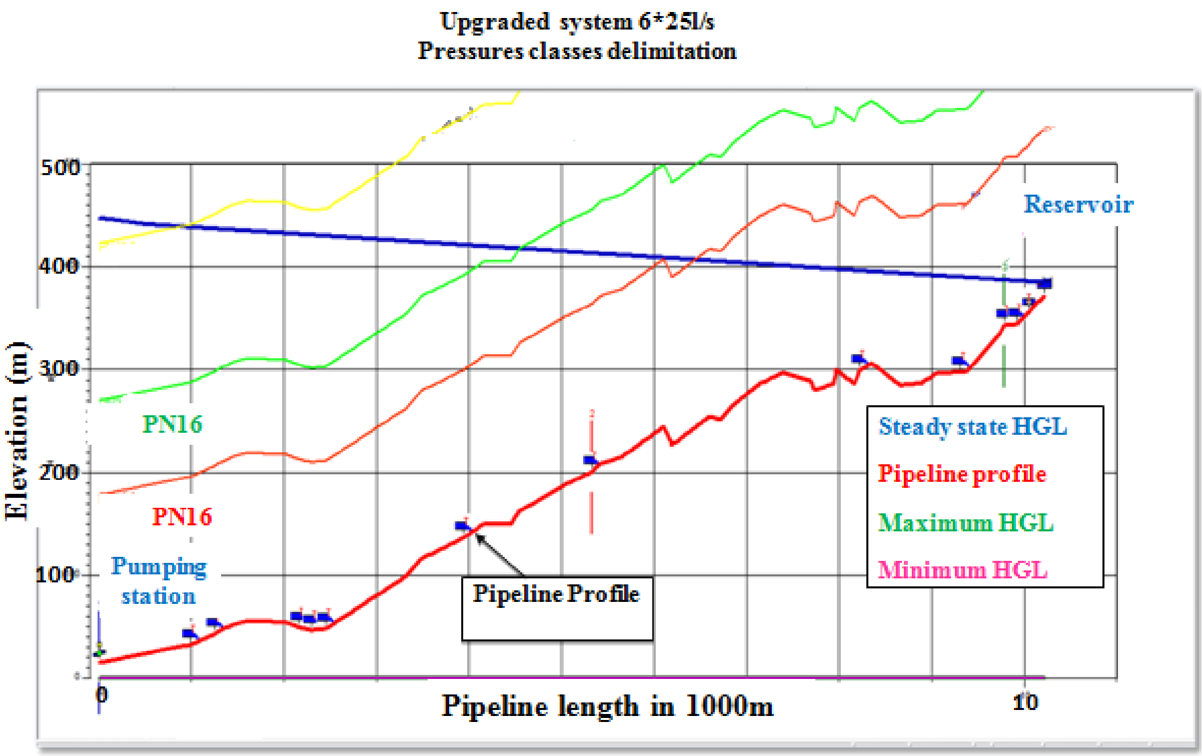

Upgraded system 6*25l/s
Pressures classes delimitation

Figure 9. Worst steady state conditions, all installed pumps are operating +inline connections are closed, pressure classes delimitation

4. CONCLUSION

The study has presented a methodology for improving the performance of a water system by coupling field measurement, and site inspection with hydraulic modeling. By applying this methodology to a case study of Ras El Ain water system located in the South of Lebanon, it revealed which areas of the pipeline are working properly and which areas require to be rehabilitated. The results of this study are significant in that they show how hydraulic modeling can be combined with site inspections and field measurements in evaluating the current condition of a water system and forecasting the performance of rehabilitation works through the measurement of the efficiency of each option of rehabilitation. Two options of rehabilitation works were studied and checked. The first option consisted of restoring the existing water system by adding accessories and protection equipment while the second option proposed to upgrade the water system by replacing a section of the system which allows rising its flow capacity. In both options of modeling, the volume of water delivered to the regional reservoir as well supplied directly through the legal connections is increased as result of leakage reduction.

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