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Fiware-enabled tool for real-time control of the raw-water conveyance system of Athens

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Abstract

The raw water conveyance system of Athens (Greece) is a complex infrastructure comprising around 500 km of aqueducts, conveying water from four reservoirs to four water treatment plants (WTPs), while serving several other local users. In this work, we focus on one of the most important parts of this system, namely the open-channel aqueduct of Mornos. This extends over 200 km and has a dual operation, namely water conveyance and flow regulation through temporary storage along the channel. This is achieved by a series of Λ-type structures, each one comprising sluice gates for flow control and a lateral broad crested weir. Currently, the flow regulation across the channel is performed through empirical rules, according to the daily water volumes requested by the operators of the downstream WTPs. However, this management policy, which is strongly based on expert's knowledge, is neither sustainable nor safe from a resilience perspective. Furthermore, the system is subject to occasional failures, due to undesirable overflows resulting to non-negligible water losses. In order to establish an optimal control policy, we developed an operational tool for the optimal real-time operation and scheduling of the sluice gates of Λ-type structures. The tool, along with other analytics and algorithms developed, has been seamlessly integrated with the existing legacy system (e.g., SCADA, databases) of the system's operator using the FIWARE standardization protocol.

Keywords: Raw-water conveyance system; Free-surface flow; Real-time control; Sluice gate; FIWARE; Data standardization

1. INTRODUCTION

The external raw water conveyance of Athens (Greece), managed by the Athens Water Supply and Sewerage Company ' (EYDAP S.A.), is a complex system (Figure 1) with the following characteristics:

- The system serves about 4,000,000 users consuming about 420 hm^3/year of water for domestic purposes (400 hm^3 in the broader Athens and 20 hm^3 locally).
- The system comprises around 500 km of aqueducts, four large reservoirs and four major Water Treatment Plants (WTP).
- The regulation of the flow conveyed across the aqueduct network is performed with several means, such as complex structures coupling sluice gates and lateral spillways (termed as Λ-type structures), stilling basins for energy dissipation and small hydropower stations.
- The system is monitored via a network of water quantity and quality sensors and is operated remotely.

One of the main disadvantages of the current practice is that flow regulation is conducted on the basis of empirical rules, suffering from the subjective perception of each operator, and hence the level of his/her expertness. Needless to say, that this approach is neither sustainable nor safe, from a resilience perspective. Therefore, in this work, we present an operational tool to provide automated decision support on the optimal settings of Λ-type flow regulation structures depending on the water volumes required by the operators of water treatment plants.

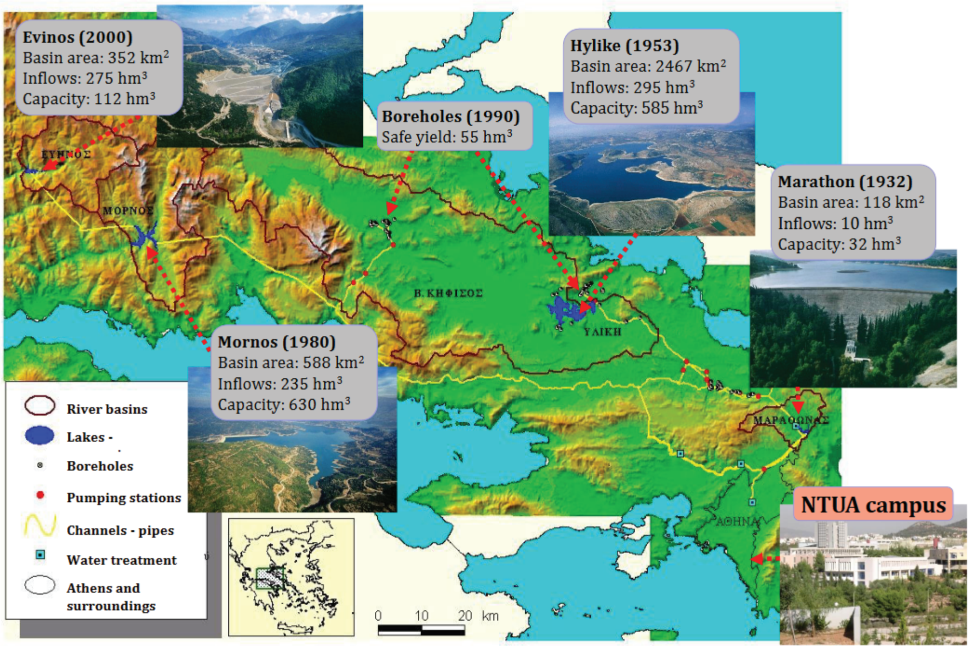

Figure 1. The external raw-water conveyance system Athens.

2. MATERIALS AND METHODS

2.1 Case study

The developed tool is assessed to regulate the flow in one of the most important parts of the conveyance system, namely the open-channel aqueduct, connecting the Mornos-Evinos reservoir complex with Athens, with a length of 200 km of free-surface aqueducts. In general, the channel has a dual nature: a) water conveyance and b) flow regulation through temporary storage along the channel. This is achieved by a series of *ad hoc* Λ-type structures, which are comprised by a sluice gate composed by two parts (left and right) which regulates and store the flow and lateral broad crested weirs, as depicted in Figure 2. The case study used for tool testing is in between Λ-type structures Λ7-Λ11 as shown in Figure 3.

Figure 2. A typical view of a Λ-type structure. The observer looks towards the downstream part of the channel.

Figure 3. Part of Mornos channel and locations of Λ-type structures.

2.2 Theoretical background and assumptions

The cumber stone of the tool is a conceptual model that incorporates the following assumptions:

- If there is no action at the sluice gates, flow is considered as steady. Regarding the space, flow is considered non-uniform at the parts of the channel which are downstream and upstream of a sluice gate. In the rest of the channel, the flow is considered as uniform (normal depth is achieved). If there is an action to a sluice gate, the operation of a Λ-type structure does not affect the operation of the other relevant structures (Figure 4).
- The Λ-type structure has two flow components, namely through the sluice gate (Q_{sluice}) and over the lateral spillway ($Q_{spillway}$), which can be described by theoretical and semi-empirical hydraulic formulas, considering as unknown parameters the discharge coefficients of all sluice gates. The opening of the sluice gate is common for both left and right components. Figure 5 depicts a top view (left) and a longitudinal section of a Λ-type structure (right).

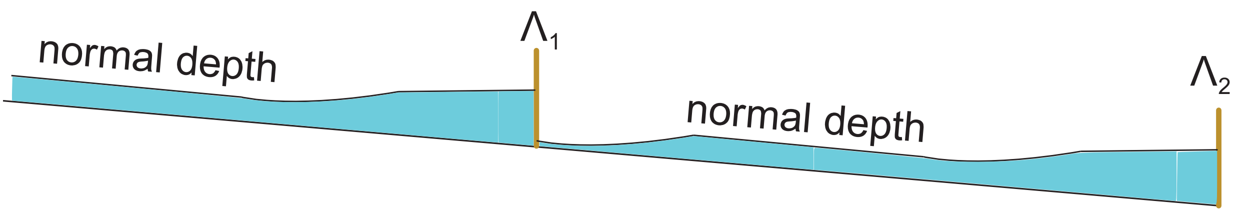

Figure 4. Water profile of Mornos channel: steady flow combining uniform and non-uniform parts.

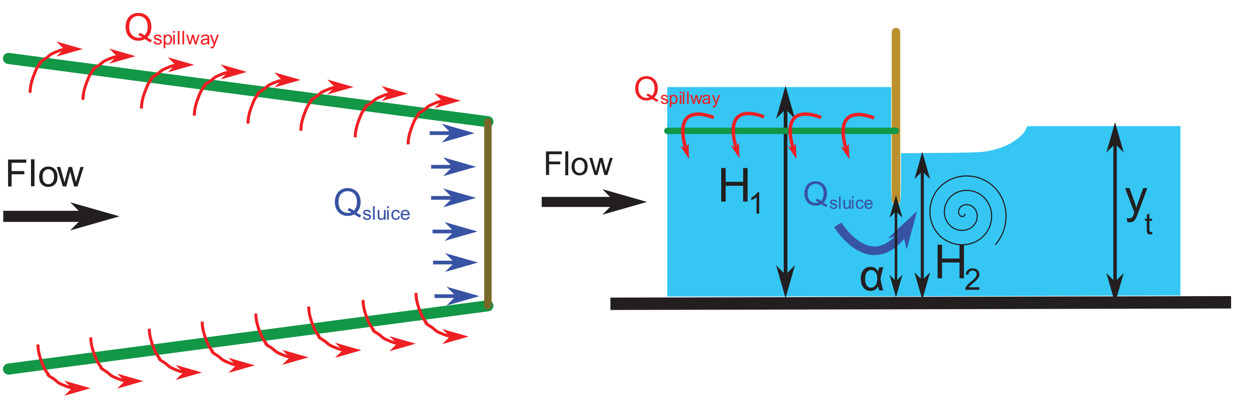

Figure 5. Top view (left) and longitudinal section (right) of a Λ-type structure.

The theoretical background of the model is based on the formula proposed by Wu and Rajaratnam (2015) for the flow through rectangular sluice gates and on the equation for flow over an ogee spillway (Chanson, 2004). Specifically, when the hydraulic jump occurring downstream of the sluice gate is submerged (which is the case), the discharge can be calculated as follows:

$$Q_{sluice} = C_d\, a\, B \sqrt{2g(H_1 - H_2)} \qquad [1]$$

where C_d is the discharge coefficient of the sluice gate, a is the opening of the sluice gate, B is the width of the sluice gate, H_1 is the water depth just upstream of the sluice gate and H_2 the water depth just downstream of the sluice gate (right part of Figure 5). The depth H_2 is calculated by:

$$H_2 = C_d\, a \left(2C + \sqrt{4C^2 + A^2 - 4BC}\right) \qquad [2]$$

where:

$$A = \frac{y_t}{C_d\, a}; B = \frac{H_1}{C_d\, a}; C = 1 - \frac{C_d\, a}{y_t} \qquad [3]$$

For a non-submerged hydraulic jump $H_2 \approx 0.61a$ and Eq. [1] becomes less complex (Wu and Rajaratnam, 2015) i.e.:

$$Q_{sluice} = C_d\, a\, B \sqrt{2g(H_1 - 0.61a)} \qquad [4]$$

Similar equations can also be found in Swamee (1992).
Regarding the flow over an ogee spillway, the well-known spillway equation is used for estimating the discharge:

$$Q_{spillway} = C_s\, L\, H^{3/2} \qquad [5]$$

where C_s is the discharge coefficient, L is the length of the spillway crest and H is the hydraulic head over the spillway's crest.

3. PRESENTATION OF THE TOOL

3.1 Structure

The structure of the model consists of the input data (classified as real-time and geometrical data), the main processes of the tool (including a calibration phase classified as real-time or off-line) and the output, which is the new opening of the sluice gates for the desirable new discharge given by the user. A flow chart depicting the structure of the proposed tool is shown in Figure 6.

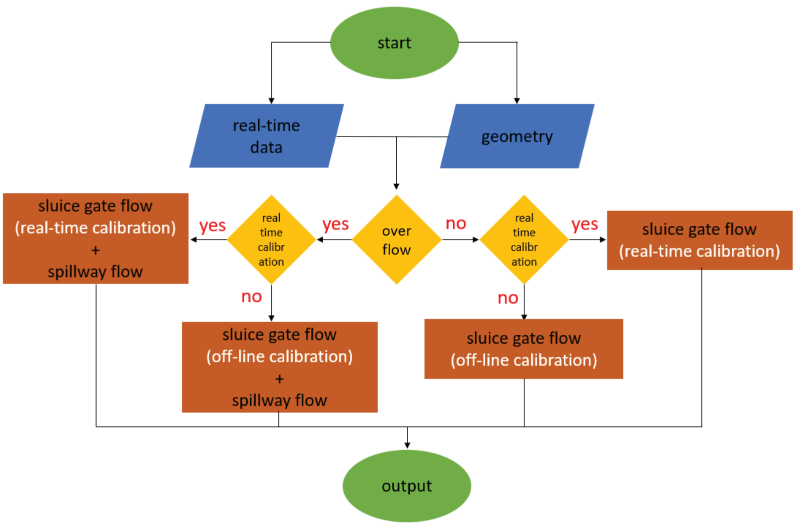

Figure 6. Structure of the tool

3.2 Input data

The known model inputs are the geometrical characteristics of Λ-type structures and the real-time data for discharge, water level and gate opening, which are obtained from the monitoring system of the channel. A list of the input data and their type is given in Table 1. It should be noted that although spillway coefficient is usually, calibrated, this is performed by the constructor of the channel and therefore we selected the proposed typical value $C_s = 1.85$ m$^{1/2}$/s, which is a realistic value in comparison with literature values (Chaudhry, 2008). For all the Λ-type structures the above parameter takes the same value and is classified as a geometrical input.

Table 1. List of the input data

Input data	Type
Sluice gate height	Geometrical
Sluice gate width	Geometrical
Spillway coefficient	Geometrical
Spillway length	Geometrical
Current discharge	Real-time
Upstream water depth	Real-time
Left opening of the sluice gate	Real-time
Right opening of the sluice gate	Real-time
Desirable discharge	Given by the user

3.3 Calibration

The key challenge is the determination of the sluice gate coefficients, C_d. This is employed through a grey-box approach, in which the model parameters are calibrated in continuous mode, using real-time data (Kroll, 2000; Bellos et al., 2018). To check the plausibility of the discharge coefficients, as derived by the real-time calibration phase, a comparison is made with the corresponding coefficients that are estimated by historical data (off-line calibration).

The reason for following this strategy is that the accuracy of the monitoring system (which can be characterized as low since each length measurement has an uncertainty of about ±2 cm) does not correspond with the accuracy of the difference between the current and the desirable discharge (usually ±0.5 m^3/s). This approach differs with older attempts oriented more to data-driven and black-box methodologies (Vamvakeridou Lyroudia and Giovanopoulos, 1999).

Real-time calibration is performed solving Eqs. [1-3] in respect to the sluice gate coefficients C_d, given the input data, both geometrical and real-time. Due to the implicit nature of equations, an optimization technique is used, namely the L-BFGS-B algorithm (Zhu et al., 1997). Since sluice gate coefficients are considered grey-box parameters, the calibrated values cannot take completely arbitrary values. For this reason, we performed an off-line calibration using historical data, trying to find a global value of this coefficient. With this way, we created a "safety net": if the real-time calibration gives completely unrealistic values, the global, off-line calibrated value is selected for the calculations.

For the off-line calibration, we first employed a screening and filtering of raw historical data. Then, we tried to correlate the discharge coefficient with respect to ratio a/H_1, according to theory (Swamee, 1992; Wu and Rajaratnam, 2015). An indicative diagram is depicted in Figure 7, for Λ10. Since the correlation between the two quantities is poor and the variability of C_d is relatively limited, we finally applied a generic value of $C_d =$ 0.4.

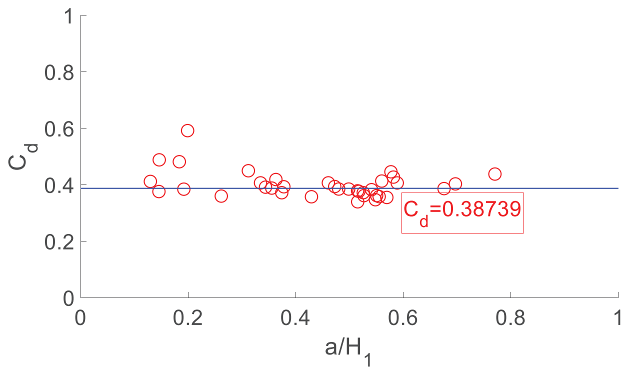

Figure 7. Scatter plot of spillway coefficient against ratio a/H_1.

3.4 Output

As previously mentioned, the output of the tool is the new openings of the sluice gates, so as to achieve a new desirable discharge. For the calculations, Eqs. [1-3] are also used, but they are solved in respect to the opening. The equation derived is implicit again and therefore an optimization methodology shall be used. Since the opening values are discrete and not continuous (the step is 5‰ while the percentage denotes the ratio of the opening divided by the sluice gate height), a grid search-based calibration is implemented. Specifically, the objective function (formalized as the residual between the desirable discharge and the discharge obtained by the tool) is calculated for the entire range of feasible openings. The minimum value of the objective function corresponds to the new opening. Figure 8 depicts an indicative figure of the tool's output for Λ10. It is noted that the discontinuity observed in the right part of the diagram is due to the fact that the hydraulic jump becomes free and not submerged and therefore Eq. [4] is used instead of Eqs. [1-3]. Although this is unrealistic, we included this option to the tool in order to preserve the theoretical consistency but the openings never take such extreme values.

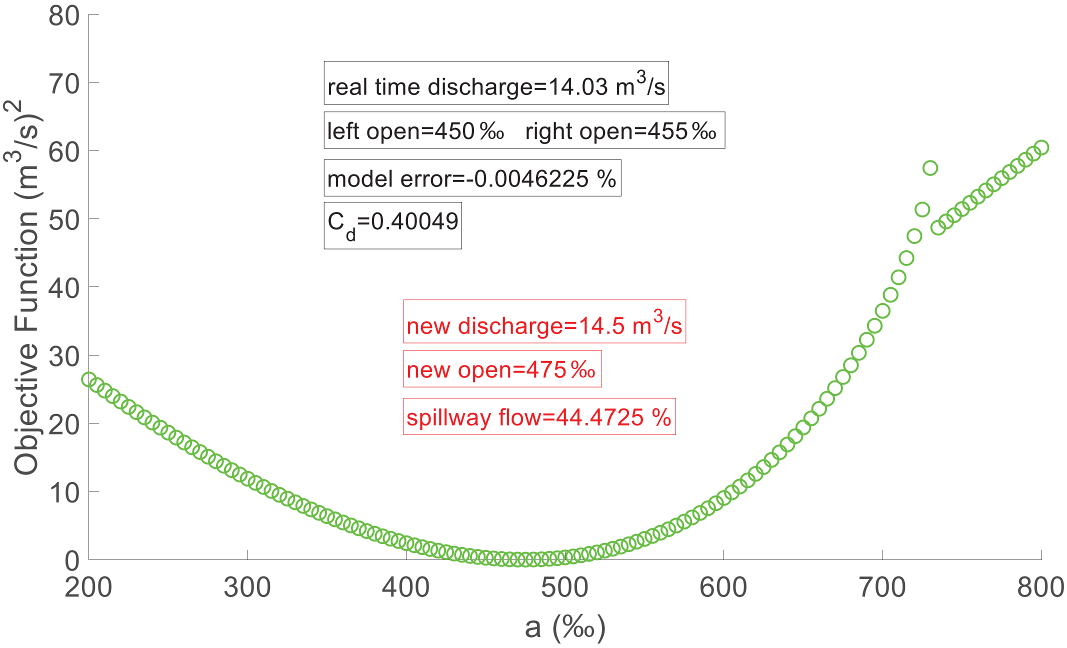

Figure 8. Output of the tool: black boxes denote the real time data and the calibrated sluice gate coefficient and red boxes the new opening of the sluice gates in respect of the desirable discharge and the percentage of the overflow through the lateral spillways.

4. A FIWARE-ENABLED OPERATIONAL IMPLEMENTATION OF THE TOOL

Raw-water conveyance systems are characterised by high complexity and a large-scale dynamics. The external conveyance system of Athens is a typical case, composed by different interconnected hydraulic works and infrastructures (e.g., reservoirs, aqueducts, water regulation structures, diversion structures, energy production and dissipation units), which serve different targets (e.g., reliable water supply, energy production, water storage, environmental target, flood protection etc.). Throughout the years, different sensors and metering devices have been installed and a wide range of models and tools have been developed to support the management and operation of such a complex system. However, these services co-exist within the water utility, as standalone and isolated solutions, creating a highly fragmented and of limited integration and extension capability environment. A remedy to this is data standardization that provides the means for the seamless integration of different data sources and the development of interoperable and portable solutions (Makropoulos and Savić, 2019).

In this light, we implemented and integrated the above-described tool, with the existing legacy system of EYDAP, using the FIWARE standardization protocol (FIWARE, 2021). FIWARE is a curated framework of open-source platform components, which can be assembled together or with other third-party applications, to accelerate the development of smart solutions. This framework has been funded and supported extensively by the European Commission, providing a set of technologies and standards that aim to facilitate SMEs and developers in creating cross-domain interoperable and standardised internet services. Recently, FIWARE expanded for the water sector and much of this effort has been performed in the framework of EU-funded Fiware4Water project (2019 - 2022) (Fiware4Water, 2021). In the context of this project, the above-described tool was transformed into an operational service that consumes data from the relevant sources (water depth and flow sensors) of EYDAP on real-time basis, using the FIWARE protocol. To achieve this, we exploit the recently developed data-driven models (i.e., standardised representation of elements of data and their interrelationships), tailored especially for raw-water applications (see Kossieris et al., 2021). The tool is available to the operation staff of EYDAP via a web service, which enables them to get advice on the optimal sluice gate settings depending on the latest flow conditions on the channel.

5. CONCLUSIONS

In this paper, we presented a new tool for the automatization of the real-time flow regulation, which can be used in an operational level from a water company in the raw-water conveyance system. The main challenges addressed in this work are the following:

- There is a discrepancy between experimental findings in an ideal condition of a laboratory and the conditions met in a real-world hydraulic structure of large scale.
- The accuracy of the current monitoring system is far from the accuracy needed for achieving the usual regulation of the flow.

These challenges are overcome with the proposed strategy, considering the sluice gate coefficient as a grey-box parameter and performing real-time calibration, which consists one of the major novelties of this work. The new tool was integrated seamlessly with the legacy system (e.g., SCADA, databases) of the water company of Athens, using FIWARE standardization protocols, to create an operational service that aim to support the operation staff in the optimal management and control of the flow in the large and complex raw-water conveyance system that serves the city of Athens.

6. ACKNOWLEDGEMENTS

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