Agricultural Water Management 204: 301-313 (2018)

Assessing zebra mussel colonization of collective pressurized irrigation networks through pressure measurements and simulations

Mario Morales-Hernández[1], Enrique Playán[1], Yolanda Gimeno[2], Alfredo Serreta[3] and Nery Zapata[1]

Abstract

Zebra mussel (*Dreissena polymorpha*) colonies are becoming a real problem in pressurized irrigation networks. The zebra mussel infestation of the 45 Water Users Associations (WUAs) of the *Riegos del Alto Aragón* (RAA) irrigation project (121 thousand hectares located in northeastern Spain) was assessed during the period of 2013 to 2017. Maps of WUA infestation stages were produced. A survey of the WUAs made it possible to assess the relevance of certain structural and management practices in the control of zebra mussels. A method to monitor zebra mussel colonization of pressurized collective irrigation networks was presented. The method is based on the combination of pressure measurements at network hydrants and hydraulic simulations. Normalized pressure, estimated as the difference between simulated and observed pressure, should approach zero in all hydrants in a properly characterized, non-infested network. A positive normalized pressure can indicate the presence of zebra mussel colonies. The methodology was validated using two different test cases located in two RAA WUAs: the first case involved a discrete chemical treatment, while the second case was based on the analysis of three years of telemetry pressure data and remote operation of network hydrants. The existence of an infested reservoir upstream of the WUAs was the most likely source of zebra mussel colonization of the WUA pressurized networks in the RAA project. The desiccation

[1] Dept. of Soil and Water, EEAD-CSIC. Avda Montañana 1005, 50059 Zaragoza, Spain (corresponding author Mario Morales-Hernández, mmorales@eead.csic.es).
[2] Riegos del Alto Aragón. Ramón y Cajal 96, 22006 Huesca, Spain.
[3] Universidad de Zaragoza. Escuela Politécnica Superior de Huesca. Crta. Cuarte s/n, 22071, Huesca, Spain.

and chemical treatment of the small WUA reservoirs was associated with pest control. The hybrid (measurement-simulation) methodology is able to characterize the presence of zebra mussel colonies in specific reaches of pressurized irrigation networks.

Keywords: Dreissena polymorpha, hydraulic simulation, irrigation piping network monitoring, normalized pressure.

1. Introduction

The zebra mussel (*Dreissena polymorpha*) has been classified as one of the 100 of the world's worst invasive alien species, together with eight other aquatic invertebrates (Lowe et al., 2014). In the beginning of the 19^{th} century, the species started to spread from its area of origin in the Caspian and Black seas, reaching Britain in 1824 (Aldridge et al., 2004). It took quite a long time for zebra mussels to appear in North America in the mid-1980s (Herbert et al., 1989) and in Spain in 2001 (Araujo and Álvarez, 2001). Although natural vectors can play a role in the dispersal of the species, human activity (transportation, recreation and fishing) seems to be the key factor (Banha et al., 2016).

The species was characterized by Naddafi et al. (2011) as a successful invader since it has very high reproduction and growth rates, and it can develop in a wide range of physical and chemical conditions. However, its colonization potential is very low when water temperature is lower than 15 °C or higher than 27 °C, when water velocity exceeds 2.0 m/s, and when dissolved oxygen is lower than 4 ppm (ZMR, 1993).

Females can lay between forty thousand and a million eggs a year (CHE, 2007). Larvae first move freely in the water. At an age of 18-90 days, larvae adhere to hard substrates (i.e., concrete, plastic materials) using up to 200 filaments, known as byssal threads (Roberts, 1990). Only about 2% of larvae successfully adhere and develop. During the rest of their life, zebra mussels continue to adhere to the substrate. Adults start reproduction when they reach a size of 6 mm, and can live for 3-5 years (CHE, 2007). The size of a one-year adult is about 1 cm, growing about 1 cm a year.

Zebra mussels have created very important worldwide economic damage by blocking pipelines and other infrastructure, and by modifying river and lake hydrology (Aldridge et al., 2004). In the United States, yearly damage has been estimated at 5 G$/yr

(Khalanski, 1997). In the recently infested Ebro Valley of Spain damage is still quite low: the total cost was estimated as 14 M€ for the period of 2001-2009 (CHE, unpublished internal report, 2009).

Shortly after the detection of the species in an area, zebra mussels start creating problems in different types of infrastructure. Zebra mussels latch to bridge abutments, water intake pipes, metal grids and screens, forming a dense mat of shells (Roberts, 1990). Regarding irrigation infrastructures, reservoirs and canals of all sizes can be colonized by the species. In general, this does not seriously compromise water delivery, except in screens used to filter debris. Mussels latch to concrete lining much better than they latch to the polyethylene film used for irrigation reservoir lining. Large, low-pressure pipelines used for reservoir intake can be strongly colonized by zebra mussels, severely reducing water passage by forming layers of adults completely covering pipeline walls. The most severe damage to irrigation infrastructure is associated with pressurized networks connected to colonized reservoirs and canals. In these systems, larvae are transported with flowing water from these reservoirs and canals into the pressurized systems, colonizing pipelines, filters and occasionally on-farm irrigation systems (sprinkler or drip). Adults grow and reproduce inside these system elements, reducing the conveyance capacity and blocking water passage.

The control of zebra mussels in irrigation infrastructure follows several strategies. Desiccation and exposure to extreme temperatures are commonly applied in irrigation reservoirs. Chemical substances (i.e., chlorine or hydrogen peroxide) are added to the water to control growth inside irrigation pipelines (Klerks and Fraleigh, 1991; Waller and Fisher, 1998; Seral et al., 2012). Chemicals are injected in the network in shock treatments, retained inside the pipelines for a few hours or days, and then flushed away. Alternatively, chemicals can be continuously added to irrigation water. Chemical treatments kill all development stages of the zebra mussel, including adults. When killed by the chemicals, the byssal threads let go and the shells freely move inside the pipelines. In the absence of adequate pipeline drains, shells can accumulate in filters and block pipeline sections, often producing more nuisance to farmers than latched adults do. In large irrigation projects of Spain, benefiting from economies of scale and including experienced technical staff, the yearly cost of chemical treatments rarely exceeds 10 €/ha.

Reports have been found in literature documenting and forecasting zebra mussel expansion. Bossenbroek et al. (2007) considered aspects such as the overland movement of recreational boaters or the chemical properties of reservoirs to model the expansion of the species in the United States. Bosso et al. (2017) used a maximum entropy algorithm to model the expansion in Italian rivers, lakes, watersheds and dams. These works led to observed or projected expansion maps.

In Spain, a very large irrigation modernization programme has been implemented since 2000, commonly leading to the replacement of canals and surface irrigation systems by collective pressurized networks and sprinkler or drip on-farm irrigation systems. MAPAMA (2015) estimated that irrigation modernization policies had been applied to 1.5 M ha since 2000. Consequently, drip and sprinkler irrigation currently represent 50% and 26% of the national irrigated area (respectively), estimated as 3.7M ha (MAPAMA, 2016). The importance of pressurized irrigation and the prevalence of overland water *vs.* groundwater represent a relevant vulnerability of Spanish irrigation systems to zebra mussels. Farmers have always volunteered to participate in irrigation modernization programmes. Persistent zebra mussel infestation is the only reason why farmers have occasionally (in the middle of a crisis) expressed that they would be better off with their old surface irrigation systems.

Farmers' problems with zebra mussels have not yet received relevant scientific interest. In fact, scientific databases only contain information about the development and control of the species in industrial, urban and environmental infrastructure, including multipurpose reservoirs and canals. As an exception, Seral et al. (2012) addressed zebra mussels in collective pressurized irrigation networks from the perspective of optimizing chlorine application.

Hydraulic modeling has been commonly used to generate flow-control strategies for drinking water networks (Cembrano et al, 2000; Pascual et al., 2013). The objective of these strategies is to meet demand and/or to optimize performance indexes, such as economic cost. These techniques generally use a telemetry system gathering information from a set of passive (pipes and reservoirs) and active network elements (valves, pumps and turbines). Pressure-based methods combining simulation and measurement sensors have often been applied to monitor leaks (Landeros et al., 2009; Abdulshaheed et al., 2017).

The problems associated with zebra mussel infestation in collective pressurized irrigation networks can be related to: 1) The geographic spread of the species; 2) The monitoring of the species in a network; and 3) The treatment of the network to control zebra mussel population. In this research, we target aspects 1) and 2) within the geographical scope of the *Riegos del Alto Aragón* (RAA) irrigation project, located in the Ebro river basin of northeastern Spain (Figure 1a). The main hypothesis of this research is that the presence of zebra mussel adults and shells can be monitored by a combination of pressure measurements at different points of the network and hydraulic modeling. The objectives of this research include:

1. Documenting the progress of the infestation of the collective pressurized networks of the RAA project, relating infestation to the main hydrological and structural aspects of the project;
2. Developing a methodology to assess the presence of zebra mussel adults and shells in the pipelines of collective pressurized networks by comparing distributed pressure measurements with hydraulic simulation results;
3. Validating the methodology with data sets obtained in networks located in the RAA project; and
4. Discussing the possibilities for large-scale application of this methodology for monitoring and precision treatment purposes in pressurized collective networks.

2. Materials and methods

In this section, procedures are presented to document the colonization of irrigation infrastructure in the RAA project and to assess colonization through the comparison of pressure measurements and simulations. Finally, two pressurized collective irrigation networks are described. These networks are used to verify and apply the proposed assessment methodology.

2.1. Colonization of the RAA project

The RAA project (121 k ha) is divided into 45 Water Users Associations (WUAs), with an average area of 2.7 k ha. The corporate GIS of the RAA project was used to map these WUAs and to produce thematic information (Figure 1b). Two major reservoirs divert irrigation water into the project from the *Cinca* and *Gállego* rivers: *El Grado* (400 M m^3) and *Sotonera* (189 M m^3), respectively. The canals originating in these reservoirs connect in the northwest area of the project. As a consequence, parts of the project are irrigated from *El Grado* (44%), *Sotonera* (9%), or from a blend of both water sources (47%) (Figure 2). Most of the project (76%) uses pressurized irrigation (sprinkler and drip). A small part of the project (24%), irrigated from *Sotonera* or blended waters, is surface irrigated (using borders and level basins). Figure 2 also presents the irrigation method used in each WUA.

The status of zebra mussel infestation in the RAA WUAs has been established based on two variables: larvae analysis and treatment effect. Larvae analyses follow the methodology by Marín et al. (2016). The method uses a water sample of at least 0.1 m^3 that is passed through two successive filters of 50 and 25 μm, respectively. After vital staining, live and dead larvae are counted using common and cross-polarized light microscopy (Frischer et al., 2012). A sample is considered positive if exceeding 0.06 larvae L^{-1}. The RAA zebra mussel protocol specifies that following a positive analysis WUAs enter a treatment program using chlorine or hydrogen peroxide. A treated WUA is considered controlled if – after treatment and shell removal – farmers do not detect abnormal pressure reductions or clogging in the network pipelines during the irrigation season. In RAA it often takes two years for a treated network to be under control. The combination of both variables was used to classify the status of zebra mussel infestation in the RAA WUAs in four stages: 0) Larvae analysis not performed or negative; 1) Larvae analysis positive; 2) Under treatment, uncontrolled; and 3) Under treatment, controlled. The records kept at RAA made it possible to classify the infestation of each WUA from 2013 (when zebra mussels were first detected in the system) to 2017.

A survey was performed in RAA WUAs to generate a database on structural traits and managerial practices potentially related to zebra mussel infestation. The survey contained closed questions designed to test the effectiveness of the following six traits, which were suggested by WUA managers as characteristic of resilient networks: 1) Regular desiccation and/or chemical treatment of WUA reservoirs, controlling zebra mussel reproduction in the reservoirs; 2) A short conduit connecting the canal turnout to the WUA reservoir (these conduits are difficult to treat, and large conduits can magnify the problem); 3) A lined WUA reservoir, with lining materials making it difficult for adults to latch; 4) Presence of pumping stations, which contain difficult-to-treat elements; 5) Adequate drainage of the WUA reservoir, allowing complete desiccation; and 6) Installation of ad-hoc drainage valves facilitating the flushing of shells after a treatment, thus reducing the impact of shells at the downstream end of the networks.

2.2. A method to assess colonization through pressure measurements and simulations

The proposed method is based on the use of a hydraulic modeling software for networks of branching closed conduits, such as the classic EPANET (Rossman, 2000). Use of this software requires a complete characterization of the network, including at least the x, y and z coordinates of the nodes separating pipeline sections, the length, diameter and roughness of the pipelines, the location and discharge of the hydrants, and the network inflow point (or points) and its pressure. On-farm irrigation systems were not hydraulically simulated in this research.

During a stationary period of network operation, there is no modification of the open or closed status of the network hydrants, and flow velocity and pressure do not change in time at any point in the network. In these conditions, EPANET can provide the simulated pressure at the hydrants. Manual or telemetry values of observed pressure at the hydrants can be obtained and compared to simulated values. Stationary periods are required to discard disturbances resulting from the opening or closing of the hydrants for irrigation. The opening and closing of the sector valves of the on-farm irrigation systems and their effect on hydrant discharge and pressure were not considered in this study.

If the main hypothesis of this research holds, the difference between simulated and observed pressure can be attributed to the presence of zebra mussel colonies. It is expected that an appropriate hydraulic characterization of the network and the presence of zebra mussel colonies will lead to higher simulated than observed pressure. This difference will be referred to as normalized pressure. Small values of normalized pressure indicate adequate simulation of head losses, implying a null or very low infestation by zebra mussels. In contrast, high values of normalized pressure indicate that EPANET underestimates head losses due to a strong presence of zebra mussels (adults or shells), or other obstacles to flow within the network pipelines.

Although pressure can be manually measured at the hydrants (for instance with a portable measurement device), telemetry and remote control (TM/RC) systems provide automatic and continuous data that can be used for zebra mussel detection. TM/RC systems are commonly installed in collective pressurized irrigation networks in Spain (Playán et al. 2018).

The vast majority of TM/RC systems have pressure transducers installed at some hydrants and at singular points of the distribution network. Periodic readings of these sensors are recorded in the telemetry database. The calibration status of the pressure sensors of the TM/RC system is an important issue for the success of this methodology.

Moreover, TM/RC systems can be used to identify stationary periods of network operation. In WUAs where irrigation decisions are generated at the headquarters and implemented via the TM/RC system, this is done by inspecting the records of the TM/RC database. In WUAs operating on demand, this is done by analyzing the time series of water meter readings at each hydrant, leading to an indirect identification of the times of hydrant opening/closing.

2.3. Network I, Collarada Segunda Water Users Association

The *Collarada Segunda* Water Users Association (CS-WUA) is located in the central part of the RAA project. It covers an irrigated area of 3,126 ha (Figure 3, Table I). Out of this total area, 426 ha are surface irrigated, while 2,700 ha are sprinkler irrigated from two pressurized irrigation networks.

Zebra mussels were first detected in the CS-WUA in 2013. In 2015, the WUA started the control program, applying two hydrogen peroxide treatments per year. The WUA succeeded in controlling zebra mussel growth inside its networks, minimizing problems to farmers during the succeeding irrigation campaigns. However, accumulations of zebra mussel shells and adults were detected in parts of network I during the first months of the 2017 season. Problems were particularly important in the southeast part of the WUA (Figure 3a). Several hydrants were completely obstructed by zebra mussel shells, to the point that irrigation could not proceed. Figure 3b presents the hydraulic layout of the affected area of Network 1.

An additional chemical treatment was applied to eliminate the infestation detected in 2017. The treatment started by setting up a fixed configuration of open hydrants. With irrigation water flowing into the network, hydrogen peroxide was injected at hydrant

17 (at the upstream end of the problematic area). Hydrogen peroxide concentration was periodically monitored at certain control points using pH test strips. Once the product reached the control points, all hydrants were closed to keep the hydrogen peroxide inside the network for a period of 24 h. After that period, a different set of hydrants was open to sweep off the zebra mussel shells and clean the pipes.

We devised an experiment to test the proposed infestation assessment methodology using the additional chemical treatment: evaluating normalized pressure before and after the treatment. Three sets of pressure measurements were performed: preliminary (P), before (B) and after (A) the treatment. Preliminary measurements were taken five days before the treatment. The objective of P measurements was to assess the coherence between estimates of normalized pressure with similar infestation (P and B). It is important to note that a different set of open hydrants was used in the three pressure measurements. The list of all network hydrants downstream from the injection point (17) is presented in Table 2, along with their opening and measurement status during the P, B and A events.

Hydraulic simulations were performed using information obtained from the built project report. A Darcy-Weisbach roughness coefficient of 0.01 mm was used in all pipelines. The location and elevation of all hydrants was verified using an altimeter consisting in a high precision GPS receiver (model GS15 receiver Leyca Geosystems AG, Heerbrugg, Switzerland). GPS measurements were corrected in real time (RTK) using the permanent network of active geodesy of the *Aragón* region of Spain. The measurement error of the device was lower than 0.02 m.

2.4. Network Violada, Almudévar Water Users Association

The *Almudévar* Water Users Association (AL-WUA) is located in the northwest area of the RAA project (Figure 1, Table 1). It covers an irrigated area of 3,744 ha using five collective pressurized networks, each of them fed from a reservoir using a pumping station. The AL-WUA was completely transformed from 2008 to 2010, modernizing all irrigation infrastructures from surface to pressurized irrigation. The TM/RC governs the irrigated area, issuing orders to open and close hydrant and sector valves and reading the water meters and the pressure transducers installed in the network hydrants.

One of the AL-WUA networks, called "*Violada*", was selected for this study. The network irrigates an area of 1,400 ha. Its location within the WUA and hydraulic layout are presented in Figure 4. The network counts on eight pressure transducers installed at hydrants H213, H241, H245, H256, H276, H277, H286 and H296. The TM/RC database for 2011, 2015 and 2016 was available for this study. Only pressure sensors at hydrants H213, H276 and H277 contained acceptable information during the years of study.

According to the AL-WUA external TM/RC maintenance service, the law for recording the pressure of every sensor is as follows: "data are recorded every 10-12 minutes if the deviation respect to the previous recording exceeds 20 kPa". This law generates periods without pressure recordings. In order to apply the proposed methodology, pressure recordings are required at the stationary periods of the network. Therefore, a procedure was needed for reconstructing the pressure data series at fixed time intervals by filling in the gaps between pressure measurements. Two possible approaches were considered: 1) Assigning the constant value of the previous record until a new record is available; and 2) Interpolating between the previous and the following available data. Figure 5 illustrates both alternatives.

The procedure for stationary flow detection involved selecting periods of a preset duration without changes in hydrants opening/closing. The selection criteria requires: a) a minimum total network delivery discharge of 400 L/s; and b) a reconstruction pressure time of 5 minutes (for both constant and interpolated techniques). Since pumps are shut off at intraday periods of high-energy costs, the minimum discharge condition prevents selecting stationary periods without water service or corresponding to network pressurization or depressurization transients following the start/stop of the pumping station.

In order to exemplify the procedure, Figure 6a presents the opening of hydrants H1 to H9 during a period of two days. For a given hydrant on the vertical axis, the horizontal grey line spans from the beginning to the end of a given irrigation event. Stationary periods can be identified in Figure 6b, enclosed in boxes.

The minimum duration of the stationary period was studied with a sensitivity analysis, exploring from 10 to 50 minutes, with 10 min increments. Periods shorter than 10 min could compromise the quality of pressure estimates, due to the chosen reconstruction time (5 min). Further increase in the minimum duration of the stationary period (beyond 50 min) could result in a very low number of stationary periods, compromising the robustness of the results. The analysis also included constant *vs.* interpolated pressure and the three years of data. The selection of the minimum duration of the stationary time and the interpolation method to be used in all simulations was based on the Root Mean Square Error (RMSE) between the simulated and observed hydrant pressure.

Hydraulic simulations were performed using information obtained from the built project report. A Darcy-Weisbach roughness coefficient of 0.01 mm was used in all pipelines.

The analysis of this case study involved comparisons of the population of normalized pressures in the years of available data. These years are representative of incipient (2011) and established (2015 and 2016) infestation of the AL-WUA networks, including *Violada*.

3. Results

3.1. Colonization of the RAA project

Figure 7 displays the evolution of zebra mussel infestation along all the WUAs of the RAA project. In a time span of five years, RAA passed from the first detection of the species to the control of a relevant part of the infested WUAs. The pest is currently present in 80 k ha, (66% of the project). Actions taken by the RAA board during these years have led to the control of 23 k ha (19% of the project). Consequently, zebra mussel infestation is currently incipient or not controlled in 57 k ha (47% of the project). This figure includes WUAs using surface and pressurized irrigation methods. Infested surface irrigated WUAs do not create problems to farmers and do not receive chemical treatments. Therefore, none of these WUAs has passed stage 1 during the analyzed period. If surface irrigated WUAs are excluded from the analysis, zebra mussel infestation is currently incipient or not controlled in only 35 k ha (29% of the project).

The first detection of zebra mussels in the project was registered in 2013, with the detection of larvae in the northwest area of RAA. Until 2016, all affected WUAs received water from Sotonera reservoir, pure or mixed with El Grado water (Figure

2). The Sotonera reservoir has been targeted by the analyses performed by RAA and the River Basin Authority. Sustained, very high larvae concentrations have been found in particular areas of the reservoir, indicating that it acts as a source of zebra mussel larvae for the RAA project. In fact, during the study period, zebra mussel colonization extended towards the southeast, colonizing WUAs receiving water from the Sotonera reservoir. WUAs exclusively supplied from El Grado reservoir remained free of zebra mussel larvae until 2016. In 2017, larvae were detected in three WUAs supplied from El Grado reservoir, totalizing 20 k ha.

Zebra mussel infestation has been fast, with WUAs often moving from stage 0 to stage 2 in less than a year. However, moving from stage 2 to stage 3 typically took two years. Reaching and maintaining stage 3, today requires at least one chemical treatment per year in the pressurized collective networks of the affected WUAs.

The WUA structural factors analyzed in the survey addressed the opportunities for zebra mussel settlement, the capacity to evacuate the shells or to completely desiccate the reservoirs. The results of the survey carried out at the RAA WUAs are presented in Figure 8 as pie charts. Results are only presented for WUAs using pressurized collective networks (29 WUAs).

Each RAA WUA has at least one internal reservoir in order to provide flexibility in irrigation water delivery. Adequate management of WUA reservoirs seems essential to control the dissemination of zebra mussel larvae and the settlement of juveniles. According to survey results, 15% of RAA WUAs use both annual desiccation and chemical treatment, while another 15% only use desiccation. The remaining 70% does not use specific reservoir management practices. Six out of the eight WUAs that have controlled zebra mussel infestation (passing from stage 2 to 3) desiccated the reservoir and/or applied a chemical treatment to it. Results suggest an association between these practices and the control of the pest.

Long conduits between the canal turnout and the WUA reservoir do not seem to be a problem in RAA since only 4% of the WUAs use long conduits.

Zebra mussels can settle on a variety of hard substrata and their attachment significantly varies with the material and the surface roughness. The survey indicates that 70% of the RAA WUAs reservoirs are lined with plastic (polyethylene) film. Some degree of infestation (stages 1, 2 or 3) is present in 57% of the WUAs with lined reservoirs, vs. 71% of the WUAs with unlined reservoirs. Only lined reservoirs practice desiccation to control infestation.

Regarding pumping stations, about 46% of the surveyed WUAs have a pumping station, and 54% of these present some stage of infestation. Among the 54% of WUAs without a pumping station, 71% present some stage of infestation.

A large majority of WUAs (89%) reported having suitable reservoir drains, required for effective reservoir desiccation. All WUAs that have controlled zebra mussel infestation (passing from stage 2 to 3) have suitable reservoir drains. More than half (54%) of the surveyed WUAs reported having appropriate drainage valves along the piping network.

3.2. Hydraulic assessment of the effect of a chemical treatment in a colonized network

From the three sets of pressure measurements performed at the CS-WUA before and after a chemical treatment, the P and B events reflect similar conditions of zebra mussel infestation. Normalized pressures between both events were compared at hydrants 108, 26 and 126. Adequate agreement was observed, with a RMSE of 2.6 kPa. These results endorse the use of the proposed methodology based on EPANET to simulate pressure in the network and to standardize the conditions created by the opening of different hydrants. Hydrants 26 and 126 showed positive values of normalized pressure in the P and B events, with average values of 26.4 and 9.8 kPa, respectively. Hydrant 108 showed a negative average normalized pressure of -7.7 kPa.

The proposed method was applied to analyze the effect of the chemical treatment on normalized pressure. Figure 9 presents a comparison between normalized pressure before (B) and after (A) the chemical treatment. Results show different effects of the treatment in different hydrants. Hydrant 22B shows no impact of the chemical treatment (normalized pressure before and after the treatment are similar). In a number of hydrants (16, 20, 21, 22, 108, 144) the treatment produced a moderate decrease in normalized pressure. In the hydrants located at the downstream end of the network (28, 29, 128, 130, 26, 126, 127, 117), an increase in normalized pressure was observed.

The difference in normalized pressure (after minus before the treatment) is presented in Figure 10a for the simulated hydrants. Negative values (in green) imply a decrease in normalized pressure, while positive values (in red) imply an increase. Figure 10b presents the same information in the form of a network map. Our interpretation of these results is linked to the dynamics of zebra mussel colonies and shells following the chemical treatment.

3.3. Hydraulic assessment of the colonization of a network

The colonization of the *Violada* network of the AL-WUA was assessed with the proposed hydraulic method. The use of a minimum duration of the stationary period ranging from 10 to 50 min in the three years of study allowed for the selection of 3,325 to 171 stationary periods, respectively (Table 3). As expected, the number of stationary cases decreased with the increase of the minimum duration.

Table 4 presents the Root Mean Square Error (RMSE) between the simulated and the measured pressure for hydrant H213 for the different steady period durations and the two interpolation methods for pressure measurements. The RMSE slightly grew with the minimum duration of the stationary period. However, differences were particularly important for T40 and T50. Similar results were found for H276 and H277. Despite the small differences in RMSE, it seems advisable to use a low value of the minimum duration in order to minimize RMSE. Regarding the pressure data reconstruction techniques explored in this paper, slightly lower values of RMSE were observed for constant pressure than for interpolated pressure. To balance accuracy and computing time, a stationary period of 20 minutes (T20) and the constant pressure reconstruction technique were selected for simulations in the *Violada* network of AL-WUA.

Figure 11 displays the seasonal evolution of normalized pressure for 2011, 2015 and 2016, and for hydrants H213 and H276. Each point in the plots corresponds to the simulation of a stationary period. Only the months corresponding to the irrigation campaign (from April to October) are presented. The line $y = 0$ represents the line where measured pressure equals simulated pressure.

A progressive increase in normalized pressure can be observed between 2011, 2015 and 2016 for both hydrants. The average yearly values of normalized pressure were 18.9, 95.6 and 108.3 kPa for H213, and 63.5, 77.3 and 111.5 kPa for H216. A similar trend was observed for H277 (data not shown), with yearly averages of 78.4, 145.6 and 154.0 kPa for 2011, 2015 and 216, respectively.

The increase in normalized pressure matches the evolution of zebra mussel colonization presented in Figure 7 for the AL-WUA. Zebra mussel colonization may not be the only explanation for the time evolution of normalized pressure. In fact, discrepancies between the real network and the project information, the estimation of the roughness coefficient or the evolution of the pipelines (wearing, deposits or biofilms) could also contribute to the differences. However, these factors do not seem adequate to produce a progressive, consistent increment of normalized pressure, as presented in Figure 11. The vertical data lines particularly present in H213 and in 2015 and 2016 correspond to the effect of the start/stop of the *Violada* pumps, which influenced pressure during periods that were considered stationary.

4. Discussion

4.1. Infestation analysis

This paper has presented the evolution and causes of the zebra mussel expansion inside an irrigation project (RAA), as well as the development of a methodology to assess the presence of zebra mussels inside the pipelines of collective pressurized networks and its application to two WUAs.

From the analysis of the evolution, it can be deduced that the time required to control the infestation seems to be related with the fact that many WUAs were strongly colonized by adults by the time larvae analyses were first performed. It can be assumed that early detection will lead to a faster control. RAA WUAs have understood that they must learn to live with zebra mussels, since the complete elimination of the species appears to be impossible.

Reservoirs have been reported to constitute the target for the settlement of zebra mussel colonies (Schneider et al., 1998, Allen & Ramcharan 2001, Havel et al. 2005, Johnson et al., 2008 and Smith et al., 2015). In the case of the RAA project, *Sotonera* reservoir is responsible for transmitting the zebra mussel pest. Furthermore, in terms of reservoir management inside the WUAs, annual desiccation (Leuven et al., 2014) and/or chemical treatment (Klerks and Fraleigh, 1991; Waller and Fisher, 1998; Seral et al., 2012) are key management practices to control zebra mussel infestation. Kobak and Januszewska (2006) stated that unlined reservoirs (built with loose materials) have lower probability of zebra mussel colonization than reservoirs lined with rigid materials. However, an interaction has been detected in this paper between reservoir lining and reservoir management.

Other hydraulic infrastructures that may influence the zebra mussel spread are long conduits just upstream of the internal reservoirs, stations to pump the majority of the water in the network or drainage valves to allow shell removal. Long conduits between the canal turnout and the WUA reservoir can magnify the problem of zebra mussels since water velocity is often low (Tosenovsky and Kobak, 2016) and treatment is difficult. However, this trait does not appear important in the RAA project. Besides, the presence of pumping stations in the WUAs has been identified in the literature as disadvantageous for zebra mussel colonization. Turbulence and high water flows disturb the latching of zebra mussels (Tosenovsky and Kobak, 2016). Accordingly, a greater percentage of zebra mussel colonization has been detected in the WUAs without pumping stations. Furthermore, the adequate disposal of shells is critical to avoid clogging of hydrants located downstream from the colonies. Additional drainage valves are being built in the networks of the RAA project, and should be included at the design phase of new collective pressurized networks in infested areas.

The proposed methodology to detect the presence of zebra mussels inside the network is based on the definition of normalized pressure as the difference between simulated and measured pressure. Values close to zero are in agreement with a clean pipeline. Nevertheless, a normalized pressure different from zero can result from the following circumstances: 1) Presence of zebra mussels (adults or shells) or other obstacles to flow within the network pipelines. This would result in a positive normalized pressure; 2) Poor hydraulic characterization of the network. Although the network was revised on-terrain with the manager of the CS-WUA, built information was used to create the EPANET file. The roughness coefficient was used as in the construction project. In the absence of zebra mussels, the roughness coefficient could have been calibrated using pressure measurements; and 3) Accuracy of the pressure measurements. The pressure transducer had an accuracy of 1%.

Considering the hypotheses and the potential limitations of normalized pressure, the proposed methodology has been proven effective when applied to two WUAs. In the first configuration, a chemical treatment was applied to eliminate zebra mussels inside a section of the network. The difference in normalized pressure between after and before the treatment can be interpreted in terms of the behaviour of zebra mussel colonies inside the pipelines. The areas with negative differences hosted zebra mussel colonies. In these areas, the chemical treatment succeeded in cleaning the pipelines: mussels were detached and flushed, reducing roughness and increasing pressure. These zones correspond to the pipelines connecting the hydrants with negative differences in normalized pressure. Figure 10b maps these pipelines in green. The cleaned area of the network is located near the injection point, close to the reservoir. This is in agreement with reservoirs being hubs of zebra mussel reproduction and settlement (Schneider et al., 1998, Allen & Ramcharan 2001, Havel et al. 2005, Johnson et al., 2008 and Smith et al., 2015). The areas with positive differences were adversely affected by the treatment. Despite the flushing of shells after the treatment, these areas accumulated shells in large amounts. The absence of appropriate network drains to evacuate shells permitted them to travel long distances within the network and to obstruct flow in areas apparently not colonized by the species. Figure 10b presents these areas in red. The red areas are coincident with those reported by farmers as particularly problematic. It is interesting to note that WUA farmers were more affected by shells than they were by mussels. Shells can move freely with the flow and have a strong capacity to clog hydrant filters, hindering irrigation.

This methodology was also applied to the analysis of the TM/RC system of the AL-WUA. The pressure sensors of the TM/RC system were not properly maintained: pressure data were only available for selected years and hydrants. Five of the eight pressure sensors were out of order. Despite this fact, the history of zebra mussel colonization was recorded in the TM/RC database. The proposed method has proven useful to unveil this information, revealing the progressive decrease in operational pressure. Even if measurements are not particularly accurate, the analysis of a time series of normalized pressure supports the assessment of zebra mussel infestation.

It is interesting to note that farmers did not realize about clogging until it was too late. In the vast majority of the network hydrants of the AL-WUA, the pressure regulator operates to reduce pressure to the target service pressure (350 kPa). Given the pressure distribution in the network pipelines, zebra mussel colonies can reduce the pressure at many hydrants by 100 or 200 kPa before the hydrant service pressure is below the target.

4.2. Perspectives for future research

The proposed methodology is based on normalized pressure as the main variable characterizing the presence of zebra mussel colonies inside the pipelines of a network. Although this methodology has been robust in estimating the areas of infestation, it could be combined with the analysis of flow velocity and its connection with zebra mussel colonization capacity (ZMR, 1993).

Moreover, in future research, a software could be developed to monitor network colonization by zebra mussels. The software could be used to assess the continuous, real-time evolution of the infestation (as in AL-WUA) or the effectiveness of discrete chemical treatments (as in CS-WUA). The large volume of data required to assess continuous evolution requires the use of TM/RC systems. Manual recording of hydrant pressure could be used to assess the effect of point chemical treatments, as was done in this research.

The software for real-time assessment would use a database of stationary periods with their pressure measurements. Hydraulic analyses would be used to issue warnings when thresholds of normalized pressure are systematically exceeded. An expert system could analyze normalized pressure to extract trends and to identify areas of infestation and areas of shell deposits.

Although normalized pressure is considered a clear indication of the presence of zebra mussels, the problem remains of assessing the degree of infestation. Providing quantitative or qualitative infestation indexes relating head losses to the density of zebra mussels stands as a relevant challenge. Infestation indexes could be used in the future to facilitate WUA decision-making about chemical treatments or other pest management practices. Laboratory experiments seem required for this purpose, analyzing the head losses (the roughness coefficient) produced by different densities of zebra mussels in pipelines of different diameters. The proposed methodology seems capable of producing real-time maps such as the one presented in Fig. 10b. These maps will indicate the infestation degree in a given WUA, in each of its networks and in the specific branches of the network. Maps will address the current uncertainty when it comes to deciding the optimum moment and the optimum injection point for a chemical treatment.

The implementation of the methodology presented in this work through a monitoring software requires a TM/RC system with three capabilities:

1. Pressure sensors located at hydrants and specific network points. Maintenance and calibration of these sensors will be required for accurate mapping. The frequency of pressure sampling should be regular (to avoid interpolations), between 5 and 10 min. The higher the sensor density, the better the assessment. The design of the *Violada* network included a sensor every 175 ha.
2. Registers of the opening/closing of each hydrant. Information would be completed if the discharge of each irrigation event was registered in the database.
3. Communication with the zebra mussel software using a standard protocol. This will facilitate the generalization of the control software. Playán et al. (2018) documented the difficulty of communicating between TM/RC systems and other management software used at the WUAs. The generalization of a standard for the communications of these systems would facilitate the control of zebra mussels in collective pressurized irrigation networks.

5. Conclusions

1. The existence of an infested reservoir upstream of the WUAs was the most likely source of zebra mussel colonization of the WUA pressurized networks in the RAA project. All WUAs irrigated from *Sotonera* reservoir show various stages of infestation. Three WUAs irrigated from *El Grado* reservoir (20 k ha) have recently developed the first stage of infestation.
2. A combination of structural and managerial practices of the WUA infrastructure and periodic chemical treatments have made it possible to control zebra mussel colonization in eight RAA WUAs.
3. The desiccation and treatment of the WUA reservoirs are associated with zebra mussel control. WUA reservoirs and networks should have adequate drains to allow for desiccation and flushing of shells.
4. The hydraulic methodology to monitor zebra mussel colonization in collective pressurized networks by a combination of pressure measurements and simulations proved successful in the application to two networks located in RAA WUAs.

5. When applied to a discrete chemical treatment event, the method enabled the mapping of the location of zebra mussel colonies removed by the treatment and the areas of shell deposits.
6. When applied to three years of irrigation using a TM/RC system, the method made it possible to assess the time evolution of zebra mussel infestation in different hydrants.
7. The proposed methodology could be implemented in a software gathering data from a TM/RC system and providing real-time mapping of network infestation. Such a system would support decision-making about the timing and location of chemical treatments in infested WUAs.

6. Acknowledgements

Thanks are due to the managers of the Collarada Segunda and Almudévar Water Users Associations. Their cooperation made this research possible.

Funding: This work was supported by the European Agricultural Fund for Rural Development (EAFRD) and by the Government of Aragón. Both institutions funded the IRRIZEB (*Programa integral para el control y mitigación del impacto de la plaga de Mejillón Cebra en sistemas de regadío*) grant of the *Plan de Desarrollo Rural* (PDR).

7. References

Abdulshaheed, A., Mustapha, F., Ghavamian, A. 2017. A pressure-based method for monitoring leaks in a pipe distribution system: A Review. Renewable and Sustainable Energy Reviews 69: 902-911.

Ackerman, J.D., Cottrell, C.M., Ethier, C.R., Allen, D.G., Spelt, J.K. 1996. Attachment strength of zebra mussels on natural, polymeric, and metallic materials. Journal of Environmental Engineering: 122 (2): 141-148.

Aldridge, D.C., Elliott, P. Moggridge, G.D. 2004. The recent and rapid spread of the zebra mussel (Dreissena polymorpha) in Great Britain. Biological Conservation, 119(2): 253-261.

Allen, Y.C. and Ramcharan, C.W. 2001. Dreissena distribution in commercial waterways of the U.S.: using failed invasions to identify limiting factors. Canadian Journal of Fisheries and Aquatic Sciences 58: 898-907.

Araujo, R., Álvarez, R.M., 2001. El mejillón cebra en el Ebro: un grave caso de riesgo ambiental en Aragón. Naturaleza Aragonesa, 8:39–46.

Banha, F., Gimeno, I., Lanao, M., Touya, V., Duran, C., Peribanez, M.A., Anastacio, P.M. 2016. The role of waterfowl and fishing gear on zebra mussel larvae dispersal. Biological Invasions, 18(1):115-125.

Bossenbroek, J.M., Johnson, L.E., Peters, B., Lodge, D.M. 2007. Forecasting the expansion of zebra mussels in the United States. Conservation Biology. 21(3): 800-810.

Bosso, L., De Conno, C., Russo, D. 2017. Modelling the Risk Posed by the Zebra Mussel Dreissena polymorpha: Italy as a Case Study. Environmental Management, 60(2):304–313.

Cembrano, G., Wells, G., Quevedo, J., Pérez, R. and Argelaguet, R. 2000. Optimal control of a water distribution network in a supervisory control system. Control Engineering Practice, 8(10),1177–1188.

CHE. 2007. El mejillón Cebra en la Cuenca del Ebro. Confederación Hidrográfica del Ebro. Zaragoza, Spain. Depósito legal Z-2.475-2007. 48 pp.

Frischer, M.E., Kelly, K.L., Nierzwicki-Bauer, S.A. 2012. Accuracy and reliability of Dreissena spp. larvae detection by cross-polarized light microscopy, imaging flow cytometry, and polymerase chain reaction assays. Lake and Reservoir Management, 28 (4): 265-276.

Havel, J.E., Lee, C.E., Vander Zanden, M.J. 2005. Do reservoirs facilitate invasions into landscapes? BioScience 55:518-525.

Herbert, P.D., Muncaster, B.W., Mackie, G.L. 1989. Ecological and genetic studies on Dreissena polymorpha (Pallas): a new mollusc in the great lakes. Canadian Journal of Fisheries and Aquatic Sciences 49, 1587–1591.

Johnson, P.T.J., Olden, J.D., Vander Zanden, M.J. 2008. Dam invaders: impoundments facilitate biological invasions into freshwaters. Frontiers in Ecology and the Environment 6: 357:363.

Khalanski, M., 1997. Industrial and ecological consequences of the introduction of new species in continental aquatic ecosystems: the zebra mussel and other invasive species. Bulletin Francais de la Peche et de la Pisciculture 344–445, 385–404.

Klerks, P.L., Fraleigh, P.C. 1991. Controlling adult zebra mussels with oxidants. Journal American Water Works Association. 83(12):92-100.

Kobak, J., Januszewska, M. 2006. Impact of substratum type on attachment and survival of Dreissena Polymorpha (Bivalvia). Folia Malacologica 14(2): 51–56.

Landeros E., Pérez R., Peralta A., C.G., 2009. Leakage detection using pressure sensors and mathematical models. Water Loss 2009, Cape Town, South Africa.

Leuven, R.S.E.W., Collas, F.P.L., Koopman, K.R., Matthews, J., van der Velde, G. 2014. Mass mortality of invasive zebra and quagga mussels by desiccation during severe winter conditions. Aquatic Invasions Volume 9, Issue 3: 243–252

Lowe, B., Browne, M., Boudjelas, S., De Poorter, M. 2004. 100 of the World's Worst Invasive Alien Species. The Invasive Species Specialist Group (ISSG) of the World Conservation Union (IUCN), Auckland, New Zealand. 11 pp.

MAPAMA. 2015. Aumenta la superficie regada en España pero se mantiene una tendencia a la baja en el volumen de agua de riego utilizado en el sector agrario. http://www.mapama.gob.es/es/prensa/noticias/aumenta-la-superficie-regada-en-espa%C3%B1a-pero-se-mantiene-una-tendencia-a-la-baja-en-el-volumen-de-agua-de-riego-utilizado-en-el-sector-agrario-/tcm7-367091-16# (accessed 16/8/2017).

MAPAMA. 2016. Encuesta sobre Superficies y Rendimientos Cultivos (ESYRCE). http://www.mapama.gob.es/es/estadistica/temas/estadisticas-agrarias/agricultura/esyrce/ (accessed 16/8/2017).

Marín, N. Companys, C. Peñalver, T., Sanchez, R. 2016. Aplicación de ultrasonidos para el tratamiento del mejillón cebra (*Dreissena polymorpha*) en espacios confinados. Tecnoaqua, 21:64-71.

Naddafi, R., Blenckner, T., Eklöv, P., Pettersson, K. 2011. Physical and chemical properties determine zebra mussel invasion success in lakes. Hydrobiologia 669:227–236.

Pascual J, Romera J, Puig V, Cembrano G, Creus R, Minoves M (2013) Operational predictive optimal control of Barcelona water transport network. Control Eng Pract 21(8):989–1156

Playán, E., Salvador, R, Bonet, L., Camacho, E., Intrigliolo, D., Moreno, M.A., Rodriguez-Díaz, J.A., Tarjuelo, J.M., Madurga, C., Zazo, T., Sánchez-de-Ribera, A., Cervantes, A. and Zapata N. 2018. Assessing Telemetry and Remote Control Systems for Water Users Associations in Spain. Agric. Wat. Manage. 202: 89-98.

Roberts, L. 1990. Zebra Mussel Invasion Threatens U.S. Waters. Science, New Series, 249(4975):1370-1372.

Rossman, L.A. (2000) EPANET 2: Users manual. US Environ. Prot. Agency, Washington, D.C. EPA/600/R-00/057, 2000.

Schneider, D.W., Ellis, C.D., Cummings, K.S. 1998. A transportation model assessment of the risk to native mussel communities from zebra mussel spread. Conservation Biology 12:788-800.

Seral, P., García, S., Aliod R., Paño J., Faci, E. 2012. Development of Tools and Strategies for Controlling the Zebra Mussel in Pressurised Irrigation Networks. World Environmental and Water Resources Congress 2012: Crossing Boundaries. American Society of Civil Engineers. Albuquerque, USA. 11 pp. 2138-2148

Smith, B.R., Edds, D.R., Goeckler, J.M. 2015. Lowhead dams and the downstream dispersal of zebra mussels. Hydrobiologia 755:1–12.

Tosenovsky, E., Kobak J. 2016. Impact of abiotic factors on aggregation behavior of the zebra mussel Dreissena polymorpha. Journal of Molluscan Studies 82: 55–66.

Waller, D.L., Fisher, S.W. 1998. Evaluation of several chemical disinfectants for removing zebra mussels from unionid mussels. Progressive Fish-Culturist, 60(4):307-310.

ZMR. 1993. Evaluating the Susceptibility of Structures to Zebra Mussel Infestation. U.S. Army Engineer Waterways Experiment Station, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199. Zebra Mussel Research Programme. Technical Note ZMR-1-11. 2 pp.

8. List of tables

9. List of Figures

Table 1

Characteristic	CS-WUA	AL-WUA
The WUA		
Irrigated area, ha	3,126	3,744
Pressurized area, %	84	100
Collective pressurized networks	2	5
The network under study		
Name	Network 1	Violada
Pumping station, Y/N	N	Y
Irrigated area, ha	1,890	1,400
Service discharge, m^3/s	2.9	1.6
Number of hydrants	155	107
Minimum hydrant discharge, L/s	18	18
Maximum hydrant discharge, L/s	83	100
Length of pipes, km	46.1	32.1
Minimum pipe diameter, mm	131	115
Maximum pipe diameter, mm	1,400	1,176

Table 2

Hydrant	Event			Hydrant	Event		
	P	B	A		P	B	A
H16		X	X	H114			
H20		X	X	H123			
H21		X	X	H122			
H22		X	X	H115			
H22B		X	X	H117		X	X
H107				H118			
H108	X	X	X	H119			
H26	X	X	X	H28		X	X
H110				H29		X	X
H111				H128		X	X
H121				H144		X	X
H126	X	X	X	H130B			
H127		X	X	H130		X	X

Table 3

Duration	Year		
	2011	2015	2016
T10	1,953	3,325	3,286
T20	885	1,790	1,694
T30	506	983	922
T40	305	673	507
T50	171	440	264

Table 4

Year	Preset Duration	RMSE (kPa)	
		Constant Pressure	Interpolated Pressure
2011	T10	26.8	27.8
2011	T20	26.9	27.2
2011	T30	27.8	27.6
2011	T40	31.9	30.8
2011	T50	35.9	34.8
2015	T10	111.4	114.8
2015	T20	109.2	113.2
2015	T30	110.3	113.7
2015	T40	110.0	114.8
2015	T50	113.6	117.8
2016	T10	113.3	117.0
2016	T20	117.8	122.0
2016	T30	124.1	127.1
2016	T40	128.8	133.7
2016	T50	137.6	142.6

Figure 1

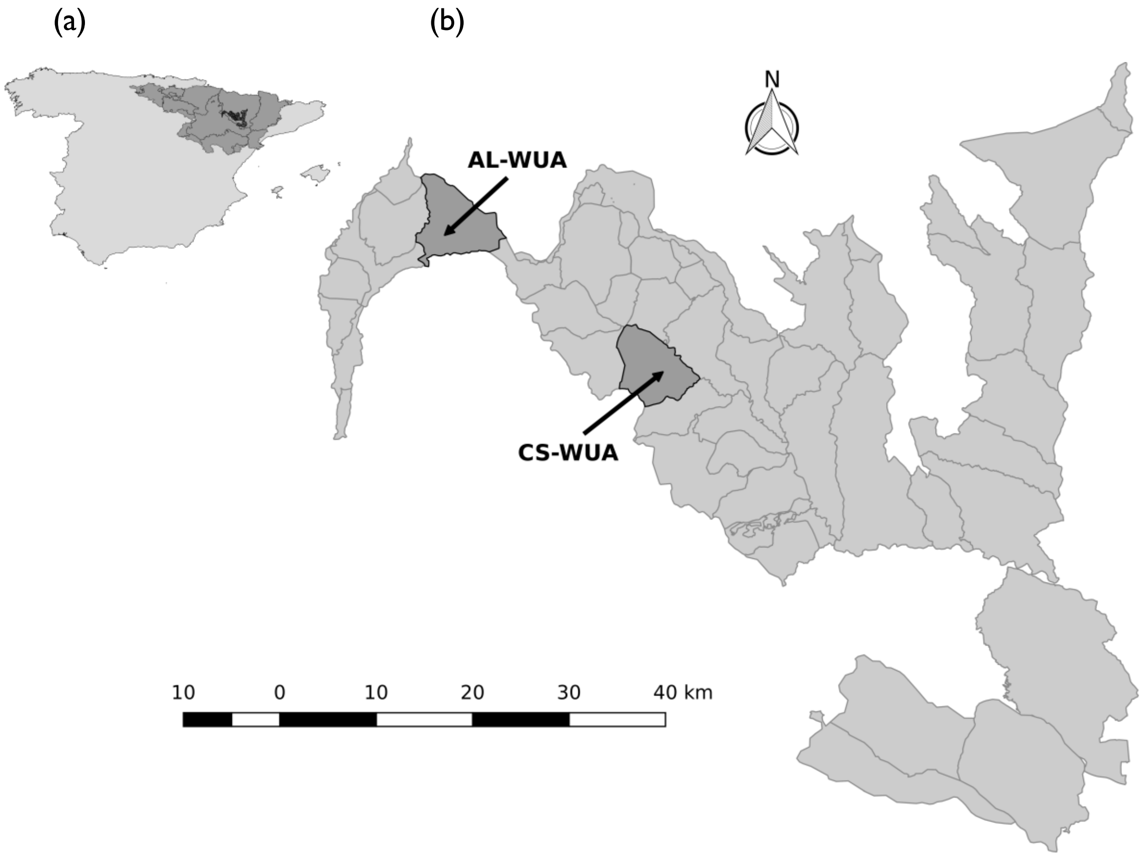


Figure 2

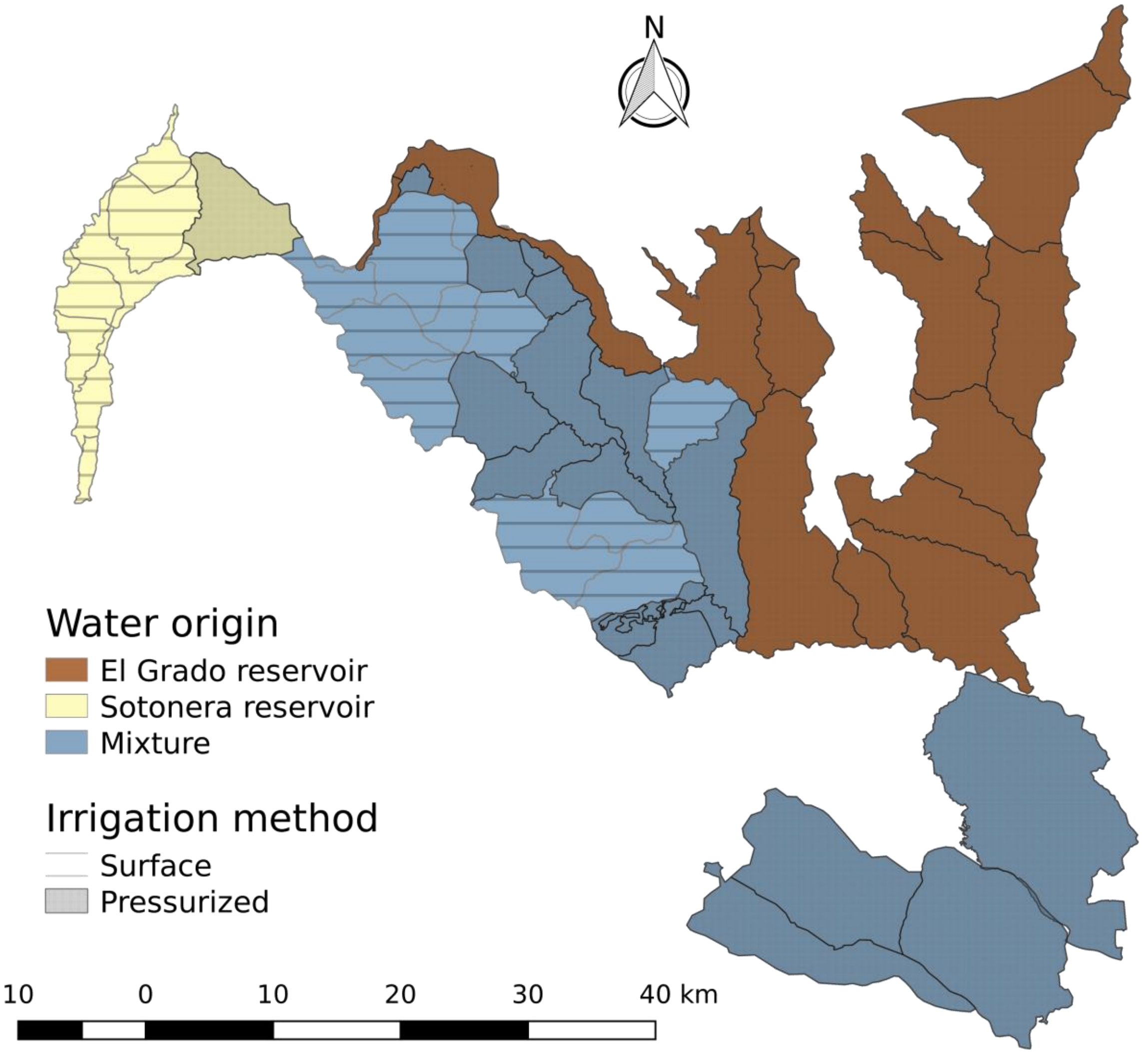

N
Water origin
El Grado reservoir
Sotonera reservoir
Mixture
Irrigation method
Surface
Pressurized
10
0
10
20
30
40 km

Figure 3

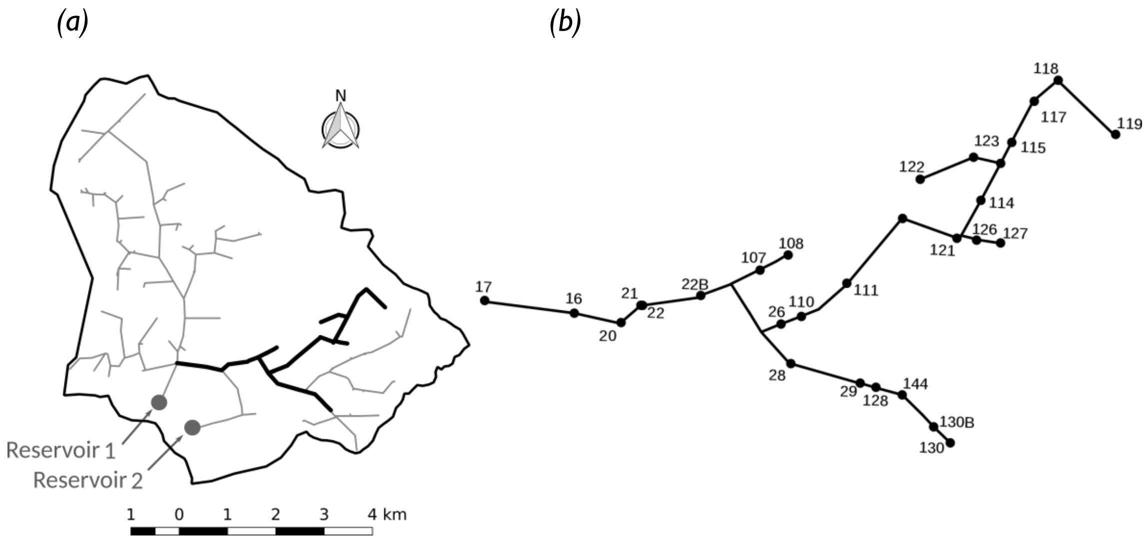

(a)
(b)
N
Reservoir 1
Reservoir 2
1 0 1 2 3 4 km
17
16
20
21
22
22B
107
108
26
110
111
28
29
128
144
130B
130
121
126
127
114
122
123
115
117
118
119

Figure 4

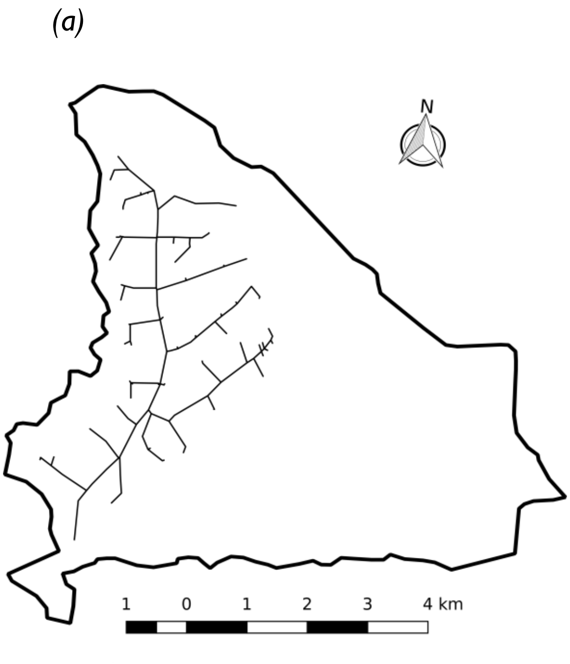


Figure 5

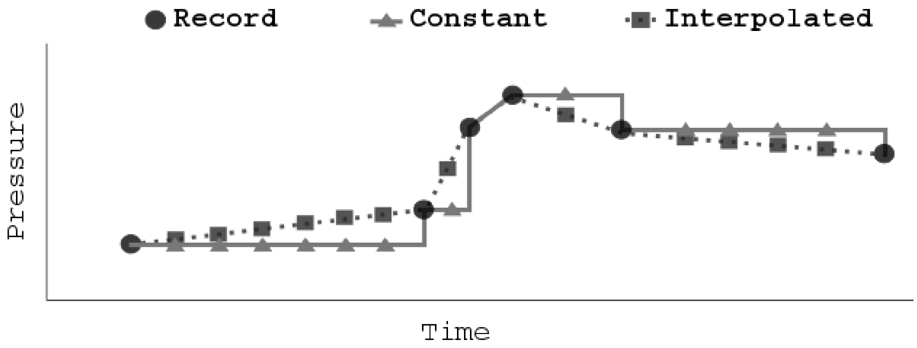


Figure 6

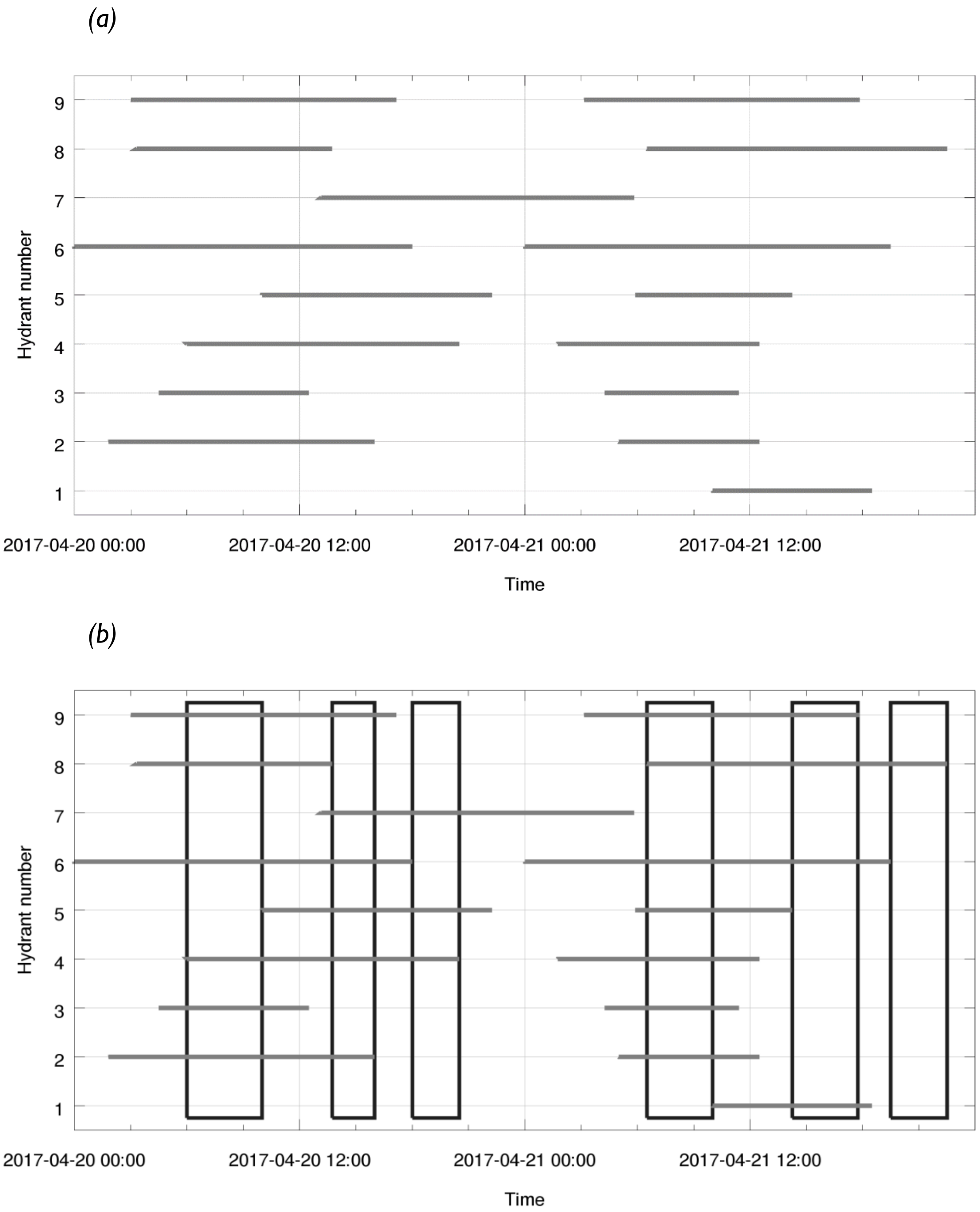
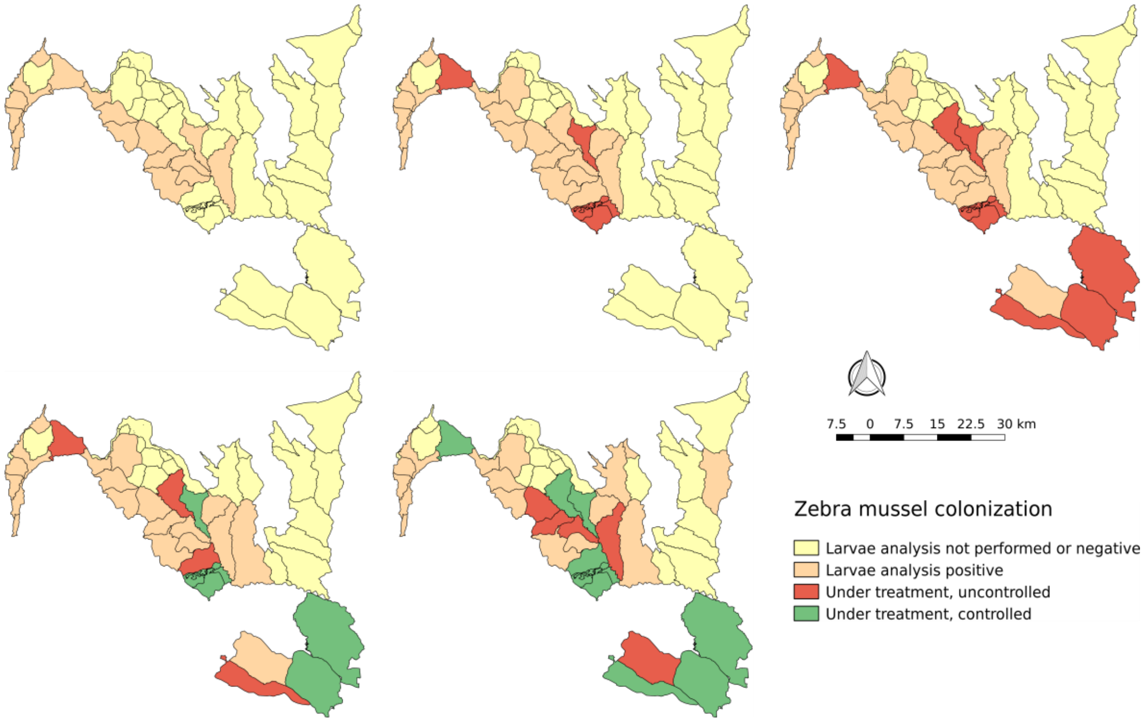

(a)
9
8
7
6
5
4
3
2
1
Hydrant number
2017-04-20 00:00
2017-04-20 12:00
2017-04-21 00:00
2017-04-21 12:00
Time
(b)
9
8
7
6
5
4
3
2
1
Hydrant number
2017-04-20 00:00
2017-04-20 12:00
2017-04-21 00:00
2017-04-21 12:00
Time

Figure 7



7.5 0 7.5 15 22.5 30 km
Zebra mussel colonization
Larvae analysis not performed or negative
Larvae analysis positive
Under treatment, uncontrolled
Under treatment, controlled

Figure 8

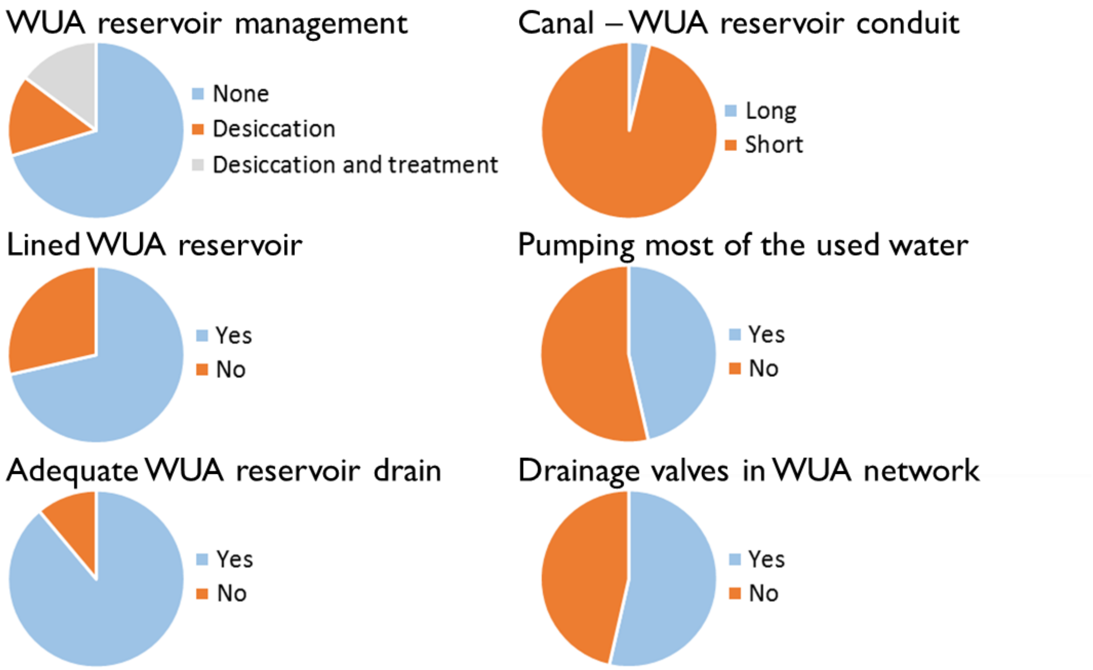

WUA reservoir management
None
Desiccation
Desiccation and treatment
Canal – WUA reservoir conduit
Long
Short
Lined WUA reservoir
Yes
No
Pumping most of the used water
Yes
No
Adequate WUA reservoir drain
Yes
No
Drainage valves in WUA network
Yes
No

Figure 9:

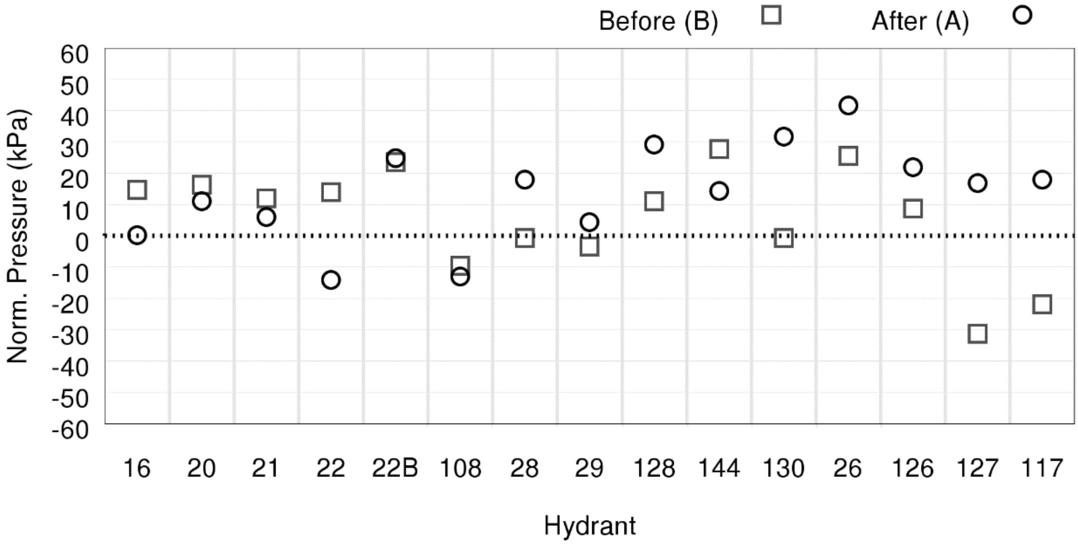
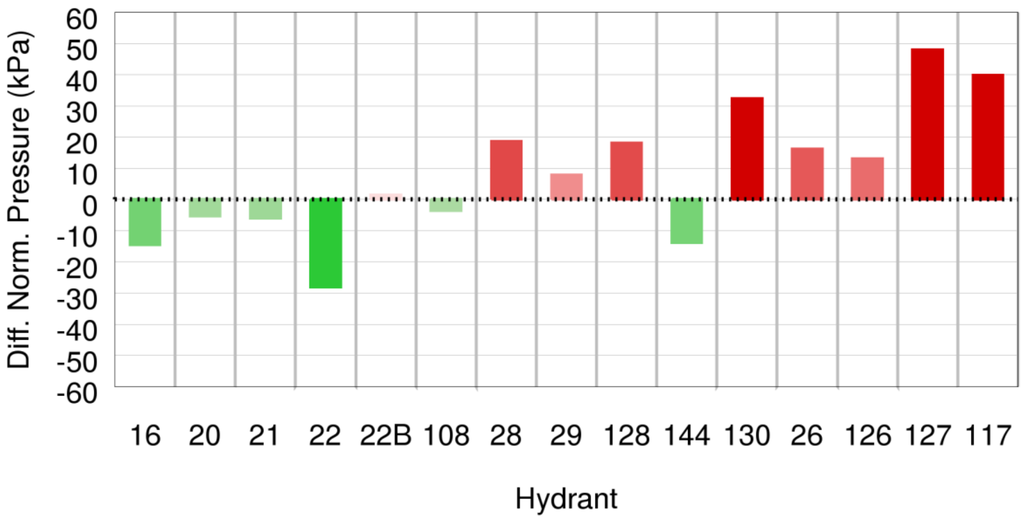

Before (B)
After (A)
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
Norm. Pressure (kPa)
16
20
21
22
22B
108
28
29
128
144
130
26
126
127
117
Hydrant

Figure 10

(a)


Diff. Norm. Pressure (kPa)
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
16 20 21 22 22B 108 28 29 128 144 130 26 126 127 117
Hydrant

(b)

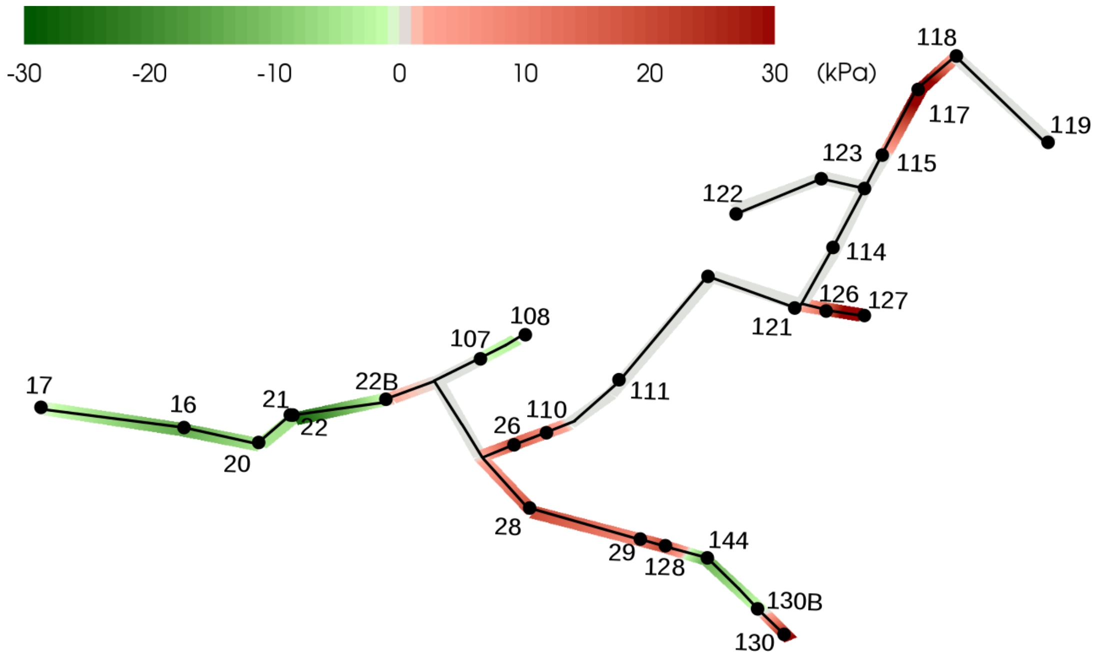
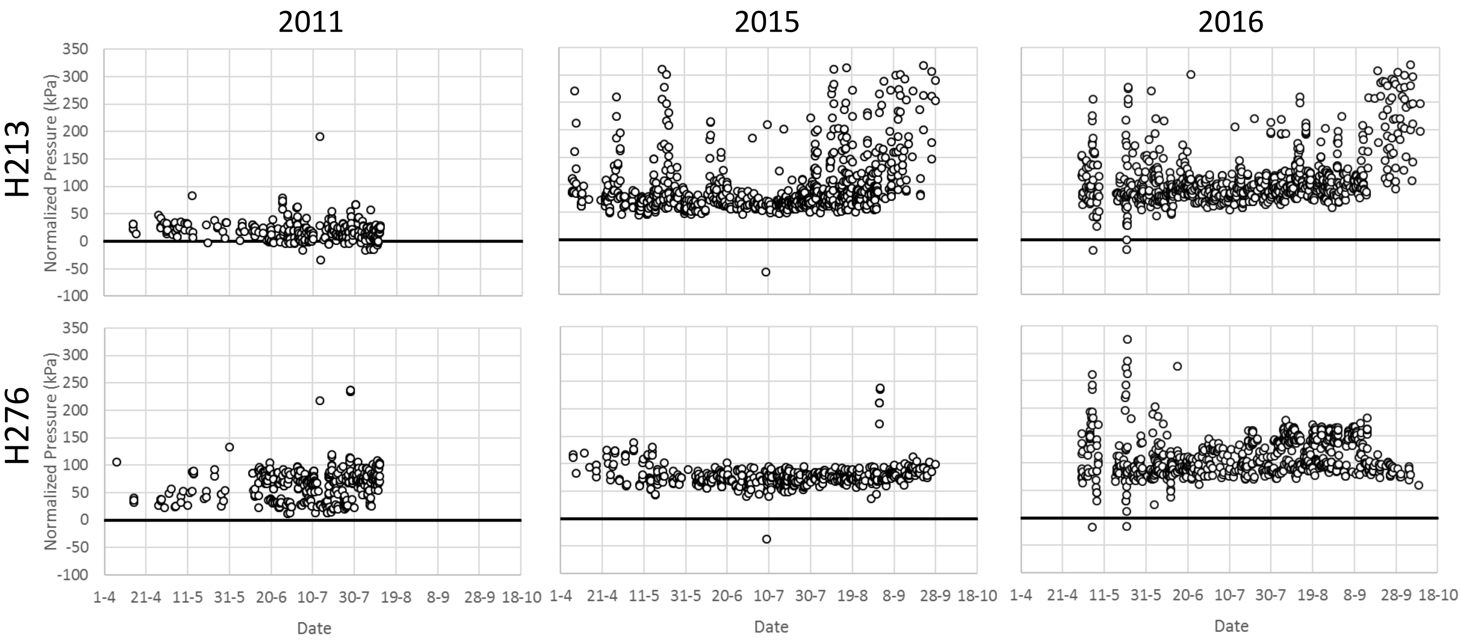

-30
-20
-10
0
10
20
30
(kPa)
118
117
119
123
115
122
114
126
127
121
108
107
17
16
21
22B
22
20
111
110
26
28
29
128
144
130B
130

Figure 11


2011
2015
2016
H213
H276
Normalized Pressure (kPa)
350
300
250
200
150
100
50
0
-50
-100
1-4
21-4
11-5
31-5
20-6
10-7
30-7
19-8
8-9
28-9
18-10
Date