Development of Tools and Strategies for Controlling the Zebra Mussel in Pressurised Irrigation Networks.

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ABSTRACT

Chemical products, mainly chlorine, are often used to control or eradicate the Zebra Mussel, *Dreissena Polymorpha*, in pressurised irrigation pipes, although other disinfectants have been used, such as hydrogen peroxide. An optimum application of these substances is essential to achieve maximum effectiveness at minimum cost, without harmful effects on crops or the environment. This work defines tools and techniques for satisfactory process design, taking into account the specifics of operation and flow structure in irrigation system networks (very different from those of domestic water supply), the species to be combated and the high concentration of organic material in irrigation water. New specific functions have been implemented and applied in GESTAR 2010 (www.gestarcad.com), the software application for designing and managing pressurised irrigation networks, facilitating the use of the urban network water quality simulation module from the EPANET2 programme, adapting it for these purposes and obtaining predictions for the evolution of the concentration of the additive used over time at all points in the network, considering the reaction in the raw untreated water supply and the reaction with the wall, due to the effect of interaction with the invasive mollusc species (not necessarily zebra mussel).

1. - INTRODUCTION AND OBJECTIVES.

The Zebra Mussel (*Dreissena polymorpha*, Pallas) in continental water taken for use in irrigation systems has a devastating effect on these systems, adhering to pipelines and hydraulic infrastructure, leading to a significant increase in maintenance costs and loss of efficiency, blocking filters and taking hydrants out of service.

The first populations of zebra mussel in the Ebro basin (Spain)were detected in July 2001, in the Flix reservoir. The population explosion of *Dreissena polymorpha* once it is introduced, reaching very high population densities, makes it practically impossible to stop the gradual colonisation of the different natural and artificial substrates in contact with the river. This threat to river ecosystems presents a serious risk of ecological and socio-economic disaster in the short and mid term wherever it is found. Its invasive nature was made clear when analysing the extent of infestation in August 2009 (Figure 1), when bodies of water affected by the mussel were found in practically the whole length of the Ebro and the following tributaries: Gállego, Guadalupe, Jalón, Noguera-Pallaresa, and Zadorra. This spread directly affects irrigation systems, colonising the infrastructures supplied by water from the Ebro basin throughout its river system.

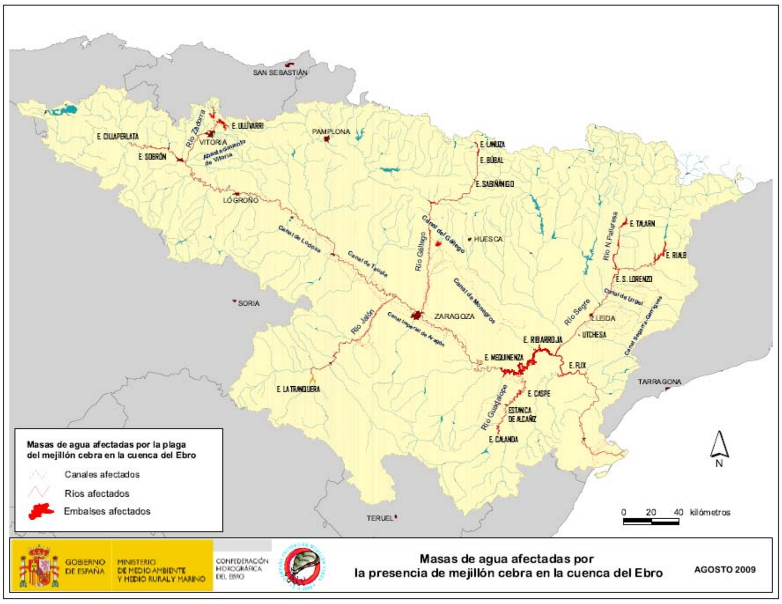

Figure 1: Bodies of water affected by the presence of zebra mussel in the Ebro basin (Spain) in August 2009.

Treating the water outside the natural environment with chemicals is one of the traditional methods of controlling *Dreissena polymorpha*, most often using chlorine, but its effectiveness depends on many variables (such as application dose, duration of the treatment, temperature, pH of the water, the presence of organic and inorganic compounds, pipe materials) which are not systematically factored into interventions in irrigation networks. Research is being carried out on a protocol for designing chemical treatment applications which will be effective and economical, while minimising its adverse effects. For this, simulation techniques are used to estimate the evolution of disinfectant concentrations throughout the network. The results are illustrated by their application to a specific network affected by zebra mussel.

2. - MATERIALS AND METHODS

The methodology developed is demonstrated for a real irrigation system, Cuesta-Falcón, located un Aragon región (Spain), based on data provided by SIRASA (Sociedad de Infraestructuras Rurales Aragonesas S.A.) in GESTAR format.

GESTAR is a computer programme for hydraulic engineering in pressurised irrigation systems (collective distribution networks and systems for applying irrigation in plots), enabling improved design, execution and management.

The system takes water from the Mequinenza dam, and is pumped to the regulating reservoir with a capacity of 39,957 m^3. The irrigated area is 579.07 ha, divided into three independent areas. The simulations carried out circumscribed the 416.97 ha area which can be irrigated using natural pressure (network sketch, Figure 4). For the rest of the system two independent pumping systems were planned, ensuring minimum pressure for irrigation.

Using a specific functionality introduced in GESTAR, the network can be converted directly to the EPANET format (GESTAR2010, from the menu *File/ Export/ Epanet file*), Figure 2, to take advantage of the resources of this application for modelling the distribution of chemical substances in pressurised networks.

EPANET is a programme used for analysing water quality in drinking water supply networks, developed by the US Environmental Protection Agency (EPA), enabling simulations of the application of additives, modelling the corresponding reactions, the aspect we exploit in this new context. Due to EPANET's orientation to modelling drinking water supply systems, there are some limitations for the implementation of the real operations of irrigation systems, especially in networks with direct pumping and intermittent random demand at hydrants, as individual patterns must be modelled for every hydrant in each scenario analysed, registering the variation in opening of hydrants over time. Moreover, the overall modelling of the hydraulic and energy response of the direct pumping stations is very difficult or impossible.

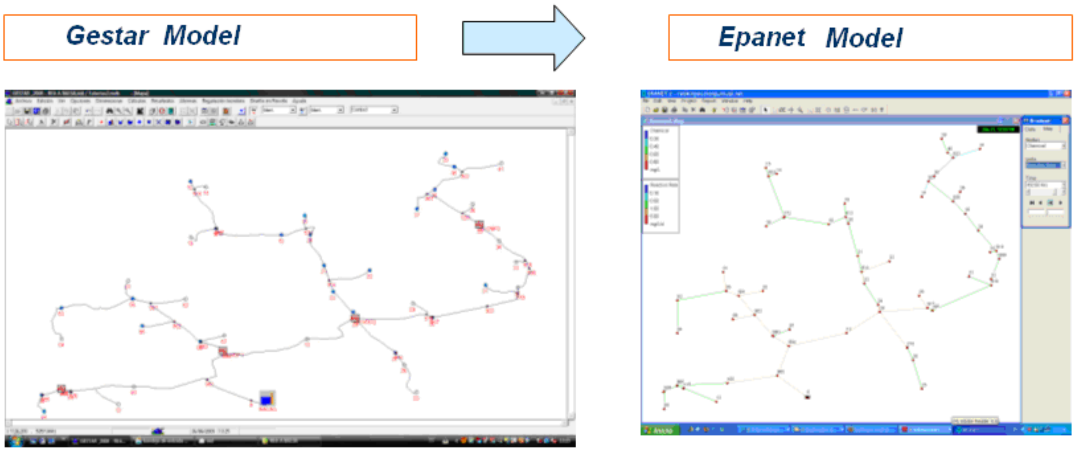

Figure 2: Automatic Conversion of the GESTAR format network to the EPANET format

The chemical product most used to treat infestations of Zebra Mussel is sodium hypochlorite. This product is widely used in drinking water treatment systems, and thus is competitively priced, with existing dosing technology. However, for it to be used appropriately and effectively in irrigation systems, a set of specific questions must be analysed, and have been taken very much into account in this work:

- The minimum chlorine requirements (concentration and contact time) for controlling or eradicating a macro invertebrate are different to those needed for bactericidal treatments.
- In the case of irrigation systems, the pipes carry untreated water with a much higher concentration of organic matter than in an urban water supply, leading to faster breakdown of the chlorine present in the network, and greater disinfectant persistence problems.
- Also, as irrigation networks are branched, there may be long periods where water is retained in branches where the nodes are closed downstream, leading to a reduction in chlorine levels. This does not happen in loop type water supply systems, where recirculation homogenises the concentrations and reduces the amount of chlorine that must be added. Additionally, irrigation networks must have well-designed protocols for regular opening of hydrants to renew the disinfectant.
- In preventative treatment, it is essential to ensure that the concentration added to the hydrant is harmless to the crops. The free residual chlorine parameters tolerated for human consumption are well-known and legally regulated. However, while specific research is currently underway, there is a great deal of uncertainty as to the quantification of tolerance levels for crops.

Meanwhile, before the computer simulation, a field study will be needed to estimate how badly the system is affected. If the infestation is very heavy, with many adult mussels, a shock treatment will be needed to eliminate them. If the network is free of bioincrustation, the application will be preventative, during the larval season, avoiding colonisation.

Also, the larval stage of the mussel is more sensitive to chlorine, so that different concentrations and application times are required for effective treatment. Application simulations were run for various cases: preventative treatments, i.e., continuously adding sodium hypochlorite during the larval season to avoid colonisation, and shock treatments with individual additions of chlorine to control or eradicate an established population.

Chlorine treatment values

The percentage of mortality of *Dreissena polymorpha* in the larval and adult stage, depending on the concentration of residual chlorine, contact time and water temperature, has been determined by a review of the literature (Table 1).

For treatments in the larval phase, the table shows results obtained in the laboratory. In real preventive treatments, it is unknown if larvae are present in the network, but the treatment must be continuous during the larval period to prevent them from entering and settling. Thus, the concentrations of residual chlorine suggested in the literature (Klerks et al, 1993) are lower (from 0.25 to 0.5 mg/l), and must be maintained during the months of treatment

Mathematical model of chlorine decay

As well as considering the physical process of transporting the reactive via the circulating water, the process of residual chlorine reacting with the organic matter it encounters must be taken into account, as this reduces its concentration as an active agent.

Table 1: Chlorine concentration and contact time for the eradication of *Dreissena polymorpha*.

Dreissena polymorpha	**Residual chlorine (mg/l)**	**Temperature (ºC)**	**Duration**	**Mortality (%)**	**Reference**
European population	0.50	21	7 days	70	Greenshields &Ridley,1957
Size: 10 mm	2.00	21	7 days	100	
	0.25	12-15	21 days	90	Jenner, 1985
	0.50	12-15	16 days	93	
	1.00	12-15	14 days	95	Rajagopal et al, 2002
	0.25	20	45 days	100	
	0.50	20	37 days	100	
	1.00	20	25 days	100	
	2.00	20	19 days	100	
	3.00	20	11 days	100	
	0.50	25	20 days	100	
	0.50	10	44 days	100	
American population	0.50	18-22	18 hours	100	VanBenschoten et al, 2003
Veliger	1.00	18-22	5 hours	100	

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According to Rossman (1993), this decay process can be formulated as a chemical reaction which takes place in the water and the walls of pipes. The most common characterisation has been taken, which simulates both reactions by a first order kinetic.

The expression for the kinetic reaction term under this assumption is:

$$\theta(c) = -K \cdot C$$

where C is the current concentration of the substance and K is the global constant equal to:

$$K = k_b + \frac{k_w \cdot k_f}{R_H \cdot (k_w + k_f)}$$

where k_b is the first order constant of reaction in the water, k_w is the constant of reaction with the pipe wall, k_f is the coefficient of transference between the water and the pipe wall, and R_H is the hydraulic radius of the pipe. As simulations are being run on EPANET, the values of k_b and k_w for the example case have had to be entered, while k_f is calculated internally by the programme.

The preliminary simulations used the global decay coefficients for drinking water supply systems found in the literature (Powell et al, 2000), adopting a value of

0.36 day-1. The value of this coefficient was established in parallel in the laboratory with water samples from the Mequinenza area. This analysis is essential for treatments in irrigation systems, given that, as remarked k_b above, the overall decay coefficient depends significantly on the amount of organic matter present in the fluid.

At a constant temperature, residual chlorine concentration values are obtained after different periods in non-reactive glass recipients. The analysis used the HI 93414 Turbidity and Free/Total Chlorine Meter, with a measurement range of 0 to 5 mg/l. Readings were taken every fifteen minutes for the first four hours, continuing with hourly readings until the residual free chlorine had disappeared.

As this was a first order reaction, representing against time the natural logarithm of concentration C_t at instant t in relation to concentration C_0 at the initial instant, a straight line was obtained, with a slope value of k_b, Figure 3.

For a correlation coefficient of -0.987755 and R squared of 97.5%, the value of k_b equals 0.076 hour^{-1} (-1.8 day^{-1}). As a control sample, the same analysis was carried out on tap water, obtaining values of k_b of -0.077 day^{-1}.

The calibration of k_w, constant of reaction with the pipe walls, can only be done based on data from measurement campaigns in the field. The variability of this parameter is a function of pipe material, age and degree of colonisation. The values initially adopted were obtained from the literature (Al-Jasser, 2006), taking a value of k_w of -0.75 day^{-1} for the Cuesta-Falcón system.

The extent of the measurements taken to determine chlorine concentrations in the field will enable better estimations to be made in the future. In preventative treatments, without detectable colonisations, similar values are expected to be found, while where the species has colonised, the presence of numerous specimens adhering to the walls of the pipes will notably increase the effect of reaction with the walls.

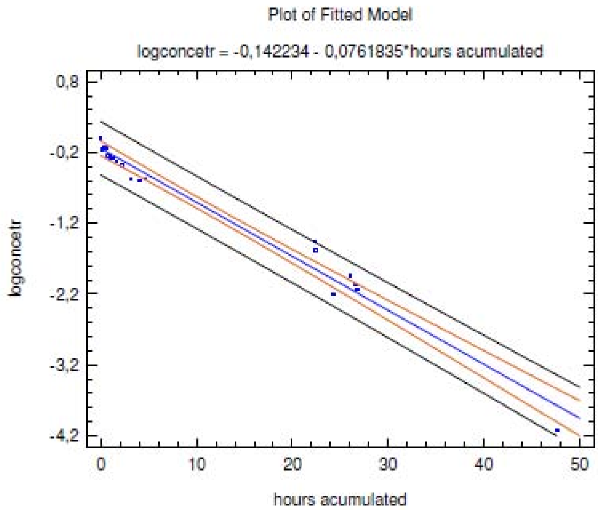

Figure 3: Simple regression graph obtaining value k_b with Mequinenza area water.

3- RESULTS AND DISCUSSION

Disinfectant application simulations were run considering various hypothetical cases, obtaining results for variations in the concentration of residual chlorine due to the transportation and decay processes at any point of the network over time.

Shock treatments

Shock treatments, with individual additions of chlorine to control or eradicate an established population, require high levels of chlorine. This means contact time can be reduced, but the treatments must be carried out when irrigation is not taking place, as these concentrations are too high for the crops. The strategy is implemented as follows:

- End hydrants are opened in a preset sequence, transporting the reactive from the point of application.
- The hydrants are closed as the chlorine reaches the appropriate concentration at branch ends.
- Additions will be made from time to time as the chlorine falls below the desired value in the most distant points, and the affected hydrants will be opened until the chlorine content is replenished.
- The analysis of system behaviour by simulation allows us to programme the opening of each hydrants, and the concentrations and periods of chlorine injection for optimising the treatment.

A sample shock treatment design was created for the Cuesta Falcon irrigation System, considering a large population of adult mussels adhering to the pipe walls throughout the network. According to the values of Table 1, for an exposure time of 25 days at a temperature of 20 ºC, a residual chlorine concentration of 1 mg/l is required to achieve 100% mortality.

The measured value of -1.8 day^{-1} is adopted as the reaction constant in the raw water. By trial and error procedures the required dosage at the head (5 mg/l) is obtained and the hydrants opening patterns are fitted as follows:

- The hydrants farthest away must be opened for 4 hours every 8 hours.
- The rest are set to open for 2 hours every 12 hours.
- Some hydrants which are not end-of-line nodes (nodes 13, 40, 5, 100) will be permanently closed during treatment to avoid high chlorine concentration emission.

Given the high concentration of organic matter present in the water used for irrigation in this area, chlorine decay in the network is very marked (Figure 5), and the dosages must be administered more frequently to avoid the residual chlorine in the network falling below 1 mg/l. It is advisable to design different opening patterns, due to the wide range of concentrations obtained for the different nodes in the network.

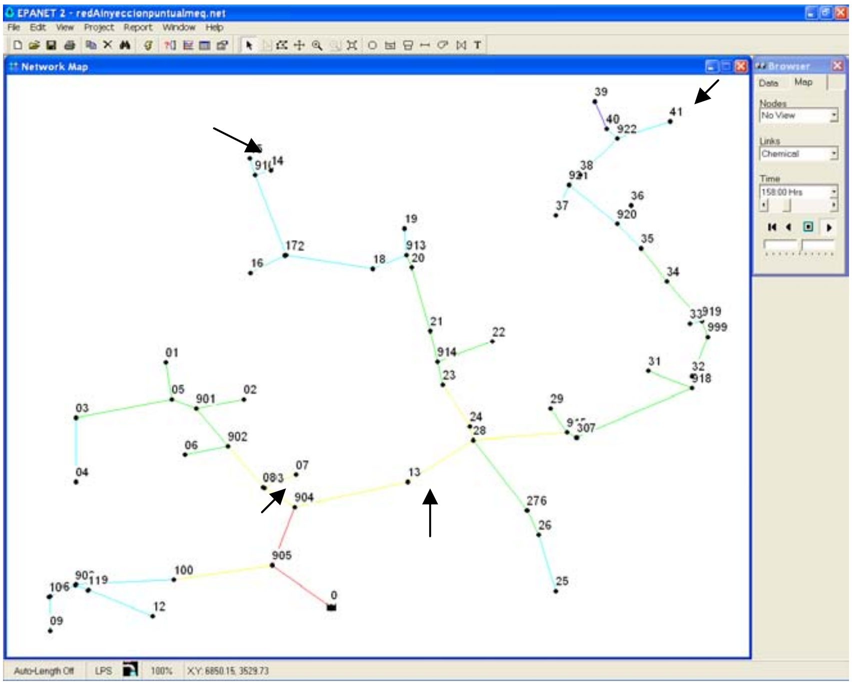

Figure 4: Network map in EPANET format, indicating the nodes providing the results given in Figures 5, 6.

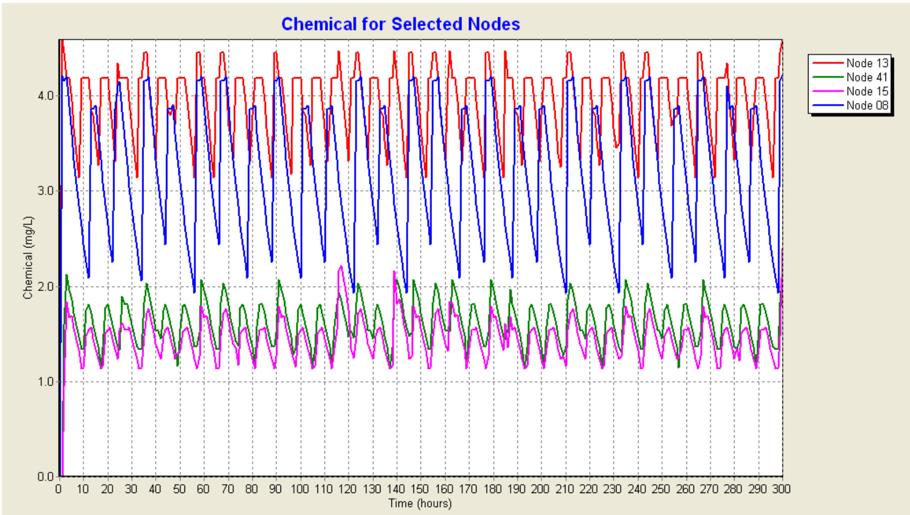

Figure 5: Results for residual chlorine concentration (mg/l) at various points in the network for a simulation of shock treatment.

Preventative treatments

A sample application is carried out for a hypothetical preventative treatment, i.e., the continuous addition of sodium hypochlorite during the larval period to prevent colonisation.

The irrigation patterns are adjusted to simulate a month during the irrigation campaign which coincides with the appearance of larvae. A minimum chlorine requirement of 0.25 mg/l is set. Care is taken that where the hydrants receive the most concentration, it is not enough to harm the crops.

Using the measured global decay value of -1.8 day^{-1}, we found the initial concentration at the head to 1.25 mg/l. Despite this, at the farthest points of the network, a residual chlorine concentration can only be ensured for a value above 0.25 mg/l during the irrigation, exceeding the value of 0.1 mg/l at all times. Given that the possible entrance of larvae in the network is through the head tank, the results obtained are considered to be sufficient. As shown in Figure 6, concentration values under 0.25 mg/l are concentrated in residual stretches at the ends of lines.

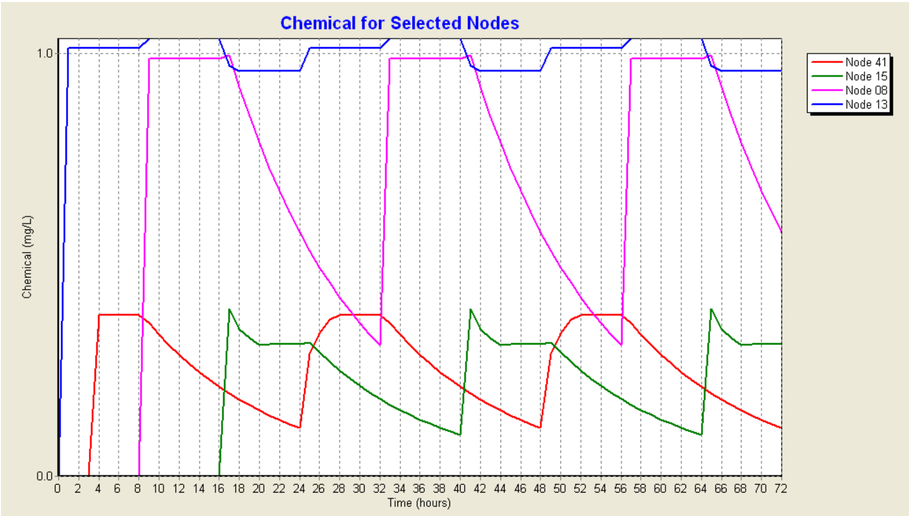

Figure 6: Results for residual chlorine concentration (mg/l) at various points in the network for a preventative treatment.

It must be taken into account that for this network, as the maximum chlorine concentration value found at the hydrants close to network input is 1.03 mg/l, increasing the concentration of the additive is not advised. If the concentration needs to be higher in any section of the network, a second dosage unit should be installed at an internal point in the network.

4.- CONCLUSIONS AND RECOMMENDATIONS

A novel methodology was applied to optimise the application of reactive disinfectant substances to combat Zebra Mussel infestation in pressurised irrigation networks, identifying the critical aspects to be taken into account and establishing operational guidelines. This methodology is based on predicting the variation of the concentration of the additive over time, in all points of the network, for each of the alternative treatments. These predictions are based on techniques using the functions of the EPANET programme for simulating water quality in urban drinking water networks. If the irrigation network studied is defined in the GESTAR 2010 code, the task is simplify, since the individual consum pattern of each hydrant, necessary for the numerous trial simulations required, is easily defined with GESTAR resources and automatically exported to EPANET by means of specific new tools. Comparing these results with the concentrations and contact times needed for the required mortality percentages, a general strategy can be drawn up for applying the treatment, which must be particularised for each specific network, and which is effective both for prevention and for controlling infestations. It also optimises the use of the additive, with consequent economic benefits, of vital importance to the agricultural sector, given its scanty profit margins. All of this contributes to reducing the total quantity of residual chlorine added, minimising the possible adverse effects of these control strategies on the environment and on crops.

5.- ACKNOWLEDGEMENTS

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