Factors affecting the efficacy of acrolein in irrigation channels in southern Argentina

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Summary

Growth of the submerged weed *Potamogeton pectinatus* L. is a major problem in the irrigation channels located in the Lower Valley of the Colorado River (39°10′–39°55′S; 62°05′–63°55′W) in Argentina. Previous studies indicate that weed control with acrolein is effective in reducing submerged plant biomass. In this study, we evaluated the influence of some variables affecting acrolein and its dissipation in water. Three main parameters, acrolein dosage, the height of the plants and the velocity of water contributed to 80% of the reduction of the submerged weed biomass. Water flow and concentration of the chemical explained 68% of the factors influencing the dissipation of the herbicide. Water velocity, electrical conductivity, pH and the duration of application have a secondary effect in the dissipation process. The constant rate of dissipation (K) was 0.235 L h^{-1} (SD ± 0.125), implying that the chemical will disappear from the system in < 24 h. As a practical guideline for the control of mature, dense stands of *P. pectinatus* within the irrigation system under study, the following conditions are advisable: flow volumes of 500 L s^{-1} or higher, water velocity of 0.42 m s^{-1} or more and *c*. 6.5 mg L^{-1} concentration of acrolein for at least a 11-h period.

Keywords: acrolein, *Potamogeton pectinatus*, irrigation channels, weed control.

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Introduction

The irrigation district administrated by the Corporation of the Lower Valley of the Colorado River (CORFO) covers 140 000 ha in the south of Buenos Aires Province, Argentina (Fig. 1). The biggest hurdle to the proper management of water in this system is the excessive growth of the rooted submerged weed *Potamogeton pectinatus* L. The landscape is almost flat with a very slight incline (0.002%), and hence water flow is greatly impeded because of the presence of aquatic weeds. The submerged plant biomass reduces water availability for crops and increases water level in the system. Often this is also the cause of flooding. Problems caused by the weeds became a management issue in the irrigation channels in the early 1990s. Prior to the building of the Casa de Piedra dam 700 km upstream from the irrigation area, a high load of clay-suspended sediments resulted in a very turbid-reddish water (giving the name 'Colorado' to the river). As a result of the extreme light attenuation, no submerged vegetation was present in the irrigation channels at all. Since the closure of the dam in 1989, the turbidity decreased greatly because of the deposition of the clay sediment load in the reservoir. This, in turn resulted in an increase in light penetration, followed by the rapid growth of submerged macrophytes in most of the 5400-km irrigation network, dominated by *P. pectinatus*. This species undergoes an initial growth phase early in the spring (late August to September), followed by an exponential growth from October to December or February. Higher *P. pectinatus* biomass accumulation occurred during February and March, with a maximum of 1654 g dry weight (DW) m^{-2} and an absolute growth rate of 9 mg day^{-1} (Bentivegna *et al*., 2004). Every year, during winter (May to August), these channels are allowed to dry for maintenance purposes (cleaning,

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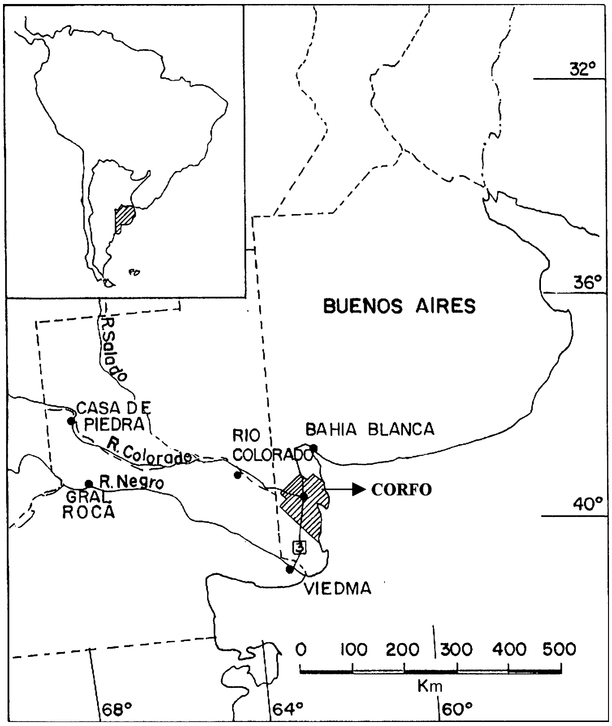

Fig. 1 Irrigation District of CORFO, in Argentina.

remodelling). New growth in spring is associated mainly with the persistence of rhizomes, tubers and seeds, which are stored in the sediment bank (Acosta *et al.*, 1999).

Until recently, the only method used to reduce aquatic plant biomass has been mechanical control with hydraulic excavators. This method is costly and slow to deal with the large areas involved. Because of the high rate of plant growth during summer, some places required repeated control two or three times during the same growing season. In addition, in some channels, the lack of proper bank facilities limits the access of heavy equipment. Under these circumstances, it was found that the injection of the aquatic herbicide acrolein (Magnacide H, active ingredient 96% acrylaldehyde, 2-propenal; Baker Petrolite, Bakersfield, CA, USA) was a low-cost alternative for reducing submerged plant biomass. In most instances, the application of acrolein led to proper water flow (Bowmer & Sainty, 1979; Bentivegna & Svachka, 1997; Bentivegna *et al.*, 1998).

Acrolein is a colourless, volatile liquid, with 22% water solubility. Because of its potential for effective weed control with only short contact times, its use is recommended for flowing systems infested with submerged vegetation (Bowmer & Sainty, 1977; Gaddis & Kissel, 1982; Fernández *et al.*, 1987a; Sidorkewicj *et al.*, 2004). It is routinely used in channels of the western United States, Australia and in Egypt (Khattab & El-Gharably, 1986). Acrolein acts as contact herbicide, reacts with sulphydryl groups on a variety of biomolecules, destroying enzyme systems and cell membranes. It kills aquatic vegetation within minutes or hours of application (van Overbeek *et al.*, 1959; Fritz-Sheridan, 1982; Hansen *et al.*, 1983; Weed Science Society of America, 1994).

Weed control operations are not restricted in the CORFO area by the need to safeguard other aquatic biota, as the system is maintained formally for irrigation and drainage purposes only. Moreover, within a few hours of treatment, the water can be used for irrigation without problems to other crops (Nordone *et al.*, 1997; Caldironi *et al.*, 2004).

The usual method of application in flowing waters is to inject acrolein at constant rate to maintain a certain concentration of the product for a certain period (Bowmer & Sainty, 1977), so that a pulse of herbicide moves downstream being absorbed by the target weeds as it passes by. The concentration of the chemical will tend to diminish with increasing distances from the point of application, up to a point at which the chemical would not be effective in terms of aquatic weed control. During this flow transport, the eventual fate of acrolein is determined by the action of several physical and chemical processes, which may influence the effectiveness of the treatments (O'loughlin & Bowmer, 1975; Bowmer & Sainty, 1977, 1979; IPCS International Programme on Chemical Safety, 1992). Scarce experimental data exist as to the extent different environmental factors of the irrigation system may influence the effectiveness of the treatments or the dissipation of the herbicide. Answers to questions of this kind would help to explain why submerged vegetation in some cases do not receive the minimum lethal dosage for adequate control, or the inconsistency of some treatments. The results of this study may help to improve the precision of the treatments, lead to a safer and more economical utilization of the herbicide and develop data for an integrated management strategy (Fernández, 1982; Fernández *et al.*, 1987a).

In this study, our aim was to determine the influence of some environmental variables on the herbicidal activity of acrolein on submerged foliage of *P. pectinatus* and on the dissipation of acrolein in the CORFO irrigation channels.

Materials and methods

The following parameters were measured at the moment of the treatments: water temperature, electrical conductivity (Hach CO150 model 50150; Hach Company, Loveland, CO, USA), pH (Hach EC10 model 50050), turbidity (Hach model 2100 P), water velocity and flow (SIAP V947; Servicio Integral de Aparatos de Precisión, Universidad Nacional de La Plata, La Plata, Buenos Aires, Argentina). Other technical data recorded were the duration of the treatments, amount of acrolein applied (litres, kg = litres × 0.847), concentration (mg L^{-1}, active ingredient) and dosage (mg L^{-1} × time) (Bowmer & Sainty, 1977). At each sampling place, weed density (per cent cover) was visually assessed using a scale from 0 (without weeds) to 9 (full, dense cover). Water depth ranged from 95 to 120 cm. The injection of the herbicide was made by qualified personnel, using a container pressurized with oxygen-free nitrogen (Baker Petrolite, 1999) to vary the dosage.

Potamogeton pectinatus submerged plant biomass was determined in three successive years, before and after the herbicide treatments to monospecific stands in 34 irrigation channels. Ten random biomass samples of 30 × 30 cm of the foliage of *P. pectinatus* were harvested at selected sites downstream from the point of injection of the herbicide, 1 day before and 7 days after the application. Plant samples were washed and dried to constant weight at 70°C. The maximum sampling distance was 3000 m, taken as the point at which the observed effect of the chemical was markedly reduced or negligible. The effects of acrolein on individual plants were evaluated by measuring the height of five plants at each sampling site during the first year and 15 plants in the second and third year (Bentivegna & Svachka, 1997).

For the dissipation studies, data were collected from 146 treatments in irrigation channels during three successive years under different conditions. The downstream concentration of the chemical was measured as a function of time at several sites along the first 5 km from the application point. The measurement was made with a colorimeter (Hach DR100) by conversion of acrolein to 2,4-dinitrophenylhydrazine (DNPH) (Smith *et al.*, 1995). With this DNPH colorimetric method, it is possible to quantify the initial concentration of acrolein applied and to track the movement of the treated water. However, it has to be taken into account that all aldehydes can give a positive colorimetric reading response, including 3-hydroxypropanal, the first-stage degradation product of acrolein. Therefore, for long-term assessments, the actual amount of acrolein might be lower than the measured values.

Dissipation was assessed by measuring the variations of the chemical concentration in the water at several locations downstream from the site of injection, as well as by the calculation of the constant rate of dissipation (K) in litres per hour. The dissipation constant (K) for each treatment was assessed using the following equation:

$$K = U \,\mathrm{Ln} \frac{C_a / C_b}{X_b - X_a}$$

where U is the average water velocity, C_a and C_b are the maximum concentration between two sites (a and b) in mg L^{-1}, and X_a and X_b are the distance from the application point (Bowmer & Sainty, 1977; Bowmer & Smith, 1984).

Multiple linear regression was used to determine the relative influence of the measured factors on the reduction in plant biomass and on the dissipation of acrolein. The dependent variable was transformed to natural logarithm to improve the fit. The selection of variables included in the model to better explain the reduction of plant biomass and the dissipation of acrolein was determined by using two methods: Forward and Backward (F:4 entrance and F:3.99 exclusion) (BMDP New System Statistical Software, 1994).

Results

The reduction of plant biomass caused by acrolein treatment varied between 30 and 50% in most instances. Nevertheless, in some cases, the effect of acrolein on the plants was almost total (94%) or practically nil, with an average value of 45.9 ± 24.4%. In general, only young plants were totally eliminated. Table 1 shows the maximum, minimum and average values used for the formulation of the equation representing the biomass reduction of *P. pectinatus*, where the dosage, water velocity and plant height explain 80% of the reduction effect [biomass reduction (g DW m^{-2}) = −36.19 + 0.85 × dosage + 124.22 × water velocity − 0.88 × plant height (R^2 = 0.80)]. Temperature, turbidity, pH, water flow, duration of treatment, conductivity and the amount of acrolein applied were of secondary importance.

Table 2 shows the maximum, minimum and average values used for the calculation of the multiple linear regression equations for acrolein dissipation. The relative importance of the variables on the dissipation process are represented in Fig. 2. The overall results show a high correlation with water flow and the concentration of acrolein, accounting for 68% of the herbicidal loss from the water system [Ln loss of herbicide (mg L^{-1} km^{-1}) = −0.59 − 1.20 × water

Table 1 Maximum, minimum and average values of the data used for the calculation of the multiple linear regression equations for *Potamogeton pectinatus* biomass

Parameters	Maximum	Minimum	Average ± SD
Biomass reduction (%)	94.1	0	45.9 ± 24.4
Plant height (cm)	101.1	14	56.7 ± 26
Water velocity (m s^{-1})	0.47	0.05	0.27 ± 0.1
Dosage (mg L^{-1} × h)	48.8	8.6	26.4 ± 10.1
Temperature (°C)	25	14	18.9 ± 2.7
Duration treatment (h)	8	2	5.3 ± 1.5
Turbidity (NTU)	85.7	7.2	32.5 ± 23
Amount of acrolein (L)	183	14	79.5 ± 42.8
Electric conductivity (mS cm^{-1})	1.25	0.77	1.04 ± 0.12
Water flow (m^3 s^{-1})	1.19	0.06	0.45 ± 0.27
pH	8.2	7.1	7.8 ± 0.3

NTU, nephelometric turbidity units.

Table 2 Maximum, minimum and average values of the data used for the calculation of the multiple linear regression equations for the dissipation of acrolein

Parameters	Maximum	Minimum	Average ± SD
Dissipation (mg L^{-1} km^{-1})	4.95	0.31	1.61 ± 0.88
Concentration (mg L^{-1})	15	2	8.9 ± 2.7
Water flow (m^3 s^{-1})	0.723	0.04	0.26 ± 0.13
Duration of the treatments (h)	12	2	6.47 ± 1.93
pH	8.26	6.84	7.67 ± 0.3
Water velocity (m s^{-1})	0.56	0.05	0.25 ± 0.09
Weed cover*	9	1	3.99 ± 1.54
Turbidity (NTU)†	85.7	2	26.8 ± 19.9
Electric conductivity (mS cm^{-1})	1.4	0.85	1.15 ± 0.13
Temperature (°C)	24	11.8	18.9 ± 2.3

*Visual scale plant density: 0, without weeds; 9, full dense cover.
†NTU, nephelometric turbidity units.

flow + 0.14 × acrolein concentration ($R^2 = 0.68$)]. Variables like the velocity of the water, conductivity, pH and duration of treatment have a lesser effect on the dissipation process, while the volume of product applied, temperature, turbidity and level of weed infestation were unimportant.

The constant rate of dissipation (K) was 0.235 L h^{-1} (SD ±0.125). The dissipation average by kilometre was 1.607 mg L^{-1} (SD ±0.884). This indicates that within < 10 km, all acrolein will be dissipated. The dissipation half-life was calculated to be around 9 h.

Discussion

The results of this study showed that the main parameters which determine the efficacy of acrolein in the CORFO irrigation systems for the control of *P. pectinatus* fall into three main types: (i) the direct toxic effects caused by dosage, (ii) the effect of some environmental components of the aquatic system influencing toxicity and dissipation of the chemical and (iii) plant growth at the moment of the treatments. Figure 3 shows a conceptual model of the interactions involved in the use of acrolein for the control of aquatic weeds in irrigation systems.

Multiple linear regression results of the data indicated that plant height is a significant factor when considering susceptibility to acrolein. Bentivegna and Svachka (1997) reported a major reduction of plant biomass when the plants were < 45 cm in height; only plants below that size were totally eliminated (Bentivegna *et al.*, 2004). Previous studies of Fernández *et al.* (1987a,b) in drainage channels of the same irrigation system attest that *P. pectinatus* at the initiation of their growth cycle in spring is less tolerant to acrolein than mature plants. It is evident that plant growth plays an important role in the susceptibility of *P. pectinatus* to acrolein applications. Hence, the minimum effective dosage would be variable, dependent on the susceptibility that the target plant displays throughout the annual growth cycle. If no other seasonal factors are limiting (e.g. temperature), lower dosages of acrolein would be required for the control of *P. pectinatus* early in the season.

A component affecting the effectiveness of the treatments, to be taken into consideration, is water velocity. A general recommendation is to apply the herbicide between water velocities of 0.44 and 0.88 m s^{-1} (Magna Corporation, 1981, 1984). Thus, the maximum downstream water velocity registered in this study (0.47 m s^{-1}) was near the lower limit recommended. Nevertheless, diminishing flow rates from this maximum local value were positively correlated with less-efficient treatments. It is apparent that for each situation there are a range of water velocities which are the most effective, below or above which it will be necessary to increase the concentration of the product and/or the duration of the treatments. For higher water velocities, the flattening of the plant foliage against the bottom of the channels lessens the chance of herbicide contact with the plant tissue. In addition, when a high plant density also occurs, the herbicide solution is channelled amid the plants. The result is a non-homogeneous distribution of the chemical within the channel profile; part of the submerged foliage is not in contact with the minimum amount of acrolein needed for an effective response. In the case of very low water velocities, the limited advance of the herbicide wave results, in most cases, in a reduction in the effective distance of control from the point of injection. It is postulated that as acrolein is lighter than water, the lack of turbulence facilitates the floating of the chemical on the water surface and its volatilization. Other reasons for reduced efficacy associated with a slow water flow would be the adsorption of the chemical into the many components of the aquatic ecosystem.

The most important variables in the dissipation of acrolein were the concentration of acrolein and the water flow. Acrolein is known to hydrolyse rapidly in water, with first-order kinetics, resulting in the production of various short-lived non-toxic metabolites (Bowmer & Higgins, 1976; Nordone *et al.*, 1996a,b). The results of our study indicate that higher dosages corresponded to higher amounts of acrolein dissipated. Other researchers have reported that the dissipation increases considerably when acrolein it is applied at low concentrations (2–3 mg L^{-1}) in low-flowing water because of adsorption and volatilization (Bowmer *et al.*, 1974; Bowmer & Higgins, 1976).

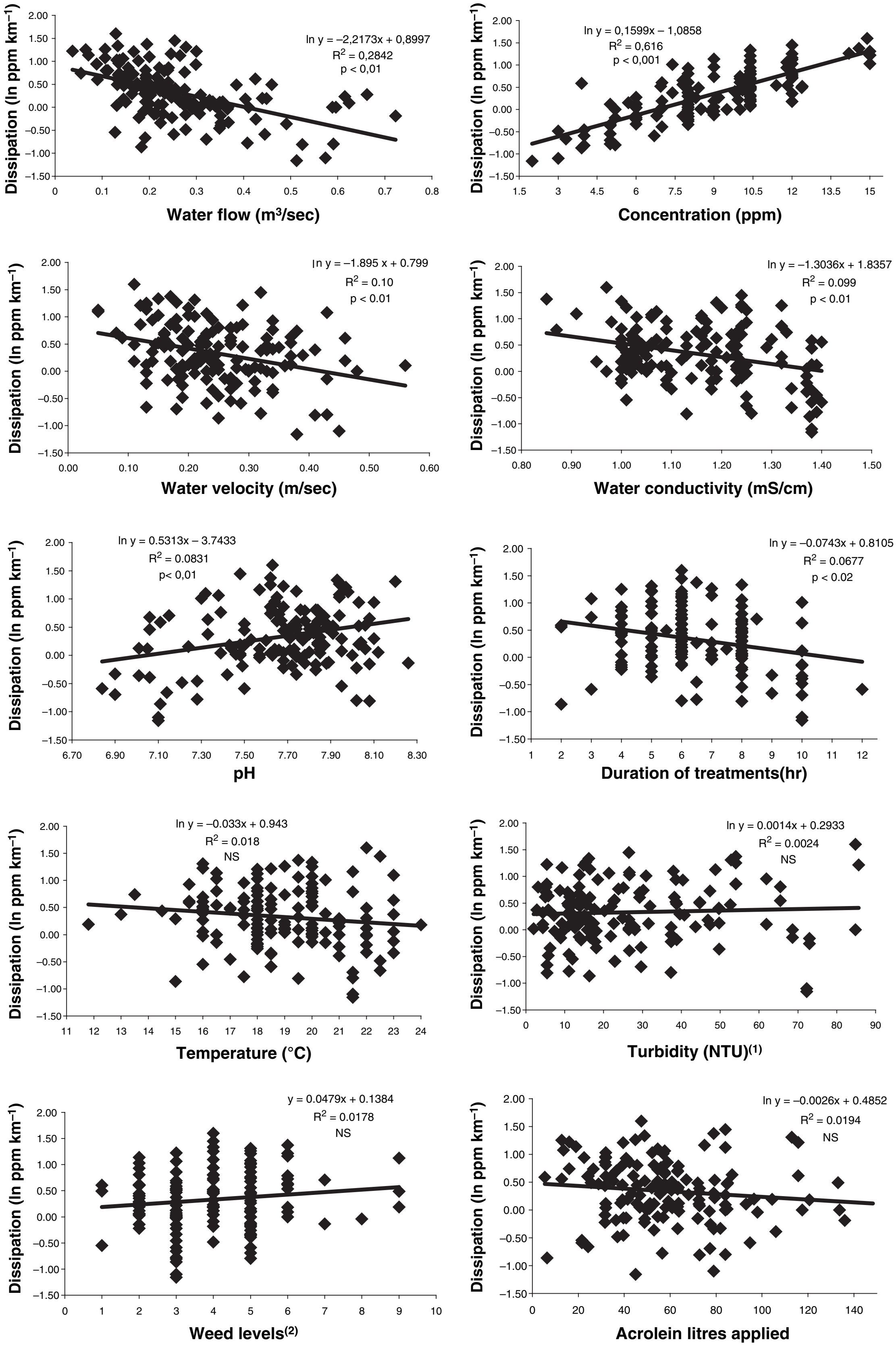

Fig. 2 Linear regression values for the dissipation of acrolein as affected by water flow, concentration, water velocity, water conductivity, pH, duration of treatments, temperature, turbidity, weedy level and litres of acrolein applied. [1]NTU: Nephelometric Turbidity units. [2]Visual scale plant density: 0 – without weeds; 9 – full dense cover.

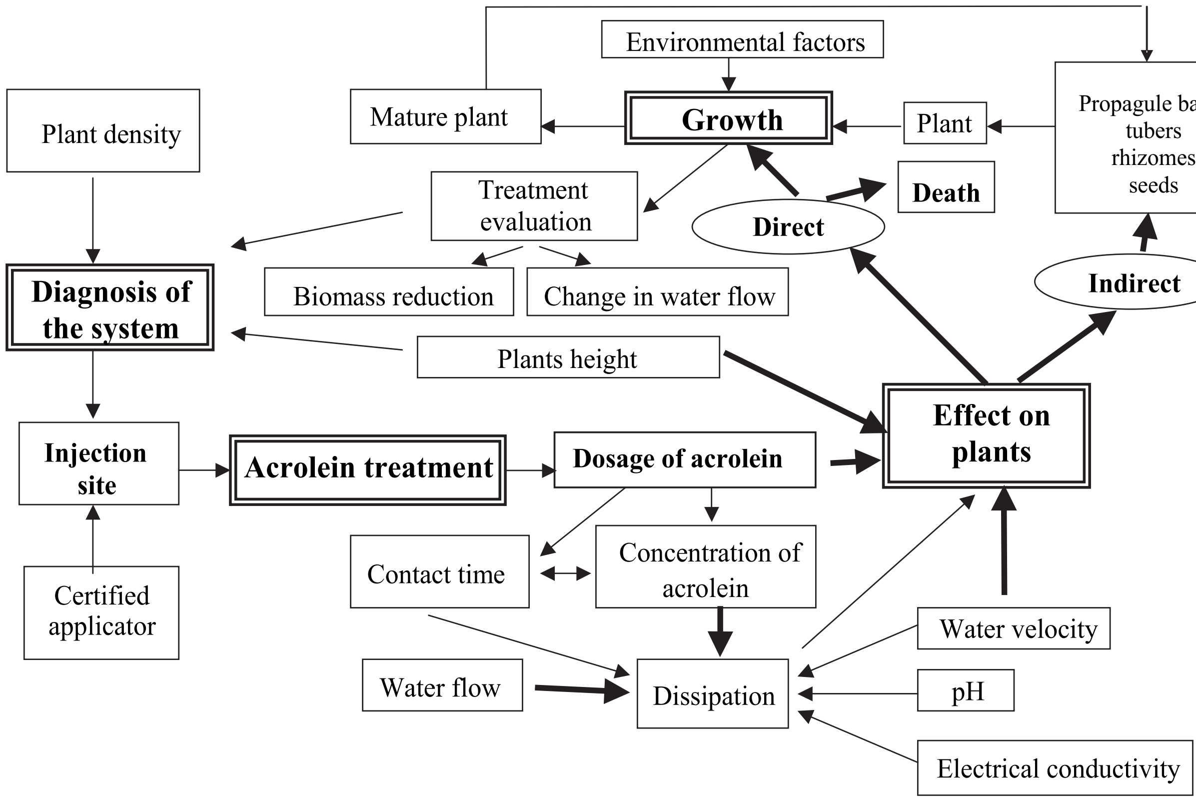

Fig. 3 Conceptual model of the interactions involved in the application of acrolein in irrigation systems. Main effects are indicated by thick lines.

Water velocity, electrical conductivity, pH and duration of the treatment have a minor influence on the dissipation of acrolein. However, high pH and salinity are factors capable of reducing the effectiveness of acrolein (Magna Corporation, 1981); none of the parameters in this study were within the limits to interfere with the herbicide. The temperature at ≤15°C reduces the solubility of acrolein (Baker Petrolite, 1999). However, treatments in this study were always applied when the temperature of the water exceeded 15°C.

Within the range registered in the canals, water turbidity was not an important factor in the dissipation process. A satisfactory aquatic weed control was reported in muddy waters by Bowmer and Smith (1984). Other results (Nordone *et al.*, 1996a), indicate that an increase in turbidity may result in higher volatilization of the chemical. Moreover, the amounts of weed cover or volume of herbicide applied have no significance in the dissipation of acrolein. Other studies have reported greater herbicidal losses as a result of short-time treatments (Bowmer & Smith, 1984).

The dissipation rate for acrolein found in this study (as indicated by the concentration of aldheyde) implies that the chemical will disappear from the system in < 24 h of application. Other researchers have registered values ranging from the same to two times quicker than this (Bowmer & Higgins, 1976; Bowmer & Sainty, 1977).

As a practical guideline for the control of mature, dense stands of *P. pectinatus* within the irrigation system under study, our results indicate the following conditions to be optimal: flow volumes of ≥500 L s^{-1}, water velocity of ≥0.42 m s^{-1} and *c.* 6.5 mg L^{-1} concentration of acrolein for at least an 11-h period. Treatment of younger plants early in the growing season is likely to yield highly effective results. Variations around the quoted values for any particular situation should allow the operator to improve the precision of the treatments, maximizing the impact on the target weed.

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References

Acosta LW, Sabbatini MR, Fernández OA & Burgos MA (1999) Propagule bank and plant emergence of macrophytes in artificial channels of a temperate irrigation area in Argentina. *Hydrobiologia* **415,** 1–5.

Baker Petrolite (1999) *Magnacide®* H Manual de aplicaciones y seguridad. Baker Petrolite, Bakersfield, CA, USA.

Bentivegna DJ & Svachka O (1997) Control de *Potamogeton pectinatus* L. con acroleína en canales de riego del valle inferior del Río Colorado, Argentina. In: *Proceedings 1997 XIII Congreso Latinoamericano de Malezas*, Buenos Aires, Argentina, 275.

Bentivegna DJ, Sabbatini MR, Curvetto NR & Fernández OA (1998) Effect of acrolein on *Potamogeton pectinatus* L. in irrigation channels. In: *Proceedings 1998 10th European Weed Research Society International Symposium on Aquatic Weeds*, Lisboa, Portugal, 319–322.

Bentivegna DJ, Fernández OA & Burgos MA (2004) Acrolein reduces biomass and seed production of *Potamogeton pectinatus* in irrigation channels. *Weed Technology* **18,** 605–610.

BMDP New System Statistical Software (1994) *BMDP New System for Windows Users Guide*, Version 1.1. University of California Press, Berkeley, CA, USA.

Bowmer KH & Higgins ML (1976) Some aspects of the persistence and fate of acrolein herbicide in water. *Archives of Environmental Contamination and Toxicology Management* **5,** 87–96.

Bowmer KH & Sainty GR (1977) Management of aquatic plants with acrolein. *Journal of Aquatic Plant Management* **15,** 40–46.

Bowmer KH & Sainty GR (1979) Management of *Elodea* in Australian Irrigation System. *Journal of Aquatic Plant Management* **17,** 4–12.

Bowmer KH & Smith GH (1984) Herbicides for injection into flowing water: acrolein and endothalamine. *Weed Research* **24,** 201–211.

Bowmer KL, Lang ARG, Higgins ML, Pillay AR & Tchan YT (1974) Loss of acrolein from water by volatilization and degradation. *Weed Research* **14,** 325–328.

Caldironi HA, Bentivegna DJ & Rhea MR (2004) Irrigation of pepper plant (*Capsicum* sp.) with water containing acrolein. *Agricultural Water Management* **67,** 235–240.

Fernández OA (1982) Manejo integrado de malezas. *Planta Danhina* **5,** 69–79.

Fernández OA, Irigoyen JH, Sabbatini MR & Brevedan RE (1987a) Aquatic plant management in drainage canals of Southern Argentina. *Journal of Aquatic Plant Management* **25,** 65–67.

Fernández OA, Irigoyen JH, Sabbatini MR & Svachka O (1987b) Recomendaciones para el control de *Potamogeton pectinatus* y *Chara contraria* en distritos de riego. *Malezas* **15,** 5–46.

Fritz-Sheridan RP (1982) Impact of herbicide Magnacide-H (2-propenal) on algae. *Bulletin Environmental Contamination Toxicology* **28,** 245–249.

Gaddis CW & Kissel CL (1982) Acrolein in irrigation waterways. In: *Proceedings 1982 6th European Weed Research Society Symposium on Aquatic Weeds*, Novi Sad, Yugoslavia, 164–170.

Hansen GW, Oliver FE & Otto NE (1983) Controlling weeds and aquatic-fouling organisms with herbicides and antifoulants. In: *Herbicide Manual*, 97–168. Water Resources Technical Publication. US Department of Interior, Denver, CO, USA.

IPCS International Programme on Chemical Safety (1992) Acrolein. *Environmental Health Criteria* **127,** 119.

Khattab AF & El-Gharably Z (1986) Management of aquatic weeds in irrigation systems with special reference to the problems of Egypt. In: *Proceedings 1986 7th International Symposium on Aquatic Weeds*, Loughborough, UK, 199–206.

Magna Corporation (1981) *Herbicida Magnacide H. Manual de aplicación de tambores*. Magna Corporation, Bakersfield, CA, USA.

Magna Corporation (1984) Magnacide H, herbicide. In: *Product Data Bulletin*. Herbicide Division. Magna Corporation, Bakersfield, CA, USA.

Nordone AJ, Matherly R & Bonnivier B (1996a) The mobility and degradation of acrolein in agricultural canals treated with Magnacide® H herbicide. *Chemosphere* **32,** 807–814.

Nordone AJ, Matherly R & Bonnivier B (1996b) Effect of Magnacide H® herbicide residuals on water quality within wildlife refuges of the Klamath Basin, CA. *Bulletin Environmental Contamination and Toxicology* **56,** 964–970.

Nordone AJ, Kovacs MF & Doane RA (1997) [^{14}C] Acrolein accumulation and metabolism in leaf lettuce. *Bulletin of Environmental Contamination and Toxicology* **58,** 787–792.

O'loughlin EM & Bowmer KH (1975) Dilution and decay of aquatic herbicides in flowing channels. *Journal of Hydrology* **26,** 217–235.

van Overbeek J, Huges WJ & Blondeau R (1959) Acrolein for the control of water weeds and disease-carrying water snails. *Science* **129,** 335–336.

Sidorkewicj NS, Sabbatini MR, Fernández OA & Irigoyen JH (2004) Aquatic weeds. In: *Weed Biology and Management* (ed Inderjit), 115–135. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Smith AM, Mao J, Doane RA & Kovacs MF Jr (1995) Metabolic fate of [^{14}C] acrolein under aerobic and anaerobic aquatic conditions. *Journal of Agricultural and Food Chemistry* **43,** 2497–2503.

Weed Science Society of America (1994) Acrolein (2 propenal). In: *Herbicide Handbook*, 7th edn (ed. WH Ahrens), 7–9. Weed Science Society of America, Champaign, IL, USA.