J. Aquat. Plant Manage. 17: 4-12

Management of Elodea in Australian Irrigation Systems

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ABSTRACT

The occurrence, adverse effects, and control of elodea (*Elodea canadensis* Rich.) in the irrigation systems of South East Australia are described. Eradication of new infestations by soil-residual herbicides has been attempted, but the disadvantages of phytotoxic concentrations of 2,3,6-trichlorophenylacetic acid (chlorfenac) in irrigation water, and the high costs of 2,6-dichlorobenzonitrile (dichlobenil) have limited this approach. Obstructive weed growth in canals is temporarily controlled by injection of herbicides—acrylaldehyde (acrolein), aromatic solvents or ammonia—into flowing water; however major research emphasis is being placed on finding more economical and more permanent controls. Injections of high concentrations of 2-tert-butylamino-4-ethylamino-6-methylthio-1,3,5-triazine (terbutryn) for several hours (8.3 ppm for 2.4 hr; 1.1 ppm for 22 hr) were not successful; neither was the treatment of static water (1.0 ppm) when displaced with fresh water after 7 days. Other treatments which would be economical for smaller irrigation canals in Australia include short-time, high-concentration injections of the alkylamine salt of 7-oxabicyclo[2,2,1] heptane-2,3-dicarboxylic acid (endothal) and application of 2-chloro-4,6-di(ethylamino)-1,3,5-triazine (simazine) after channel drainage. For reasons of convenience, economy and safety, acrolein appears to be the only herbicide suitable for larger irrigation canals at present. However 'placement techniques' and slow-release formulations (e.g., with alginates, polymers or invert emulsions) may make possible the use of other herbicides in the future.

INTRODUCTION

Elodea (Figure 1) a native plant of North America, was first noticed in the irrigation systems of South Eastern Australia (Figure 2) about 20 years ago. It has spread rapidly by vegetative means, and is particularly troublesome in the larger supply and drainage canals which carry water throughout the irrigation season, spreading rapidly by stem fragmentation.

The distribution of elodea in Australia has been described by Aston (6) and the subject has been reviewed recently by Mitchell (35).

HISTORY AND DISTRIBUTION

Elodea was first observed in the River Murray near Yarrawonga in 1957-8 and now infests an area there of about 2,500 km^2. It was observed near the Torrumbarry River about 150 km downstream of Yarrawonga in about 1962-3, and began to spread rapidly through that system about 8 years later.[1]

In New South Wales it was first observed in major canals in the Berriquin Irrigation District in 1958. The following year mechanical methods which were used for control, assisted establishment by fragmentation and dispersal in the flowing water. The area of infestation gradually increased until, by 1963-4, elodea occurred throughout the District, sometimes reducing channel capacities up to 60%. In 1960, it was observed near Deniliquin, and during the following 4 years these Districts became heavily infested. It now occurs throughout the Deniboota, Denimein, and Wakool Districts, which are supplied with water from the River Murray, and the Tullakool Irrigation Area which is also supplied from the Edward River.

Chemical control began in the Berriquin Irrigation District in 1963, in the Denimein and Deniboota Districts in 1965, and in the Wakool District in 1968. Of the 1500 km of irrigation channels there, approximately 900 km are treated annually with acrolein and with smaller quantities of aromatic solvents and anhydrous ammonia. Elodea appears to have displaced the native flora in the Murray Valley system, and is now the dominant submerged species.

Elodea was first recorded in the Murrumbidgee system in 1973 when it appeared in the Coleambally Irrigation Area (CIA). Eradication was achieved by judicious application of chlorfenac and dichlobenil, but re-invasion has recently occurred. In 1974, elodea appeared in the Murrumbidgee River and the Murrumbidgee Irrigation Areas (MIA), and has now become well-established within the existing complex association of submerged native plants which includes several species of pondweeds (*Potamogeton tricarinatus* F. Muell, & A. Benn., *P. perfoliatus* L., *P. crispus* L., *P. ochreatus* Raoul), ribbonweed (*Vallisneria* spp.), filamentous algae, and the partly-emergent milfoils (*Myriophyllum propinquum* A. Cunn., *M. elatinoides* Gaudich., *M. verrucosum* Lindl.).

ECOLOGY

Elodea invaded European waterways in the last half of

[1]L. Jackel, State Rivers and Water Supply Commission, Rochester, Victoria. Report to Irrigation Research and Extension Committee, Elodea Co-ordination Control Subcommittee, Griffith.

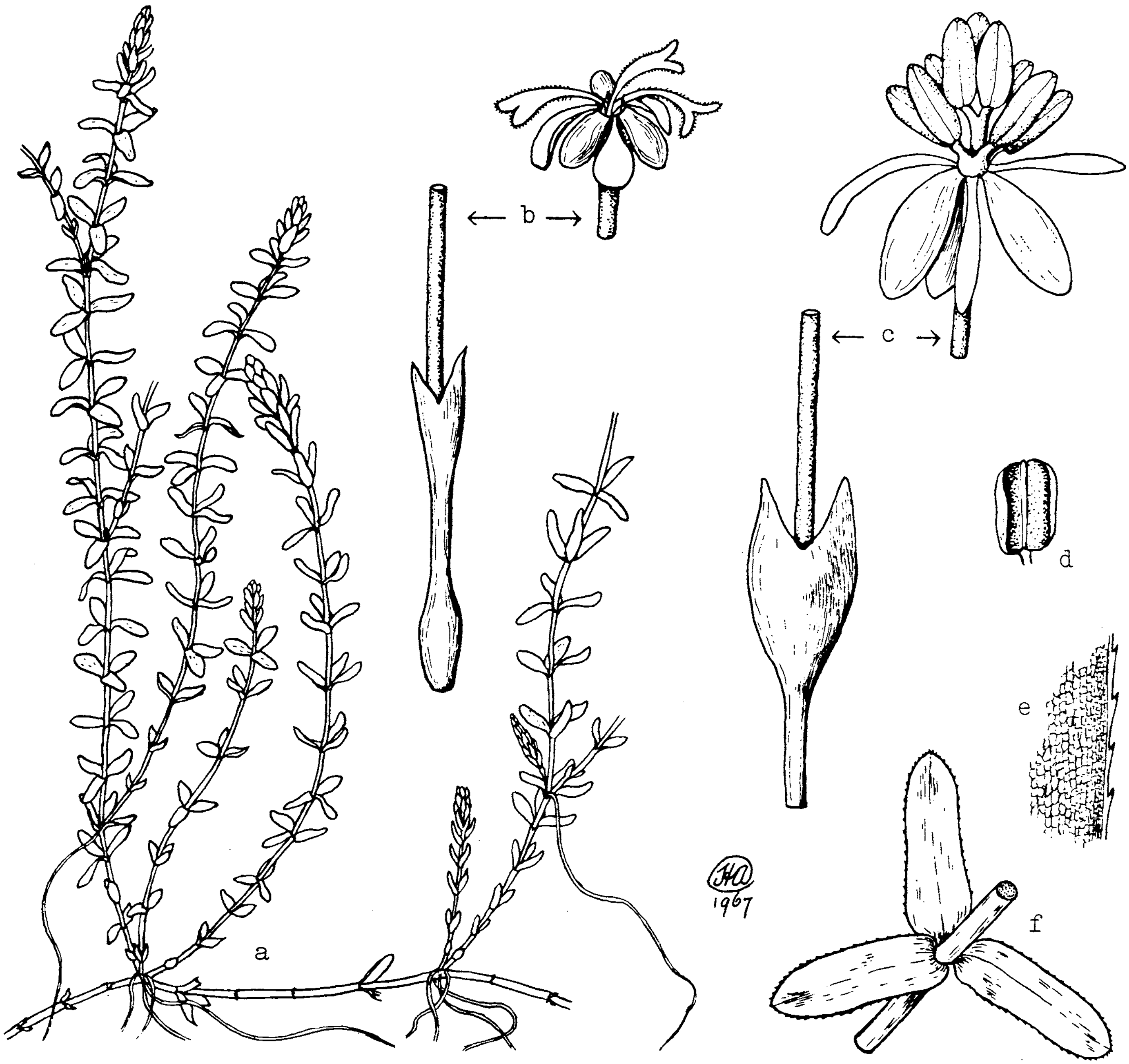

Figure 1. *Elodea canadensis:* (a) habit, x0.8; (b) female flower and spathe (portion of hypanthium omitted), x4; (c) male flower and spathe (portion of hypanthium omitted), x4; (d) dehisced anther showing each locule forming only one valve, x4; (e) portion of leaf margin, x24; (f) whorl of leaves, x4. From Aquatic Plants of Australia by Helen I. Aston (Melbourne University Press, 1973)—reproduced with permission.

the 19th century, exhibiting spectacular increases in distribution. There, a period of abundance lasting up to 5 years in a particular locality was followed by a phase of decline (43). It appears that the phase of decline has not yet occurred in Australia, although elodea has been well-established in some localities for nearly 15 years.

Elodea is a submerged perennial plant which thrives in temperate climatic zones. In Australia, the plant survives the winter in moist situations in a semi-dormant state in which the leaves are densely-crowded on the apices. Vigorous growth occurs in September and October when temperatures reach 15 C and continues rapidly as temperatures increase to about 25 C, until February-March.

Some of the conditions reported to be favourable for successful colonization include a silty rather than a sandy substrate (43, 48) and the availability of nutrients, including bicarbonate as a carbon source (44) and a supply of iron in the reduced form (38).

Steer and Higgins[2] have analysed previous data on the

[2]B. T. Steer and M. L. Higgins. Ion concentrations and phytoplankton numbers in waters of the Murrumbidgee Irrigation Areas, N.S.W. CSIRO Division of Irrigation Research. Unpublished Report.

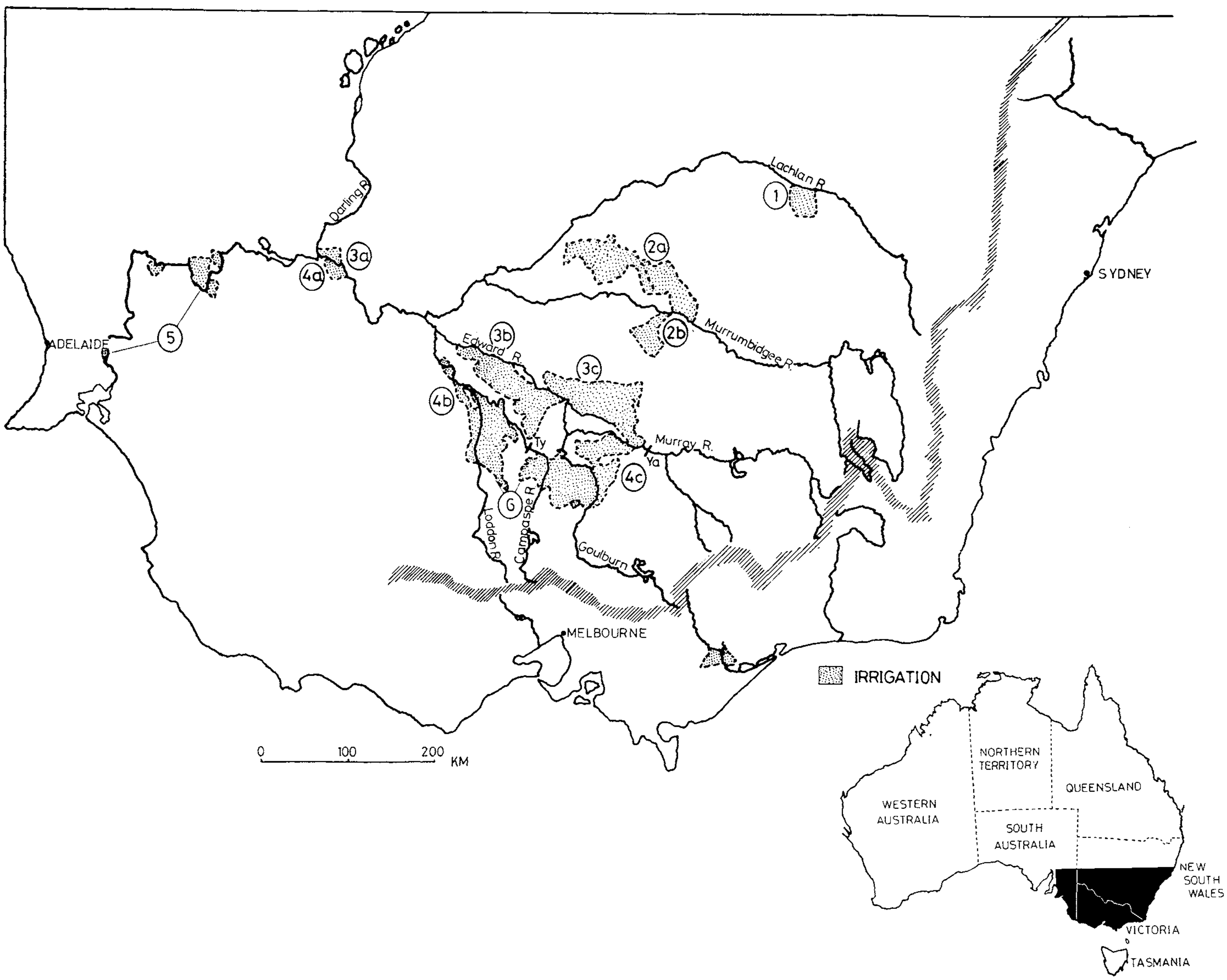

Figure 2. Major irrigation systems of South East Australia (3, 4, 32) 1. Lachlan River, 13,000 ha, 2. Murrumbidgee River (2a. Murrumbidgee Areas, 131,000 ha, 2b. Coleambally, 29,000 ha). 3. Murray River in New South Wales (3a. 4,000 ha, 3b. Wakool-Tullakool-Deniboota, 57,300 ha, 3c. Denimein-Deniboota, 34,000 ha), 4. Murray River in Victoria (4a. 18,600 ha, 4b. from Torrumbarry Weir, 110,000 ha, 4c. from Yarrawonga Weir, 59,000 ha), 5. Murray River in South Australia, 23,500 ha, 6. Loddon-Campaspe and Goulburn Rivers, 262,000 ha. Total including private diversions, 1,169,000 ha.

quality of MIA water (17, 21), and comment that the anionic balance differs from world average fresh water (19), and many other Australian waters (52), in that bicarbonate dominates sulphate and chloride concentrations. Higgins (27) reports plentiful supplies of iron in submerged MIA soils, but the role of iron as a limiting nutrient is now being further investigated.

Some data are available on the nitrogen and phosphorus concentrations in the River Murray (2) and Murrumbidgee irrigation systems (5, 31, 46, 47) which show that nutrient levels are relatively high. However, turbidity and colored material (gilvin) may attenuate most of the photosynthetically active radiation at depths of 1.5 to 2.0 m (29, 30) thus reducing productivity.

Observations in New Zealand show that elodea displaces native species in the Rotorua Lakes (18) and is in turn displaced by lagarosiphon (*Lagarosiphon major* (Ridley) Moss). Brown *et al.* (15) report that the dominance of elodea is reduced in the Waikato River as waters become less transparent. They comment that these changes might well relate to relative photosynthetic capacities, and show that under laboratory conditions elodea is a relatively light-demanding species compared with lagarosiphon. The compensation point of elodea fragments at pH 8 was 130 μeinsteins m^{-2} sec^{-1} and light saturation was greater than 600 μeinsteins m^{-2} sec^{-1}. However, Brown[3] notes that elodea is an ecological paradox in New Zealand lakes, demanding high light intensity but also plentiful nutrients, so it usually occupies more turbid lakes than lagarosiphon.

In comparison, a compensation point of 9 μeinsteins m^{-2} sec^{-1} and light saturation of 300 μeinsteins m^{-2} sec^{-1} have been reported (29) for cut leaves of ribbonweed and curly pondweed (*P. crispus*) so that attenuation of light would

[3]J. M. A. Brown, Botany Department, University of Auckland, N.Z. Personal Communication.

disadvantage elodea compared with these Australian native species. However, as suggested by Brown's observations in New Zealand this disadvantage may be outweighed in Australia by the availability of nutrients, allowing the successful colonization of irrigation waters with elodea.

The European carp (*Cyprinus carpio* L.) spread rapidly throughout the irrigation systems in the mid-1960's[4]. Its importance in eroding silty sediments, increasing turbidity and aiding spread by fragmentation has been reviewed by Butcher[5].

MANAGEMENT COSTS

Elodea is extremely obstructive in irrigation canals, and since the supply of water for rice and other crops is critical, it is regarded as a threat to agricultural production. In the MIA and CIA alone the return to growers from rice exceeds 32 million Australian dollars[6] while other water-demanding crops contribute another 34 million dollars.

The total annual cost of control with herbicides, including application, in the Murray Valley Districts is estimated at \$A140,000, excluding growers' costs of maintaining the smaller on-farm channels. If elodea becomes widespread in the Murrumbidgee system it is anticipated that there will be an additional cost of similar order.

[4] K. D. Shearer, Inland Fisheries Research Station, New South Wales State Fisheries. Personal Communication.

[5] Victoria Fisheries and Wildlife Department. 1962. The implications of the introduction of European carp into Victorian waters. Report presented to the State Development Committee, pp. 16-22.

[6] \$A1 = \$US1.18 (30 October, 1978).

Previously the MIA's main supply canal, with a capacity of 5000 megaliters day^{-1} and length of 150 km, was used as a reservoir for the storage of potable water. A secondary consequence of the infestation of elodea is the 1.3 million dollars required for the construction of additional storages.

CONTROL METHODS

Mechanical, Cultural and Biological Techniques. Elodea is not effectively controlled by non-chemical methods. Because of high labour costs and low efficiency of mechanical removal, the use of excavating machines is only warranted for desilting and remodelling channels. Also, mechanical control fragments the plants and aids further spread.

Elodea is able to recover from the effects of fluctuating water levels (36). However, control is aided by draining and exposure of sediments to high summer temperatures or winter frosts (45), but this is not always effective and is not feasible in the larger canals.

There has been little progress on the biological control of submerged weeds in Australia (e.g. with fish), apparently because of the difficulty of evaluation, except by large scale field releases, and the fear of adverse effects on wildlife.

Chemical Control. Herbicides reported to control elodea are listed in Tables 1 to 3 but some are unsuitable for Australian situations. Their suitability may be illustrated by considering their application in typical supply channels (Table 4). The small farm channel, A, is the responsibility of the grower; the spur-channel, B, and the major irrigation supply canal, C, are situated in the Berriquin Irrigation Dis-

TABLE 1. HERBICIDES REPORTED TO CONTROL ELODEA IN FLOWING WATER.

Herbicide (formulation)	Active ingredient per unit discharge[a] (kg per megaliter day^{-1})	Treatment conditions		Distance treated[b] (km)	Cost per unit discharge[c] (\$A per megaliter day^{-1})	References
		Concentration (ppm)	Contact time (hr)			
Acrolein	1.2-3.6	15 (max)	1.9-5.8	2.1-21	4.2-12.6	1,42
Aromatic solvent and emulsifier	12-15	670-860	0.5	1-3	7.2-9.4	42
Anhydrous ammonia	10	700	0.33	~0.3	3.6	41,42[d]
Copper sulphate dumped	0.3-0.6[e]	>8[ef]	0.01	137	0.8-1.6[f]	42[g]
continuous	9.3-18.6[e]	0.1-0.2[ef]	∞	15	25-50[f]	10,42
Cyanatryn (slow-release pellets)	1.0	0.01-0.05[h]	>240	na	nfs	25,39
Endothal-alkylamine (liquid)	0.08-0.42[i]	1-5[i]	2	na	1.3-6.5	[j]
	0.2[i]	1.6[i]	3	>30	3.1	40
Terbutryn (granules)[k]	0.05-0.1	0.05-0.1[h]	na	na	nfs	20
(flowable)	>1.0[l]	>1	>24	na	>15	[l]

[a] Flowing water: one megaliter day^{-1} is equivalent to 0.41 cfs; 1.0 kg of herbicide per megaliter day^{-1} is equivalent to an injection of 24 ppm for 1 hr. Static water: one megaliter is equivalent to 1 ha of water 10 cm deep.

[b] Depends on average velocity.

[c] \$A1 = \$US1.18. October, 1978.

[d] Reference to control of submerged aquatic species, although not elodea specifically.

[e] As metallic copper.

[f] Application rates and cost are calculated on the basis of 'continuous' treatment for an irrigation season of 100 days. Seven 'dumped' treatments are assumed, one every 2 weeks.

[g] G. D. Nielson. 1967. See footnote, page 9.

[h] Variable during treatment as granules or pellets dissolve.

[i] As acid-equivalent.

[j] Pennwalt Corporation.

[k] Only slow release granules are approved in Europe.

[l] Conditions required for control have still to be established. Static water trials (see text) suggest that these conditions are minimal.

[m] M. J. Hood and G. R. Sainty. 1967. Unpublished Data. Geigy Australia Pty. Ltd.

[n] For all flowing water treatments, Canal C treated at a reduced discharge of 200 megaliters day^{-1} as described for acrolein injection (see text). 7 injections of aromatic solvents and 66 injections of anhydrous ammonia were needed.

[o] Price is based on liquid flowable formulation available in Australia.

na not available

nfs not for sale in Australia

TABLE 2. HERBICIDES REPORTED TO CONTROL ELODEA IN PONDED WATER.

Herbicide (formulation)	Concentration (ppm)	Cost per megaliter[c] ($A) (1 ha of water 10 cm deep)	Reference
Ametryn (granules)	1.7[h]	19[o]	24
Anhydrous ammonia	18	7	41[d]
Copper sulphate	1.3-10[e]	3-27	34
Cyanatryn (slow-release pellets)	0.05[h]	nfs	25,39
Diquat	0.25-1	13-50	42
Endothal-alkylamine (liquid)	1-5[i]	16-77	j
Simazine (wettable powder)	0.5-5	4-38	7,22
Terbutryn (wettable powder or granules)	0.02-0.5	0.2-7.7[o]	7,20,33,49[k]
Hexazinone (wettable powder)	0.1-1.0	3-53	23[d]

For explanation of footnotes, see Table 1.

TABLE 3. SOIL-RESIDUAL HERBICIDES USED AFTER DRAINAGE TO CONTROL ELODEA.

Herbicide	Treatment (kg ha^{-1})	Cost per ha[c] ($A)	Reference
Chlorfenac (liquid)	17-22[i]	265-345	42[m]
Dichlobenil (granules)	10-20	259-517	13,42
Simazine (wettable powder)	30-60	225-500	22,24

For explanation of footnotes, see Table 1.

trict of southern New South Wales (Figure 2) and are administered by the Water Resources Commission. These channels illustrate the extremes in velocity which are encountered in supply channels. However, the average velocity in many of the smaller channels is about 0.1 m s^{-1}. The extent of weed infestations vary considerably with situation and time. Drainage channels, which are also treated, are even more variable in character, since they carry surplus water from the supply system, tile-drainage and run-off in largely unpredictable quantities.

The relative costs of herbicide treatments for these typical situations are listed in Table 5. This is not to imply that economy is the sole criterion for selection. Environmental considerations may preclude some treatments in similar channels, depending on location, because when herbicides are used in supply systems it is important that contaminated water does not reach irrigated crops. This is achieved either by the use of acrolein which is rapidly dissipated from the water, or by the discharge of contaminated water to the drainage system, or onto tolerant crops or fallow land when more-persistent herbicides are used. Movement of herbicides away from the treated area must be strictly regulated. The MIA's drainage water is re-used for irrigation, livestock-watering and domestic purposes, partly by

TABLE 4. TYPICAL CANAL DIMENSIONS.

Canal	Discharge (megaliters day^{-1})	Ponded volume (megaliters)	Length (km)	Width (m)	Area (ha)	Velocity (m s^{-1})	Travel time (hr)
A Griffith 2533-1	5	2	1.2	3	0.36	0.037	9
B Berrigan 6C	11	5	1.0	3	0.30	0.025	11
C Berrigan Main	735	490	20	27	54	0.34	16

TABLE 5. RELATIVE COSTS OF HERBICIDE TREATMENTS FOR CONTROL OF ELODEA IN THREE TYPICAL CANALS. (SEE TABLE 4)

Type of Treatment	Herbicide	Rate[a]	Cost ($A)[c] Canal A	Canal B	Canal C[n]
Flowing water (kg per 10^6 l. day^{-1})	Acrolein	1.2	21	46	840
	Aromatic solvents	12	36	79	~10,000
	Anhydrous ammonia	10	72	119	~47,500
	Copper sulphate 'dumped'[f]	0.6[e]	8	18	320
	'continuous'[f]	18.6[e]	250	550	~10,000
	Endothal-alkylamine (liquid)	0.2	16	34	620
	Terbutryn (flowable)	>1.0	>75	>165	>3,000
Ponded water (kg per 10^6 l., equivalent to kg ha^{-1}, 10 cm deep)	Ametryn (flowable)	1.7	38	95	9,310
	Anhydrous ammonia	18	13	32	3,175
	Copper sulphate	2[e]	11	27	2,626
	Diquat	0.25	25	63	6,125
	Endothal-alkylamine	2[i]	64	160	15,680
	Simazine (wettable powder)	5	76	190	18,620
	Terbutryn (flowable)	1.0	31	77	7,546
	Hexazinone (wettable powder)	1.0	107	167	16,333
Soil-residual (kg ha^{-1})	Chlorfenac (liquid)	20[i m]	112	93	16,800
	Dichlobenil (granules)	20	186	155	27,918
	Simazine (wettable powder)	30	81	68	12,150

For explanation of footnotes, see Table 1.

direct diversion and partly after storage and dilution in a natural drainage basin, and water from the CIA and Murray Valley Irrigation Districts drains eventually to the River Murray system (Figure 2).

Of herbicides listed for use in flowing water (Table 1), acrolein, aromatic solvents and anhydrous ammonia are used routinely for effective management of elodea in Australia, and 4-(1-cyano-1-methylethylamino)-6-ethylamino-2-methylthio-1,3,5-triazine (cyanatryn), endothal-alkylamine, terbutryn and copper sulphate have been used experimentally.

Although herbicides used in ponded or static water (Table 2) are well-reported in the literature, they have seldom been used in Australian irrigation systems because of the continual demand for water during summer and the problems of relatively-persistent residues. Terbutryn and 1,1′-ethylene-2,2′-bipyridylium ion (diquat) have been used on an experimental basis. Long-term control and eradication of elodea has been achieved with the soil-residual herbicides chlorfenac and dichlobenil (Table 3).

Emphasis on Treatments for Flowing Water. The current emphasis is on the use of short-persistence herbicides which can be injected into flowing water. Aromatic solvents containing xylene isomers and emulsifiers are useful in smaller channels. These treatments are relatively economical (Table 5) but prices are rapidly increasing. They are not used extensively by state authorities for larger channels since booster injections are required every 1 to 4 km (42).

Anhydrous ammonia has been used extensively in India (41) but since booster additions are required every 0.3 km (42) its use in Australia is limited to the smallest channels.

State authorities use relatively large quantities of acrolein to treat submerged weeds in about 4000 km of canals and channels every year. Large weed infestations are treated quickly and injecting the herbicide into flowing water results in minimum interruption to growers downstream.

Acrolein, however, is extremely toxic to fish so movement of contaminated water must be regulated carefully. Water supplied to growers should be free of herbicides so the delivery of water is restricted for 48 hr after treatment, assuming this to be adequate for the concentration in the water to be reduced to safe levels.

In laboratory experiments, it was found that acrolein reacted rapidly with water to produce non-toxic products (12). In the irrigation canals additional losses, probably by evaporation and uptake by weeds and sediment, further reduced the residual acrolein (37). Measurements in several typically weedy canals in the Murrumbidgee and Murray irrigation systems gave consistent results; approximately half the acrolein was removed from the water in 4 hr (14). This information was used to calculate the additions of booster quantities of acrolein required for weed control downstream and also to confirm that water supplied to growers would be virtually free of acrolein.

The quantity of acrolein required at the injection point may be calculated (14) from data on the minimum lethal dosage required at the downstream limit of the weed infestation, the average velocity of the water, and the first order rate constant of decay (0.16 hr^{-1}). For the typical channels described in Table 4 (assuming a minimum lethal dosage downstream equivalent to a concentration of 1 ppm for a contact time of 2 hr) additions of 0.36, 0.50 and 1.13 kg per megaliter day^{-1} would be required for canals A, B and C, respectively, compared with accepted recommendations[7,8] of 1.2 to 3.6 kg per megaliter day^{-1}. Booster injections only become economical when travel times approach 15 hr, so would not be relevant in these situations.

In practice it has been found that savings can be effected in some large canals by application at a reduced rate and use of a technique in which the discharge is reduced during injection then restored to capacity, flushing the herbicide along the canal. Elodea was controlled for a distance of about 27 km in canal C (Table 4) using 1.2 kg of acrolein per megaliter day^{-1}, based on the reduced discharge during injection. Acrolein is therefore regarded as a most useful and economic herbicide. It is relatively non-toxic to a variety of crops at concentrations greater than 15 ppm (11), and germinating rice, which is of major importance in Australia, tolerates at least 5 ppm in irrigation water.

Acrolein provides only temporary control, and its use requires special equipment and training, so it is not available to growers to maintain the smaller farm channels. Two major considerations are the hazards to personnel during the storage and handling of the material, and the possibility that supplies in Australia may be restricted in the future.

FUTURE PROSPECTS

Adaptation of Conventional Treatments to Irrigation Practice. Many herbicides are reported to be effective against elodea in ponded water (Table 2) or in static assay, where contact with the treated water continues for several days or weeks. However, due to the continual demand for water during the irrigation season, it is impossible to withhold water supplies for more than a few days in Australian irrigation systems. There are three alternatives: treatment of flowing water during the summer, retention of water in the fall for static treatments, or the application of soil-residual herbicides in winter after drainage.

'Total water treatments' have been tried in the Berriquin Irrigation District, Australia. Diquat was tested (0.7 ppm) in slowly moving water (0.01 m s^{-1}) by spraying the water surface or by dumping the herbicide into the water from the bank at intervals of about 27 m. Copper sulphate was used in water flowing at about 0.1 m s^{-1}. Coarse mesh bags containing copper sulphate granules were suspended in the water upstream. The theoretical concentration was 4.8 ppm as copper ion, for a treatment time of 20 to 30 minutes, which is equivalent to a dosage of about 0.1 kg per megaliter day^{-1}. This compares (Table 1) with dosages of 0.04 to 0.08 kg per megaliter day^{-1} which have been routinely used in the Friant-Kern Canal, California[9], where treatments were usually repeated every 2 weeks.

Poor control of elodea was obtained in the Berriquin trials. This may reflect the partial inactivation of copper by

[7]Anon. 1965, Aqualin herbicide process handbook. Revision 1. Shell Chemical Corporation, New York, pp. 5-7, 17.

[8]1.2 kg per megaliter day^{-1} is equivalent to 1 US gallon of formulated product per cfs.

[9]G. D. Nielsen. 1967. Practical method of controlling algae in irrigation canals. Paper presented at the American Society of Civil Engineers Water Resources Conference, New York City, October 1967. 20 pp.

precipitation, and of diquat by adsorption onto suspended clay particles. It may be possible to reduce these problems by using 'placement techniques'.

The use of diquat and copper ion with the invert emulsion system has provided good control of hydrilla (*Hydrilla verticillata* L. f. Royle) in Florida (8), and it is reported that this technique produces good results even in muddy waters. Addition of copper ion to irrigation waters in Australia may not be permitted because of the problems of chronic copper poisoning in sheep, but the invert emulsion principle is regarded with interest for the application of diquat alone, or for use with other herbicides. Formulations of herbicides with alginates (9), polymers[10, 11] and elastomers (16) are further possibilities.

Cyanatryn gave excellent control of elodea in irrigation channels in New South Wales, but this herbicide has been withdrawn from sale. A slow-release pellet formulation was used to maintain low concentrations for at least 8 days. Apparently this approach was required because cyanatryn could be eluted from the plant, and at shorter contact times the plant could recover (39).

Slow-release granules of terbutryn, at concentrations of 0.05 to 0.1 ppm are reported (20) to control elodea in Europe in water velocities up to 0.3 m s^{-1} but this formulation is not available in Australia.

The disadvantages of slow-release granules and pellets are the expense of formulation, the problem of maintaining a constant flow for relatively long periods, and the hazard to non-target organisms through contamination of large volumes of water.

In general there seems to be very little information on the relationship between concentration and contact time required for effective weed control. In laboratory experiments Johannes[12] found that elodea was controlled with terbutryn exposures ranging from 0.02 ppm for 6 days to 0.7 ppm for 2 hr to 10 ppm for 15 minutes. A concentration of 0.02 ppm in water would not be hazardous for irrigation or other uses so that low concentration treatments would be advantageous; however, a constant flow could seldom be maintained for the long contact time required. Exposure to high concentrations for short times would be more amenable to water management practices, with protection of irrigated crops by discharge of treated water to waste or onto tolerant crops or fallow land. This approach might also be applicable to 3-cyclohexyl-6-(dimethylamino)-1-methyl-s-triazine-2,4(1H,3H)-dione (hexazinone) and endothal.

However, in contrast to Johannes' results, we found that when rooted fragments of elodea were exposed to terbutryn for 2 hr then transferred to fresh water, massive concentrations of the order of 45 ppm were required for control. Results for hexazinone were even less encouraging. In accord with these observations poor results were obtained with terbutryn in irrigation channels using injection treatments of 8.3 ppm for 2.4 hr, and 1.1 ppm for 22 hr, and this approach has now been abandoned.

The usefulness of endothal in high-concentration, short-time injections remains to be investigated. Several salts and formulations are available. The dipotassium salt of endothal in an invert system with copper ion has recently been approved for control of hydrilla in Florida but it is recognised[13] that this salt does not give satisfactory control of elodea. This is supported by Keckemet (28) who reports that elodea may metabolize endothal-acid more rapidly than *Potamogeton nodosus* Poir., hinting that elodea is relatively resistant, and confirmed by Yeo (53) who found that elodea was not controlled in farm reservoirs by 0.5 to 4 ppm of the disodium or dipotassium salts although four species of pondweed were. The mono (N,N'-dimethylalkylamine) salt gives better control of elodea. Label recommendations[14] do not refer to flowing water specifically but suggest a minimum contact time of 2 hr of the alkylamine salt at 1 to 5 ppm acid equivalent. Price (40) used the amine salt at 3 to 4 ppm for 3 hr, equivalent to 0.2 kg acid equivalent per megaliter day^{-1} (Table 5) in canals in the Western USA, and reported good control for 30 km for most submerged species, although elodea is not mentioned specifically. A similar treatment (6 ppm for 3 hr) has been tried in flowing water in the Berriquin Irrigation District of Australia with limited success. However, if higher concentrations were effective, its use would still be economically feasible (Tables 1 and 5). Another alternative is the use of the N,N'-dimethylcocoamine salt. It is reported to control submerged macrophytes and algae more effectively than other endothal salts and is dissipated rapidly from the water (51). In areas where fish kills can be tolerated it would be suitable for treatment of flowing water by injection.

The success of high-concentration, short-time treatments in flowing water depends on the relatively rapid uptake and retention of a lethal quantity of herbicide by the plant. While acrolein gives adequate results with a contact time of 2 hr (14), reports from the literature for other herbicides are not encouraging. The comment that cyanatryn is eluted from submerged macrophytes (39) has been mentioned earlier. Haller and Sutton (26) report that endothal-acid is taken up very slowly by hydrilla, and imply that long contact times are required to achieve toxic concentrations in the tissue.

As a consequence of disappointing results with herbicides in flowing water in Australia, the usefulness of static water treatments is now being reviewed. Excellent control of elodea was obtained with 1 ppm terbutryn in the Berriquin Irrigation District in a canal where the water was held static during the summer, a practice not usually possible, but treatment with 1.0 ppm for 7 days was not satisfactory. It is possible to increase exposure time by retaining static water in the canals at the end of the irrigation season; however, trials with 5 ppm terbutryn gave poor control of ribbonweeds and pondweeds, probably due to reduced effectiveness of herbicides at lower temperatures. Similar trials in elodea-infested canals are now in progress, using terbutryn concentrations of 1 ppm. Other herbicides which have been used successfully in similar situations overseas include simazine

[10]R. J. Gates. 1978. The use of polymers in the application of aquatic herbicides. Paper presented at the 18th Annual Meeting of the Aquatic Plant Management Society, Inc., Jacksonville, Florida, July 1978.

[11]Nalquatic(R) (polycarboxylate polymer), Nalco Chemical Company, Chicago, Illinois.

[12]H. Johannes, Ciba-Geigy, Basle, Unpublished Internal Report, 1972.

[13]Keckemet, O. 1978. Pennwalt Corporation. Personal communication.

[14]Pennwalt Corporation Agchem Division, Fresno, California.

(22) and 2-ethylamino-4-isopropylamino-6-methylthio-1,3,5-triazine (ametryn) (24). These treatments would be suitable for smaller channels, but neither economical nor manageable in larger canals since the problems of contamination of water would preclude their use.

Smaller earthen channels are often treated with residual herbicides after drainage. To reduce potential hazards from residues, the first discharge of water is often discarded before using water for irrigating sensitive crops.

Small quantities of chlorfenac and dichlobenil have been used in the CIA in an attempt to eradicate elodea. Chlorfenac was extremely effective and eradication was achieved, but because of relatively high residue concentrations in the discharge water it is not registered for aquatic use in Australia. In two trials where dichlobenil was applied 10 to 12 weeks before the first water discharge, most of the dichlobenil was dissipated, probably by evaporation, and residues in the discharge water were much lower than the concentration of 0.3 ppm acceptable for irrigation (13). However, control was not complete and the high cost of dichlobenil (Tables 3 and 5) limits its usefulness to treatments of localized infestations in smaller channels. Application in the spring using lower dosages has been tried in an attempt to reduce costs, but was not successful.

Simazine has given promising control of elodea in Europe (22), and Van Rijn (50), working in the Ord Irrigation Project of Western Australia, has shown that water management techniques can be employed to safeguard irrigated rice. In the MIA, excellent results have been obtained when pondweeds and ribbonweed were treated with simazine applied to drained channel sediment at 30 kg ha^{-1}. If control of elodea is confirmed in current trials, this will be a major advance in the management of aquatic weeds in Australia's irrigation channels.

CONCLUSIONS

For smaller farm channels, or if acrolein were not available, aromatic solvents and ammonia can be used to provide temporary control. Chlorfenac is exceptionally effective for longer control and eradication, but due to its water solubility it is not available for general use. Dichlobenil is only moderately effective and is expensive. Alternative treatments would be advantageous if they were both economical and permanent. Flowing water treatments with endothal-alkylamine and endothal-cocoamine, ponded water treatments with terbutryn, simazine and ametryn, and soil-residual treatments with simazine seem promising, but remain to be investigated for control of elodea in Australian situations.

For larger canals, use of endothal-amine salts appear to be worth investigation but their persistence could be a problem for satisfactory water management. Other herbicides will be tested in conjunction with invert emulsions, alginates or other placement techniques, to achieve long-term control at reasonable cost, with minimum environmental contamination.

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British Columbia Aquatic Plant Management Program

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ABSTRACT

A substantial and concerted effort has been made since 1972 by the Water Investigations Branch, British Columbia Ministry of Environment, to investigate the ecology, impacts and management of Eurasian watermilfoil (*Myriophyllum spicatum* L.). By 1977, this plant had spread to occupy about 580 ha of littoral zone in the Okanagan Valley mainstem lakes in British Columbia. The main elements of the British Columbia Aquatic Plant Management Program have included: surveys, mapping and documentation of Eurasian watermilfoil, research on its ecology, evaluations of mechanical and chemical control technologies, and attempts at containment and quarantine. Historical perspectives of the organization and functional components of the present program are presented.

INTRODUCTION

Aquatic plant management in British Columbia has become increasingly important since about 1970. The Water Investigations Branch (W.I.B.) of the British Columbia Ministry of Environment has been instructed to investigate, advise, and report on nuisance aquatic plant populations. This work has been performed as part of the general W.I.B. responsibility for studies on water quality and possible conflicts with multi-purpose uses, and to provide environmental protection of waters within the Province. The Aquatic Plant Management Program (A.P.M.P.) is the largest of a number of water quality-related studies currently being performed by the Environmental Studies Division, one of four divisions of the W.I.B. (see Figure 1). The Federal Government of Canada has supported some research on aquatic plant removal technology but has designated weed removal as a Provincial responsibility.

The water resources of British Columbia have been subject to growing exploitation and development for hydroelectric generation, navigation, flood control, irrigation supply, and the tourism industry. Tourism, which was in 1977 British Columbia's third largest industry, and the related increasing demand for improved aquatic recreational facilities, are important factors which stimulate concern about nuisance aquatic plants.

Public interest in the protection of traditional patterns