Aquatic Vegetation in Irrigation Canals

A Guide to Integrated Management

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For:

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and

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Region X

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Preface

Preparation of this guidance manual for integrated aquatic vegetation management in irrigation canals was stimulated, in large part, by the accidental release of acrolein-treated irrigation water into Bear Creek in southern Oregon. The resulting fish kill brought into focus the need to examine the methods available for managing aquatic vegetation in flowing water. Furthermore, it demonstrated the need for technical assistance on aquatic vegetation management in Oregon.

Vegetation management in flowing water is a difficult undertaking. The interconnectedness of natural and manmade water conveyance systems, the tenuous status of many aquatic species, and the necessity of water delivery for profitable and productive agriculture in Oregon and much of the Northwest interact to focus attention on the way that aquatic vegetation management is conducted. Endangerment of fish species in the Pacific Northwest requires a detailed examination of agricultural operations.

This manual is intended to provide water conveyance system managers a summary of available technologies for aquatic vegetation management and to outline the concepts and procedures necessary for development of an integrated management plan for vegetation growing in canals. With the adoption of a thoughtful approach to aquatic vegetation management, and with technical assistance and research on the problem plants and control techniques, aquatic vegetation can be managed without severe off-site and non-target impacts. It is hoped that this manual will assist in reaching that goal.

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Introduction

Much of the western United States is arid and dependent upon a network of reservoirs and canals for agricultural, domestic, and industrial water distribution. The western water system includes over 100,000 km (62,140 miles) of canals and over 1.7 million ha (4.2 million acres) of reservoir storage (Timmons 1960, 1966, Anderson 1993). Major facilities built and managed by the U.S. Army Corps of Engineers and Bureau of Reclamation generate power and store and distribute water in the West. The Bureau of Reclamation alone transports about 37 billion (10^9) m^3 (30 million acre-feet) of water each year, with 80 to 85 percent used to irrigate over 48 million ha (119 million acres) that produce about $7.4 billion in crops (US Bureau of Reclamation 1985) (Figure 1). Increasing demand for food, and water scarcity, necessitates efficient use and protection of these valuable water resources (Brown 1996).

Management of this massive water conveyance system includes control of pest species that interfere with system operation. Aquatic pests, such as rooted aquatic macrophytes, reduce storage capacity in reservoirs, block screens and intakes on pumps, interfere with hydroelectric production, distort canal design features (increase sedimentation, decrease channel flow, etc.), degrade recreational uses, and reduce water quality and wildlife habitat value. In general, designed capacity of irrigation canals in the West has not accounted for flow resistance caused by aquatic vegetation (Pitlo and Dawson 1993) although recent work provides the empirical basis for such design considerations (Kouwen 1992, Abdelsalam et al. 1992)

Costs of aquatic weed management are estimated at over $50 million annually in the 17 western states (Anderson 1993). The cost for aquatic weed management in the relatively small, and fairly typical, Talent Irrigation District (TID) in southern Oregon is approximately $30,500 per year. Aquatic weed management in larger irrigation districts can exceed $100,000 per year (Hollie Cannon, TID, personal communication). Drainage districts have similar aquatic vegetation management problems as irrigation districts.

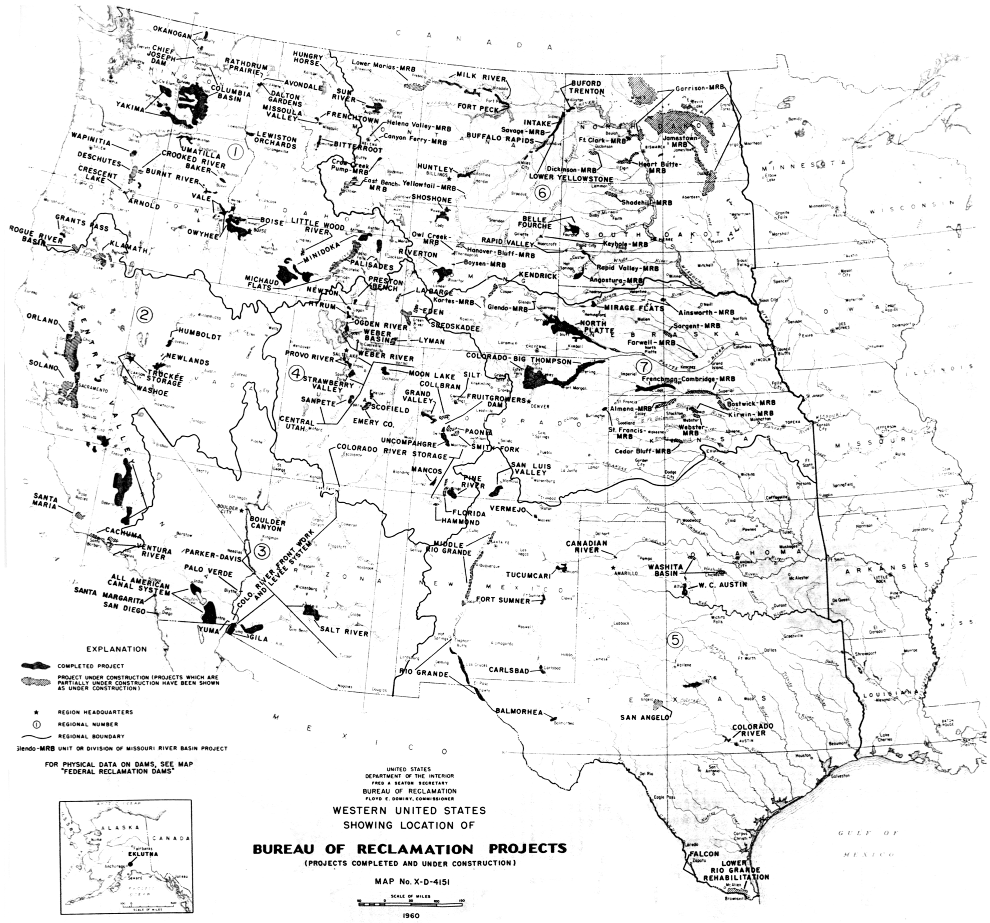

Figure 1. U.S. Bureau of Reclamation projects in the seventeen western states.

Lack of a comprehensive botanical survey and the use of common names, which can vary from district to district, limits description of the problem species in irrigation canals. From the limited botanical surveys conducted, two plants are likely to account for most of the aquatic plant problems in irrigation districts in Oregon – Sago pondweed (*Potamogeton pectinatus*) and Canadian pondweed (*Elodea canadensis*). Other non-native species, such as Brazilian eldoea (*Egeria densa*), Eurasian watermilfoil (*Myriophyllum spicatum*), and Curly-leaf pondweed (*Potamogeton crispus*) also create flow blockage in irrigation systems in the state. Bartley et al. (1974) reported that *Potamogeton* species are the most common nuisance plants in western irrigation canals.

Management of aquatic vegetation in Oregon, and much of the West, has not been conducted in the context of the integrated pest management (IPM) paradigm. Lack of adequate planning has resulted in inappropriate management and non-target effects that have raised public concern (West 1996, Mohler 1997). In many systems, management activities have been typically conducted on a prescribed schedule using fast-acting, broad-spectrum biocides. Consideration of potential interactions of plant biology, environmental conditions, and timing of activities with management options, and efforts at optimizing efficacy of management activities has been limited.

This manual provides managers of aquatic vegetation in irrigation systems with information on integrated pest management concepts, a summary of available technologies, and an outline of the components of an integrated aquatic vegetation management plan. The focus in this manual is on vegetation management in Oregon irrigation systems, however, the concepts and techniques discussed can easily be applied to irrigation systems throughout the West.

IPM and EBPM Concepts

Humans have always managed pests. Early agriculturists, through trial and error, learned and implemented pest management practices that maintained a balance between pests and their enemies (National Research Council 1996). Development of economical and effective pesticide technology, however, led to an increased reliance upon intensive, chemical control of pest species. Development of herbicides revolutionized weed pest management and led to increased yields and a “green revolution” in agriculture (Ashton and Crafts 1973, Levins 1986).

Concern about pesticide resistance, nontarget effects, and health impacts of chemical control has stimulated interest in more balanced pest management techniques. These “integrated” techniques are based on a thorough understanding of the biology of the pest and the pest's interaction with other organisms and the physical environment. IPM necessitates identification of pests and economic injury levels, and uses selective control techniques that focus on vulnerable life stages and minimize deleterious effects on nontarget species (Horn 1988). The practice of IPM, however, has not always been fully integrated. Early IPM programs focused on control of insects, and were often limited to pest scouting and precise applications of pesticides. Development of IPM programs for weed management has been slow (National Research Council 1996).

A fundamental tenant of IPM is identification of economic injury level (EIL) and economic threshold (ET). The threshold concept rests on the premise that not all pests require management; some level of pest abundance is tolerable. The EIL defines how much pest impact is acceptable. The ET determines whether or not management is needed (Higley and Pedigo 1997). IPM in weed management has focused on determining EIL and ET in crop systems, where economic criteria are easily measured (Mortensen and Coble 1997). Weed management in non-crop systems has focused on preventive and therapeutic measures to protect and restore native plant communities, and management decisions have not been based on established EILs and ETs.

Recently, ecologically based pest management (EBPM), which relies on an increased understanding of the biology and ecology of pest species and systems, has been proposed. EBPM builds on the IPM framework with the fundamental goals of providing safe, profitable, and durable management of pest populations (National Research Council 1996).

Pest Management in Aquatic Systems

IPM/EBPM for aquatic vegetation in canals has some unique characteristics. As in cropping systems, IPM/EBPM in aquatic systems requires consideration of the ecological and environmental requirements of the pest species, site constraints, the efficacy of the various control methods, and potential for nontarget or offsite impacts. Vegetation management in irrigation systems, however, is complicated by the interconnectedness of manmade and natural systems, multiple uses of water, the chemical and physical characteristics of water, the unique biology of aquatic pest species, and the limited management options available.

Establishment of EILs and ETs in irrigation systems is problematic. Presence of <u>any</u> aquatic vegetation in irrigation canals impacts flow characteristics of the canal. Aquatic vegetation is almost always present in canals and can grow rapidly and quickly block flow. Demand for water is dependent upon weather conditions and can vary substantially from week to week. Consequently, it is difficult to establish EILs and ETs that are applicable over the potentially wide range of conditions that influence supply and demand functions for water. As a result, vegetation management is typically prophylactic or therapeutic, *i.e.*, implemented in anticipation of, or as a consequence of, flow blockage. Prophylactic treatments are generally preferred because they permit the flexibility in system operation that is required to meet the water demands of growers.

Interconnectedness and multiple uses of water in irrigation and natural systems increase the likelihood of non-target and off-site impacts of management activities and limit aquatic plant management options. Management goals and objectives may be radically different in manmade and natural aquatic systems, and vegetation management activities that may be appropriate in manmade systems may seriously damage natural systems. Furthermore, relative to terrestrial systems, aquatic systems contain a high proportion of organisms that are threatened or endangered (Master 1990). The potential for impacts on natural systems is particularly problematic in Oregon and the Pacific Northwest, where many natural aquatic systems contain culturally and economically important threatened and endangered plants and animals.

The concept of integrated pest management for aquatic vegetation is generally considered to be a desirable and practical approach (Charudattan 1986, Sorsa et al. 1988, Murphy and Pieterse 1993); however, IPM has not been commonly implemented in western irrigation systems. Aquatic vegetation management has been primarily with chemical techniques. Alternative management strategies, ecological and environmental influences on aquatic plant growth, the potential interaction between environment and management actions, and the potential for enhanced efficacy when two dissimilar management techniques are used in combination have not been explicit considerations in aquatic vegetation management. Lack of technical assistance and information has limited irrigator’s access to IPM protocols for aquatic vegetation management and limited implementation of non-chemical approaches to aquatic plant management.

Aquatic Vegetation Management Technologies

Aquatic vegetation can be managed using a variety of techniques, including chemical, physical, biological, and environmental manipulation. Decisions on the use of aquatic plant management techniques for aquatic vegetation are not based entirely on economy and efficacy; there are many inexpensive and effective ways to remove aquatic vegetation from canals. Rather, management decisions are often constrained by a requirement to minimize potential for off-site and non-target impacts. This section describes the technologies available for management of aquatic vegetation. In some instances, a technique may be efficacious but have unacceptable potential non-target and off-site effects and/or use restrictions that do not permit use in irrigation canals.

Chemical

Acrolein

Acrolein (acrylaldehyde, 2-propenal) is an aliphatic, α,β-unsaturated aldehyde that occurs naturally as a product of combustion and as a metabolite. Acrolein is a pungent, colorless, highly volatile liquid used as a mulluscicide and herbicide, as a fixative in histochemical investigations, and as an intermediate in the production of numerous chemicals and reagents, including acrylic acid and DL-methionine (an essential amino acid used to supplement poultry and cattle feed) (Ghilarducci and Tjeerdema 1995). In 1983, approximately 98 percent of all production went to the manufacture of acrylic acid and DL-methionine (Ghilarducci and Tjeerdema 1995). Approximately 54,000 tons were produced industrially in the United States in 1992 (Anonymous 1992, as cited in Ghilarducci and Tjeerdema 1995). The main source of acrolein and the principal mode of human exposure, however, is through incomplete combustion in residential fireplaces, manufacturing, photochemical oxidation of airborne hydrocarbons, cigarette smoke. The compound is also produced naturally in metabolic processes in soils (formation of humic substances) and in food (dehydration of glycerol) (Ghilarducci and Tjeerdema 1995). In a study of human exposure to acrolein, the greatest measured concentrations in typical ambient air occurred in heating animal and vegetable cooking oils (57.6 - 103.6 mg/m^3), near automobile exhaust (0.13 to 50.6 mg/m^3), and in a coffee roasting outlet (0.59 mg/m^3) (references in Table 4 of Ghilarducci and Tjeerdema 1995).

Acrolein is a cell toxicant of high reactivity. The compound is capable of spontaneous polymerization, which must be inhibited by hydroquinone. The chemical characteristics of acrolein, in particular the induced polarity caused by electronegative carbonyl oxygen atom, allows the molecule to react with nucleophilic reagents that contain sulfhydryl groups, such as free cysteine or cysteine-containing proteins. Thus, the compound can react with proteins and nucleic acids and induce cross-linkages and macromolecular rearrangements that result in tissue damage (Ghilarducci and Tjeerdema 1995).

Acrolein is highly toxic. The acute EC_{50} and LC_{50} for bacteria, algae, crustacea, and fish range from 0.02 to 2.5 μg/L; reported 60-day no-observable-effect-level is as low as 11.4 μg/L (WHO 1992, as cited in Ghilarducci and Tjeerdema 1995). Westerdahl and Getsinger (1988) reported that fish are killed when exposed to concentrations greater than 1 mg/L. Concentration-dependent histopathological effects on coho salmon gills, kidneys, and liver were found with exposures ranging up to 100 μg/L, and 100 percent lethality at 75 μg/L within 144 hours (Lorz et al. 1979). To protect freshwater animals from adverse effects, USEPA recommends a water quality limit of 1.2 μg/L for a 24-hr. average and a maximum of 2.7 μg/L; to protect human health from ingestion of treated water and organisms, the maximum concentration is 6.5 μg/L (Sittig 1980). Acrolein at 6 to 10 mg/L is used as an algaecide, molluscicide, and herbicide (WHO 1992, as cited in Ghilarducci and Tjeerdema 1995). Registered use concentrations are 1-15 mg/L (Dave Blodgett, Baker Petrolite, personal communication, 4 Dec. 1997). Because many investigators failed to account for volatilization in test systems, acrolein toxicity may be higher than the toxicology studies indicated. Acrolein is not carcinogenic and shows little embryotoxic and teratogentic behavior (Ghilarducci and Tjeerdema 1995)

Plants treated with acrolein become flaccid and disintegrate within a few hours of even a short exposure. Phytotoxicity is temperature dependent; the concentration required at 60 F is double that required at 80 F (Ashton and Crafts 1973). Bartley and Gangstad (1974) reported that for aquatic plant control, acrolein is applied full strength (92%) directly to the water using metering equipment calibrated to produce a rate not greater than 15 mg/L. In larger canals, applications are often made at 0.1 mg/L over a 48-hour period. In smaller canals the same quantity of materials is applied over a shorter period. In Argentina, 2-5 mg/L acrolein, applied for 24 hours resulted in 30 to 50 percent reduction in biomass of *Potamogeton striatus* up to 10 km downstream from the application point (Fernández et al. 1987). Acrolein treatments monitored in concentration and dissipation studies in the Columbia Basin indicated that acrolein concentration was reduced to approximately 0.03 mg/L 15 miles downstream from a 0.1 mg/L application (Bartley and Gangstad 1974). Sublethal concentrations of acrolein (<0.1 mg/L) stimulated growth of *Elodea canadensis* plants in Australian tests (Bowmer and Smith 1984).

Acrolein is relatively nonpersistent. The half-life in aquatic systems ranges from less than 1 to approximately four days (Callahan et al. 1979, Bowmer and Higgins 1976, WSSA 1994). Volatilization is of major importance in loss from aquatic systems (Ghilarducci and Tjeerdema 1995), however, it is not the only mechanism. The primary fate process is hydration. Upon hydration, β-hydroxypropionaldehyde is produced and is easily biotransformed (Reinert and Rodgers 1987). Half-life in water is not a function of the aerobic or anaerobic condition. Photolysis, hydrolysis, oxidation, and sorption are not considered significant fate processes (Callahan et al. 1979, Mabey 1981).

In irrigation systems, acrolein is applied subsurface at the upstream end of a canal. The herbicidal activity is a function of the length of the treated water plug, the concentration of chemical, temperature, and flow rate. Because of its high toxicity, and short contact time, acrolein is highly efficacious in irrigation systems (Bowmer and Smith 1984). The compound is a contact herbicide, however, and repeated applications through the growing season are often required to maintain flow. In the Talent Lateral, biweekly applications are typically required from June to September. A study of acrolein use by the Tulelake Irrigation District found that, with adherence to precautionary measures in the application, acrolein residuals did not impact receiving waters in the Tulelake National Wildlife Refuge (Bonniver 1994).

Xylene

Xylene (1,2-, 1,3-, and 1,4-dimethyl benzene) is an aromatic solvent registered for aquatic weed control for use in programs of the Bureau of Reclamation, Department of the Interior, and cooperating water user organizations.

Xylene is insoluble in water and must be applied with an emulsifier. In 1967, over 750,000 gallons of xylene was used in Oregon, Washington, and Idaho for aquatic weed control in irrigation districts (Frank and Demint 1967) at rates up to 740 mg/L (Anderson 1993). More current xylene-use data could not be located. Xylene is an effective contact herbicide at concentrations as low as 200 mg/L (Otto 1970).

Xylene is highly toxic to aquatic organisms. The 96-hr LC_{50} for rainbow trout was estimated to be 12 mg/L, with 100 percent mortality at 16.1 mg/L, and “anesthetic-like” effects after 2-hour exposure to 3.6 mg/L. Chronic (56 days) exposure to concentrations as low as 0.36 mg/L caused significant off-flavor in rainbow trout fillets. The no-effect level was established at 7.1 mg/L for a two-hour exposure. At treatment concentration, the emulsifier, Emcol AD-410, is much less toxic to rainbow trout than xylene (Walsh et al. 1975).

Xylene persistence in water is low. The predominant fate process is volatilization (Daniels et al 1975, cited in Reinert and Rodgers 1987). Other factors that contribute to loss of xylene from irrigation water include: breaking or disruption of the emulsion and absorption by plants (Frank and Demint 1970).

In humans and other mammals, xylene exposure can result in a variety of central and peripheral nervous system effects (Gandarias et al. 1995). There is no evidence that xylenes are mutagenic or carcinogenic (EHIS 1993).

Xylene is an effective herbicide in irrigation systems because of its phytotoxicity and minimal residual effects on crop plants. High toxicity to fish and other aquatic organisms, however, necessitates a high level of applicator competence and attention.

Fluridone

Fluridone (1-methyl-3-phenyl-5-[(trifluoromethyl) phenyl]-4 (IH)-pyridinone) inhibits plant growth by interfering with a desaturase enzyme complex that converts phytoene to gamma-carotene (Sandmann and Boger 1986), which leads to chlorophyll degradation and the characteristic bleaching of leaves in treated plants. Fluridone has selective herbicidal characteristics at low concentrations, but at higher concentrations the compound is a broad-spectrum herbicide. The compound is slow acting, and at low concentrations requires long contact times for systemic effects. Liquid and pellet formulations are available. Use of pelletted formulations for maintaining low concentrations in flowing water has been suggested as a viable technique for control of aquatic weeds in irrigation canals, however, crop tolerances have been examined in only a few crops (Langeland and Tucker 1987, Kay et al. 1994). Label restrictions require seven to 30 day holding times for treated water are recommended to avoid potential injury to irrigated crops.

Primary fate processes for fluridone in aquatic systems are photolysis, microbial metabolism, and soil adsorption (WSSA 1994, Joyce and Ramey 1986, Mossler et al. 1989). Microbial degradation is the major degradation process in terrestrial soils, however, photolysis is the primary degradation process in aquatic systems. Fluridone is strongly adsorbed to organic soils, and then slowly leaches out of the soil. Half-life of fluridone in water is approximately 21 days. Half-life in hydrosoils is approximately 90 days (West et al. 1983, Reinert and Rodgers 1987).

Fluridone has not been found to cause acute or chronic toxicity in laboratory mammals, and has not been shown to be teratogenic, oncogenic, or mutagenic (West 1984). 96-hour LC_{50} and 48-hour EC_{50} concentrations for aquatic organisms are greater than maximum label application rates for the compound (WSSA 1994). The toxic photolytic breakdown product of fluridone, NMF (N-methylformamide), which was observed in laboratory studies, has not been found in outdoor applications (Osborne et al. 1989).

Fluridone is used to control a variety of aquatic plant species in ponds and lakes. Selectivity is dependent upon concentration, contact time, and species. Low plant iron content (Spencer and Ksander 1989) and use in combination with fungal pathogens (Netherland and Shearer 1996) enhance efficacy. The compound is used to control vegetation in aquaculture facilities (Kamarianos et al. 1989) and has been used to selectively remove non-native and restore native plant communities in the Northwest (Burns 1995). Application of fluridone in irrigation systems is complicated by the contact time required for herbicidal activity, limited crop tolerance information, and holding time required before use of water on crops. Fluridone may be useful as a preseason treatment for aquatic vegetation if treated water can be flushed from the canal.

Endothall

Endothall (7-oxabicyco[2.2.1]heptane-2,3-dicarboxylic acid) is a broad-spectrum herbicide for aquatic plants. Endothall is a white crystalline odorless acid that forms water-soluble salts with sodium, potassium, and amine bases (Ashton and Crafts 1973). The dipotassium salt is used to control aquatic plants, and the mono-amine salt is used for control of aquatic plants and algae. The compound is a membrane-active herbicide that inhibits protein synthesis in plants. Translocation within the plant is limited. The endothall is a contact herbicide, killing only the parts of the plant exposed to the chemical (Westerdahl and Getsinger 1988).

Microbial degradation of endothall occurs rapidly in aquatic systems. Typical half-life in water is 1 to 7 days, with undetectable levels in water and hydrosoil in 1 to 3 weeks (Extoxnet 1995, Westerdahl and Getsinger 1988); no hazardous metabolites have been found (Westerdahl and Getsinger 1988). Degradation products of endothall are incorporated into amino acids, proteins, and lipids, or are released as CO_2 (O. Keckemet, Elf Atochem, personal communication). Endothall does not bioconcentrate (Reinert and Rodger 1987). The recommended treatment rate for aquatic plants is 1 to 4 mg/L. Algae control rates are 0.05 to 0.8 mg/L.

Endothall is moderately toxic. Inorganic salts of endothall are safe to fish at 100-500 mg/L concentrations, however, the amine salts are toxic to fish at treatment concentrations in laboratory studies (Extoxnet 1995, Westerdahl and Getsinger 1988). 21-day bioassays of the dipotassium salt using rainbow trout indicated that minimal or no mortality occurred at 10 mg/L (Westerdahl and Getsinger 1988). The dipotassium salt of endothall caused increased mortality in juvenile chinook salmon when fish were challenged with seawater, however, this effect was not evident in coho smolts exposed to the endothall acid (Serdar and Johnson 1996 and references cited therein). The mono (N,N-dimethylamine) salt of endothall did not affect osmoregulation in chinook smolts, however, 45 percent mortality occurred in fish exposed to 200 μg/L when they were challenged with seawater (Serdar et al. 1995). Mortality was attributed to respiratory distress caused by gill irritation that was exacerbated with exposure to seawater. Laboratory toxicity may not be representative of risk in the field. During 35 years of field use at 3 ppm, no fish kills have been reported (O. Keckemet, Elf Atochem, personal communication), however, salmonids may be more sensitive to endothal than warmwater species that are present where endothal has been used extensively.

Endothall is commonly used for treatment of aquatic weeds and algae in ponds, lakes, reservoirs and irrigation canals. The relatively low toxicity of the salts of endothall and the biodegradation rate allows for localized treatments and quick knockdown of nuisance plants. Since the compound is a contact herbicide; regrowth occurs and retreatment is often required. Fish in the treatment areas should not be consumed for 3 days after treatment, and water should not be used for irrigation or domestic purposed for seven to 25 days after treatment, depending upon treatment concentration (Elf Atochem, label information).

Use of endothall for control of aquatic plants in irrigation systems is complicated by the contact time for herbicidal activity (2 hours), lack of crop tolerance data, and the consequential holding time required before the treated water can be used for irrigation. Experimental use of metering devises for low-concentration (as low as 0.2 mg/L), long-duration (120 hrs) treatments have proven effective in some irrigation systems (Sisneros and Turner 1995; David Sisneros, US BOR, personal communication), however, label restriction currently prohibits use of the water for irrigation during such a low-rate treatment. If sublethal and/or behavior effects on salmon species occur at 0.2 mg/L, as noted above, even such low rate applications may be problematic in the Pacific Northwest.

Diquat

Diquat (6,7-dihydrodipyrido[1,2-α:2”,1’-*c*]pyrazinediium ion) is a heterocyclic organic cation in the bipyridylium quaternary ammonium class. The diquat cation interacts with the photosynthetic biochemistry in plants to produce a free radical that is phytotoxic. The diquat free radical undergoes autooxidation in the presence of oxygen to form H_2O_2 or OH^-, which is probably primarily responsible for the herbicidal effects of diquat (Ashton and Crafts 1973, Westerdahl and Getsinger 1988). Therefore, the diquat ion requires the photosynthetic apparatus, light, and molecular oxygen as co-factors to produce herbicidal effects.

The primary and most important fate process for diquat in aquatic systems is its very rapid and complete inactivation by soil. The double positively charged cation forms complexes with negatively charged sites on clay minerals present in soils and sediments. Diquat may even insert into the layer planes of montmorillonite clays. When bound, diquat is not considered bioavailable (Reinert and Rodgers 1987). Microbial and photochemical degradation are also important fate process.

Diquat is a contact herbicide that is minimally translocated (Joyce and Ramey 1987). Rapid adsorption by suspended sediments limits efficacy in turbid water. Although diquat adsorption and other fate processes result in an overall aqueous half-life from 0.8 to 3.8 days (Westerdahl and Getsinger 1988), toxicity to early life stages of fish reduces the safety margin in its use; LC_{50}s are near treatment concentrations (Paul et al. 1994). Exposure of yearling coho salmon to 0.5 to 3.0 mg/L diquat for 96 and 285 hours inhibited migration. Exposure to 3 mg/L diquat for 360 hours resulted in degenerative necrosis of the liver and kidneys; gills showed hypertrophy and hyperplasia lamellar and interlamellar epithelium (Lorz et al. 1979).

Diquat, formulated at 2 pounds diquat cation per gallon (Reward®), is labeled for use in lakes, ponds, canals, streams, rivers, and drainage ditches that are quiescent or slow moving by the Corps of Engineers or other federal and state public agencies and contractors or licensees under their direct control. A less concentrated formulation (Weedtrine®), which does not have the federal/state agency use restriction, is labeled for non-flowing systems where there is little or no outflow of water and which are totally under the control of the product’s user. Treated water cannot be used for animal consumption, spraying, irrigation, or domestic purposes for 14 days after treatment. Long holding time prior to use of water for irrigation and discharge limits diquat use in irrigation systems.

Glyphosate

Glyphosate, (N-phosphonomethyl) glycine, is a broadspectrum herbicide used to control emergent aquatic vegetation. The isopropylamine salt of glyphosate (Rodeo®) is registered for use in all types of aquatic systems (WSSA 1994). Glyphosate inhibits the biosynthesis of aromatic amino acids by interfering with the activity of ESSP (5-enolpyruvylshikimate-3-phosphate) synthase in the shikimic acid pathway (WSSA 1994). The compound is translocated throughout the plant and kills underground roots, rhizomes, and propagules.

Glyphosate does not bioaccumulate and is minimally retained and rapidly eliminated by mammals, birds, and fish (Brandt 1983, as cited in Reinert and Rodgers 1987). The Rodeo formulation has low toxicity to fish and invertebrates (96-hr. LC_{50} for trout >1,000 mg/L; for *Daphnia magna* 930 mg/L) (WSSA 1994). There are no use restrictions on water after treatment of emergent aquatic plants with glyphosate.

The compound is strongly adsorbed to soil colloids, hydrosoil silt, and suspended solids in the water column (Reinert and Rodgers 1987), and has no measurable phytotoxic activity when sorbed to sediments (Westerdahl and Getsinger 1988). No measurable leaching from soil has been detected (Brandt 1983, as cited in Reinert and Rodgers 1987).

Glyphosate does not contain photolyzable or hydrolyzable groups and does not degrade by either route, but does biodegrade with a half-life of 60 days (WSSA 1984). Within six months, 90 percent of applied glyphosate is degraded (Westerdahl and Getsinger 1988).

Low toxicity, lack of use restrictions, and systemic effects make glyphosate a valuable tool for control of emergent vegetation in irrigation canals and reservoirs (Comes and Kelley 1989). The compound does not control submersed vegetation.

Copper

Copper was first used as a algaecide in the nineteenth century and is still widely used to control algae and higher aquatic plants (Murphy and Barrett 1993). Recently, chelated copper complexes have been produced that are effective in water with widely varying chemistry and less toxic to fish than copper salts, such as copper sulfate. Chelating compounds include ethylenediamine, alkanolamine, and triethanolamine. The ethylenediamine complex is most effective on rooted, aquatic plants (Anderson et al. 1987, 1993) and the alkanolamine and triethanolamine complexes are used as algaecides (WSSA 1994).

Copper is a required nutrient for plants and is important in a number of physiologically important compounds and processes, however, copper phytotoxicity occurs at high concentrations (Epstein 1972, Mengel and Kirkby 1987, Marschner 1986). Toxicity relates to the ability of copper to displace other metal ions, particularly iron, from physiologically important centers. Chlorosis is a common symptom of copper toxicity, superficially resembling iron deficiency (Mengel and Kirkby 1987). Chlorosis can also be a direct response to copper that results from the action of high copper concentrations on lipid peroxidation and thus the destruction of the thylakoid membranes (Marschner 1986).

Since it is an elemental metal, copper is persistent in the environment. Copper ion is highly reactive, and tends to adsorb to clays and dissolved organic carbon in the water to form inorganic and organic complexes (WSSA 1994). The majority of copper applied to an aquatic system will eventually sorb to the sediments. The soluble copper ion is considered the toxic form and is bioavailable to most species (Reinert and Rodgers 1987). Complexed and adsorbed species are considered nontoxic (USEPA 1980, as cited in Reinert and Rodgers 1987), although fish-kills and loss of invertebrates in some lakes have been attributed to long-term copper application for algae control that led to extremely high sediment copper concentrations (Hanson and Stafan 1984). The 96-hour LC_{50} acute toxicity to cutthroat trout ranges from 15.7 to 367 mg/L in water ranging in hardness from 18 to 205 mg/L $CaCO_3$; for rainbow trout the 96-hour LC_{50} ranged from 57 to 574 mg/L in water ranging from 42 to 194 mg/L $CaCO_3$ (Westerdahl and Getsinger 1988).

Copper efficacy is a function of temperature and pH. Copper is more effective at high temperatures and under acid or neutral conditions. At high pH, copper reacts with dissolved carbonates and is precipitated as copper carbonate. Efficacy of chelated formulations is less susceptible to water chemistry and less toxic to fish (Murphy and Barrett 1993). At concentrations less than 1 mg/L, there are no restriction on use of copper-treated water. In water with low alkalinity (50-100 mg/L $CaCO_3$) ethylenediamine-complexed copper controls most common aquatic weeds at 0.75 to 1 mg/L.

Low-rate, long-exposure copper treatments may be effective in control of some aquatic plants. In some irrigation canals copper is applied as a continuously metered supply at concentrations ranging from 0.005 to 0.02 mg/L for periods of days or weeks (Gangstad 1986, as cited in Murphy and Barrett 1993). In a very short exposure, the ethanolamine formulation applied at 0.07 mg/L did not provide effective control of Sago pondweed in the Rogue River Valley Irrigation District (Jim Pendleton, RRVID, personal communication). Chelated copper is often mixed with other herbicides (e.g., fluridone, diquat, and endothall) as a tank-mix for increased efficacy. Copper is sometimes used in irrigation canals to kill epiphytic algae prior to acrolein treatment. Such pretreatment increases the efficacy of acrolein for aquatic weed control.

2-4,d

2-4,d ((2,4-dichlorophenoxy) acetic acid) is one of a family of chlorinated phenoxy acid compounds with herbicidal characteristics (Ashton and Crafts 1973). Chlorophenoxy herbicides are plant growth regulators with systemic, hormone-like activity at low concentrations and act have contact-herbicide characteristics at high concentrations. Phenoxy herbicides are generally selective for broadleaf, dicot species but in water some monocots, e.g., water hyacinth, are susceptible (Murphy and Barrett 1993).

A number of formulations of 2,4-d are available, however, the amine salts, e.g., dimethylamine (DMA), and the butoxyethyl ester (BEE) formulations are the most commonly used (Westerdahl and Getsinger 1988). Liquid and pellet formulations are available. 2,4-d can be used for aquatic weed control in quiescent or slow moving water at a maximum label rate of 0.1 mg/L for control of *Myriophyllum* (milfoil) species. It is less effective on other common aquatic plants, e.g., Coontail (*Ceratophyllum demersum*), and *Najas* species; it is not effective in the control of *Potamogeton* species (Westerdahl and Getsinger 1988).

Depending upon the formulation and environmental conditions, the half-life for 2,4-d in water ranges from 0.02 to 26 days (Reinert and Rodgers 1987). Persistence in sediments is longer (DeLaune and Salinas 1985, WSSA 1994). Degradation of 2,4-d BEE is through photolysis, hydrolysis, and biological processes; biological processes degrade 2,4-d DMA but photolysis and hydrolysis are insignificant (Reinert and Rodgers 1987). Ester formulations are generally more phytotoxic and more toxic to fish than the amine salt formulations (Westerdahl and Getsinger 1988). Histological and biochemical changes in liver, vascular system, and brain were noted in bluegill sunfish exposed to 2,4-d, however, no effects on coho salmon survival or gill ATP-ase activity were noted (Lorz et al. 1979).

Limited efficacy on pondweeds and long holding times (three weeks) required prior to irrigation, dairy animal watering, and domestic use limit the practicality of 2,4-d use in flowing systems. Where these use constraints can be met, , e.g., reservoirs and other static systems, 2,4-d may be useful particularly for control of dicot species in pre- and post-irrigation seasons.

Physical/mechanical removal

Hand-pulling

Hand-pulling has been effective in control of some aquatic weeds in small canals and nearshore areas (Sculthorpe 1967, Shibayama 1988, Thamasara 1989), and less effective in others (Varshney and Singh 1976, as cited in Wade 1993). A number of tools have been developed to assist in hand-harvesting of aquatic weeds, including scythes, cutter bars, and mechanized hand-held cutters (Robson 1974, Cooke et al. 1993, McComas 1993). While hand-pulling is the most common method used for small scale aquatic plant management (Madsen 1997), the cost and difficulty of manual labor is often prohibitive and the efficacy limited when plant biomass is substantial and the infestation widespread (Wade 1993). Miles (1976, cited in Wade 1993) estimated the cost of manual control in a 20-m section of canal was more than three times the cost of using a tractor-mounted flail. A diver-operated dredge has proven effective, but expensive, in removing scattered plants in lakes (Madsen 1997).

An evaluation of hand-pulling was conducted in the Talent Lateral in 1997. About 5 m of a 6 m wide canal could be hand-pulled by one person in an hour. Vegetation removal efficiency was about 82 percent. Estimated cost of hand-pulling was $1100/mile/day.

Hand-pulling has some environmental impacts. Hand-pulling increased suspended sediment concentration by over 1600 percent and produced seven times as many plant fragments in the canal. Suspended sediments can degrade salmon spawning beds and mobilize sediment metals. In addition, high sediment loads in irrigation water can clog emitters used to increase efficiency of irrigation water use.

Several factors influence the cost and efficiency of hand-pulling for aquatic vegetation management. Physical factors such as channel width, depth, and current velocity affect the rate at which people can move around in the channel. Vegetation density influences the rate of vegetation removal, and worker fatigue can quickly reduce efficiency. For hand-pulling to be a viable option for vegetation management in canals it most likely be in small areas where other techniques cannot be employed. Canal flow should be reduced as much as possible to increase efficiency and safety of hand-pulling.

Chaining

Dragging a chain attached to tractors on either side of the canal is a common and effective technique for aquatic plant removal (Wade 1993, Armellina et al. 1996). Chaining dislodges plant material that must be removed from the canal manually or by mechanical means. Plant material that is not collected may contribute to the dispersal of the plants and more extensive weed infestation.

As with many control techniques, timing of the treatment influences efficacy. Like other harvesting operations, rapid regrowth necessitates repeat treatment. Treatments that result in inhibition of propagule formation may have more long-term efficacy (Armellina et al. 1996), although all disturbance-based control methods probably have low efficacy against disturbance-tolerant species, such as many problem aquatic weeds (Sabbatini and Murphy 1996). Chaining for removal of canal vegetation also requires a roadbed on both sides of the canal, which may limit its applicability in many systems.

Excavator/backhoe

Plants may be physically removed from canals with a backhoe, dragline, or similar excavating equipment. Significant drawbacks in the use of an excavator for aquatic weed control in canals include damage to the canal profile and bottom seal and production of abundant plant fragments and turbidity. Over excavation of a dewatered canal followed by backfilling to grade with packed gravel would enhance the efficacy of excavation by providing a substrate that is less susceptible to plant colonization, and provide a firmer surface for future work in the canal with excavation equipment.

Mechanical removal of aquatic vegetation with a backhoe was not highly effective in the Talent Irrigation District in 1997. Removal efficiency was highly variable because sediment suspension limited the operator’s ability to see the plants in the canal. Suspended sediment concentrations increased by 150 times, and plant fragment generation increased by 100 times during backhoe operation. In addition, two weeks following treatment plant biomass was greater than before treatment, suggesting that mechanical removal would have to be repeated frequently.

Mechanical harvesting

Several types of mechanical harvesters have been developed for cutting and removing weeds from lakes and canals. These machines typically include a height-adjustable cutter bar and a basket or conveyor for collecting the cut plants. Floating machines that operate in lakes and reservoirs often have an integrated barge for transporting the cut plants to shore for off-loading. Machines that operate from the bank for use in canals are typically tractor-mounted, hydraulically controlled booms with cutter bars and baskets for collecting the cut plants. When risk of downstream dispersal of problem plants is low, choppers or cutters that leave the plant material in the canal may be more cost-effective than harvesters (Sabol 1987).

Mechanical harvesters must be able to remove approximately two tons of plant material for every mile of canal economically and effectively . In most cases, multiple harvests in a growing season will be required to control aquatic plants (Madsen et al. 1988, Thamasara 1989). Canals to be harvested must be accessible via maintenance road; and not blocked by trees, bridges, fences, and other obstructions. While plants may be piled on the maintenance road in some instances, plant disposal may be necessary near residences to avoid odor problems. Transportation of cut plants adds substantially to the costs of harvesting.

Mechanical harvesting impacts fish and wildlife when the animals are harvested along with the plants (Mikol 1985, Serafy and Harrell 1994), and may cause a shift in the aquatic plant community (Best 1994). Machines that chop plants without removing them from the water may also destroy wildlife living in the canal. Timing of the harvest operations to seasonality in plant physiology may enhance the efficacy of harvesting (Kimbel and Carpenter 1981, Perkins and Sytsma 1987) by reducing regrowth rates.

Ecological (Environmental Manipulation)

Water level

Submersed aquatic plants are dependent upon water for physical support, and lack of a cuticle makes them particularly susceptible to desiccation. Drawdown and exposure has been used to effectively control some aquatic plant species. Drawdown is particularly effective in winter when sediments freeze. Some aquatic plants are adapted to fluctuating water levels (Sculthorpe 1967), and species vary in their response to drawdown (Cooke et al. 1993). Species with propagules that are resistant to desiccation, such as Sago pondweed, may survive exposure through water level drawdown. Seed germination in some species is enhanced by desiccation (Stanifer and Madsen 1997).

Timing of water level manipulation and understanding of the lifecycle of the problem species is critical to efficacy of water level manipulation for aquatic plant management. Early flooding of a California irrigation canal, for example, stimulated precocious germination of Variable-leaf pondweed (*Potamogeton gramineus)* winter buds. Subsequent drying of the canal prior to the irrigation season resulted in a reduction of *P. gramineus* and increase in spikerush biomass in the canal for several years (Spencer and Ksander 1996).

Drawdown effects highly species specific and variable. Unlike Variable-leaf pondweed, Sago pondweed in the California canal was not effected by the early flooding and subsequent drawdown in the California canal noted above. Winter drawdown of a lake in Oregon did not provide effective control of Eurasian watermilfoil, primarily because sediments remained wet and freezing conditions did not occur (Geiger 1983). growth was reduced by Drawdown and rapid filling of a reservoir in India reduced water hyacinth (*Eichhornia crassipes*) growth (Ramaprabhu et al. 1987). An increase in depth reduced Eurasian watermilfoil abundance in a productive Swedish lake (Wallsten and Forsgren 1989)

Efficacious use of water level manipulation for aquatic weed management in Oregon irrigation canals will require a better understanding of seasonality in plant growth and propagule production and germination. Combination of water level manipulation and other treatments, such as herbicides, may increase efficacy (Spencer and Ksander 1992). For example, introduction of water to canals well before the irrigation season may stimulate propagule germination and provide an opportunity for use of herbicides that cannot be used during the irrigation season because of water-use restrictions; or as in California, early water-up and subsequent drawdown and desiccation of plants prior to the irrigation season may provide long-term control.

Sediment amendment

Rooted aquatic plants require sediment for attachment and for nutrient supply. Although some nutrients are acquired from the water column, most nitrogen and phosphorus is obtained from the sediments (Barko and Smart 1986). Nitrogen is typically in shorter supply than phosphorus, relative to the needs of the plant (Madsen 1997). Sediment characteristics are a major determinant of aquatic plant distribution (Overath et al. 1991, Anderson and Kalff 1988), and alteration of sediment characteristics may be an effective way to alter aquatic plant growth and distribution in canals.

Inhibition of the rate that sediments supply nutrients to aquatic plant roots may reduce plant growth rates and alter plant community composition. Aquatic plants grow best in sediments with between 10 and 20 percent organic matter (Barko and Smart 1986), with Sago pondweed more tolerant of high organic matter content than some other *Potamogeton* species (Lehmann et al. 1997). Inhibition of plant growth by sediment organic matter may relate to sediment nutrient density and concentration. Preliminary investigation of the efficacy of organic matter addition on inhibition of growth of Narrow-leaf pondweed (*Potamogeton pusillus)* provided encouraging results (M.D. Sytsma, Portland State University, unpublished data), but needs additional investigation.

Decomposition of organic matter in anaerobic sediments produces low molecular weight acids, such as acetic acid (Gotoh and Onikura 1971). Spencer and Ksander (1995) showed that that acetic acid at low concentrations can inhibit regrowth and sprouting of aquatic plants and their propagules. Experimental field application of acetic acid on sediments exposed by drawdown suggested that the alteration of sediment pH with acetic acid could affect Narrow-leaf pondweed growth (M.D. Sytsma, Portland State University, unpublished data). Application of acetic acid to canal bottoms prior to water-up may be an effective management strategy.

Sediment amendment with barley straw and acetic acid in the Talent Lateral was very effective. Barley straw applied to the exposed canal bottom on April 8 (one week prior to water-up) resulted in virtual elimination of Sago pondweed from the experimental plots during the growing season. Similarly, application of 2.5 percent acetic acid to canal sediments in containers to about 4 percent that in control containers. Five percent acetic acid completely eliminated Sago pondweed in containers.

Several factors limit large scale application of sediment amendment for vegetation management in canals. Most of the barley straw applied to dewatered canals is washed away when water is introduced to the canal, causing maintenance problems at downstream screens. Concentrated acetic acid is caustic and must be handled with care. Furthermore, sediment water content will influence the efficacy of acetic acid in controlling aquatic vegetation.

Sediment removal

Dredging to remove nutrient rich sediment can provide long-term control of aquatic plant growth. Excavation to depths below the light compensation point or to a substrate that does not support plant growth is critical to the success of dredging for aquatic plant control. Aquatic plants are tolerant of extremely low light intensities, and deepening to increase light limitation is probably not feasible in irrigation systems, however, if low-nutrient sediments or sediments that do not permit rooting and attachment of aquatic plants can be exposed through dredging permanent and effective plant control may be achieved (Cooke et al. 1993, Madsen 1997). Potential negative impacts of dredging for aquatic plant control in irrigation districts include: increased turbidity and suspended sediment in the water, which may impact efforts to conserve water through drip irrigation; damage to canal seal and increased loss through seepage; and changes in the gradient and flow characteristics of the canal.

Sediment removal reduced mean plant biomass in treatment plots in the Talent Lateral in 1998. Plant biomass was more patchily distributed in the sediment removal plots than in control plots, suggesting that sediment removal must be consistent to achieve best results.

Sediment cultivation

Bottom tillage, or derooting, has been used successfully in British Columbia lakes for control of Eurasian watermilfoil (Newroth and Maxnuk 1993). In British Columbia the technique is applied during the winter months using a barge-mounted tiller with a six to ten-foot wide rotating head. The sediment is tilled to a depth of four to six inches to uproot and dislodge overwintering root crowns. Uprooted plants float to the surface where they are collected. Winter application provides 80 to 90 percent reduction in stem density and provides two to three years of control.

Bottom tillage has not been used extensively in the United States. The treatment creates turbidity and plant fragments, and may mobilize sediment metals and other contaminants. Shallow (2-4 cm) bottom tilling during a winter drawdown of Lake Oswego was found to reduce mean Narrow-leaf pondweed biomass by 28 percent the following summer; bottom tillage in combination with organic matter incorporation reduced mean biomass by 78 percent (M.D. Sytsma, unpublished data). Bottom tillage in irrigation canals, especially in combination with organic matter addition, may be an effective macrophyte control technique although disturbance of the canal bottom may increase seepage.

Canal lining

Earthen canals provide a good substrate for aquatic plant growth. Lining the canals with geotextile material or concrete, poured in place or sprayed, would reduce availability of rooting substrate and reduce plant problems. Sediment deposition in the lined canal, however, may quickly negate benefits. Concrete-lined canals typically crack and require relining every 10 years, and commonly have weed problems (Fred Nibling, USBOR, personal communication). In the Talent Irrigation District in southern Oregon, aquatic plant establishment and development of up to 30 percent cover in lower, gunnite-lined sections of the Ashland Main Canal have been reported.

A new bituminous geotextile material for canal lining may provide a relatively inexpensive, long-term solution to aquatic weed growth in canals (L. Busch, BOR, personal communication). In addition to reducing aquatic vegetation management costs, canal lining also reduces seepage losses from canals and is an important water conservation tool.

Shading

Aquatic plants, like all plants, require light for photosynthesis. Submersed aquatic plants, however, are well adapted to the low-light conditions that result from light scatter and absorption by water and suspended materials in water. Decline of rooted aquatic plants in systems with high turbidity caused by suspended sediment (Johnstone and Robinson 1987; Engel and Nichols 1994) and phytoplankton (Phillips et al. 1978; Hough et al. 1991) has been attributed to light inhibition.

A number of techniques may be used to reduce light availability for aquatic plants, including dyes, shade fabrics, canal bank vegetation, and piping. Light absorbing dyes, such as Aquashade, are commonly used in closed (no outflow) systems, but is not registered for use in flowing systems. The shading effect of bank vegetation has been reported to impact aquatic plant growth (Dawson 1978, Dawson and Haslam 1983, and Pieterse and van Zon 1982, cited in Wade 1993).

The ultimate shading technique for aquatic plant control is to entirely cover the canal with light-blocking material or to pipe the water. Because of the radius of turns required, adequate right-of-way may not be available for pipe installation in large canals. In smaller canals, however, piping water may provide a long-term (25 years) solution to aquatic weed problems. Use of pipe for water delivery depends upon canal slope and canal size. Pipe diameters up to 36 inches may be economically installed in existing canal beds, and provide capacity for 15 to 20 cfs. Pipe installation has the added benefit of eliminating seepage and evaporation losses and provides the highest level of water conservation.

Stormwater flows may reduce the practicality of pipe for water delivery. Some canals in the RRVP are used for stormwater management during winter, and the pipe size necessary for irrigation water delivery may not be adequate for handling stormwater flows. Restricted stormwater flows may causes flooding upstream of piped canal sections. Where possible, stormwater flow should be directed to natural water courses and diverted from irrigation canals. Diversion of stormwater would facilitate use of pipe for water delivery and reduce sediment deposition in canals; thereby increasing water conservation, minimizing the availability of aquatic plant rooting substrate, and reducing the requirement for aquatic plant management efforts with the associated environmental risks.

Covering the canal with shading material stretched over a framework of metal or plastic may be less expensive initially than pipe for control of aquatic plant growth. An even less expensive alternative may be to train existing canal bank vegetation, *e.g.*, blackberries, to grow over a metal framework to provide shade. Relative to piping water, however, canal covers would have a high maintenance cost and short lifespan.

Shading the canal may produce additional benefits as well as some drawbacks. An ancillary benefit of shading the canal would be a decrease in water lost through evaporation. Use of vegetation to shade the canal, however, may increase water loss through evapotranspiration and entail a maintenance cost associated with tree trimming and fallen branch removal. Root growth into canal banks may also compromise canal bank integrity and increase water loss through seepage.

Shading the Talent Lateral with neutral-density shade cloth reduced plant biomass in the canal, however, rather dense shading (80 percent of incident light) was necessary to achieve substantial biomass reduction. The Talent Lateral results suggest that canal bank vegetation may be used to reduce aquatic vegetation in canals in some areas, however, because canal bank vegetation can interfere with maintenance and lead to leakage of canals shading is not likely to be widely applicable. In some limited situations, where aspect and canal morphology are appropriate, bank shade can be used to reduce canal vegetation problems.

Biological

Fish

Several fish species have been considered as biological control agents for aquatic vegetation. Van Zon (1976) listed 29 species that are phytophagous, feeding primarily on phytoplankton or macrophytes. In practice, however, only one species, the grass carp (*Ctenopharyngodon idella*), has been used for large scale aquatic weed control (van der Zweerde 1993). The grass carp, which is a member of the *Cyprinidae* or minnow family, is a voracious feeder. Small fish may consume a daily ration of aquatic plants equal to several times their body weight per day (Opuszynski 1972, cited in California Dept. Fish and Game 1989). Larger fish may consume a ration equal to their body weight (Leslie et al. 1996, Stocker 1996).

The biology and physiology of grass carp contribute to their effectiveness for aquatic plant control. Grass carp have a short gut, for a herbivore, which allows them to process and eliminate consumed plants quickly (Leslie et al. 1996). Grass carp are essentially 100 percent herbivorous at lengths greater than 3 cm. Although animal prey is not sought by larger fish, animals will be consumed when they are presented in the absence of plants, and inadvertently when they are attached to consumed plants (van der Zweerde 1993).

Grass carp grow rapidly (up to 29 g/day) under uncrowded conditions with abundant food and optimal temperatures (Shelton et al. 1981, Sutton and van Diver 1986, cited in Leslie et al. 1996). In temperate regions, feeding begins at 3 to 9 C, with consumption and growth are typically greatest between 21 and 26 C. Regional acclimation may result in varying temperature optima (Leslie et al. 1996). Plant consumption is reduced at dissolved oxygen concentrations lower than 4 mg/L (Rottmann 1977).

Although rather indiscriminate in their feeding, and not a biocontrol agent in the classical sense (*sensu* Doutt 1967; Roush and Cate 1980; Pietersee 1993, DeLoach 1997), grass carp do exhibit preferences for certain aquatic plant species. Plant preference depends upon the age, size, physiological state of the fish, and on environmental conditions. Small grass carp select small or soft plants, such as duckweeds, filamentous algae, and softer pondweeds. Larger fish still prefer softer plants (although algae are less preferred) but will accept more fibrous plants (Opuszynski 1972, Rottaman 1977).

Site differences influence palatability of plants. Grass carp preference for a species may differ among plants collected from different sites. In one study (Bonar et al. 1990), consumption was positively correlated with plant calcium and lignin content, and negatively correlated with iron and cellulose. Plant nutrient content is, in turn, determined by site characteristics (Hutchinson 1975). These site difference are likely responsible for the sometimes contradictory results of feeding preference studies (Bowers et al. 1987, Chapman and Coffey 1971, Pine et al. 1989, Pauley et al. 1994).

Grass carp are endemic to the large rivers of Asia from the Amur River in Siberia south. All fish introduced into the U.S. are warm-water acclimated fish of Chinese origin (Pauley et al. 1994). Grass carp were first introduced into the U.S. in 1963 and the first documented stocking for weed control occurred in 1970 in Arkansas (Bailey and Boyd 1972, cited in Leslie et al. 1996). Since then, grass carp have been widely distributed in the U.S. for aquatic weed control .

Escape and establishment of reproductive populations of grass carp into river systems (Brown and Coon 1991, Webb et al. 1994, Raibley et al. 1995, Elder and Murphy 1997), and growing concern about the potential environmental impacts of the fish, stimulated some states to ban grass carp. Research on production of mono-sex fish and sterile hybrids provided unsatisfactory results (Leslie et al. 1996). In the 1980s, however, fish culturists were successful in inducing triploidy in grass carp using heat-shock (Thompson et al. 1987) or hydrostatic pressure-shock (Cassini and Caton 1986) of fertilized grass carp eggs. Triploid grass carp are functionally sterile (U.S. Fish and Wildlife Service 1988).

Diploid grass carp are illegal in West Coast states. Beginning in 1990, Washington permitted the introduction of triploid fish into lakes and ponds for aquatic weed control with requirements for containment (Pauley et al. 1994). A recent evaluation of the grass carp stocking program found that stocking in lakes typically resulted in aquatic plant eradication or no control; use of grass carp for maintenance of a desired amount of vegetation was rarely successful (Bonar et al. 1996). Current recommendations for grass carp use in Washington are more restrictive than in the past.

Grass carp were introduced into California to manage hydrilla in the Imperial Irrigation District (IID) in Southern California. Prior to grass carp introduction, costs for aquatic weed management in the IID were $250,000 to $400,000 per year. These costs did not include labor costs of individual farmers required to maintain pipe, pumps, etc. free of plant fragments. The pre-grass carp program was primarily mechanical, and included management of only the worst problems and provided only enough control to maintain flow in the system. The grass carp management program costs approximately $250,000 per year (1992 dollars) to provide plant-free water flow in 2,575 km of canal (approximately $97/km) (Stocker 1996).

Despite a serious aquatic weed problem in many lakes, streams, drainage and irrigation canals and a high level of public demand, Oregon has maintained a prohibition on grass carp for aquatic weed control. Citing concerns over potential reproduction, parasites, and escape, Oregon has permitted only experimental use of triploid grass carp in one lake, Devils Lake. Grass carp were permitted in Devils Lake to evaluate their efficacy, environmental impact, and because the lake discharges to the Pacific Ocean via the D River, which essentially flows from the lake across the beach.

In the early 1980s use of Devils Lake was restricted because of excessive growth of the introduced aquatic plant Eurasian watermilfoil. Triploid grass carp were introduced in 1986 to manage the vegetation at a stocking rate of 180 fish/vegetated acre (27,090 fish; 6.1 fish/ton wet weight vegetation). The management goal was to reduce plant cover to 20 to 25 percent of the lake surface. Within three years Euarasian watermilfoil was eliminated from the lake and Brazilian elodea, another introduced, noxious weed dominated the plant community. Plant biomass increased, however, fish grazing kept the Brazilian elodea from reaching the surface of the lake. In 1993, in response to the perception that weed control was decreasing because of loss of fish through mortality and predation, an additional 5,000 fish were introduced to the lake. In 1994, all plants were eliminated from the lake and the lake has been plant-free since (Sytsma 1996).

While eradication of all vegetation was not the management goal and is in fact detrimental to fish habitat quality in Devils Lake, it may be an appropriate management goal for irrigation canals. Most irrigation canals were designed, and are operated, for the sole purpose of providing water for agriculture; use of canals by fish and other vertebrate and invertebrate wildlife is an ancillary benefit. When stocked at high enough rates, grass carp will eliminate all aquatic vegetation from canals at a cost that is lower than most other aquatic weed management techniques. Complete removal of vegetation may result in some bank erosion as fish start to graze the zone immediately above the water level (van der Zweerde 1993).

When grass carp are used for aquatic vegetation management in irrigation canals that are subject to periodic drawdown, as are the Rogue River Valley Project canals, the vegetation management program essentially becomes a grass carp management program. Maintenance of fish screens, removal of fish from canals prior to winter drawdown, transport to and maintenance in holding facilities, and reintroduction upon water-up of canals in the spring requires experienced personnel and specialized equipment. Grass carp are sensitive to handling and stress during removal, transport, and reintroduction. Mortality could be significant without proper handling procedures.

Grass carp are typically only one component of an integrated approach to aquatic vegetation management in irrigation canals. For example, grass carp prefer a water depth greater than one meter and will move out of vegetated, shallow canals even when food plants are not available in adjacent deeper water; and prefer earthen canals to concrete-lined canals (Stocker 1996). Other, often mechanical, plant management techniques are required for canals where grass carp will not feed or where fish containment cannot be assured.

Several stocking models have been developed for grass carp in lakes and reservoirs (Stewart and Boyd 1994, Bonar et al. 1994) and irrigation canals (Spencer 1994). Development of models for stocking multiple-use lakes and reservoirs has outpaced flowing water, irrigation canal models, primarily because complete eradication of vegetation in canals is often the management objective, and overstocking has no serious environmental consequences. In lakes and reservoirs, however, complete eradication is usually not a management objective and correct stocking rates are more critical in vegetation management. According to one model (Spencer 1994), costs for use of grass carp in irrigation canals varies with management objective and stocking strategy. A management objective that allows for partial control for the first few years after stocking, with a strategy that removes fish during winter and restocks the same fish the following spring, provided the most economical control.

Smaller fish (20-25 cm, < 300 g) are typically provided by hatcheries for stocking. Small fish are often preferred because they are less expensive, and their plant consumption rate (kg plant/kg fish/day) is greater than that of larger fish. Small fish, however, require finer mesh screens for containment and are more susceptible to predation (Shireman et al. 1978, cited by Stocker 1996). Mortality related to hauling is a function of hauling density and time (Clapp et al. 1994). Post-stocking mortality for triploid grass carp (approx. 300 mm fish) in lakes in Arkansas and Florida ranged from 6 to 62 percent (Clapp et al. 1994).

The stocking rate required to control vegetation in irrigation canals depends upon a variety of environmental, plant, and fish factors. High standing stock and species of aquatic plants, water depth and temperature, fish size, predation and mortality all influence feeding rates and stocking requirements. In Europe and Egypt, 200 to 360 kg fish/ha provides control but not elimination of all aquatic plants (van der Zweerde 1993). In irrigation canals in the southwestern U.S., complete removal of aquatic vegetation has been obtained using 50-187 fish/vegetated ha in water velocities less than two m/s; in larger canals, with velocities form 0.3 to 1.2 m/s, 12 fish/ha can provide over 75 percent removal within two years (Stocker 1996). In Florida canals, 25-623 fish/ha prevented regrowth following chemical application (Sutton et al. 1996). Using a modeling approach for California canals, Spencer (1994) found that stocking 250 kg/ ha (1768 fish/ha) would result in complete control in the first year. Stocking 50 kg/ha (357 fish/ha), with removal in the winter and restocking in the spring in subsequent years, resulted in partial control initially and complete control after one to two years.

Uncertainty inherent in stocking models, variability in fish feeding rates and control, and dictates of water management may require removing fish from a waterbody. In canals subject to winter drawdown fish must be removed from the canal and held overwinter. Live capture and handling of grass carp is labor intensive, expensive, and typically only partially successful. In some situations it may be more economical to obtain new stock from suppliers than to catch, hold, and redistribute them (Stocker 1996).

Grass carp have a strong aversion to traps and nets. Various types of traps and nets have low catch-per-unit-effort (Hestand 1996). Baited traps and nets, especially in areas devoid of aquatic vegetation, are more effective than unbaited traps (Schramm and Jirka 1986). Although labor intensive, a baited lift net proved effective in capturing grass carp from a 50 ha, heavily stocked (300 fish /ha) lake (Hestand 1996). Seining has proven effective in some lakes (Bonar et al. 1993) and canals, however, grass carp are notorious jumpers and large fish may be a danger to personnel operating the seine (Stocker 1996).

Destructive capture techniques include use of piscicides (rotentone), angling, explosives, and electroshocking. Fish management bait, a rotenone-laced alfalfa-based pellet, provides selective removal of grass carp, without impacting non-target fish (Mallison et al. 1994). The success of angling for removal of grass carp is cost-effective when only a few fish (< 500) must be removed from lakes with few preferred plant species and anglers are interested and skilled (Mallison et al. 1994b). Bow hunting has limited efficacy, and is only marginally effective with skilled archers, cool water (< 18 C), and low hunting pressure (Hestand 1996). Use of explosives for removal of grass carp was highly ineffectual (Metzger and Shafland 1986). Electroshocking, although typically employed as a non-destructive sampling technique, is often lethal to grass carp (Hestand 1996).

Grass carp containment is critical to effective use in irrigation canals. Physical attributes of canals often influence fish distribution and efficacy. Grass carp avoid areas with high velocity flow, concrete lined canals, turbulence from drops, hydroelectric plants, gates, culverts, siphons, and other structures (Beyers and Carlson 1993, Stocker 1996). In some cases, trash racks already installed in canals can be modified for fish containment. Screen size required for grass carp containment is a function of the size of the fish. Other techniques that may be effective in containing and directing grass carp movements include light, sound, electrical barriers (Curtin 1994).

Competitive plants-spike rush

Some plants have growth characteristics that allow them to dominate and exclude other species from the community. These dominant plants are considered “more competitive” than the plants they displace (Gopal and Goel 1993). Often, the “more competitive” plants are non-native species that have been introduced without their natural control agents. There are also native plants that are adapted to specialized conditions, not well-tolerated by other species, which can form nearly monospecific stands and block flow.

Extensive research has been conducted on the ability of *Eleocharis*, or spikerush species, to “crowd out” and prevent establishment of other species. Spikerush are low-growing and have a negligible effect on flow. Some of the spikerush species form dense mats of roots and rhizomes that form a sod or turf. Slender or Needle spikerush (*Eleocharis acicularis)* and Dwarf spikerush (*Eleocharis coloradensis)* have been observed to replace dense growth of Canadian pondweed and Curly-leaf pondweed, as well as other *Potamogeton* species (Yeo and Fisher 1970, cited in Pieterse 1993). Species vary in susceptibility to spikerush crowding. Sago pondweed is one of the least susceptible species, however, Sago pondweed tuber production is reduced in the presence of spikerush (Yeo and Thurston 1984).

There is some evidence that spikerush influences growth of other species through excretion of growth-retarding substances in addition to physically preventing establishment through preemption of rooting space. Excretion of compounds that restrict growth of neighboring plants is called allelopathy, and is well described and accepted in terrestrial plant communities (Rice 1984). In aquatic systems, allelopathy is less well established. Laboratory studies have demonstrated that extracts of many aquatic plants, including spikerush, have allelopathic properties (Frank and Dechoretz 1980, Elakovitch and Wooten 1989, Sutton and Portier 1989, Sutton and Portier 1991), Although allelopathic effects have been documented in the laboratory, evidence that allelopathy is important under natural conditions has not been demonstrated.

Slender spikerush grows better at low temperatures and low light intensities than Dwarf spikerush (Ashton and Bissel 1987a), and may be better adapted to the environmental conditions present in Northern California and Southern Oregon irrigation canals (Ashton and Bissel 1987b). Spikerush became established in the Corning Canal in California following acrolein treatment (L.W.J. Anderson, USDA/ARS Aquatic Weed Lab., Davis, CA, personal communication), however, attempts to develop a spikerush nursery to serve as a source of seed and sod have been unsuccessful (L.W.J. Anderson, USDA/ARS Aquatic Weed Lab., Davis, CA, personal communication). Pericarp-induced dormancy and low-temperature after-ripening necessitates scarification and cold treatment for good seed germination (Yeo 1986).

Pathogens

Although some pathogens, primarily fungi, have been identified for biocontrol of emergent aquatic plants (Bernhardt and Duniway 1982, Bernhardt and Duniway 1984, Charduttan et al. 1985, Charduttan 1986), very few have been used effectively for submersed plant management. Underwater systems impose ecological and technological constraints on the use of pathogens to manage submersed plants. At present, pathogen control is feasible only for emergent aquatic plants (Charduttan 1993).

Insects

Insects were first used for control of terrestrial weeds over 100 years ago, but there first use for aquatic weed control was in 1964. Since then, insect biocontrol projects have been implemented on emergent Alligator weed (*Alternanthera philoxeroides*), floating Water hyacinth (*Eichhornia crassipes)*, Water fern *(Salvinia molesta)*, and Water lettuce (*Pistia stratiodes*), and submersed species [Hydrilla (*Hydrilla verticillata)* and Eurasian watermilfoil] (Harley and Forno 1993, Cofrancesco and Grodowitz 1994).

Biocontrol of aquatic weeds in the Northwest has focused on emergent species, particularly Purple loosestrfe (*Lythrum salicaria*). A suite of arthropods have been introduced to control the plant and have produced dramatic effects in some Oregon populations (Eric Coombs, Oregon Dept. of Agriculture, personal communication). Investigation of insects for biocontrol of submersed species has been extremely limited. Although some investigations have been conducted on *Euryopsis lecontei* (or its cogenor *E. albertana*), a weevil that feeds on Eurasian watermilfoil (Tamayo et al. 1997), the insect has not successfully controlled Eurasian watermilfoil growth and spread. There have been no biocontrol studies on the native plant Sago pondweed or the non-native Curly-leaf pondweed.

Other

Heat treatment

The use of heat for control of aquatic plants has received little study, although tests of steam treatments for terrestrial weed control has shown promising results (Riley 1995). Eurasian watermilfoil fragments drawn through the cooling system of a powerplant was severely reduced after exposure to 45-50 C for 10 minutes (Stanley 1975). Burning has been studied for control and to enhance nutritional value of emergent aquatic plants (Shay et al. 1987).

Steam treatment of soil did not inhibit germination of tubers of Hydrilla or Sago pondweed (Spencer and Elmore 1993). Steam treatment of aquatic plants exposed by drawdown has not been investigated. Although steam treatment may kill above ground portions of the plants, the effect would likely be similar to a contact herbicide treatment. Periodic retreatment would likely be required throughout the growing season. The time required and probable costs of steam treatment of submersed aquatic plants exposed after drawdown of canal water are likely to be prohibitive.

Components of an IPM Plan for Aquatic Vegetation in Canals

Description of project

Canals and infrastructure

A clear description of the project and problem weeds are needed for development of an IPM Plan for vegetation management. An IPM Plan should include a map that clearly delineates the system design and infrastructure, water and sediment characteristics, and biology of the system. System maps should clearly illustrate where canal water is withdrawn from, or re-enters, natural systems. Headgate locations should be shown and/or described. The typical water management schedule should also be described, including estimates of seasonal demand and periods of drawdown.

Water and sediment

Physical and chemical characteristics of water and sediment can influence plant growth and efficacy of some management options. Water pH and hardness, for example, are important determinants of the toxicity to fish of some chemical (e.g., copper) control options, and water temperature can influence the performance of some biological agents (e.g., triploid grass carp). Important characteristics of the system to document include water temperature, alkalinity or hardness, and pH; and sediment depth and type (rock, gravel, sand, silt).

Biology

Plant distribution, abundance, and species composition within the system should be described. Latin names, rather than common names, should be used to identify plant distribution in the system. Use of common names varies from system to system, and often for individual to individual, making clear communication difficult. Correct identification of the weeds present can be obtained by contacting local extension agents, universities, or the state Department of Agriculture. Line drawings of aquatic plants commonly found in Oregon irrigation canals is included in Appendix C.

Aquatic systems in the Pacific Northwest also contain a number of threatened and endangered species. Some control methods can impact these species. Documentation of the presence, or absence, of these species in the system and in receiving waters is important to ensure that management activities avoid impacts. Documentation of abundance of wildlife in canals may provide an indication of beneficial management if follow-up evaluation of the management actions document an increase in use.

Current Management Practices

A critical evaluation of the benefits and problems encountered with ongoing management activities provides a useful baseline for development of a management plan that enhances cost-effectiveness and efficacy of aquatic vegetation management in canals. Current management activities and associated costs should be described and evaluated.

Assessment of management alternatives

Integrated management requires a consideration of all management options, including combinations of management options, to ensure high efficacy and cost-effectiveness. Some management options present a high risk of nontarget and offsite impacts, while others are clearly too costly for large scale use. Still other management options may have limited efficacy, but and extremely low-cost that makes them cost-effective.

Costs/Benefits

It is difficult to comparable costs and benefits of various management options. Cost per mile of control varies with canal size and water velocity and type of treatment. Duration and efficacy of control is unknown for some techniques, such as some of the innovative chemical and sediment treatments. Because of these unknowns, several assumptions are required to develop standardized and comparative costs for the various techniques. One assessment of benefits, drawbacks, cost estimates, and assumptions is shown in Table 4. Using this scheme, when one treatment provides multiple years of control (*e.g.*, pipe), cost per mile per day is amortized over the lifespan of the treatment.

Costs and benefits can also be developed with a ranking process. A benefit ranking for each technique is calculated as the average of separate rankings for toxicity, efficacy, longevity, and non-toxic effects (turbidity, damage to canals, danger to humans, etc.). An example of this ranking scheme is shown in (Table 5). For some techniques efficacy and longevity are unknown and a range of values must be used to estimate the assigned rank score. Although the ranking requires some crude assumptions and estimates, the average benefit score does provide a relative assessment of the benefits of each treatment.

Using the costs from Table 4 and rankings in Table 5, several techniques clearly rank as high-benefit/high-cost methods: including piping, geotextile lining, and gunnite lining (Figure 12). Hand-pulling and sediment cultivation rank as high-cost/low-benefit treatments. The remaining treatments could be classified as relatively low-cost methods. Grass carp ranked as a high-benefit treatment. Preseason fluridone, and low-rate endothall and copper chemical treatments all had higher benefit rankings, and costs, than xylene. Efficacy of these chemical techniques, however, needs to be clarified. Non-chemical techniques that had a high benefit ranking included: trees, sediment removal, and vegetative cover. The benefit ranking of many methods has low reliability because of assumptions made in ranking efficacy and longevity. In addition, efficacy and practicality of several high-benefit treatments including piping, geotextile canal lining, and gunnite lining, is dependent upon reducing sediment deposition and diverting stormwater flows from canals. Mechanical harvesting and chopping have low benefit scores due to potential non-toxic effects on wildlife. Chaining ranks as a low-benefit technique primarily because of turbidity and fragment generation and its limitation to canals that have maintenance roads on both sides. Backhoe and hand-pulling rank low because of turbidity and fragment generation.

Table 1. Costs, benefits, and drawbacks of various aquatic vegetation management techniques.

	Pros	Cons	Cost/mile	Cost/mile/day	Comments and Assumptions
Chemical					
Acrolein	Very fast acting	Highly toxic to all plants and animals/Requires canal drawdown	$120	$8.57	30 cfs/15 ppm/2 hour treatment/ 3 mile canal/14 day control
Xylene	Very fast acting	Highly toxic to all plants and animals/requires high concentration for herbicidal effectREquires canal drawdown	$289	$20.64	30 cfs/ 600 ppm/ 40 min application/$2.89/gal/treatment of 3 mile canal/14 days control
Copper	Fast acting/low rate applications possible/no interuption in supply	Toxic in soft water/persistent in sediments	$467	$15.56	60 cfs/0.01 ppm/$25 per gal. Komeen/ 3 mile canal/ 90 day control
Fluridone	Systemic/low toxicity	No crop tolerance information/Pre-season application only	$397	$4.41	Static water treatment at 100 ppb of 6.5 m wide, 0.5 m deep, 1.6 km long canal/Sonar at $361per qt./90 day control
Physical					
Hand-pulling	Non-toxic	Generates turbidity and fragments/low efficacy/unsafe	$15,484	$1,106.00	1 person clears 5 m canal in 4 hours @ $12/hr/14 day control
Chaining	Non-toxic	Requires access on both sides of canal/generates turbidity and fragments	$60	$4.29	2 hrs labor/mile for 2 people for chaining and screen cleaning @25/hr/every 2 wks/+ $10 fuel cost
Backhoe/ Excavation	Non-toxic	Low efficacy/generates turbidity and fragments/alter canal hydrology/may increase seepage	$291	$20.81	Based 1997 work in Talent Lateral/assumes 14 day control
Harvesting	Non-toxic	Disposal of plants/kills animals/generates fragments	$50	$7.14	0.5 miles/hr@$25/hr, 7 days control/Requires design and manufacter of equipment

Table 1. Continued.

		Pros	Cons	Cost/mile	Cost/mile/day	Comments and Assumptions
Chopping		Non-toxic	Kills animals/generates fragments	$25	$3.57	1 mile/hr@$25/hr, 7 days control/Requires design and manufacter of equipment
Biological						
Grass carp		Non-toxic/high efficacy/long-term control	Escapement may damage native plant communities/holding and handling required	$60	$0.13	Based on costs of Imperial Irrigation District program; 90 day control; 5 years
Ecological						
Sediment amendment		Non-toxic	Unknown efficacy	Depends on material	Depends on efficacy	
Sediment removal		Non-toxic	Unknown efficacy/disposal of sediment	$291	$6.48	Based 1997 work in Talent Lateral but conducted during drawdown period/assumes 45 day control
Canal lining						
	Gunnite	Non-toxic/reduce evaporative and seepage losses	Cracks may permit plant rooting	$155,232	$345.00	$1.40/sq.ft; 60 cfs canal; 45 day control for 10 years
	Geotextile	Non-toxic/reduce evaporative and seepage losses	Sediment deposition may permit plant rooting	$110,880	$92.40	$1.00/sq. ft.; 60 cfs canal; 60 day control for 25 years
Shading						
	Pipe	Non-toxic/reduce evaporative and seepage losses	Small canals only (< 20 cfs) depends on slope; not sized for stormflow and may cause winter backup and flooding	$158,400	$70.00	$30/ft; 90 day control for 25 years

Table 1. Continued.

		Pros	Cons	Cost/mile	Cost/mile/day	Comments and Assumptions
Bank vegetation						
	Trees	Non-toxic/reduce evaporation	Limited efficacy/root damage to canal bank/increased evoptranspiration loss/interfere with access	$528	$3.77	528 trees/mile; 14 day control for 10 years
	Vegetative Cover	Non-toxic/reduce evaporation	Limit access to canal/marginal increase in evapotranspiration loss	$5,280	$11.73	$1/ft to construct trellis; 90 day control for 5 years
Cultivation		Non-toxic	Inadequate canal drying during drawdown/unkonwn efficacy/potential damage to canal bottom and increased seepage	$3,871	$86	5 m/hour @ $12/hr; requires design and manufacture of equipment; 45 day control
Drawdown		Non-toxic	Unknown efficacy	$0	$0.00	Requires better understanding of propagule germination cues
Heat		Non-toxic	Unknow efficacy/requires dewatering of canal/short-term effect			

*Days of control is surogate for efficacy. Full season, 100 percent control is 90 days.

Table 2. Ranking of benefits and cost of various management techniques

	Toxicity	Efficacy	Longevity	Non-target (not toxic) effects	Average Score	$/mile/day
Chemical						
Acrolein	1	15	1	17	8.5	4.47
Xylene	1	15	1	17	8.5	20.64
Copper	6	7	6	17	9	11.92
Fluridone	10	12	10	17	12.25	4.41
Endothall	10	10	6	17	10.75	9.70
Physical						
Hand-pull	17	5	1	6	7.25	1106.00
Chain	17	8	1	14	10	4.29
Mechanical Harve	17	5	1	5	7	7.14
Chopping	17	4	1	2	6	3.57
Backhow	17	5	1	3	6.5	20.81
Grass carp	17	16	16	10	14.75	19.54
Ecological						
Sediment cultivati	17	8	4	17	11.5	86.00
Sediment removal	17	10	8	17	13	6.48
Pipe Shade	17	17	17	17	17	70.00
Bank Trees	17	10	15	15	14.25	3.77
Veg. cover	17	7	13	17	13.5	11.73
Canal liner	17	15	14	17	15.75	92.40
Gunnite	17	12	13	17	14.75	345.00

generation. Acrolein and xylene ranked as low-benefit treatments because of high toxicity. Techniques that were judged ineffective, that cannot be implemented, or where efficacy and cost estimates were impossible to assign (*e.g.*, heat treatment, competitive plants, and sediment amendment) were not ranked.

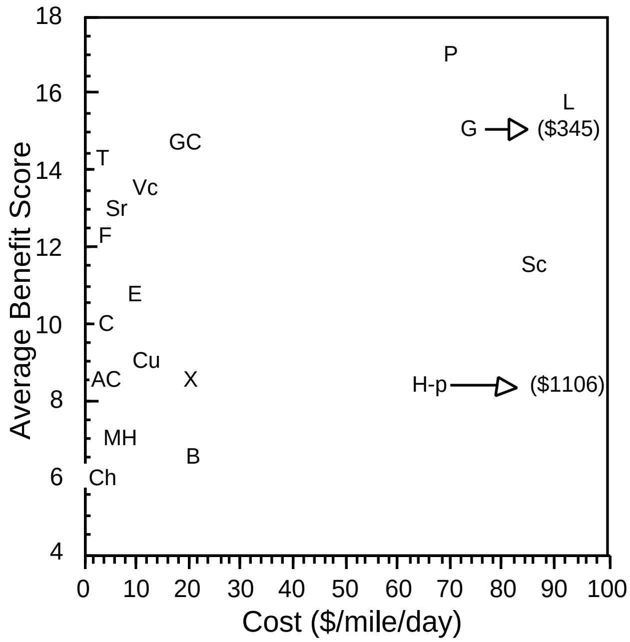

Figure 2. Costs and benefits of irrigation canal aquatic vegetation control techniques. (X=xylene, AC=acrolein, Cu=copper (Komeen), F=fluridone, T=bank trees, MH=mechanical harvesting, Ch=in situ chopping, C=chaining, B=backhoe Hp=hand-pulling, Sr=sediment removal, Sc=sediment cultivation, Vc=vegetative cover, L=geotextile liner, G=gunnite, P=piping.

Management Plan

Integrated aquatic vegetation management requires consideration of plant susceptibility, costs, efficacy, and site and use constraints. Site and use constraints are especially important in management of aquatic vegetation in irrigation canals. Irrigation systems and natural systems are often interconnected, and risk of off-site impacts of management activities is high. As noted previously, decisions on the use of aquatic plant management techniques for aquatic vegetation are often not based entirely on economy and efficacy; management decisions are often constrained by a requirement to minimize potential for off-site and non-target impacts. In addition, management actions must not interfere with use of the water for irrigation. These constraints, along with cost and efficacy considerations, limit the options available for aquatic vegetation management in irrigation canals.

A generalized decision tree is provided to aid in selection of control method in the large delivery canals (Figure 13). The tree is structured to give a high priority to prevention and non-chemical techniques; chemical control is limited to those canals where prevention and non-chemical control cannot effectively and economically control vegetation. Techniques that have not been shown to be efficacious or cost-effective in canals, or that are not applicable in the majority of systems have not been included in the management scheme. Examples of techniques that were eliminated from consideration include use of competitive plants, heat treatment, and chaining. Other techniques, which may be effective but require further development, are recommended for testing before they are incorporated into the management program. Specifically, the use of shade, removal and amendment of sediments, and some innovative chemical treatments require further evaluation for efficacy.

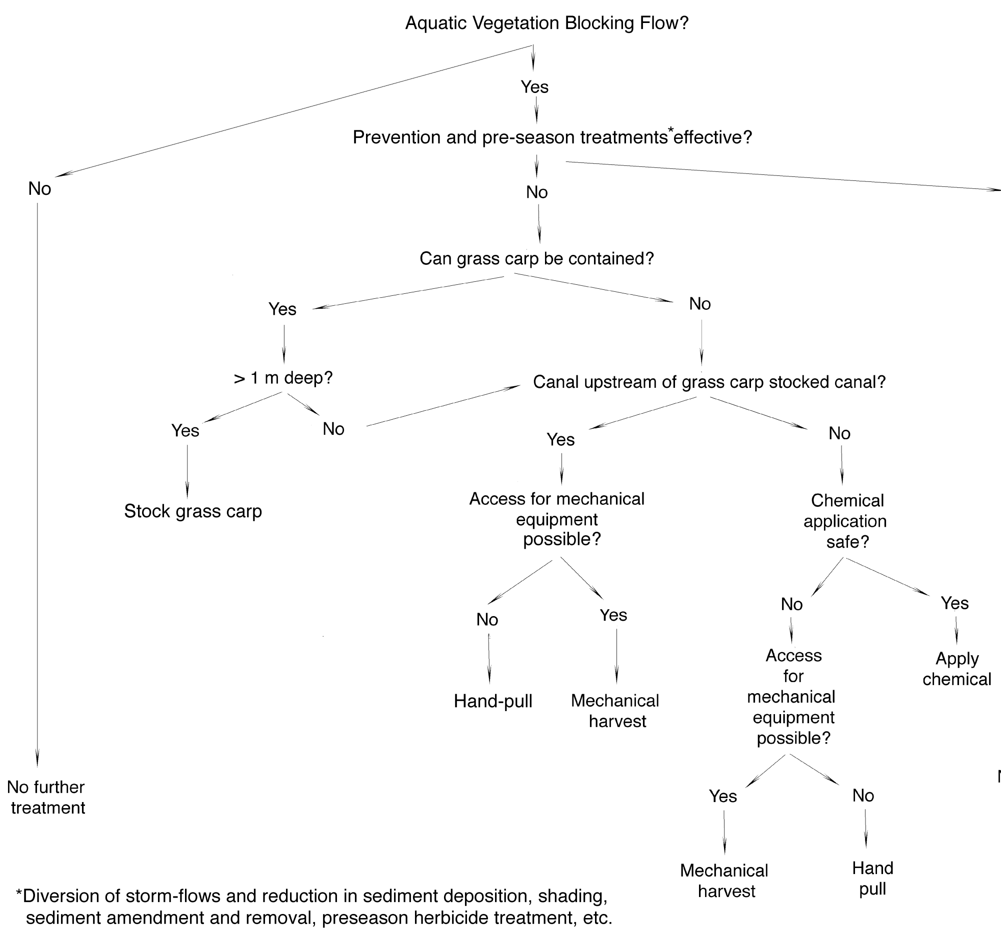

Figure 3. Decision tree for selection of aquatic vegetation management technique for control of aquatic vegetation in irrigation canals.

Prevention

Prevention of aquatic plant problems should be the first consideration of any aquatic vegetation management program. Prevention includes prevention of introduction of new species that could create even greater management problems than currently exist. Prevention of new problems is inexpensive and highly cost-effective. For example, ditchriders should be able to identify species, such as Hydrilla, that are management problems in irrigation districts elsewhere.

Early detection and eradication of newly introduced species may prevent bigger, more intractable problems after the plant is established and widespread in the system. Reservoirs that are used for recreation in addition to storage are particularly vulnerable to hydrilla introduction through recreational boating. Hydrilla infestation of system reservoirs could result in distribution of the plant throughout the canal system and severely impact system operation. Eradication of hydrilla from the reservoirs, should it become established, may compromise water delivery and impact irrigated agriculture throughout the system. Regular surveys of storage reservoirs for hydrilla should be included in a management plan. Additional measures to prevent introduction of hydrilla to the reservoirs should also be investigated, including signage at boat ramps, boat inspections, and wash stations.

Prevention also includes efforts to reduce plant growth rate. Reduction in the rate of plant growth will reduce the frequency, expense, and potential non-target and off-site impacts of any management activity. The efficacy and cost-effectiveness of management actions that focus on reducing plant growth rates have not been clearly defined in some instances. It is clear, however, that efforts to prevent sediment deposition in canals can reduce aquatic plant problems. Diversion of stormwater from canals would reduce wintertime sediment deposition and eliminate the substrate that is critically important for aquatic plant establishment. Diversion of stormwater would also facilitate use of pipe for water delivery in smaller canals, which would eliminate the need for aquatic plant control and contribute to more efficient water use by reducing seepage and evaporative water loss from canals. The multiple benefits suggest that pipe should be used for water delivery whenever possible.

Rooting substrate, nutrient supply, and light are the basic requirements for aquatic plant growth and should be the target of plant growth reduction efforts. Reduction of plant growth rate may be accomplished by removal of rooting substrate through dredging, if the dredging can be accomplished without altering flow characteristics and damage of the bottom seal of the canal. Alternatively, if rooting substrate cannot be removed, it may be made less hospitable for plant growth through cultivation or amendment with organic matter, gravel, or treatment with acetic acid.

Shading the canal may reduce light levels and limit plant growth. In some situations, trees may be used to shade the canal and reduce aquatic plant growth. Trees should be planted to intercept summer sun (south side of canal). Trees should not be used for shade when roots may infiltrate canal banks and lead to leakage and water loss, or where trees will interfere with normal maintenance operations.

Grass carp

Grass carp are appropriate for aquatic vegetation management in canals in Oregon where containment is assured and where they can be incorporated into an integrated, system-wide management plan. Escape risk can never be completely eliminated, however, careful attention to screening and security to prevent theft can minimize risk. Predators may move live fish to natural waters, however, use of large fish should minimize these losses. The potential for damage to natural systems by escaped, sterile grass carp is low relative to the known lethal effects of the accidental release of herbicide-treated water. Furthermore, most aquatic systems in Oregon are infested with non-indigenous aquatic weeds that have more severe impacts on ecosystem function than would be anticipated from escaped grass carp.

Grass carp use in canals will likely require substantial retrofitting of outlet and inlet structures; fish screens of sufficient dimension to prevent grass carp escape will have to be installed on all inlets and outlets. In situations where natural streams enter canals the canal and stream flow must be separated. Such infrastructure changes to the system will require time, a substantial capital investment, and may limit the use of grass carp in the short-term.

Grass carp stocking rates necessary for weed control in Oregon irrigation canals must be determined. Stocking rates in canals with similar water temperatures to those typical in Oregon canals have been evaluated with stocking models (Spencer 1994) and through empirical methods (Fred Nibling, USBOR, personal communication), however, rates may require some adjustment for the plant growth rate and water temperatures in specific locations. Grass carp stocking early in the season, before plants establish substantial biomass in the canals is recommended.

Use of grass carp for aquatic vegetation management in irrigation canals has the ancillary benefit of enhancing the habitat value of the canals for wildlife, particularly the western pond turtle. Of all the control techniques available, grass carp are most compatible with wildlife use of irrigation canals.

It is strongly suggested that all grass carp used for weed control in water conveyance systems in Oregon be marked with a passive integrated transponder (PIT tag). Each tag is programmed with an unique alphanumeric code, so that each individual fish can be identified. The estimated tag life is more than 50 to 100 years. Passive tags are energized by the detector, which activates the tag and then transmits its unique code for display or data storage. Fish identification with PIT tags will permit determination of ownership should grass carp be captured outside the permitted site. The ability to identify the owner of an escaped grass carp will protect districts that employ management practices that ensure containment.

Harvesting

Where prevention actions are inadequate, grass carp cannot be contained, a canal is upstream of a grass carp-stocked canal, and/or chemical application cannot be done safely aquatic vegetation must be removed mechanically or by hand. Mechanical removal is recommended where access is possible. Several designs for machines that can remove vegetation from canals are available (Wade 1993). The primary limitation of mechanical harvesting is the time required for removal and disposal of the harvested vegetation. A design that chops plants *in situ*, without removing them from the canal, may accelerate treatment rate, reduce costs, and increase cost-effectiveness. Where downstream spread by fragments is not a concern, such an aquatic vegetation chopper may provide a mechanical technique that is more economical than mechanical harvesting. Chopping is a new technique that requires further development.

Mechanical harvesting and chopping may impact wildlife in the canals. Harvesters remove animals along with plants. Chopping plants *in situ* would undoubtedly destroy animals along with the plants. Incidental mortality to wildlife should be examined before widespread adoption of harvesting an/or chopping is implemented.

Hand removal may be required in areas that can not be accessed for mechanical removal. Although areas requiring hand removal are expected to be few, the cost of hand removal may make modifications to facilitate mechanical control worthwhile.

Chemical control

Chemical control of aquatic vegetation should be limited to areas where grass carp cannot be contained and where the application can be done safely, without impacting natural systems. Chemical applications should be performed only when and where plants prevent delivery of adequate water. Furthermore, chemical control should only be used after development of a rigorous application protocol that minimizes risk of applicator error and assures that chemically treated water does not escape from the canal.

Conclusions

Aquatic vegetation management in irrigation systems in the future will require use of a variety of techniques to maintain the water flow critical to agricultural productivity and profitability and to protect and preserve important natural resources. Decreased reliance on herbicides, especially highly toxic biocides, should be a goal of all management plans. Prevention of problems through reduction in sediment deposition in canals, shading, and sediment amendment should also be a priority. Use of pipe for water delivery in smaller canals would also prevent aquatic plant problems and have the added benefit of enhancing water conservation in the Districts. Where plant growth cannot be prevented, a combination of techniques including grass carp, sediment amendment, shading, harvesting, and chemical control should provide weed control with minimal risk of off-site and non-target impacts.

Colonization of canals by hydrilla and/or zebra mussels would cause even more severe problems than irrigation districts currently face. Surveys of canals and reservoirs for hydrilla and zebra mussels should be conducted at least twice per year. A signage, boat inspection, and boat washing program at reservoir boat ramps should be developed to protect the system from invasion. A contingency plan for hydrilla and zebra mussel eradication should be developed to prevent spread of an infestation.

Finally, any management plan must be reconsidered on a regular basis. Management methods and timing may have to be modified periodically. All management activities have potential off-site and non-target impacts, and efficacy and risk assessment should be an ongoing activity. Such adaptive management will optimize control over aquatic vegetation in irrigation canals, minimize risks of accidents, and provide the highest level of protection of natural resources.

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Appendix A. Glossary of scientific and common plant names

Potamogeton pectinatus ....Sago pondweed, Mare's tail
Potamogeton crispus ....Curly-leaf pondweed
Potamogeton gramineus ....Variable-leaf pondweed
Potamogeton pusillus ....Narrow-leaf pondweed
Elodea canadensis...............................Canadian pondweed
Myriophyllum spicatum........................Eurasian watermilfoil
Egeria densa ....Brazilian elodea
Ceratophyllum demersum.....................Coontail
Alternanthera philoxeroides.................Alligatorweed
Eichhornia crassipes............................Waterhyacinth
Salvinia molesta ....Water fern
Pistia stratiodes ....Water lettuce
Hydrilla verticillata..............................Hydrilla
Cladophora glomerata ....Frog moss
Eleocharis acicularis .... Slender or Needle spikerush
Eleocharis coloradenis ....Dwarf spikerush

Appendix B. Metric conversions

cubic meter (m^3)..................................35.3 ft^3
hectare (ha)..2.47 acres
milliliter (mL)......................................0.06 in^3
liter (L)...1.76 pint
milligram (mg)....................................0.000035 oz.
gram (g)..0.035 oz.
kilogram (kg)......................................2.2 lb.
millimeter (mm)..................................0.039 in.
centimeter (cm)...................................0.39 in.
meter (m)..1.09 yd.
kg/ha..0.89 lb./acre
mg/m3...ppb
μg/L..ppb

mg/L...ppm
m/s..3.28 ft/s
cm/s..0.033 ft/s
m^3/s..35.32 ft^3/s