Herbicide Resistance Stewardship in Aquatic Plant Management

Aquatic Plant Management Society, Inc.

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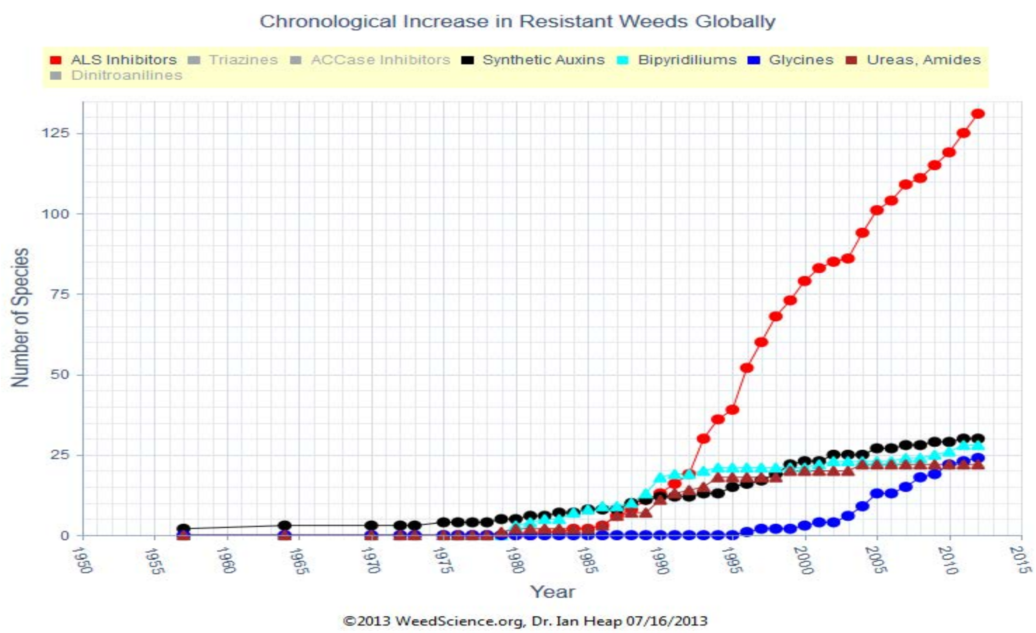
Lesson 1: Background on the Aquatic Herbicide Portfolio, Resistance in Aquatics and Description of Aquatic Plant Management Venues and Plant Types

Aquatic Portfolio and Resistance Concerns

Most aquatic plant managers agree that resistance management strategies are an increasingly important component of any long-term plant management program that employs the use of herbicides. Increasing emphasis on resistance management is heightened by the fact that all of the aquatic herbicides registered since 2003 including carfentrazone, penoxsulam, imazamox, flumioxazin, bispyribac, and topramezone are single site of action compounds (i.e. herbicides target a plant specific enzyme) which have shown potential for weed resistance development in terrestrial systems. Figure 1 shows herbicide classes in which resistance has been confirmed in terrestrial sites during the past five decades. While enzyme inhibitors have great advantages in terms of non-target toxicity and label language that leads to few use restrictions for treated waters, aquatic managers need to recognize that single site of action compounds may be more prone to resistance development.

Figure 1. Number of Plant Species that Have Developed Resistance to Different Herbicide MOAs since the Mid-1950s.



Perspectives on Resistance Development in Aquatic Plant Management

It is important to note there are very few documented cases of true herbicide resistance in aquatic plant management. The widespread development of resistant strains of hydrilla (*Hydrilla verticillata* L.f. Royle) to the phytoene desaturase (PDS) inhibiting herbicide fluridone has been well documented (Albrecht et. al. 2004, Arias et al. 2005, Dayan and Netherland 2007). Outside of this high profile instance, other examples are fairly minor and site specific. For example, a duckweed species (*Landoltia punctata)* was discovered in a single Florida canal system that possessed a 50-fold resistance to diquat (a Photosytem I inhibitor) (Koschnick et al. 2006). Low level resistance of hydrilla to label rates of endothall dipotassium salt (a contact herbicide that inhibits multiple serine/threonine phosphatases (Bajsa et al. 2012)) was reported in two Central Florida Lakes (Berger et al. 2011). Outside of Florida, there have been no documented cases of aquatic plants developing herbicide resistance.

Issue: Adapting to Fluridone Resistance in Hydrilla in Florida Lakes

While the hydrilla resistance to fluridone represented a significant impact to a cost-effective and selective management program for large-scale hydrilla management, there is another perspective on this issue. Prior to resistance confirmation in 2000, fluridone was the only herbicide available for large-scale hydrilla management that provided long-term (12-18 months) selective control with few water use restrictions. The registration of herbicides such as penoxsulam, imazamox, flumioxazin, bispyribac, and topramezone was significantly influenced by the perceived opportunities in the Florida hydrilla control market afforded by the loss of fluridone as a management tool due to resistance development. Additionally, it is important to note that despite the issues with fluridone-resistant hydrilla in Florida, there have been no additional documented cases of fluridone resistance outside of Florida, despite widespread use over a period of nearly 30 years. The specific factors that influenced fluridone resistance in Florida remain a key question for aquatic plant managers and researchers. In the meantime, fluridone continues to be used successfully to control hydrilla in many lakes and ponds in the state. A genetic test is available to managers to determine if the site contains a susceptible or resistant population. Many of the resistant strains of hydrilla in Florida are still susceptible to label rates of fluridone; however, issues regarding increased costs and selectivity to conserve non-target plants have limited the applicability of this use pattern.

Species Shifts Due to Reliance on a Single Mode of Action

While resistance development remains a concern in aquatic plant management, the repeated use herbicides with similar mode of action has more often been associated with a shift to a plant species or variant (hybrid) that is less susceptible to the repeated management strategy. A documented example of this includes a shift from the more susceptible Eurasian watermilfoil (*Myriophyllum spicatum*) to hybrid watermilfoils which have shown increased tolerance to fluridone as well as 2,4-D and triclopyr (auxin mimics) (Thum et al. 2012, Berger et al. 2012, LaRue et al. 2013). There are numerous other examples of shifts in weed spectrums in aquatic plant management and at present this issue is of much greater operational concern to aquatic managers when compared to herbicide resistance. The selection for a more tolerant species is not the same as resistance; however, it illustrates an additional rationale for managers to implement resistance management strategies where feasible.

Rotation and Resistance Management

With growing interest in resistance management, there is increasing discussion about the appropriateness of using the terms *herbicide rotation* and *resistance management* interchangeably. Herbicide rotation is one of the many stewardship (or resistance management) strategies considered by aquatic plant managers presented in this document. Herbicide rotation is a cornerstone of resistance stewardship in commercial crop management. However, plant management in aquatic sites is dependent on a number of environmental and situational issues that can change rapidly throughout the season. This means that aquatic managers are often left with few viable and cost-effective alternatives for certain weed management issues.

Description of Aquatic Plant Management Venues
It is tempting to suggest that the most successful resistance management strategies from commercial crop management should be incorporated into aquatic plant management. However, the similarities and differences in these plant management venues must be assessed before developing an aquatic herbicide resistance management program. In defining the term "control" from an aquatic plant manager's perspective, the Aquatic Plant Management Society (APMS) reported a diverse continuum of expectations and outcomes related to amount and duration of aquatic plant control. To grasp the divergence in opinion on what defines "acceptable" levels of weed management, it is important to understand the basic venues and types of aquatic plants that are under consideration. After this, assessing which crop management strategies may or may not apply in aquatic situations can be discussed. Following are descriptions of the two basic venues where aquatic plants are managed and the considerations that are critical in establishing herbicide resistance management programs.

Natural or modified natural areas:
- include ponds, lakes, reservoirs, streams, rivers, canals, and wetlands
- most plant and animal species present are considered valuable to the ecosystem
- management strategies should provide effective control of the target plant while conserving or enhancing native or other valuable plant and animal species
- to preserve desirable species, selectivity considerations may:
  - limit the number of herbicide active ingredients that are available
  - limit the rates and timing of application
  - influence the cost and amount of control that can be accomplished
- key differences between crop and aquatic plant management
  - crop management - many weeds targeted among 1-2 non-target species
  - natural areas invasive plant management – generally 1-2 plant species targeted
    - ✓ among many desirable plant and animal species
    - ✓ conserving or enhancing non-target species is equally or more important than control of the target plant
    - ✓ water exchange and ability of plants to move within aquatic systems

Man-made sites:
- include irrigation canals, aqueducts, water retention and water feature ponds (e.g. golf courses, homeowner associations, industrial parks)
- any amount of macrophyte growth may be considered as undesirable
- objectives can be similar to commercial crop herbicide application strategies
  - plants are subject to maximum control efforts with lesser emphasis on selectivity
  - more herbicides may be available to incorporate into management operations

Description of Aquatic Plant Types

There are four general plant morphologies or plant types controlled in aquatic plant management venues: emergent, floating, and submersed vascular plants, and algae. For each plant type, an herbicide may have very different effects. For example: glyphosate is effective when applied to above-water leaves of floating water hyacinth (*Eichhornia crassipes*) or emergent cattail (*Typha* spp.), but is ineffective if injected into the water to control a submersed plant species. Further, glyphosate is effective in controlling torpedograss (*Panicum repens*) leaves and stems above the waterline, but does not translocate to submersed shoots or roots. Conversely, many aquatic herbicides have activity via both application methods; foliar control of floating or emergent species and control of several submersed species. While discussion of individual aquatic herbicide use patterns is beyond the scope of this document, information on use patterns, use rates, herbicide degradation, etc. can be found in Netherland (2012).

Emergent plants:

- include grass, sedge, and rush species and numerous broadleaf emergent plants (e.g., *Pontederia, Sagittaria, Eleocharis, Scirpus, Typha,* spp.)
- control, especially large-scale control, is similar to commercial crop management
    - vast area monocultures like torpedograss, phragmites (*Phragmites* spp.), and cattail are targeted with herbicides, often via aerial application
    - herbicides are applied directly to plant foliage
    - herbicides can be precisely applied within a defined area
    - limited off-target herbicide movement via aerial or boat-mounted spray equipment
- small scale or spot control is frequently practiced
    - selectivity concerns may reduce the number of herbicides available and size of areas to which herbicides are applied
        - ✓ notably when controlling invasive grasses growing among desirable native grasses or other emergent vegetation

Floating plants:

- include large species - (water hyacinth and water lettuce (*Pistia stratiotes*)) and small plants (*Salvinia* spp., duckweeds (*Lemna* spp.), and watermeal (*Wolfiella* spp.)).
- herbicides are most often applied directly to the foliage of large floating plants
    - large-scale application strategies are likewise similar to commercial crop applications
- injecting herbicides into the water column for root uptake is becoming an alternative approach with some ALS and Protox inhibitors and has been used extensively with fluridone for duckweed, salvinia, and watermeal

Submersed plants:

- include invasive hydrilla, Eurasian watermilfoil, curlyleaf pondweed (*Potamogeton crispus*), and egeria (*Egeria densa*) prevalent in natural areas
- sago pondweed (*Stuckenia pectinata*) and other species in irrigation canals
- submersed plant control is usually the most expensive control from a per-acre perspective
- most strikingly different from commercial crop management
    - entire water column may be treated vs. foliar application in crop management
    - herbicide exposures in aquatic systems range from hours / days for fast acting herbicides to weeks / months for slow acting compounds

- water exchange (via gravity, wind, and internal heating and cooling convection currents) can dramatically impact both the herbicide rate and exposure time
    - herbicides begin to disperse from the target zone after application
    - entire three dimensions of ponds and lakes may be dosed with an herbicide application
- plants in a portion of the water body may be targeted (e.g. 10 acres in a 1,000-acre lake)
- management objectives in natural areas usually include controlling invasive species while conserving or enhancing many comingled non-target species
    - selective plant management:
        - ✓ usually limits the number of available compounds,
        - ✓ dictates length of exposure, rate and timing of application,
        - ✓ may limit the amount of control attempted
- pre-emergent strategies are rarely applicable for submersed plant control except during drought or planned water level drawdown where the herbicide can be applied to the dried exposed sediments

Algae:

- include filamentous (multi-cellular), phytoplankton, blue-green (cyano bacteria), and macrophytic algae
- blue-green algae can produce toxins, cause taste and odor issues in drinking water, and degrade the value of property when these plants bloom or form dense surface mats
- copper-based compounds have been the dominant mode of action to control algae for decades
- few realistic alternatives to copper currently exist
    - most aquatic herbicides do not have algal control activity at label use rates
    - amine salt of endothall, peroxide based algaecides, enzyme-based approaches currently have minor niche uses in algal control market
- ability to rotate modes of action or develop other resistance management strategy is difficult given:
    - the current reliance and proven track record of copper
    - the increased cost and variable activity of other current options
- this area of aquatic plant management may be the most difficult in which to currently develop a resistance management strategy based on herbicide rotation

Lesson 2: Resistance Management Considerations in the Realm of Available Herbicides, Aquatic Plant Growth Patterns, and Current Control Strategies

Herbicide Application Strategies that Influence Resistance Management

Some weed scientists infer that one resistant individual is present in a population and repeated applications of the same herbicide allows proliferation of the resistant plant(s). The inference is often followed with a caution to use maximum label rates and rotate modes of action. Aquatic plants are found in many different combinations with other plant and animal species. They are also found growing under many different ecological and climatological conditions in waters with widely varying uses and functions. Managers employ differing strategies to cope with each situation; therefore, there is no one strategy to address resistance management in aquatic plant management situations.

Following are considerations that confront aquatic plant managers along with rationale and examples from frequently encountered scenarios in aquatic plant management. Singly, these scenarios present difficulties for managers controlling plants in multiple use systems under conditions that can change considerably from one application to the next. Adding to the complexity, most issues noted below occur collectively within each water body - each influencing management plans and anticipated outcomes. These examples express the difficulties encountered when managing submersed aquatic plants.

- **Large-scale vs. spot applications**

Large-scale applications expose a greater number of target plants to an herbicide, intuitively increasing the potential for resistance. Consequently, managers often increase surveillance, especially for invasive plants that are present in the ecosystem, to control smaller populations before they manifest into large problems. While acting early may reduce the amount of herbicide ultimately applied to the system, many small-scale herbicide applications may expose plants outside the target area to repeated sub-lethal herbicide doses through dissipation or dilution, presenting additional pathways toward potential resistance development.

Managers face several obstacles in employing early detection and rapid response (EDRR) management strategies in public waters, especially for submersed plant control in multiple use systems (e.g. real estate, boating, fishing, recreation, potable water). Unless detailed and frequent surveys are conducted, submersed plants are difficult to detect until they become established across a broad area. Additionally, stakeholders often oppose the use of pesticides in public waters until large-scale problems develop. Stakeholders are increasingly pressing managers and elected officials to exploit ecological services provided by invasive plants, postponing control and allowing large populations to establish that in turn require long-term and intensive management with herbicides.

- **Large lakes or reservoirs vs. smaller ponds**

Whole-lake herbicide applications are usually more economically and logistically feasible in small lakes and ponds than in large systems. There may often be a larger array of management options available for smaller waters that have fewer overlapping or competing uses. Surveillance and follow-up management is often more effective in smaller systems. Larger lakes usually equate to more comprehesive herbicide applications to control plant populations. However, invasive or nuisance aquatic plants rarely are allowed to cover or fill an entire system. Nonetheless, once plants reach a certain level, treatments may result in whole-lake concentrations of the herbicide. Additionally, there may be many small-scale applications in a large waterbody resulting in frequent sub-lethal exposures outside of the targeted area. It is important to note that despite multiple thousands of herbicide and algaecide applications to small ponds over a period of decades, there have been no cases of documented herbicide resistance emanating from these venues.

- **Plant populations with many individuals per surface area**

It is important to note that most invasive aquatic plant species grow and persist via vegetative propagules, budding, or cell division (algae), and sexual reproduction is often a minor factor in plant expansion. It would seem intuitive that some plant species may be more susceptible to developing resistance based on the number of plant individuals or growing apices within the population. For example, water lilies may have 10-20 leaves per square meter vs. hundreds of thousands of individual plants per square meter for duckweeds or salvinia. In the case of fluridone-resistant hydrilla strains that developed in Florida, large-scale applications dosed thousands of acres and exposed hundreds of millions of growing tips to fluridone for several months during a single control event. Similarly, diquat resistance was reported after multiple applications to control dense growths of *Landoltia punctata* in a Florida canal in which plant densities can reach 0.5 – 1.0 billion plants per acre. Conversely, no resistance issues have been reported after years of fluridone applications to control *Wolfiella* spp. that can reach densities approaching 5 – 10 billion plants per acre. Copper has been applied for decades to control planktonic algae, with cell counts approaching 20 million cells per ml of water, and no documentation of resistance.

- **Invasive vs. native plant control**

Invasive plants like hydrilla, Eurasian watermilfoil, torpedograss, and giant salvinia usually have much faster growth rates than native plants, therefore requiring more frequent management. Additionally, invasive plants usually interfere with designated water uses and functions more than native plants and consequently are more often targeted for control. However, some native plants like algae, duckweeds, and watermeal can reach nuisance levels and are targeted for control with similar frequency and in similar sites as invasive aquatic plants**.**

- **Sub lethal herbicide doses**

A frequently recommended herbicide resistance management strategy is to apply full label rates to control target plants. While this strategy is emphasized in commercial crop management, in aquatic sites the maximum label rate may be many times higher than the lowest effective rate for a target plant species (e.g. effective rates of fluridone can be 30X lower than the maximum label rate). The practice of using lower than label use rates in aquatic plant management is especially important in natural systems where selectivity to conserve or enhance non-target plants is often as or more important than target plant control.

Additionally, applying maximum label rates is difficult for aquatic plant control in natural areas from a cost perspective, especially for large-scale management programs financed with public funds. Further, governments have funded decades of research to identify the lowest herbicide rates possible when controlling aquatic plants in natural areas to meet increasing stakeholder and regulatory (NPDES) demands of limiting herbicide discharges to public waters, and to improve selectivity in controlling target plants while conserving or enhancing comingled native vegetation.

Issue: The Inevitability of Sub-lethal Herbicide Exposures in Submersed Aquatic Applications

Most herbicide treatments to control emergent and floating plants are fairly straight forward with the majority of foliar herbicides applied directly to leaves at a prescribed rate. Submersed applications of herbicides are immediately subject to dissipation through dispersion from the treatment site. Managers often try to control small areas of submersed invasive plants before they become widespread disruptive populations. This results in many small-scale lake perimeter or spot applications. Unless the entire water column throughout the entire water body is treated at a maximum label rate, there will likely be plants outside of the target area exposed to a sub-lethal herbicide dose. Paradoxically, selecting maximum rates for spot applications may enhance the lake-wide exposure to sub-lethal rates via dissipation of a greater volume of herbicide applied.

- **Herbicide modes of action and their likelihood of resistance development**

Since the early 1980s, ALS herbicides have shown the greatest propensity for resistance in terrestrial applications. While several new chemistries have been registered since 2003 by the U.S. Environmental Protection Agency for use in aquatic sites, seven of the ten herbicides available to control hydrilla are active on one gene site and three of these herbicides target the ALS enzyme. Managers should be aware of which herbicide modes of action have the highest number of resistant weed species in terrestrial venues and design aquatic plant management application strategies that consider these statistics.

Issue: A Matter of Scale? Comparing Weed Management in Production Agriculture vs. Aquatic Systems

Aquatic plant managers generally agree that incorporating resistance management strategies into herbicide application programs is logical from a stewardship perspective. Evidence of resistance development in weeds controlled in crop production is compelling in that many of the herbicides used in aquatic plant management venues are from the same MOAs used in agricultural settings. However, it is important to note that there is a considerable difference in scale between the volume of herbicides applied in crop production vs. aquatic plant management. An estimated 175 million acres of corn and soy beans are planted in the U.S. and herbicides may be applied for weed control 2-3 times per year to this acreage. The Florida Fish and Wildlife Conservation Commission oversees the largest aquatic plant control program conducted in natural areas in the U.S., managing an average of 70,000 acres of aquatic plants each year (0.04% of the corn/soybean crop acreage). Further, these applications are spread out in about 300 lakes and rivers across the state. Most of the applications are to small acreages compared to overall waterbody size or spot treatments, and some of these sites may be treated only once in several years.

- **Plant growth patterns and the likelihood of developing resistance**

Aquatic plant managers are faced with several dilemmas regarding plant growth and reproduction when drafting management strategies using herbicides. Should managers be more assertive implementing resistance management strategies to control fast-growing invasive plants that may need multiple control events each year vs. native plants that are controlled once every several years in a given aquatic system? Does prolific sexual reproduction equate to a greater possibility of resistance development? Do plants that only reproduce vegetatively have a lower potential for resistance? What about plant species that have multiple asexual reproductive avenues in addition to sexual reproduction? It is important to note here that fluridone resistant hydrilla developed in Florida from an asexually reproducing population due to somatic mutation and resistance took several years to develop after nearly continuous exposure to some level of the herbicide.

Resistance Management Strategies Considered in Aquatic Systems

Following are several strategies that aquatic plant managers consider when developing and implementing herbicide resistance stewardship programs. Cautionary considerations are warranted prior to selecting an herbicide application strategy outlined below, particularly if implementing a rotational strategy. There are few registered herbicide compounds available from which to select an initial control strategy. From nearly a century of applying chemicals to control aquatic plants, managers have learned that eradication or containment, especially for invasive plants established over a broad area, requires a persistent and dedicated effort. In most situations, the initial control effort represents the most cost-effective and selective strategy available. Therefore, follow-up efforts using alternative herbicides, if any are available, may represent a more costly, less selective, and/or less effective control strategy.

- **Practice EDRR or Maintenance Control where possible vs. waiting for problems to develop**
  - eradicate pioneer invasive plant populations before they establish
    - e.g. eradicate pioneer hydrilla populations in FL and giant salvinia in SC
  - control plants when success is most likely
    - small populations vs. large
    - early in the season when plants are generally most susceptible and biomass is low
    - spot applications (fewer individuals) vs. large-scale treatments
  - apply herbicide strategies that are most effective on target species
    - may require multiple applications with the same mode of action
    - apply herbicide before plants go to seed or produce asexual vegetative propagules

- **Herbicide application strategies to consider where applicable**
  - rotate active ingredients
  - combine active ingredients with differing MOAs
    - follow-up strategy after single herbicide application to control survivors / outliers
    - apply different MOA or different application method or timing
  - integrate bio control or other physical / cultural method - for example:
    - stock low rate of herbivorous fish after initial herbicide application to control hydrilla
    - burn phragmites or torpedograss to reduce biomass and apply herbicide to control regrowth

- apply at time of highest probability for control to minimize need for follow-up
    - use plant phenology information to choose the herbicide and application timing
    - apply in conditions that minimize herbicide degradation (light/temp/microbes) and dissipation (water exchange) before the herbicide can be fully effective on the target
- apply effective rates to control target plants

Limitations to Herbicide Resistance Management Strategies in Aquatic Systems

While it may not be readily apparent, aquatic plant managers consider resistance management practices when drafting plans that include the use of herbicides. Practical stewardship solutions are incorporated where appropriate, but often few alternatives are available. Aditionally, many sites require long-term data development to justify product use. It is difficult to alter a strategy and rotate to a new active ingredient unless similar long-term efficacy and non-target species data development projects are completed. Some key constraints influencing herbicide resistance management strategies are listed below.

- cost, especially for public-funded aquatic plant control
- reduced non-target plant species selectivity, especially at higher herbicide use rates
- limited effective / selective options
- water exchange - maintaining optimum use rate in control site for submersed control
- regulatory constraints for certain products (e.g. drinking water / irrigation restrictions)
- stakeholder opposition

The Spectrum of Herbicides Available in Aquatic Plant Management

Fourteen herbicides are registered by the U.S. EPA for use in aquatic systems, representing nine modes of action. Nine of these herbicides are enzyme-specific inhibitors (Table 1). At first glance, this appears to provide managers with an adequate array of options to weave into herbicide resistance management programs. However, two examples below from Florida provide insight into the difficulty facing aquatic plant managers in selecting responsible, cost-effective herbicide resistance management strategies.

Case 1 - Hydrilla Management in Florida Public Lakes and Rivers

Ten of the 14 herbicides registered for use in Florida waters have activity in controlling hydrilla. While the available herbicide options appear to be relatively high, site conditions usually reduce practical hydrilla management strategies to one or two alternatives for each water body. State regulatory requirements limit copper in public lakes and rivers to sites where no other viable control method is available. Diquat is relatively ineffective in controlling hydrilla when applied alone. Carfentrazone and flumioxazin have moderate hydrilla activity and are degraded in a matter of minutes in waters with a pH above 9.0; a typical condition in Florida waters. Imazamox acts primarily as a growth regulator rather than a herbicide for hydrilla control. Topramezone was registered by U.S. EPA for use in water during late 2013 and is under evaluation for its potential use in Florida waters. When used alone, bispyribac, fluridone, and penoxsulam, require exposure periods of several months for effective hydrilla control, presenting challenges including sustaining effective concentrations, limiting water uses over an extended period (i.e. irrigation), and non-target plant selectivity. After years of research and operational monitoring, managers often opt to apply endothall alone or in combination with other of the aforementioned herbicides, each combination of which has different levels of effectiveness in controlling hydrilla or impacting different assemblages of comingled non-target plants.

Case 2 - Torpedograss Management

At the other end of the spectrum, only glyphosate and imazapyr provide effective torpedograss control in Florida waterbodies and wetlands. Torpedograss continues to expand its range and is already present along shorelines and in shallow waters of more than 80% of Florida's 460 public lakes and rivers. Glyphosate alone may provide temporary control, requiring multiple applications each year. Imazapyr cannot be applied within one mile of a functioning water intake, including ever-increasing irrigation intakes for lawns and gardens in residential / riparian areas. This effectively limits torpedograss control in most Florida public waterbodies to repeated applications of one moderately effective tool.

Table 1: Registered Aquatic Herbicides, Primary use Pattern, Year of Registration, and Mode of Action

Herbicide	Primary Application Site	Year of Registration	Mode of Action
Copper	Algae / Submersed	1950's	Undefined plant cell toxicant
2,4-D	Submersed / Emergent / Floating	1959 (ester) 1976 (amine)	Auxin hormone mimic
Endothall	Submersed / Algae	1960	Inhibits multiple serine / threonine phosphatases
Diquat	Submersed / Emergent / Floating	1962	Photosystem 1 inhibitor
Glyphosate	Emergent	1977	Plant enzyme inhibitor - EPSP
Fluridone	Submersed	1986	Plant enzyme inhibitor - PDS
Triclopyr	Submersed / Emergent	2002	Auxin mimic
Imazapyr	Emergent	2003	Plant enzyme inhibitor - ALS
Carfentrazone	Submersed / Emergent / Floating	2004	Plant enzyme inhibitor - PPO
Penoxsulam	Submersed / Floating	2007	Plant enzyme inhibitor - ALS
Imazamox	Submersed / Emergent / Floating	2008	Plant enzyme inhibitor - ALS
Flumioxazin	Submersed / Emergent / Floating	2011	Plant enzyme inhibitor - PPO
Bispyribac	Submersed / Floating	2012	Plant enzyme inhibitor - ALS
Topramezone	Submersed	2013	Plant enzyme inhibitor - HPPD

Considering the Potential Role of Use Patterns and Resistance Management

There remains significant speculation regarding factors that lead to widespread resistance of hydrilla to fluridone in Florida public waters. While multiple successive applications are likely the key factor that drove selection of the resistant strains, various attributes of fluridone may have also contributed to the onset of resistance. Treatment strategies often relied on near maximum label rate applications in a specific area of a waterbody with the intent of impacting hydrilla via dispersion throughout a much larger area or the entire lake. This was possible as fluridone can have relatively long half-lives in water (as much as 30-35 days for winter/spring applications in Florida waters). These long half-lives and the slow death of the plant over a period of months allowed for an extended period of time in which selection pressure was being exerted on hydrilla recovering from fluridone stress. In this case, both the excellent control and increased potential selection of a resistant strain were due to the same use strategy with fluridone. In hindsight, other than avoiding multiple successive fluridone applications, it is unlikely that application strategies would change. The use patterns of ALS herbicides such as bispyribac, penoxsulam, and topramezone also rely on extended exposures at low use rates to provide selective control of submersed plants. Given the issues with ALS resistance issues in terrestrial systems and fluridone in Florida, managers should develop programs that do not rely on successive large-scale applications of products that have long aqueous half-lives and high levels of activity at low rates.

Roles of Aquatic Herbicide Users in Regards to Resistance Management

While resistance management practices are viewed as necessary for long-term sustainability of herbicide control tools, implementing stewardship practices are mostly voluntary. Governments can require resistance management practices: U.S. EPA via label language, or state / local agencies via permits, rules, or ordinances. However, effective regulations require enforcement that must be both practicable and affordable across all scales of application. With voluntary compliance, concern then becomes, should a potentially more costly, less selective, less effective herbicide strategy be integrated for plant management for one water body if an adjacent water manager does not adopt such a program? If resistant plants develop in this jurisdiction there is significant potential of movement of plants to adjacent waters where resistance management is implemented. Listed below are stakeholder groups that play important roles in the implementation of herbicide resistance management efforts, especially in public waters.

- regulatory agencies
  - U.S. EPA registers herbicides for use in waters
    - ✓ requires regulatory label language
    - ✓ label language for newly registered herbicides provides management precautions regarding resistance management (penoxsulam, flumioxazin, and bispyribac)
  - state departments of agriculture
    - ✓ register herbicides for use within most states
    - ✓ enforce label requirements
  - permitting agencies
    - ✓ usually state (rules) and sometimes local governments (ordinances)
      - e.g. DEQ / DEP / DNR / DEC / DOE / DOC / FWC, etc.
    - ✓ regulate through permit requirements
      - can require sampling / testing to determine level of susceptibility (e.g. fluridone)
      - can require resistance management strategies for repeated control efforts
- industry
  - encourage users to incorporate resistance stewardship strategies
    - ✓ recommendations via technical support personnel
    - ✓ produce and distribute research findings and product literature
    - ✓ include voluntary label language related to mode of action and resistance stewardship
  - draft labels for U.S. EPA requirements / acceptance

    - ✓ label language can be advisory or enforceable
- entities that apply herbicides to water
    - government agencies apply or contract herbicide applications in public waters
        - ✓ fund or conduct research or monitoring to develop resistance management strategies
    - private companies with many applicators and accounts in public / private waters
    - individual riparian owners, small herbicide application company

Comparisons for Herbicide use to Control Plants in Commodities vs. Aquatics

Table 2 summarizes the similarities and differences among commercial crop weed management and weed management in private and public waters. This may be helpful in providing insight into the difficulties and sometimes reluctance of aquatic plant managers to employ traditional herbicide rotation as a viable resistance management strategy in aquatic venues.

Table 2: A Broad Comparison of Issues Related to Commodity-Based Weed Control and Aquatic Weed Control in Private and Public Waters.

Commodities	Aquatics - private water	Aquatics - public water
Business operation	Business operation	Resource management
Decisions based on fundamental economics - individual often decides management strategy	Decisions based on fundamental economics driven by customer demands	Decisions based on quantity and quality of area managed - often with substantial stakeholder input
Budget from cash flow, credit, etc. - can tolerate increased cost if the result is increased revenue	Budget based on bid price or contract - limited flexibility to operate outside of contract price	Defined budget - no flexibility in overall budget - some flexibility for individual project budgets
Sexually reproducing species with significant seed dispersal	Strong focus on algae in ponds: invasive and nuisance vegetation in small areas of lakes	Vegetatively reproducing annual / perennial weeds - focus on invasive plants: low seed viability
Herbicides applied to surface area - in two dimensions	Herbicides / algaecides often applied to water volume - in three dimensions	Herbicides often applied to water volume - in three dimensions
Can rotate crops	Cannot rotate weeds or algae	Cannot rotate weeds or algae
Limited impacts of dilution	Potential for rapid dissipation	Potential for rapid dissipation
One desirable species with many weeds possible	Site dependent: often few desirable plant species	Site dependent: often one target weed among multiple desirable species
Many herbicide options and mixtures	Limited options	Limited options and subject to substantial regulation
Commodities have very limited public input into management decisions	Paying customers with limited other issues	Regulatory, permitting, non-target, public perception issues
Rarely have hybrid weeds	Rarely have hybrid weeds	Hybrid weeds and invasive polyploids are prevalent

Lesson 3: Operational Examples of Situations that Challenge Traditional Herbicide Resistance Management Practices in Aquatic Sites

Following are several examples of current application strategies to control aquatic plants that need to be considered before compelling managers, either voluntarily or through regulation, to incorporate herbicide resistance management practices.

Case 1: Considering Repeated Applications of the Same Herbicide MOA on a Diminishing Plant Population

There is significant debate regarding eradication strategies for monoecious hydrilla which often rely on repeated use of fluridone herbicide. Likewise there has been discussion regarding curlyleaf pondweed turion reduction strategies that have relied on repeated annual applications of endothall. In both cases the management strategy is to target the plant at a specific time to reduce the vegetative propagule bank. This means treating plants annually until the tuber / turion bank is exhausted. In both cases, initial management is implemented prior to the formation of new propagules. The initial plant infestation can be fairly dense while subsequent treatments target a much lower density of plants that are sprouting from dormant vegetative propagules formed prior to herbicide exposure. It is argued by some that these multiple treatments are “recipes for resistance”. In this argument, the issue is not just repeatedly treating the same plant, it is also applying a tremendous amount of selection pressure to the system with repeated applications through time. Given the ample evidence of resistance development in annual weed systems, these repeated treatments can be problematic. The counter argument is that aquatic managers are treating a rapidly diminishing vegetative propagule bank (numbers are much lower than seed densities) that represents new plants that have sprouted each year. While annual treatments suggest a sustained selection pressure, this pressure is placed on a smaller population each treatment cycle.

Case 2: Considering Herbicide Resistance Management Strategies where few Alternatives Exist

The western irrigation canal market provides an example of the dilemma facing irrigation managers when it comes to resistance management strategies. There are only three active ingredients labeled for in-season irrigation water treatment in the western states; acrolein, copper, and endothall. Acrolein was the mainstay of the irrigation market for aquatic macrophyte control for decades; however, due to NPDES regulatory issues and the introduction of endothall as a new tool, many irrigation companies have shifted to endothall for economic, regulatory, and efficacy reasons. While multiple applications of endothall through time do not suggest the best resistance management strategy, convincing irrigators to incorporate acrolein or copper in the name of resistance management may prove difficult due to the regulatory complexity. Efforts are underway to evaluate pre-emergent strategies with products like fluridone and penoxsulam; however, irrigators may choose the most cost-effective approach that results in the fewest regulatory hurdles. Given the time and costs associated with registering a new product in the aquatics market, it is unlikely that additional modes of action will provide immediate relief. This theme of a mode of action becoming dominant for efficacy, regulatory, and social reasons is common in natural areas as well and challenges the ability to develop a simple resistance module for aquatic plant management.

Case 3: Considering Time between Large-scale Applications of the Same Herbicide MOA

There is significant debate among aquatic plant managers regarding a potential length of time between large-scale treatments with the same mode of action that may reduce the possibility of resistance development. In contrast to terrestrial weed control, particularly in row crop production venues, annual large-scale applications are not always necessary when controlling aquatic plants in natural areas. Large-scale treatment with products like fluridone, 2,4-D, or an ALS inhibitor may result in near complete control of the target vegetation for two to three years. The slow recovery of the target plants may result in small-scale spot applications in the intervening years; however, if the plants recover and require additional whole-lake or large-scale management, aquatic managers are likely to support use of a mode of action that initially provided two to three years of control. This issue is likely one that will continue to resonate as managers, applicators, and researchers debate how long between treatments with the same mode of action is long enough.

Case 4: Considering Alternate Herbicide Strategies where no Evidence of Resistance Exists after Prolonged Application of a Current Practice

Thousands of acres of water hyacinth have been controlled in Florida each year since the early 1950s using 2,4-D. A similar amount of water lettuce has been controlled over the past several decades with a near exclusive reliance on diquat. To date there has been no indication of resistance in either plant species. Should resistance management measures now be implemented for water hyacinth and water lettuce after more than 50 years of intensive use without incident? Recent trials focusing on penoxsulam and flumioxazin suggest both have good fits in the water hyacinth and water lettuce control programs where improved selectivity is desired. Convincing managers to switch to these newer modes of action makes sense in areas with diverse vegetation where selectivity is desired. Nonetheless, convincing managers to rotate for resistance management in programs that have been successful from an efficacy as well as cost perspective for 50+ years may require much greater evidence or incentive.

Case 5: Considering Herbicide Resistance Management Strategies that may be less Cost-effective, Require more Regulatory Restriction, or have little to no Public Support

Developing an operational use pattern in aquatics often requires many years of research, monitoring, and treatment refinement, especially in natural areas where conserving non-target vegetation is as important as cost-effectiveness. These efforts are typically initiated after the label has been granted and continue for years as new suites of non-target plants and waterbody conditions are encountered. Moreover, use patterns are typically developed for a single mode of action on a target plant. Once use patterns are established, managers, regulatory agencies, and stakeholders develop a level of acceptance for a given approach. This creates difficulties for introducing a new mode of action into an established program. There typically needs to be a compelling reason (e.g. reduced cost or water use restrictions, increased selectivity) to incur the costs associated with developing a major new use pattern. Resistance management is not currently viewed as a compelling reason for altering the vast majority of large-scale use patterns in aquatic plant management.

Case 6: Considering Herbicide Resistance Management in Large Public Waters where Resistance Management is not Practiced in Adjacent small Private Lakes or Ponds

In Florida, hydrilla is managed with herbicides in more than 150 public waters, some as large as 30,000 acres. As discussed earlier, managers are struggling to fund research and operational monitoring to develop rotation strategies for proven cost-effective and selective hydrilla control strategies. In some cases, hydrilla is being controlled without resistance management strategies in adjacent small ponds and private lakes, some of which have direct surface water connections to the big public waters. Resistance management strategies will work best when practiced by all managers. While the threat of developing resistance in smaller water bodies may be low, consequences of a newly selected resistant plant moving into large public waters become highly significant. We recommend that APMS and regional chapters become more engaged in educating all resource managers regarding the importance of resistance management and early reporting when they may suspect the presence of a plant population that is not responding to management strategies that have worked in the past.

Case 7: Considering Herbicide Resistance Management in Multiple use Systems

Lake Tohopekaliga (Toho) is an 18,000-acre reservoir supplying flood management for the upstream cities of Kissimmee and St. Cloud in central Florida and downstream water for irrigation and wetland habitat mitigation. It is a Federal Navigation and Flood Control Project that is renowned for ecotourism and fishing in addition to providing recreational boating, waterfowl hunting opportunities, and nesting and foraging habitat for several listed species including the endangered Everglades Kite. However, Lake Toho once had over 15,000 acres of hydrilla, making it one of the most heavily hydrilla-infested waterbody in Florida

Various stakeholder promote hydrilla for ecological services ensuring yearly herbicide management in plots ranging from 25-5,000 acres in size in order to conserve Lake Toho's multimillion dollar uses and functions. Optimum timing for large-scale hydrilla control in central FL is January through April as hydrilla is actively growing while native submersed plants are mostly dormant. Sunlight intensity and water temperatures are at annual lows reducing photolysis and microbial breakdown of herbicides (extending potential control) and increasing dissolved oxygen levels to buffer dying plant decomposition. Seasonal rainfall is at its lowest, reducing off site dissipation or complete flushing from the system from water flow. Spring applications also ensure hydrilla is under control during tropical storm season (May – November) and surface mats will not impede flow during emergency water discharge events.

Stakeholder requirements not only influence the amounts and areas in which hydrilla is controlled, but also the timing. These considerations in turn influence the herbicide types, dose, and exposure period. Consequently large-scale hydrilla operations in Lake Toho are further reduced from purely climatological considerations to very narrow windows in late fall and February 1 through April to accommodate waterfowl hunting interests. Additionally, potential restrictions from January 1 through July or August to accommodate Everglades kite nesting, foraging, and fledging compel managers to control hydrilla as early as possible after the conclusion of water fowl hunting season. Figure 2 diagrams influences that various uses, functions, and conditions associated with Lake Toho have on large-scale hydrilla control decisions, which in turn are necessary to conserve the uses and functions of Lake Toho.

Figure 2: Major Uses, Functions, and Conditions Influencing Large-scale Herbicide Applications to Control Hydrilla in Lake Toho, FL

	Month											
Waterbody use / function / condition	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Higher temp. / lower dissolved oxygen								Control not advisable				
High rainfall / flushing								Control not advisable				
Hurricanes / flood control									Control not advisable			
Peak native plant growth							Control not advisable					
Waterfowl scouting / hunting	Not									advisable.		
Sportfish spawn				Consideration								
Large national fishing tournaments		Control not advisable										
Small local fishing tournaments							Consideration					
Endangered snail kite nesting/fledging				Control not allowed in key areas								

Major conditions influencing large-scale hydrilla control decisions

Large-scale hydrilla control windows of opportunity with least amount of competing use