# Summary of a Survey of the Literature on the Economic Impact of Aquatic Weeds

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## Abstract

Invasive aquatic plants affect aesthetics, drainage for agriculture and forestry, commercial and sport fishing, drinking water quality, fish and wildlife habitat, flood control, habitats for other plants, human and animal health, hydropower generation, irrigation, navigation, recreational boating, swimming, water conservation and transport, and, ultimately, land values. Because most invasive aquatic plants species have been introduced to this country from abroad, they do not have natural control agents or competitors and they tend to dominate the aquatic systems to which they are exposed. The magnitude of only a few of their impacts has been measured and then, generally, over limited areas. A few well-documented studies, however, provide a basis for estimating the general scale of these affects for the nation as a whole, and might serve as a guide for an appropriate magnitude of response.

There are difficulties in estimating the economic impacts of aquatic weeds (or, conversely, the benefits of their control) due to the "public-good" nature of aquatic resources and the resulting fact that few of these impacts or benefits pass through economic markets. In spite of these difficulties, it can be conservatively estimated that the values-at-risk from aquatic invasive plants in the US is in the range of billions of dollars per year.

Significant sums (at least $100 million) are spent each year in the control of aquatic weeds, however, and the estimated benefits of control are consistently reported to be much higher than these costs. Given the continuing spread of problem species and the difficulty of organizing collective action to control aquatic weeds, it seems likely that too little is being spent on control rather than too much. Furthermore, much could be done to facilitate the further development and use of aquatic weed control techniques.

Although the costs and environmental effects of aquatic weed control have been intensively studied, new technologies for their control are continually being evaluated and developed. Continued attention seems warranted to develop weed control techniques and strategies that moderate costs, meet competing objectives, and minimize the potential for unintended environmental harm. In addition, an accelerated invasion of exotic animal species suggests a more integrated approach to the management of aquatic ecosystems.

## Background

Invasive aquatic plants and their control are a worldwide problem, especially in climates, habitats, or plant forms in which plant dormancy and seasonal diebacks from freezing or drought are limited. There are a wide variety of species (submersed, floating, and emergent), however, and nearly any aquatic ecosystem is subject to invasion from some of them. These problems develop when non-native ("exotic") plants are introduced either intentionally or by accident into ecosystems in which they did not previously occur.

Invasive aquatic plants affect aesthetics, drainage for agriculture and forestry, commercial and sport fishing, drinking water quality, fish and wildlife habitat, flood control, habitats for other plants, human and animal health, hydropower generation, irrigation, navigation, recreational boating, swimming, water conservation and transport, and, ultimately, land values. Because most invasive aquatic plants species have been introduced to this country from abroad, they do not have natural control agents and they tend to take over the aquatic systems to which they are exposed.

The growth, effects, and treatment of these aquatic nuisance plants or weeds are affected greatly by the characteristics of the waters in which they occur. Bayous, canals, estuaries, lakes, ponds, reservoirs, and rivers can all be affected, and such bodies vary greatly in terms of acidity, bottom conditions, depth, water flow and fluctuation, native plant and animal life, nutrient availability, salinity, temperature, water quality, and wind and wave exposure, as well as by use and surrounding human development.

Similarly, aquatic weed species vary greatly in terms of:

- form and habitat;
- places of and time since introduction, means and rate of spread, past management history, and their resulting geographic distribution;
- their effects on aquatic ecosystems and the human uses of those systems; and
- their susceptibility to a variety of control techniques.

A description of some of the more common problematic species can be found in lists maintained by the Aquatic Plant Management Society in the "plants" section of http://www.apms.org/, with distribution maps by the US Geological Survey at http://nas.er.usgs.gov/plants/sp_accnts.htm , and in great detail with distribution maps at the University of Florida Center for Aquatic Plants at http://plants.ifas.ufl.edu/seagrant/aquinv.html.

Finally, a wide range of control or treatment mechanisms are available, including mechanical, chemical, and biological. Generally, after plant populations are initially treated, a lower "maintenance" level of treatment is needed to keep them under control. A survey of control techniques and strategies for using them can be found in the "management" section of the Aquatic Ecosystem Restoration Foundation website at www.aquatics.org (Madsen, 2000).

The economic impacts of aquatic weeds include their diminution of the uses and ecological functions of waters and surrounding lands listed above and the costs that are incurred in their control. The "optimal" level of control can be thought of as that which minimizes the sum of these two costs.

## A Brief History of Aquatic Weeds and their Harm, Control, and Economic Impact Estimation in the United States

Non-native aquatic plants may have been introduced into what is now the United States by Spaniards as early as the 16th Century (Schmitz et al.) The economic issue of aquatic weeds in the US gained national attention in the late 19th Century, however, when water hyacinth was introduced into the Gulf States and rapidly colonized previously open waterways throughout the region's flat, wet, and warm coastal plain. Federal studies – including economic impact estimation – and federal funds for control came soon thereafter (Gowanloch, c. 1944), but the amount appropriated ($10,000) by Congress was only one-fifth of the amount requested by the US Army Corps of Engineers (Wunderlich, 1968).

By the late 1940s, the US Fish & Wildlife Service estimated the loss of fish and wildlife due to water hyacinth and alligator weed in Florida and Louisiana alone at over $20 million per year (Lynch, Chamberlain, & Smith). In 1957, 110,000 miles of canals were infested with aquatic weeds in seventeen Western states, and about 60,000 of these miles were receiving treatment (Gangstad, 1982, p. 6). Federal programs were expanded in 1959 in response to the spread of alligator weed in the Southeast (Gunkel and Barko, 1998), and the "Expanded Project" was annually yielding an estimated $14 million in control benefits by 1963 at a cost of $187,100 (Gangstad, 1982, p. 6- 7).

A decade later, although nearly $4 million were being spent for control in Louisiana (Wunderlich), annual losses to the water hyacinth in agriculture, drainage, fish and wildlife, navigation, and public health in that state alone were estimated to be $35 million (USAID, 1971, p. 6).

Meanwhile, $6 million were being spent annually on weed control in Florida (USAID, p. 7). About $2 million of this amount was being spent in the 18-county (then) Central and Southern Florida Flood Control District, allowing the overall benefits estimated for the project to reach $82 million (Huser, 1968), which was broken down as follows:

| | |
|---|---|
| Flood damages prevented - | $30,467,300 |
| Increased land use - | 49,498,100 |
| Recreation - | 1,794,100 |
| Fish and wildlife - | 395,100 |
| Navigation - | 51,000 |

The flood control and land use figures reflect extensive land reclamation by drainage in Florida. Thunberg (1991, p. 13) notes, however, that not all of these benefits would likely be lost in the absence of weed control. Additional benefits cited by Huser but not quantified include agricultural irrigation, municipal water supplies, and the prevention of saltwater intrusion.

The introduction and spread of additional species continues. Hydrilla was introduced into Florida in the early 1950s and has since spread aggressively throughout the Southeast, accounting for half of Florida's $14 million aquatic weed control budget in 1989 (Schmitz et al.). By 1988, twenty-two of 137 aquatic plant species in Florida were non-native.

## An Overview of Benefit/Cost Estimation Methods

Because large aquatic ecosystems are primarily “open access” public resources (not private property), typical economic markets do not work well in regulating their management and use. Instead, some sort of public action is needed to manage these systems. Such actions rely on collective decisions which, in turn, commonly rely on information as to the magnitude of problems and the benefits and costs of alternative extents, means of treatment, and politics.

The “public-good” nature of aquatic resources that requires public action and analysis also makes it difficult to estimate the economic value of the impacts of aquatic weeds. Economic “benefit/cost” analysis is generally used by public agencies to overcome such problems in an objective manner and inform decision-makers, and water resource economics has been a leader in this area. Since there are no market transactions to measure directly, researchers estimate the quantities of the harm done by aquatic weeds (and/or the harm prevented by their control), and multiply these quantities by estimates of their per-unit values.

The standard approach used by researchers is as follows:

1. Researchers estimate the quantities of the various water uses with and without the presence of the aquatic weeds – this is the harm or impact of the weeds.

2. Researchers estimate the quantities of these uses with and without control – this is the benefit of the control methods.

3. Researchers estimate the per-unit values of the units of harm or benefit either through questionnaires (such as “how much is it worth to you to fish for a day?”) or by imputing values from characteristic indicators of the uses (estimating the value of a fish caught). Care must be taken in using these values, however, because they might include indirect values derived from the uses (how much was spent for everything used in fishing) in addition to the direct value of the use (how much it was worth to actually have access to a lake). Also, benefits (like fishing) lost in one location could simply shift elsewhere (to another lake) and may not be a net social loss (Thunberg. 1991).

4. To derive the total values, the quantities of harm or benefit are multiplied by the per unit values and, if various uses are considered, added together.

5. Sometimes, a comparison of the values of the benefits and the costs of weed control are compared. A standard expression of this comparison is simply to divide the total benefit value (the reduced harm to the uses) by the cost of control, yielding the traditional “benefit/cost ratio”. For example, if $10 of cost yields $50 in benefits, the “B/C ratio” would equal 5 (or “five to one”, “5/1”, or “5:1”). (For benefits and costs that occur unevenly through time, future values are typically “discounted” to the present but, because benefits and costs of weed control are generally thought of as stable through time, this additional step can often be forgone.)

For more on economic estimation methods, most documents cite the US Water Resources Council (1983) and/or, especially for recreation effects of aquatic weeds, Milon et al. (1986).

## An Analytic Survey of Recent Literature

In the existing literature, the magnitude of only a few of the impacts of aquatic weeds has actually been measured and then, generally, only over limited areas. Eric Thunberg performed an extensive literature review in 1991 and concluded that:

> *The literature search identified limited published material dealing with valuation of aquatic plant control. In the majority of the surveyed literature, estimation of aquatic plant control benefits received only a cursory treatment. In most cases, few details of the benefit estimation procedures are offered, making it difficult to judge the reliability of the benefit estimates. In only one instance was more than one benefit category vigorously pursued. The majority of project evaluations were based solely on recreation benefits. While relatively large recreation benefits tend to be generated, consideration to other project benefits may be warranted.* (p. 21)

In spite of a decade of concentrated research on the part of a few individuals, much the same could be said today. Weed control costs receive far more attention than does the estimation of harm or benefits. Individual research papers still tend to focus on only one body of water and one function (like recreation or flood control), and no recent studies were found that examine multiple benefits over large areas. In addition, whether due to being the locus of the worst early problems, the location of researchers, or the literature search strategy employed, the literature reviewed focused primarily on Florida and the Southeast. Finally, much of the published literature cites benefit estimates from US Army Corps of Engineers project or (more rarely) program analyses that were not directly available to this reviewer.

In spite of these limitations, however, a few well-documented studies provide a basis for estimating the general scale of the impacts of aquatic weeds on the nation as a whole. The studies are examined below under the topics of flood control benefits in Florida, recreation benefits, and the application of benefit/cost ratios to the total cost of aquatic weed control.

### Benefits of Flood Control Florida

Of the $82 million in annual benefits from the (then) Central and Southern Florida Flood Control District that Huser identified in 1968, over $80 million were from flood control and increased land use values. Twenty-plus years later, the general price level had nearly quadrupled and the population of the eleven southernmost of the District's 18 counties had doubled. As a result, for an area about one-thousandth the area of Huser's study, Thunberg, Milon, and Pearson (1991) found annual benefits of $7,257,000 in residential damage control for an total annual cost of $50,000 (for a very high benefit/cost ratio of 145:1, and found that these benefits could be increased significantly by expending more and eradicating the plants).

Even if the latter figure is expanded by one hundred times (rather than one thousand), both studies put the flood control protection benefit of South Florida aquatic weed control in the range of several hundred million dollars or, by now, probably closer to one billion dollars. It appears that these numbers annually recount avoided damages, however, and a more realistic approach might be to figure the annual services of the property protected, which would be more in the range of $100 million per year, yielding a B/C ratio closer to 15:1.

Thunberg and Pearson (1992) followed this study with a similar study of the benefits of weed control to improve drainage for citrus production, and found benefits of nearly $5000 per acre, which could be increased to nearly $8000 per acre with moderate increases in weed control. Adjusting for inflation and a steady increase in the numbers of trees per acre, using only annual services, and assuming drainage of only 10% of the state's almost 900,000 acres of citrus, the benefits of weed control for drainage are also in the neighborhood of $100 million per year. If Thunberg and Pearson's additional work on Florida's vegetable production (1993) yielded similar results, about $300,000 in benefits have been accounted for.

Another approach to estimating the impacts of aquatic weeds is by looking at the costs of control, estimated in Florida for those waters requiring State permits at just over $14 million in 1988 (Schmitz et al., p. 325). Applying a B/C ratio of 15:1 and adjusting for inflation, the resulting figure of about $300 million dollars compares favorably to the magnitude of the benefits of flood protection reported by Thunberg (above). (More on this approach below.)

## Recreational Benefit Estimation

Recreation benefits are the most commonly estimated of all the benefits of aquatic weed control. The estimation of non-market public recreation benefits, however, is particularly problematic for the reasons stated at point "3" under "An Overview of Benefit/Cost Estimation Methods", above. In addition, issues of crowding and competing recreational specialties (anglers versus water-skiers) complicate estimation even more. Finally, a particular issue for the estimation of the recreational benefits of aquatic weed control is that, for anglers, having too few weeds can harm fish habitat, creating more of a direct trade-off between different kinds of recreators (Henderson, 1993). (More technical estimation issues, which are quite complex and even controversial, are beyond the scope of this paper. For a more complete – but still not exhaustive – review of the issues, see Thunberg, 1991.)

In any event, a fairly wide array of studies estimate the recreational benefit of aquatic weed control, but most are specific to particular bodies of water (invariably lakes and reservoirs) and use various methods that are difficult to compare (in part because the size of the lakes studied is not reported). In summary, the following results were found:

| Author(s) | Lake(s) | Annual Benefits | B/C Ratio |
|---|---|---|---|
| Singh et al. (1984) | three in Illinois | $1,345,000 (WTP) | 8:1 to 24:1 (annual)<br>24:1 to 91:1(discounted) |
| Milon et al. (1986) | Orange & Lachloosa (Florida) | $480,000 (WTP)<br>> $5 million (Exp)<br>> $10 million (EI) | (costs not reported) |
| Colle et al. (1987) | Orange (Florida) | $900,000 (Exp) | 1:1 to 300:1 |
| Milon & Welsh (1989) | Harris & Griffin (FL) | $176,000 (WTP)<br>$1.7 million (Exp) | (costs not reported) |
| Newroth & Maxnut (1993) | 16 (British Columbia) | $85 million(Cdn) (Exp) | 243:1 |
| Henderson (1995) | Guntersville (AL) | > $100 million (Exp) | (costs not reported) |

*Benefit Key: WTP = recreators "willingness-to-pay" for currently free services*
*Exp = total recreation expenditures EI = economic impact*

There are several ways to try to generalize these results:

- Using the approximately ten-to-one ratio of total-recreation-expenditures to willingness-to-pay from the two Milon studies to adjust the Henderson expenditures to a $10-million willingness-to-pay estimate (and not double counting Orange Lake), the resulting total for the six lakes in the four US studies is $12 million, most of which is from one large lake.

- A quick look at a US maps shows about 30 "Lake Guntersvilles" in larger reservoirs (tens to hundreds of thousands of acres) in the Southeastern US. If they share the characteristics of that lake, they represent $300 million in potential recreational benefits from weed control, which is about the value of flood control in Florida. If Lake Guntersville (AL) is an extreme case, this estimate would be lower.

- The inflation-adjusted $750,000 for the four large (thousands to tens of thousands of acres) lakes in Florida would have to be replicated about 300 times across the state to match to the comparable figure for the value of flood control in the state. Again, a quick look at a Florida map suggests that these four lakes might be replicated more like 30 times across the state (not counting Lake Okeechobee), pointed to a potential benefit value closer to one-tenth that of flood control.

It is also important to note that Colle et al.'s expenditure figure for Orange Lake is about one fifth that of Milon et al's for Orange and Lachloosa Lakes combined, which are nearly adjacent and fairly close in size. Note also that the study of Bell et al (1998) for the 2500-acre Lake Tarpon (also in Florida) estimated about $20 million in willingness-to-pay for weed control (with a benefit/cost ratio of about 200:1), which would be about twice as high as for the several-times-larger Lake Guntersville. These two comparisons demonstrate the high variability of recreation benefit estimates, and the difficulty in generalizing their results.

<u>Benefit/Cost Ratios and the Total Cost of Control</u>

A third approach to estimating the harm of aquatic weeds and the benefits of their control can be inferred from two information sources common in the literature: the benefit/cost ratios of weed control (generally for smaller projects) and the total cost of weed control over large areas. As shown in the "Brief History", above, "program-wide" studies combining the two factors were common when large new programs were being proposed, but have become less common in recent decades.

One difficulty with this approach is in establishing a range of B/C ratios to apply to large programs. There is a wide range of findings in the literature, noted above as ranging from 1:1 to 300:1 -– and that range within one study of one lake. Still given the wide variation in both waterbody conditions and control methods, such a range is probably justified. It would also be expected that both the actual highs and lows would not be found in the literature, since the actual "high-B/C" cases are more obvious and likely to be eliminated without study and the actual "low-B/C" cases are unlikely to draw much attention. In addition, complications are added by the difference between "start-up" cases (when heavier treatments are needed and, hence, B/C ratios are lower) and "maintenance" cases (when B/C ratios rise).

The fact that the unstudied "frontier" of new start-up cases (with lower B/C ratios) where aquatic weeds are becoming established and control programs are not yet in place (and, hence, not in the literature) would suggests conservatism in the choice of general figures. The lack of the estimates for many of the undocumented benefits of weed control and occurrences of problems, however, suggests the use of higher figures. The approach taken here is to take the more conservative approach and to adjust directly for the undocumented factors later.

For the estimates derived below, a standard benefit/cost ratio of 10:1 will be used, because:

- Gangstad (1982) cites benefit/cost ratios of 5:1 to 15:1;
- This range is within the more conservative range in the literature;
- One might expect any bias in the literature to favor high B/C ratios; and
- This rate is easy to use for calculations and easy to adjust to test other assumed rates.

To establish a starting point, once again, we use the estimate of $14 million for the cost of treating about 85,000 acres of infested waters for which permits were needed in Florida in 1989 (Schmitz et al.). If we assume that expanded programs and inflation have raised that amount to $25 million today, the B/C rate of 10:1 would yield a total benefit of $250 million in Florida. As a result, it appears that the two figures are at least roughly compatible, and an estimate of total realized or potential benefits in the neighborhood of $300 million to $400 million in Florida is within reason and that a figure of $500 million would not be out of the question.

Then, taking a range of figures for Florida along with a range of assumptions about Florida's proportion of the nation's aquatic weed problem, we can derive a range of estimates of the total national potential impact aquatic weeds in billions of dollars:

| Florida's Problem ($millions) | Florida as a Percent of the National Problem ($billions) 5% | 10% | 20% |
|---|---|---|---|
| $200 | $4.0 | $2.0 | $1.0 |
| $300 | $6.0 | $3.0 | $1.5 |
| $400 | $8.0 | $4.0 | $2.0 |
| $500 | $10.0 | $5.0 | $2.5 |

In other words, we get a rough estimate in the neighborhood of one to ten billion dollars for the annual impact of aquatic weeds on the nation as a whole. Assuming benefit/cost ratios different from 10:1 would change these estimates proportionately.

A similar approach to estimating the national impact of aquatic weeds is based on national data on the use of chemicals used to treat weeds. In 1979, the US-EPA suspended all uses of 2,4,5-T and silvex in the US. In 1983, Gangstad estimated the benefits and costs of the use of silvex on aquatic weeds in the US. Without elaboration, he estimated the benefits of silvex use to be about $40 million on about 60,000 acres at a total cost of about $4.8 million, for about $80/acre and a benefit/cost ratio of over 8:1. (In 1985, however the US District Court in Washington, DC, banned all use of 2,4,5-T and silvex in the U.S.)

Using data from Lembi and Szmedra (both 1996), an estimate of $17 million as the total US cost of applying 2,4-D to 223,000 acres of aquatic weeds (at a cost of about $76/acre) is derived as follows:

| | cost per acre ($/year) 2,4-D | labor | total | total acres treated/year | total expenditures ($million/year) 2,4-D | labor | Total |
|---|---|---|---|---|---|---|---|

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| water hyacinth | 5 | 60 | 65 | 213,000 | 1.09 | 12.75 | 13.85 |
| watermilfoil | 171 | 148 | 319 | 10,000 | 1.71 | 1.48 | 3.19 |
| average or total | 13 | 64 | 76 | 223,000 | 2.80 | 14.23 | 17.04 |

(Showing little detail, Lembi estimated a total cost of $33 million, but the more conservative and transparent figure is used here). In addition, Lembi stated that a total of about 400,000 acres of inland water surface area were being treated each year with herbicides for weed control, and that the total amount spent on these herbicides is $19.3 million. Since $2.8 million was spent on 2,4-D, this means that the chemical cost of treating the remaining 177,000 acres was over $93 per acre. If the total cost of chemically treating these other acres is:

$150 per acre the resulting $26 million would bring the total* to about $ 50 million per year,
$200 per acre the resulting $35 million would bring the total* to about $ 60 million per year,
$300 per acre the resulting $53 million would bring the total* to about $ 80 million per year, or
$400 per acre the resulting $71 million would bring the total* to about $100 million per year.

***(* = total national chemical treatment cost, adjusted for inflation)***

These figures are just below the $100-125 million of Gallagher and Haller (1990) for 1987 based on methods not fully documented. By applying a benefit/cost ratio of 10:1 to these figures, we derive a total national chemical treatment benefit range of $500 million to $1 billion.

The big question, then, is, if only 0.8 % of the nation's inland waters are treated with chemicals, how much more is treated non-chemically and to what benefit? If we use $750 million as the estimate of the total benefits of chemical treatments, the following range of assumptions about these other factors yields the following table of results for the total national impact of aquatic weeds in billions of dollars:

| Non-chemical treatment benefit per acre as a proportion of chemical treatment benefit | Chemical acreage treatment as a percent of total national aquatic weed acreage treated ($billions) | | | |
|---|---|---|---|---|
| | 10% | 25% | 50% | 75% |
| 0.5x | $4.1 | $1.9 | $1.1 | $0.9 |
| 1.0x | $7.5 | $3.0 | $1.5 | $1.0 |
| 1.5x | $10.9 | $4.1 | $1.9 | $1.1 |
| 2.0x | $14.3 | $5.3 | $2.3 | $1.3 |

This range of findings of $900 million to almost $14 billion compares favorably with the range of one to ten billion dollars derived above using Florida's program as a base.

Coincidentally, both estimates are close to "A ballpark range for total direct non-indigenous weed costs is $3.6 billion to $5.4 billion annually" for all weeds (US OTA, 1993, p. 66). Oddly, a widely-cited paper (Pimentel et al., 1999) puts the total damages and costs of all invasive plants and animals in the US at $138 billion, but at only $110 million for aquatic weeds: $10 million in damages (attributed to two lakes in Florida, citing Center at al, 1997, and probably referring to Milon et al., 1986) plus $100 million in total control costs (citing the US OTA, which cites the 1987 estimates by Gallagher and Haller, 1990).

## An Evaluative Summary of Available Information, Literature, and Programs

As mentioned in the methods overview, above, the purpose of estimates of the harm of aquatic weeds and the benefits of their control is to help make public decisions about the treatment of weeds, whether for a lake for one year or for a multi-year national program. The harm and benefit estimates indicate what would be lost by not treating weeds and the benefits are the harm that would be avoided by treating them. The costs of treatment indicate what society gives up to reap the benefit of preventing the weeds' harm. The benefit-cost ratio is a measure of the size of the benefits gained (the harm prevented) relative to the size of the costs of treatment.

In an attempt to arrive at a national estimate of the total harm in the previous section, however, this approach was turned a little on its head: because we have more information about the costs of weed control than we do about the benefits, we used a conservative generic benefit / cost ratio derived from the literature to estimate what the benefits might be based on the costs being expended. In a sense, a step like this might be considered unnecessary, since individual treatment decisions and even multiyear regional program decisions might be based on more specific and relevant estimates and studies. In another sense, however, there may well be larger-scale decisions that can only be made in light of this more general, national-level information. Such decisions include:

- **strategies** to provide a more "proactive" coordinated approach to controlling the harm – and especially the spread – of aquatic weeds,
- providing better **information** about the presence and spread of aquatic weeds to facilitate such strategies,
- encouraging research and **technological innovation** in aquatic weed treatment to improve the effectiveness, lower the cost, and improve the environmental impacts of weed control,
- supporting more **research in the estimation of the benefits and costs** of treatment to support better strategic, program, and project decisions, and
- supporting the **development of institutional arrangements** to help make aquatic weed treatment decisions in the many instances in which the jurisdiction of existing governmental units do not match the ecological scope of a problem.

These five decision areas are addressed in more detail below.

### Strategies to Coordinate Aquatic Weed Control

Significant sums (>$100 million) )are spent each year in the control of aquatic weeds, and the estimated benefits of control are generally reported to be much higher (ten times or more) than these costs. Existing research has likely been done, however, where problems are the worst and most recognized and perhaps also where the most treatment has been done. The estimates above are particularly conservative, therefore, because they probably account only for the places where control has occurred (or at least its need been recognized) and probably do not include places where the problem has not been recognized or addressed. In addition, since treatment does not eliminate all problems, the estimated benefits may not include continued residual harm from weeds in waterbodies that are already being treated.

The most striking fact about our lack of knowledge of the total magnitude of harm, however, is not just that it is probably greater than we think. The larger problem is that existing control decisions are likely made by considering only the harm to be prevented within the jurisdiction making the decision, without considering the additional harm caused if plants spread to other jurisdictions.

A more comprehensive national approach to problems would take into account the fact that early detection and treatment would have the benefit of preventing harm that would not otherwise develop, following the age-old maxim that "an ounce of prevention is worth a pound of cure". The US Center for (human) Disease Control is based on these exact principles, but with billions of dollars of potential harm at stake, it would seem that there is no equivalent "Center for Aquatic Health Control".

## Better Information in Support of an Aquatic Weed Control Strategy

This study was begun with the assumption that information on aquatic weeds would be as available as is national agricultural, forest, soil, and weather information. Many websites were found (see http://www.invasivespecies.gov/databases/apdb.shtml) that address aquatic weeds, but none were found that provided a national inventory of the presence or treatment of aquatic weeds. This is particularly striking, because there are at least three web sites that offer comprehensive water-quality data with barely a mention of aquatic weeds:

The USGS National Water Information System (http://water.wr.usgs.gov/pnsp/), for which, "The Site Inventory System contains and provides access to inventory information about sites at stream reaches, wells, test holes, springs, tunnels, drains, lakes, reservoirs, ponds, excavations, and water-use facilities. About 300 components make up the descriptive elements of the site inventory. The retrieval program can be used for retrieving information about sites in summary lists, in detailed tables, or a file suitable for input to other programs." Unfortunately, this system tracks only chemical contaminants in water but not biological contaminants like aquatic weeds.

The US-EPA Office of Water's STORET Legacy Data Center, "site of the world's largest repository of ambient Water Quality Data. From this site you will be able to access a database that holds over 200 million water sample observations from about 700,000 sampling sites for both surface and ground water." – But again, this site tracks chemical and there is nothing on aquatic plants. (http://www.epa.gov/storpubl/legacy/gateway.htm)

The USGS National Water-Quality Assessment (NAWQA) Program: "In 1991, the U.S. Geological Survey initiated a full-scale National Water-Quality Assessment Program. The three major objectives of the NAWQA Program are to (1) provide a consistent description of current water-quality conditions for a large part of the Nation's water resources, (2) describe how water quality is changing over time, and (3) explain the natural and human factors that may affect observed water-quality conditions…..In more than 50 major river basins and aquifers covering nearly all 50 states, USGS scientists collect and interpret data about water chemistry, hydrology, land use, stream habitat, and aquatic life." This "aquatic life", however, apparently does not include aquatic weeds. (http://water.usgs.gov/nawqa/)

This lack is particularly striking because most water-quality problems are characterized primarily by the spread of inert agents flowing passively downhill in water – the aquatic weed problem is unique in that it is a biological problem that spreads and establishes itself in water, including by being carried overland by humans and animals. A coordinated strategy for managing these infestations requires comprehensive information about the problems at hand. The realization that this is a multi-billion-dollar program might assist the realization that the collection of such information is warranted.

## Technological Innovation in the Treatment of Aquatic Weeds

Some desired aquatic weed treatments might not occur because of perceptions that the cost is too high (making for a benefit/cost ratio that is too low) or that there is a risk of related undesirable environmental and human health effects of treatment. Because most of the control technologies are offered by private firms, however, this is one area in which markets can be expected to work and apparently do work. As a result, there are ongoing efforts to improve, fine-tune, or replace traditional treatment techniques, which have the overall effect of lowering costs while addressing environmental concerns.

As in many other areas of technological innovation, however, there are always elements of "basic research" that are difficult for private firms to support, especially if the resulting technologies are easily copied by others. One way to lower costs and improve on the overall environmental effects of weed control is for government to support such basic research. A multi-billion-dollar problem would seem to justify such support, especially considering the benefits that could come from integrating the treatment of aquatic weeds with the treatment of another host of problems of comparable magnitude floating in the same watery medium – the growing threat of invasive aquatic vertebrate and invertebrate animal species. However, federal funding for basic and applied aquatic plant control research has been in a steady decline since 1995 (Gunkel and Barko).

## Enhancement of Benefit and Cost Estimation

In spite of the decades of research cited (at least in part) in this paper, there is little comprehensive understanding of the costs and – especially – the benefits of aquatic weed control. For most benefit categories and for most regions of the country (beyond the Southeast), very little relevant literature was found. For example:

Of 123 entries in the 1994-2001 bibliography of the USDA Exotic & Invasive Weed Research Unit (http://wric.ucdavis.edu/exotic/techtran/sort_Five_year_bibliography.html), only 28 were on aquatic weeds, and three-quarters of these were by one primary author. Only one of these appeared to address economics, and that was related only to construction costs.

In four years of abstracts from the annual meeting of the Western Aquatic Plant Management Society (1997 and 2000-2002, at http://www.wapms.org/abstracts02.html), only one (Patten) addresses economics at all comprehensively, and that only on the cost side (not the benefits).

There simply do not seem to be the tools, information, and analysts available that would be necessary to guide a national program with multi-billion-dollar, multi-purpose significance.

Institutional Development to Support Programs

The National Invasive Species Management Plan (National Invasive Species Council, 2001) proposes many new programs and institutional arrangements to address the issues raised above. By addressing the whole range of aquatic and terrestrial animals and plants, however, the Plan – of necessity – is very preliminary, broad, and general.

As mentioned above, part of the program with aquatic weed control is the establishment of effective bodies who can make and implement decisions related to public resources, of which Florida's water districts are a prime example. Another example is lake associations, which are often formed by shoreline owners to make decisions about weed treatment in "their" lakes.

Especially if such bodies are organized to address small, local problems, they need help in formation, decision-making, and administration, not to mention in considering their decisions within the broader context of the prevention of the spread of aquatic weeds.

Finally, given the impact of local decisions on the broader-scale spread of aquatic weeds, financial cost sharing would seem to be an appropriate way of accounting for the interdependence of otherwise-isolated weed control decisions.

In spite of the importance of such institutional arrangements, there is very little in the literature that addresses them and seemingly little support for them in fact. Since such arrangements, in effect, lower the cost of control, this is a rather inauspicious arrangement for confronting a national problem of a multi-billion-dollar magnitude.

## Qualifications of the Findings and their Implications

As opposed to comparable studies that place their findings within a fairly narrow range, this study provides a wide range of possible findings. This approach explicitly recognizes both the actual uncertainty of findings of this sort and the specific assumptions that, if varied, could lead to different conclusions. In addition, it provides specific guidance on the impact of those assumptions on the conclusions so that readers with better information or different assumptions can see the impact of their different point of view.

This approach was necessitated by both the high variation in aquatic conditions and the lack of comprehensive data on the occurrence and impacts of aquatic weeds. The resulting reliance on a generic benefit-cost multiplier introduces its own uncertainties, many of which have been addressed above. However, the choice of the use of 10:1 as the base for the "B/C ratio times total cost" approach is believed to provide both a conservative estimate and ease in testing the impact of that estimate (since a different assumed B/C ratio changes the result proportionately).

In this approach, the use of terms like "benefits", "harm", and "potential" for the numerator of the B/C ratio has the additional drawback of creating ambiguity about the current status and meaning of the analysis. A better way to think of the numerator would be to use the term "values at risk", which more clearly includes and suggests that it applies to what could be lost, what has been lost, and what might be restored. This term has the additional advantage of including and suggesting a more dynamic comprehension of the problem, since it more naturally includes the important and transcendent considerations of weed spread and the prevention of spread. (A striking example of such dynamics is found in Patten, 2000.)

As a result, the term "values at risk" also tends to suggest:

- the importance of considering each situation in its larger context,
- the importance of comprehensive strategies to address spread,
- the actual dependence of any "value-at-risk / cost" analysis on assumptions about overall aquatic weed management strategies, and
- the obvious – if sometimes elusive – fact that total harm can be reduced by incurring relatively moderate weed control costs.

These general points being made, more specific qualifications of this study (that depend at least, in part, on these general principles) include:

- Existing studies do not distinguish well between the cumulative and the marginal values-at-risk or costs. An example would be drainage studies, for which the downstream impacts of quicker drainage and the unmentioned assumption of downstream drainage maintenance costs are barely mentioned. (Henderson's distinction between the regional and national accounting for beneficiaries who can move from an impacted site to a less impacted site is a special case of this class of issues.)

- The lack of clarity about the annual value of flood control in relation to the value of property protected can throw off values-at-risk estimates in this area by an order of magnitude. (Again, for this study, the more conservative approach was taken, and the reported values were divided by ten to derive an estimate for the annual services of property in this major values-at-risk category.)

- The valuation of recreational values-at- risk is particularly problematic. Although the undesirability of weeds for some forms of aquatic recreation is clear and is a major impetus for weed control in many situations, the impact of moderate weed growth – or, for that matter, exotic versus native weed growth – on fisheries habitat and fishing is somewhat ambiguous. (See, for example, Furse and Fox.) This impression is not lessened by the fact that anglers themselves often seem at odds or confused regarding the impacts of aquatic weeds (see, e.g., Kirk and Henderson)

- In current studies, the distinctions between transient and local recreators and shoreline residents are couched almost exclusively in terms of travel-cost and expenditure-pattern differences. These distinctions seem to miss the significance of "sunk costs" (for example, in housing) to the values-at-risk, and the implications for both valuation and strategy (like lake associations) also seem to have been missed. Exceptions might include Milon (1989) and Driscoll et al (cited in Henderson, 1995), but even their results are preliminary, tentative, and rather inconclusive.

- Current studies still focus on only a few of the values-at-risk and do not quantify:
    - human and animal health concerns,
    - other environmental effects of drainage,

  - the potential for and problems of aquatic weeds removing certain pollutants from water,
  - the effects of drainage on forests,
  - effects on hydropower, irrigation, and water transportation, and
  - effects on wildlife habitat, including that of invasive wildlife species (see, e.g., Partington, 1968).

- Current studies do not distinguish clearly between the effects or the treatment of exotics, native US species outside of their natural range, and local native weeds.

## Significance and Conclusions

In spite of the qualifications offered above, there is a strong "central tendency" showing that a conservative estimate of the annual values-at-risk of invasive aquatic plants in the United States is in the billions of dollars. Especially given the continuing spread of new and existing species and the difficulty of organizing collective action to control aquatic weeds, it seems likely that these estimates are too low rather that too high, and that too little is being spent on control rather than too much.

The analysis also indicates that technologies exist to significantly reduce the risk of aquatic weeds at a cost that is a small fraction of the values-at-risk. In addition, the analysis suggests that there is much that public policy could do to facilitate and improve the use of such technologies.

This is a particularly important finding since the recently burgeoning literature on invasive species seems to rely heavily on the impression given in one study that invasive aquatic plants represent less than one-tenth of one-percent (0.0008) of the economic impact of all invasive species in the US. (The "pedigree" of this estimate also shows how easily careless analyses can be replicated in the literature and gain general credence. For an overview of this most recent literature, see Hall, 2000.)

The modern invasive species movement could gain considerably from a greater appreciation of the experience and leadership of the longest-standing and most organized efforts combating invasive species in the US – those arrayed against aquatic weeds. A better recognition of the magnitude and history of the aquatic weed issue might help to strengthen its role in what has emerged as a major – if not the major – environmental issue of our day. It might also help to provide more support for the work that this group is doing.

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