Areviewofaquaticplantmonitoringandassessmentmethods

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ABSTRACT

Aquaticplantmanagementhasbecomeincreasinglyscrutinizedbyfederalandstateregulatoryagencies,including the recent implementation of a National Pollut-ant Discharge Elimination System permitting program ineach state. Many states require documentation of nuisanceacres, and an evaluation of management success. Despitethisneed,nowidelyaccepted‘‘standardmethods’’forquantifying nuisance plants has been published. We reviewthe most commonly used quantitative methods for moni-toring plant distribution, species composition, and abun-dance,andmakegeneralrecommendationstosupportmanagement activities in monitoring plant populations andassessing management efficacy. It is important to choose anappropriate method to meet the goals and objectives of agiven program, and to be willing to change methods as theneeds and objectives of the program change. It is unlikelythat the same monitoring and assessment method will beusedthroughoutaprogram,especiallyalong-termpro-gram.Werecommendchoosingmethodsthatare1)quantifiable, that is, data can be statistically analyzed, 2)follow an appropriate sampling design, and 3) are repeat-ableandflexibleenoughtochangeonthebasisofneedsandpersonnel.Ideally,monitoringandassessmentmethodsneedtoincorporatebothtargetandnontargetimpacts,collect data that are objective and can be quantified, and arelaborandcosteffective.

Keywords:distribution,mapping,plantabundance,quantification,survey.

INTRODUCTION

Understandingthedynamicsofaquaticplantpopula-tionsinagivenwaterbodyhasbecomeincreasinglyimportantbecauseoftheintroductionandspreadofnumerousnonnativespecies.Theseplantsaregenerallyintroducedfromotherpartsoftheworld,someforseeminglybeneficialorhorticulturaluses;however,themajorityhaveescapedcultivationandnowcausewide-spread problems (Madsen 2004). Nonnative plants affectaesthetics, drainage, fishing, water quality, fish and wildlifehabitat,floodcontrol,humanandanimalhealth,hydro-powergeneration,irrigation,navigation,recreation,and ultimately land values (Pimentel et al. 2000, Rockwell 2003).For example, the estimated total cost of invasive aquaticplants,includingmanagementandlosses,intheUnitedStatesisapproximately$110million/yr(Pimenteletal.2005).The costofaquaticweedcontrolinirrigationdistricts in 17 western states was estimated to be greaterthan $50 million/yr (Anderson 1993). Florida state agencieshavespentnearly$250milliontomanagehydrilla(*Hydrillaverticillata*[L.F.] Royle) in Florida waters over the past 30 yr;ifoneaccountsforlocalgovernmentandlocalwatermanagementdistricts,thistotalapproaches$750millioninmanagementcostsassociatedwithhydrillaalone(Schardt,pers.comm.).

The direct economic impacts, such as those listed above,are easy to quantify; however, there are other impactsofaquaticplantsthataremuchmoredifficulttoascertain. Theseimpactsincludetheintrinsicbenefitsofaquatichabitats and the ecosystem services these habitats provide(Charles and Dukes 2007). Ecosystem services provide animportantportionofthe total contribution to humanhealth and welfare on this planet (Costanza et al. 1997).Globally, it is estimated that marine systems provide $21trillioninecosystemservices,followedbyfreshwaterhabitatsat$4.9trillion(Costanzaetal.1997).Theseestimates highlight the importance of conserving aquatichabitats and the services they provide to human welfare(Costanza et al. 1997). By any measure, the cost of invasion issignificant, and the investment in management and researchhas not kept pace to minimize the costs associated withinvasions(Sytsma2008).

As the threat of nonnative plant species increases, thedevelopmentandrefiningofmethodstodetect,monitor,andultimately assess management of these species is critical.However, the use of quantitative methods to monitorandassessaquaticplantshasnotbecomeasstandardizedasothercomponentsinaquaticsystems,suchasthebioticorphysicalcomponents (Lind 1979, Madsen 1999). Pursuant to this,millions of dollars are spent every year in managing aquaticvegetation in waters throughout North America; however,onlyasmallfractionisallocatedtoacquiringreliablequantitative data regarding plant populations or in assessingmanagement techniques (Madsen and Bloomfield 1993).

Inmanycases,quantitativeassessmentsareleftoutcompletelybecauseofbudgetconstraints,untrainedpersonnel,oralackofunderstandingwithrespecttowhatmethodsareavailableandhowtoimplementthemeffectively. There is a growing consensus among researchersandmanagers from all aspects of aquatic ecology and manage-mentthateffectiveandquantitativemethodsshouldbeutilizedorstandardizedtomaximizemanagementefforts

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andmonitornontargetimpacts.Withrespecttoassessingmanagementtechniques,effectivemonitoringisneededtoevaluate new biological control projects to determine whichagentsareeffectiveandwhatfactorslimitorenhancetheirsuccess(Blossey2004).Oftentimesmonitoringprogramsareunderfundedorinadequateinscopeanddonotidentifywhereandwhycontrolisorisnotsuccessful(Blossey2004).Thedevelopmentorimprovementonmethodsforevaluat-ingnontargetimpactsofherbicidesisalsocritical,especiallywithrespecttonativespeciesofconcernorthreatenedandendangeredspecies(Getsingeretal.2008).Environmental factors can alsohavean impact onplantgrowthandfunctiontostructureaquaticplantcommunitiesbothspatiallyandtemporally.Forsubmersedandemergentplantcommunities,zonationalongadepthgradientisoftenobservedasafunctionoflightavailability(MiddelboeandMarkager1997).Sedimentcompositionalsoinfluencessubmersedplantcolonizationand distribution (Doyle1999,Madsenetal.2001,CaseandMadsen2004,Madsenetal.2006).Floatingaquaticplantgrowthisoftenlimitedbyavailablenutrientsinthewatercolumn,withnuisancegrowthfollowingtemporalchangesinnutrientloading.Forexample,waterhyacinth(*Eichhorniacrassipes*)respondstofloodingeventsinlargeriverinesystemswhereduringfloodcycles,watermovesoutintoadjacentlandsanduponrecedingbringswithitanincreaseinnutrientstosupportwaterhyacinthgrowth(Kobayashietal.2008).Ingeneral,thereareseveralfactorsthataffectplantgrowthacrossspatialandtemporalscales,andeffectivemanagementrequiresanunderstandingofaquatic plant biology andtheresponseofplants(bothtargetandnontarget)tomanagementactions(Sytsma2008).Theonlywaytoeffectivelyachievethisistoutilizemethodsthatcandocumentthedistribution,growth, andabundanceof aquaticplants overtime(Sytsma2008).

Assessment and monitoring of aquatic plants has becomemore important over the last year as the National PollutantDischarge Elimination System (NPDES) permit program hasbeen implemented to regulate aquatic plant managementactivities, most notably the use of herbicides. One of therequirementsincludedinthefederalNPDESpesticidegeneralpermitisforthequantitativeassessment ofnuisance plant coverage to document that the target speciesexceed a nuisance threshold. Quantitative methods are alsorequired to assess the impacts of management activities ontarget and nontarget plant species. Therefore, the objectivesof this paper are to 1) offer a broad overview of availablemethods that can be utilized for aquatic plant monitoringand assessment, and 2) provide guidelines regarding the useof these methods for assessing aquatic plants, as well aspointing out methods that are not effective for this purpose.Theseguidelineswillcoversubmersed,floating,andemergent plant species for lakes and flowing waters. Thegoal is to equip professionals in aquatic plant managementwith the tools and justifications to address questions andconcerns related to management activities such as nontar-getandhabitatimpacts,management implementation inthe correct areas, regulatory compliance (NPDES), publicrelations(includingcompetingusesforwaterresources), andprofessionalcredibilitytopeopleoutsideoftheaquaticplant managementfield.

OVERVIEWOFAQUATICPLANTMONITORINGANDASSESSMENTMETHODS

Before undertaking any sort of monitoring or assessmentprogram, one must correctly identify the species of interest.Often,whenincorrectidentificationsoccur,the processused to document species identifications is poor, includingthe lack of herbarium specimens (Hellquist 1993) or digitalphotography adequate to correct these misidentifications.Correct identification of both target and nontarget plants iscrucial in identifying rare or threatened species, as well asaiding in delineating areas with species of special concern(Hellquist1993).Devotingtimeandresourcestoconstructaproper species list for a given water body can be invaluableindevelopingamanagementplan;furthermore,specieslistsareoftenrequiredinthepreparationofenvironmentalimpact statements and permitting requirements (Hellquist1993).

Severalmethodsexistforsamplingaquaticplantstodevelopaspecieslist,determinedistributions,andtoestimate abundance in a given water body. These methodsrange from low-cost visual estimations of plant occurrenceand cover to high-cost remote sensing that can sample awater body or an entire landscape. An important factor toremember when selecting a method is to choose the methodthat will meet the desired objectives for the project, but,more important, to choose a method that is quantifiable andcanbesubjectedtostatisticalanalyses(MadsenandBloom-field1993,SpencerandWhitehand1993).MadsenandBloomfield point out the following justifications for usingquantitativemethods:

- Quantitative data are objective measurements, andrelying on subjective measurements leads to opin-ion,whichisnotasoundbasisformanagementdecisions.
- Quantitativedatacanbesubjectedtorigorousstatistical analyses that can lead to the developmentofscientificallybasedmanagementguidelines.
- Quantitativedatacanidentifymanagementtech-niques that were ineffective and thereby reduce thecostofamanagementprogram.
- Quantitative data can be utilized by different usersotherthantheobserver.

Toensurethatmonitoringandassessmentdataarecollectedinamannerthatissuitableforquantifiableanalyses, it is important to collect data using an appropriatesampling design. The four most common sampling designsarethecompletelyrandom,stratifiedrandom,random–systematic, and systematic designs. A conceptual represen-tation of these sampling designs is depicted in Figure 1. Ingeneral,thecompletelyrandomdesignremovesbiasesassociated with the selection of sampling locations; however,Barbour et al. (1999) points out several limitations to thisdesigninlargerareas:

- Arandomselectionofpointsmayplacepointsin

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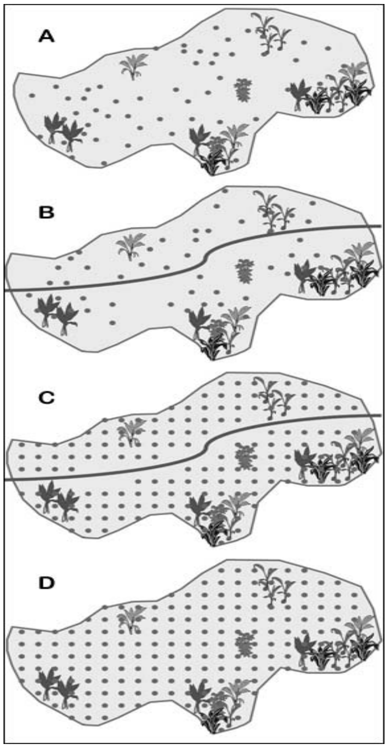

Figure1.A conceptual representation of plant community samplingdesigns(A)completelyrandom,(B)stratifiedrandom,(C)random–systematic,and(D)systematic.

difficult-to-accessorinaccessibleareas,andthelittleinformationthesepointswouldprovidedoesnotcompensatefortheaddedtimeitwouldtaketosamplethem.Thefieldtimerequiredtosamplerandompointsislargeandwouldlikelybeaninappropriatechoiceforlargesurveys.

- Arandomselectionofpointsmayresultinthelocationofsomepointsbeingclumped,leavinglargeareasundersampled.
- Acompletelyrandomdesignwouldundersamplerare yet important species that would be sampledusingotherdesigns.
- Acompletelyrandomdesignmaymakeitdifficulttoconductanysortoftime-seriescomparisons,ordetectspatialchangesasnewrandomsitesarevisitedduringeachsamplingevent.

Astratifiedrandomdesignistypicallyutilizedifagradientexists in the survey location; for aquatic surveys this couldincludeariverorstreamchannelrunningthroughareservoir.Theareacanbedividedintohomogenoussections

withsamplingpointsrandomlydistributedwithineachsection. Thesystematicsamplingdesignplacessamplelocationswithin anareaonthebasisofgridwithapredetermined spacing. The systematic design works wellforaninitialsurveyasitwillcovertheentirewaterbodyandthe observer is more apt to find most species dependingupon the distance between points. If the distance betweensamplepointsissmalltheprobabilityofdetectionincreases;if the distance between sampling points is large then theprobabilityofdetectiondecreasesandrarespeciesaremissed .Also,ifdatasuchaswaterdepthorSecchidepthare collected at sampling locations, the maximum depth ofplant colonization can be determined and the littoral zonedelineated for future surveys. A random–systematic designselectsareaseitherbyrandomorusingastratifiedapproach.The survey is then initiated by selecting the starting pointeitheratrandomorinastratifiedfashion,andthenconducted using a systematic sampling approach (Barbouret al. 1999). The random–systematic design works well if agradient is present, or if the littoral zone is well defined,thereby allowing sampling locations to be stratified withinthelittoralzone.

A summary of the more common aquatic plant samplingmethods (including nonquantifiable) are listed in Table 1,withspecificguidelinesdiscussedinlatersections.Thesimplest estimates of plant cover and abundance can beachieved using visual observations while on a water body.Generally, total acreage is estimated for each species on thebasis of the total area of the water body. Visual estimationsare highly subjective, are not repeatable, and are highlyvariableamongobservers,therebymakingthemnonamend-abletostatisticaltreatment.Also,itisverydifficulttoestimate abundanceofsubmersed aquatic plants,andassuchspeciesaremissedorunderestimated.

A compromise between subjective estimates and quanti-tative methods would be a semiquantitative survey in whichpreselectedareasaresurveyedusingapresence/absenceapproachtoestablishthefrequencyofoccurrenceforspecies (Madsen and Bloomfield 1993). Divers or a plantrakecanbeutilizedtosamplesubmersedspecies.Thismethod would be useful to establish basic plant communitycompositionifseveralsitesweresurveyed,andwouldcapturemorespeciesthansubjectiveestimates.Thoughagain, similar to subjective estimates, these data cannot bereadily analyzed and may not be adequate in establishingthresholdstomeetpermittingrequirements.

Quantitativemethodsthatcanbeutilizedtorapidlycollectinformationregardingplantoccurrence,speciesrichness, and distribution include the point-intercept andline-transect methods. These methods can be used in bothsmall plots and in multiple locations within a water body toestablish plant community characteristics or assess manage-mentefficacy.Point-interceptsurveysaretypicallycon-ducted using a preselected grid of points at a user-specifiedinterval (Madsen 1999). By preselecting points, it removesthe subjectivity with respect to sample locations. Once onthe lake a global positioning system (GPS) is then used tonavigate to each point where a plant rake is deployed tosamplesubmersedvegetation.Emergentandfloatingvegetationcanalsoberecordedateachpointaswell.The

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TABLE1. SUMMARYOFVASCULARAQUATICPLANTMONITORINGANDASSESSMENTMETHODS(ADAPTEDFROMMADSENANDBLOOMFIELD1993).

Method	Techniques	Effort	Variability	Recom-mendation[1]	Applications
Pointintercept	Presence/absence	Low	Low,canbespatiallyvariable	S,E,F	Small-plotassessments,baseline surveys,whole-lakemonitoring,andlong-termassessments
Linetransect	Points,quadrats	Moderate	Moderate,canbespatially variable	S,E,F	Small-plotassessments,monitoringspeciesdistribution
Subjectiveestimates	Visual	Low	Low-high,dependsonhowmanypeoplearemakingestimates	S,E,F	Initialsurveythoughthismethodishighlysubjectiveandnotquantifiable
Semiquantitative	Visual	Low	Low,canbespatiallyvariable	S,E,F	Initialsurveys
	Rake fullness or spinningrakemethods	Moderate	High	S	Small-plot assessments,willover-orunderestimatespeciesdependingoncomposition
Biomass	Coring,quadrats,boxsampler,ponardredge	High	High,canbespatially andtemporallyvariable	S,F	Small-plotassessments
Nondestructive	Hydroacoustics	Moderate	Moderate,canbe temporally and spatiallyvariable	S	Small-plot assessments,whole-lake long-termmonitoring
	Plant morphologicalmeasurements	Moderate-high	Moderate,canbe temporallyvariable	E,F	Small-plotassessments
	Geographicinformationsystem,remotesensing	Moderate	Low-high,willdependon theresolutionofimages	E,F	Visualization ofdata,whole-lakelong-termmonitoring,notspeciesspecific
	Mathematicalmodels	Low-high	Low-high,willdependon dataunderlyingthemodels	S,E,F	Potentialpredictability,estimationsoffutureinvasionsandplantgrowth,evaluateeffectsofalternativeapproaches

[1]S¼submersed,E¼emergent,F¼floating.

pointinterceptmethodisveryadaptabletomeetthedesiredobjectives of a management program. More important,surveysaredevelopedonthebasisofagivensamplingdesign (random, stratified random, random–systematic, andsystematic),whichallowsdatatobestatisticallyanalyzedto compare changes in species occurrence over time and toassess the effectiveness of management techniques (Wersaletal.2010).WithadvancesinGPSandgeographicinformationsystems(GIS)technologies,pointinterceptsurveyprotocolscanbedeveloped,implemented,andresultsanalyzedwhilestillonthewater.Pointinterceptisarobustsamplingmethodthatislesssensitivetodifferencesin abundance or season. However, this method may notdetect the differences in abundance or seasonal effectsthatareoftenthefocusofmanagementassessments.Pointinterceptsurveysalsomaymissspeciesthatoccurinnearshoreareasthataretooshallowforaboattonavigatetoandthusunderestimatethesespeciesinthesurvey.Line-transect methods aresimilar to the point-interceptmethod; however, with transects one can collect presence/absence data, cover data, or use quadrats along transects tocollect density and abundance measurements (Grieg-Smith1983,Titus1993,Madsenetal.1996,Getsingeretal.1997).In general, the line-transect method requires less technol-ogythanpointinterceptsurveys,astransectscanbeestablishedadsampledwithouttheuseofacomputeror GPS technology (Madsen 1999), though these technologiesare more readily available and more cost effective than inprevious years and are routinely used for transect estab-lishment. Transect lengths can be any lengthfrom large field-based projects (Titus 1993) to small-scale (3-cm) intervals to estimate foliage coverage of submersedplants(SidorkewecjandFernández2000).Thelinetransect method is particularly useful in determining aquatic plantcommunitycharacteristicsinsmallstudysitesovertimeand toassessmanagementefficacyinsmallplots(Figure2).

Inadditiontoconstructingaspecieslistthroughpresence/absenceinformation, oftentimes it is of interestto collect plant abundance data to assess changes in theplantcommunityduetomanagementactivities.Plantabundance can be characterized using a biomass harvestingtechniquesuchasacoringdevice,quadratswithandwithout divers, ponar dredge, or the semiquantitative rakefullness method. Biomass harvesting is labor intensive andcan be subject to spatial and temporal variability dependinguponplantdensities,plantcommunitycomposition, andlife historytraits.However,biomasstechniquesprovidethe

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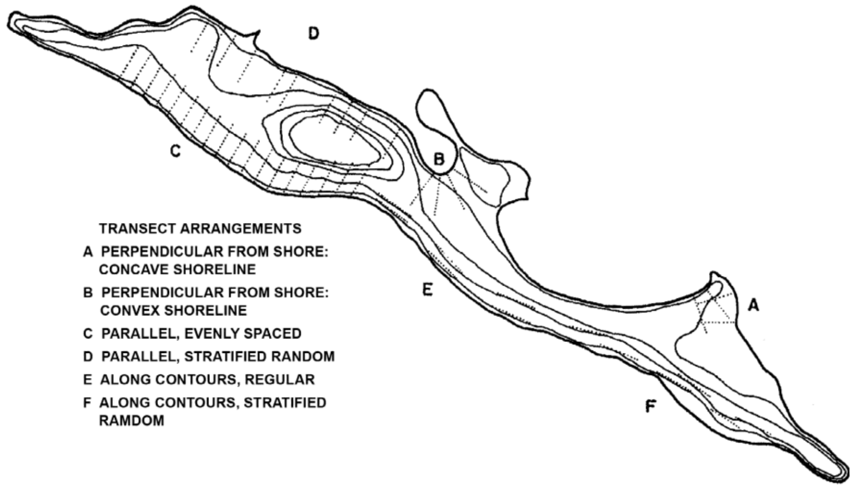

Figure2.Line-transectsamplingdesignsforaquaticplantmonitoringandassessmentinriverinehabitats.

bestinformationonspeciesabundanceaslongasanadequatenumberofsamplesiscollectedtoovercomeissueswithvariability(Madsen1993,MadsenandBloomfield1993). Pursuant to this, biomass techniques such as coringdevices,box corers, and dredges are the only techniquesthatcanadequatelysamplebelowgroundplant biomasssuch as root crowns, rhizomes, tubers, and turions (Madsenetal.2007,Owensetal.2010).However,emergentvegetationisoftendifficulttoharvestwithcorersanddredges.

Before undertaking a biomass sampling program, it isnecessary to understand the trade-offs between the laborinvolvedinusingthesamplingdevice,theareaofthesamplingdevice,andthenumberofsamplesneededtoadequatelyassess thetargetplantpopulation(Madsen1993).For example, box corers generally have an area of 0.1 $m^2$and polyvinyl chloride (PVC) coring devices an area of 0.018m^2; therefore, fewer samples are needed with the largersampling device to overcome issues with variability andcollect a statistically-relevant number of samples (DowningandAnderson1985).However,largersamplersrequiremore processing time, and therefore it may be beneficial touse a smaller sampling device and collect more samples(DowningandAnderson1985).Forinstance,acorerof 0.018 m^2 (Madsen et al. 2007) may require 30 samples in agivencommunitytogetastatistically-significantsample,butmayactuallyrequirelesstimetocollectandsortthanthe10samples needed for a statistically adequate sample with a0.1-m^2quadrat.

The spinning rake method is conducted by lowering aplant rake on a fixed pole to the bottom of the water body(Skogerboeetal.2004,SkogerboeandGetsinger2006,Owens et al. 2010). The plant rake is then turned once 3608to harvest aboveground plant material. The rake head has aknown length, and when turned, serves as a circular quadratinwhichanareacanbecalculated.Althoughthis methodis easy and low intensity, it is less precise than other biomassmethods,especiallyindensevegetation(JohnsonandNewman 2011), where it tends to overestimate abundanceand will not sample belowground plant structures. As withanyquantitativemethod,biomasstechniquesshould beused following a sampling design, and in doing so, will allowfor statistical analysis of collected data. To determine if astatistically-adequatenumberofsampleshasbeencollected,a power analysis should be performed on an initial set ofdata from the site (Downing and Anderson 1985, Madsen1993,SpencerandWhitehand1993).

To overcome the labor intensity associated with biomasstechniques,someresearchershavedevelopedplantrakemethodssuchastherakefullnessmethod(IndianaDepartment ofNaturalResources2007,Hauxwelletal.2010).Therakefullnessmethoddividestherake(andsometimes tines) into discrete increments and when plantsareharvestedanabundancerankingisgivenforeachspecies.Thismethod,althougheasyandlowintensity,relieson subjective ratings by an observer. Visual ratings tend notto be consistent between observers and should not be reliedupon as a stand-alone measurement. Pursuant to this, YinandKreiling(2011)alsoreportedpotentialissueswithusing rake methods to estimate density, and concluded that cross-species comparisons are not encouraged unless the efficien-cy of the rake method has been determined for each speciesbeing compared. This would increase survey time and theoverallcostofamanagementprogram.

Insomeinstancesitmaynotbedesirabletoharvestbiomass or use a method that may damage existing aquaticplants,especiallyinthepresenceofrareorthreatenedspecies in the area. In these cases, nondestructive methodscould be used to estimate plant abundance, though somemethodslikehydroacousticsandremotesensingcannotdifferentiate plant species. Hydroacoustic sampling targetssubmersedaquaticplantsbyusinganechosounderor

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TABLE2.DECISIONMATRIXTOGUIDESELECTIONFORAQUATICPLANTMONITORINGANDASSESSMENTMETHODS.

Initial Methods	Survey	DesiredApplication Small-PlotAssessment	Whole-LakeAssessment	Long-TermMonitoring	Quantifiable	Cost	Satisfies NPDESRequirements[1]
Pointintercept	X	X	X	X	X	Low	Yes
Linetransect	X	X		X	X	Low	Yes
Subjectiveestimate	X	X				Low	No
Semiquantitative(visual)	X	X				Low	No
Semiquantitative(rakefullnessorspinningrake)	X	X		X	Marginal	Moderate	Yes
Biomass		X		X	X	High	Yes
Plantmeasurements		X		X	X	Moderate	Yes
Geographicinformationsystem				X	X	Moderate	No
Remotesensing			X	X	X	High	Yes
Mathematical modeling				X	X	Low	No

[1]NPDES¼NationalPollutantDischargeEliminationSystem.

fathometer(depthfinders)thatcan record informationfrom the transducer onto flash memory devices (Sabol et al.2002,Hohausováetal.2008,Saboletal.2009).The equipment neededto perform hydroacoustic surveys hasbecomemuchsimplertouseandmorecostefficient.Shallow -range (0 to 7 m) chart recorders are standard onmany low-cost commercial echo sounders (Thomas et al.1990).Naturalresourceagenciesthatusethesesystemsregularlycouldmapsubmersedvegetationforapproxi-mately $2.06/ac (Sabol et al. 2009). Maceina and Shireman(1980) reported that the principle advantage of utilizing arecording fathometer for vegetation surveys is that savingsintimeandmanpowercanbeaccomplished;forexample,inLakeBaldwin,FL,14transectscoveringatotaldistanceof 11.3 km were completed in 3 h. Hohausova´ et al. (2008)reported a positive relationship between the hydroacousticsignal and dry biomass, though the relationship could notdifferentiate species and results would likely be influencedby the dominant species present. With respect to monitor-ing and assessment, hydroacoustic surveys allow for theestimation of total biovolume of plants in a given area,which could be used to quantify seasonal changes in thewhole plant community over time. Species-specific infor-mationcannotbedeterminedunlessanothersamplingmethod like point-intercept surveys are utilized to constructaspecieslist.

Unlike hydroacoustic surveys, remote sensing is mosteffectiveintargetingriparian,emergent,andfloatingvegetation (Everitt et al. 2007, Liira et al. 2010, Midwoodand Chow-Fraser 2010, Robles et al. 2010). Remote sensing isoften expensive as satellite images of the target area have tobepurchased,specializedsoftwareisneededtoanalyzeimages, and trained personnel are needed to complete theanalyses. However, remote sensing is useful in long-termquantification of vegetation in a given area without havingtoactuallyusesurveycrewsyearafteryear.Italsoallows forthe monitoring of larger areas than what are feasible usingsurveycrewsalone,thoughitisrecommendedtoimplementsome sort of ground-truthing survey to verify plant speciescomposition and the spatial accuracy of remotely senseddata. Remote sensing can also be used to assess herbicideinjury, as the sensors can detect changes in light reflectancedue to herbicide exposure before the human eye can see theplantdamage(Roblesetal.2010).Othernondestructive sampling can also be done at smaller scales to estimateabundancebasedonplantmorphologymeasurements(Daoust and Childers 1998, Thursby et al. 2002); however,thisistypicallyonlyusedonemergentorfloatingvegetationasthesespeciesarereadilyaccessibleandmeasurementscanbetakeneasily.

GUIDELINESFORSAMPLINGAQUATICPLANTS

When considering which method or methods to choosefor a monitoring or assessment program it is essential toconsider the target species, co-occurring nontarget species,the growth form of the target species, species life-historytraits,andthescaleatwhichtheprogramwillbeimplemented. Ultimately, a method should be chosen tomeettheobjectivesofthemanagementplan.Wehaveoffered a decision matrix to assist in choosing a monitoringorassessmentmethod(Table2),andhavedeveloped guidelines for the three growth forms of aquatic vascularplants along with planktonic and filamentous algae. Theseguidelines are not meant be exhaustive or definitive, but areeffectivemethodsthathavebeenverifiedbyscientificevaluations or are recommended in the Standards Methodsfor the Examination of Water and Wastewater (Rice et al.2012)toestimateplantcoverageorabundance.

Submersedspecies

Estimating cover and distribution in lakes. The simplestquantitativeapproachtoestimating submersed aquaticplantcoverand distribution in a monitoring program istoperformapoint-interceptsurvey.Thepoint-interceptsurveyworkswelltocharacterizetheaquaticplantcommunity (Mikulyuk et al. 2010) and monitor trends incommunity composition through time within a water bodyor system (Case and Madsen 2004, Madsen et al. 2006,Wersal et al. 2006, Madsen et al. 2008). The point-interceptmethod(orvariationsofrakemethods)has becomestandardsamplingprotocolinthestatesofWashington(Parsons 2001), Idaho, Montana, Minnesota (Beck et al. 2010,Valley and Heiskary 2012), and Wisconsin (Mikulyuk et al.2010) to collect initial plant community information and toestablishmanagementareas.

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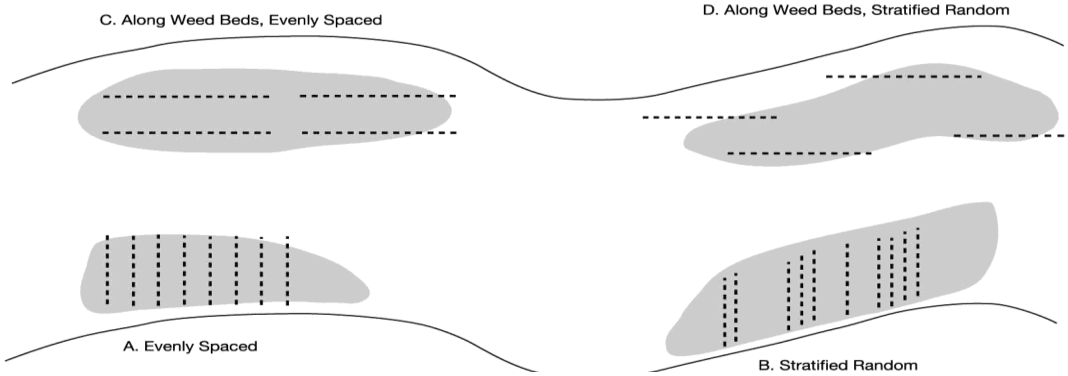

Figure3.Line-transectsamplingdesignsforaquaticplantmonitoringandassessmentinlakes,adaptedfromTitus(1993).

The point-intercept survey works well in assessing field-scale studies and operational management programs. Pointscan be generated in any treatment area and rapidly sampledto assess several small plots or effects throughout a waterbody in the case of a whole-lake treatment (Parsons et al.2001, Madsen et al. 2002, Parsons et al. 2004, Parsons et al.2007, Parsons et al. 2009, Wersal et al. 2010, Robles et al.2011, Getsinger et al. 2013, Getsinger et al. 2014, Cox et al.2014, Madsen et al. 2015). This method offers a more strictassessment compared with abundance method as plants areeither present or absent and will be influenced by spatialvariability in plant beds. It is also important to note thatsurveyresolutionwillaffectdetectionratesanditisadvisable to set one grid interval and maintain that intervalin successive years to make comparisons easier and moremeaningful.Also,acommonmisconceptionwiththismethodisthatdatacanbeinterpretedasabundance;however,samplepointsareadimensionlessunitsoabundanceestimatesarenotpossible.

Estimating cover and distribution in rivers. In riverine habitatsitismuchhardertoquantifysubmersedplantspeciescharacteristics because of flowing water and inaccessibilityinmanyareas.Submersedaquaticplantsoftengrowinbands along the shoreline of rivers with depth distributionlimited by high flows and unsuitable substrate. However, inlarger rivers transects have been effective in quantifyingplant species cover and assessing management operations(Getsingeretal.1997).Insmallerrivers,linetransects couldbeestablishedperpendiculartotheshoreline to runthrough the vegetation band toward the middle of the riverchannel, or, line transects could be established parallel tothe shoreline to follow the contour of the vegetation bands,withtransectsevenlyspacedorinastratifiedrandomdesign(Figure 3). In very small rivers or creeks, a line transectcould be established across the entire width of the channel,ifflowspermit,andspacetransectsinanappropriatesamplingdesign.

Estimating abundance in lakes. When plant abundance isimportant, biomass collection techniques offer data that arespeciesspecific.Thereareseveralbiomasscollectiontechniquesanddevices,andtheappropriatetechnique should be chosen to meet the objectives of the project, butalsotoadequatelysamplethetargetspecies.ThePVCcoring device as developed by Madsen et al. (2007) worksvery well in sampling submersed aquatic plants, especiallybelowgroundreproductivestructures.ThePVCcorer canbe utilized in monitoring the abundance of native aquaticplants over time (Case and Madsen 2004, Madsen et al. 2006,Wersal et al. 2006) or nonnative plant abundance in smallplots (Woolf and Madsen 2003, Wersal et al. 2011). Whenusing the PVC corer it is important to collect an adequatenumber of samples; we typically recommend 20 to 30 coresamples per site. The PVC corer does not sample emergentaboveground biomass very well, especially tall plant species.Also, in dense beds of Eurasian watermilfoil (*Myriophyllumspicatum*L.) and curly-leaf pondweed (*Potamogetoncrispus*L.),care must be taken to ensure that the coring device has cutthroughthevegetationandrootcrownsandhas beenpushed deep enough into bottom sediments. Failure to dothis will result in a lost sample and extra expenditures inlabor.Owensetal.(2010)suggestedthataboxcorer(similartoanEckmanorponardredge)maysamplesomespeciesofsubmersed aquatic plants more effectively than the PVCcoringdevice.However,theboxcorerislargeandcumbersome to operate and any benefit from using it cangenerally be overcome by collecting more samples using asmallerareasamplersuchasthePVCcorer.

Anotherabundancetechniqueisfordiversto setquadratsonthebottomofthelake.Sampling in thismannerwillallowforthecollectionofspecies-specificpresence/absence, species density, and biomass data. Re-search suggests that the diver quadrat method results ingreater accuracy and precision with respect to abundanceestimates than boat-based methods (Capers 2000, Johnsonand Newman 2011). In particular, small species and lessfrequentspeciesareoftenunderestimatedusingboatmethods (Capers 2000). However, in-water methods (diverquadrat)incurmorerisktoperform, require specialtraining (i.e., scuba), and are more time consuming thanother methods, and thus limit the spatial extent of this typeofsamplingcomparedwithothermethods.

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Thespinningrakemethod(Skogerboeetal.2004,Skogerboe andGetsinger2006,Owensetal.2010)hasbeenusedtomeasurea bovegroundplantabundance.Thespinning rake method was found to be a suitable alternativetothediverquadratmethod,especiallyinlarge-scalestudiesrequiring a high sampling intensity (Johnson and Newman2011).Itwasconcludedthattheincreasedsamplingefficiency that the spinning rake method offered offset itsinherent lower precision (Johnson and Newman 2011). Thespinningrakemethodwillalsobeinfluencedbydensevegetationandoverestimatebiomassofthedominantspecies present (Johnson and Newman 2011). Furthermore,rake methods are not as effective in sampling species withbasal growth forms such as wild celery; or in samplingbelowground structures (Owens et al. 2010). To adequatelysample belowground structures, one should use the PVCcoringdevice(Madsenetal.2007).

Recently,therehasbeenagreatdealofattentiontoadaptingplantrakemethodstocollectplant biomassinstead of using coring devices and divers. The aforemen-tionedrakefullnessmethod(Indiana Department ofNatural Resources 2007, Hauxwell et al. 2010) has beenutilized to rapidly assess plant communities. In Florida, itwas determined that a rake-based fullness method was asuitable alternative to a ponar dredge and diver-harvestedquadrats in estimating submersed plant abundance (Rodus-kyetal.2005).

If species-specific abundance data are not required for agiven project, then remote sensing (including hydroacousticsampling) can be used to estimate abundance (biovolume) ofaquatic plant species (Rice et al. 2012). In general the largerthe area, the greater the advantage of using remotely senseddata especially if sampling is required over long timescales(Rice et al. 2012). Some studies have reported that remotesensingcouldbeusedtomonitor canopy-forming sub-mersed aquatic plants (Everitt et al. 2003, Fitzgerald et al.2006, Nelson et al. 2006, Everitt et al. 2011). Remote sensingwasusedundermesocosmconditionstodifferentiatesubmersedspeciessuchascurly-leafpondweed,hydrilla,Eurasian watermilfoil, northern milfoil (*Myriophyllumsibir-icum*Kom.), hybrid milfoil (*Myriophyllumspicatum*3 *Myrio-phyllumsibiricum*), and parrotfeather [*Myriophyllumaquaticum*(Vell)Verdc.]using hyperspectral reflectance data (Everittetal.2011).Theauthorsdeterminedbyusingstepwisediscriminantanalysisonreflectancedatathat 9 bands forMay 11 and 10 bands for May 30 in the blue to near-infrared(NIR) spectral regions had the highest power to discriminatebetweenspeciesofsubmersed aquatic plants. During theJuly sampling period only seven bands in the red–NIR edgeandNIRregionswereusefulfor discriminating amongspecies (Everitt et al. 2011). The change in the reflectancebands used for species separation is likely due to phenologyandchangesintheplantsoverthecourseofthegrowingseason.Althoughspeciesseparationwasachievableunderexperimentalconditions, it is much more difficult toachieveatthe landscape level because of larger expansesof open water, which serves as a sink for light energy. Usingsatelliteimageryandaerialphotographycanwork well aslongasplantsareatornearthewatersurface,thoughitis stillrecommendedtoconductsomeground-truthingsurveys.

Large-scalemanagementprogramsinTexashaveutilizedaerialphotographytosuccessfullyassesstheefficacyofgrasscarp(*Ctenopharyngodonidella*)herbivoryonhydrillainLakeConroe(Martynetal.1986).Similarly,hyperspectralimagerywasusedtoevaluatetheefficacyofherbicideapplicationsintheSacramento–SanJoaquinRiverdeltainCalifornia(Santosetal.2009).Inregardtosubmersedplants,anunderestimationislikelytooccurdependinguponthereflectancebandsusedintheanalysis,waterclarity, andthedepthtowhichsubmersedplantsaregrowing.Itmaybemorecosteffectivetoutilizehydro-acousticsurveysforsubmersedaquaticplants,especiallysince manyconsumersonarunitsarelessexpensiveandrecordtransectdatatoportablememory(Maceinaetal.1984,Saboletal.2009). Hydroacousticsurveyscangiveaverypreciseestimateoftotalplantvolumeinagivenwaterbodyandarerelativelyrapidtoperform(Saboletal.2009).*Estimatingabundanceinrivers*.Linetransectsanddiver-harvestedquadratswereusedtoassessherbicideefficacyandnontargetimpactinthePendOreilleRiver,WA(Getsingeretal.1997).Coresamplerscouldalsobeutilizedtorandomlycollectbiomasssampleswithinplots,ortocollectsamplesalong a line transector gridinsteadofusingdivers.Infact,thePVCcoringdevicewasusedinLakePendOreille,ID(inboththelakeandriverineportion)to assessplantabundancebeforeandafterherbicidetreatmentsand diver-operatedsuctiondredging(MadsenandWersal2008).Inlargerdeeperriversitmaybepossibletousehydro-acousticsurveystodelineateplantbedsandestimatecover.Satelliteandaerialimagerycanalsobe usedtomonitorandassesssubmersedspeciessuchashydrillaandegeria(*Egeriadensa*)inlargeriversaslongastheyareatornearthewatersurface(Everittetal.1999,Everittetal.2003,Santosetal.2009).Submersedaquaticplantbiomasscanbeharvestedinsmall rivers and shallow creeks using quadrats following anappropriatesamplingdesign(MadsenandAdams1988, MadsenandAdams1989).

Emergentandfloatingspecies

Estimating cover and distribution in Lakes. For whole-lakemonitoring,apoint-interceptsurveycouldbeused tocollect basic information regarding emergent and floatingspecies composition, cover, and distribution (Robles et al.2011). However, the line-transect method may be a betterchoicetoeffectivelymonitorandassessemergentandfloating aquaticplantcommunities in small plots withinlakes as their distributions are typically more concentratedin smaller areas than with submersed species. The line-transect method is likely a better choice than the point-interceptmethodastransectstypicallystartalongtheshorelineandmoveoutintodeeperwater.Thepoint-intercept method may underestimate emergent and floatingspecies in small plots because the dispersion of points maylimit detection. Titus (1993) offers a detailed descriptionregardingtheuseoftheline-transectmethod,samplingdesigns, sample number, and data that can be collected. Toproperlyimplementaline-transectprotocolwerecommend

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usingasamplingdesignthatwillmeetthedesiredobjectivesforth eproject.Effectivetransectsamplingdesignsaredepicted in Figure 2 and are adapted from Titus (1993).Linetransectshavebeenusedtocharacterizetheplantco mmunitiesinwetlandsofSouthCarolinaandalsoallowedforthe developmentofalandscapemodeltopredictchanges in the vegetation type on the basis of hydrologicandenvironmentalfactors(DeStevenandToner200 4).

Foremergentvegetation,Radomskietal.(2011)describethe reproducibility of using GIS to delineate field poplua-tionsofbulrushes(*Schoenoplectus*spp.)byusingthreedifferent surveyorstoconductrepeatedsurveysinfiveMinnesotalakes.T heauthorsconcludedthatcoveragemapping could be completed in a timely manner and withreasonable precision (Radomski et al. 2011). They did notdetectanydifferencesamongsurveyorestimatesorthewhole -lake stand coverage. For lakes that had a monospe-cific bulrush stand, the method could detect a whole-lakechangeof10%(Radomskietal.2011).

Estimating cover and distribution in rivers. When samplingrivers foremergentandfloating plant species, the samefactors that limit sampling of submersed vegetation stillapply. Therefore, it is recommended to follow a similarsamplingprotocolasoutlinedin the aforementionedsection on estimating cover and distribution of submersedaquaticplantsinrivers.

Estimatingabundanceinlakes.Iftheobjectiveistomonitoror assess small plots as part of a management program,establishing permanent quadrats in these plots would allowfor repeated sampling over longer periods of time to assessimpacts on both target and nontarget species. Welling et al.(1988) utilized permanent quadrats to assess the recruit-ment and zonation of emergent vegetation in response todrawdown events in prairie wetlands. Overall, quadrats arebetter for sampling taller emergent species (Wersal et al.2013)andfloatingspeciesasthesegrowthformsdonotlendthe mselves well to sampling with box corers or the PVCcorer.

In addition to biomass sampling, remote sensing can beused to delineate emergent and floating plant beds, assesslargescalechangesinareainresponsetomanagementtech niques and the cumulative effects of lakeshore devel-opment(Radomski2006),and,unlikewithsubmersedaquatic plants, emergent and floating plants can often beclassified using spectral signatures (Marshall and Lee 1994,Hanlon and Brady 2005, Midwood and Chow-Fraser 2010).Pursuant to this, remote sensing has the potential to predictherbicide injury to aquatic plants before the human eye candetect any effect (Robles et al. 2010). If a remote-sensingapproach is implemented, it may be necessary to periodi-callyground-truthdatatoensuretheaccuracyoftheimagery and algorithms used to monitor and assess plantcommunities. Nondestructivemeasurementsofemergentplantssuchasplant height,stemdensities,leaflength,stemdiameter,number of leaves, leaf thickness, number of axillary stems,and number of nodes can be used to construct mathemat-icalmodelstoestimateabovegroundbiomassofplantspecies (Daoust and Childers 1998, Thursby et al. 2002,Spenceretal.2006,Gourardetal.2008).Additionally,a combinedapproachusingbothremote-sensingdataandplantmorphometric data can be used to estimate biomassof floating aquatic plants without the need for destructivesampling (Robles et al. 2015). The development of modelsbasedonnondestructivemeasurementsto estimate plantbiomass may be beneficial in cases where sampling of rareorthreatenedspeciesisnecessary.

However, it may be necessary to harvest a subsample ofindividuals to assess which types of measurements could beuseful in developing a predictive model. For example, Vanetal.(2000)harvested138melaleucatrees(*Melaleucaquin quenervia*) in South Florida to determine relationshipsbetween dry-weight biomass and stem diameter measure-ments. Their resulting model based on inside-bark diametermeasurements explained 97% of the total variation in dry-weight biomass. It was concluded that this model would beuseful in assessing the impacts of biological control agentsbyallowingestimationofbiomassfrommeasurementsm adein melaleuca stands where destructive sampling was notpossible(Vanetal.2000).

Estimating abundance in rivers. Many of the same methodsused to estimate abundance of submersed vegetation couldbe used for emergent and floating vegetation including linetransects and quadrats. However, remote sensing may be agood choice, especially if large areas of a river basin ordrainage are being monitored or assessed. Remote sensinghasbeenutilizedintheRioGrandesystemtomonitorcha nges in wild taro (*Colacasiaesculenta*), giant reed (*Arundodonax*), and water hyacinth populations (Everitt et al. 2003,Everitt et al. 2007, Everitt et al. 2008). Herbicide effects ontheaquaticplantcommunityinthe Sacramento–SanJoaquin River delta were assessed from 2003 to 2007 usinghyperspectralremotesensinginSantosetal.(2009).

CONCLUSIONS

Wehaveofferedseveralaquaticplantcommunitysampling methods that can be used for large-scale long-termmonitoringandforsmallscaleassessmentsofmanagement techniques.Itisimportanttochooseanappropriate method to meet the goals and objectives of agiven program, and to be willing to change methods as theneeds and objectives of the program change. It is unlikelythat the same monitoring and assessment method will beusedthroughoutaprogram,especiallyalong-termpro-gram.Werecommendchoosingmethodsthatare1)quantifiable, that is, data can be statistically analyzed, 2)follow an appropriate sampling design, and 3) are repeat-ableandflexibleenoughtochangeonthebasisofneedsandperso nnel.Ideally,monitoringandassessmentmethodsneedtoincorp oratebothtargetandnontargetimpacts,collect data that are objective and can be quantified, and arelaborandcosteffective.

Monitoringandassessmentarecriticalindocumentingthesucce ssorfailuresofaparticularmanagementtechnique, and will allow for the evaluation of differenttechniques if needed, thereby preventing costly mistakes. Along-termmanagementplanshouldbedevelopedandincorporate not only year-of-treatment management eval-uations,butalsolong-termmonitoringoftheaquaticplant

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community. Intensive monitoring has been cited as the onlyeffectivewaytodetermineaprogram'ssuccessandwhentot erminateamanagementprogram(Simberloff2003).However, all too often, monitoring and assessment proto-cols are the first items to be removed from managementprogramswhenfundingislimited.

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