Chapter 12: Watershed management strategies to prevent and control cyanobacterial harmful algal blooms

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Abstract

The tenets of watershed management – a focus on the land area linked to the water body, the incorporation of sound scientific information into the decision-making process and stakeholder involvement throughout the process – are well-suited for the management of cyanobacterial harmful algal blooms (C-HABs). The management of C-HABs can be viewed as having two main areas of focus. First, there is mitigation – control and/or removal of the bloom. This type of crisis response is an important component to managing active C-HABs and there are several techniques that have been successfully utilized, including the application of algicides, physical removal of surface scums and the mechanical mixing of the water column. While these methods are valuable because they address the immediate problem, they do not address the conditions that exist in the system that promote and maintain C-HABs. Thus, the second component of a successful C-HAB management strategy would include a focus on prevention. C-HABs require nutrients to fuel their growth and are often favored in longer-residence time systems with vertical stratification of the water column. Consequently, nutrients and hydrology are the two factors most commonly identified as the targets for prevention of C-HABs. Management strategies to control the sources, transformation and delivery of the primary growth-limiting nutrients have been applied with success in many areas. The most effective of these include controlling land use, maintaining the integrity of the landscape and applying best management practices.

In the past, notable successes in managing C-HABs have relied on the reduction of nutrients from point-sources. Because many point sources are now well-managed, current efforts are focused on non-point source nutrient reduction, such as runoff from agricultural and urban areas. Non-point sources present significant challenges due to their diffuse nature. Regardless of which techniques are utilized, effective watershed management programs for decreasing the prevalence of C-HABs will require continuing efforts to integrate science and management activities. Ultimately, it is increased coordination among stakeholders and scientists that will lead to the development of the decision-making tools that managers require to effectively weigh the costs and benefits of these programs.

Introduction

Watershed management programs (Davenport 2002) have been effective tools for addressing ecological problems in bodies of water, including lakes, rivers, estuaries and coastal seas. They are derived from the reasoning that integrative management of the activities within the confines of the catchment of a body of water can affect the amount and transport of pollutants to the water body of concern (Fig. 1) (US EPA 1996). The concept of watershed-based management also includes involving area stakeholders in key decisions – all the way from the establishment of baseline data, to codifying rules to reduce the levels of the pollutants of concern. There are many prominent examples of the application of watershed management throughout the world, including the Chesapeake Bay (Hill and Nelson 1994, Cestti et al. 2003) and Baltic Sea (Elmgren and Larsson 2001). Cyanobacterial harmful algal blooms (C-HABs) occur in waters with sufficient nutrient supply and light levels, factors which are directly affected by human activities in watersheds (Paerl 1997). Like eutrophication, C-HABs are often linked to human modification of nutrient supplies (Watson et al. 1997). This contribution will discuss watershed management activities aimed at preventing C-HABs from occurring and management options designed to remediate water bodies once a C-HAB has occurred.

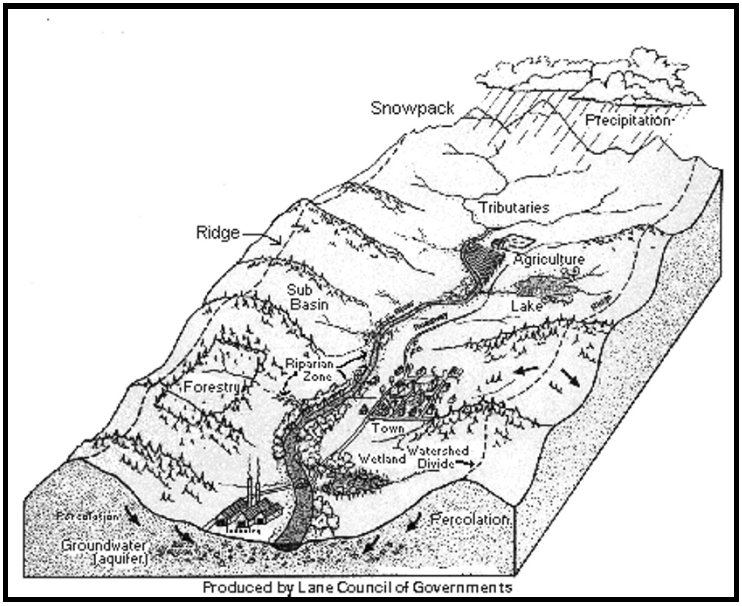

Fig. 1. The geographic, hydrologic and land use properties typical of watersheds. Working within these boundaries is the hallmark of watershed management. (From http://www.epa.gov/owow/watershed)

A summary of the research investigating the relationship between watershed management strategies and the occurrence of C-HABs

In past efforts to control C-HABs, management strategies have been developed to control the factors that affect C-HAB formation and persistence, particularly nutrients and hydrology. Watershed management strategies to reduce the prevalence of C-HABs most often include nutrient controls, specifically for nitrogen and phosphorus. In the past, single nutrient controls were implemented in some systems (Edmondson and Lehman 1981). However, due to the variation in nutrient limitation throughout the freshwater- marine continuum, dual N and P reductions may be required (Paerl et al. 2004). Reduced N to P ratios (Smith 1983) and eutrophic conditions have been shown to result in cyanobacterial dominance in some water bodies (Paerl 1997). Hydrologic manipulations such as increasing base flow, timed increases in discharge and destratification can also be effective when there is sufficient water available (Chorus and Bartram 1999). C-HAB prevalence has likely been enhanced by human activities in watersheds, and management efforts are designed to ameliorate the human impacts.

Human impacts

Growing population and changing land use (Vitousek & Mooney, 1997) often result in significant impacts on the delivery of nutrients to surface waters (Schueler and Holland 2000). Sources of nutrients generally increase as human use of a region increases. Wastewater, agricultural discharge, stormwater and industrial sources of nutrients are among the major contributors. Another change that accompanies human development of the landscape is an alteration of the transport mechanisms of nutrients to waterbodies (Line et al. 2002). Increased imperviousness (amount of land through which water can not infiltrate) within the watershed, ditching, channelization of streams and rivers and removal of the native vegetation contribute to increases in rates and quantities of nutrients transported from the land to the adjacent water bodies (Schueler and Holland 2000). Finally, human activities often lead to significant loss of the natural landscapes that either retain or remove nutrients. Losses of wetlands and landscape alterations at the watershed scale are well-documented and greatly impact both nutrient and water transport from human-dominated regions (Vitousek et al. 1997). There is likely a cumulative impact on nutrient export from human development of the landscape that includes the effects of increased sources, modified transport and altered biological processing of nutrients (Fig. 2).

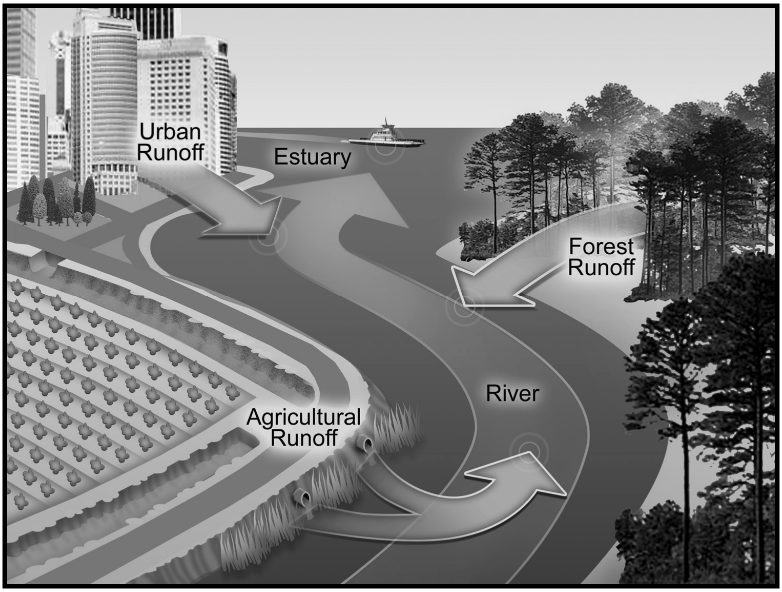

Fig. 2. Changes in land cover and land use resulting from human activities can lead to both changes in sources of pollutants and transport of water from the landscape. Both of these changes affect the success of C-HABS and must be considered in management strategies.

Sources of nutrients that increase with human activity include sewage treatment plant discharges, fertilizers associated with agriculture and other activities (e.g., lawns, gardens and golf courses), increased atmospheric N deposition and increased stormwater carrying myriad non-point sources associated with urbanization (Paerl 1997, Boesch et al. 2001a). In the first stages of human development, the shifts in land use are generally from forest to agriculture and residential. Once an area is populated, a secondary shift in land use away from open space (forest and agriculture) toward residential and industrial often occurs (Beach 2002). Through this sequence of land use alteration, the nutrient sources change and the trend generally results in more nutrients transported to aquatic environments (Line et al. 2002).

Human modification of the transport of water from land to surface waters has occurred in a large proportion of watersheds on a global scale (Vitousek et al. 1997). If sources of nutrients are present, transport of water from the landscape to the aquatic systems usually translates into enhanced nutrient transport. Urbanization leads to increased imperviousness due to increases in the areal coverage of roads and rooftops (Schueler and Holland 2000). However, imperviousness alone is not responsible for changes in transport of stormwater and entrained pollutants (Beach 2002). Urban areas are often not designed with consideration for their impact on nutrient export. The result is areas with more and wider roads that have the additional affect of encouraging more automobile use, and thus creating larger sources of nutrients and other potential pollutants (Trobulak & Frissell 2000). Consideration of the complex interactions development has on water quality during the design and planning process can reduce detrimental effects. An approach that includes strategies to reduce street and parking lot coverage, plan the siting of building lots and conserve natural areas has been demonstrated to reduce the impacts of urbanization on stormwater transport to adjacent waters (Schueler & Holland 2000).

Attenuation of nutrients during transport through the watershed can be significantly affected by human activities. Water transport form the landscape to the aquatic environments is significantly increased by ditching, channelization and increased imperviousness (Williams et al. 1997). The resulting shorter residence times often reduce biological attenuation of the nutrient load from a watershed. Higher volumes of faster moving water are less likely to be effectively filtered in small headwater streams, wetlands and riparian areas. Human activities also lead to direct negative effects on natural systems that attenuate the nutrient load from the landscape. Degradation of headwater streams that often occurs in areas with intensive human use is likely to significantly reduce nitrogen removal and retention (Peterson et al. 2001). In the US, wetland loss is on the order of 50% since the pre-settlement era and despite legal protections, loss is likely to continue to increase (Mitsch & Gosselink 2000). Even with laws in place to protect wetlands, management of wetland resources is a significant challenge (La Peyre et al. 2001). Wetlands are known sinks for nutrients transported to them from watersheds (Reddy & Gale 1994) and they further enhance water quality by transforming N from highly biologically available inorganic forms to less labile organic forms (Craft et al. 1989). Significant biological removal of nitrogen also occurs in riparian areas via denitrification (Jacobs & Gilliam 1985, Spruill 2004). The function of the riparian areas can be compromised by human activities, diminishing the ability of the landscape to retain and remove nutrients (Groffman et al. 2003).

Management techniques

Management activities in watersheds aimed at decreasing the occurrence of C-HABs can be roughly divided into efforts to control environmental factors that promote blooms (e.g., nutrients, water residence time) and other efforts to remove blooms once they have occurred (e.g., algicides, removal of scums and destratifying the water column). These two approaches can be generalized into preventative measures and mitigation measures. Some combination of both approaches will likely have to be included in effective management plans.

Preventative measures are most often the preferred approach to managing C-HAB occurrence. As described above, controlling nutrients and freshwater discharge are the most common management strategies. In order to effectively control these factors, steps must be taken to repair damage to the landscape and water bodies that are contributing to the enhanced load of nutrients. Nutrient management and water management clearly overlap because of the importance of water as a vector for transport of nutrients. Typical water management activities to control C-HABs include minimizing consumptive uses of water by residential, industrial and agricultural activities, among others. There are also examples of C-HAB management plans including the removal of stream obstructions, such as dams and impoundments. Efforts to maintain or restore the natural connectivity between aquatic and terrestrial systems are also effective tools to manage surface flow. Finally, when tenable, management of flow regimes can be an option to reduce C-HABs (Maier et al. 2001).

Nutrient management has been pursued in the context of broader eutrophication control in many aquatic systems throughout the world (NRC 2000). The process for managing nutrients to control C-HABs includes conducting monitoring and experiments to determine the nutrients limiting C-HAB success in the specific system. Phosphorus is generally believed to limit C-HAB growth in freshwater, and nitrogen is thought to limit their growth in salt water. There are however, many site specific factors along the freshwater marine continuum that can make this determination complicated. Once the limiting nutrient is identified, the major sources of that nutrient in the watershed should also be identified. Monitoring, modeling and experimental work must then be undertaken to set an effective and achievable target for nutrient reductions. With the target set, management practices can then be put in place to reduce export of nutrients from the landscape to the aquatic environment. Point sources of nutrients are generally managed first, followed by non-point sources.

Specific nutrient reduction approaches are designed for the type of land use being addressed. Agricultural and urban landscapes are most often management targets and clearly have different sources and transport vectors for nutrients. Sources of nutrients in urban watersheds include automobile exhaust, sundry materials deposited on streets (fertilizer, deicer, vegetation) and un-permitted sewage discharges (Novotony 2002). Urban planning to prevent conditions conducive to nutrient export from urban watershed were discussed above. Other techniques can be utilized in existing urban watersheds including, decreasing impacts of imperviousness (utilizing pervious pavement, decreasing connectivity of impervious areas), increasing surface storage (stormwater treatment and retention structures) and engineering for increased infiltration (Novotony 2002). In agricultural watersheds, best management practices have been designed to minimize sources of nutrients such as fertilizer, and maximize nutrient retention on the landscape. Examples of effective practices include no-till farming, installation of water control structures, maintaining riparian buffers and variable nutrient applications (Lilly 1991).

C-HAB mitigation measures are designed to curtail a bloom once it has started. They are more often applied in drinking waters because of the higher risks of human exposure. Examples of remedial techniques include the application of algicides, oxidants and coagulants (Chorus and Bartram 1999). Caution needs to be taken to avoid the exacerbation of the effects from C-HABs by untimely application of mitigation measures. Active blooms can release their toxins after the application of algicide and create a more dangerous situation (Jones and Orr, 1994, Kenefick et al. 1992). Details of the application of mitigation strategies in drinking waters can be found in Westrick in this volume.

Examples of watershed management strategies reducing the occurrence of C-HABs

Several systems with C-HAB issues have documented significant reduction or elimination of C-HABs resulting from effective watershed management. Among them are Lake Washington in the United States, which in large part to reduction of P inputs from point sources (sewage), experienced a dramatic decline in C-HABs (Edmondson and Lehman 1981), Also, Lake Erie in the US (Likens 1972), and Himmerfjärden in Sweden have shown large declines in C-HABS as a result of a combination of reduction in sewage inputs and some non-point sources including agriculture (Elmgren and Larsson 2002).

There are also examples of successful C-HAB management plans whose primary focus has been on non-point source nutrients. Among those commonly identified are the work of the Murray-Darling Basin Commission (MDBC 1993) and the New South Wales Blue-Green Algal Task Force (NSWBGATF 1993). These successful plans share many attributes. Among the important components of successful plans to prevent and remediate C-HABs are complete public involvement, broad educational efforts across all stakeholders, a sound scientific basis, tangible metrics of success, identification of costs and benefits, mechanisms for adaptation and the inclusion of both preventative and remedial strategies. These programs have not yet documented cause and effect links between the applications of watershed management strategies geared toward non-point source nutrients and C-HAB reductions. However, given the soundness of the plans described above, a good model has certainly developed for effective management plans and documented successes in bloom control is likely to occur soon.

There are other challenges faced by current efforts to control and prevent C-HABs beyond the difficulty of controlling non-point source nutrients. Some management programs lack clear metrics of success, which prevents the establishment of causal links to management activities. To increase the likelihood of demonstrable successes of watershed management in reducing the prevalence of C-HABs, continued and expanded coordination between managers and scientists is required. Scientists must clearly identify which factors will control C-HABs in specific settings and must help managers identify the relevant processes to monitor in order to evaluate success. Management plans must include sufficiently rigorous assessments of the metrics that are being evaluated to permit a statistical assessment of their success. This often means that whole ecosystem monitoring must be a significant component of the programs.

Components of successful watershed management programs to reduce the prevalence of C-HABs

The US Environmental Protection Agency (EPA) model for watershed management includes four major components in its suggestion for how activities should proceed (US EPA 1996). First, the activities should all include broad **stakeholder involvement**. By including stakeholders in the process from planning to codifying laws, programs will be understood and valued by the public at large. Second, the focus of the management strategy is based on the **geographic unit of the watershed**, which often requires cooperation among multiple jurisdictions. There is some deviation from the physical boundaries of the catchment with mobile sources such as atmospheric deposition, but the primary focus is at the watershed level. The watershed management plans must apply sound management principles and this includes **coordinated management activities**. Finally there should be a clear **management schedule**.

The EPA model also calls for the use of sound science to support all levels of decision making including:

- Ecological assessments
- Identifying environmental objectives based on the ecological and societal requirements
- Identifying of priority issues
- Developing of detailed action plans
- Implementing the plans
- Evaluating and adapting the plans as they proceed

The elements of this watershed management framework are applicable and appropriate for preventing and controlling C-HABs. Because of the high profile health and ecological impacts of C-HABs, significant stakeholder involvement is beneficial in many respects: as an educational outlet, in empowering the affected parties and in creating ownership of the plans among the public at large. C-HABs are highly visible and evoke strong emotions among the public. The watershed management process could provide a constructive outlet for the rational concerns that these blooms cause. There are now significant resources available for guiding the development of watershed management programs to restore and protect watershed function (US EPA 2003).

Considerations when applying watershed management strategies to drinking water and recreational waters

In drinking water reservoirs management of the occurrence of C-HABs must be more aggressive because of the enhanced risk to public health (Chorus and Bartram 1999). The risk management context largely determines the nature of the management strategy. In recreational waters, a preventative strategy to reduce nutrient loading and perhaps modify the flow regime would be a viable approach. Recreational waters are more often managed within the context of the functioning of the ecosystem in which they are located. In managing the occurrence of C-HABs in drinking water supplies there must be fast and effective crisis management tools present in the management plan. Some of these approaches include application of algicides and flocculants. Details on drinking water supply management are presented by Westrick in this volume.

Research gaps: Improving watershed management strategies to reduce the occurrence of C-HABs

There is a significant body of literature on the application of watershed management to reduce environmental problems (NRC 2000). Application of watershed management to control C-HABs, particularly in systems with predominantly non-point source nutrient loading has not been as extensive. Among the basic information that remains to be determined are the nutrients limiting C-HAB productivity along the continuum from freshwater to marine environments, the importance of variation in ratios of limiting nutrients and the potential for micronutrient limitation. There are broad data from some systems such as re-oligotrophying lakes (Jeppesen et al 2005), but accurate generalizations can not yet be made with sufficient certainty in all systems. Once a more accurate prediction of which nutrients limit C-HAB success in specific systems is developed, it is critical to examine the impacts of existing watershed management programs with other goals on C-HAB potential. Some programs with more general goals such as eutrophication control may also effectively control C-HABs, while others may in theory promote them (Piehler et al. 2002).

There are also some more specific, but critical pieces of information that would significantly further our ability to prevent C-HABs and our ability to forecast the effectiveness of the management regimes. Assessing the response time of the ecosystem to nutrient management in systems with significant sedimentary nutrient supplies is critical. There are many systems that have years of nutrient supplies stored in the sediments, which clearly affects the timing of results from controls of external nutrient supplies (Marsden 1989, Sondergaard et al. 2003). This information may also lead to the consideration of management options for internal loading that have been applied in some systems (Chorus and Bartram 1999). It is important that we acquire better data on the chemical forms of phosphorus and nitrogen loads from varied land uses and relate the nature of the loads to C-HABs nutritional requirements.

Land use changes are affecting sources, transport and fate of nutrients (Correll et al. 1994) that control C-HAB potential. Some extrinsic factors such as impervious cover have been utilized as indicators of land use change. Studies to develop generalizable intrinsic indicators of land use change that can be applied as predictive tools for C-HAB potential would significantly enhance our ability to effectively manage bloom potential. Changes in freshwater discharge from water use, global climate change and relative sea level rise are affecting the full suite of aquatic C-HAB habitats. Freshwater supplies downstream will be affected by changes in consumptive uses, releases from reservoirs, and changes in precipitation patterns and amounts. Increases in relative sea level due to global climate change will push salt water farther upstream. A better understanding of the cumulative changes in C-HAB habitat that will result from these forcing features would be highly desirable. Because water management is an option currently utilized to control C-HABs in some areas, examining the interactive effects of freshwater flow modification on nutrient supplies, hydrologic properties and temperature would also be highly beneficial.

Requirements for models of costs and benefits of watershed management strategies to control C-HABs

Because watershed management strategies are driven by, and affect a suite of different costs and benefits, models to predict their effectiveness will have to consider several different factors. Clearly, human health effects of C-HABs will be the first consideration. There are myriad costs and benefits associated with the level human health effects associated with C-HABs that are addressed in other chapters throughout this volume. Consideration must also be given to the ecological costs and benefits of management. These costs and benefits must consider the impacts that C-HABs have on the ecology and biogeochemistry of the systems in which they are present. Finally the economic costs and benefits will have to be included in any rigorous modeling effort. Determining the economic implications of watershed management includes assigning an economic value to both human health and ecology, and balancing that against the costs of the management program. There are additional economic considerations in the cost-benefit analysis, including costs associated with the loss of recreational space, indirect costs resulting from modifications of human activities and impacts of C-HABs on tourism and real estate values.

Conclusions

Watershed management is an integral part of efforts to control diffuse inputs of material to bodies of water. It provides a basis to construct the scientific, social, and policy frameworks that are required for a successful management program. Because nutrients are often identified as the driving forces behind the expansion of C-HABs, and the sources of nutrients are often dominated by non-point source forms, application of watershed management is an excellent option for C-HAB control. Reduction of nutrient inputs and maintenance of flow regimes using watershed management tools are likely the best choices for long term success in preventing and controlling C-HAB development. Mitigation techniques that are applied once a bloom has formed are an important part of any management plan, but prevention is the better choice when it can be achieved. Effective C-HAB plans that are currently underway include sound science to achieve the preventative goals described above and they also include significant public participation in the management process. To sustain C-HAB management programs the public must both value, and be integrated into, the effort. Fully incorporating the unique combination of potential impacts of C-HABs (ecological risk, human health risk and economic impacts) into the decision making framework will provide a valuable tool in efforts to prevent and control these blooms.

References

Beach D (2002) Coastal Sprawl: The effects of urban design on aquatic ecosystems in the United States. Pew Oceans Commission, Arlington, VA.

Boesch DF, Burroughs R H, Baker JE, Mason RP, Rowe CL, Seifert RL (2001) Marine Pollution in the United States: Significant accomplishments, future challenges. Pew Oceans Commission, Arlington, VA.

Cestti R, Srivastava J, Jung S (2003) Agriculture Non-Point Source Pollution Control: Good Management Practices – The Chesapeake Bay Experience. 54 pages, World Bank Publications.

Chorus I, Bartram J (1999) Toxic Cyanobacteria in Water. E&F Spon, London, 416 PP.

Correll DL, Jordan TE, Weller DE (1994) The Chesapeake Bay watersheds: Effects of land use and geology on dissolved nitrogen concentrations. Pages 639-648 in Toward a Sustainable Coastal Watershed: The Chesapeake Experiment. Smithsonian Environmental Research Center, Norfolk, VA.

Craft CB, Broome SW, Seneca ED (1989) Exchange of nitrogen, phosphorus, and organic carbon between transplanted marshes and estuarine waters. J. Environ. Qual. 18, 206-211.

Davenport TE (2002) The Watershed Project Management Guide. CRC Press, New York. 296pp.

Edmondson WT, Lehman JT (1981) The effect of changes in the nutrient income and conditions of Lake Washington. Limnol Oceanogr 26:1-29

Elmgren R, Larsson U (2001) Nitrogen and the Baltic Sea: Managing nitrogen in relation to phosphorus. The Scientific World 1(S2): 371-377

Groffman PM, Bain DJ, Band LE, Belt KT, Brush GS, Grove JM, Pouyat RV, Yesilonis IC, Zipperer WC (2003) Down by the riverside: urban riparian ecology. Front. Ecol. Environ. 1(6), 315-321.

Hill P, Nelson S (1995) Toward a Sustainable Coastal Watershed: The Chesapeake Experiment. Proceedings of a Conference 1-3 June 1994. Chesapeake Research Consortium Publication No. 149.

Jacobs TC, Gilliam JW (1985) Riparian losses of nitrate from agricultural drainage waters. J. Environ. Qual. 14, 472-478.

Jeppesen E, Sondergaard M, Jensen JP, Havens KE, Anneville O, Carvalho L, Coveney MF, Deneke R, Dokulil MT, Foy B, Gerdeaux D, Hampton SE, Hilt S, Kangur K, Kohler J, Lammens E, Lauridsen TL, Manca M, Miracle MR, Moss B, Noges P, Persson G, Phillips G, Portielje R, Schelske CL, Straile D, Tatrai I, Willen E, Winder M (2005) Lake responses to reduced nutrient loading - an analysis of contemporary long-term data from 35 case studies. Freshwater Biology 50:1747-1771.

Jones GJ, Orr PT (1994) Release and degradation of microcystin following algicide treatment of a Microcystis aeruginosa bloom in a recreational lake, as determined by HPLC and protein phosphostase inhibition assay. Water Research 28: 871-876.

Kenefick Sl, Hrudey SE, Peterson HG, Prepas EE (1992) Toxin release from Microcystis aeruginosa after chemical treatment. Water Science and Technology 27:433-440.

La Peyre MK., Reams MA, Mendelssohn IA (2001) Linking actions to outcomes in wetland management: An overview of US state wetland management. Wetlands 21, 66-74.

Likens GE (ed) (1972) Nutrients and Eutrophication. American Soc Limnol Oceanogr Special Symp 1

Lilly JP (1991) Best management practices for agricultural nutrients. North Carolina Cooperative Extension Service.

Line DE, White NM, Osmond DL, Jennings GD, Mojonnier CB (2002). Pollutant Export from Various Land Uses in North Carolina. Water Environ. Res. 14, 100-108.

Maier HR, Burch MD, Bormans M (2001) Flow management strategies to control blooms of the cyanobacterium Anabaena circinalis, in the River Murray at Morgan, South Australia. Regulated Rivers-Research and Management. 17:637-650

Marsden MW (1989) Lake restoration by reducing external phosphorus loading – The influence of sediment phosphorus release. Freshwater Biology 21:139-162.

MDBC (1993) Algal management strategy and technical advisory group report. Murray-Darling Basin Commission. Canberra, Australia.

Mitsch WJ, Gosselink JG (2000) Wetlands, 3rd edition. John Wiley and Sons, Inc., New York, NY.

National Research Council (2000) Clean Coastal Waters. National Academy Press, Washington DC.

Novotny V (2002) Water Quality: Diffuse Pollution and Watershed Management 888 pp, John Wiley and Sons.

NSWBGATF (1993) Blue-green algae. First Annual Report of the NSWBGATF, New South Wales Department of Water Resources. Parramatta, Australia.

Paerl HW (1997) Coastal eutrophication and harmful algal blooms: Importance of atmospheric deposition and groundwater as “new” nitrogen and other nutrient sources. Limnol. Oceanogr. 42, 1154-1165.

Paerl HW, Valdes LM, Piehler MF, Lebo ME (2004) Solving problems resulting from solutions: The evolution of a dual nutrient management strategy for the eutrophying Neuse River Estuary, North Carolina, USA. Environmental Science & Technology 38:3068-3073

Peterson BJ, Wollheim BM, Mulholland PJ, Webster JR, Meyer JL, Tank JL, Marti E, Bowden WB, Valett HM, Hershey AE, McDowell WH, Dodds WK, Hamilton SK, Gregory S, Morrall DD (2001) Control of nitrogen export from watersheds by headwater streams. Science 292, 86-89.

Piehler MF, Dyble J, Moisander PH, Pinckney JL, Paerl HW (2002) Effects of modified nutrient concentrations and ratios on the structure and function of the native phytoplankton community in the Neuse River Estuary, North Carolina USA. Aquat. Ecol. 36, 371-385.

Reddy KR, Gale PM (1994) Wetland processes and water quality: A symposium overview. J. Environ. Qual. 23:875-877.

Schueler T, Holland HK (2000) The Practice of Watershed Protection. Center for Watershed Protection, Ellicot City, MD.

Smith VH (1983) Low nitrogen to phosphorus ratios favor dominance by blue green algae in lake phytoplankton. Science 221:669 671

Sondergaard M, Jensen JP, Jeppesen E (2003) Role of sediment and internal loading of phosphorus in shallow lakes. Hydrobiologia 506:135-145.

Spruill TB (2004) Effectiveness of riparian buffers in controlling ground-water discharge of nitrate to streams in selected hydrogeologic settings of the North Carolina Coastal Plain. Water Science & Technology 49:63–70.

Trobulak SC, Frissell CA (2000) Review of ecological effects of roads and terrestrial and aquatic communities. Conservation Biology 14(1) 18-30.

US Environmental Protection Agency (1996) Watershed Framework Approach. EPA Report 840-S-96-001.

US EPA (2003) Watershed Analysis and Management (WAM) Guide for States and Communities. EPA 841-B-03-007.

Vitousek PM, Mooney HA (1997) Estimates of coastal populations. Science 278, 1211-1212.

Vitousek PM, Mooney HA, Lubchenco J, Melillo JM (1997) Human domination of earth's ecosystems. Science 277:494 – 499.

Watson SB, McCauley E, Downing JA (1997) Patterns in phytoplankton taxonomic composition across temperate lakes of differing nutrient status. Limnology and Oceanography 42:487-495.

Williams JE, Wood CA, Dombeck MP (eds) (1997) Watershed Restoration: Principles and Practices. 549 pp, American Fisheries Society.