An Alternative Approach to Regaining Designated Uses of Clean Water Act Section 303(D) Impaired Waters

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The need for an adequate supply of useable freshwater is undeniable. But, the economic costs of protecting pristine surface waters and restoring designated uses in impaired waters in the United States increasingly challenges the already strained budgets at local, state, and federal levels. Tax- and rate-paying citizens, and their political representatives, are demanding more effective (and less expensive) freshwater-management strategies than those currently being implemented. This article briefly describes: 1) the increasing problem of freshwater eutrophication due to excessive nutrient loads; 2) current U.S. policy for controlling eutrophication; 3) an alternative approach for managing eutrophic waters exemplified by a projected cost and outcome comparison; and 4) U.S. legislation that authorizes federal programs that help finance freshwater protection and restoration projects.

The evidence indicates that freshwater protection and restoration can be achieved in the near term at reduced costs by a policy that complements the most effective and cost-efficient practices of watershed management, with technologies deployed in impaired waterbodies to reduce stress on aquatic biochemical processes and enable the recovery of designated uses. Satellite monitoring for phosphorus, chlorophyll-a, and phycocyanin is a comprehensive and cost-effective means for assessing eutrophication, planning restoration projects, and monitoring results.

Figure 1. A systems approach describes a set of components and dynamic processes that provide the functionality needed by the systems' users. This figure illustrates a systems approach for making policy determinations for HAB risk management. The HAB pathway, ranging from causes to effects, is assessed to determine the risks HABs pose for health and ecosystems, so that appropriate intervention strategies can be developed to reduce the risks. Risk assessments provide the scientific basis for making policy determinations, which are based on HAB risks within the context of other societal concerns and priorities. Risk management practices implement selected strategies to prevent or suppress HABs and mitigate the risks. Policy determinations concerning the issuance of regulations or guidelines for HABs and their toxins require sufficient information on: 1) the occurrence of blooms in U.S. freshwaters to determine if incidence warrants action; 2) dose-response relationships between toxin concentrations and adverse health effects and/or cell densities and ecological impacts to determine if the risks warrant action; and 3) methods to prevent, control, and mitigate HABs to determine if cost-effective means of reducing or eliminating the risks are available. The EPA has not begun the process for making policy determinations (Hudnell, 2008, 2010).

The box and text around the causes component of the HAB pathway illustrate current policy for preventing eutrophication and restoring eutrophic waterbodies. Watershed management strategies attempt to prevent further nutrient input to receiving waters; it does not address the need to reduce internal loads or suppress HABs through artificial circulation.

Many states currently implement HAB risk management practices, such as educating the public about HAB risks, monitoring to detect HAB and cyanotoxin occurrence, and warning the public to avoid HAB, through media outlets and beach postings (Hudnell et al., 2012).

The Nutrient, Eutrophication, and Harmful Algal Blooms Problem

Waterbodies that no longer provide their designated uses, such as supporting a diversity of aquatic biota, healthy fisheries, suitable drinking source water, and safe swimming and other recreational activities, must be listed as impaired pursuant to Clean Water Act (CWA) Section 303(d). Impairments are primarily caused by excessive concentrations of nutrients, toxic substances, and pathogens. Approximately 44 percent of river and stream miles, and 64 percent of lake and reservoir acres, are impaired. The U.S. Environmental Protection Agency (EPA) estimated in 1972 that 10 to 20 percent of lakes and reservoirs were eutrophic (Hudnell et al., 2012); today, approximately 50 percent are now eutrophic or hypereutrophic (EPA National Lakes Assessment). Excessive nutrient concentrations that cause eutrophication, characterized by the periodic predominance of freshwater harmful algal blooms (HABs), are a major cause of impairment in Florida, and worldwide. Freshwater HABs are rapid and massive expansions of cellular populations, such as cyanobacteria (blue-green algae) and Prymnesium parvum (golden algae) in aquatic ecosystems. The HABs pose serious risks for human and animal health, aquatic-ecosystem sustainability, and economic vitality. Cyanotoxins are among the most potent toxins known (Hudnell, 2010). Cyanotoxins cause acute and chronic health effects in humans and other mammals through inhalation, ingestion, and dermal contact exposures. Aerobic bacterial digestion of huge algal biomasses following HAB die-offs deplete dissolved oxygen in the water column, causing fish death through asphyxiation. Eutrophication is conservatively estimated to cost the U.S. economy between $2.2 billion and $4.6 billion annually (Hudnell, 2010a).

Current U.S. Policy for Controlling Eutrophication

The EPA and state policies centered on watershed management, or preventing the flux of nutrients from watersheds to receiving waters, for more than 30 years. States are required to develop lists of CWA Section 303(d) impaired water bodies, prioritize those water bodies based on the ecosystem services they provide, calculate Total Maximum Daily Loads (TMDLs), develop nutrient management programs, and implement nutrient management strategies to reduce loading in hope of restoring designated uses. Waterbodies impaired due to eutrophication are delisted from Section 303(d) when nutrient management strategies are implemented, before any water quality improvement is attained. No future improvement is required to remain delisted.

Point sources of nutrient and other pollutant input, as at wastewater utilities, have been regulated through National Pollution Discharge Elimination System (NPDES) standards since CWA Title IV was enacted in 1972. The NPDES limits on pollutant discharge levels greatly reduced point source discharges, although additional reductions of pollutant discharges in stormwater are needed in many municipalities. Point source discharges now account for only about 5 to 10 percent of nutrient loading, whereas non-point source discharges account for approximately 90 to 95 percent of nutrient loading (Hudnell, 2010a).

Non-point source pollutant control primarily relies on best management practices (BMPs) to improve soil conservation and limit non-point source loading. However, BMPs are difficult and expensive to implement over large areas, and vary widely in efficacy. The return of designated uses typically is not anticipated for two to three decades due to BMP limitations and existing nutrient loads within waterbodies. The rapid rate of increasing eutrophication indicates that watershed-management policy, particularly for non-point sources, is insufficient for preventing eutrophication and restoring designated uses in the near term. Insufficient efficacy and high cost signal the need to reevaluate current surface water management and restoration policy, and identify more effective and cost-efficient strategies (Hudnell, 2010a).

An Alternative Approach for Managing Eutrophic Waters

Watershed management targets the causes component of a systems approach to eutrophication and HAB risk management by attempting to prevent pollutant input, but does

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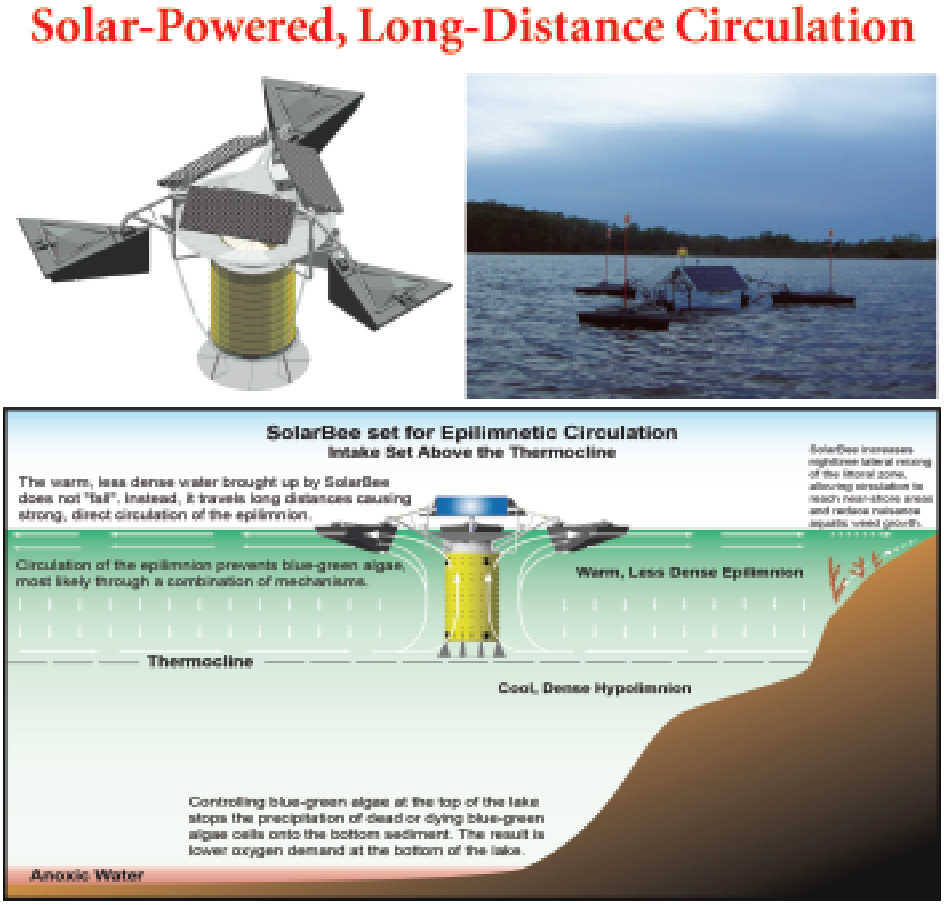

Figure 2. Top, illustrates a SB10000V18 solar-powered, long-distance circulator, and shows a unit deployed in freshwater for HAB control. Each unit consists of three pontoons that provide buoyancy for above-water, near-surface, and underwater components. Solar panels, a low-voltage, 18 V, high-efficiency brushless (gearless) motor, a digital-electronic control box, and accessories are mounted on an above-water frame. A distribution dish, impeller, and battery are suspended from the frame just below the surface. A 0.914 m diameter, flexible, intake hose is attached to the frame at the base of the impeller. A steel plate suspended 0.305 m beneath the hose intake causes water to be drawn in radially with near-laminar flow. Adjustments of chains attached to the plate and frame control intake depth. Additional chains attached to the frame and two moorings maintain the spatial position of the unit. The battery powers the motor to rotate the impeller at 60-80 RPM (all newer, and most older, units now rotate at 80 RPM) 24 hours a day, seven days a week. If prolonged periods of low-light incidence cause the battery charge to fall below 60 percent, the electronic controller reduces the RPM or shuts down the unit until sunlight recharges the battery. The units transport approximately 37,850 L/min of water to the surface. Approximately 11,355 L/min of direct flow ascends through the hose, and another 26,495 L/min of induced flow ascends external to the hose. Water departs radially from the units without turbulence, both above and below the distribution dish. The outflow mixes with other surface currents to redistribute water across the treatment area. The units are designed for low maintenance and a 25-year lifetime guarantee (Hudnell et al., 2011). The bottom drawing depicts epilimnetic deployment for HAB control.

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not attempt to directly suppress HABs or remove nutrients from waterbodies (Figure 1). Waterbody management is the implementation of sustainable technologies within waterbodies to provide supportive therapy and restore designated uses in the near term. A policy that encourages waterbody management as the natural complement to watershed management will suppress HABs and reduce nutrient and other pollutant levels within waterbodies in the near term.

Physicians provide therapy to patients who become ill in spite of following council to practice healthy lifestyle habits. The current policy of watershed, but not waterbody, management strategies essentially limits policy to the practice of healthy lifestyle habits. An impaired water body is analogous to an ill person in need of supportive therapy to reduce stress on impaired biochemical processes and enable recovery.

Freshwater HAB occurrence requires quiescent, stagnant water, as well as excessive nutrient concentrations. Freshwater flow rates are decreasing as drought frequency and duration increase due to global climate change, and withdrawals increase due to rising usage demand (Hudnell, 2008). Recent evidence indicates that artificial circulation through solar-powered circulation suppresses HABs, even in nutrient-enriched water bodies (Figure 2a; Hudnell et al., 2010; Medora Corp., SolarBee and GridBee). Freshwater HAB suppression is achieved by circulating only the epilimnion or photic zone in which HABs occur (Figure 2b). The circulation units are spaced at an average density of one unit/0.15 km^2 (35 ac). Solar-powered, long-distance circulation suppresses HABs, while promoting beneficial algae and eliminating the need for chemical algaecide treatments that also adversely impact aquatic biota. The suppression of HABs without algaecides creates robust fisheries by enabling nutrients to ascend the trophic levels of aquatic food webs, from edible diatoms and chlorophyta (green algae) to zooplankton, and to filter feeding and carnivorous fish that can be harvested. Nutrients do not degrade water quality when channeled to the highest trophic levels; they become valuable and sustainable resources for human consumption and commercial applications (Hudnell et al., 2010). Solar-powered circulation units are currently deployed in over 250 U.S. freshwater bodies for HAB suppression.

Circulation also improves other aspects of water quality. Pathogens such as fecal coliform are deactivated through repeated exposure to ultraviolet light as water is continuously circulated from near the thermocline to the surface during epilimnetic circulation to suppress HABs (Hudnell et al., 2011; Ward et al., 2011). Metals such as iron and manganese are precipitated from the water column through oxidization, as dissolved oxygen levels increase throughout the treated portion of the water column. The release of hydrogen sulfide to air is prevented, as dissolved oxygen oxidizes toxic and malodorous hydrogen sulfide to benign sulfates. The methylation of inorganic mercury by anaerobic bacteria to toxic methylmercury is prevented when hypolimnetic circulation is deployed by lowering the water intake hoses to the deepest areas of the waterbody, thereby increasing dissolved oxygen levels throughout the water column (Hudnell, 2010a).

Additional reduction of free nutrients in the water column to protect downstream waters is achievable using technologies such as floating islands or mats. Anaerobic bacteria within the island or mat matrix perform denitrification by converting nitrate to nitrogen gas. Nitrogen removal rates varied between 270-540 mg/day/sq ft in laboratory studies without circulation. The rate increased to 10,600 mg/day/sq ft when combined with artificial circulation. Circulation also increased phosphorus uptake by bacteria and plants in laboratory studies from 38-52 mg/day/sq without circulation to 428 mg/day/sq with circulation (Hudnell, 2011).

Sidestream flow-ways are deployed by nutrient-laden inlets or at wastewater treatment sites to remove nutrients prior to the water entering lakes, reservoirs, or rivers (Figure 3, One Water Inc.). The AlgaeWheel system promotes the growth of chlorophyta (nontoxic green algae), which uptake nutrients from the water for growth. The algae can be harvested and processed to produce biofuel, animal feedstock, and/or fertilizer. Inputs to the system are nutrient-laden water, sunlight, and air. The air turns the wheels that contain media in the interior, which support aerobic bacterial growth

Sidestream Flow-Ways, AlgaeWheel: Converting Nutrients to Green Algae for Capture and Reuse

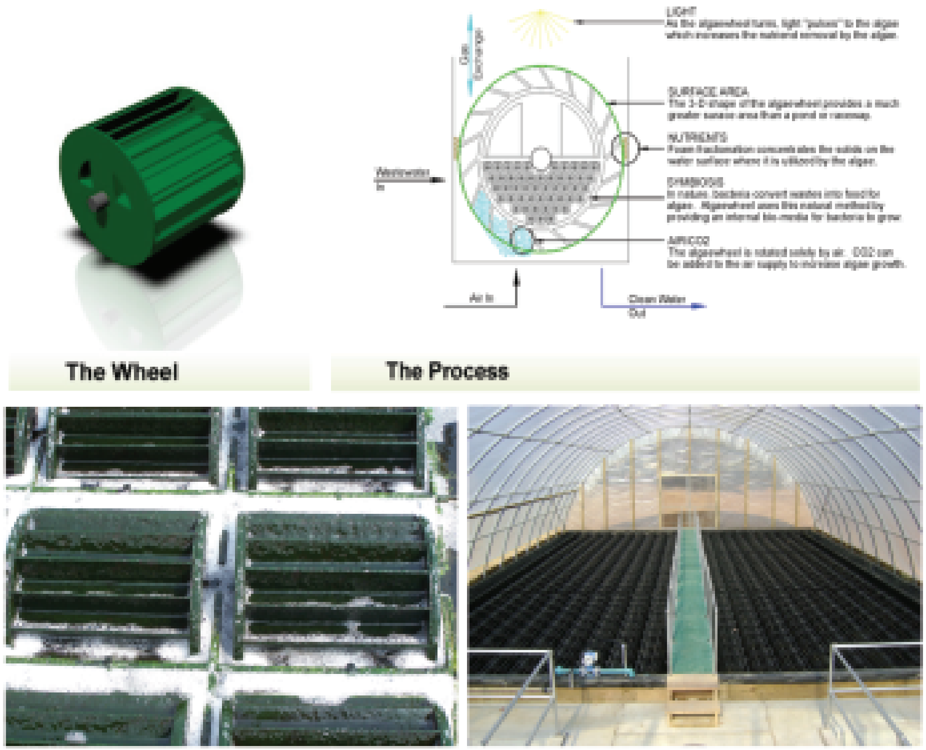

Figure 3. Top, AlgaeWheels utilize nutrients from water, air, and sunlight in a process that produces clean water and green algae. The algae are harvested to produce biofuel, animal feedstock, and/or fertilizer. Bottom, the algae grow on the wheel blades until they sluff off due to gravity and flow with the water to a collection area. The photograph on the right shows a 600 wheel, pilot, tertiary-treatment system in Hopewell, Va. A smaller, redesigned system in Phase II achieved near 100 percent phosphorus removal. Commercial facilities using the AlgaeWheel system include Indiana Dunes State Park and Cincinnati Nature Center. Pilot systems located in Charleston, Ill., and Avon, Ind., are investigating tertiary municipal wastewater applications, sludge digester supernatant, and high-strength wastewater treatment (One Water Inc.).

utilizing oxygen from the air. The air and bacteria supply carbon dioxide to the algae that grow on the outer blades of the wheels. The algae use the carbon dioxide, nutrients, and sunlight, and emit oxygen. Virtually all of the nitrogen and phosphorus can be removed from the water by adjusting the system's parametric values. This sustainable process provides clean water, while capturing the nutrients for reuse.

Other sustainable waterbody-management strategies include the use of: 1) aeration systems to increase dissolved oxygen levels; 2) flocculants to remove cyanobacterial cells, phosphorus, or metals from the water column; 3) bacteria to perform nitrification and denitrification or degrade toxic substances; 4) biological manipulations such as fish population management to increase filter feeding or reduce sediment disturbances that resuspend phosphorus in the water column; and 5) hydrologic manipulations such as the release of water from impoundments to increase water flow rate and mixing.

A systems approach to restoration of impaired waterbodies would combine waterbody management technologies that target the restoration of designated uses with the most effective and cost-efficient watershed management strategies to prevent pollutant input. Many eutrophic waterbodies have some watershed management BMPs in place, even before formal nutrient management strategies are implemented. Deployment of appropriate waterbody management technologies may restore the designated uses prior to the development of formal nutrient management strategies. Waterbodies can be delisted from Section 303(d) when their designated uses are restored. Restoration prior to TMDL development obviates their need. The combined implementation of appropriate waterbody and watershed management strategies, whether through formalized or informal processes, provides states with the flexibility to restore the designated uses of impaired waterbodies in the near term at the lowest possible cost. As exemplified, the cost of waterbody management implementation is a small fraction of the estimated cost to implement nutrient management strategies.

The Falls Lake, North Carolina Example

Falls Lake was constructed in 1983 for flood control, drinking water supply, recreation, and aquatic and wildlife habitat (Figure 4). The designated uses of Falls Lake include aquatic life propagation and biological integrity, wildlife habitat, primary and secondary

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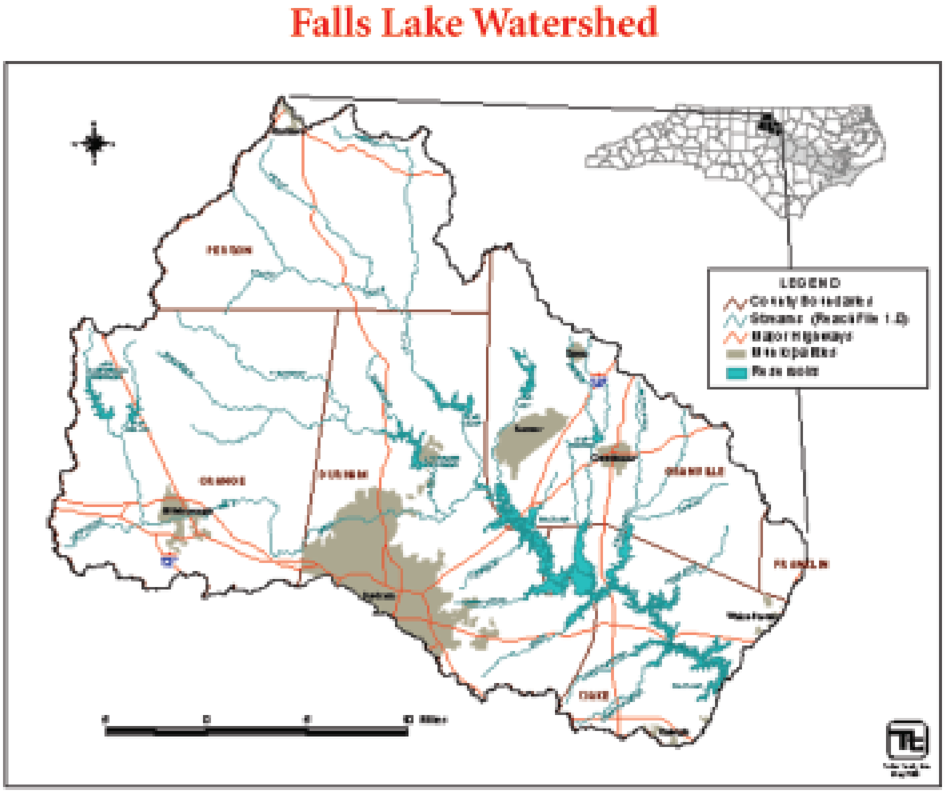

Figure 4. The Falls Lake watershed covers approximately 770 sq mi. The 12,000-acre Falls Lake reservoir has a storage volume of approximately 10 bil gal, and provides approximately 67 mgd of drinking source water that serves approximately 450,000 residents of Wake County (courtesy of Sarah Bruce, Triangle J Council of Governments/Upper Neuse River Basin Association).

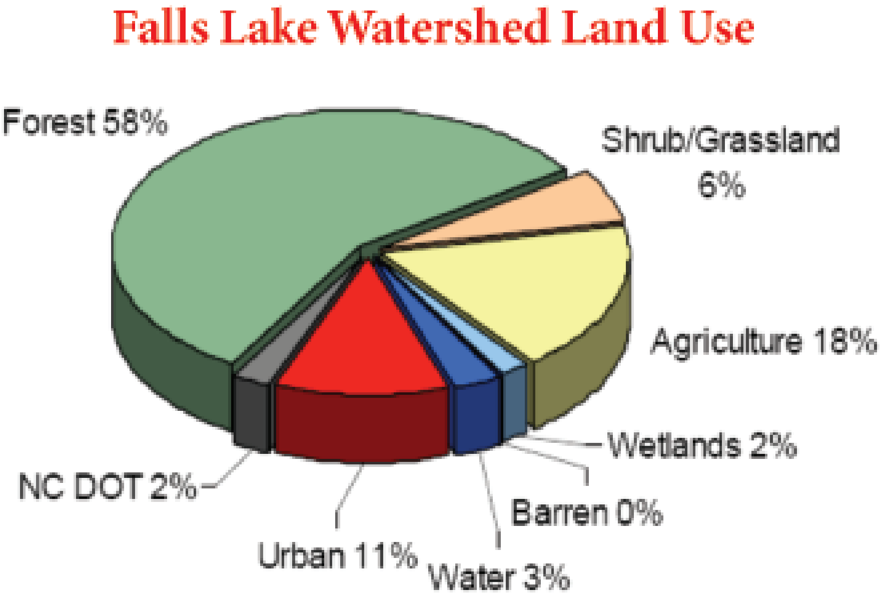

Figure 5. More than half of the watershed is forested, but more than 90,000 people reside in the watershed, and the population is projected to double by 2025 (courtesy of Sarah Bruce, Triangle J Council of Governments/Upper Neuse River Basin Association).

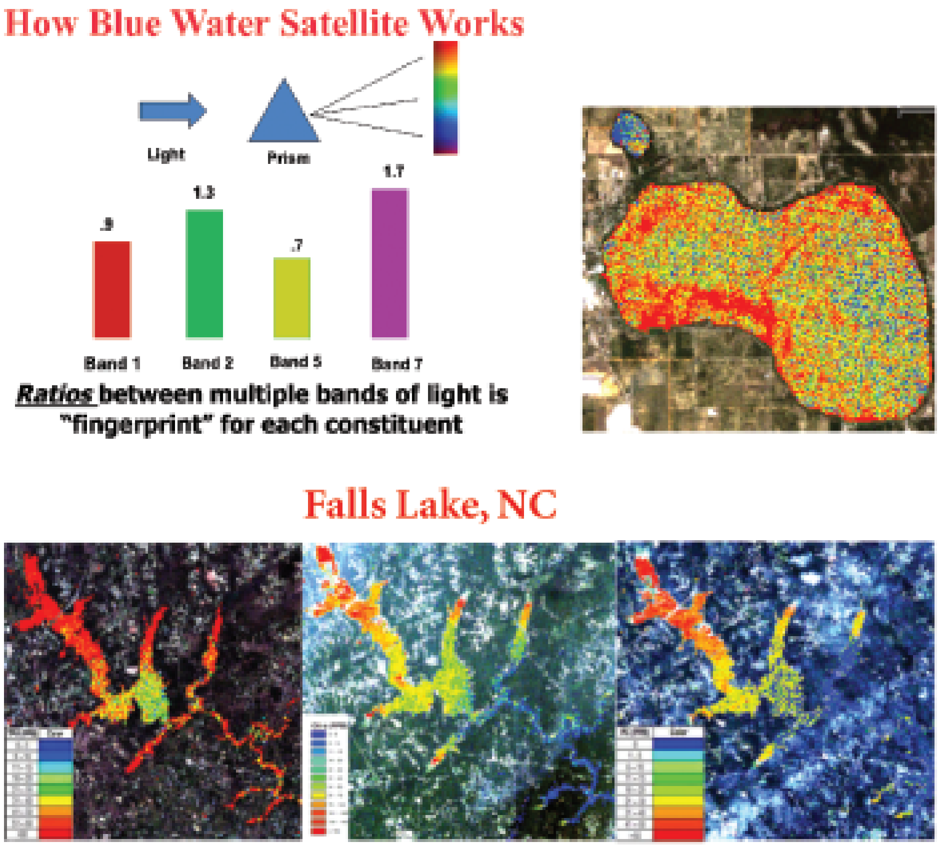

Figure 6. Top, left, Bluewater Satellite Inc., uses computer algorithms to extract information from spectral bandwidth files to produce quantitative images of phosphorus, chlorophyll-a, and phycocyanin (pigment specific to cyanobacteria). Images can be created over long time spans, from the present to more than 20 years in the past. Top, right, free QGIS software enables users to zoom in, click on a particular pixel, and see a numeric concentration value. Spatial resolution in 30x30 m, and images are available at eight-day intervals. Bottom, Falls Lake; left, spring phosphorus concentrations; middle, summer chlorophyll-a concentrations; right, summer phycocyanin concentrations.

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recreation, and drinking water supply. The lake is 12,000 acres in size, has an average depth of 16 ft, a maximum depth of 33 ft, and a safe yield of 67 million gallons per day (mgd) for drinking water. Total storage is approximately 10 bil gal. The Falls Lake Watershed is the headwaters of the Neuse River basin, which drains to the Pamlico Sound on the North Carolina Coast. The watershed is 770 sq mi in size and spans portions of six counties (Wake, Durham, Orange, Granville, Person, and Franklin) in the northern part of the Research Triangle area; also included are portions of seven municipalities (Raleigh, Durham, Hillsborough, Creedmoor, Butner, Roxboro, and Stem). More than 90,000 people reside in the watershed, and the population is projected to double by 2025. Current land cover in the watershed is approximately 58 percent forest, 18 percent agricultural (row crops and pasture), and 11 percent urban development (Figure 5). The lake serves as a water supply to more than 450,000 residents in Wake County. The Falls Lake watershed contains eight other water supply reservoirs that serve Orange, Durham, and Granville Counties.

Studies conducted prior to the construction of Falls Lake indicated that it would soon become eutrophic. The HABs occurred the first year after the reservoir was constructed. The state's chlorophyll-a standard of 40 µg/L was repeatedly exceeded, with levels exceeding 100 µg/L during most summers. The state listed the lake as CWA Section 303(d) impaired, developed TMDLs and a nutrient management plan, and is initiating the nutrient management strategy. The North Carolina Department of Water Quality estimates that the total watershed management cost will be between $1.90 billion and $2.06 billion through 2035. The non-point source portion is estimated to be between $1.42 billion and $1.58 billion. Restoration of designated uses is not anticipated for several decades. In addition, the drinking water utility at Falls Lake anticipates spending $155 million in 2014 to upgrade the facility to process high carbon levels caused by the HABs. The carbon provides natural organic matter (NOM) that may react with chlorine during treatment to produce disinfection byproducts such as trihalomethanes and haloacetic acids. The HABs also produce taste and odor compounds that affect the quality of the finished water.

Satellite images of Falls Lake in central North Carolina during 2011 show that high phosphorus inputs in the spring are followed by high chlorophyll-a concentrations in the summer that primarily consist of cyanobacteria (Figure 6, Blue Water Satellite). The images were used to develop a waterbody management treatment plan that was presented in a workshop during the 2011 University of North Carolina Conference on Water and Health: Where Science Meets Policy (Hudnell, 2011a). Satellite monitoring also provides a convenient and inexpensive method for tracking results after treatment implementation.

The waterbody management plan presented at the workshop included the deployment of 141 solar-powered, long-distance circulation units to suppress HABs throughout the entire lake (Figure 7). Full-lake treatment is expected to suppress cyanobacteria to densities well below bloom levels (WHO 20,000 cells/mL) beginning the first year of treatment. The capital cost of the units is $7.775 million, and the service and full warranty option from 2013-2035 cost is $6.902 million. The total cost of treatment, service, and full warranty through 2035 is $14.677 million.

A plan was also presented that would protect only the area near the drinking water utility from HABs. Similar partial-lake treatment implementations to protect source waters around utilities are located in Lake Manatee, Fla., and Lake Houston, Texas. The Falls Lake plan called for deploying 35 solar-powered, long-distance circulation units in the eastern portion of the lake. The capital cost is $1.925 million, and the optional service and warranty program cost is $1.617 million. The total cost of treatment, service, and full warranty through 2035 is $3.542 million.

The proposal presented at the workshop also included floating islands to remove nutrients from the lake inlets and coves. The removal of nutrients, in addition to helping suppress HABs in the lake, would help protect waters downstream of the lake in untreated areas. A total of 4 acres of 8-in. thick floating islands were proposed. The islands were projected to remove a total of 16,988 lbs of phosphorus per year, using a standard removal rate of 0.13 lb/cu ft of matrix/year. Nitrogen removal rates at 1.2 lb/cu ft of matrix/year were projected to remove a total of 156,816 lbs of nitrogen. Total cost of the 4 acres of floating islands is $3.485 million.

In addition to proposing the installation of passive floating islands, an option for including active floating islands was included. Each floating island would surround a SolarBee circulation unit to form an active floating island. The addition of active circulation to an island with 1,600 cu ft of bioreactor space was conservatively estimated to increase nutrient removal rates by four times. Each active floating island is projected to remove 12,480 lbs of phosphorus per year, and 38,400 lbs of nitrogen per year. The cost of each active floating island is $0.445 million. The deployment of 15 active floating islands in the lake is projected to remove at least 187,200 lbs of phosphorus per year, and 576,000 lbs of nitrogen per year. The cost of 15 units is $6.825 million.

Sidestream flow-way units could be deployed as tertiary treatment for the waste-

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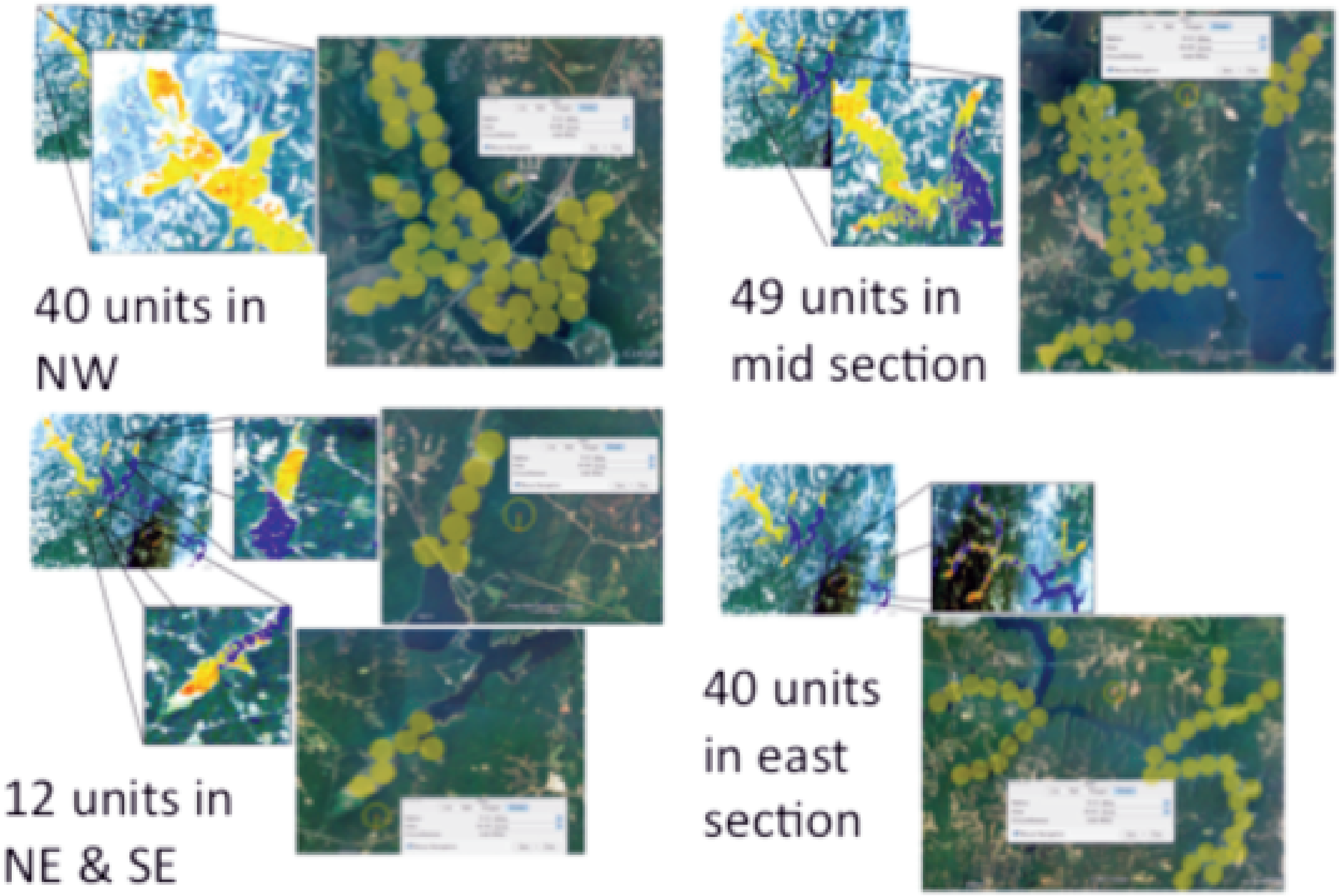

Figure 7. Deployment locations of 141 solar-powered, long-distance circulation units for full-lake treatment to suppress HABs in Falls Lake.

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water utility that discharges into Falls Lake, or along the shores of the nutrient-laden inlets to the lake. When deployed by an inlet, some or all of the inlet water would be diverted through the flow-way for treatment. The cost and size of the flow-ways would depend on the amount of water to be treated and the levels to which the nutrient concentrations would be lowered. The price range of the flow-ways is anticipated to be $2 million to $5 million each.

Full implementation of the Falls Lake waterbody management plan would cost approximately $30 million. A nutrient management strategy that combined waterbody management tools with the most effective and cost-efficient watershed management BMPs and point source controls would restore the waterbody's designated uses in the near term at a cost less than that currently projected for watershed management alone.

U.S. Legislation and Water Management Financing

The Federal Water Pollution Control Act enacted in 1948 provided initial authority for the regulation of pollutant discharges into surface waters and for water quality standards. The Water Quality Act of 1965 authorized the first mandatory federal requirement for standards. Amendments enacted in 1972 significantly reorganized and expanded the Act. Those amendments included establishment of the NPDES permit program for the regulation of point source pollutant in Section 402, and the Clean Lakes Program (CLP) for restoring publicly-owned lakes and reservoirs in Section 314. The Act became commonly known as the Clean Water Act (CWA) through amendments enacted in 1977. The CWA amendments enacted in 1987 established the non-point source management program through Section 319 to address pollutant runoff (EPA History of the Clean Water Act). Congress acknowledged and addressed the financial burden the CWA placed on states and local communities through grant and loan programs that evolved over the years.

Federal grants for treating non-point sources are available from EPA through the CWA Section 319(h) grant program. Section 319(h) grants cover up to 60 percent of the cost of watershed and waterbody management projects, with states providing the remainder. The EPA suggests that states use a minimum of 5 percent of their Section 319 funds for clean lake activities to address the restoration and protection needs of priority, publically-owned lakes, ponds, and reservoirs (EPA Clean Lakes Program). The Agency's top priorities for use of Clean Lakes Section 319 funds include:

- Lake Water Quality Assessment (LWQA) Projects
- Phase 1 Diagnostic/Feasibility Studies
- Phase 2 Restoration/Implementation Projects
- Phase 3 Post-Restoration Monitoring Studies

A specific activity must be included in a state's non-point source nutrient management program to be eligible for Section 319(h) grants. The Agency encourages states to update their non-point source nutrient management programs, plans, and strategies to include these activities where needed (EPA Guidance on Lakes and Reservoirs).

The CWA amendments in 1987 transitioned the Title II grant program for the construction of publically-owned treatment works or sewage treatment plants to the Title VI Clean Water State Revolving Fund (CWSRF) loan program. All states have capitalized CWSRF loan programs; federal appropriations through Title VI totaled $36 billion through 2012. States primarily use the CWSRF program to fund wastewater treatment facility construction projects, although the funds can also be used for non-point source management projects (EPA Guidance on Lakes and Reservoirs). However, only about $650 million has been used to fund non-point source projects since 1989. The EPA encourages greater use of the CWSRF for the implementation of non-point source management programs.

The Safe Drinking Water Act Amendments of 1996 (SDWA) authorized the Drinking Water State Revolving Fund (DWSRF). Section 1452 contains provisions for protecting and restoring surface water and groundwater drinking source waters through the loan program. Projects that address the most serious health risks to humans are the top priority of the DWSRF program. The HAB suppression is a top priority because HABs may produce highly toxic compounds and huge amounts of NOM that may react with chlorine to produce disinfection byproducts.

Conclusion

The cost of treating eutrophic lakes, streams, and rivers with waterbody management technologies is far less than that projected for traditional watershed management projects. The combination of waterbody management technologies that eliminate impairments and high-yielding watershed management BMPs will provide Florida with the flexibility needed to develop strategies for water quality restoration at reduced costs.

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