Can Windmills Save the Bay?

The Scientific and Technical Advisory Committee (STAC) of the Chesapeake Bay Program has reviewed the proposal by J. Adam Hewison entitled "How Oxygen and Windmills can save the Bay." We believe Mr. Hewison should be commended for thinking creatively and proposing an innovative approach to addressing the problem of anoxia/hypoxia in the Bay. It is our opinion that the concept of mechanical aeration, powered by windmills, may have some limited practical applications in subsystems of the Bay and its tributaries. The idea does not, however, represent a potential solution to the low dissolved oxygen conditions found in deep waters of the Bay mainstem.

The proposal to aerate the Bay with windmills addresses a symptom, not the cause of the Bay's problem. Reducing nutrient inputs is the only long-term solution to extensive hypoxia in the deep waters of the Chesapeake Bay.

Introduction

Aeration of hypoxic water bodies seems an appealing solution and it has been tried many times with reasonable success on freshwater ponds and small lakes. Pond and small lake aeration is, in fact, in wide commercial use for destratification, oxygenation, and prevention of ice cover. But mechanical aeration has never been successful on large lakes or coastal waters.

There have been a number of previous proposals and ideas for aeration of the Chesapeake Bay bottom waters, as well as others around the world. Researchers have evaluated using the turbulent eddies flowing off the trailing edge of a wing to passively induce mixing across the pycnocline with tidal currents (Wright et al. 1992). With appropriate tethering, the wing could be allowed to swing freely and orient into prevailing currents so as to work continuously. Other scientists have proposed large fixed-position, submerged physical structures that could divert natural flows, forcing mixing of oxygenated waters toward the bottom. An engineering firm has proposed pumping water up from below the pycnocline and having that water run as a broad, shallow stream down an incline positioned on a barge. Direct contact with the atmosphere would then allow re-aeration of the hypoxic water. In Hawaii, researchers have tested a simple wave-driven upwelling device. None of these ideas has found practical application for problems at the scale of the Chesapeake Bay.

At the scale of moderate rivers, there are some ongoing aeration programs designed to offset undesirable hypoxia associated with storm runoff, wastewater discharge, and/or existing instream chemical and biological oxygen demand. One of the better-known systems operates from two mobile barges on the Thames River in England. The Thames Bubbler and the Thames Vitality inject oxygen directly into the river during hypoxic events generally related to storm runoff. A similar, though smaller, system is now being deployed in Shanghai, China on the Suzhou Creek. In both of these applications, the scale of the treated system is much smaller than the Chesapeake Bay and in the case of the Thames River, the implementation is intermittent and event-driven.

Evaluation

The concept of using windmills to power air pumps is technically feasible, but when the application is at the scale of hypoxia in the Chesapeake Bay, nothing is simple. In this analysis, we have simply tried to identify a number of issues and questions that address the practicality of the idea, the probability of achieving some of the intended impacts, and the possibility of creating undesirable impacts.

Practicality

- *how many windmills would it take?*

The proposal suggests that 10,000 windmills on 1,000 barges might be deployed to address the problem of hypoxia in the Bay. To guage whether these numbers approximate the potential requirements, we estimated the available wind energy in the upper Bay region, the potential of windmills to convert that energy to a useable form, and the resulting energy available to pump air into the Bay. These calculations are summarized in the attachment at the end of this report and are based on a windrose developed for the Baltimore, MD area as part of the air quality monitoring program run by EPA. The calculations lead us to estimate the available windmill-derived energy in the upper Bay region at 2.2×10^{-2} KW m^{-2} of windmill.

To estimate the amount of air that would need to be pumped into the deep waters of the Bay, we made a number of very simple calculations. These are summarized in the attachment and resulted in an estimated need for 1.3×10^{8} liters hr^{-1} to treat a 100 square mile area. Given that recent measures of the extent of hypoxic waters in the Bay suggest the area may be as much as twice this size, and given that the estimation is based on conservative assumptions about oxygen demand in the system and the effective rate of oxygen transfer, we believe this number may be significantly less than the actual requirement. But it suffices for our coarse evaluation of practicality.

Finally, based on engineering equations for air compressor operation, we estimated that it would require 5.86×10^{3} KW to deliver the required amount of air. This number is certainly a significant underestimate since it makes no allowance for horizontal distribution of the air at depth. It simply estimates the energy requirement to get the air from the surface to depth.

Combining these calculations, we estimate it would take approximately 6,500 windmills with blades 5.6 meters long, to provide the air required to treat a 100 square mile portion of the Bay. Given the uncertainties inherent in these rough calculations, we would estimate that 10,000 windmills is at least in the ballpark for the potential requirement. The size of the windmills makes it unlikely an 80 x 30 ft. barge could support more than two windmills so thousands of barges would be required to treat the deep waters of the Bay.

- *maintenance*

From a purely practical point of view, this number of mechanical devices and moored vessels would require an enormous maintenance program and budget. There would be more windmills and barges in the Bay than the total number of aids to navigation currently maintained by the Coast Guard's entire Fifth District (all of the Bay plus Delaware Bay and the North Carolina sounds). Keeping navigation channels free of obstructions would become a major task given the necessary co-location of the windmills with the primary deepwater channels.

- *onshore location*

Location of windmills onshore raises issues of competition for limited riparian lands, impacts on biota (particularly birds) that tend to concentrate at shoreline ecotone, and conflicts of air delivery infrastructure with other uses in the littoral zone. The increased transmission distances also increase the energy requirements and thus the potential number of windmills.

Intended impacts:

- *aeration of the Bay will reduce algae levels*

Susquehanna River discharge in late winter-spring would still yield a spring diatom bloom. The bloom usually ends as the delivered dissolved nitrogen is consumed. The resulting organic matter is advected down the Bay and as the bloom senesces, sinks to the deep trough portion of the stratified Bay.

Aeration along the deep trough would result in a homogeneous water column basically from the Bay Bridge south, with vortices of ascending aeration-generated bubbles in one area and relatively quiescent areas in between the rising bubble centers. This approach could lead to diatom production from the spring through fall with some sedimentation in quiescent areas between rising bubble centers. The end result would be diatom accumulation in low energy, aerobic, non-bubbled areas with aerobic decomposition. Boynton and Kemp have shown that nutrient flux rates are lower in aerobic sediments than anaerobic sediments. Thus, lower recycling of bound nutrients might be expected, leading to only modest productivity for July-September. Additionally, Newell et al. (2002) argue that more of the nitrogen reaching an oxygenated bottom will be denitrified than under stratified, oxygen-poor conditions. This would lead to lower amounts of available nitrogen to support overlying phytoplankton production. Phosphorus might also be less available as low redox conditions would be less likely, keeping it bound in iron-phosphate complexes.

Because the water column would be mixed and aerobic, bottom-feeding herbivorous and detritivorous fishes, benthic filter-feeders, and other pelagic-feeders might increase. This could result in more macrofaunal-mediated nutrient recycling than currently occurs, providing for some continued diatom production in overlying waters.

The deep trough area might behave like a large mixed lake with a net southward flow. Salinities in the trough would be vertically homogeneous with a horizontal gradient of increasing salinity to the south. At the southern end of the trough where aeration ends, gravitational circulation would be reestablished, with the up-Bay transport of salty, dense bottom waters. Water quality, dissolved oxygen, and phytoplankton biomass would resemble what is currently observed in the southern portion of the Bay, with perhaps slightly higher surface chlorophyll levels.

The net result might be more mixing of current nutrient loads, continuous diatom production through summer, elevated living resources in the upper Bay, and conditions in the lower Bay similar to what are currently observed.

- *aeration of marinas may reduce degradation times for certain pollutants*

In fact, aeration could increase degradation of organic pollutants (e.g., hydrocarbons and other organics) by facilitating the growth of aerobic bacteria that are more efficient energy users. The problem is that the aerobic bacteria generally degrade the small organic compounds (sugars, proteins, detritus) that are omnipresent in an estuary and have limited interaction with more complex compounds such as hydrocarbons and other man-made pollutants. Aeration can potentially lower other trace metal pollutant loads (e.g., arsenic, chromium, copper) that have oxidation states that render them water soluble. But the kinetics of these reactions may limit the relative benefit (oxidation reactions can be slow for some metals).

- *aeration of oyster reefs may enhance oyster growth and disease resistance*

Mr. Hewison has observed that oysters grow the fastest when suspended in the upper water column (e.g., oysters grown in floats) and he has extrapolated that this is due primarily to higher dissolved oxygen found near the surface. However, there are several environmental variables that likely result in better growth for oysters grown near the surface, including higher temperatures and increased phytoplankton abundance. Additionally, we know of no direct evidence that increased oxygen levels relieve disease stress on oysters. Therefore, it is unlikely that this approach would benefit oysters as directly as hypothesized.

- *poor water quality can be permanently improved by aeration for a limited time period*

The Bay is a dynamic system with water masses constantly moving through the system, carrying with them nutrients, sediments, pollutants, and biota. While aeration may speed the degradation of legacy pollutants in some areas, it is unlikely that the system can be reset to a healthier state by a single treatment. Management of pollutant loads is the only effective means of maintaining desirable conditions long-term.

Potential impacts:

- *reduction/elimination of stratification with potentially significant impacts on natural circulation patterns*

The Chesapeake Bay exhibits a net circulation pattern that has fresh water flowing down the Bay at the surface and saline oceanic waters moving up the Bay along the bottom toward the head of the deep trough in the upper Bay. This pattern is established by the density difference between fresh and salt water. Aeration of bottom waters would mix the two water masses, reducing the density gradient and reducing or eliminating the natural circulation pattern. The resulting cessation of significant up-Bay transport in the deeper waters of the upper Bay may impact recruitment of organisms such as blue crabs that move in and out of that area each year. The alteration of normal circulation patterns may also impact the dispersal of resident organisms, such as oysters, that have planktonic larval stages.

- *increased algal production in the Bay*

Aeration by bubbling deeper layers would create an airlift that moves subpycnocline, bottom waters to the surface. This would inject large quantities of nutrients into the photic, surface waters during the summer when phytoplankton production is nitrogen-limited. This would fuel more organic production, some of which would sink to the bottom layer, demanding more oxygen. At a minimum, some of the mechanical oxidation would be offset and this could actually make matters worse, for example by reducing light penetration needed to sustain SAV production during the summer.

Simply adding dissolved oxygen will improve water quality, but will not solve all of the problems if that is the only management option undertaken. Nutrient control programs will still be necessary if the root cause of the water quality problem is to be solved. The basic problem is excessive nutrients that support excessive algal blooms. The algae die and dead algae settle, greatly increasing the organic content of the sediments. Then, bacteria begin consuming the dead algae using whatever electron acceptor is available. If it is dissolved oxygen, then degradation takes place rapidly. The sediment interface stays highly oxic, and iron-bound phosphorus is not released to the water column where it could stimulate new algae blooms. If the electron acceptor available is oxidized nitrogen, i.e., nitrite and nitrate, then degradation also takes place rapidly, the sediment interface is still oxic enough to prevent release of iron-bound phosphorus, and algae blooms are reduced. However, if neither of these electron acceptors is available, then true anaerobic metabolism will dominate. Organic compounds will be the end products of the bacteria-mediated degradation. Bacteria growth in the water column will be accelerated when the organics diffuse to where either oxidized nitrogen or dissolved oxygen is available as the electron acceptor. Then the subsequent release of sediment-bound phosphorus under anaerobic conditions makes abundant nitrogen the limiting nutrient, and algal blooms are maximized. The problem is that if the windmills are applied without nutrient control strategies, the dissolved oxygen they supply will simply increase the assimilative capacity of the Bay for organics, but there is no guarantee that the new assimilative capacity will be large enough to exceed the total mass of algae that will still be produced. If this is the situation, the organic inputs to the sediments will continue to increase until additional windmills will have to be constructed.

- *physical obstruction of uses*

Windmill arrays for power generation have become controversial in many places because of perceived negative effects on scenic values and wildlife. The potential number of windmills will clearly result in major visual impacts in the Bay environment. With 65 windmills per square mile, the quality of most viewsheds in the upper and middle Bay would be dramatically altered. The potential number and density of windmills will also unavoidably alter the habitat quality of the Bay for many resident and migratory waterfowl. Human uses of surface and subsurface areas would also be physically obstructed by barges and the attendant air distribution system.

References

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Newell, R.I.E., J.C. Cornwell, and M.S. Owens. 2002. Influence of simulated bivalve biodeposition and microphytobenthos on sediment nitrogen dynamics: A laboratory study. Limnology and Oceanography 47(5):1367-1379.

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How many windmills?

Baltimore Windrose
April 1 to October 31, 87-88, 90-92
Percent of time by speed and direction
interpolated from windrose available at
http://www.epa.gov/ttn/naaqs/ozone/areas/windr/93721.gif

Direction	Wind speed in knots					
	1 to 3	4 to 6	7 to 10	11 to 16	17 to 21	>21
N	0.0	1.0	1.6	1.0	0.1	0.0
NNW	0.0	1.0	2.0	1.2	0.2	0.0
NW	0.0	1.0	3.0	3.4	0.3	0.0
WNW	0.0	2.0	4.0	3.8	0.3	0.1
W	0.0	3.1	3.3	2.4	0.2	0.1
WSW	0.0	2.0	2.8	1.2	0.2	0.0
SW	0.2	1.8	3.0	1.8	0.2	0.0
SSW	0.1	1.8	3.0	2.0	0.2	0.0
S	0.1	1.8	2.5	1.4	0.1	0.0
SSE	0.0	2.0	3.0	1.2	0.1	0.0
SE	0.0	2.0	2.6	1.0	0.2	0.0
ESE	0.0	1.0	2.0	0.2	0.1	0.0
E	0.0	2.0	3.2	0.7	0.1	0.0
ENE	0.0	2.0	3.0	1.0	0.2	0.0
NE	0.0	2.0	3.0	1.0	0.1	0.0
NNE	0.0	1.0	2.0	0.8	0.1	0.0
Total %	0.4	27.5	44.0	24.1	2.7	0.2

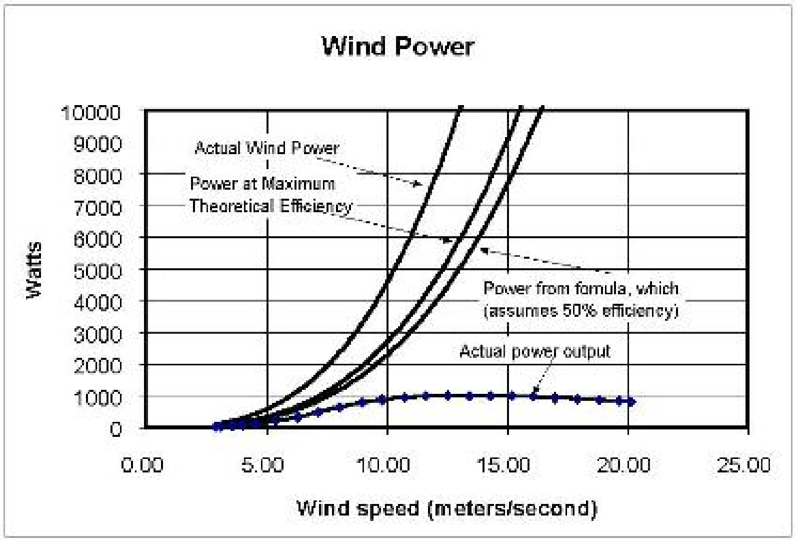
(note: calm winds reported 1.1% of time)

Calculation of available wind energy at Baltimore, MD

Wind speed in knots	1 - 3	4 – 6	7 - 10	11 - 16	17 - 21	>21
Wind speed in m/sec	1	2.6	4.4	6.9	9.8	11
Equivalent Watts/m^2	0.6	10.8	52.2	201.2	576.5	815.2
% time at speed	0.4	27.5	44.0	24.1	2.7	0.2
Apr 1 to Oct 31 hrs	21	1412	2260	1238	139	10
Available Watt-hours	13	15200	117916	249100	80131	8152
Total Watt-hours	470512					

Available wind energy Apr 1 to Oct 31 = 470 KWH/m^2
Or averaged over the period = 0.09 KW/m^2

Figure 1. Windmill efficiency
(from http://www.energyadvocate.com/fw91.htm)



The theoretical maximum efficiency of a windmill is 59%. A more typical performance, averaged over typical wind speeds is estimated at 20%.

Using an estimated 25% efficiency, **Bay windmills might be able to extract 2.2 x 10 $^{-2}$ KW m^{-2}.**

Oxygen demand in the sediments of the Bay varies from 0.1 to 10 g m^{-2} d^{-1} (Cerco, 1985; HydroQual, 1987; Kuo, et al. 1991). To estimate conditions in the Bay we use a value of 1 g m^{-2} d^{-1}. This can be viewed as a very conservative estimate since it is on the low end of the documented range and it does not consider water column demand. This value is equal to 4.0 x 10^{-2} g m^{-2} hr^{-1}. If air at sea level is 21% oxygen, and has a mass of 1.22 Kg m^{-3}, the oxygen content of air at sea level will equal 2.56 x10^{-1} gO_2 l^{-1}. This implies that satisfying the sediment oxygen demand would require 1.6 x 10^{-1} l air m^{-2} h^{-1}. Assuming that the dissolution of oxygen from air bubbled through water at depth would result in something less than a 50% efficiency of delivery results in **an effective need for air delivery of approximately 0.5 liters m^{-2} hr^{-1}.**

If there are **100 square miles** of Bay area with hypoxic conditions (another conservative estimate based on recent records), there would be 2.59 x 10^{8} m^{2} exhibiting the estimated oxygen demand. This **implies an air delivery requirement of approximately 1.3 x 10^{8} liters hr^{-1}.**

The energy requirement to supply this quantity of air can be estimated by calculating the requirements to pump air to a depth of 100 feet (used as an average depth for deep hypoxic waters in the Bay). While this depth may be argued, it probably still results in a significant underestimate of the total energy requirement since we do not attempt to assess the demands of any horizontal distribution requirements at depth, merely the vertical displacement.

Using the calculation of compressor horsepower requirements for adiabatic compression of air having 36% relative humidity at 68^oF (an average condition in a temperate climate):

i.h.p. = (m.e.p. x PD x 144 in^2/ft^3) / (33000 ft-lbs/HP-min)

where: i.h.p. = indicated horse-power of the compressing cylinder(s)
m.e.p. = mean effective pressure in lbs/in^2
$= (n/n-1)P_1\{(P_2/P_1)^{n-1/n} - 1\}$
PD = piston displacement in $ft^3\ min^{-1}$
n = exponent of total volume (1.3947 for these conditions)
P_1 = intake pressure in lbs in^2 (15 lbs in^2 at surface)
P_2 = discharge pressure in lbs in^2 (60 lbs in^2 at 100 ft depth)

To deliver 1.3×10^8 liters air hr^{-1} (or $7.52 \times 10^4\ ft^3\ min^{-1}$)

i.h.p. = 7.86×10^3 HP

Since 745.5 Watts = 1 HP, **the energy requirement to provide the necessary volume of air is 5.86×10^3 KW**. If windmills can provide 9×10^{-2} KW m^{-2}, it would require approximately $6.5 \times 10^4\ m^2$ of windmill surface to collect the necessary energy. If each windmill has an area of approximately 100 m^2 (equivalent to blades 5.6 meters long), **it would require approximately 6,500 windmills to meet the oxygen demand over a 100 square mile area** based on these calculations.

References:

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