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Potential societal and economic impacts of wastewater nutrient removal and recycling

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Abstract Because adequate nutrient controls were not established when there were past opportunities to do so, nutrient pollution of estuaries and coastal waters has resulted in the impairment of ecosystems and major reductions or collapse of fisheries at numerous sites around the world, resulting in major economical and societal impacts. The root of the problem is that the political policies and processes have permitted municipalities, developers, industries and farmers to expand and operate without paying the full cost of their activities, and this has been done at the expense of those who rely on the productivity and recreational value of our estuarine and coastal waters. Some governments have developed remedial nutrient control programs, but most of them have been under funded and inadequately enforced, resulting in small increments of progress that tend to be lost because of inadequate land use and immigration controls. It is believed that nutrient recovery and controlled reuse can provide a major tool for the control of nutrient pollution and should be widely implemented. Plans are currently being developed to promote widespread use of nutrient recovery and reuse in the Chesapeake Bay region of the USA. An example of phosphorus reuse is presented.

Keywords Economic impacts; ecosystem impacts; estuarine and coastal fisheries; nutrient pollution; nutrient recovery and reuse; societal impacts

Introduction

Shortly after passage of the Clean Water Act of 1972, the U.S. Environmental Protection Agency (EPA) developed a construction grants program that did not include nutrient removal as a wastewater treatment requirement. The political decision also was made that nutrient pollution generated by farmers could not be regulated, even though the use of manufactured fertilizers was rapidly increasing at that time. The long term results of political decisions made and policies established by EPA during the 1970s are that a large majority of the estuaries in the USA are excessively eutrophic and this has resulted in deterioration of water quality, including the creation of large "dead zones" of low dissolved oxygen (DO) during the growing season, and a decline in fisheries (National Ocean Service, 2000). Notable examples of highly eutrophic estuarine USA waters and impacted fisheries are the Chesapeake Bay, the Albemarle and Pamlico Sounds of North Carolina, New York Bight, Long Island Sound near New York City, Mobile Bay, Alabama, and Tampa Bay, Florida. Furthermore, there is a large hypoxic (< 2 mg/L DO) area on the Louisiana Shelf of the Gulf of Mexico that seasonally exceeds the combined areas of the states of Rhode Island and Connecticut (Figure 1). The nutrient loads carried into the Gulf by the Mississippi and Atchafalaya Rivers have caused this hypoxic area, and it has grown in size over the past decade, from 11,000 km^2 in 1992 to 17,500 km^2 in 1993 to more than 18,000 km^2 in 1995.

The low DO area of the Louisiana Shelf of the Northern Gulf of Mexico is not exceptional. The DO conditions of many major coastal ecosystems around the world have been adversely affected through the process of eutrophication (Diaz and Solow, 1999), with annual summertime hypoxia the most common form of low DO event (Diaz and Rosenberg, 1995). A few of these systems are listed in Table 1, with comparison of the hypoxia-related ecological and economic effects. It can be seen that the degree of obvious ecological and economic effects of the combined problems of eutrophication and hypoxia

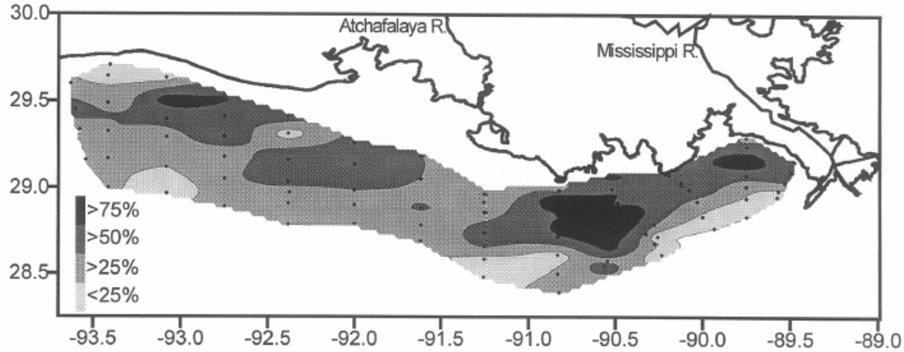

Figure 1 Distribution of frequency of occurrence of mid-summer hypoxia from 1985 to 1997 (data from Rabalais, Turner, and Wiseman hypoxia monitoring cruises). Rabalais, 2000

varies from system to system. The most serious effects are seen in the Black Sea and Baltic Sea where demersal trawl fisheries have been either eliminated or severely stressed (Mee, 1992; Elmgren, 1984). Hypoxia in the Kattegat, the sea between Denmark and Sweden, caused mass mortality of commercial and noncommercial species. Large-scale migrations and/or mortality among demersal fish and the Norway lobster (*Nephrops*) continue, resulting in a changed species composition and reduced growth and biomass. Hypoxia is believed to be partly responsible for the overall decline in the stock size, recruitment and landings of commercial fish over the last two decades. Two other stress factors are eutrophication (Caddy, 1993) and harmful algal blooms (Karup *et al.*, 1993), both resulting from nutrient over-enrichment. In the Baltic Sea, declining DO levels were noted as early as the 1930s, and hypoxia was reported in the 1950s (Fonselius, 1969), resulting in loss of demersal fisheries, with hypoxia as a bottleneck for cod recruitment.

Economic and societal consequences

Hyper-eutrophication will inevitably lead to destruction of habitat and changes in the food web that will result in species changes, most of which will be detrimental to the established fisheries. As the fisheries collapse, there are major societal impacts such as the loss of employment and the migration of workers and their families. The relationship between fishery production and yield, and nutrient loading has been discussed by Diaz and Solow

Table 1 Comparison of ecological and economic effects of anthropogenic hypoxic zones from coastal seas around the globe similar to the northern Gulf of Mexico hypoxic zone (Diaz and Solow, 1999)

System	Area affected (km^2)	Benthic response	Benthic recovery	Fisheries response
Louisiana Shelf	15,000	Mortality	Annual	Stressed, but still highly productive. No reports of mortality, except 'jubilees'.
Kattegat, Sweden-Denmark	2,000	Mass mortality	Slow	Collapse of Norway lobster, reduction of demersal fish. Hypoxia prevents recruitment of lobsters.
Black Sea North-west Shelf	20,000	Mass mortality	Annual	Loss of demersal fisheries; shift to planktonic species.
Baltic Sea	100,000	Eliminated	None	Loss of demersal fisheries, shift to planktonic species. Hypoxia is bottleneck for cod recruitment.

Note: Data from various sources cited in text

(1999). They state that there is an initial increase in production and yield as nutrient loading increases, followed by the final collapse of the ecosystem after nutrient loading exceeds the assimilative capacity of the system.

Chesapeake Bay ecosystem

The Chesapeake Bay is a prime example of a fragile estuarine ecosystem that has been brought to near collapse by nutrient pollution. It is the largest estuarine bay in the USA, and has a watershed that includes Washington, D.C. and parts of six states in the mid-Atlantic region, Delaware, Maryland, New York, Pennsylvania, Virginia and West Virginia. The population of the Bay region has increased substantially in recent years, resulting in large increases in nutrient pollution from all sources, i.e. wastewater treatment plant effluents, urban/suburban runoff pollution, automobile exhaust emissions, agricultural pollution and power plant stack emissions. In 1985 the total nutrient loads to the Bay were 163 million kilograms (358 million pounds) N, and 13 million kilograms (28.7 million pounds) P. Of that total, agricultural sources contributed 42 and 40% of the N and P loads, respectively, wastewater treatment plant effluents 24 and 32%, respectively, and direct water surface air pollution deposition plus forest and urban runoff most of the rest (Chesapeake Bay Program, 2000). It has been determined that, currently, 25% of the N load to the Bay comes from atmospheric sources, i.e. originates as air pollution, and that 62% of the airborne N originates from outside the watershed. About 66% of the airborne N consists of oxidized forms (Kerchner *et al.*, 2000). It is also estimated that 8% of the P load is directly deposited on the water surface from airborne sources (Chesapeake Bay Program, 2000).

The nutrient pollution has been especially detrimental to the Bay ecosystem because the increased algal blooms cause shading of the submerged aquatic vegetation (SAV) and also result in large hypoxic areas during the growing season. The SAV is essential habitat for the survival of newly hatched fish, crabs and oyster spat, but is very light sensitive. Algal shading has caused extensive reduction of SAV in the Bay and this has substantially reduced the fisheries productivity of the Bay. The potential SAV habitat in the Bay is 600,000 acres (242,820 hectares), but the area was only 40,000 acres (16,188 hectares) in 1984.

Chesapeake Bay fisheries

The hypoxia in the Gulf of Mexico has not yet resulted in fisheries declines sufficient to cause major societal changes in the region, but declines in fisheries sufficient to cause major societal changes have already taken place in the Chesapeake Bay region. Most notable are the declines in the American Shad and oyster fisheries. During the 19th century, the shad fishery was the largest in the Bay, with catches of 22,000 metric tons/yr. It declined for >80 years, and by 1992 had shrunk to only 700 metric tons. In the late 1800s, the oyster harvest from the Bay was more than a billion pounds (454 million kg) per year. It has averaged less than 2 million pounds (0.91 million kg) per year for the past decade. The tremendous decline in the oyster population has severely impacted the fishery and the cultural tradition of the watermen that ply the Bay bottom for this seafood product (National Marine Fisheries Service, 2002). During the 15 year period from 1970 to 1985, approximately 50% of all of the oyster processing facilities in Maryland ceased to function, putting thousands of employees out of work. Similar declines can be seen in other Bay fisheries. The catch of white perch has been declining since 1969. American eel landings have declined since 1981. Red drum has ceased to be an important commercial species although the catch was once as high as 180,000 pounds/year. The decline reaches into the coastal waters and bays beyond the Chesapeake Bay. Menhaden fishing is one of the most productive and important fisheries on the USA Atlantic Coast, but it, too, is in serious decline (NOAA CBO, 2002).

In 1955 there were 150 menhaden vessels in operation. This had shrunk to 31 in 1993. There were 23 shore-side reduction facilities in 1955 but only 5 in 1993.

Nutrient controls, recovery and recycling

The information given above makes it clear that excessive nutrient pollution of estuaries and coastal areas is now a worldwide crisis with major economic and social repercussions. It seems reasonable to say that this widespread crisis has occurred because our political and social structures have permitted population growth without adequate regulation of agricultural, municipal and industrial sources of nutrient pollution. The political policies and processes have permitted municipalities, developers, industries and farmers to expand and operate without paying the full cost of their activities, and this has been done at the expense of those who rely on the productivity and recreational value of our estuarine and coastal waters. In some cases, the fisheries have been permitted to fully collapse without any efforts at remedial actions, such as in the Baltic Sea. In other cases, the governments have developed somewhat belatedly, usually inadequate, and nearly always under funded remedial programs. For example, even when major remedial efforts such as the Chesapeake Bay Program are instituted and funded, the funding is inadequate for rapid reduction of nutrient inputs and no institutional efforts are made to establish land management and to control immigration into the region. The result is that established goals are not reached, and nutrient reductions achieved by the program are short-lived because, even with more effective point and non-point controls, the absence of land use and population controls results in increased pollution from population growth and increased pollution causing activities that overcome any reductions achieved through technology.

Given the political, social and demographic realities, what are some appropriate ways to establish and maintain effective nutrient controls? It is proposed that the most effective nutrient controls are those that follow “green engineering” principles. Green engineering can be defined as, “the utilization of technology that improves or is highly compatible with the environment, eliminates or minimizes secondary environmental impacts, and minimizes the costs of implementation”. While all processes that remove nutrients from wastewaters and minimize the amounts that return to the aquatic environments can be characterized as green engineering, biological nutrient removal (BNR) more precisely fits the definition than chemical nutrient removal processes if the resulting sludges are simply sent to disposal. For example, both enhanced biological phosphorus removal (EBPR) and denitrification utilizing the wastewater as the organic carbon source reduce the amount of energy that must be consumed for the transfer of oxygen to complete COD removal. The reduction of energy requirements reduces the secondary environmental impacts of energy generation, i.e. fuel consumption, stack emissions, mining or extraction activities, etc. The reduction of chemical usage reduces the secondary impacts of chemical manufacturing and shipping. Additionally, denitrification and EBPR operation produce less waste sludge for the same operating conditions than aerobic COD removal and chemical addition processes, and this reduces the amount of secondary impacts related to waste sludge processing and disposal. Of course, if chemical processes can be used to reduce the lifetime costs of the treatment system when all costs including sludge dewatering and disposal are accounted for, then they can become the method of choice.

While biological processes are potentially more environmentally compatible than chemical processes, their advantages can be improved even more if they can be combined with recycle and reuse. The Hampton Roads Sanitation District (HRSD) of Virginia is an example of an organization that has implemented nutrient recycle through sludge processing, packaging and reuse. The District operates 11 WWTPs in the Tidewater Virginia region (Norfolk, Portsmouth, Newport News, Hampton, Virginia Beach, Williamsburg, etc.), two of which are three stage BNR plants. HRSD and the author worked together demonstrating and developing BNR wastewater treatment from 1985–1988, and phosphorus-rich sludge composting and recycle was implemented in 1986 in conjunction with the York River WWTP BNR demonstration project. The York River WWTP was designed as a 56.8 ML/d capacity conventional aerobic activated sludge facility. It was designed with aerated grit removal, a minimum of 30 minutes of pre-aeration, three primary clarifiers, six parallel aeration basins with coarse bubble aeration, three secondary clarifiers, sludge thickening by both gravity (primary) and dissolved air flotation (secondary), and two stage anaerobic digestion followed by belt filter press dewatering. The flow at the time of the BNR demonstrations was less than 26 ML/d, so only two of the parallel aeration basins were modified so that they could be operated for either two or three stage BNR operation, i.e. the other four were not used during BNR operation, which resulted in nominal hydraulic retention times (HRTs) of less than 6 hours in the activated sludge basins (Figure 2).

The percentage phosphorus in the York River activated sludge exceeded 15% during one phase of the two stage (EBPR) BNR experiments because of the low COD/TP ratio in the process influent, and averaged in excess of 10% throughout the first year once steady-state was achieved. Only a small fraction of the phosphorus in the waste activated sludge (WAS) was released during DAF thickening when it was properly operated. It was mixed with the thickened primary sludge immediately before entering the primary anaerobic digester, and the full stream entered the digester. Only one primary and one secondary digester were available at the WWTP, and because the flow was less than 50% of design flow, the HRT within the digesters was approximately 90 days. The digesters were always mixed and were never supernated to minimize the amount of phosphorus recycled to the BNR process.

The data in Table 2 compares inorganic chemical concentrations in the primary digester before and after EBPR was established and had come to steady state. The data show that the TP increased by 750 mg/L, but the soluble P increased by only 250 mg/L. This indicates that a large fraction of the phosphorus released in the digesters precipitated.

Potassium does not have an insoluble precipitate under the conditions in the anaerobic digesters, so the comparison of the increase in soluble K relative to the increase in the total K reveals the fraction of P release from the sludge because K is always taken up and

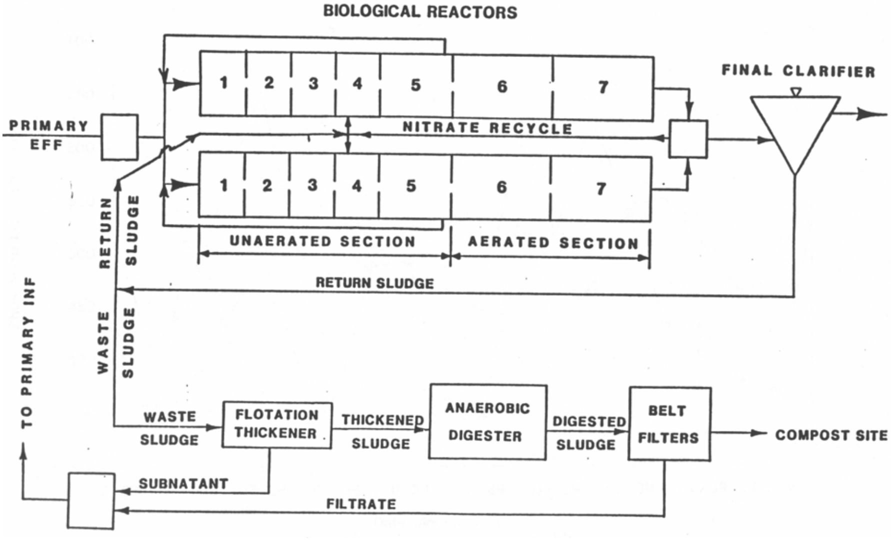

Figure 2 York River WWTP BNR modifications

Table 2 Inorganic chemical concentration changes in the York River digesters

Parameters	Chemical Concentrations, mg/L Before EBPR	After 9 months of EBPR
Total phosphorus	350	1,100
Soluble phosphorus	50	300
Total potassium	60	300
Soluble potassium	55	230
Soluble magnesium	10	10
Soluble calcium	100	30
Ammonium	316	390

released with P during EBPR. Total K increased by 240 mg/L, whereas soluble K increased by 175 mg/L, indicated that 73% of the phosphorus in the cells was released during anaerobic digestion. Soluble magnesium did not increase at all indicating that all of the Mg released from the microbial cells precipitated upon release, and that Mg was the limiting chemical in the precipitation. Ammonium increased, but by only 74 mg/L, indicating that most of the released ammonium precipitated. The results indicate that both ammonium and Mg precipitated as struvite, i.e. $MgNH_4PO_4$, and that even more ammonium and phosphate would have precipitated if more Mg had been present. The formation of struvite was confirmed by the recovery of crystals from the dewatered digested sludge, and utilization of X-ray diffraction. In fact, the struvite crystals were so large and so numerous that the sludge sparkled when exposed to light.

The data show that the soluble calcium decreased by 70 mg/L after EBPR was instituted. The amount of calcium associated with P during EBPR reactions is typically small, i.e. less than 10% of the cations involved, and it may be near zero (Pattarkine, 1991). The reduction in soluble calcium clearly indicates that the high phosphate concentrations induced calcium phosphate precipitation within the anaerobic digesters. Mass balance calculations indicated that the reaction was non-stoichiometric. Regardless, most of the P released to solution during anaerobic digestion of the phosphate rich bacteria precipitated within the digesters and was retained in the sludge, not the supernatant. From mass balances it was determined that 30% of the P removed during EBPR was recycled back to the headworks in the belt filter press filtrate, and 70% of it was retained with the sludge cake. The retention of the struvite and calcium phosphate precipitates significantly increased the concentrations of P, ammonium, magnesium, and calcium in the sludge cake and increased its value as a fertilizer. Composting the waste sludge sterilized it and made it safer to handle.

The composted sludge is packaged in 40 lb (18.2 kg) bags and marketed locally as “NutraGreen”. Each bag is currently sold for US$1.00. Additionally, it is sold in bulk for \$14 per yd^3 (US\$18.31 m^3). Currently, all of the sludge from the five HRSD operated treatment plants on the Virginia Peninsula is composted and completely recycled in this manner. The recycling effort has been very successful, and has been well received by the regional community. There are state regulations in place to mandate that the nutrient-rich composted material is appropriately utilized to minimize runoff pollution to the streams and estuaries in the region. There are plans underway to encourage similar nutrient recovery and recycle programs throughout the Chesapeake Bay region. This will begin with a workshop during the spring of 2003 that is currently being developed by the author.

Conclusions

Improved nutrient controls are needed in much of the world to protect and recover water quality and to preserve fisheries. Failure to do so will cause major economic and societal disruptions. The recovery and reuse of nutrients is recommended as a means of control.

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