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The Athalie Richardson Irvine Clarke Prize

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Fourteenth Annual Lecture

July 12, 2007

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The 2007 Clarke Prize Lecture, Elimination of Eutrophication through Resource Recovery *by James L. Barnard, Ph.D., Pr.Eng, BCEE, was first presented on Thursday, July 12, 2007, at the Fourteenth Annual Clarke Prize Award Ceremony and Lecture, held at the Hilton Waterfront Beach Resort in Huntington Beach, California.*

The National Water Research Institute (NWRI) of Fountain Valley, California, established the Clarke Prize in 1993 to recognize outstanding research scientists who have demonstrated excellence in water-science research and technology. Dr. Barnard was the fourteenth recipient of the prize, which includes a gold medallion and $50,000 award.

The Clarke Prize was named after NWRI's co-founder, the late Athalie Richardson Irvine Clarke, who was a dedicated advocate of the careful stewardship and development of our water resources. Mrs. Clarke's daughter, Mrs. Joan Irvine Smith (also an NWRI co-founder), is patron of the award.

National Water Research Institute

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The 2007 Clarke Lecture

Elimination of Eutrophication Through Resource Recovery

James L. Barnard, Ph.D., Pr.Eng., BCEE

Abstract

Undiminished growth in the world's population and the spread of industrialization to former agricultural societies have put relentless pressure on resources for food and fuel, as well as on rejected energy in the form of plant nutrients that can seriously pollute receiving waters. This paper will look at the causes of deterioration of the water environment and how plant nutrients can be recovered while solving many pollution problems.

Proteins can be recovered from wastewater to augment food supplies, urine can be separated and used as fertilizer, phosphorus can be recovered and used in fertilizers or incorporated in compost, algae can be grown and harvested for converting to biodiesel fuel, wastewater biosolids can be turned into organic fertilizers, and water can be reclaimed for reuse, which would prevent the deterioration of receiving water quality.

Introduction

Over the past 35 years, the population of the world has doubled, from roughly 3 billion to about 6 billion, with most of the growth in cities. It is expected that, by 2050, the world population will stabilize at around 10 billion.

Population growth will not be spread uniformly around the globe, but will be concentrated in countries that are already disadvantaged. A concentration of people leads to a concentration of pollution and the need to treat wastewater generated in the urban areas occupied by this population. As an example, the population of Mexico City now exceeds 30 million, but the wastewater produced there receives virtually no treatment. It is simply used to irrigate land to produce food.

Increases in population mean increases in the demand for food and for fertilizers to grow this food. The Green Revolution, spanning the period from 1967/68 to 1977/78, changed India from a starving nation to one of the world's leading agricultural producers. This change came as a result of harvesting two crops a year from the same land, developing high-yield grains, and using more water, fertilizer, pesticides, fungicides, and certain other chemicals.

The United States and Canada produce more than 60 percent of the surplus food in the world to make up for the shortfall in other countries. Crop yields in the United States have been increased by intensified agriculture, a massive increase in fertilizer application, and the installation of under-drainage to leach out the build-up of minerals in the soil. The leachate containing nitrates and phosphorus was discharged to streams and eventually began to enrich receiving waters. McCarty (1969) described methods used for reducing the discharges of nitrates to San Francisco Bay. The intensified production of meat led to the use of large feed-lots for raising cattle, which resulted in massive discharges of nutrients, mainly nitrogen and phosphorus, to receiving streams.

Discharges of wastewater effluent containing excess nitrogen and phosphorus can contribute to the growth of algae in receiving water, which results in eutrophication.

What Is Eutrophication?

The term “eutrophication” comes from the Greek word “eutrophos,” meaning well-nourished. It referred to the ageing of water bodies through the natural addition of nutrients. However, in modern terms, “eutrophication” refers to the enrichment of receiving waters with excess nutrients. It is not unusual to find lakes and rivers that have become rich in nutrients, such as carbon, silicon, nitrogen, and phosphorus, as a result of erosion or runoff from adjacent soils.

Other nutrient sources include drainage and wash down of excess nutrients from applied fertilizers, agricultural feed lots, and domestic and industrial wastes. In the receiving water, these nutrients support the growth of phytoplankton (algae), which are the first link in the food chain and, hence, the basis of all aquatic life. In surface waters, particularly in oceans, this “primary production” speeds the diffusion of carbon dioxide from the atmosphere to the oceans – the largest sink for carbon dioxide.

The food chain itself consists of many links, each with complex interactions but, in the simplest terms, can be described as follows: phytoplankton are consumed by zooplankton, such as daphnia (water fleas) – the food for many species of small fish. These fish are consumed by larger predatory fish that, together with their prey, are food for birds and mammals and, indeed, man.

A healthy and well-nourished water body (river, lake, or sea) sustains a rich and diverse aquatic life with all components of the food chain existing in a dynamic equilibrium of production and consumption. A healthy food chain can often survive large changes in nutrient load or climatic conditions with remarkable resilience without any long-term changes in water quality or species diversity.

However, the pressures of expanding population, urbanization, industrialization, and agricultural intensification in many regions have resulted in a massive increase in the loadings of not just nutrients, but also of untreated or secondary treated sewage into rivers, lakes, and estuaries. Industrial discharges, pesticides, animal wastes, and countless other pollutants can have a direct and devastating effect on the food chain.

The combination of greatly increased nutrient input and a wide range of other (potentially ecotoxic) inorganic and organic products that reach the water can have serious effects on the aquatic ecosystem. While the production of algae is promoted by the increased nutrient supply, the ability of zooplankton (usually the most pollution-sensitive organism in the food chain) to respond to this increased food supply is impaired by the presence of other kinds of pollutants. The result is often that the balance of production and consumption in the food chain is disturbed, which – in most cases – leads to algae becoming the dominant life form in water.

In the worst case, algae will proliferate in a way that can no longer be controlled at higher levels in the food chain. This growth may lead to the decline in the populations of other water plants, particularly the bottom-growing plants that fail to obtain adequate light in the turbid-water column. In the most extreme cases, toxic algal scum may be formed and water may become deoxygenated, resulting in fish kills. There are many lakes and reservoirs where elevated nutrient levels have not caused the water quality problems associated with high algal biomass, while other lakes with similar nutrient loads exhibit signs of algal domination.

An example of such imbalance can be found in the deteriorating condition of Lake Erie in the early 1970s, which was of particular concern (Knud-Hanson, 1994). Approximately 20,000 pounds of phosphorus per day discharged into the lake resulted in an estimated 2,600 square-mile area of the lake with no oxygen within

10 feet from the bottom (Beeton, 1971). As of 1967, mats of attached algae covered Lake Erie's shoreline, and the populations of desirable fish, such as whitefish, blue pike, and walleye, had either severely declined or disappeared altogether.

The deterioration of the lake was a great concern at the time and even led to a poem:

"You're glumping the pond where the Humming-Fish hummed!
No more can they hum, for their gills are all gummed.
So I'm sending them off. Oh, their future is dreary.
They'll walk on their fins and get woefully weary
in search of some water that isn't so smeary.
*I hear things are just as bad up in Lake Erie."**
~ *The Lorax* by Dr. Seuss

The so-called "Gulf Anoxia" is caused by excessive amounts of nitrogen being discharged into the Gulf from the Mississippi River, which enhances the growth of algae. When algae die, oxygen is consumed, leading to the development of a zone where the dissolved oxygen is too low to support fish and other aquatic life, while causing large swings in the pH value as carbon dioxide (CO_2) is extracted or returned to the water. Midsummer coastal hypoxia in the northern Gulf of Mexico was first recorded in the 1970s. From 1993 to 1999, the extent of the bottom-water hypoxia covered between 16,000 and 20,000 square kilometers (km^2) and was twice the size of the Chesapeake Bay, rivaling the extensive hypoxia of the Baltic and Black Seas (Rabelais et al., 1998, 1999). This area exceeds the area of the states of Connecticut and Rhode Island.

Much of the initial work on nutrient removal was sparked by the situation around Johannesburg, now known as the Province of Gauteng, South Africa, with a population close to 10 million people. The City is on the continental divide, and water is pumped to it from long distances. In spite of rigid effluent standards, by the early 1970s, eutrophication of the reservoirs to the north and south of the City became severe enough to resemble pea soup. Inevitably, as the urban areas grew, recycled wastewater effluent began to constitute an ever higher percentage of the flow to these reservoirs, which in turn supplied water to downstream users. With the salinity of drinking water reaching a concentration of 800 milligrams per liter (mg/L) during years of drought, the addition of chemicals for the removal of phosphorus was not considered an option. Activated carbon was used to remove tastes and odors at potable water treatment plants.

*After an extensive cleanup campaign in the 1970s substantially rejuvenated Lake Erie, Dr. Seuss had the last line about Lake Erie removed from later editions of *The Lorax*.

The Concept of a Limiting Nutrient

Algae, the lowest link in the food chain, need a number of conditions to sustain growth: sunlight for photosynthesis, an elevated temperature, certain water conditions (turbulence), and nutrients (in particular, carbon, nitrogen, and phosphorus, which, broadly speaking, are required in the ratio 100:10:1, respectively), as well as a wide range of trace elements. This "primary production" is the foundation of the food chain that sustains all higher life forms: invertebrates, fish, birds, and mammals. If any one of these essential conditions is removed, the primary production ceases and, with it, all higher life forms.

In a healthy ecosystem, the ability of the food chain to adapt to variations in nutrient load can be quite remarkable. In its simplest sense, the water body is capable of sustaining a richer and more productive food chain. This adaptability can also be achieved without any deterioration in water quality. While the availability of nutrients causes the production of algae to increase, the process is balanced by an increase in the consumption of algae by the organisms higher in the food chain that prosper on the increased food supply. Such a situation can often be beneficial by supporting a productive sport or commercial fishery and wildlife.

Since carbon dioxide is freely available from the atmosphere, reducing either nitrogen or phosphorus in discharges to the receiving water will limit the growth of algae. In inland water, phosphorus is mostly the limiting nutrient, while in bays and estuaries, nitrogen is predominantly the limiting nutrient. In some environments, both nutrients may be limiting.

Where Do the Main Nutrients Come From?

Secondary treatment of wastewater is widely practiced in the United States, Europe, Japan, Australia, and South Africa. Wastewater is treated by exposing it under aerobic conditions to organisms that promote the breakdown of carbonaceous compounds (proteins, sugars, soaps, etc.) to carbon dioxide and water. Typically, nitrogen and phosphorus compounds in domestic wastewater are in excess of that required for organism growth in the treatment plant. The excess nutrients are not removed, but merely converted from the organic to the inorganic form. The process is depicted on Figure 1. Protein is a combination of many elements, but mainly carbon, hydrogen, nitrogen phosphorus, and sulfur. The bound ammonia is converted to ammonia or, when it is further oxidized, to nitrites and nitrate. The phosphorus radical, PO_4^{-3}, is discharged with the effluent.

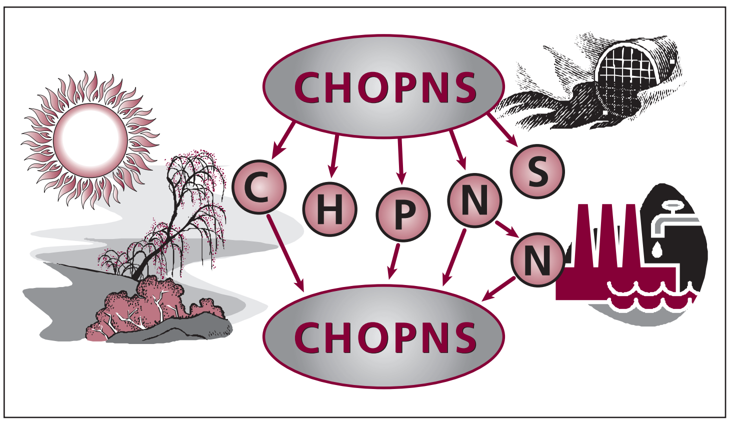

Figure 1. Conversion of typical wastewater to secondary effluent.

Until 1974, phosphorus used in detergents made up about 50 percent of the phosphorus in wastewater effluent. After a heated battle between environmentalists and the detergent industry, a number of states outlawed the use of phosphorus in detergents, which resulted in the reduction of phosphorus in treated waste-water effluent from around 11 mg/L to between 5 and 7 mg/L.

The sources of nutrients that are discharged to water bodies vary from one place to another. Nutrient sources in the European Union are shown in Figure 2. Even there, the contribution from human sources equals the contribution from livestock. Those two

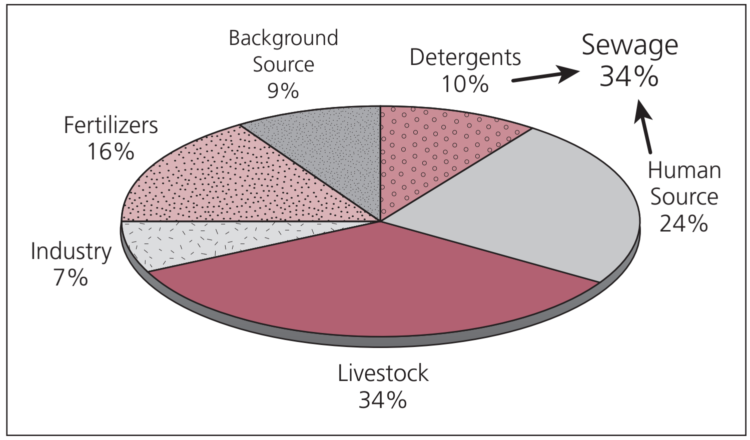

Figure 2. Sources of phosphorus in receiving waters in the European Union.

sources, combined with industry, can be considered "point sources," meaning that nutrients are discharged at discrete points as opposed to dispersed runoff from crop fields, lawns, and parks where fertilizers are applied.

Nitrogen is more often the limiting nutrient for the growth of algae in bays and estuaries and is the main cause of anoxic conditions in the Gulf of Mexico. Sources contributing nitrogen to the Gulf Anoxia are indicated on Figure 3.

Only 11 percent of the total nitrogen in the Mississippi comes from municipal and industrial point sources in the catchment of the river system, which include cities such as Chicago, St. Louis, Minneapolis, Kansas City, Nashville, Memphis, and New Orleans, while 15 percent originates in animal manure and more than 50 percent comes from fertilizers and mineralized soil through tile drainage systems from crop fields (Hey et al., 2005). With the expected increase in crop production for the biofuel program, the problem will increase in severity. In the Long Island Sound, where

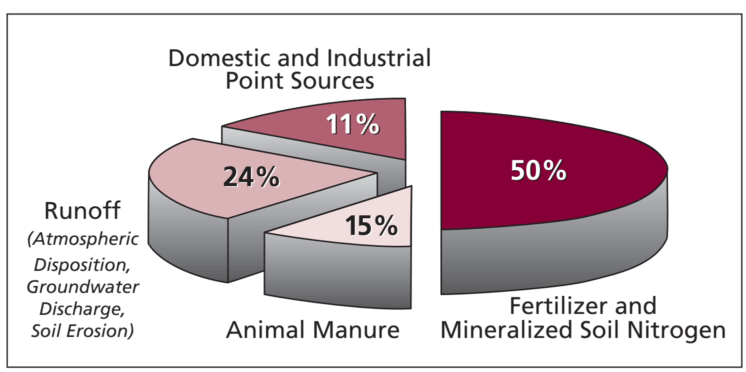

Figure 3. Sources of nitrogen in the Mississippi River.

algae growth is also nitrogen-limited, more than 50 percent of the nitrogen originates in wastewater treatment plants for the City of New York, Westchester County, and the State of Connecticut. Many cities in the United States have begun removing nitrogen from municipal wastes, but little effort has gone into tackling the bigger problem of removing nitrogen from agricultural and other diffused sources.

The Las Vegas metropolitan area discharges all wastewater effluent to the Las Vegas Wash and into the arm of Lake Mead that serves as the area's water supply. Because of low rainfall in the area, most of the flow into that arm consists of municipal effluent, and the contribution of point sources can be more than 90 percent of the total. Thus, all nutrients contained in the effluent will make up a high percentage of the total going into that arm of the lake. At present, there is sufficient exchange of flow between the Las Vegas Wash and the main body of Lake Mead, but as lake levels drop, the exchange will be reduced and the effluent of the treatment plants will make up a larger proportion of the domestic water supply.

How Do We Deal with This Surplus of Nutrients?

Multiple strategies will be required to reduce the nutrients that affect water bodies. The first line of attack is to remove nutrients from point sources, such as domestic and industrial wastewater treatment plants. However, because only 10 percent of the nitrogen going into the Gulf of Mexico originate from point sources, other strategies will be required. For point sources, the following technologies are available.

Phosphorus Removal: At domestic or industrial waste treatment plants, phosphorus can be removed either by precipitation with metal salts, such as aluminum and iron salts (which form an insoluble precipitate of aluminum or ferric phosphate), or by incorporation into biological cells. The solids containing the phosphorus can be removed by settling and disposed of with the treated excess biosolids.

In response to public concern about the eutrophication of Lake Erie, pollution control laws were adopted in both countries to deal with water quality problems, including phosphorus loadings to the lakes. In 1972, Canada and the United States signed the Great Lakes Water Quality Agreement to begin a binational Great Lakes cleanup that emphasized the reduction of phosphorus entering the lakes. Iron or aluminum salts were added in the wastewater treatment plants to precipitate phosphorus.

The later development of processes for the biological removal of phosphorus is of particular significance for sustainable practice because it also facilitates the recycling and reuse of phosphorus, as discussed further below. All living things need phosphorus to grow, but certain microorganisms can store phosphorus in excess of their biological needs.

To trigger the mechanism by which these organisms take up phosphorus, the organisms are continuously recycled from an aerobic to an anaerobic environment, where they come in contact with influent wastewater. While these bacteria are strictly aerobic, they can store phosphorus in the form of high-energy polyphosphate bonds when dissolved oxygen is available, forming a large pool of polyphosphates within the cells.

When they are recycled and contacted in the absence of dissolved oxygen or nitrates, with short-chain volatile fatty acids that are natural constituents of "older" wastewater, these pools of high-energy phosphorus can supply the energy to take up and store these acids as an intermediate product, breaking the phosphorus bonds and releasing phosphorus.

When they are passed back to the aerobic environment, they have a surplus of stored food that they can use to provide energy to take up all the phosphorus they released during the anaerobic phase, plus all the surplus phosphorus in the influent. They are very efficient and can take up the soluble phosphorus to levels as low as 0.03 mg/L.

When the solids are separated from the liquid, up to 98 percent of the phosphorus can be removed. This plays an important part in the recovery of phosphorus, as discussed below.

In Figure 4, the polyphosphate within the bacteria stains black on the electron microscope picture. The right-hand picture shows the aerated zone where virtually all the phosphorus has been taken up into the bacterial cells. A portion of the phosphate-rich solids are continuously removed from the bacterial mass, thus removing the phosphorus from the main stream.

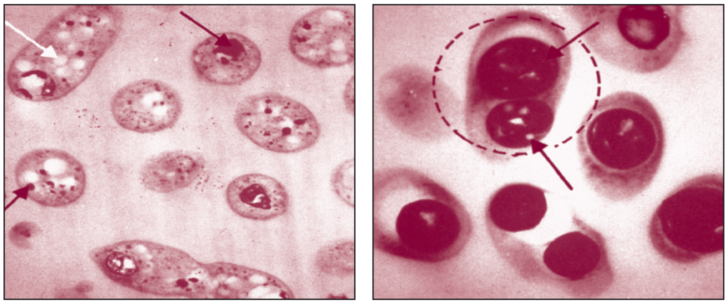

Figure 4. *Release and uptake of phosphorus in biological phosphorus removal process.*

Nitrogen Removal: Urea and complex nitrogen compounds are converted to free ammonia compounds in solution by biological wastewater treatment processes.

The ammonia is converted to nitrates and nitrites (nitrified) by specialized soil bacteria in the presence of surplus dissolved oxygen and then reduced by another set of organisms to nitrogen gas in the absence of oxygen. These "anoxic" bacteria need a supply of organic carbon to grow while they obtain their energy from the reduction of nitrates to nitrogen gas.

Most of my work concerned the discovery and development of processes for simultaneous biological removal of nitrogen and phosphorus using internal carbon sources.

While there are many treatment plants in the country that remove more than 90 percent of nitrogen and more than 95 percent of phosphorus, much still needs to be done, and billions of dollars are being spent to remove nutrients from discharges to sensitive water bodies (those that have no capacity to absorb anymore nutrients without change), such as Chesapeake Bay, other estuaries on the East Coast and Florida, the Great Lakes, and many inland reservoirs. In some sensitive areas, such as Las Vegas and the water supply reservoirs in New York and Washington, phosphorus in the effluent needs to be removed to less than 0.02 mg/L. Although the power consumption for these processes is high, it is a tiny fraction of 1 percent of the carbon footprint of the average person, amounting to less than 25 kilowatt-hour (kWh) per person per year, but efforts at sustainability demand that we take a new look at the resources in wastewater that are not used beneficially.

Phosphorus Recovery

"The phosphorus content of our land, following generations of cultivation, has greatly diminished. It needs replenishing. I cannot over-emphasize the importance of phosphorus not only to agriculture and soil conservation, but also the physical health and economic security of the people of the nation. Many of our soil deposits are deficient in phosphorus, thus causing low yield and poor quality of crops and pastures…"

– President Franklin D. Roosevelt (1938)

Thus, the President underscored the importance of phosphorus for food production.

Although the United States currently produces more than 25 percent of the world's supply of phosphorus, Morocco has more than six times the reserves of the United States. A war has already been fought over Morocco's phosphorus deposits.

Some of the richest lodes of phosphorus in the United States lie under cities such as Jacksonville, Florida, and will probably never be exploited. Production is limited to a few countries, such as Russia, Tunisia, Jordan, Brazil, and South Africa. Predictions as to when the reserves will run out vary, but it is generally accepted that in less than 50 years, there will be fewer producers and, thus, higher possibilities of severe competition for securing future supplies. Known reserves may be depleted within around 200 years if nothing is done to recover and recycle phosphorus.

The highest-quality deposits are being depleted rapidly. Lower-grade ore will require more energy for processing. The price of fertilizer will increase. This scenario does not accord with the notions of sustainability. The world will eventually be faced with a shortage and, if even at this point the poorer countries cannot afford the price of fertilizers, the future scenario seems bleak.

In a 1999 report, the European Environmental Agency indicated rivers that were cleaner as a result of phosphorus removal at wastewater treatment plants were one of the few environmental success stories. Almost 10 more years have passed, and the next 10 years will see a considerable increase in the conversion of phosphorus from the liquid to the solid state at treatment plants in the United States, where it will be present in the surplus biosolids produced. At the same time, the amount of phosphorus recycled for agricultural use is reduced as there is pressure to reduce the application of biosolids on land. As a result of alternative disposal methods, more of the phosphorus is dispersed in the environment and, thus, lost to future generations.

However, the concept of biological phosphorus removal lends itself to recovering phosphorus from wastewater, as demonstrated in Figure 5. The phosphorus-accumulating organisms concentrate it in their cells in the aerated section of the main plant and release it in the anaerobic section. The solids are separated by sedimentation or, more recently, by membranes. The separated surplus solids containing all the phosphorus are then held under anaerobic conditions that cause them to release the phosphorus to solution, and the phosphorus-rich supernatant can be decanted.

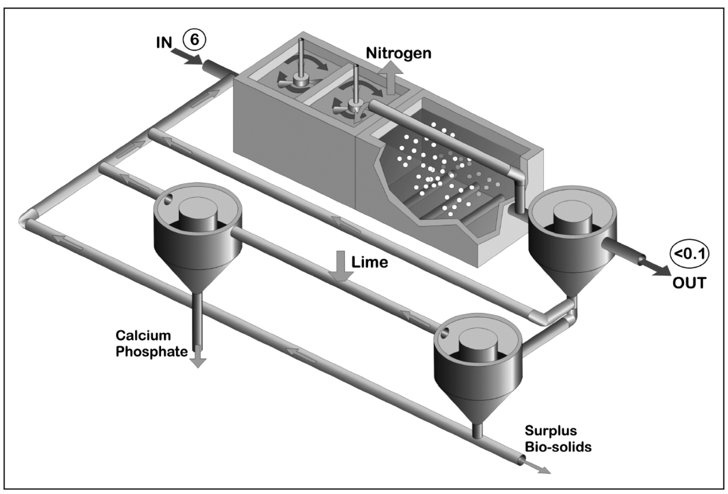

Figure 5. Process for removing nitrogen and recovering phosphorus from wastewater.

When treated in an upflow column with lime, the phosphorus precipitates on small calcium phosphate granules in a form that is readily accessible to plant growth. While the excess biosolids are subjected to anaerobic conditions for releasing phosphorus, acid fermentation takes place to form volatile fatty acids, which are the sole substrate used by phosphorus-accumulating organisms for growth and which then allows them to take up phosphorus from the main stream. One could almost liken this to a sponge that soaks up phosphorus and can then be squeezed to release it as a concentrate.

Recent work at the University of British Columbia has perfected a way of precipitating struvite or magnesium ammonia phosphate from the concentrated stream (Huang et al., 2006). Successful trials at a number of treatment plants have demonstrated the viability and economics of this process. Phosphorus can be released and concentrated in a side stream (as shown in Figure 5) or can be released during anaerobic digestion of the biosolids. Magnesium is taken up in the biological cells during phosphorus uptake and released when phosphorus is released. Ammonia is released in the digestion process and is normally returned to the plant for nitrification and denitrification, consuming energy in the process. With excess ammonia available, magnesium is usually in short supply; more may need to be added for crystal formation. The cost is relatively low because most of the nutrients are present in the side stream from the wastewater treatment plant.

Processes like these are presently operating in Holland, Germany, and Japan, producing substantial amounts of fertilizer. With the potential to remove 5 mg/L of phosphorus from wastewater treated in a 100 million gallons per day (mgd) plant (a typical size for smaller cities), 4,200 tons of superphosphate fertilizer can be produced annually.

Other methods of recovering phosphorus include simply drying the biosolids containing the phosphorus into pellets that could be applied to land. However, this is energy-intensive. Bulk dumping of biosolids on land as a means of disposal and to increase the organic content of the soil has resulted in the application of excess phosphorus to the land. The move to restrict the land application of biosolids has led to large-scale incineration, especially in Europe. Incineration does not destroy phosphorus, which can be extracted from the residue. Matsuo (1996) was able to extract more than 80 percent of the phosphorus from incinerated biological phosphorous (Bio-P) biosolids using water at 86°C. Veeken and Hamelers (1999) used citric acid to elutriate metal salts and between 80 and 90 percent of the phosphorus from sludge, making land application possible without excess phosphorus application, while capturing phosphorus for use where needed.

Composting

An alternative method of recovering phosphorus is to concentrate it in the solids (as above), then compost the solids to destroy pathogens, and apply the compost to land.

The Kelowna Pollution Control Center serves a population of 65,000 and produces 27.5 megaliters per day (ML/day) of wastewater. Placed in service in 1982, the Kelowna treatment plant was the first in Canada and the second in North America to use the new technology of biological nutrient removal that incorporated phosphorus in the biosolids without chemical addition.

The plant produces 13,000 wet metric tons of biosolids each year. The biosolids contain pathogens and require further treatment to make them safe to handle. Composting uses the natural heat generated during aerobic decomposition to kill pathogens, and active decomposition stabilizes the biosolids, transforming them into a valuable, environmentally safe, and economically beneficial resource. The phosphorus from the plant wastewater influent is concentrated into composted material and recycled.

This method of removing nutrients and incorporating them into compost is widely used in western Canada.

Recovery of Nitrogen

The history of nitrogen as a fertilizer is in some ways similar to the future situation facing phosphorus. Before the industrial revolution, animal manure was the main, if not the only, source of both nitrogen and phosphorus as fertilizers. The industrial revolution led to reduced reliance on animals while also contributing to the growth of (especially urban) population.

With many European nations near the point of starving, guano (discovered on the islands off the Pacific coast of South America) was imported and used as fertilizer. After the guano resources were exhausted, only limited supplies of crystalline nitrogen were available and became the cause of wars between Chile and Bolivia (Leigh, 2004).

In 1798, Malthus wrote his historical thesis, *Essay on the Principle of Population,* on the eventual fate of man due to quadratic growth of the population while food production was increasing only linearly. The development of the Haber-Bosch process in the nineteenth century for the industrial fixing of nitrogen and hydrogen atoms to form ammonia saved the world from nitrogen deficiency. The process requires high pressure, high temperature, and metal catalysts using natural gas as feedstock. When natural gas is depleted, a new challenge or price increase may result, and the process may be switched back to using coal gas as the feedstock.

According to Leigh (2004), the secret of how plants and algae fix nitrogen still needs to be discovered. While nitrogen could be "fixed" from the huge reservoir in the atmosphere, there is no such reservoir of phosphorus other than deposits of ore.

Nitrogen can be recovered from wastewater, but the cost of recovery far exceeds that of fixing nitrogen from the atmosphere. Attempts were made more than 30 years ago to remove ammonia and phosphorus by adding lime to the effluent containing ammonia and raising the pH above 11.5. The phosphorus could be precipitated in the form of calcium phosphate (hydroxyapatite) and the ammonia stripped from the liquid in a closed loop reactor and dissolved in sulfuric acid to form ammonia sulfate, which could be recovered. This method was not economically viable and is no longer practiced. However, as mentioned above, some ammonia can be precipitated with phosphorus in struvite at low cost.

The main problem with nitrogen today is not shortage but, rather, overabundance resulting from excessive use of fertilizers, as indicated by the pie chart on Figure 3 showing the contribution to the anoxia in the Gulf of Mexico. Hey et al. (2005) suggested that huge wetlands be created to remove nitrogen from streams such as the Illinois River. Barnard and Andrews (2006) proposed a biological method whereby a source of organic carbon is added for denitrification of the nitrates to nitrogen gas in a way similar to nutrient removal at wastewater treatment plants. This process would require the consumption of ethanol that produces greenhouse gases.

Urine Separation

This revolutionary, yet age-old approach to the control and recovery of nutrients is vigorously promoted by the Stockholm Environment Institution with large exhibits during Stockholm Water Week. Urine contains approximately 70 percent of nitrogen and more than 50 percent of phosphorus and potassium in all household wastewater, while its volume is comparatively small. Using urine-separating toilets, the urine could be "harvested" and used as fertilizer (Kvarnström et al., 2006). Urine is already fairly pathogen-free, but when kept for a few days, its pH increases as a result of hydrolyzation of ammonia, which then contributes to further disinfection.

Urine diversion is a complementary sanitation technology that has been implemented in several countries. Technical and organizational experience gained in Sweden and elsewhere is now applied widely for meeting the Millennium Development Goals of the World Health Organization, especially Goal 7 (See Figure 6).

Figure 6. United Nations Millennium Goals.

A urine-diverting toilet has two outlets and two collection systems: one for urine and one for feces. Other than that, the system consists only of conventional technical construction materials/devices, even though they might be used in completely or partly new ways. The urine-diverting toilets can be either water-flushed or dry-flushed, depending on cultural differences.

There are ways of achieving urine diversion in both rural settings and urban areas. Research and experience show that the systems function in all these different settings, provided that they are properly installed, operated, and maintained. Urine diversion in itself should be seen as a complementary technology, as other wastewater flows (feces fraction, grey water, and storm water) also need to be handled and treated. The fecal fraction will, due to its possibly high content of pathogens, constitute the main hygienic risk. Effective treatment to reduce the pathogen content, combined with safe handling procedures, is of importance to manage health risks.

A new upscale development near Stockholm has installed urine separating toilets with a two-pipe system. The urine is collected in strategically placed basins for use by farmers. The toilets were designed so that, during flushing, a small quantity of water spills over to wash the urine side without substantially increasing the volume. During a visit to such a housing development during Stockholm Water Week in 2005, it was discovered that the owners had no complaints, except that it was necessary for the men to sit down. There is obviously some difficulty in persuading the farmers to use this as fertilizer when the cost of fertilizer is still very low, but some progress is being made (Kvarnstöm et al., 2006).

Source-separated human urine is a complete, well balanced fertilizer with its nutrients readily available to plants. The nitrogen effect was found to be close to that of chemical fertilizer (~90 percent). It varied between 70 percent and more than 100 percent during different years. The phosphorus effect was equal to that of chemical fertilizer (Jönsson, 2001; Johansson et al., 2001).

In developing countries, where a low percentage of people have access to water (not to mention toilets), the concept is more appealing, especially in light of the cost of fertilizers, which is mostly beyond reach for ordinary people. The results of demonstration projects on increasing crop production for the impoverished are astounding and have created great interest in using this technology to increase food production on small plots. According to Kvarnström et al. (2006), urban agriculture in the City of Kampala, Uganda, supplies a substantial percentage of its food. An example of such a garden is shown in Figure 7.

Figure 7. An experimental vegetable garden similar to gardens used in Kampala, Uganda.

One of the main unknowns associated with the use of diluted urine as fertilizer is the fate of pharmaceuticals and endocrine disrupting compounds. The consensus is that they should have less impact when applied to land than to water because of the much longer time available for breakdown by natural decay than provided in a wastewater treatment plant.

A significant source of nutrients in the Chesapeake Bay catchment is the contribution from the septic tanks and tile fields of households that are not connected to municipal sewer systems. The separation and application of urine as fertilizer needs to be promoted in these areas.

A substantial volume of knowledge is available on the subject of urine separation, as well as a great willingness by the population to protect water bodies and reduce carbon footprint. A good start would be to install urine-separating toilets in housing developments around golf courses to supply fertilizer for the fairways. Swedish studies have shown that when the material is applied correctly, it can be quite acceptable.

Use of Algae as Biofuels

According to statistics from the U.S. Department of Energy, 60 billion gallons of petroleum-based diesel fuel and 120 billion gallons of gasoline are consumed annually in the United States. The economic strain on the United States resulting from the $100 to $150 billion spent every year to buy oil from other nations makes the development of alternatives to oil one of the highest priorities.

In the United States, roughly two-thirds of all oil is used primarily for transportation. Developing an alternative means of powering our cars, trucks, and buses would go a long way towards weaning us, and the rest of the world, off oil. While hydrogen is receiving a lot of attention in the media as fuel for automobiles, the best alternative at present, according to Briggs (2004), is biodiesel that can be used without modifying existing diesel engines.

Biodiesel can be produced from vegetable oils or animal fats – even biosolids from wastewater treatment plants. Micro-algae offer the best option for producing biodiesel in quantities sufficient to replace petroleum. While traditional crops can yield around 50 to 150 gallons of biodiesel per acre per year, Briggs (2004) estimates that algae can yield 5,000 to 20,000 gallons per acre per year. Nutrients derived from waste streams, drainage fields, and human and animal wastes are well-balanced for the optimal production of algae.

The Office of Fuels Development, a division of the U.S. Department of Energy, funded the National Renewable Energy Laboratory program known as the "Aquatic Species Program" from 1978 through 1996 (Sheehan et al., 1998). The focus of this program was to investigate high-oil algae that could be grown specifically for the purpose of reducing the emissions of CO_2 from the stacks of power generation plants. Noticing that some algae have very high oil content, the project shifted its focus to growing algae for another purpose – the production of biodiesel fuel.

Some species of algae are ideally suited for biodiesel production because of their high oil content (up to well over 50 percent) and extremely fast growth rates. The research discovered over 300 species of algae that have suitable oil contents. One of the advantages of biofuel is that it fixes CO_2 from the air and could even be used to remove it from the stack emissions.

Algae can be grown in shallow ponds, with perhaps some circulation to ensure the uptake of CO_2 from the air. There are more than 10,000 pond systems in the United States used for treating domestic and industrial wastes. The algae, growing on the nutrients present in the wastewater, supply the oxygen to enable other bacteria to break down wastewater compounds.

Middlebrooks et al. (1974) described several ways of harvesting algae from the ponds, such as centrifugation, microscreening, coagulation and sedimentation, the dissolved aeration process, skimming off the algae, or some other innovative method such as cross-flow screening.

Durand-Chastel (1980) described the long-existing method of cultivating *Spirulina* in Mexico as a food source with great health benefits. He described the culture of the alga *Dunaliella* as a potential raw material for glycerol in semi-saline waters, such as around the Dead Sea in Israel, and predicted that, by the year 2020, 30 percent of petrochemicals will be obtained from agricultural products.

Pretorius and Hensman (1984) described a method of selecting desirable algae for cultivation. He used a mechanically circulated looped pond with a retention time of 10 days. For each unit volume of liquid added to the pond, a similar volume is removed and passed through a 200 micrometer (μm) cross-flow screen. Algae retained on the screen are recycled into the pond while those that pass through the screen are washed out. Eventually, through this selection process, only the algae that can be retained on the screens will grow in the ponds. Pretorius retained a culture of *Stigeoclonium* in the pond. The surplus production could be removed mechanically and compressed to 20 percent solids content. It is not clear whether this strain of algae had a high oil content, since the work was not related to biofuel production, but it demonstrates how algae could be grown and harvested. Pretorius also developed a system for growing high-rate activated sludge biosolids that could be harvested in a similar way to produce protein for animal fodder.

Growing biomass on the scale required for the production of biofuels will entail massive use of plant nutrients, so why not look at nutrients that are presently waste products that must be removed from many rivers and streams?

The bar chart on Figure 8 shows an increase in nitrogen and phosphorus in the Illinois River at Valley City. The Illinois River contributes to the anoxia problems in the Gulf of Mexico. The U.S. Geological Survey National Water Quality Assessment (NAWQA) Program of the highly-agricultural Lower Illinois River Basin (LIRB) concluded that nitrate concentrations in this basin were among the highest in the country. Agriculture is the predominant land use in the area (typically, corn and soybean row crops). It accounts for the use of 88 percent of the overall land, whereas forests account for 7 percent and urban areas about 2 percent. The remaining land, about 3 percent, is mostly grassland, wetlands, and water (Groschen et al., 2000). The annual discharge of nitrogen in the

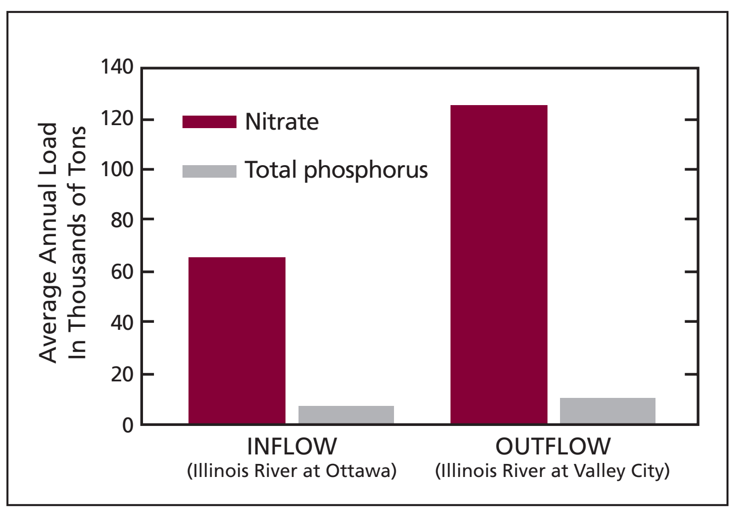

Figure 8. The loads for the upper Illinois River Basin upstream from Ottawa are about one-half of the respective loads for the lower Illinois River Basin.

Illinois River, mostly in the form of nitrate nitrogen, was estimated at around 120,000 metric tons, and the discharge of phosphorus at around 10,000 metric tons.

Hey et al. (2005) suggested that farmers in the Mississippi flood plain be paid for turning their farms into wetlands to reduce the discharges of nitrates. Barnard and Andrews (2006) suggested that a small-footprint biological process with ethanol as feed be used as a complementary process to reduce nitrates. However, this process would produce (rather than reduce) CO_2.

It can be expected that every piece of land in the areas now contributing nutrients to the Gulf Anoxia will be planted with crops for producing ethanol, thus increasing (rather than decreasing) the discharge of nutrients, in an effort to produce biofuel to replace petroleum-based fuel. It is suggested that, instead, most of the farms in the lower flood plains be converted to ponds for using the nutrients already contained in the main rivers to propagate algae for conversion to biodiesel. Processing the algae will release a large portion of the nutrients that could be used again to grow more algae, making this a very sustainable process for producing fuel. With all these preconditions, the cost of producing the algae will be very low, since all the energy comes from the sun.

In addition, if the runoff from farms and feedlots (which contributes more nitrogen to the Gulf than all the urban areas) could be collected and treated through bacterial breakdown and algae production in scientifically designed pond systems, a secondary industry for fuel production could eliminate another large source of nutrients to the Gulf.

In existing pond systems for the treatment of domestic wastewater, the algae-rich biosolids that are captured need further treatment. In some instances, the removed algae are returned to the anaerobic section of the pond system to undergo anaerobic digestion with the release of methane, a highly active greenhouse gas.

Meiring (1992) and Meiring and Ollerman (1995) proposed an elemental system for upgrading algae-rich ponds in the Petro process, which in its simplest form consists of a series of ponds, the first being anaerobic, allowing for the sedimentation and digestion of solid organic matter, and followed by more ponds for abundant growth of algae. The ponds are followed by a bed of rocks or plastic media with sprinklers to distribute pond effluent over the media. About 20 percent of the flow from the anaerobic pond is then mixed with the algae pond effluent. The readily biodegradable substance in the anaerobic pond effluent provides a bacterial layer on the filter media, which traps the algae in the effluent very efficiently. The attached algae change their energy supply from phototrophic to chemotrophic and help in the purification process. The excess biosolids mixture sloughs off from the media and can be settled and used for the production of biofuels.

The method proposed by Meiring (1992) and Meiring and Ollerman (1995) was used to upgrade the large pond treatment system on the Werribee Farm, treating 480,000 cubic meters per day (m^3/d) of wastewater from the City of Melbourne, Australia. In this case, the captured algae were returned to covered anaerobic ponds, where they were fermented to produce methane gas (which, in turn, was used to generate power). During fermentation, the nitrogen is again released to the liquid phase, where it stimulates algae growth in the following ponds. The follow-up activated sludge process includes a step for converting nitrogen in the effluent to nitrogen gas while capturing the solids.

"As a result of the upgrade, a large supply of high-quality recycled water can be used for agricultural, horticultural, and other applications. The upgrade is also opening up opportunities for renewable energy generation and new agricultural land uses at the plant. The Victorian Coastal Award for Excellence 2006 in Water Quality was awarded to Melbourne Water in recognition of the environmental improvements achieved through the upgrade. The award recognizes excellence in developing, adopting, or implementing practices that have improved water quality in the marine environment" (Melbourne Water website).

Water Recovery and Reuse

The reuse of treated effluent should be the ultimate goal in preventing eutrophication, since it implies resource recovery. Water recovery for potable purposes remains an emotional issue even though the technology exists today in its most naked and direct form in the space station. In its most natural form, rainwater is nature's way of recycling. In almost any inland city, some portion of the water in use passed through the sewers of another city. Today, we can imitate nature and produce recycled water of the same purity as that falling from the heavens. The greater the need for water, the more people are willing to accept water reuse.

Whether one believes in global warming or not, the issue facing us in the engineering field is that, for whatever reason, we are in a warming trend that cannot be ignored when planning for the immediate future.

What is interesting in the graph on Figure 9 is that before the increase in CO_2 dating from the industrial revolution, the CO_2 concentration in the atmosphere was higher than at any time before, yet the average temperature of the Earth was lower than during previous times and fluctuated markedly. In fact, the last mini ice age started during this period, which coincided with the reign of Mary Queen of Scots and Elizabeth I. What cannot be disputed, however, is that according to information supplied by the National Academy of Science, the temperature of the Earth has been rising at an accelerated pace since the last mini ice age to the present. In Australia, the flow in rivers has been declining for more than 30 years, and the trend has not bottomed out yet. Whether or not one believes that global warming is temporary, we cannot build sound engineering on beliefs, but rather on observed trends, and those trends show drought to be an issue in many places on Earth.

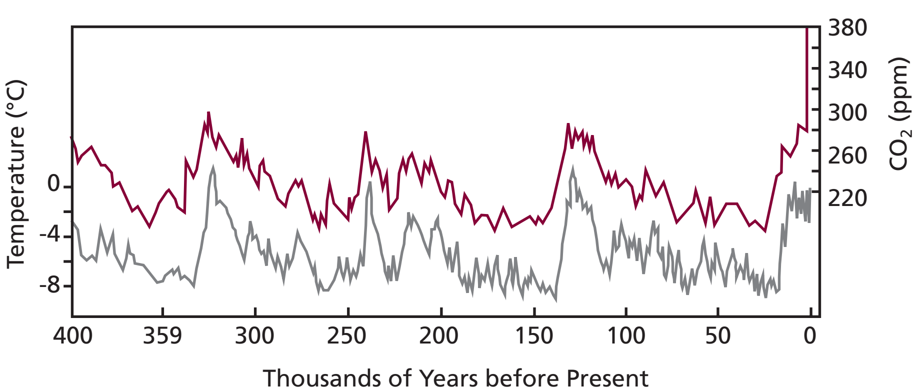

Figure 9. Global temperature and CO_2 levels in the atmosphere (Fedorov et al., 2006).

The issue of water reclamation for potable use is complex, and a recent book (2007) compiled by Professor Takashi Asano, a recipient of the Stockholm Water Prize, covers more than just the narrow subject of this paper of water reclamation as a means to reduce the effect of nutrients on the environment. It was the vision of the late Dr. Gerry Stander, during pilot work for the much-hailed reclamation scheme for the City of Windhoek in Namibia, that all wastewater treatment plants should be turned into water reclamation plants to lessen the impact of nutrients on receiving waters.

This scheme is already being implemented in many cities in the United States, such as St. Petersburg, Florida, where 100 percent of the treated effluent is reused for watering parks and golf courses or for deep-well injection. Other examples are Phoenix, Arizona, where satellite treatment plants extract wastewater from major sewer lines and treat it to very high standards for irrigation of parks, lawns, and golf courses. The City of El Paso, Texas, also has an extensive recycling program for nonpotable reuse. In this way, most of the nutrients in the effluent are applied to land and reused. All equipment used to convey and distribute reclaimed water for nonpotable use, including the pipes themselves, have a very noticeable purple color to limit accidental cross connections. These purple-colored appliances are becoming a common sight at many wastewater treatment plants.

Long-term planning to ensure the integrity of a country's water supply is essential. In Australia, the government is aiming to reduce daily per capita water consumption to around 150 liters per person (L/person). This number could be compared with the United States average of around 400 L/person and that for the City of Vancouver in British Columbia of 800 L/person per day. In New York City, the average per capita water consumption was reduced by 20 percent over a period of 15 years through subsidies program by replacing the old system of toilet flushing, using around 16 liters per flush (L/flush), with a system using 1 L/flush.

Shower heads in apartment buildings were also replaced with fine-spray, low-volume units. The resulting savings in water consumption had the beneficial effect of freeing up space in the 14 wastewater treatment plants of the City to implement biological nitrogen removal for reducing the discharge of nitrogen to Long Island Sound.

As another example of long-term planning, the government of South Africa has used tax credits to entice all industries producing a high-salinity effluent, such as textile industries, to move their production facilities to the coast. Due to the high concentration of the population in the interior of a water-scarce country, a high percentage of reuse takes place naturally and the buildup of salinity has become a major problem.

Concluding Remarks

During the negotiations for political change in South Africa, Clem Sunter, Chairman of the Anglo American Chairman's Fund of Johannesburg, South Africa, described the political situation with these words, "The future is not what is used to be" (Illbury and Sunter, 2005). This is even truer of the water situation around the world. We need new visions, paradigm shifts, and young professionals at a time when we see an alarming decline in the number of graduates at our universities. To improve (or even just maintain) the quality of receiving reservoirs, estuaries, and bays, we need massive investments in sustainable solutions. Resource recovery and water reclamation to hitherto unthinkable proportions must be considered.

Thanks

In accepting the Athalie Richardson Irvine Clarke Prize, I would like to first thank the Irvine Family, represented by Mrs. Joan Irvine Smith, for their vision and interest in the quality of water, one of our most precious resources, and in setting up NWRI and this prestigious prize. Also, I would like to express my great appreciation to the Clarke Prize Executive Committee who considered me worthy of this great honor and to the staff of NWRI, who worked hard to make this such a wonderful event.

One of the defining moments in my life was when I met my friend and former partner, Pieter Meiring, who first taught me the basics of wastewater treatment and who became an advisor when I applied to study in the United States. He then persuaded the City of Johannesburg to construct the first of three 60-mgd biological nutrient removal facilities based on the first results of the laboratory-scale treatment plant. He became my partner and supporter in further endeavors and canvassed in support of previous awards. Pieter was truly a giant silent force who spearheaded the transition from theory to practice.

My thanks go also to my professors at the University of Texas and at Vanderbilt University, Professors Gloyna and Malina, and especially to my advisor, the legendary Professor Wesley Eckenfelder, a man who instilled confidence and taught me to think outside of the box. He taught me to look at the bigger picture. He was also my only professor who allowed me to win at both squash and also at a technical argument.

I also highly value my long friendship with Professor Perry McCarty, first of all for his outstanding book (which has probably passed through the hands of every graduate student in sanitary engineering of the past and many of the present), and secondly for coming to South Africa at a crucial time and leaving some ideas about nitrate reduction that started me off in the right direction.

Many thanks also to my present employer, Black & Veatch, where I am spending the best years of my life as a Global Practice and Technology Leader, working with outstanding colleagues. The only downside is that they will not allow me to retire.

And, finally, thanks also to my biggest supporter – and critic – my wife, Maryna, who stood by my side through adversity and hardship, pulling up the tent pegs and coming with me to the University of Texas at a time when most of our friends were settling down and buying homes. I also thank my daughter, Yvette, my pride and joy, who came all the way from Cape Town for this ceremony. Every Sunday, she would go with me to the pilot plant where I made the discovery of biological phosphorus removal.

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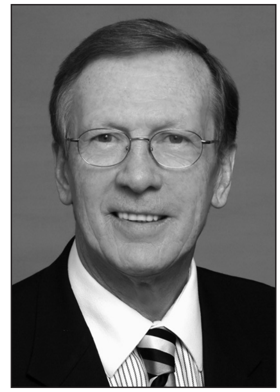
The 2007 Clarke Prize Honoree

JAMES L. BARNARD, PH.D., PR.ENG., BCEE



For over 40 years, Dr. James L. Barnard has traveled the world researching and implementing better ways to conserve water resources and improve wastewater treatment. His groundbreaking application of bacteria to remove both nitrogen and phosphorous from water revolutionized wastewater treatment processes, allowing treatment plants to employ Barnard's biological nutrient removal (BNR) as a more economic and environmentally friendly alternative to traditional chemical treatment. By enabling nutrient removal with a natural biological process, BNR makes it possible to return treated wastewater to receiving waters (such as rivers and oceans) with minimal detrimental impact to environmental quality.

Deemed "the Father of BNR," Barnard not only created the process, but also actively designs and supervises the construction and start-up of BNR systems in various parts of the world, constantly adapting his innovative technology to varying climates, existing infrastructure, and environmental pressures. Another of Barnard's most notable achievements includes his 10-year service on the Nitrogen Technical Advisory Panel for the New York City Department of Environmental Protection, where he helped guide a $50 million BNR research and development program for the Upper East River and Jamaica Bay areas.

Barnard received a Ph.D. in Environmental Engineering and Water Resources from Vanderbilt University in Tennessee, an M.S. in Environmental Health Engineering from the University of Texas at Austin, a B.Sc. in Engineering from the University of Pretoria in South Africa, and both a B.Sc. and B.Ing, in Civil Engineering from the University of Stellenbosch in South Africa. At present, he serves as a Global Practice and Technology Leader for Advanced Biological Treatment at Black & Veatch Corporation in Kansas City, Missouri.

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