THE ACTIVATED SLUDGE PROCESS IN SERVICE OF HUMANITY

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ABSTRACT

In a recent National Geographic book on a thousand events that shaped the world, mention was made of Dr. John Snow removing the handle of the Broad Street pump in London which stopped the Cholera epidemic that resulted from leaking cesspools. His actions led to disinfection of water. What was missing from the book was the discovery of the activated sludge process in 1914 which has had an equally profound effect on human health. For 100 years we have had the benefit of the process for producing safe effluent from wastewater (used water) with emphasis on the growing need for its direct or indirect use. This paper will discuss the drivers that sustained the development of the process over the last 100 years and probably well into the future. With the diversity in climate, geography, population concentrations and future agricultural needs, activated sludge in various forms will continue to be the backbone of global efforts to maintain the planet as a fit habitat for generations to come. The history of the process is a lesson in sustainability.

INTRODUCTION

In the early 20th century used water was considered a resource and all the efforts of treatment was aimed at making the effluent safe for agricultural use due to its fertilizer value especially that of nitrogen which was in desperately short supply. The pressure on resources of nitrogen fertilizers towards the end of the 19th and the beginning of the 20th century led to an emphasis on the reuse of the nitrogen in treated used water effluent. In parallel the shortage of nitrogen fertilizer in Germany led to the discovery of the Haber-Bosch process in 1913, mainly for strategic reasons. At present the recovery of nitrogen is deemed less urgent than that of phosphorus thanks to the Haber-Bosch process that fixes nitrogen from the air even though the carbon footprint of this industry is large due to the use of 1 to 2% of all the energy generated in the world and an equal percentage of natural gas. After the discovery of the activated sludge process, nitrogen in the treated used-water effluent was seen as an asset but the concern about it causing eutrophication in receiving water many years later inspired efforts to remove nitrogen in the treatment process. The removal of phosphorus followed for the same reasons but the emphasis has now shifted to the recovery of phosphorus due to the limits of supply.

HISTORICAL BAKGROUND

When villages were small and farming a major means of employment, most of the human waste was returned to land and together with the use of animal manure sustained agriculture. As the cities grew larger, cesspools were constructed but soon these were filled up and overflowed to the nearest water course at best and at worst seeped into the groundwater supplies or into the streets while much excrement and solid waste was dumped into the streets and squares where rain would wash it into the nearest stream. Towards the end of the 19th century, rivers in Europe were mostly septic, producing hydrogen sulphides that resulted in deaths as recorded in newspapers at the time of the grim reaper (Figure 1). In Germany the intent to clean up rivers is given in a decree issued in 1888: “The permissible degree of pollution is to be measured in a way that unmistakable signs of stinking rottenness have to be absent even at the lowest level of the river water and the highest heat of summer”

The Great Stink of 1858 when high temperatures created septic conditions in the Thames River that drove the members of parliament out of their chambers in Westminster and finally brought action from the legislature which resulted in the construction of massive interceptor sewers –

engineering marvels at the time – to convey the waste to “sewage farms” for irrigation and the use of the nutrients to grow food. This came at a time when the supply of nitrogen fertilizer became critical and the world faced starvation. Many companies were formed to exploit this source of fertilizer due to the value for agriculture and feeding the growing population of the cities. However, the formation of slime layers and the clogging of the drainage in addition to health hazards led to looking at ways to make treated effluent safer, less obnoxious and amenable to irrigation. In addition some of the cleaner effluent would flow back to the rivers and estuaries.

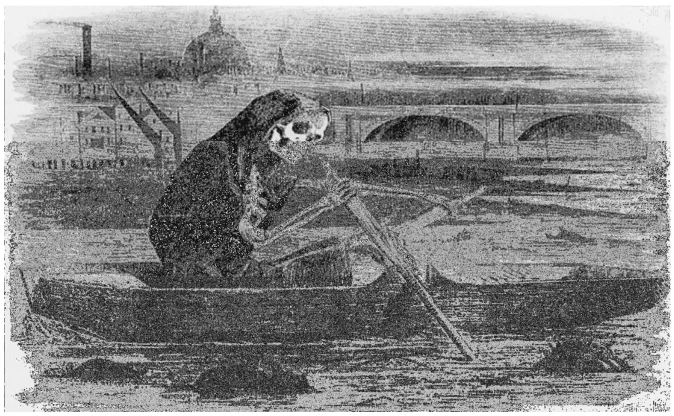

Figure 1. Satirical Cartoon from Punch Journal (1858) with the title “The silent highway man” (Föhl and Hamm 1985[1]).

The driving force at this point which led to the formation of a number of Sewage Companies was to develop of process that could render the effluent safe for irrigation so that the nutrient value could be realised. Various early efforts to render the used-water safe by aeration failed. The discovery of the trickling filters in the early 20th century was a step to achieving this goal. With the advance of biological sciences and the microscope it appeared that benevolent organisms would grow on river stones as slime layers which assisted in purification of water. In trickling filters the slime layers were growing on solid media with the contaminated liquid passing over it in the presence of oxygen. It was recognized at the time that the slime layers contained numerous beneficial organisms that consumed the organic matter and broke it down to simpler forms in the presence of oxygen. At the time the degree of conversion of ammonia to nitrates was considered a measure of the removal of putrescibility from the effluent. Another version was the fill-and-draw basins in which slates were stacked in a basin with large passages for air and liquid between the stone media. Slime layers were formed on the stone media and when filled the organisms were in contact with the organic matter which they adsorbed and during the emptying cycle, air was sucked in to supply the oxygen required by the organisms. Parallel efforts of simply aerating the used water were considered less successful in that it took a considerable time to achieve stabilisation. It was recognized that a way must be found to retain the organisms in contact with “fresh sewage” either on a continuous or on a batch basis.

It was against this background that Arden & Lockett [2,3] made the “bombshell discovery” as described at the time by Fowler (Record of discussions) of retaining the biologically active sludge to treat the next batch of used water. In the light of the emphasis on nutrient recovery it is telling that the research was funded by the Worshipful Company of Grocers. The details of the discovery have been described in the papers by Arden and Lockett and numerous other papers over the course of a century. Some excellent publications describing these early years are by Alleman & Prakham [4] and Stensel & Makina [5]. It needs to be said that Fowler paid a visit to the Lawrence Massachusetts in 1913 and noted in the discussions of the paper be Arden & Lockett [2] “It is only right to admit that the illuminating idea which originated the work was really due to a visit he had paid while in the US, to the Mecca of sewage purification, namely the experimental station at Lawrence in the State of Massachusetts, where he saw the bottle, described in this paper, in which sewage had been completely purified by 24 hours aeration.”

In their second paper, Arden & Lockett [3] described the operation of a pilot plant consisting of batch reactors in which the used-water was added to the residue from decanting clear liquid off the settled slime flocs, then aerating this mixture of “old” solids with “fresh” used-water for some hours before allowing it to settle again and decanting the treated water. They called this process “activated sludge” as a way to describe activity of the retained sludge for oxidation of organic substances and ammonia in a new batch of used-water. The activated sludge process consists of 5 basic functions: (1) suspension of a flocculent slurry of microorganisms by mixing and/or aeration, (2) oxidation of soluble and particulate organic matter with oxygen or nitrate/nitrite to produce gaseous products and additional biomass, (3) liquid–solids separation to produce a treated effluent with a low TSS concentration, (4) return of solids from the liquid-solids separation zone to the suspended growth treatment reactor or the retention of the solids in the treatment reactor during effluent separation and removal, and (5) wasting of excess sludge to maintain a desired mass of solids. The mass sludge under aeration divided by the mass of surplus sludge wasted per day was referred to as the “sludge age” or later the solids retention time (SRT).

Arden & Lockett [3] were also mystified by the disappearance of nitrogen in the process which as a consequence, would then not be available as fertilizer. They also noticed the formation of granular activated sludge in the pilot plant and remarked on the exceptional amount of phosphorus in the remaining surplus sludge. While not aware of the impact it would have on later practice they did record simultaneous nitrification and denitrification of ammonia and excess biological phosphorus removal. The mystery of nitrogen removal in the process was still discussed in later papers. Buswell [6] reported on a study of efforts to find the reason for the missing nitrogen but it was gradually accepted that it was lost as nitrogen through the bacterial action. Surprisingly, there was a comment in the paper that when nitrite is contacted with ammonia, it is reduced to nitrogen gas. That could have been an observation of the Anammox process.

A testimony to the acceptance of the activated sludge process by the scientific community is well recorded by Porter [7] who compiled a summary of more than 600 papers on activated sludge which is available from Cornell University Library website
http://www.archive.org/details/cu31924005016419

EXPLOITATION OF THE ACTIVATED SLUDGE PROCESS AND MINIMIZING COST

The discovery of the industrial Haber-Bosch process for the synthesizing ammonia from nitrogen and methane gas moved the emphasis for the activated sludge process away from ammonia recovery to pollution control. There was an explosion of construction of activated sludge plants over the world but more so in the USA and the emphasis was on reducing cost and energy. Arden & Lockett [2] considered full nitrification as a sign of stable operation which was probably influenced by trickling filters experiences. Buswell & Long [8] showed that plants could be operated safely at a shorter retention time removing BOD without nitrification which then became the norm for design of high rate plants. In many plants constructed then, nitrification was considered as a nuisance since it increased the energy consumption and resulted in denitrification in the final clarifiers. The explosion of activated sludge plants was somewhat muted by patent issues arising from England demanding a steep payment for using the process. This led to the shut-down of many plants and switching to trickling filters while some authorities like Chicago and Milwaukee decided to challenge this in court but lost. Also from the beginning, the production of surplus sludge posed a disposal problem. By 1926 the City of Milwaukee decided to dry, sterilize and bag their surplus bio-mass and market it as Milorganite, a soil conditioner with high nitrogen fertilizer value. This was done in part to generate revenue to pay the levies demanded by the patent holders but proved so successful that it is used to this day. Most surplus sludge was land applied with some nutrient value or simply dumped into the ocean.

The interest in the activated sludge process was demonstrated by the publication of a 400 page book by Arthur Martin in 1927, called simply “The Activated Sludge Process”. Howson [9] read a paper to the Institution of the Chemical Engineers in London titled “Sewage Treatment in America” in 1933 and noted that activated sludge systems achieved 85 to 95% BOD removal (similar to today). While he stated that sewage treatment was still in its infancy with many large cities situated on large water bodies such as New York, still relying mainly on dilution, his description of the development of the activated sludge process and associated unit processes such as screening, sedimentation and digestion, were remarkable. Howson also commented on the fact that even though the primary reason for construction of large plants discharging to large bodies of water or large rivers was to remove nuisance there may be concern about the effluents discharged to water bodies that became the drinking water supply for cities lower down. The 1930s experienced a surge in used-water treatment plants in the USA as a result of stimulus money from the Great Depression. Amongst these were New York (8 m^3/s), Providence RI (2.5 m^3/s), Cleveland OH (5 m^3/s) and Chicago (9 m^3/s). Interestingly, the latter has since been expanded to 36 m^3/s without any basic changes to the design and still produces a very high quality effluent.

With steady growth through the 1940s a slow movement towards nitrification took place in specific locations due to ammonia toxicity and the reduction in dissolved oxygen (DO) downstream as a result of the oxidation of ammonia, leading to problems for migrating fish. The activated sludge process again filled this role and advances followed, leading to a better understanding of the mechanism and the role of the solids retention time (SRT) in nitrification. Since nitrification was part of the original process developed by Arden & Lockett, they already noted the need for a longer retention time required because of the slower growth rate of nitrifiers, the effect of nitrification on alkalinity and the effect of temperature and pH on the growth rate of nitrifiers. Buswell & Long [8] reported on the higher oxygen supply needed for nitrification. A more rational design approach related to nitrification kinetics and SRT requirements will only be developed later by Downing *et al*. [10]. Better understanding of the effect of inhibition and the control of industrial discharges by Downing *et al*, [11], followed

EUTROPHICATION AND WATER RE-USE

It is interesting to note that indirect re-use was already considered an issue in 1933. A case can be made that indirect water re-use has for the longest part of a century been one of the main drivers for improved used water treatment and its importance are increasing. This was more apparent on some locations than others. Chicago is a prime example where wastewater effluent polluted the drinking water supply in Lake Michigan. Fortunately for them it was possible to dig a channel to discharge to the Mississippi River system but there was already some concern over the discharge from cities higher up on Lake Michigan, such as Milwaukee that did not have this option. Other examples are the Ruhr catchment which saw an explosion of industry and population from the beginning of the 20th century in a minor river valley, leading to the need to form the Ruhrverband to control water use from and release to the river in a sustainable way. The activated sludge process became an active instrument in managing the water use in the catchment. It is not surprising that used water treatment was and remains today a high priority in the Netherlands who were at the receiving end of many polluted rivers such as the Rhine, Niers and Maas that originated in other countries.

Due to the situation of the Pretoria- Johannesburg-Vereeniging (now Gauteng) on the continental divide in South Africa with the main water supply reservoirs downstream of the conurbation, indirect re-use steadily increased over the course of a century and an ammonia standard of around 80% reduction, was promulgated in 1954. In the same decade all industries producing effluents with high salinity which could not be removed by biological processes, were encouraged to move to cities near the coast. Cities like Windhoek, Namibia and Harare, Zimbabwe were also situated in the catchment of their main reservoirs.

Eutrophication

Eutrophication manifested itself in many parts of the world resulting from the discharge of nutrients, mainly nitrogen and phosphorus from agricultural run-off and from used-water treatment plants. In many instances eutrophication was part of the problems associated with indirect re-use of effluent from used-water treatment plants. By the 1960s it appeared more often that animals died from drinking water from reservoirs infested with Cyanobacteria (blue-green algae) in South Africa. In some locations where the receiving body did not serve as a water supply, it resulted in unsightly thick slime layers and fish-kills. The deteriorating conditions in the Great Lakes between Canada and the USA caused great concern. After an outbreak of algae in Qingdao, China, the on-line ChinaDaily reported on August 4, 2014 that 22 000 metric tons of algae were removed from the bay by 230 fishing boats a week before the picture in Figure 2 was taken.

Figure 2 Bathers in algae bloom at coastline near Qingdao, China

When used-water was collected and diverted from Lake Washington in Seattle, full recovery of the lake within 4 years demonstrated the advantage of removing nutrients from the Lake. Work by Vollenwieder [12] and others showed the phosphorus was the limiting nutrient for inland lakes and reservoirs while nitrogen was the limiting nutrient in bays and estuaries. This work of Vollenweider led to an agreement between Canada and the USA to remove P from discharges to the Great Lakes (Great Lakes Water Quality Agreement, 1972). It was fortunate that chemicals such as ferric salts and alum could be added to the activated sludge process to precipitate phosphorus with no detriment to the biological process. Widespread addition of chemicals to the activated sludge process followed to precipitate P and remov it with the waste sludge. At the time of writing this paper, there were news headlines in the USA about toxicity in the potable water supply of the City of Toledo which gets water from Lake Erie resulting in the loss of potable supply to 400,000 inhabitants. In spite of removal of phosphorus to less than 1 mg/L the agricultural runoff ensured that eutrophication is still a problem. An imbalance in the phosphorus to nitrogen ratio resulted in a shortage of nitrogen which caused a bloom of Cyanobacteria that can fix nitrogen from the air but also produce Microcystis which attacks the liver of humans and animals.

ADVANCES IN NITROGEN REMOVAL IN THE ACTIVATED SLUDGE PROCESS

The history of biological nitrogen removal is well documented since the first observations in 1891 of nitrification and denitrification in soil by Winogradsky [13]. Arden & Lockett [3] very likely had simultaneous nitrification and denitrification (SND) based on their reported inexplicable loss of nitrogen in a batch reactor. Later, nitrification was considered as an unnecessary expense and for decades the emphasis was on high rate plants that did not remove ammonia, culminating in the development of high rate BOD removal processes in New York City during the 1940s (Gould, [14]; Setter and Edwards [15]) in Germany in the 1970s (Böhnke, [16]), and the use of high purity oxygen in the U.S. in the 1970s to further reduce the treatment plant footprint (Kalinski, [17]). However the need for nitrogen removal became more pressing with the observations of eutrophication and the effect on receiving water bodies that served as water supply (indirect re-use). Design for nitrification was rationalised by Downing *et al.* [10] based on the growth rate of the autotrophic organisms responsible for converting ammonia into nitrites and nitrates. By the 1960s the focus moved to denitrification by adding another activated sludge or attached growth system process after the nitrification stage to which methanol was added as a carbon source for denitrification (Barth et al., [18]; McCarty et al, [19]). The development of channel systems and the revival of Sequencing Batch Reactors nitrogen loss was reported through SND (Matsche, [20]; Irvine & Davis, [21], Irvine & Davis, [22]). Efforts by several researchers such as Ludzack & Ettinger [23], Whurmann [24]; Balakrishnan & Eckenfelder [25]) to accomplish denitrification using the carbon in the used-water led to the development of the Modified Balakrishnan- Eckenfelder (MBE) by Barnard [26], later referred to as the Modified Ludzack- Ettinger (MLE) process, and the four-stage Bardenpho process for removal of nitrogen without addition of external carbon sources. This in turn led to the use of anoxic zones preceding channel system where the combination of denitrification using influent carbon in the anoxic zone and SND in the channel system cum aeration basin, resulted in a very efficient system for removal of nitrogen to very low levels. The main used water treatment plant (UWTP) plant in Vienna Austria treats 18 m^3/s using this strategy (Wandl *et al.* [27]). At the Strass plant in Austria this combination is used in an energy self-sufficient plant by Wett *et al.* [28].

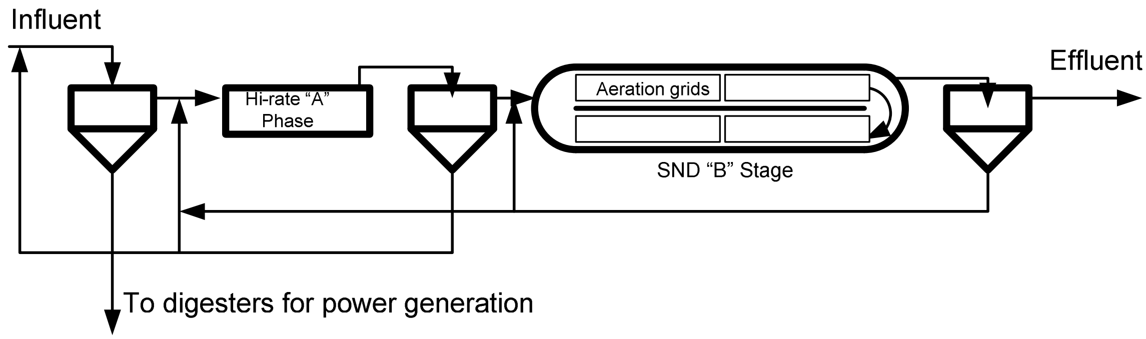

Figure 3 Diagram of Strass, Austria plant with high rate first stage and channel aeration system for SND

ADVANCES IN PHOSPHORUS REMOVAL

Enhanced biological phosphorus removal (EBPR) probably occurred in the SBR pilot used by Arden & Lockett [3] as can be inferred by their satisfaction with the 'exceptionally high' phosphorus content of the surplus sludge. As a result of later observations by Snirath [29], Vacker [30], Yall [31] and Milbury [32] of high phosphorus removal efficiency in high rate plug-flow plants without chemical addition, more attention was paid to a biological removal phenomenon. Milbury noted that all plants showed a pattern of releasing of phosphorus at the inlet end of plug-flow basins. Barnard [33] noticed phosphorus removal in a four-stage nitrification/denitrification plant which coincided with a release of phosphorus in the 2nd anoxic zone to more than 30 mg/L and concluded that an anaerobic first stage followed by nitrification and denitrification could remove nitrogen and phosphorus. Fuhs & Chen [34] attributed biological phosphorus uptake to the selection for phosphate accumulating organisms (PAO) and the biochemistry of the process was later further developed by others Comeau [35] and Wentzel et al. [36]. The PAOs , which are naturally present in activated sludge, required a certain amount of volatile fatty acids (VFA), mostly in the form of acetic or propionic acid, in the feed to remove a fixed amount of phosphorus. Most treatment plants do not have enough VFA in the influent to sustain phosphorus removal which led to the development of fermenters in which primary sludge was passed through a phase of acid fermentation to produce these acids (Rabinowitz and Oldham, [37]). This turned out essential for reliable phosphorus removal. Based on the pilot plant observations where a portion of the mixed liquor was fermented and passed back, more energy efficient fermentation of a portion of the mixed liquor was introduced by Barnard et al [39]

LIMITS OF THE ACTIVATED SLUDGE PROCESS

With sufficient VFA in the influent, EBPR can reliably produce effluent orthophosphates concentrations of less than 0.1 mg/L with average total phosphorus of less than 0.15 mg/L after filtration. Chemical addition in a tertiary stage is required to reduce this to lower levels. The main need of chemicals is for coagulation and precipitation of particulate and colloidal phosphorus. The necessary molar ratio of metal salts to phosphorus to reach less than 0.10 mg/L soluble phosphorus increases rapidly from one to around 10 for achieving less than 0.02 mg/L P which is the practical limit for soluble phosphorus removal due to the nature of the residual species. Given that there will always be some phosphorus from non-point sources in receiving water, the cost of removing phosphorus to levels below 0.04 mg/L should be carefully considered. Bioassay studies by Li and Brett [39] have also shown that at high chemical doses needed to remove phosphorus to below 0.10 mg/L only 20 to 30% is bioavailable for algae growth.

WATER RE-USE AS DRIVER FOR ACTIVATED SLUDGE APPLICATION

Howson [9] already noted in 1933 that re-use of effluent would dictate the process needs for the treatment of used-water. This became more evident as the population rapidly increased since that time and in ever increasing parts of the world the only water available comes from sources to which treated effluent are discharged.

The main reasons for the value of the activated sludge in water re-use processes are

- The ability to remove nitrogen to low levels of inorganic nitrogen
- Discharge of nitrates when required for enhancing the quality of the receiving water
- The ability to remove phosphorus without adding salinity
- The removal of personal care products and endocrine disruptors
- Serving as a buffer and indicator of industrial pollution
- The ability to target specific compounds in industrial waste

Problems with physical-chemical methods to remove nitrogen

During the 1960s, a growing number of researchers suggested alternatives to the activated sludge process due to the perceived instability and unreliability of the process. Independent physical/chemical processes that were proposed raised the pH with lime addition followed by ammonia stripping or ion exchange, breakpoint chlorination (BPC) for disinfection and removal of residual ammonia, followed by activated carbon filtration for removal of remaining organic and chlorinated carbon compounds, sand filtration and a final disinfection step. The main problem was that in warmer climates the formation of fermentation products in sewers was inevitable and short chain volatile fatty acids (SCVFA) are not efficiently removed on activated carbon columns which then served as anaerobic biological reactors. No amount of chlorination could stop this inevitable biological activity since it was established that attached growth bacteria thrived on the readily biodegradable COD in the feed that was not removed by any of the previous processes.

Van Vuuren *et al.*, [40] proposed trickling filters for removal of BOD but used lime addition to high pH for phosphorus removal and ammonia stripping followed by re-carbonation from burning methane for CO_2, sand filters and BPC, followed by activated carbon and final chlorination. This process was constructed as a 5,000 m^3/d demonstration plant in Pretoria and for the initial Windhoek, Namibia Water Reclamation project. Due to the water conservation, the influent TKN in Windhoek used-water ranged from 85 to 120 mg/L and in winter the stripping towers could not reduce this to below 10 to 12 mg/L which then required about 120 mg/L chlorine for removal of the remaining ammonia. The activated carbon filters could not remove all the chlorinated hydrocarbons. During this phase Namibia went through an unusually wet rainy cycle but with the approach of the dry cycle, an activated sludge plant was constructed in a fast-track design (Barnard and Pybus, [41]). After the series of ponds between the used water treatment plant and the water reclamation plant, the effluent total N was consistently below 3 mg/L and water reclamation became possible (van Vuuren [42]). In Windhoek the activated sludge plant also served as a bio-monitor. While all industrial waste was diverted to another catchment, the plant lost nitrification soon after start-up and there was a greenish tint to the influent used-water. There was a chrome-plating plant in the catchment but it was not connected to the domestic used water system. Nevertheless, the industry was given a warning and in the following 40 years another such incident did not occur and effluent ammonia concentration was almost non-detectable. This has established activated sludge as an essential part of water reclamation. While no specific carbon footprint studies were performed, the same activated sludge plant still serves as the most cost and energy efficient way of treating the high BOD and total nitrogen used water and had been incorporated in the recent upgrade of the water re-use plant as reported by Asana et al [43]

Flexibility in controlling nitrogen species discharged

The Upper Occoquan plant discharges to the Occoquan reservoir in Virginia, USA. The reservoir is the water supply for Fairfax Co which is a suburb of Washington D.C. The contribution of the used water plant to the inflow to the reservoir varies from 8% during wet periods to 90% during prolonged droughts (Asano et al, [43]). The treatment train includes activated sludge, lime treatment, recarbonation, filtration, carbon contactors and chlorination. Originally nitrogen removal consisted of high rate activated sludge with ammonia removal through ion exchange. Subsequent studies showed that nitrogen removal was much more efficient and cost-effective by using nitrification and denitrification in the activated sludge process. Quoting from Asano et al [43] "Performance is substantially enhanced by the preceding reliable and high quality secondary treatment". The growth of algae in the reservoir was controlled by phosphorus and reducing the nitrogen too much stimulated the growth of Cyanobacteria. Discharging nitrates improved the quality of the reservoir water by growing green algae and preventing anaerobic conditions in the hypolimnion which could cause the release of ammonia and phosphorus from the sediment. The activated sludge plant is mostly operated without nitrate reduction but has the flexibility to use denitrification when the contribution to the reservoir from the treatment plant exceeds a certain predetermined percentage. (Cubas *et al*. [44]).

Biological phosphorus removal

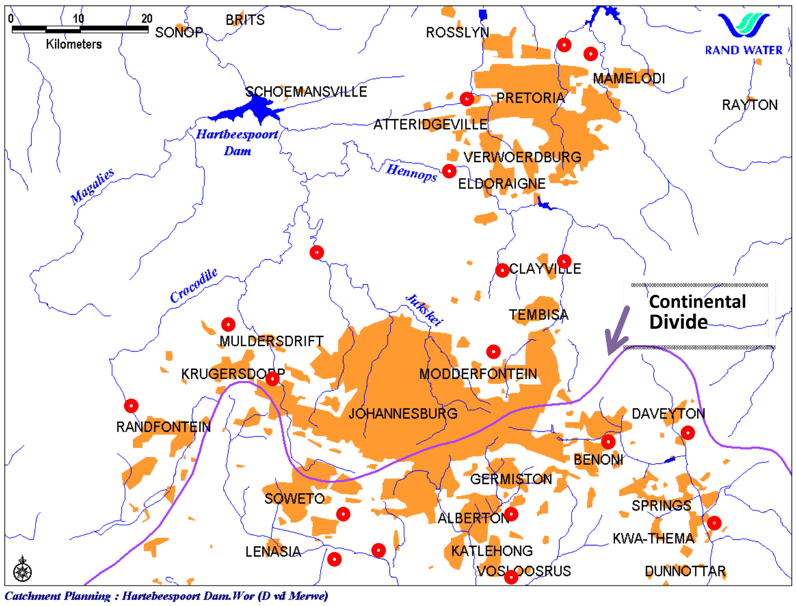

Figure 4 Portion of the Gauteng Conurbation, showing some of the most severely affected reservoirs and most of the BPR plants as red circles

The conurbation around Johannesburg South Africa, now the province of Gauteng with a population of 8 to 10 million, was built on the continental divide between the Indian and Atlantic Oceans. Water is pumped from the main reservoir 300 m below the city to the south and which also received a portion of the treated used-water from that area. Water is also pumped to Pretoria 300m below Johannesburg to the North and used-water treatment plant effluents were discharged to reservoirs which in turn became the water supply for communities further North. Due to the high rate of indirect re-use taking place the salinity of the water supply already exceeded 800 mg/L which was higher than the WHO specification and the addition of chemicals for phosphorus removal could not be considered. At that time all plants, with the exception of one or two small plants consisted of nitrifying trickling filters with very low energy consumption. It was against this background that biological phosphorus removal was discovered in 1974 and immediately put to practice as it did not result in an increase in salinity. Figure 4 shows part of the area with the main supply reservoir off the bottom of the picture. Presently upwards of 40 biological phosphorus removal plants protect the dual purpose reservoirs from severe eutrophication and their impairment as water supply reservoirs. The removal of nitrogen followed as a bonus since there was a requirement for ammonia reduction, denitrification became part of the flow diagram due to the need to save energy through denitrification, recover alkalinity and reduce nitrates so as not to interfere with the phosphorus removal mechanisms.

Removal of Endocrine disrupting chemicals (EDC), Pharmaceuticals and Personal Care Products (PPCP) and

A wide variety of substances from naturally excreted hormones and from the use of pharmaceuticals and personal care products (PPCPs) have been termed micropollutants and are present in used-water at ng/L to ug/L concentrations. Discharge of these compounds to the environment or where direct or indirect water reuse takes place, raises a variety of concerns including their effects on endocrine system. The endocrine system is one of the two main regulatory systems in humans and other organisms. It consists of glands that secrete hormones that act to control body functions, including reproduction, growth, and development. Simply stated, an endocrine disrupter is an exogenous substance that disrupts the function of the endocrine system, affecting the way an organism or its progeny reproduces, grows, or develops. Sexual disruption of fish has been linked to estrogenic substances in treated used-water treatment plant effluent (Purdom *et al*. [45]; Jobling *et al*. [46]; Pickering and Sumpter, [47]). Such effects on wildlife have led to concerns about adverse health consequences in humans, as it is possible that humans can be exposed to EDCs and PPCPs through their drinking water and food. The majority of endocrine-disrupting activity in treatment plant effluent is from anthropogenic estrogen compounds, including synthetic estrogen, 17 α -ethinylestradiol (EE2), and the natural human hormone estrogens, estrone (E1) and 17 β -estradiol (E2). Other EDCs are related to industrial products such as bisphenol A. In addition pharmaceutical and personal care products (PPCPs) pose additional concerns and they are ubiquitous in the environment because of their seemingly endless number of uses and origins in residential, industrial, and agricultural applications.

Research shows that although some PPCPs and EDCs will not be completely removed, greater than 90% biodegradation of many chemicals of concern can be achieved in the activated sludge system with extended solids retention time (SRT). Because of the low concentration of the micropollutants, the bacteria that degrade them must grow on the used-water carbon source. There have been a few instances linking degradation to ammonia-oxidizing bacteria but heterotrophic bacteria account for most of the micropollutant degradation. Because most biological nutrient removal (BNR) plants have long SRTs they are very compatible with micropollutant degradation. A recent study by Ziels et al. [48] showed similar estrogen degradation kinetics for biological phosphorus removal, biological nitrogen removal and aerobic treatment only processes and that oxidation ditch processes may select for more efficient degrading populations. For some micropollutants that are very persistent or if extremely low effluent concentrations are required, higher level removal technology may be needed. Several advanced technologies, such as activated carbon adsorption, ozonation, advanced oxidation processes (AOPs), and nanofiltration/reverse osmosis (NF/RO), have successfully removed micropollutants from activated sludge-treated used water. Most of these technologies, however, are expensive to implement and to operate and would be difficult to implement at many smaller plants discharging to water sources. Optimization of the activated sludge process is a less costly option. Removal of these pollutants from treatment plant effluents may solve much of the apparent endocrine disruption problem in the water environment, in addition to providing a cleaner source for drinking water.

Energy use and recovery

Energy neutrality in treatment plants has become one of the most popular points of discussion in the field of sustainability of the activated sludge. However, widespread claims that energy use for wastewater treatment can be as much as 5% of the total energy consumption of a country are misleading. In some studies, energy used for used-water treatment is included in the overall energy consumption of the water cycle that may differ with location. In one study (Griffiths-Sattenspiel *et al*. [49]) found that the global energy used in the water cycle was 3 to 4% of total energy used but it included pumping raw water, water treatment, distribution, wastewater collection and pumping to the used-water treatment plant and effluent pumping either to irrigation or to deep wells. In addition, water heating in homes which totaled 85% of the energy used in the overall cycle, was included. When quoting the annual cost of energy for treatment of wastewater, the total sums may appear excessive, but when the energy use is compared to overall consumption on a per capita basis, the real perspective is apparent. Figure 5, shows allocation of energy use by 47 wastewater

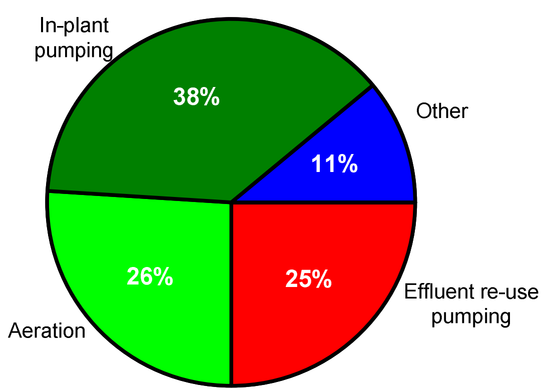

Figure 5 – Average energy use fractions from survey of 47 treatment plants (NACWA Report)

treatment plants using a total of 2.1 billion kWh of electricity, in response to a survey by the US National Association of Clean Water Agencies (NACWA).

The energy consumption of a well-designed and operated BNR plant including the aeration, RAS pumps, mixed liquor recycle pumps and mixers for the USA comes to less than 40 kWh /ca/annum for a plant designed for energy efficiency, without considering possible on-site power generation. The comparative consumption for a number of other functions is shown in Table 1. The fraction of energy used for BNR in this case is 0.4% of the domestic consumption. The per capita energy consumption in developing countries is much lower which would increase this fraction which may require considering other forms of achieving the goals. As discussed before, Namibia could be considered as a developing country but activated sludge was the most cost-effective process for the removal of nitrogen for water reclamation.

Table 1. Per capita use of power

Energy used for	kWh/c/a
BNR wastewater treatment only	40
Average pumping energy for 21 plants	69
Switching one lamp from 100 to 30 W low energy - 4 h/day	102
Pumping water from Missouri River to Kansas City	60
Energy use for pumping water to Southern California	355
Desalination of brackish water	200
Desalination of Seawater	525
Office lights for one person @ 12 hours per day	2 000
Household per person	9 600

The same was true of Zimbabwe where treated used-water effluent was discharged to the water supply. Kroiss & Cao [50] discussed the role of energy in the purification and re-use of effluent and made a strong statement that our first obligation is to focus on getting the best quality of effluent regardless of energy use to achieve that, then focus on energy efficiency. They pointed out that used-water fees must cover the capitol cost and operating cost of the entire collection system and treatment plant construction and operation. From benchmarking information it was established that energy accounts for less than 8 - 10% of the rates paid by the public.

A number of studies aimed at energy self-sufficiency in biological nutrient removal plants (Wett *et al*. [29]) looked at limiting the amount of BOD needed for denitrification. In the Strass plant a very high rate process is used ahead of the activated sludge process to remove a major part of the BOD and direct it to anaerobic digestion to produce methane for power generation. Use is then made of simultaneous nitrification and denitrification (SND) in the activated sludge plant to reduce the carbon requirement for denitrification. Return stream ammonia is then treated by using Anammox bacteria (discussed later) to reduce energy requirement. Siphoning off carbon in the first phase may not need be incompatible with achieving low effluent total nitrogen but the Strass plant discharge up to 6 mg/L TKN at certain times of the day. It may require more energy if effluent ammonia levels needed to be very low. Consistently low effluent ammonia is essential for nitrogen removal for re-use. Wandl et al. [27] pointed out that the main plant for the City of Vienna which uses the same process sequence but will need to add organic carbon if nitrogen removal to lower levels are required. The longer SRT needed and use of the influent carbon to remove the EDCs and PPCPs removal may however, still be possible with plants of this type. However, hese plants still show a substantial reduction in energy consumption.

While membrane bio-reactors (MBR) use about twice the energy of conventional BNR the benefits of producing a high quality effluent and EDC and PPCP removal with the longer SRT may have benefits that outweigh the higher energy cost. It does not appear that high energy cost will in future displace the activated sludge process due to its intrinsic advantages but rather focus on the energy efficiency.

In colder climates such as Winnipeg MB Canada, effluent must be cooled before discharge to frozen rivers. This energy can be recovered from the plant effluent for heating buildings or drying sludge. Steinherr, [51] found that the recoverable energy can be as high as ten times the energy use of the process.

A current WERF study on the reliability and GHG development of various processes for the removal of phosphorus found that for removal to less than 0.1 P mg/L, biological phosphorus removal in the activated sludge process with or without some chemical standby had the lowest overall carbon footprint when compared with only chemical removal. Even removing phosphorus to less than 0.03 mg/L by a combination of biological and chemical processes, only increased the carbon footprint of the plant by about 6%.

Treatment of industrial used water

One of the reasons for proposals to abandon the activated sludge process in the 1960s in favour of physical/chemical treatment was the perception that the process would be upset too readily by slugs of organic chemicals that could upset the process. Abortive attempts to use pure physical/chemical methods led to a re-evaluation of the activated sludge process as a cost-effective and sustainable process which resulted in more intensive research on the treatment of various industrial wastes amenable to breakdown by micro-organisms, such as food and agricultural wastes, many pharmaceutical wastes, refinery and petro-chemical wastes. Many contaminants e.g. phenol that were considered toxic to activated sludge were found to be degradable provided the concentration was not too variable and that the flow and load was equalized. Completely mixed activated sludge is preferred since the bacteria are only exposed to very low concentrations of the chemicals discharged to the plant. These studies also led to trade-waste control regulations requiring pre-treatment of the used-water for the removal at the industry of substances that could inhibit the biological process and to requirements for flow and load balancing to prevent slug loads. This also had the beneficial by-effect of producing bio-solids that were safer for application on land (Hundal *et al*. [52]). Other than for domestic wastewater, the organic compounds in industrial waste may only degrade slowly and may need a longer SRT to ensure low BOD values. Treatability studies may be needed for determining design parameters. Many industrial wastes such as refinery waste lack sufficient phosphorus or nitrogen in the feed to sustain biological life while mostly these nutrients are present on domestic wastewater much in excess of their needs. This makes a good case for co-treatment.

Many highly concentrated organic wastes such as brewery waste or waste from soft drink manufacturers may contain little nutrients but may be amenable to anaerobic breakdown that will produce energy and need only a fraction of the nutrients required by the activated sludge process. However, most such organic waste is polished by using the activated sludge process. Again the versatility of the activated sludge process found a useful application for treating a variety of industrial wastes in a cost-effective manner while reducing energy and GHG emissions.

RESOURCE RECOVERY

There has been a paradigm shift away from seeing used-water as a problem to seeing it as an opportunity for recovering of resources. There are many opportunities at used-water treatment plants for the recovery of resources both in the process itself and especially from industrial waste before discharge to the plant. Whatever organic matter is removed and re-used before entering the treatment plant will reduce the load on the plant and the carbon footprint. The obvious targets are cellulose, high strength soluble waste such as that from soft drink manufactures which could be trucked to used-water plants and used for phosphorus removal or denitrification, and fats, oil and grease which could be co-digested to provide energy. Already most blood produced in abattoirs is recovered as protein.

Protein recovery. Even before the used water reaches the treatment plant there are opportunities for recovering useful products such as protein or urine. Many food processing wastes such as abattoir effluent, dairy waste and even brewery wastes could be used for protein recovery using a process similar to activated sludge. De Villiers [53] produced high protein activated sludge at full-scale from the effluent of an abattoir processing 2 000 cattle unit per day. The biomass had a protein content of between 27 and 37% and was recycled to the protein recovery plant that processed protein for animal feed supplement. Previously the abattoir effluent was discharged to the municipal sewer system for treatment at the centralized treatment plant. A sequencing batch reactor (SBR) process was used that produced recoverable biomass with low sludge volume index and which had a granular appearance. De Villiers estimated that the owner made a profit of $88,000 p.a. on the sale of protein but saved over $1 million in treatment fees. Rather than destroy the proteins in food wastes, it can be recycled and re-used. Protein can also be recovered from pure hydro-carbon wastes, such as beer brewery waste, by adding some nutrients. Protein in the form of algae can also be recovered as animal feed.

Urine recovery contains about 70% of all the nitrogen in used-water effluent and 65% of all the phosphorus. The removal and use of urine in developed countries may not be a significant factor but in many of the developing countries, the cost of fertilizer is already out of the reach of many people and recovering the urine has many advantages. Most of the phosphorus and a large portion of the organic nitrogen compounds are recovered and re-used but it also reduces the energy consumption at the treatment plant and would allow simpler and low energy treatment. In Kampala, Uganda, about half the food consumed in the city is produced in backyard gardens, using urine as fertilizer. With the inevitable rise in the price of phosphorus fertilizer (see discussion below) we may in future see urine separating toilets in high-rise apartment buildings with struvite recovery plants in the basement.

Energy recovery has been discussed above and should be an integral part of any modern plant. The surplus activated sludge is difficult to dewater and on average less than 40% of the volatile suspended solids (VSS) will be reduced. However, the development of thermal hydrolysis of the surplus sludge can increase the degradation to just fewer than 60% allowing more energy recovery as well as dewatering to a higher solids content and having a sterile sludge for land application. (Barnard *et al*. [54])

Water as a resource The resource that is perhaps most important is the treated effluent for direct or indirect re-use. The efficient removal of nutrients as well as most of the PPCP makes the activated sludge process indispensable in the sequence of processes for water re-use. For direct re-use more barriers to the passage of PPCPs and endocrine disruptors will follow the activated sludge process but in the majority of incidents of indirect re-use these barriers are not available and the activated sludge process serve a major function in reducing these compounds.

Ammonia recovery. A century ago the recovery of nitrogen compounds was deemed essential due to the shortage of ammonia fertilizer. This need was less urgent after the discovery in 1913 of the energy intensive Harber-Bosch process. Since there is no shortage of the nitrogen gas as feedstock for this process, the recovery of nitrogenous compounds from used water must be cost-competitive. An ion exchange process using the natural zeolite clinoptilolite, was used at the Upper Occoquan used-water treatment plant in Virginia to remove ammonia produced by a high-rate activated sludge process. Lime was added to raise the pH and remove phosphorus. The ammonia could be recovered after regeneration of the media with NaCl. The process failed after three months and was abandoned, the activated sludge plant operated to produce nitrates which were discharged to the lake where it was found to improve the water quality (Cubas *et al*., 2014). Ammonia have been recovered from return streams after anaerobic digestion but the cost of reducing the ammonia to nitrogen gas through the use of the Anammox process makes the recovery of ammonia even less competitive. See discussion below.

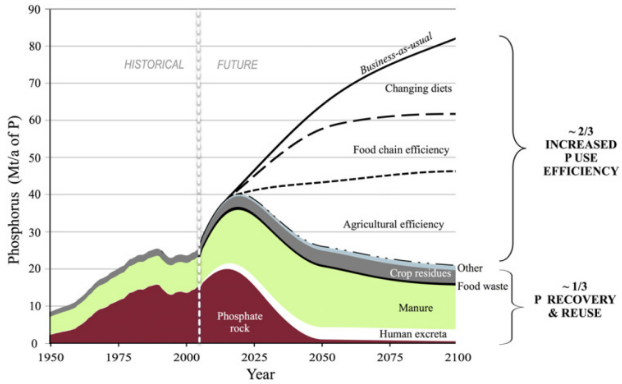

Figure 6 Prediction of future availability of phosphorus, present consumption rates and the need for recovery

Phosphorus recovery. Phosphorus is a limited resource and the rate of mining ore is unsustainable. There are various estimates as to when the world will run out of recoverable phosphorus ore. Figure Xd shows one scenario and the need for recovery of phosphorus not only from UWTPs but also from all agricultural wastes. The picture may not be as simple as that shown in Figure 6 (Cordell et al. [55]) and the available ore may last somewhat longer. However, the richer ore is used up at an unsustainable rate and while the ore supplies may last for a longer time, the cost and energy requirements of the product will rise inexorably due to the need for removing a higher content of impurities. The ability of the activated sludge process to concentrate the phosphorus in the sludge or in the case of incineration of the sludge, in the ash, is well established. The biological removal of phosphorus also renders just under 50% of all the phosphorus in the influent recoverable from the sludge while the remainder will be either taken up in the residual organic matter or precipitated as a metal phosphate in the sludge. After sludge digestion the phosphorus in the return streams could be captured as struvite, a slow release fertilizer much in demand in certain sections of agriculture. About 20% of the ammonia in the return stream will also be recovered in the struvite. After incineration about half of the struvite in the ash will be available to plants. The remainder would need to be recovered by chemical extraction methods. Incinerator ash from EBPR plants should be mono-landfilled if the phosphorus is not recovered immediately. This will make the phosphorus recoverable in future when the prices rise. The goal in many European countries is to recover 70% of the phosphorus in the influent.

Anaerobic pre-treatment of industrial used-water. While the activated sludge process can treat readily biodegradable high-BOD material, the power cost could be offset by using anaerobic pre-treatment. In this case the activated sludge process could be used for post treatment in order to produce an effluent comparable with domestic effluent standards. When treating an effluent with TKN concentration of over 250 mg/L, such as found in abattoir discharges, the anaerobic process may be too efficient in removing BOD needed for denitrification requiring that used water be passed around to an acid fermentation process only to assist denitrification of nitrates to save energy and reduce the need to add alkalinity. On the other hand, individual streams high in ammonia, say above 500 mg/L may be separated and treated on site with Anammox bacteria to effect nitrogen removal at low cost.

Recovery of by-products. Ruiken et al. [56] reported on the recovery of cellulose from toilet paper in used-water. In addition surplus sludge may contain compounds such as alginates (Lin *et a*l, [57]), bio-plastics (Tabakatake *et al.* [58]), polyelectrolytes and surfactants that can be recovered.

Odour control and gas emissions. While there is concern in densely populated areas of the release of gases such as VOCs and other toxins and green-house gases, these concerns are less in more rural settings and in most plants in lessor developed countries. The emission of nitrous oxide, a GHG 300 times more potent than CO_2 is also a concern but recent studies showed that this could be limited by ensuring full nitrification and denitrification in BNR plants (Ahn et al. [59]). However, the activated sludge process could also serve to oxidize offensive odours, reducing the amounts that need to be treated by other methods if necessary. E.g. the foul odours emanating from thermal hydrolysis of sludge prior to digestion or from the inlet works and primary sedimentation tanks can effectively be treated in the activated sludge process. Activated sludge systems are being used for effective treatment of many industrial odours. (Adams [60])

NEW DEVELOPMENTS

Anaerobic ammonium oxidation (Anammox)

Side-stream applications It could be argued that the Anammox process is not strictly an activated sludge process but while it removes no BOD, in a sense it follows the same principle of growing organisms under controlled conditions then retaining these (activated) organisms for intensified treatment. Moreover, use of this process on the return stream after anaerobic digestion reduces the overall energy requirements for converting ammonia to nitrogen gas. The recently discovered, slow growing Anammox bacteria have the characteristic of using an equal amount of nitrites and ammonia to produce nitrogen gas and some nitrates. In this process about half of the ammonia is converted to nitrites by in the outer layers of the Anammox bacteria granules and then the nitrites are reduced to nitrogen gas while the ammonia is converet to nitrogen gas. The sketch in Figure 7 is a presentation by Paques of a possible pathway against the background of the conventional pathway. The Anammox pathway is following the red arrows.

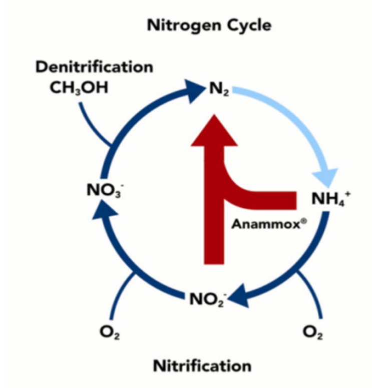

Figure 7- Pathway for reactions of Anammox bacteria and a typical cluster of cells

Oxygen is only required for converting half of the ammonia to nitrites and no carbon is required for denitrification (denitritation) of the nitrites. Initially the nitritation (converting ammonia to nitrates) and the denitritation reactions, took place in separate vessels but a number of processes has been developed which can achieve the full reaction in one basin. These include the upflow granular sludge concept used by Paques, (van der Star *et al.* [61]), DEMON (Wett *et al.* [28]) in which the slow growing granular granules are separated by a cyclone and the AnitaMOX process (Christianson *et al.* [62]) in which the bacteria grow on suspended plastic media retained by sieves in the reactor to which the ammonium is fed. Nitritation takes place in the outer layers of the granules or bacterial layers while the denitritation takes place in deeper layers. Repression of nitrate formation is paramount and achieved by controlling a combination of factors including free ammonia concentration, free nitrous acid concentration, temperature, pH, DO and aerobic SRT.

Main-stream applications. Interest in utilizing Anammox bacteria in the main-stream process was driven by the prospect of energy saving and working towards energy neutrality in plants. Due to their slow growth at lower temperature, the Anammox bacteria would need a means of prolonging the SRT for use in either conventional or granular activated sludge plants. Jetten *et al.* [63] was first to propose the use of this technology in the high rate first stage of the A-B process proposed by Bönke [16]. The B-stage is used for SND. Intensive research is under way to exploit this advantage at a number of plants (Wett *et al.* [28]). Anammox bacteria have already been observed in high rate, high temperature plants in the Singapore Changi UWTP (Cao *et al.* [64]). The main challenge is the stability of nitritation i.e. the repression of the growth of nitrite oxidizing bacteria (NOB). Recent findings by Winkler *et al.*, [65] showed that at low temperature Anammox bacteria can use acetate for the conversion of nitrate into their substrates nitrite and ammonium which would have a positive outcome for the goal of utilizing the energy saving benefits of these organisms.

Granular Activated sludge

The formation of granules in activated sludge is not new and was apparently first observed a century ago by Arden & Lockett [3] in a batch reactor. The phenomenon was also observed by Barnard [26] when operating a high rate contact-stabilization process, achieving a mixed liquor suspended solids (MLSS) of 16 g/L. Earlier papers (Morgenroth *et al*. [66]) pointed to the advantages of selecting for granular sludge. Since it was established that granular sludge will grow naturally under high organic loadings or food to micro-organisms (F/M) ratios, the key to the successful application of this technology was to wash out the less dense and filamentous bacteria, leaving mainly granules with diameter from 1 to 3 mm which settled rapidly. Lee *et al*., [67] achieved SND and 100% phosphorus removal in a batch reactor when growing granular sludge. Giesen *et al*. [68] describe the more recent developments of the Nereda™ process, which is a modification of the SBR process, stating that about 40 plants are either under construction or in use at this time. The process relies on a high F/M selection for the formation of granular sludge and consists of SBRs in which the influent is discharged evenly into the settled sludge blanket during the decant phase while pushing the clear supernatant through stationary launders at the top. The concept of feeding during the decant phase has also been used in the 11 m^3/s SBR plant at Ringsend, Dublin producing an SVI of less than 60 mL/g even though this plant is operated under much less ideal conditions and without preferential washout of filaments. Giesen [68] stated that once a culture of granular sludge has been established, a settling rate in excess of 10 m/h is achieved using less than 40% of the energy needed for conventional BNR plant and occupying only 40% of the footprint of conventional plants. Most of the nitrogen is removed though very efficient SND while EBPR of up to 90% was also achieved. Winkler *et al*. [69] found that while at 30℃ more GAOs were formed in these plants, the GAO granules are lighter and during the stratification of the sludge they could be selectively removed by wasting from the top of the sludge blanket, leading to consistent 99% removal of phosphorus. This is clearly a process maturing very rapidly and holds the promise of simplifying the activated sludge process and being more reliable while reducing the footprint and energy use.

THE FUTURE OF ACTIVATED SLUDGE

Many of the activated sludge plants being constructed at present will function 60 to 70 years from now, especially if the plants can be more energy efficient, provide resource recovery and greatly reduce micro-pollutants. As an example the Stickney plant in Chicago was designed in the 1930s and is still producing effluent of the highest quality including EBPR. Since the structures are still sound there is no prospect in the near future of abandoning or replacing them. Schaumburg [70] published a rather satirical one-page paper showing the graph in Figure 7. He points out that even though the number of papers exploded between the mid-1960s and 1980, the efficiency of BOD removal has not changed since the inception of the process. This is true but at about that time the value of the activated sludge process for nutrient removal and the treatment of industrial used water developed rapidly and if the graph were to be extended, the growth of publications will probably become exponential with a further acceleration into the 21st century brought about by the intense interest in producing a higher quality effluent, using less energy and having a smaller footprint. In the same way as the beer brewery technology is basically centuries old but has been adapted with more modern technology and instrumentation to produce a more consistent and reliable product, the activated sludge process will stay basically the same for at least another century, but with refinements.

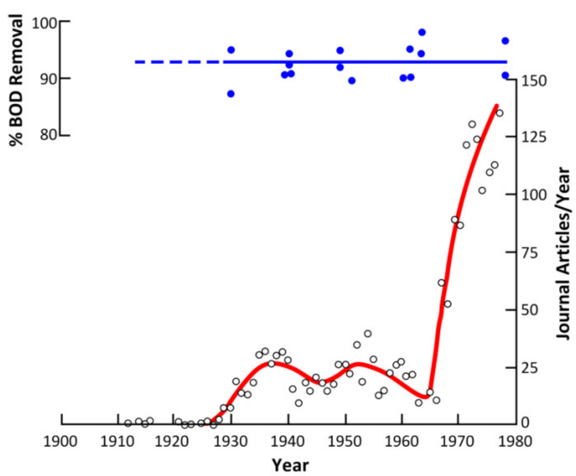

Figure 7 Proliferation of papers on activated sludge (Schaumburg, [70])

Future activated sludge process design will vary depending on the plant size and treated water use. They will also need to counter eutrophication but above all produce effluent for direct or indirect re-use. Where direct re-use is considered, the activated sludge remains an indispensable link in the sequence of processes required for production a high quality product such as in Windhoek Namibia, Southern California, Australia or Singapore. In many poorer countries we may see a shifting emphasis to more indirect water re-use and here the advantages of the activated sludge process for the removal of nutrients but also a major reduction in PPCP and EDCs will ensure its survival. As examples the BNR plants in Windhoek, Namibia for direct re-use and in Harare Zimbabwe for a high percentage of indirect re-use are operated to protect the water reservoirs. In poorer countries where ponds are commonly used for the treatment of used water, the Petro process developed by Meiring & Oellermann [1971] uses a small inexpensive activated sludge plant to upgrade the pond effluent. About 20% of the flow from the first or anaerobic pond is discharged to unaerated zones of the activated sludge plant and the final pond effluent is added to the aeration section. It was found that when captured the algae switched from phototrophic to chemotrophic behaviour; exuded polymer resulting in good SVI and clarity. Total removal of algae was observed, producing a sparkling effluent with full nitrification and a high degree of denitrification. The algae-rich surplus sludge is wasted to the anaerobic pond. When covered, this pond can produce methane gas for generating electricity. In these plants the activated sludge plant could be constructed as a very elementary channel system or a simple lined basin with some surface aerators set to one side to create anoxic zones for nitrogen removal using the action of the surface aerators for mixing and recycling. A number of these were constructed in Zimbabwe.

Many of the changes that have led to improved activated sludge performance, more stable operation or increased capability have been the result of reactor configuration changes and/or changes in operation condition that assisted in selection for the most efficient organisms. Chudoba *et al.* [72] noted that the different designs selected for different microbial populations and used the term selector to describe process configuration impacts. The most improvement in activated sludge technology in the future will probably come from better bio-selection mechanisms. The very process itself came about by selecting for bio-mass that will settle better and be retained as activated sludge. Nitrification and denitrification came about through selecting for nitrifying organisms and those that can use nitrates as electron acceptors. We have already seen the value of selectors for PAOs, which incidentally also selected for non-filamentous organisms and the advantage of selecting against foam-forming organisms (Parker *et al*. [73]). In the granular activated sludge process the high settling velocities and mixing energy, select against filamentous bacteria which are continually washed out of the granules. Other selective mechanisms such as the finding of Winkler *et al*. [69] that the selective wastage from the top of stratified granular activated sludge processes could favour the growth of PAOs over GAOs or that Anammox bacteria could be retained in conventional or granular activated sludge by selective wastage of lighter solids, will lead to vast improvements in the process. Cyclones used in the DEMON process for selection of Anammox bacteria may be also be applied to select for better settling sludge in conventional plants. Improved instrumentation will be useful for optimizing selective forces.

Advances in molecular biology will likely assist in the development and assessment of optimal activated sludge processes and bio-selector designs. These methods include fluorescent in-situ hybridization (FISH), quantitative polymerase chain reaction (qPCR), metagenomics, and proteomics. FISH involves the use of labeled oligonucleotide probes that can be detected by fluorescence when they connect with target organisms. This method is useful for observing the presence, approximate density, and location of a target microorganism in an activated sludge floc, in a biofilm or suspension or in a granular sludge particle. The presence of specific microbial populations can be followed in a more quantitative way using qPCR. Examples of potentially useful applications of this method would be (1) to follow the effect of a bio-selector operation on the depletion or proliferation of a particular organism or type of organism, (2) determine the density of unique microorganism such as the Anammox bacteria or ammonia-oxidizing archaea in an activated sludge process, and (3) determine the fate of microorganisms added to an activated sludge process to enhance a desired biological reaction rate.

Metagenomics and proteomics are more recent techniques that can now be employed at much lower cost, which makes its use in the evaluation of activated sludge feasible. Metagenomics involves sequencing an activated sludge community DNA to determine complete genomic information in addition to phylogenetic information. Study of the genomic sequence can lead to an understanding of the physiological and adaptive capabilities of microorganisms that are important in meeting the performance goals of the activated sludge process. In proteomics population protein profiles can be obtained that may then help determine important metabolic functions and the genes expressed. With such information the gene expression can be followed in the activated sludge process to assess the effect of process configuration or operational changes on important biological reaction rates. These tools provide useful methods to assess the effect of activated sludge design changes and/or changes in operating conditions. It may be possible that some form of these methods may be used in the future at the used-water treatment facility for studying process conditions and operating stability. As we learn more about the microorganisms and gene expression in activated sludge processes the range of process capability should be increased and the economics improved.

SUMMARY AND CONCLUSIONS

The theme of this conference is sustainable management of used water. The activated sludge process has served humanity well and the strength of it lies therein that it is a completely natural and sustainable process and all we ever did as scientists and engineers were to optimize the process so that nature could work most efficiently, reducing energy needs, reducing the green-house gas emission and thereby improve the sustainability. The process in all its manifestations have not been invented but discovered. The versatility of the process shown by its many applications to do specific tasks such as removal of nutrients, breaking down phenols in industrial waste or the removal of algae from ponds and the adaptability as shown by the latest development in granular sludge will not go away and will still be around for generations. It is difficult to see how we can improve on nature – only have a better understanding and use it in a more optimal way.

They energy consumption for all these benefits are comparatively low but ongoing optimization and adapting plants to new selective processes such as main-stream Anammox and/or granular activated sludge can save energy to the point of being self-sufficient especially when used in conjunction with generation of power from sludge digestion. On the other hand in densely populated areas, sludge incineration may become more common and the possibility still exists for generating heat as a means of energy recovery. In addition, much of the PPCPs and RDCs that are adsorbed in the activated sludge process may survive digestion and still be polluting the receiving streams, in which case incineration would be essential. Incineration ash from BNR plants will contain all the phosphorus removed from the main stream and should seriously be considered for future sustainable phosphorus recovery.

With the rapid increase in direct or indirect water re-use, some form of the activated sludge process will be an essential part of the treatment sequence for the foreseeable future if not for the centuries to come. We live in the golden age of resource consumption and diminishing resources will drive our descendants to even more sustainable solutions which mean making more of what nature does very efficiently.

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