The European Union (EU) has implemented effluent (emission) standards since 1991, while North America practices a risk-based, imission approach. Progressing eutrophication and large fees for discharged loads push EU countries toward more stringent effluent concentrations, below total nitrogen (TN) levels of 10 mg/L and total phosphorus (TP) levels of 1 mg/L. In North America, the limit of treatment technology (LOT) concept has been defined as the lowest economically achievable effluent quality, which for TN is <1.5 to 3 mg/L and TP is <0.07 mg/L. These limits are becoming targets in fragile ecosystems in North America and drive the technology solutions towards a combination of advanced biological nutrient removal process trains, followed by chemical polishing and solids separation by granular or cloth filters or membranes. In Western Canada one-biomass biological nutrient removal processes are used, such as Westbank or Step-feed, often followed by filtration to achieve low effluent total phosphorus levels. Eastern Canada has a less stringent approach to nitrogen control and practices chemical phosphorus removal. Requirement for total nitrogen removal and rising costs of phosphorus precipitation drive designers towards advanced one-biomass processes and full utilization of carbon (for denitrification and phosphorus removal) available in raw wastewater and primary sludge. New processes are developed to take advantage of carbon available in waste activated sludge or even in the recycled activated sludge. Sludge treatment return streams have high nutrient loads and novel processes are introduced for their treatment, some utilizing generated nitrifier biomass for bio-augmentation of the main stream nitrification process. The impact of sludge processing on the liquid train and vice versa is now fully embedded in the design process.

Key words: nutrient removal, Europe, Canada, U.S.A., activated sludge, BNR, sludge liquor treatment, biofilm reactors, membrane reactors

Introduction

When nutrient removal was first implemented in the late sixties to protect Lake Tahoe, Nev., physical-chemical processes were used. The high cost of such treatment and the development of biological nutrient removal (BNR) processes in the early seventies (Barnard 1974a,b) led to the proliferation of a combination of biological and chemical processes which exist today. Varying ecological needs of receiving streams and lakes have led to different regulations and the development of different design practices in various regions of America and Europe. The goals have also shifted from phosphorus- and ammonia-only removal to the current emphasis on the limit of treatment processes (LOT) and to targeting a particular nutrient or a group of compounds, such as pharmaceutical and personal care products (PPCP). The objective of this review is to compare the differences and similarities of the regulatory and design approaches to nutrient removal as practiced on the two continents.

Regulatory Background

European Union

The European and the North American approaches to the management of watersheds and to the regulation of wastewater treatment plant (WWTP) effluent quality, were, so far, different. In the EU the Wastewater Directive 98/15/EC is an emission-based regulation which defines required effluent quality in terms of COD, BOD and nutrient concentration (Table 1) based primarily on plant size. As various bodies of water (e.g., the Baltic Sea, the Adriatic or parts of the North Sea) are becoming eutrophic, the imission and watershed integrated management approach is being adopted by individual countries—with the anticipated new EU Directive expected to address this issue.

The EU Council Directive 91/676/EEC (Nitrate Directive) aimed at reducing nitrates from agricultural sources, inadvertently led to banning or abandoning of land application of biosolids in some countries (e.g., in Switzerland, the Netherlands, Sweden). The Watershed Directive 2000/60/EC (WFD) requires Member States to establish river basin districts and for each of these districts, a river
basin management plan (with a goal to reach a “good status” by 2015). Each plan will have four elements to the integrated river basin management cycle: characterization and assessment of impacts on river basin districts; environmental monitoring; the setting of environmental objectives; and the design and implementation of the program of measures needed to achieve them. This signals an official move from emission- to imission-based standards. The Danube River multinational river basin, in dire need of improvement, is one example of such a watershed (Bloech 2005), while Ruhr River basin (Ruhrverband) serviced by 86 WWTPs and 500 stormwater treatment plants, is an example of a long-established, centrally managed basin, all within one country (Bode 2005).

In the richest EU countries, the pollution from wet weather flows (WWF) is included in the total maximum daily load (TMDL) from urban watersheds (also called sewersheds). TMDL is a concept, refined in America and adopted first in Germany (Rosenwinkel et al. 2005; Segelke and Rosenwinkel 2002). Here, all wastewater loads from the sewershed (sewer drainage area) are included as impacting the river, and this forces the municipality to minimize combined sewer overflows (CSO) in the influent to the municipal wastewater treatment plant (WWTP) and look for alternatives to treating rainwater by specially designed “rainwater gardens” or pervious areas for infiltration. Management of WWF then becomes a critical issue when the municipality tries to meet strict effluent permits.

The EU grants municipalities an 80% total nitrogen (TN) removal permit, as an annual average. EU wastewater is typically “stronger” than in North America, due to much lower water consumption, at approximately 120 to 225 L/cap·d. In spite of that, some municipalities with old combined sewer systems suffer from low C/N ratios (e.g., Warsaw, Poland; Oleszkiewicz et al. 2004). The 80% permit allows significant reduction of external carbon purchases for full denitrification, particularly during the critical spring design period with influx of cold WWF.

North America

In both the U.S.A. and Canada the nutrient effluent permits are determined at the state or provincial level based on imission criteria. The imission approach considers the requirements of the receiving stream and translates them to locally different effluent requirements. In Canada’s Great Lakes region, provincial effluent permits require TP to be less than 0.25 to 0.5 mg/L P, with ammonia typically expected below 6 mg/L (Chambers 2005). Eastern Canada generally has rather relaxed total nitrogen standards. Nitrites (and in some cases ammonia) are not regulated in Eastern Canada, even in cases of lake discharge. For example, Canada’s largest plant, the Ashbridges Bay in Toronto (820 ML/d average dry weather flow; ADWF) is a C-BOD removal plant only; although there are plans for a future upgrade to biological nutrient removal (BNR).

In the U.S.A., ammonia and nitrates have been strictly regulated in most estuaries and in sensitive rivers and lakes. Total nitrogen has long been considered critical to eutrophication processes in the saline waters of the east coast estuaries such as Chesapeake Bay or Long Island Sound. The suspicion of the endocrine disrupting impact of nitrates on aquatic and non-aquatic vertebrates (Crain et al. 1998; Guillette and Edwards 2005) has led to requirements for TN removal in plants discharging to freshwater receivers in Florida. In Western Canada, the provincial regulations follow those of the EU (i.e., they are emission based) with more stringent requirements for lake discharges and trout streams, e.g., in British Columbia (TP <0.25 mg/L, TN <10 with ammonia less than 1–5 mg/L).

The United States Environmental Protection Agency (U.S. EPA) has recently released very stringent nutrient effluent criteria for 14 selected ecoregions in the U.S.A. to address the total maximum daily load (TMDL) standards for U.S. surface waters (U.S. EPA 2001, 2003). Table 2 gives examples of several criteria for sensitive waters in the U.S.A. In some regions the plants have to meet the perceived limit of treatment (LOT) effluent standards, currently at 1.5 to 3.0 mg TN/L and 0.07 to 0.1 mg TP/L (the TP value includes soluble and particulate P), or the mass load-based equivalent at the design capacity of the plant (WERF 2006). Examples include plants in the Chesapeake Bay catchment or plants in Nevada, with capacities ranging from 10 to 1400 ML/d (Pagilla et al. 2005). The lowest required TP concentration is in the Florida Everglades, at 10 µg/L. The

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Concentration</th>
<th>Minimum removal</th>
</tr>
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<tbody>
<tr>
<td>Total phosphorus</td>
<td>2 mg/L (10,100–100,000 PE)</td>
<td>80%</td>
</tr>
<tr>
<td></td>
<td>1 mg/L (&gt;100,000 PE)</td>
<td></td>
</tr>
<tr>
<td>Total nitrogen</td>
<td>15 mg/L (10,000–100,000 PE)</td>
<td>70–80%</td>
</tr>
<tr>
<td></td>
<td>10 mg/L (&gt;100,000 PE)</td>
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</tbody>
</table>

*PE; Population equivalent.
implementation of LOT in wastewater treatment plants brings about several questions, for example:

- Will the non-biodegradable fraction of total nitrogen be included in the permit?
- Should the LOT effluent quality be an annual average?
- Will the regulator allow for cold temperature and wet weather excursions?
- In case of violation how will the penalty be assessed: e.g., one per period of violation or one for every day of the violation period?

The current approach by the U.S. EPA (Koroncai 2006) is to treat all discharged nitrogen (and phosphorus) as biodegradable, even though conventional advanced wastewater treatment typically produces 0.5 to 1.5 mg/L nonbiodegradable dissolved organic nitrogen in the effluent, referred to as refractory dissolved organic nitrogen (rDON) (Sedlak 2006). This rDON spends a much longer period of time in estuaries than in the treatment plant and the U.S. EPA is of the opinion that for now it should be considered as available to algae.

In Canada the TMDL approach is being gradually implemented, leading to a variable TN permit throughout the year. During low river flows, the ammonia levels may have to be reduced to zero, e.g., in Brandon, Manitoba, for two weeks during September low flows in the Assiniboine River.

Urban drainage (sewerage or sewersheds) management is evolving rapidly (Mikkelesen et al. 2005). In the U.S.A. the U.S. EPA estimates that cities could spend upwards of $45 billion to remediate some 9000 combined sewer overflows discharging some 4.6 million ML/year of untreated sewage (BPR CSO 2004). Within watersheds and within urban drainage basins the regulators strive to reduce the load to the receiver by applying dynamic biological process simulations to arrive at the loads that can be treated effectively by the plant’s biological system. Systems are then devised to control flow and load to the plant by using sewer retention, off-site storage or increased surface retention. In some plants (e.g., the 50 ML/d Winnipeg West) off-line retention ponds are used. In others, the regulator may follow the U.S. EPA guideline and allow, for example, a maximum of four combined sewer overflow (CSO) events a year. Dedicated stormwater/CSO physical-chemical treatment facilities are one option practiced at Lawrence, Kansas, for some years; the option is now being considered in Toronto. In Chicago, Illinois, the multi-billion dollar tunnel and reservoir project (TARP) stores CSO in deep underground tunnels, discharging to a reservoir, with pumps returning the wastewater to the sewer and WWTP after the rain. To avoid the huge costs of WWF and CSO management, larger cities (e.g., New York City; Cleveland, Ohio; Ottawa, Ontario; and others) utilize the existing plant capacity by predictive modelling leading to real time sewer system control and wastewater treatment process control (BPR CSO 2004; TetrES Consultants 2006).

**Practice and Trends in EU**

There are significant regional differences in the EU which stem from regulatory and financial considerations. Rich countries in Northern Europe, particularly Germany, have been prompted to adopt stricter emission standards or move towards emission due to fees for discharged loads, which have to be paid even if the permit is met. Thus the overall effluent quality has improved with some plants continuously upgrading, e.g., the Husum FRG plant averaging 0.12 mg TP/L without chemical treatment and TN <1.7 mg N/L (Rosenwinkel et al. 2005).

With the large diversity of nutrient removal processes in Europe, the dominant process is a one-sludge BNR system, consisting of a sequence of anaerobic, anoxic and aerated zones. Commonly used BNR processes in Northern Europe and the U.K. include the modified Bardenpho process, Johannesburg process (JHB also called ISAH after the first German application) and the alternating continuous flow processes (e.g., Biodenitro, BiodeniPho) which capitalize on simultaneous nitrification-denitrification (SND). Plants practicing enhanced biological phosphorus removal (EBPR) would employ a modified Bardenpho or the JHB-type process featuring a three-stage anaerobic-anoxic-aerobic reactor with RAS pre-denitrification, similar to the Westbank process first developed in Canada. Others would employ a Phoredox-type (AO) configuration consisting of an

<table>
<thead>
<tr>
<th>Limits for phosphorus or nitrogen</th>
<th>Origin of classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤10 µg/L TP Oligotrophic</td>
<td>European Union</td>
</tr>
<tr>
<td>≤35 µg/L TP Mesotrophic</td>
<td>U.S. EPA</td>
</tr>
<tr>
<td>33 µg/L TP; 560 µg/L TN—South Central Great Plains lakes</td>
<td>Ontario Ministry of Environment</td>
</tr>
<tr>
<td>Less than 30 µg/L TP to eliminate excessive plant growth rivers</td>
<td>U.S. EPA</td>
</tr>
<tr>
<td>67 µg/L TP; 880 µg/L TN—South Central Great Plains rivers</td>
<td>U.S. EPA</td>
</tr>
<tr>
<td>76 µg/L TP; 2180 µg/L TN—Northern Great Plains rivers</td>
<td>U.S. EPA</td>
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</table>

aThe United States regulators begin to request that wastewater plants meet similar concentrations in the effluent.
anaerobic zone followed by an alternating SND process, with a racetrack reactor configuration. Some of the largest plants use this sequencing process, e.g., the Lynetten WWTP for 0.5 million PE in Copenhagen, and there are over 100 such plants in Denmark and Northern Europe. Due to lower rates of nitrification and denitrification, such reactors are often 50 to a 100% larger than tightly designed plug-flow BNR processes such as the Westbank process. Rising costs of chemicals are weaning many plants off phosphorus precipitation and chemically enhanced primary treatment (CEPT) which removes carbon necessary in denitrification. Acidogenic fermentation of primary sludge, developed in Western Canada in Kelowna, British Columbia, in the early eighties, became popular first in Poland (e.g., the plants in Jaslo, Jastrzebie, Gdansk, Bydgoszcz) and Germany (e.g., the plant in Husum, Hannover). This method of volatile fatty acids (VFA) production is now becoming popular elsewhere in Northern Europe.

An example of a plant upgrade is the Hildesheim WWTP for Hannover FRG, which employs the ISAH (JHB) process with SND (solids residence time [SRT] = 16 d) and EBPR. The plant, which has been receiving BOD₅ as low as 100 mg/L started introducing primary fermentation of primary sludge, volatile fatty acids, to the anoxic and anaerobic zones. The effluent averaged 0.12 mg TP/L and 4.0 mg TN/L in 2001, well below the EU requirements (Rosenwinkel et al. 2005). Most of the TP removal was achieved by the EBPR without chemical trimming. Significant savings were obtained from the reduction of mandatory wastewater fees collected for the discharged TP and TN loads.

Table 3, adopted from Janssen et al. (2002) illustrates performance of a number of Dutch plants practicing long SRT and a high recycle rate to the anaerobic tank ranging from 100 to 300% of the ADWF. This leads to a larger anaerobic tank (than practiced in North America) of approximately 16 to 25% of the total reactor volume. The high RAS rates may result from the very shallow final clarifiers used which may be counter-productive for EPBR. In the state-of-the-art design, a clarifier acts as a nitrate-reducing reactor (up to 5 mg N/L can often be removed without floating sludge), a process which is carefully controlled by RAS recycle as complete denitrification may lead to phosphorus release. Consistent phosphorus removal is usually only possible with excess VFA.

In the U.K. a number of plants have been built using the concepts developed in Western Canada, e.g., the Westbank process plants in Slough or Reading where the SRT is maintained at the shortest time possible while still allowing full nitrification, and the oxidation reduction potential (ORP) is well defined within each zone. The Scandinavian countries are often confined to building on tight real estate and several cities in Finland, Sweden and Norway built in excavations inside the rock. Helsinki, Finland, has the largest activated sludge plant inside a 14-hectare cave, with an ADWF of 280 ML/d and WWF of 800 ML/d (Fred and Kiiskinen 2005). Such confined sites require operating close to the minimum solids residence time (SRT) for nitrification. At the Bromma plant in Stockholm, which operates without the customary safety factor, they operate by decreasing the SRT when effluent ammonia decreases below 2 mg N/L. The SRT is maintained below 6 to 10 d in winter. Such plants are often resigned to methanol addition for denitrification and chemical precipitation of phosphorus. Helsinki uses a post-denitrification biological aerated filter (BAF) (Fred and Kiiskinen 2005) and chemical precipitation. The Grimstad plant in Norway uses the Westbank configuration with a static fermenter-thickener, designed to take primary sludge at 4 to 8% of the dry weather flow (ADWF) and operate at an SRT of 4 to 8 d and a surface load of 25 to 40 kg/m²d. Other fermenter designs (two-stage, completely mixed) have been used in Holland and Denmark but the static fermenter-thickener emerges as the preferred choice due to ease of operation, also in North America.

Tight real estate led to some innovative designs such as the Malmö’s Rya plant where nitrification trickling filters were built on top of activated sludge reactors converted to anoxic reactors receiving nitrates as recycle from the filters. The “no added real estate” plant retrofit from 350 to 518 ML/d included double-decker final clarifiers (GRYAAB 2004). One of Europe’s largest plants is the nitrogen-removing SBR facility recently commissioned at Ringsend, Dublin. The plant treats 500 ML/d of wastewater in a two-storey piggyback reactor system.

Fixed film reactors, such as moving bed biofilter reactors (MBBR) and integrated fixed film activated sludge reactors (IFAS), shown in Fig. 1, are popular where a small footprint is required. The VEAS plant, built into tunnels, and treating wastewater from 450,000 PE in Oslo, Nor-

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**TABLE 3. Performance of Dutch EBPR plants operating at 14C without chemical addition**

<table>
<thead>
<tr>
<th>Location</th>
<th>Flow mL/d</th>
<th>Gour</th>
<th>O-B</th>
<th>Putte</th>
<th>Hardenberg</th>
<th>Waarde</th>
<th>Zetten</th>
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<tbody>
<tr>
<td>Flow m/L/d</td>
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<tr>
<td>SRT d</td>
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<tr>
<td>RAS NO₃ mg N/L</td>
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<tr>
<td>Effluent PO₄-P mg P/L</td>
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</tbody>
</table>

*Soluble PO₄-P concentrations represent a moving average of 10 data points.*
way, is required to remove only 70% of TN and 90% TP. It is achieved through CEPT and a biological aerated filter (BAF) system with only 3 h HRT. The plant also treats centrate from anaerobically digested sludge by lime and ammonia stripping (Sagberg et al. 2005).

Norway initially used only the CEPT process. When nitrogen removal became necessary, they followed this with a series of nitrifying and denitrifying reactors and developed what is now called moving bed bioreactors (MBBR). Today, this is often followed by chemical post-predioxcitation for phosphorus removal and flotation (Odegaard 2005). External carbon such as ethanol or methanol is added routinely with most plants. In the case of the 5 ML/d Gardemoen plant near the Oslo airport, de-icing fluid, which contains mono-propylene glycol, is used. Nitrate utilization rates (NUR) were 3 g N/m²d at 10°C for ethanol and 1.5 g N/m²d for methanol and glycol at Gardemoen. The plant can remove total nitrogen to less than 3 mg/L.

There was initially a rapid development of suspended growth BNR technology in Poland; however, the municipalities suffered financially due to the erroneous perception of Western Europe and Scandinavian engineers (who were the initial consultants there) that enhanced biological phosphorus removal (EBPR) was not possible in cold temperatures and that methanol was the key to effective denitrification. The biological reactors in Northern Europe were typically larger than those designed by Western Canadian standards; higher wastewater concentration was only part of the reason. For example, the Husum (Germany) modified Bardenpho plant has a currently assessed treatment capacity of 13 ML/d and receives only 6 ML/d. The modified Bardenpho configuration for the COS plant in Poznan, Poland (Aquanet 2005), has 6 reactors totaling 150 ML volume for the future ADWF flow of 300 ML/d (currently approximately 200 ML/d). By comparison, the Westbank configuration plant for Kelowna, British Columbia (the world’s first cold climate BNR plant), features reactor HRT = 9 h, and meets effluent limits of TN <3 mg/L. It can reach 1 mg/L if methanol is used in the additional final denitrification zone (HRT = 20 min). The designers in Poland have adopted the South African practices and the cold wastewater design approach developed in Western Canada. After a few MUCT (Modified University of Cape Town process) plants built (e.g., 180 ML/d Gdansk East) have proved difficult to operate without chemical phosphorus trimming, a number of modified Bardenpho or JHB plants (with RAS denitrification) were commissioned, e.g., in Namswyk, Nova Sol, Wroclaw and other municipalities, ranging in size from 5 to 120 ML/d (E. Kalinowska, Lemtech Konsult, Krakow, Poland, pers. comm.). The current challenge in the new EU member countries is to attain the TN <10 mg/L effluent standard while reducing the process chemical dependency.

There is a new push to adopt EBPR in plants in the U.K. Many of the U.K. plants suffer from endemic low C:N and C:P ratios in the wastewater. The seven new plants built by RWE Thames Water (Maple Lodge, Reading, Slough, Little Marlow, Swindon, Wargrave, Aylesbury) feature VFA production using either static fermenter-thickener or fermenter-thickener twin tanks often augmented by industrial wastewater (Coleman et al. 2005). The Reading plant commissioned in 2003 for 300,000 PE and utilizing the Reading process (Bardenpho with pre-denitrification of RAS—similar to JHB or Westbank) utilizes brewery waste. The brewery waste is separately fermented with a little RAS to produce VFA, helping the plant achieve a faultless biological removal of phosphorus and total nitrogen (G. Bujoczek, Black & Veatch, RWE Thames Water, U.K., pers. comm.).

**Practice in North America**

Driven by regulations, most municipalities in the U.S.A. and Canada are planning to adopt nutrient removal. With the majority of the plants in the central part of North America still practicing C-BOD removal only, the natural tendency was to add chemical treatment for phosphorus removal, extend the aeration time to achieve full ammonia removal followed by, if necessary, dedi-
cated methanol-driven denitrification. For the many other BNR plants that have to achieve a low effluent TN value, post-denitrification is typically conducted in denitrifying filters (deBarbadillo et al. 2005). Such multi-sludge process upgrades often feature a smaller footprint and are used in large plants. For nitrogen removal down to TN <3 mg/L, the Tampa Bay Hooker’s Point has a C-BOD high purity oxygen activated sludge (HPOAS) followed by a nitrifying HPOAS, followed by denitrifying filters. The effluent is recycled for irrigation. The oldest such multi-biomass facility in North America in this category is the 150 ML/d Truckee-Meadows for Reno, Nevada (Fig. 2), which uses a Phoredox process for phosphorus removal and nitrification filters followed by denitrification fluidized bed filters to achieve, after filtration (based on TMDL), 1.9 mg TN/L at 130 ML/d and 1.5 mg TN/L at 150 ML/d flow (Gray and Brisbin 2004). The operating costs are $93.3/(ML/d) with methanol approximately $1 million/year at a dose of 2.8 kg/kg nitrate.

More plants in the U.S.A. are now adopting the one-sludge activated sludge process, using either the Bardenpho-like (Fig. 3) or various MLE (Modified Ludzack-Ettinger) configurations with chemical precipitation. A number of surface aeration modified Bardenpho plants were built in the last 15 years in Florida, e.g., at Palmetto and Largo. These racetrack design plants have an added benefit of the simultaneous nitrification-denitrification (SND), common in such configurations, e.g., the Escambia County, Florida, plant achieved a 5-year average of 1.9 TN mg/L after filtration. The coldest climate surface aerator operation is in Brandon, Manitoba, on slaughterhouse wastewater pretreated in a heated anaerobic lagoon. Where land is at a premium, many newer Bardenpho plants adopt fine-bubble aeration and 6- to 8-m deep tanks, e.g., the main BNR plant for Orlando, Florida, and the Reedy Creek plant serving Disney World.

In Eastern Canada the technology typically used is high-rate activated sludge (nitrification if required) and co-precipitation (e.g., the plants in Toronto area, including the newly upgraded 500 ML/d Peel-Toronto). As nitrates are not removed, enhanced biological phosphorus removal (EBPR) is not feasible. In Quebec, fixed-film (BAF) processes and phosphorus precipitation predominate (e.g., Laval, Quebec City) with the exception of Montreal, Canada’s largest plant which uses CEPT only due to low influent concentrations and high dilution in the St. Lawrence River. The first BAF facility in central Canada was built in Thunder Bay, Ontario, in 2006.

In western Canada full biological nutrient removal (BNR) is the norm since the 1982 commissioning of the 22 ML/d Kelowna, British Columbia, plant (currently 42 ML/d)—the first cold-temperature operation of a modified Bardenpho—now working in the Westbank mode (Fig. 4). The conservative design led to innovation resulting in a true experiment in full scale. Progressively improved operation led to the gradual decrease in residence time from 24 h down to below 10 h. Most plants in the West feature a one-biomass process (Rabinowitz et al. 2005) and the “Westbank” process, somewhat similar to the Johannesburg process, is currently the most often designed configuration, e.g., Calgary Bonnybrook: three plants on one site with a total capacity 500 ML/d; Calgary-Pine Creek, Edmonton’s Gold Bar facility; and the Capital Region plant, Banff, Alberta, Winnipeg West and many others (Fig. 4). Older, less effective technologies, such the University of Cape Town process (UCT) are converted to Westbank/Johannesburg type configuration—as in Kalispell, Mont.

Some plants, such as the 100 ML/d Lethbridge, Alberta, employ the Step BNR process with EBPR. The

![Fig. 2. World’s oldest Pho-Strip operation has been converted to in-line fermentation to biologically enhance phosphorus removal in the Phoredox activated sludge reactor and to move away from chemical precipitation. The P-removal is often too effective, which is remedied through adding controlled amounts of phosphoric acid to the denitrification tank.](image-url)
step-feed configuration allows for higher biomass inventory in the system in winter such that the nitrifiers can survive low temperatures and high flows during the spring melt down. The Lethbridge plant meets the TP <1 mg/L requirement without chemical trimming; however, it does receive industrial waste with ample VFA. Step-feed nitrification and denitrification is also used in the tight real estate plants (hydraulic retention times as low as 4–6 h) in New York where the attempts to maintain low TN in discharges to the sea call for special measures such as separate sludge liquor (SRL) treatment, alternative carbon sources and bio-augmentation with nitrifiers.

New Technologies and Trends

Design and operational experience has identified a number of factors limiting a consistent achievement of low effluent concentration of nutrients, among others:

1. High flows simultaneous with low temperatures.
2. Sludge liquors carrying high N and P load.
3. Lack of carbon for full denitrification and enhanced biological P removal (EBPR).
5. Final clarifier overload due to increased SRT during winter.

Transient Flows

Transient wet weather flows (WWF) often occur during spring thaw leading to simultaneous temperature decrease. Plants designed for such conditions would be over-designed during the rest of the year, and designers are seeking novel ways of accommodating these flows. Occasional use of CEPT is one way of reducing the load and allowing for a higher active fraction of the mixed liquor solids (MLSS) as proposed in the Winnipeg West plant, which also has large lagoons serving as equalization basins. Use of step-feed configuration or bypassing some of the WWF to the last pass of the reactor (Fig. 4) is used in plants such as Edmonton’s Gold Bar BNR facility.

Return Sludge Liquors

The issue of return sludge liquor (RSL) currently receives a significant amount of attention. There is little guidance as to the cost-effectiveness of separate treatment versus incorporating the RSL in the mainstream, e.g., by using equalization and feeding the nitrogen-rich RSL in the valleys of the diurnal cycle. An example of such an operation, in the Zurich Werdhölzli plant 600,000 PE or 219 ML/d, was discussed by Siegrist (2004). In a similar modelling exercise based on research data, Head and Oleszkiewicz (2000)

![Fig. 3. Modified Bardenpho process.](image_url)

![Fig. 4. The Westbank process first developed in the city bearing that name near Kelowna, B.C. (now called Westside). The process features introduction of influent into the anoxic zone (sometimes up to 100% Q) and RAS denitrification.](image_url)
have demonstrated a decrease of ammonia concentration excursions in the Winnipeg-North effluent by as much as 6 to 8 mg/L by simple storage and dosing of centrate during periods of low ammonia loads to the plant.

Constantine et al. (2005) identified a number of biological and physico-chemical processes and compared the capital costs of four (in 2002 USD without costs of engineering): In-Nitri—$2.8 million; BABE—$3.0 million; SHARON—$1.6 million and Anammox—$2.2 million. Anammox had the lowest operational costs, however, only BABE and In-Nitri offered bio-augmentation with nitrifiers generated in the side-stream process. The first SHARON Anammox process was installed in Rotterdam’s Dokhaven plant (M. Van Loosdrecht, pers. comm.). The 800 kg N/d process is currently being tested at a load of 5 kg N/m³d (M. Van Loosdrecht, pers. comm.). The SHARON process is being considered for plants in New York, while the staff at Washington’s Blue Plains enhanced nutrient removal (ENR) plant is initiating research on the Anammox to prepare for the future conversion of their raw sludge lime treatment (no sludge liquor) to anaerobic digestion, which will result in generation of liquor.

Phosphorus removal has attracted the attention of inventors trying to recover phosphorus from sludge or sludge liquor; however, the costs and heavy metal contamination are still prohibitory. Precipitation of magnesium-ammonium-phosphate (MAP or struvite) in sludge liquor is practiced in Japan and there are a few plants in Europe. In Canada a British Columbia company has successfully completed testing a prototype in Penticton, B.C. Paradoxically, they have identified phosphorus-deficient lake fisheries as a market for the recovered phosphorus. A simpler technique has been tried in several plants. In Winnipeg-North, addition of metal salts to sludge prior to centrifugation (using a static mixer) prevented struvite formation and saved the maintenance on the dewatering equipment, while removing phosphorus in proportion to the dose applied. One problem with struvite recovery from centrate is the fact that (as is the case in Winnipeg-North) the damage by MAP deposits is often greatest in the dewatering equipment.

**Bio-augmentation**

Initial research in Canada (e.g., Head and Oleszkiewicz 2000, 2004) showed the potential for significant decrease of mainstream SRT when augmented with nitrifiers generated in a side-stream liquor nitrification process. The side stream temperature can be above 25°C. Temperature shock when adding nitrifiers grown at high temperature to the main stream plant at lower temperature led to the development of the RAS-reaeration where sludge liquor was added to RAS, immediately equalizing to the low temperature. A number of plants operate by this principle in the Czech Republic (Krhubkova et al. 2005) and the system is gathering attention with several plants, e.g., in Appleton, U.S.A., and Garmerwolde, Netherlands, experimenting with various configurations. Winnipeg-North, a regional processing plant receiving sludge from three plants, will have the first intentional bio-augmentation facility commissioned in 2007. It will cut the plant’s ammonia-nitrogen discharge by 25 to 29% by utilizing this concept, as presented in Fig. 5.

**Electron Donor Addition**

Carbon, especially rapidly degradable COD (rdCOD), is the electron donor required for both denitrification and enhanced biological phosphorus removal (EBPR). When wastewater is carbon-deficient, methanol is used for denitrification. Methanol has a lower cost but requires the development of slow-growing specialized methanol-utilizing biomass and thus cannot be used on an “as needed” basis. Nevertheless, methanol is the most popular substrate in denitrification. Ethanol would be a preferred source for denitrification; some full-scale research in Sweden has shown the nitrate utilization rates (NUR) to be in the order of 15 mg NO₃⁻N/g VSS-h versus methanol-NUR of 4 to 5 mg NO₃⁻N/g VSS-h (Anderson et al. 1998). New York City and the Washington Area Sewer Authority are considering using ethanol during winter in the hope of achieving higher denitrification rates. Trials with Winnipeg-North centrate denitrification using industrial wastes have demonstrated that potato processing wastewater accelerated denitrification to 12 mg NO₃⁻N/g VSS-h, which was higher than methanol at 10 and lower than ethanol at 17 mg NO₃⁻N/g VSS-h (Chen et al. 2006).

Methanol and similar compounds are not suitable for phosphorus removal. Sugar wastes have been added to primary sludge fermenters which generate a combination of acetic and propionic acid. Addition of acetate only, or of sugar wastes, directly to the anaerobic zone may create conditions that encourage the growth of glycogen accumulating organisms (GAO) which successfully compete with phosphorus accumulating organisms (PAO) for the volatile

![Fig. 5. Nitrifier bio-augmentation: generated nitrifiers in the side stream treatment reactor are used for decreasing the mainstream aerobic SRT. The reactor can also be placed directly in the whole RAS stream.](image-url)
fatty acids. Adding sugar waste to the fermenter will produce the proportion of VFA compounds optimal for phosphorus removal by PAO. A case in point is the new Eagle’s Point BNR plant for South Washington County, Minn., where molasses was added to the fermenter, when needed, to improve the EBPR (Lindeke and Barnard 2005).

A variety of novel auxiliary carbon sources are used of which fermentation of mixed liquor is perhaps the most interesting. First demonstrated incidentally in Barnard’s original pilot work in 1974 (Barnard and Abraham 2005) it is an excellent way of producing the required VFA without an additional carbon load to the plant. Typically, some of the biomass is extracted from the anaerobic zone, fermented and returned to the same anaerobic zone.

In Western Canada, the U.S.A., throughout the U.K., and in northern EU countries such as Poland and Germany, fermentation of primary sludge became standard practice, greatly enhancing plant performance. An excellent case study of fermentate benefits is provided by Calgary’s 500 ML/d Bonnybrook (Westbank/JHB mode) plant where the new, fully separate, train (plant C: ADWF 100 ML/d) is equipped with 2-stage fermenters feeding short-chain volatile fatty acids (scVFA) to the anaerobic zone. Plant C operates in parallel with two separate trains (older plants, also in Westbank mode) operating without the benefit of scVFA. The fermenter-connected plant C has worked, in the words of the operator, “flawlessly” for 10 years compared to the other two trains which had phosphorus removal and TN removal problems (P. Do, Senior Process Engineer, Bonnybrook Plant, Calgary, Alberta, pers. comm.). A one-stage static fermenter (as opposed to the two-stage fermenter-thickener combination used in Calgary, Alberta, and in Saskatoon, Saskatchewan) consists of a gravity picket fence thickener, typically with 4- to 8-d SRT and 16- to 24-h HRT, and appears to be the most successful.

Edmonton’s 310 ML/d Gold Bar plant is built on a very tight site and has been retrofitted to a 4-pass BNR plant operating in a WestBank or step-feed mode. Excellent experience with a static fermenter led to the current construction of three more fermenters. The other Edmonton plant, the 70 ML/d Alberta Capital Region plant, was recently retrofitted to BNR and equipped with static fermenters (G. Stevens, EarthTech, Kelowna, B.C., pers. comm.).

In the fermentation process the key parameter is: what portion of volatile suspended solids (VSS) is fermented? The amount of fermentable scVFA per g of VSS varies with temperature, flatness of the sewer system, and the amount of fermentation taking place in the sewer. Numbers as low as 13% (Minneapolis-St. Paul, Minn.) and 28% (Westbank, B.C.) and as high as 40% of VSS in primary sludge (Kalispell, Mont.) being fermented to scVFA have been cited (Barnard 2006).

Research is underway to demonstrate the feasibility of generating carbon by ozonation of a fraction of RAS. Dytczak et al. (2005) have shown that with an ozone dose of 0.02 to 0.06 g O3/gVSS, the nitrate utilization rate (NUR) could be increased by 15 to 60% with concomitant reduction of WAS mass by 25% (Fig. 6). In processes such as the RAS ozonation process it is important to decrease the residual ORP (redox potential) in order not to jeopardize denitrification.

Lack of carbon led to the development of hydrogen-dependent autotrophic denitrification in a tertiary application. Still in the experimental stage, the process, when based on membrane technology, generates crystal clear effluent and there are no fears of residual methanol, at rates and costs comparable to the methanol-driven process (Rezania et al. 2005), particularly if hydrogen was generated on site.

Non-biodegradable TN

Refractory dissolved organic nitrogen (rDON) is defined as dissolved organic nitrogen that cannot be removed by biological wastewater treatment processes. An average rDON concentration from a fully nitrifying process treating municipal wastewater is ≈1.0 mg/L, with a common range of 0.3 to 2.0 mg/L. However, industrial inputs, particularly from dyeing and finishing operations, can greatly increase the rDON concentration, and values as high as 40 mg/L have been measured in the effluent of a relatively small (1.6 mgd) municipal treatment plant. It is not uncommon for industrial wastewater treatment plants (WWTPs) to have effluent rDON concentrations of 5 to 15 mg/L (Randall 2006). Known technologies are often too expensive to remove rDON and research is required to establish if there even is a need to remove rDON at all.

Avoidance of Sludge Liquors

With the recent interest in sludge liquor treatment one needs to critically address the whole plant mass balance and total treatment costs, including sludge management.

Fig. 6. Improvement of nitrate utilization rate (NUR) (%) as a result of generation of soluble biodegradable COD through ozonation of a fraction of return activated sludge (Dytczak et al. 2005).
Simulation of sludge digestion impact is now possible, e.g., in BioWin (Jones and Dold 2005), but there are also examples of alternative sludge management without digestion and the resulting return sludge liquor (RSL). As shown in many cases, the cost of RSL treatment (particularly in plants receiving imported sludge as well as its own) can be high. In Winnipeg-North the centrate treatment facility for RSL containing 25 to 30% of the plant’s TN load, combined with needed digester refurbishing may well cost $60M (Capex), plus the costs and liability of sludge disposal or utilization. Thermal oxidation of dewatered raw sludge would carry similar costs and would earn Kyoto points (energy generation from renewable fuel) if combined with electrical energy recovery (TOER; thermal oxidation with energy recovery). TOER appears to be a viable and environmentally sustainable method of sludge disposal (Puchajda and Oleszkiewicz 2005). This is particularly true in light of tightening CCME metal regulations in Canada and the talk of agronomic phosphorus application rates (e.g., in the Lake Winnipeg drainage area) coupled with a general public repulsion to sludge. All these may, unfortunately, drive land application of biosolids to extinction. The well publicized case of Toronto-Ashbridges Bay plant sending biosolids to a landfill in the U.S.A. is an example of negative public perception towards well-intentioned attempts at beneficial use of biosolids.

In Europe, plants transporting sludge off-site by trucks (except by pipeline as in London-Beckton, U.K.) pre-digest sludge before TOER, e.g., sludge going to TOER at Brabant North Holland or in Berne Switzerland. Plants with an on-site TOER facility use raw sludge (St. Petersburg, Russia; Vienna, Austria). Raw sludge has a heating value of 21 to 25 MJ/kg DS versus just 11 MJ/kg DS for digested sludge. Similar reasoning drove the city of Minneapolis-St. Paul (200 ton DS/d) to develop a full TOER, commissioned in 2005, against the prevailing thinking in the U.S.A. that electrical energy recovery is not cost-effective. Numerous operators (e.g., the Miami plant for Cincinnati, Ohio) maintain that they are in the wastewater business and power generation is secondary to that mandate. The newest and the largest North American thermal oxidation facility (Peele-Toronto completed in 2006, incinerating a mixture of raw and digested sludges) does not practice electricity recovery for similar reasons. This is in contrast to the European practice where electricity generation is of great interest due to higher unit energy costs. In the EU, the individual governments implement regulations to promote alternative energy generation ventures.

Conversion of the Town of Banff (Canada) plant to BNR (Westbank process) completed in 2005, provides an example of sludge liquor avoidance in smaller plants. The existing ATAD (auto-thermalpilic aerobic digestion) system was converted to raw sludge dewatering and composting, which eliminated the need for return sludge liquor treatment (G. Stevens, EarthTech, Kelowna, B.C., pers. comm.).

**Membrane Technology**

There is an increasing interest in application of membrane technology. Membranes have been used to filter effluent in competition with sand filters. The effluent solids contain phosphorus (e.g., 20 mg/L TSS usually carry 0.5 mg TP/L). The F. Wayne Hill Water Reclamation Facility is one of the plants serving Atlanta, Ga., which has recently been upgraded to BNR and expanded from 75 to 226 ML/d. Parallel tertiary granular tri-media filters and membrane filters (not membrane reactors) were compared. Both gave similar effluent concentrations of nitrogen and phosphorus (0.08 TP, 0.4 NH₄-N), however the membrane filtration process generated much lower effluent TSS. This was very important as the plant discharges to Lake Lanier, which is Atlanta’s prime drinking water source (Porter 2006).

A number of plants were built where the membrane replaced the final clarifier. The technology has been applied to plants under 40 ML/d, however, plants as large as 100 ML/d are now being designed. The most popular is the membrane bioreactor (MBR) where membrane cassettes are immersed directly in the aeration section of the BNR reactor. The largest MBR-BNR facility (at 35 ML/d) in the U.S.A. currently operates in Traverse City, Mich. (Daigger and Crawford 2005). In BNR plants the membranes are installed in a separate membrane tank. The largest plant in Europe operates in Brescia, Italy, and treats 42 ML/d in an MLE process, removing total nitrogen. Both plants feature Zenon Zee-Weed immersed membrane technology. As there is no clarification, the return streams are often arranged differently in MBR systems. Figure 7 illustrates the arrangement operating in Traverse City (adapted from Daigger and Crawford [2005]). The Westbank mode cannot be used, thus, a version of an MUCT process is adopted. The mixed liquor solids are first returned to the anoxic zone for denitrification before being sent to the anaerobic zone. The plant has to meet effluent TP <0.5 mg/L and NH₄-N <1 mg/L.

Although achieving excellent effluent clarity, the dissolved nutrient levels from the one-biomass BNR processes are subject to the same constraints as the conventional clarifier-based BNR system. Operating costs of the BNR reactor are much higher than those of a conventional activated sludge (Daigger and Crawford 2005; R. Dawson, Stantec, Winnipeg, Manitoba, pers. comm.), due mostly to high energy requirements.

**Limit of Treatment (LOT)**

Eutrophic estuaries such as Chesapeake Bay, Long Island Sound, closed bays such as Tampa Bay, ephemeral streams...
and oligotrophic lakes are extremely vulnerable to the smallest amounts of added nutrients. Currently, levels of TN <3 mg/L and TP <0.3 mg/L have to be met by many plants in the U.S.A. located on sensitive estuaries (Table 4 partly based on Pagilla et al. [2005]). Many of those plants have operated for decades (e.g., Reno, Nev., Fig. 4) and are multi-biomass rather than a one-biomass process (Wilson 2005). Takacs et al. (2005) demonstrated extremely low effluent ortho-P achieved routinely at Blue Plains and Noman Cole plants discharging to the fragile Chesapeake Bay. They pointed out, however, that side reactions lead to molar Fe/P ratios varying from 1/1 to 4/1 depending on the plant conditions. In large plants, such the Blue Plains for Washington D.C., precipitating phosphorus from a dry weather flow of 1400 ML/d, chemical costs are a very large item in the budget.

Phosphorus removal to below 0.3 mg/L is achieved most cost-effectively by a combination of EBPR and chemical trimming. Kelowna, B.C., was the first cold-climate biomass process utilizing EBPR and consistently met 0.25 mg TP/L, often without the need for filtration. A number of plants followed, e.g., Kalispell, Mont., routinely obtained an annual average of 0.11 mg TP/L after filtration, without chemical trimming (Barnard and Oleszkiewicz 2005; Emrick 2006).

A considerable amount of skill is required to achieve LOT effluent at low cost, with a minimum use of chemicals. This is because high removal of phosphorus may slow down biological nitrogen removal as the required minimum ortho-P levels for full denitrification are higher than stringent effluent levels (currently at 50 μg P/L). Some of the more important aspects of achieving LOT effluent quality are listed below (Oleszkiewicz 2006; Barnard 2006) for one-sludge BNR processes:

1. Keep SRT as low as possible—just enough to sustain nitrification.
2. Point-dose the soluble biodegradable COD generated in-plant through fermentation of primary sludge.
3. Avoid secondary release of phosphorus (e.g., in the first or secondary anoxic zone).
4. Remove O₂ and NO₃ from recycled streams (keep the redox potential low). In particular remove nitrates from streams returning to the anaerobic zone.
5. Use chemicals for P removal only after finishing with the biological P removal.
6. Assess the possibility of using hybrid processes—using inserted biomass media for biofilm formation.
7. Actively manage the redox (the effect of selectors) in the various zones.
8. Actively control NO₃-N and NH₃-N in zones. For example, complete removal of nitrates before the end of the anoxic zone may lead to secondary phosphorus release.
9. Manage biomass in the final clarifier, maintaining some level of denitrification, keeping clear of full nitrate removal to avoid P release.
10. Remove SS from effluent as they contain particulate P and N.

| TABLE 4. Examples of WWTPs achieving low TN and TP in the effluent in the United States |
|--------------------------------------|----------------|-------------|-------------|----------------------------------|
| Plant                  | Q (ML/d) | TN (mg/L) | TP (mg/L) | Process                                      |
| River Oaks, Fla.        | 38       | 1.4       | 0.30       | N/Post DN + chemical P                      |
| H. L. Mooney, Va.       | 68       | <3.0      | 0.10       | Separate stage DN packed bed + chemical P   |
| Durham, Oreg.           | 76       | N/A       | 0.05       | EBPR + chemical P                           |
| Piscataway, Md.         | 95       | 4.9       | 0.09       | Step-feed BNR with separate stage nitrification + chemical P |
| Truckee Reno, Nev.      | 151      | 1.74      | 0.3        | AS + NIT/DN + Phoredox + filtration + chemical P |
| Pinery Water, Colo.     | 12       | 5         | 0.03       | Bardenpho + chemical + filtration          |

Fig. 7. Configuration of a BNR membrane bioreactor system adopted in Traverse City, Michigan.
11. Dose the return sludge liquor in valleys of influent nitrogen load to maintain uniform nitrifier biomass distribution in the reactor. Practice nitrifier bioaugmentation.

12. Consider TN removal from sludge liquor without carbon (e.g., Anammox) or avoid sludge liquor altogether by using thermal oxidation or alternative processes.

Conclusion

The EU introduced minimum effluent (emission) standards in 1991 which led to implementation of biological nutrient removal. In North America (NA) a risk-based, immission approach is used (based on maintaining the receiver quality) although there were minimum emission standards adopted by states and provinces. As the EU moves towards immission standards, the trends are to further upgrade the effluent quality on both continents. The immission approach in NA led to very stringent requirements in vulnerable ecoregions and watersheds, with many plants required to deliver limit of treatment (LOT) effluent, e.g., TN = 1.5 mg/L and TP = 0.07 mg/L. The trends in the EU also point towards lowering the effluent nutrient levels to below those required by the Wastewater Directive, leading to lower discharge fees for the plant and better protection of eutrophic receivers.

In spite of local preferences for a particular BNR configuration, similar trends were observed in the EU and in NA. The most commonly used process is a one-biomass anaerobic/anoxic/aerobic configuration with RAS pre-denitrification, with many plants capitalizing on the simultaneous nitrification and denitrification (SND) in the racetrack configuration. Chemical phosphorus trimming is used to obtain lower than 0.3 mg P/L effluent and post-filtration is often used to lower the total phosphorus levels. Post-filtration is often combined with post-denitrification. A number of Scandinavian plants as well as several plants in NA feature multi-biomass (hybrid) systems utilizing auxiliary carbon for denitrification and chemical phosphorus removal. The new trends in the EU and NA include integrated and stand-alone biofilm and membrane technologies. Sludge liquor treatment for nutrient recovery (e.g., as struvite), novel processes of total nitrogen removal (e.g., Anammox), as well as generation of nitrifiers for bio-augmentation are being considered.

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Received: April 27, 2006; accepted: November 23, 2006.