APPENDIX

D

CONTAMINANTS OF EMERGING CONCERN IN WASTEWATER

MEMO

TO: CVRD TACPAC Committee

FROM: Indre Tunile, EIT, Al Gibb, P.Eng., WSP Canada Group Ltd.

SUBJECT: **CVRD LWMP - An Overview of Emerging Contaminants in Wastewater**

DATE: **September 20, 2019**

FILE: **18P-00276-00**

OVERVIEW

Contaminants of emerging concern (CECs), also referred to as micropollutants, emerging contaminants, emerging substances of concern, trace contaminants or microcontaminants, are the residual substances released to the water-soil-air matrix due to human activities in almost undetectable concentrations (low to sub-parts per billion (ppb)). Many of these substances are present in the natural environment and have been only recently detected, and the potential risks to public and environmental health are only now being evaluated. CECs can be divided into the following groups of chemicals:

- Persistent organic pollutants (POPs) such as diphenyl ethers (PBDEs; used in flame retardants, furniture foam, plastics, etc.) and other global organic contaminants such as perfluorinated organic acids;
- Pharmaceuticals and personal care products (PPCPs), including a wide suite of human prescribed drugs (e.g., antidepressants, blood pressure), over-the-counter medications (e.g., ibuprofen), bactericides (e.g., triclosan), sunscreens and synthetic musks;
- Veterinary medicines such as antimicrobials, antibiotics, antifungals, growth promoters and hormones;
- Endocrine-disrupting chemicals (EDCs), including synthetic estrogens (e.g.,17α-ethynylestradiol (EE2) used as an oral contraceptive) and androgens (e.g., trenbolone, a veterinary drug), naturally occurring estrogens (e.g.,17ß-estradiol (E2), testosterone), as well as many others (e.g., organochlorine pesticides, alkylphenols) capable of modulating normal hormonal functions and steroidal synthesis in aquatic organisms;
- Nanomaterials such as carbon nanotubes or nano-scale particulate titanium dioxide.

CECs as a group contain an extremely large number of chemicals with different origins. They can be polar (water soluble) or nonpolar (water insoluble), biodegradable or persistent, hydrophilic or hydrophobic and their physicochemical properties vary over a wide range (Mulder et al., 2015). For example, most PPCPs are antimicrobial agents designed to be persistent that mainly consist of polar molecules with molecular weights ranging from 150 to 1000 Daltons (DA) (Awfa et al., 2018).

Furthermore, CECs in wastewater are often found in a mixture where they can be transformed to other compounds and their synergetic and antagonistic effects are not yet known.

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REMOVAL IN WASTEWATER TREATMENT PLANTS

Conventional wastewater treatment plants (WWTPs) are designed to remove solid wastes, suspended solids, easily biodegradable dissolved organic matter and nutrients (phosphorus and nitrogen). Although conventional WWTPs are not designed to eliminate CECs from wastewater some CECs are being removed. The main mechanisms for CECs removal in conventional WWTPs are

- sorption onto particulate matter (CECs attach to particulate or colloidal particles),
- biological transformation (CECs are mineralized or biodegraded to other compounds),
- volatilization (transfer of CECs from water to air) and
- abiotic degradation (CECs are degraded through photolysis and hydrolysis) (Margot, 2015).

Relatively hydrophobic CECs such as heavy metals, polycyclic aromatic hydrocarbons (PAHs), POPs, several household chemicals like brominated flame retardants and several personal care products, are usually well removed from the liquid stream (> 70%), mostly by sorption onto sewage sludge (Margot, 2015). Easily biodegradable CECs such as surfactants, plastic additives, hormones, several PCPs, some pharmaceuticals and household chemicals, are also well removed during the treatment by biodegradation/transformation.

More hydrophilic and poorly-to-moderately biodegradable CECs are not well removed during conventional treatment. Many polar and hardly biodegradable substances, e.g., most pharmaceuticals, pesticides, and several household chemicals (corrosion inhibitors, sweeteners, ethylenediaminetetraacetate (EDTA), phosphorus flame retardants), are, however, not significantly removed even in modern biological treatments.

In general, the removal rates by various processes utilised in conventional WWTPs cannot be quantified due to varying operational conditions such as aerobic, anaerobic, anoxic, sludge retention time, hydraulic retention time, pH, redox potential and water temperature (Ray et al., 2017). As a result, different substances are removed in different degrees through different treatments at the different WWTPs. For example, removal rates from the conventional activated sludge process, as used at the existing CVRD WWTP, range from complete removal (e.g. paracetamol and ibuprofen) to poor removal (e.g. carbamezapine). The activated sludge process was also reported to be very sensitive to seasonal variations in temperature, with low removal efficiencies during the winter period (Luo et al., 2014). Furthermore, many CECs are able to pass through wastewater treatment processes due to their persistence and/or continuous introduction (Mulder et al., 2015).

ADVANCED TREATMENT TECHNOLOGIES

Advanced treatment processes such as adsorption using activated carbon, membrane technology (limited to lab-scale testing) and advanced oxidation processes using ozone are capable of removing more recalcitrant micropollutants with varying degrees of success. Table 1 summarizes the advantages and disadvantages of different treatment techniques reviewed.

Table 1 Assessment of different treatment processes for micropollutants removal (Adapted from Luo at al., 2014)

	COMMON REMOVAL EFFICIENCY				MAJOR FACTORS AFFECTING REMOVAL			
Technique	**P**	**PCP**	**SH**	**IC**	**Process-specific**	**CEC-related**	**Disadvantage/problems**	**Residues**
Activated Carbon	M-H	M-H	H	M-H	Adsorbent properties Dosage Contact time pH	Hydrophobicity Molecular size Structure Functional group	Relatively high financial costs Lower efficiency in the presence of organic mater Need for regeneration Disposal of used carbon	Used material
Ozonation	M-H	M-H	H	M-H	Dosage pH Interfering ions (e.g., Br- Wastewater composition	Compound structure	High energy consumption Formation of by-products Interference of radical scavengers	Residual
Nanofiltration	M-H	H	M-H	M-H	Membrane properties pH Feed quality	Hydrophobicity Molecular size	High energy demand Membrane fouling Disposal of brine Desorption of sorbed chemicals from membrane	Brine
Reverse Osmosis	M-H	H	H	H	Membrane properties pH Feed quality	Hydrophobicity Molecular size	High energy consumption Disposal of brine Corrosive nature of the finished water	Brine

P: pharmaceutical; PCP: personal care product; SH: steroid hormone; IC: industrial chemical; L: low; M: medium; H: high

Activated carbon is the most efficient adsorbent for the removal of CECs because of a very large surface area. Activated carbon treatment removes contaminants via the physical and chemical process of sorption. The contaminants accumulate within the pores of the AC granules and the removal efficiency depends on the activated carbon properties such as the surface area, pore volume and distribution of pore size, and the material used for production. The removal efficiency also depends on the CECs properties such as molecular size, charge and hydrophobicity. Activated carbon is very effective in removing non-polar compounds that are positively charged or neutral at wastewater pH (Krahnstöver & Wintgens, 2018). The removal of the negatively charged and neutral substances is more dependent on their hydrophobicity, the most hydrophilic compounds being eliminated to a lesser extent due to competitive adsorption (hydrophobic compounds are usually more easily and strongly adsorbed to activated carbon).

The two main types of activated carbon used in water treatment applications are granular activated carbon (GAC) with a particle size in the range of 0.5-4 mm and powdered activated carbon (PAC) with particle sizes below 50-100 µm (Krahnstöver & Wintgens, 2018).

There are multiple ways to upgrade an existing municipal WWTP with the activated carbon process for CEC removal.

GAC is mostly applied in fixed-bed absorbers (Figure 1), but it can also be used as a replacement of the upper layer in dual media filter (Krahnstöver & Wintgens, 2018). GAC material selection is critical as too coarse or too fine material may lead to rapid breakthrough (sorption capacity reached) or bed blocking (frequent backwashing), respectively. In general, GAC is simple to operate and the adsorbent can be regenerated and reused. Thermal regeneration, using rotary kiln or multiple hearth furnaces, is the most common method used to regenerate GAC. Organic matter within the pores of carbon is oxidized and thus removed from the carbon surface. Approximately 5 % to 10 % of carbon is destroyed during the process (Brooks et al., 2000).

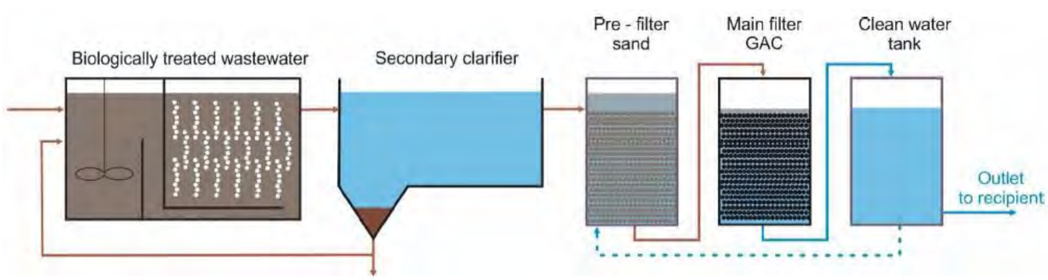

Figure 1: Example of a GAC system at WWTP (Source: Project MORPHEUS 2017 – 2019)

PAC can be dosed into the biological treatment stage or the secondary effluent. PAC dosage in the biological treatment is a low investment cost, however, higher PAC doses are required due to high concentrations of organic matter like biopolymers and humic substances in the biological sludge. In this scenario, the PAC particles are separated from the treated water together with excess sludge. Application of PAC generates additional sludge which is not able to be regenerated. PAC sludge will contain elevated concentrations of the contaminants which may affect suitability for application to land.

Lower PAC doses are required for the secondary effluent as there is less adsorption competition from organic matter. In this scenario, a separate process stage is installed (Figure 2), consisting of a contact reactor and a subsequent PAC separation step. At the entrance of the reactor PAC is dosed in the form of a feed slurry. To increase the adsorption efficiency the suspension is usually mixed by stirring or aeration. PAC is typically separated by a two-stage process consisting of the sedimentation and a filtration step such as deep bed filtration. Spent PAC is continuously removed from the system, and usually dewatered, dried and finally incinerated.

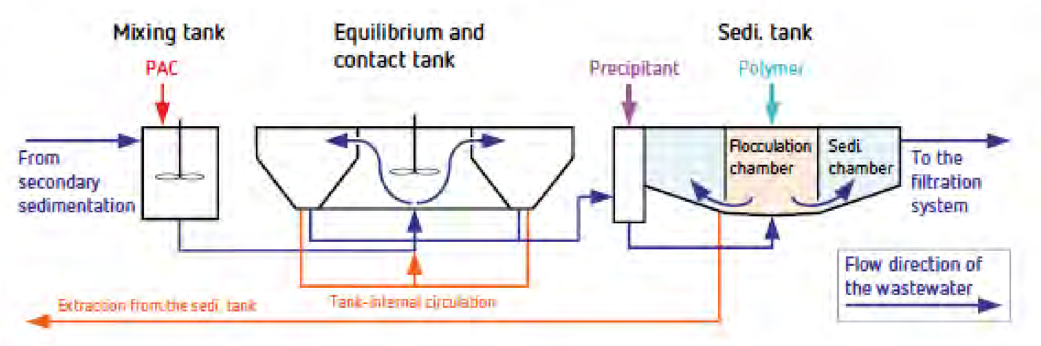

Figure 2: Example of a PAC system at WWTP (Source: Albstadt-Ebingen WWTP Fact Sheet)

Reverse osmosis and nanofiltration technologies have been found to be highly effective in removing endocrine disrupting chemicals, pharmaceuticals and personal care products but they are very expensive, and a portion of the water is lost as brine. Disposal of brine with elevated levels of CECs is a significant problem and the finished water has a corrosive nature (Rodriguez-Narvaez et al., 2017).

An ozonation step can be incorporated into an existing WWTP process. The ozone system consists of an ozone generator and a rector/contact tank (Figure 3). Ozone is generated on-site from pure oxygen or air through electrical discharge. After ozone has been generated it is mixed by injectors or diffusers with the wastewater in a contact basin. Ozone is capable of oxidizing CECs by a direct reaction with ozone or indirectly after formation of hydroxyl radicals (Mulder et al., 2015). Some CECs are more susceptible to ozone and others to hydroxyl radicals which are less selective.

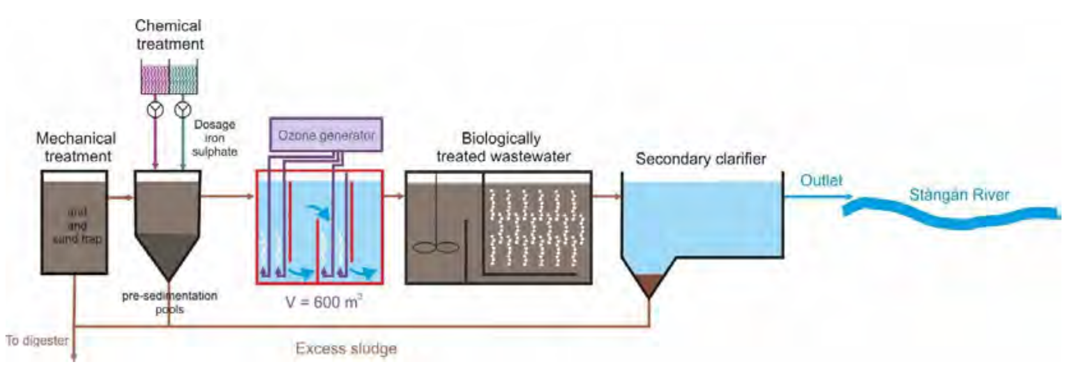

Figure 3: Example of ozonation system at WWTP (Source: Project MORPHEUS 2017 – 2019)

During the ozonation process, CECs and other substances present in the wastewater are transformed into more biodegradable compounds, and/or compounds that could potentially be harmful. As a result, the introduction of the ozonation step in the wastewater treatment process should be carefully evaluated especially for wastewaters that contain precursors for the formation of carcinogenic bromate, nitrosamines (NDMA) or formaldehyde. During the ozonation process, bromide is oxidized to bromate with increasing yields for increasing ozone doses. The ozone dose depends on organic matter and nitrite present in the wastewater that contribute to ozone demand (Krahnstöver & Wintgens, 2018). A study conducted at a full-scale ozonation treatment plant investigated the oxidation by-products and concluded that the concentration of bromate in ozone treated effluent is largely dependent on the initial bromide and bromate concentration in the incoming wastewater (Bourgin et al., 2018). Similarly, high concentrations of NDMA were detected prior ozonation and the formation had no correlation with ozone dose. Unlike NDMA that can be efficiently degraded in a sand filter, the filtration was ineffective in the reduction of the bromate concentration. Most of the ozonation transformation products cannot be quantified due to the lack of available standards. They are formed due to high ozone-reactivity with the parent compound and can be further transformed mostly by attack of hydroxyl radicals. Biological treatments proved to be inefficient in biodegrading ozonation transformation products, as these appear to be very stable compounds.

Operation of the ozone reactor requires staff training as well as specific safety measures due to the toxicity of ozone gas.

REGULATORY FRAMEWORK IN CANADA

The Wastewater Systems Effluent Regulations (WSER) is the only federal regulation that exists to control domestic wastewater releases. The WSER imposes minimum standards for municipal effluent quality nationwide. The regulations apply to wastewater systems that treat more than 100 m^3 of wastewater per day. The regulated compounds are suspended solids (TSS), carbonaceous biochemical oxygen demand (BOD_5), total residual chlorine, and un-ionized ammonia. In addition, wastewater effluents must not be acutely toxic at the point of discharge based on a 96-hour acute toxicity test for rainbow trout.

The provincial Municipal Wastewater Regulation regulates wastewater discharges to bodies of water in BC. Under this regulation, compounds such as pH, BOD_5, TSS, total phosphorus and ortho-phosphate are monitored, and their release to the receiving environment is controlled.

There are currently no federal, provincial or municipal regulations in Canada limiting the levels of CECs in wastewater effluent. The Fisheries Act is potentially the only regulatory tool that could be used to control the release of CECs. The Act prohibits discharge of substances that are deleterious to fish and is administered and enforced by Environment and Climate Change Canada.

While no regulations are currently in place, a Water Quality Guideline for Protection of Aquatic Life was created in 2018 for carbamazepine, a drug prescribed as an antiepileptic. The guideline recommends a maximum level for long-term exposure in freshwater systems of <10 ug/L.

Despite the lack of regulation to control CECs in wastewater effluent, the topic is in the forefront of communities and environmental protection organisations. In March 2018, the Canadian Water Network published a comprehensive report titled “Canada’s Challenges and Opportunities to Address Contaminants in Wastewater”. The report includes the review of existing policies and regulations nationwide, contaminants present in municipal wastewater and Canada’s options to deal with them. Given these developments, it is likely that additional guidelines, and possibly regulations will be created for other CECs in the future, though timelines are uncertain.

REGULATORY FRAMEWORK IN EUROPE

Switzerland is the only country where the removal of CECs is mandatory. A new law, effective January 2016, affects approximately 120 out of 650 treatment plants equating to 50% of the total wastewater in the country to implement an additional step by 2040 (Eggen et al., 2014). The driving forces for advanced treatment in a landlocked country like Switzerland are:

1 load reduction for downstream water use;
2 protection of sensitive waters (ecotoxicology); and
3 protection of drinking water resources (precaution) (water2020.eu).

The twelve indicator substances shown in Table 2 were chosen as non-easily biodegradable substances that exhibit poor removal during conventional wastewater treatment (Bourgin et al., 2018). These substances cover a wide range of toxicity. To meet the Swiss regulation the removal efficiency of selected indicator substances must be 80% on average over the whole WWTP from influent to effluent (WPO, 2018).

Table 2: Indicator substances for checking the performance of advanced treatment of CECs in Switzerland

	COMPOUND	COMPOUND CLASS
1	Amisulprid	Antiphsychotic
2	Carbamazepine	Anticonvulsant
3	Citalopram	Antidepressant
4	Clarithromycin	Antibiotic
5	Diclofenac	Analgesic / Anti-
6	Hydrochlorothiazid	Diuretic drug
7	Metoprolol	Beta blocker
8	Venlafaxine	Antidepressant
9	Benzotriazole	Corrosion inhibitor
10	Candesartan	Antihypertensives
11	Irbesartan	Antihypertensives
12	Mecoprop	Herbicide

The EU member states are required to monitor the prevalence of substances on the Watch List (priority substances in the field of water policy) that came into effect in September 2015. The current Watch List includes eight substances (Table 3) and the list is reviewed and updated every 2 years.

Table 3: CECs, including pharmaceuticals, antibiotics and hormones included in EU Watch List

	COMPOUND	COMPOUND CLASS
1	17-Alpha-ethinylestradiol (EE2)	Hormonal contraceptive
2	17-Beta-estradiol (E2), Estrone (E1)	Hormone
3	Ciprofloxacin	Antibiotic
4	Macrolide antibiotics (erythromycin, clarithromycin, azithromycin)	Antibiotics
5	Amoxicillin	Antibiotic
6	Methiocarb	Pesticide
7	Neonicotinoids (imidacloprid, thiacloprid, thiamethoxam, clothianidin, acetamiprid)	Insecticides

8	Metaflumizone	Insecticide

INSTALLATIONS WORLDWIDE

At present, there are eleven WWTPs in Switzerland that have implemented an additional treatment step (ozone-5; PAC-4; GAC-2) at full-scale for the removal of CECs such as hormones, pharmaceutical residues, etc., from wastewater (micropoll.ch). There are an additional twenty-two WWTPs that are under construction or in the planning/design phase.

Although, CEC removal is not mandatory in the EU, in Germany, France and Sweden an additional CEC removal step is already implemented at different WWTPs. In Germany there are twenty-two WWTPs that have implemented micropollutant removal processes (ozone-4; PAC-14; GAC-4) (micropoll.ch). In France all four WWTPs that adapted an additional step utilise ozonation process for the removal of CECs. In Sweden there are currently two full scale installations; ozone and GAC (MORPHEUS, 2017-2019).

In Canada, the J.R.-Marcotte WWTP in Montreal is undergoing major upgrades that include the installation of an ozone disinfection system to target bacteria, viruses and pharmacological toxins according to the Montreal Gazette. The plant treats 2,780,000 to 7,600,000 m^3 of wastewater per day and it currently only carries out primary treatment, removing solids and some nutrients. According to the Canadian Consulting Engineer website, the decision to add ozone disinfection was based on long-term research and public concerns for the environment; the quality of the effluent being released into the St Lawrence River. The cost of construction that is largely financed by the provincial and federal governments is estimated at $285M CAD. The project is two years behind schedule, and the new completion date is 2021.

FULL-SCALE CASE STUDIES

The following full-scale studies were adopted from the Project MORPHEUS report.

FULL-SCALE OZONATION SYSTEM

At the WWTP Neugut in Dübendorf, Switzerland, a full-scale ozonation system has been in effect since April 2014, as shown in Figure 4.

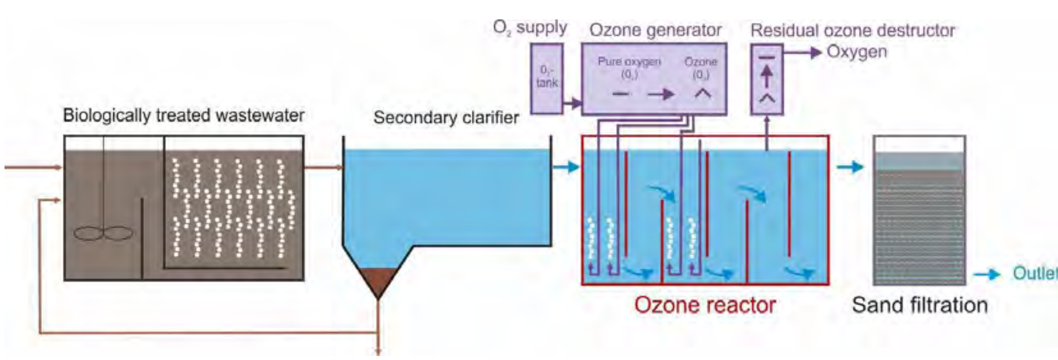

Figure 4 WWTP Neugut in Dübendorf with a full-scale ozonation system

The Neugut WWTP originally consisted of a primary clarifier, a conventional activated sludge treatment with a secondary clarifier, and a sand filter (Bourgin et al., 2018). The ozone system was installed between the secondary clarifiers and the sand filters. Some basic characteristics of the WWTP are listed below:

- **WWTP characteristics:** plant size: 155,000 PE (105,000 inhabitants and 55,000 industry); flow range: Q = 13,000–57,000 m^3/d; annual amount of treated wastewater: 21 million m^3
- **Ozone unit inflow wastewater characteristic:** COD = 16 mg/L; DOC = 5.3 mg/L; N_{NH4} = 0.08 mg/l; N_{N02} = 0.03 mg/L; pH = 7.4 mg/L; Q = 70–660 L/s
- **Ozonation unit characteristic:** pure oxygen tank 80 m^3; ozone generators: 2 x 5.5 kg O_3/h; ozone reactor: V = 530 m^3 (divided in two ozonation chambers with ceramic diffusers) water depth 6.0 m; mean residence time 37 min (min. residence time 13 min.)
- **Ozone dosage:** 0.33–0.50 g O_3/g DOC and 1.6–2.7 g O_3/m^3
- **Ozonation unit energy requirements:** pure oxygen 28 g/m^3; electricity: 0.024 kWh/m^3; entire plant: 0.42 kWh/m^3
- **Costs of ozonation:** Gross investment (excl. deduction of federal subsidy): 3.27 million CHF ($4.46M CAD); ozonation operating costs per year: 110,000 CHF/year ($150,000 CAD) including 40% pure oxygen; 20% electricity; 20% indicator compound analysis; 20% personnel and overheads
- **Removal efficiency of CECs:** average elimination of 12 indicator substances from wastewater and varied between 80% and 86%.

FULL-SCALE PAC ADSORPTION SYSTEM

WWTP Dülmen in Lippeverband, Germany, is a single-stage, conventional mechanical–biological wastewater treatment plant as shown in Figure 5.

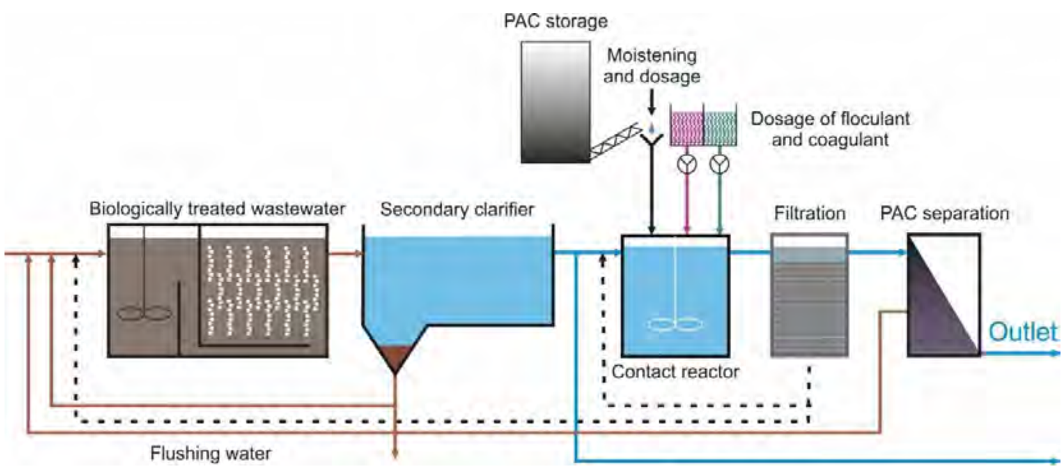

Figure 5: Scheme of the PAC system at WWTP Dülmen

The PAC unit consists of a contact basin (Vges. = 270 m^3), two converted filter cells, a newly built sedimentation basin (A = 360 m^2, V = 1440 m^3) and the remaining filter system (three filter cells). Before discharging into the receiving river Tiberbach, the clarification outflow is treated in the adsorption step for removal of CECs. Some basic characteristics of the WWTP are listed below:

- **WWTP characteristics:** plant size: 55,000 PE; flow range: Q = 10,800–17,300 m^3/d; annual amount of treated wastewater: 3 million m^3
- **Raw wastewater characteristics:** COD <60 mg/L; N_{total} <18 mg/l; P_{total} <1 mg/L
- **Applied PAC technology:** PAC storage and dosage system; PAC contact basin (V = 270 m^3), residence time: 22–150 min; PAC dosage from 10 to 20 mg /L; Sedimentation basin: V = 1470 m^3 (area = 370 m^2); three residual filter cells; filter type: two-layer spatial filtration (area per filter cell 28 m^2); Filtration speed: 7.5–13 m/h; treated wastewater flow: Q = 108–720 m^3/h
- **Costs:** the investment costs for the construction and adaptation of existing WWTP to PAC system was 4.0 million Euro ($5.9M CAD).

— **Removal effectiveness** of CECs ranged from 72 % to 97 %.

GAC FILTERING SYSTEM

The GAC filtering system was placed at the outlet of Kristianstad WWTP in Skåne, Sweden, as a fourth-stage treatment step, treating a fraction of the outgoing water as shown in Figure 6.

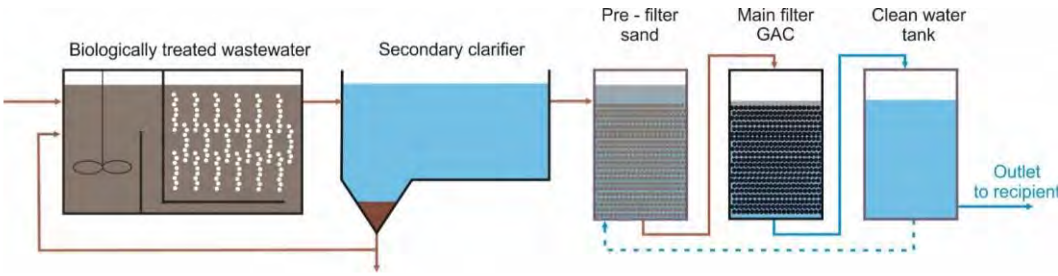

Figure 6: Scheme of the GAC filtering system at Kristianstad WWTP, Sweden

The GAC unit consists of pre-filter filled with 1 m^3 of sand to remove part of the organic material and thereby "protect" the GAC filter from high loads of such materials coming from the outlet water of the WWTP. The GAC filter has been in operation for more than 12 months. The sand filter was back-flushed around three to four times a week while the GAC filter did not need any backflushing during the entire year. Some basic characteristics of the treated outlet water at Kristianstad WWTP is shown below:

— **WWTP characteristics:** plant size: 118,000 PE; flow range: Q = 18,000–38,500 m^3/d; annual amount of treated wastewater: 8.4 million m^3
— **Conventionally treated wastewater characteristics:** BOD_7 =1.7 mg/L; N_{total} = 7 mg/L; P_{total} = 0.095 mg/L
— **Applied GAC technology:** pre-filtration through 1 m^3 sand followed by filtration through 1 m^3 of GAC. Flow: 2 m^3/h
— **Costs:** the cost for this add-on fourth stage filter was roughly 1 million SEK ($138,000 CAD)
— **Removal efficiency of CECs** is in most cases more than 90% after >20,000 bed volumes (BV).

According to the Project MORPHEUS, which investigated the full-scale advanced treatment technologies in Europe for the removal of CECs from wastewater, GAC technology has the lowest investment cost due to the simplicity of this technology's installation while ozonation and PAC treatments require relatively higher capital investment. However, GAC was found to be the most expensive to operate. The GAC costs are attached to regeneration or exchange of the material (usually after 6 months) and compared to PAC the higher amount of GAC is needed to achieve the same removal rates. The PAC system requires continuous dosage of PAC, coagulants and polymers as well as sludge treatment (dewatering and incineration). It should be noted that in Europe, incineration is a common and accepted method for sludge disposal.

In terms of energy demand, ozone technology usually requires double the energy of PAC treatment and up to twelve times more than GAC treatment.

CONCLUSIONS

- Contaminants of emerging concern (CECs) in domestic wastewater include a wide range of compounds with different characteristics that pose various risks to human health and the environment.
- Application of advanced treatment steps (ozone and/or activated carbon) for removal of CECs is currently being practiced in Europe and is expanding. Drivers for removal of CECs in Europe is largely due to the nature of the landlocked lake and river system and impacts of upstream discharges on downstream users.
- CEC removal effectiveness depends on the number of factors, but removal of indicator compounds in the range of 70% to greater than 90% have been demonstrated at full-scale plants.
- For powdered activated carbon (PAC) and ozone treatment, post treatment such as sand filtration is necessary to remove small PAC particles and oxidation by-products, respectively. Although granulated activated carbon (GAC) has the lowest investment cost, the necessity to regenerate or exchange material results in high maintenance costs.
- Wastewater treatment of CECs using activated carbon separates these pollutants from the liquid stream, but does not degrade or transform them. If GAC is used, high-temperature regeneration of the media will degrade most or all of the captured pollutants (this requires specialised regeneration facilities). If PAC is used, the captured CECs will be incorporated into the waste solids (sludge), which may make this material unsuitable for beneficial reuse such as compost production or land application. Ozonation will result in degradation of some CECs but may generate toxic by-products which may require additional treatment (filtration or activated carbon).
- Regulations relating to CEC removal are in place in Switzerland and a list of twelve indicator compounds has been identified. The EU has also developed a Watch List of eight compounds.
- No operating WWTPs were identified in North America specifically designed to remove CECs, although a plant is under construction in Montreal.
- Implementation of CEC removal technology should depend on the end use of the water or receiving environment, and must be considered together with solids handling practices.
- Similarly, implementation of CEC removal technology for a reclaimed water stream should depend on the end use of the reclaimed water, the potential risk to the receiving environment whether land, freshwater or marine, and must be considered together with solids handling practices.
- Ongoing research and development can be expected to continue advances in the detection, characterisation and control of CECs in domestic wastewater.

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APPENDIX

E

MICROPLASTICS IN WASTEWATER

MEMO

TO: CVRD TACPAC Committee

FROM: Tiffany Fong, P.Eng., Al Gibb, P.Eng.; WSP Canada Group Ltd.

SUBJECT: **CVRD LWMP – An Overview of Microplastics in Wastewater**

DATE: **September 20, 2019**

FILE: **18P-00276-00**

OVERVIEW

Microplastics (MPs) are present in air, soil, freshwater, marine environments, and biota and are quickly emerging as contaminants posing a potential risk to human health as well as receiving environments.

The purpose of this technical memorandum is to present the issues associated with MPs in the context of wastewater treatment and potential mitigating measures available as well as those still being explored.

DEFINITION

Microplastics is a term generally applied to plastic particles under 5 mm. Particles smaller than 0.1 micrometer (µm) are further classified as nanoplastics. For reference, the average diameter of a human hair strand is 50 µm.

There are between 13 and 30 types of MPs that have been identified in wastewater treatment plant (WWTP) influent and effluent streams, with polyester (PES), polyethylene (PE), polyethylene terephthalate (PET), polyamide (PA), polypropylene, and polystyrene being the most common. These are distributed among broad classifications including microfibers (derived from synthetic textiles), fragments (derived from the physical breakdown of macroplastics), nurdles (beads approximately the size of lentils), and microbeads (common in personal care products).

Defining properties of MPs include size, shape, structure, density, and polymeric composition. Shapes in various studies have been categorized as fiber (significantly longer than wide, typically 0.1 to 0.8 mm diameter), particles (similar width and length), irregular, spherical bead/pellet, flake, foam, and chip. MPs less than 300 µm are difficult to sample but are estimated to be numerous from sources such as paint chips and fibres from boat hulls in coastal marine areas (WRF Webcast, 2018).

SOURCE

The numerous sources of MPs include car tires, fisheries, textiles, personal care products, agriculture, and industry waste. These sources broadly categorize MPs as either primary or secondary based on their initial manufacturing purpose. Primary MPs are purposefully

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manufactured micro-sized particles for specific applications. Secondary MPs are indirectly produced from the breakdown of larger plastic waste or debris. Figure 1 below illustrates primary and secondary sources of microplastics discharging to marine environments from a study conducted in Norway.

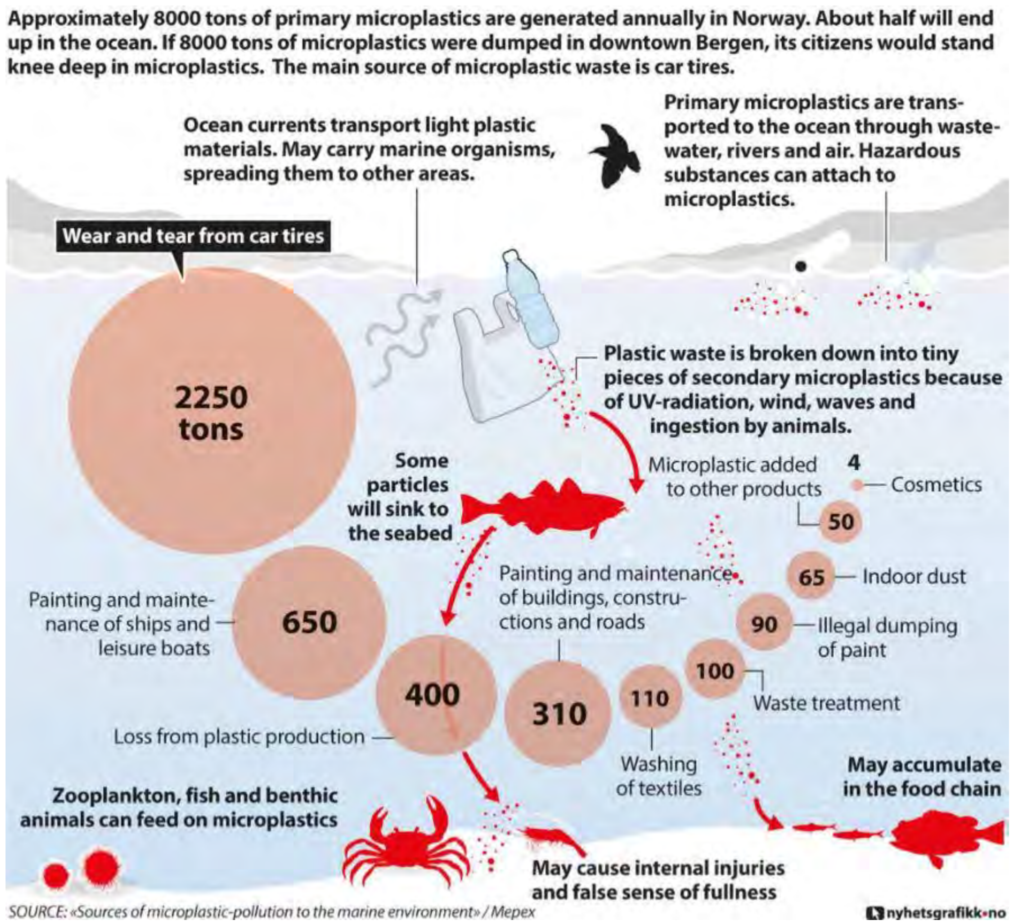

Figure 1. Typical Primary and Secondary Microplastics Sources and Loads in Norway (Mepex, 2018).

A news article recently reported on the presence of MPs in snow and rainwater samples in remote mountainous regions in Canada and the US (Desai, 2019). The article emphasizes that MPs found in these regions have likely been transferred from urban centres, in a similar way dust would be transferred due to the buoyancy associated with their small size.

Some studies reported that municipal WWTPs and water resource recovery facilities are the largest sources of MPs entering aquatic system in the US (WRF Fact Sheet, 2018). So, while Figure 1 identifies car tires as the main source of MPs entering the marine environment in Norway, given the varying conclusions provided by different reports, it is evident that there is not yet enough research available to confidently establish a single source contributing the highest quantity of MPs.

The predominant source of MPs entering WWTPs is microfibres from washing of textiles (such as polyester fleece garments), which accounts for approximately 50-70% of MPs entering WWTPs (Gies et al., 2018).

EFFECTS

A 2019 report presented by the World Health Organization (WHO) indicates that potential health risks associated with MPs have not yet been well-defined and have so far been found to pose low concern for human health (WHO, 2019).

However, the 2019 report does describe some potential negative effects associated with MPs. These come in three forms: physical from the particles themselves, chemical from their composition and potential for leaching, and biofilms that may form and cause MPs to act as microorganism carriers (WHO, 2019).

- The physical effects of MPs on organisms ingesting MPs can yield more negative impacts than chemical toxicity (WHO, 2019). The physical size and shape of MPs can impede breathing and can also lead to physical intestinal damage.
- MPs may contain a range of potentially harmful compounds including benzene, xylene, ethylene, propylene, and their derivatives, as well as chemicals added during the plastic production such as bisphenol A and S, and phthalates. When plastics break down, they can release toxic compounds including polyaromatic hydrocarbons (PAHs) and polybrominated diphenyl ethers (PBDEs). Many of these chemicals are regulated as they are known to be endocrine disrupting chemicals (EDCs).
- MPs can act as carriers by adsorbing and transporting toxic chemicals and pollutants such as polychlorinated biphenyl (PCBs) (coolants), PBDEs (flame retardants), and other persistent organic pollutants.

One study indicated that zooplankton in the NE Pacific Ocean are readily ingesting MPs, which raises the question of the accumulating effects further up the food chain (Gies et al., 2018). MPs are small enough that they can be mistaken for food by insects, plankton, fish, and other aquatic life. It appears the approximate size at which MPs become ingestible to aquatic species and may subsequently have potential biotoxic effects is 20 µm (approximately the size of one white blood cell).

The effects of MPs on human health as well as other biota and WWTP receiving environments are difficult to identify for a number of reasons, primarily:

- The diversity in the chemical and physical properties of MPs makes it challenging to distinguish, isolate, enumerate, and characterize MPs in organic matter-rich wastewater. The shape of MPs has been identified as one of the characteristics that heavily influences removal efficiencies in WWTPs..
- Risk is generally understood to be a function of exposure and hazard. Most studies tend to focus on the level of exposure, but there appears to be limited studies on the toxicity hazard of MPs (WHO, 2019). More research is needed on the toxicology of MPs and the overall relevance for freshwater resources, drinking water, and human health.

In summary, the effects of MPs on human and environmental health are not well understood and research is ongoing.

MUNICIPAL WASTEWATER TREATMENT PLANTS

Municipal WWTPs are among the largest point sources of MPs into aquatic systems. However, wastewater treatment plants do not generate MPs. Instead, they receive MPs collected from sewerage systems prior to discharging to the receiving environment, thus acting as a point source. (Gies et al., 2018). It is important to also note that WWTPs capture a significant amount of MPs prior to discharge, as described below.

REMOVAL EFFICIENCY

On average, it has been found that WWTPs with primary and secondary treatment can remove between 80-95% of MPs, depending on the MPs size and wastewater quality (i.e., amount of fats, oils, greases to entrap and remove MPs during sedimentation); this removal efficiency increases to about 97% with tertiary treatment (Sun et al., 2019). While this appears to be significant removal, the percentage not removed by WWTPs still results in large overall loads to the receiving environment due to the high volume of wastewater treated (SAPEA, 2019).

Figure 2 illustrates the estimated average removal rate of MPs at various units through typical wastewater treatment processes.

One study reported that Vancouver-area WWTPs remove about 1.8 trillion plastic particles in wastewater per year, but still release 30 billion particles to the ocean (approximately 98% removal) (Gies et al., 2018). For reference, one study quantified microbeads present as exfoliants in personal care products numbered between 137,000 to 2.8 million per 150 mL bottle (Napper and Thompson, 2015). Loads range depending on the treatment processes available and testing methods employed.

Characterization of MPs in wastewater and finding mitigating measures that encompass a large variety of loading scenarios is difficult due to the daily, diurnal, seasonal, and annual fluctuations in MPs loading and subsequent discharge by WWTPs. However, certain MPs shapes have found to be better captured during specific stages of treatment (i.e., pre-treatment is more effective at capturing fibers; skimmers from primary sedimentation are effective in capturing microbeads; fragment particles removed through secondary treatment) (Sun et al., 2019). There have been some studies indicating that the concentration of MPs has been reduced through WWTPs where sludge has been treated by anaerobic digestion (Prata, 2018).

During conventional wastewater treatment, the majority of MPs are captured as a component of the solid fraction during sludge removal processes (Sun et al., 2019). While this does not remove MPs entirely, it does divert a large portion from directly entering receiving environments via liquid discharges. Depending on the end use of biosolids (e.g., if land application of biosolids is used), MPs may still enter aquatic environments through surface runoff or may remain in terrestrial environments (Kay et al, 2018).

A potential option for targeting MPs removal from WWTPs without revising infrastructure would be to adjust relevant operational parameters of current wastewater treatment processes to improve MPs removal efficiency. For example, adjusting hydraulic retention time (HRT) to improve skimming and sedimentation in primary treatment units, contact time during secondary treatment increasing potential for surface biofilm coating to develop on MPs which can increase settlement, or amending chemical additives to be Al-based as this was shown to improve removal efficiency compared to Fe-based flocculants/coagulants (Sun et al., 2019). This option has yet to be explored to determine its viability and effectiveness.

No studies investigating the possible role of MPs in increasing exposure to pathogens were identified. However, once in the WWTP, the presence of MPs could interfere with the effectiveness of disinfection treatment.

Overall, no specific treatment process aimed at MPs removal has been implemented at a full-scale WWTP yet, and MPs-targeted treatment technology is still at the preliminary research stage (Sun et al., 2019).

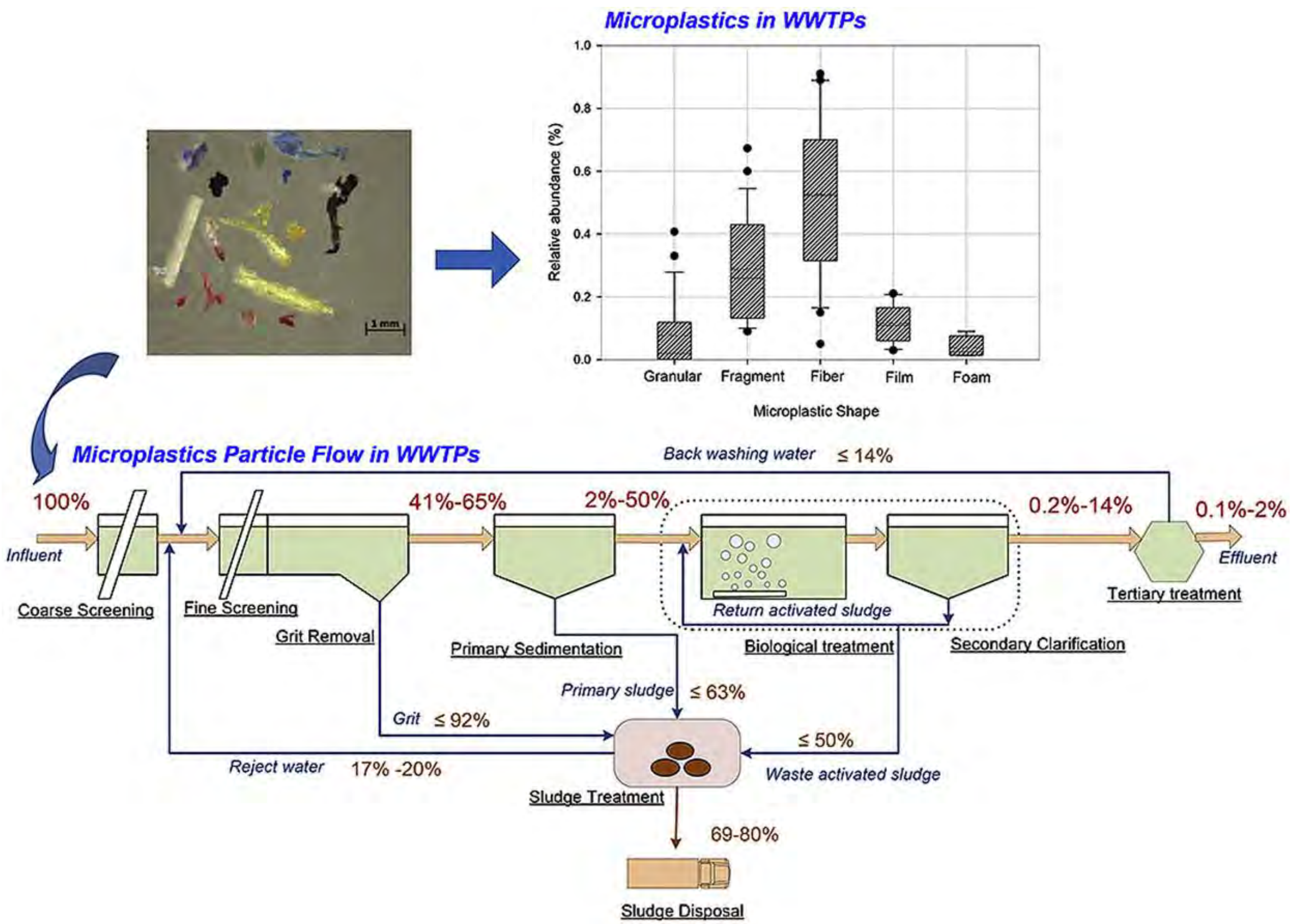

Figure 2. Estimated Average Microplastics Removal Rate Through Wastewater Treatment Plant with Primary, Secondary, and Tertiary Treatment Processes (Sun et al., 2019).

REGULATORY FRAMEWORK IN CANADA

Due to the limited framework, lack of standardized testing, inconsistency in studies performed to date, and the consequent limitations for comparing results, it has been difficult to develop regulations establishing the presence and quality of MPs in wastewater. Microbeads in most toiletries were banned in Canada effective July 1, 2018. While microbeads represent a small portion of overall MPs, it is an effective first step in reducing primary MPs sources.

An interview was conducted for this TM with Dr. Peter Ross, Vice President of Ocean Wise and Executive Director of the Coastal Ocean Research Institute (CORI), and a member of his research team studying microplastics. Their current research efforts are focussed on advancing sample analysis methods to find a way forward for comparing studies on MPs and informing policy makers and regulators.

The Province of Ontario is currently the leading Canadian jurisdiction undertaking monitoring for MPs. Scientists in the Ministry of the Environment and Climate Change (MOECC) are doing their own studies and working with academic researchers in Canada and the US to get a better understanding of MPs in the Great Lakes. These studies, however, are focussed on characterizing MPs and their load into the Great Lakes, as well as their fate and behaviour once in the Great Lakes, but do not address any standards for removal in wastewater treatment plants (Province of Ontario, 2019).

CONCLUSION

Microplastics are ubiquitous in air, aquatic, and terrestrial environments and come from a wide range of sources, both point and non-point sources. Due to their small particle buoyancy, MPs act as dust and can be transported in large quantities to sinks, such as aquatic environments and snow packs, through the atmosphere. So, while it appears that WWTPs discharge large quantities of MPs, it is important to remember that there are other sources potentially contributing far greater quantities to receiving environments, and that WWTPs are collectors rather than sources of MPs.

While no wastewater treatment process has been identified to specifically address MPs removal, conventional processes associated with sludge removal such as primary and secondary treatment appear effective in removing 80-95% of MPs entering the treatment process. Tertiary filtration could improve removal efficiency to around 97%, resulting in approximately 3% of the total load of MPs entering WWTP being discharged to the environment with effluent. However, it is important to note that MPs removed from wastewater streams are generally incorporated into the waste solids generated at WWTPs.

Risk is a function of exposure and hazard. Biosolids removed from WWTPs is often land applied, which can then release MPs into either aquatic or terrestrial environments. Both environments leave MPs susceptible to exposure or uptake by biota. While potential risks have been identified, there have been no studies that have confirmed exposure to MPs results in negative toxicological risk to biota or human health. Many studies are currently focussed on exposure, but there are not yet enough studies that provide definitive conclusions on hazards.

A Nova Scotia company design, manufactures, and sells a washing machine discharge filter called “Lint LUV-R” which is marketed to remove lint and untreatable synthetic solids from washing machine discharge. While this product will not eliminate MPs from entering the environment, it is intended to divert MPs to the landfill rather than aquatic environments.

Microplastics have been found to be difficult to analyse, and as a result there is a lack of standards of practice which makes comparison between studies challenging. A more universal protocol for sample preparation is required in order to compare results, including standard methods for collecting, identifying, analyzing, and determining toxicity and bioaccumulation.

Aside from the banning of microbeads in Canada and certain jurisdictions throughout the US, due to the difficulty in establishing analysis standards, regulations have not been developed to address MPs let alone regulations specific to WWTPs' removal or treatment of MPs.

At present, while several strategies have been proposed to reduce environmental contamination with MPs overall and by WWTPs, source control and reduction appear to remain the most economical and efficient method.

Given that studies in MPs are currently in a development state, there are no specific processes that are recommended for the CVRD WWTP upgrade to specifically address MPs. With secondary treatment already in place, it is likely that the CVWPCC is removing the typical range of 80-95% of MPs from the effluent stream and incorporated into the waste solids sent to composting.

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APPENDIX

F

VIRUSES IN WASTEWATER

MEMO

TO: CVRD TACPAC Committee

FROM: Tyler Barber, P.Eng., Al Gibb, P.Eng., WSP Canada Group Ltd.

SUBJECT: **CVRD LWMP – An Overview of Viruses in Wastewater**

DATE: **September 24, 2019**

FILE: **18P-00276-00**

OVERVIEW

VIRUSES OF CONCERN

A variety of viruses are present in domestic wastewater and these pose various risks to humans and the environment. Some studies report that wastewater contains the largest quantity of virus diversity, including viruses that have yet to be characterized or placed into specific taxa of organisms (Cantalupo, et al. 2011). The large diversity of viruses, along with difficult sampling processes, and threats posed to human health has led to significant research efforts into the field of identifying and quantifying viruses and virus inactivation. In the following memorandum we have presented the current state of the science for waterborne viruses and the means that exist to remove them from domestic wastewater.

The viruses of concern in wastewater generally researched are those that affect humans either via the waterborne route or through food that has come into contact with contaminated water. These viruses are enteric viruses as they are transmitted via the fecal-oral route, and thus are generally found in water contaminated with wastewater (Haramoto, et al. 2018). Enteric viruses are some of the most hazardous waterborne pathogens and cause outbreak related illnesses such as gastroenteritis issues (i.e. stomach flu), however more sever illnesses such as hepatitis, skin disease, and death have been reported (La Rosa, et al. 2012).

Viruses can be difficult to target for removal because they have an ability to adapt to new hosts and environments and have been reported to survive and remain infective for up to 130 days in seawater. Certain viruses also have very low infectious doses so that even a few viral particles can pose health risks (La Rosa, et al. 2012).

Viral pathogens that are believed to be transmitted through water include the viruses listed in Table 1. Also shown are the potential health risks from exposure.

Table 1: Human viruses potentially transmitted by the waterborne route (La Rosa, et al. 2012).

VIRUS GROUP	***DISEASE CAUSED***
Norovirus	Gastroenteritis – which includes vomiting, abdomen pain, diarrhea, fever, etc.
Human Enterovirus A-D	Respiratory disease, hand-foot-and-mouth disease, heart anomalies, etc.
Hepatitis A Virus	Hepatitis
Human Adenovirus A-G	Gastroenteritis, respiratory disease, etc.
Hepatitis E virus	Hepatitis
Influenza A virus	Influenza
Human coronavirus	Gastroenteritis, respiratory disease, etc.
Human polyomavirus	Skin diseases, nephropathy, etc.
Human picobirnavirus	Diarrhea
Papillomavirus	Skin warts, cervical cancer, etc.
Rotavirus	Gastroenteritis

Of these viruses the most researched with respect to wastewater appears to be norovirus. Norovirus is considered one of the leading causes of acute gastroenteritis worldwide and the leading cause of both gastroenteritis and foodborne infection in the United States. Among reported outbreaks between 2009 and 2012 in the United States, 69% were person-to-person, 23% were foodborne, 0.4% were environmental, and 0.3% were waterborne (National Advisory Committee on Microbiological Criteria for Foods 2016). The most common foodborne outbreaks are associated with leafy greens, estimated at 36% (National Advisory Committee on Microbiological Criteria for Foods 2016).

British Columbia recently had an outbreak of norovirus in 2018, with raw BC oysters being the culprit for an outbreak of acute gastrointestinal illness and two oyster farms that were implicated in the outbreak were closed (BC Centre for Disease Control 2018). The two oyster farms were located in the south and central Baynes Sound area, west of Denman Island and the cause of the outbreak is suspected to be sewage contamination near the shellfish (CBC 2018). Bivalve shellfish are affected by human viruses from filter feeding contaminated water and bioaccumulating the virus. These shellfish may include clams, geoducks, mussels, scallops, and oysters (Washington State Department of Health n.d.).

VIRUS ANALYTICS

Viruses are not a standard measurement in wastewater treatment and require specialty testing in laboratories to identify concentrations of viruses in water, and often these measurements can be costly and time consuming. The microbiological science has improved greatly in recent years and numerous methods have been developed based around the qPCR method (quantitative polymerase chain reaction), which identifies specific genomes of viruses that are present in a sample (Haramoto, et al. 2018). However, these methods have shortcomings in their ability to identify numerous types of viruses in a single sample as some of the methods can lead to inhibition of some of the viruses. Additionally, the detection methods indicate quantities of viral genome copies found in a sample and these quantities may not be related to the number of active virus particles that are infectious (Pouillot, et al. 2015). To determine if a virus is infectious, the virus needs to be grown in a stable environment in the lab on petri dishes and the number of plaque forming units (PFU) is determined, representing active infectious viruses, the concept is similar to coliform forming units (CFU) used to quantify bacteria.

In wastewater treatment, the generally accepted microbiological parameter for measurement is CFU's (or Most Probable Number, MPN) of fecal coliforms and *E.coli*. These bacteria are considered indicator organisms and act as a surrogate to indicate the presence of fecal contamination, and therefore a strong likelihood of the waterway containing enteric viruses. However, recently many studies have shown that these indicator organisms may not be indicative for viruses and new methods should be considered (USEPA 2015). There is published literature of researchers attempting to find more appropriate indicator organisms for viruses. The U.S. Environmental Protection Agency (USEPA) has suggested that Coliphages are a type of virus that infect *E. coli* and can be used as virus indicator organisms (USEPA 2015).

The measurement and activity of norovirus in a sample is of interest due to the virus' effect on shellfish and the inability to measure the virus via culturable methods. Male-specific coliphages (MSCs) have been suggested as an indicator for norovirus because they are readily found in wastewater, have a similar size and shape to norovirus, are RNA-based, and can be cultured so that the reduction of infectious particles can be measured (Pouillot, et al. 2015).

REMOVAL OF VIRUSES IN WASTEWATER TREATMENT

All stages of wastewater treatment contribute to the removal of viruses from the liquid stream. Viruses can be entrained in the solids and separated during physical separation processes in the primary and secondary treatment stages of wastewater treatment. With the inclusion of a disinfection process, it is thought that UV or chlorine disinfection provide adequate disinfection of the wastewater to remove bacteria and viruses. UV disinfection is the increasingly popular treatment process because of it's simplicity to dose the water and lack of by-products produced. When chlorine is used in disinfection the chlorine can react with organic matter in the water to form disinfection by-product's (DBP's) that can be carcinogenic. Residual chlorine in the water can also be toxic to species in the receiving environment, therefore de-chlorination of the wastewater is required after chlorination to meet regulations.

The viruses of concern studied (listed in Table 1) have an assortment of DNA and RNA structures that make up the organisms. Certain viruses have double stranded RNA that makes them resistant to UV light inactivation, other viruses have single stranded RNA that have high heat resistance, but are less resistant to chlorination than other viruses (Fong and Lipp 2005). The varying degree of resistance of different viruses makes total inactivation difficult for a single treatment technology. However, studies have been done that show activated sludge treatment of wastewater registered concentrations of single RNA stranded norovirus and astrovirus below the detection limits after UV disinfection, although trace levels of rotavirus and adenovirus were still detectable after UV disinfection (Lizasoain, et al. 2018).

A third form of disinfection is using ozone as an oxidizing agent as it is a very strong oxidant and viricide. It is the least used method in the United States in wastewater treatment, however it has been used widely in Europe for an extensive amount of time (USEPA 1999). Researchers have shown ozone disinfection to be more effective than conventional methods (UV and Chlorination), although further research is required into the effectiveness on both bacteria and viruses. Tyrrell et. al showed ozone disinfection as more effective for virus removal than chlorination, however less fecal coliforms and *E. coli* were removed by ozone when compared to chlorination in the study (Tyrrell, Rippey and Watkins 1995).

Ozone is a more complicated disinfection practice typically requiring onsite generation and treatment of any off-gas that may contain ozone, it is very reactive, produces disinfection by-productions, is corrosive requiring corrosion resistant materials, and the system can be relatively high in capital and operating costs. Ozone, if not handled properly can also be toxic substance and pose a risk to workers health. These issues with ozone disinfection have led the technology to be one of the least used for disinfection in North America. (USEPA 1999).

A fourth type of disinfection that is relatively new and has increased in use in wastewater treatment in the last 5 – 10 years is peracetic acid (PAA). This disinfection process is used locally at the Metro Vancouver Northwest Langley WWTP. PAA is a combination of acetic acid and hydrogen peroxide, which react to form peracetic acid and water, and is shown to be a strong oxidant and virucide (not as strong as ozone) (U.S. Environmental Protection Agency 2012). However, unlike chlorination, PAA does not form DBP's and has a generally lower aquatic toxicity (Bell and Wylie 2016). PAA's also require similar dosing concentrations and contact time to that of chlorination, are expected to have similar costs, and the effectiveness depends on the wastewater quality and contact time (U.S. Environmental Protection Agency 2012). Information regarding PAA's removal of viruses, specifically norovirus in wastewater, is limited. However, the general thought is that PAA is as effective or better than chlorination for norovirus inactivation, providing significant reduction in the infectivity of norovirus indicator organisms on fruits and vegetables after one minute (Girard, et al. 2016).

REGULATORY FRAMEWORK IN CANADA

The current regulations affecting wastewater treatment in the CVRD are the Provincial Municipal Wastewater Regulation (MWR) and Federal Wastewater Systems Effluent Regulation (WSER). Neither of these regulations specify maximum allowable virus concentrations for discharge to receiving environments, but rather specify indicator fecal coliform concentrations depending on the type of discharge. Discharges to shellfish marine waters require a disinfection limit of 14 MPN/100 mL at the edge of the initial dilution zone (IDZ) and discharges to recreational waterways requires 200 MPN/100 mL.

The Provincial MWR also outlines quality requirements for reclaimed water uses depending on the end use and risk to public health. An application where the public may come into contact with reclaimed water would have more stringent quality requirements than an application where only trained personnel may come into contact with the reclaimed water. A 'Greater Exposure Potential' use of reclaimed water is defined as one where public contact is likely or that presents a risk to the receiving environment, which could include things like golf course or agricultural crop irrigation. For uses of reclaimed water that fall into this category, the regulation requires virus removal, however, the regulation does not identify specific viruses of concern, nor does it specify removal rates.

We are unware of any current considerations to change the wastewater regulations with respect to viruses in the immediate future. It is likely that further research is required to determine suitable indicator organisms for active viruses before concentration limits would be specified in regulations. Based on the current regulatory framework, it is assumed that meeting the indicator organism concentration of 14 MPN/100 mL at the edge of the IDZ for discharges in shellfish bearing waters will reduce virus concentrations to acceptable levels that will not cause outbreaks from contaminated food and water.

CONCLUSIONS

The research into viruses and their effects on the environment is continually developing. The presence of the actual viruses in wastewater is extremely variable, and this complicates supply and analysis (analysis is also costly). Indicator species as MSC's are more consistently present, analysis is less costly and this appears to be the most practical approach for evaluating the effectiveness of wastewater treatment processes in deactivating viruses. The use of indicator viral organisms for viruses such as norovirus may be included in regulations in the future to determine the true infectiousness of a wastewater discharge.

The recent shellfish contamination of norovirus in BC waters was attributed to wastewater discharges, however it is unclear if these discharges were meeting the 14 MPN/100 mL fecal coliform requirement. In general, it appears that the current regulatory framework helps to minimize waterborne and foodborne outbreaks in BC, but improvements may be required as further research is completed.

As discussed previously, there is little correlation between indicator bacteriological organisms and viruses. WSP is working with another nearby municipality, who currently use chlorination as disinfection, to develop a pilot UV disinfection program targeting viruses as they discharge to shellfish bearing waters. Chlorination is generally more effective at inactivating viruses than UV light, however after chlorination the Town is required to de-chlorinate their effluent, making the process costly, and there are additional risks from chlorination such as chlorinated disinfection by-products and chlorine toxicity to fish. This pilot program has not yet begun; the objective will be to investigate the effectiveness of UV and chlorination on norovirus and potential norovirus indicators, such as male-specific coliphages.

To help alleviate some risks for the CVRD, it will be important that the wastewater treatment plant incorporates the most appropriate wastewater disinfection technology, that it is properly designed, ensuring the indicator organism concentration can be met in the discharge. Considerations can be given into providing a more advanced oxidation process for the CVRD treatment system such as ozone disinfection or a combined two-stage disinfection process such as UV and chlorination, depending on the available research and applicable guidelines at the time of design.

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